# Influence of gypsum panels on the response of cold-formed steel framed shear walls

**By**

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## ABSTRACT

Gypsum panels can be used as structural elements in cold-formed steel (CFS) framed shear walls to resist in-plane lateral loads. More commonly, however, gypsum panels are specified to solely provide sound-proofing and fire resistance, and hence are not accounted for in the structural design. Research has shown that gypsum-sheathed walls can provide in-plane lateral resistance and stiffness regardless of whether the gypsum is intended to act as a structural or non-structural component. On the one hand, the additional lateral resistance provided by the gypsum can be beneficial since a more economical design can be achieved. On the other hand, if the gypsum panels are not taken into account in the design, the additional stiffness provided by the gypsum may lead to increased seismic loads on the building. Moreover, in the current AISI S213 and S400 North American Standards for the seismic design of CFS framed structures the design must follow a capacity-based approach in which the resistance of all the members in the lateral load carrying path is greater than the probable resistance of the fuse element(s) combined with the gravity loads. Thus, the unaccounted lateral resistance provided by the gypsum panels can increase the resistance of the fuse element(s) and lead to an unexpected and possibly non-ductile failure in the other members of the lateral load carrying path.

In the AISI S213 and S400 Standards, values for the nominal resistance and overstrength factor of wood, steel and gypsum sheathed shear walls are given, but have a limited range of application (e.g. 12.5 mm thick gypsum). No recommendations are provided to take into account the influence of gypsum in strap-braced walls, or the effect on probable capacity forces. The first objective of this thesis is to conduct a test program in order to obtain design values with respect to the nominal and maximum in-plane shear resistances, as well as the stiffness, of 1-hour and 2-hour fire resistance rated gypsum-sheathed strap-braced shear walls, gypsum-sheathed shear walls and gypsum-sheathed gravity-carrying walls. The second objective is to create a numerical model representing the behaviour of the tested gypsum-sheathed walls. A total of 35 2.44 m x 1.22 m walls were sheathed with different configurations of 15.9 mm-thick gypsum panels and then tested under in-plane lateral loading. Nominal values to be used in the design of gypsum-sheathed walls were found as well as methods to predict the probable resistance of gypsum-sheathed walls for capacity-based design. Numerical models of the walls were obtained with OpenSees and can be used to incorporate the effect of gypsum panels on walls in a full building model.

# RÉSUMÉ

Les panneaux de gypse peuvent être utilisés en tant qu'éléments structuraux dans les murs à ossature en acier formé à froid pour résister aux charges latérales. Cependant, il arrive souvent que les panneaux de gypse soient uniquement employés pour l'isolation sonore et la protection incendie, et ne soient pas pris en compte dans la conception et le dimensionnement de la structure. Des recherches ont montré que les panneaux de gypse peuvent augmenter la résistance et la rigidité des murs, qu'ils aient été conçus pour agir comme éléments structuraux ou non. D'une part, la résistance latérale supplémentaire fournie par les panneaux de gypse permet de concevoir des solutions plus économiques. D'autre part, si les panneaux de gypse n'ont pas été pris en compte dans le dimensionnement, la raideur supplémentaire qu'ils apportent peut entraîner une augmentation des demandes sismiques sur le bâtiment. De plus, dans les Standards nord-américains AISI S213 et S400 pour la conception parasismique des structures à ossature en acier formé à froid, il est recommandé d'adopter une approche fondée sur la capacité (capacity design) où la résistance de tous les éléments participant au transfert des charges latérales doit être plus élevée que la résistance de l'élément fusible combinée aux charges de gravité. Par conséquent, la résistance latérale des panneaux de gypse non prise en compte peut augmenter la résistance de l'élément fusible et engendrer la rupture imprévue et potentiellement non ductile des autres membres du transfert des charges latérales.

Dans les Standards AISI S213 et S400, les valeurs de la résistance nominale et du facteur d'amplification pour les murs de refend en bois, acier et gypse sont fournies mais ont un champ d'application limité (par exemple pour les plaques de gypse de 12.5 mm d'épaisseur). Il n'y a pas de recommandation afin de prendre en compte l'influence du gypse sur les contreventements en treillis ou sur la capacité probable du fusible. Le premier objectif de ce mémoire est de mener un programme expérimental afin d'obtenir des valeurs de design concernant les résistances et les raideurs latérales nominales et maximales : de murs à contreventements en treillis, de murs de refend et de murs porteurs, tous couverts de plaques de gypse coupe-feu 1h ou 2h. Le second objectif est de créer un modèle numérique représentant le comportement des murs couverts de plaques de gypse testés. Trente-cinq murs, de dimensions 2.44 m x 1.22 m, ont été recouverts selon différentes configurations de panneaux de gypse de 15.9 mm d'épaisseur avant d'être testés sous charges latérales dans le plan du mur. Des valeurs nominales à utiliser dans le dimensionnement

des murs couverts de plaques de gypse, ainsi que des méthodes de prédiction de leur résistance maximale probable, ont été trouvées. Des modèles numériques des murs ont été obtenus avec OpenSees et peuvent être utilisés afin d'incorporer l'impact des panneaux de gypse sur les parois dans le cas d'une modélisation d'un bâtiment complet.

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# Chapter 1. Introduction and Literature Review

## 1.1 General overview

Cold-formed steel (CFS) members are typically roll-formed from thin steel sheets (0.3 mm to 6 mm) to obtain the desired structural shape. There are many advantages to using cold-formed steel in building construction. Members are light thus easy to manipulate and install. Products are reliable, versatile and recyclable. CFS construction (Figure 1.1) is an alternative to wood light framing construction. Indeed, CFS is non-combustible, has a high strength to weight ratio, is easily recyclable, has a uniform quality and is rot-proof.

A CFS wall is usually made of a bottom U-shaped horizontal track affixed to the foundation and another U-shaped track on the top of the wall. Vertical C-shaped studs are regularly spaced and fastened to the top and bottom tracks with self-drilling screws (Figure 1.2).

**Figure 1.1 Cold-formed steel building with strap-bracing**

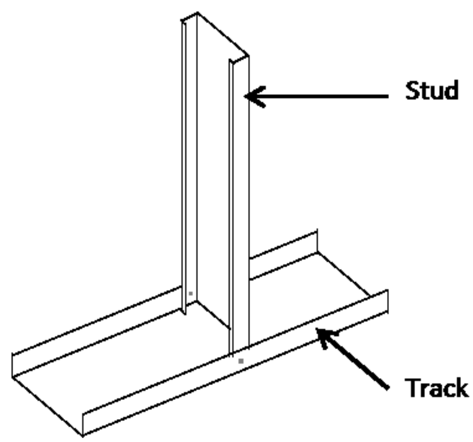



**Figure 1.2 Illustration of track and stud**

In order for a building to resist earthquakes, lateral loads applied to it need to be transferred to the ground. Two common ways to transfer lateral load in a CFS building are the use of diagonal strap bracing and the use of structural sheathing. They both transfer lateral load to the frame, which in turn transfers the load to the ground through hold-downs and shear anchor devices. Hold-downs are devices that connect the chord studs to the foundation and counteract uplift forces (Figure 1.3).

**Figure 1.3 Hold-down device screw connected to the frame and anchored to the foundation**

In current practice, when CFS strap-braced walls are designed, the only lateral resisting elements considered are the steel straps. Nevertheless, widely used non-structural components such as gypsum panels provide additional strength, which on one hand can be beneficial to the ability of the structure to resist the lateral loading. However, on the other hand, capacity-based design requirements might not be respected since the increased lateral forces on the frame during a seismic event may result in unanticipated failure of the frame and other members in the lateral load-carrying path. Gypsum panels can also increase the stiffness of the wall, which may result in greater seismic loads. Thus, there is a need to quantify the contribution of the non-structural components in order to know the increase of lateral strength in the building and the resulting increased force demand on the lateral load carrying system.

Since gypsum panels provide non-negligible strength, they can also be used as a lateral resisting element on their own if they offer enough ductility. Indeed, different sheathing types are used on CFS shear walls to resist lateral loads: plywood, oriented strand board (OSB), steel sheet, calcium silicate board and gypsum. In the current American Iron and Steel Institute (AISI) S213 Standard (2007) and in the new AISI S400 CFS Seismic Design Standard (2015), values for the nominal resistance of wood, steel and gypsum sheathings are given but have a limited range of application.

Gypsum panels on non-structural walls (partition walls) or gravity carrying walls (bearing walls) can also transfer lateral forces to the structure and to the foundations. Thus, even if gypsum panels are not part of a shear or strap-braced wall anchored with hold-downs and shear connectors, they can contribute to the overall lateral resistance of the building. If their contribution is significant, the predicted overall behaviour of a building based on the contribution of the structural walls alone could be far from the reality.

## 1.2 Statement of problem

According to the 2010 National Building Code of Canada (NBCC) by the National Research Council of Canada (NRCC), 1-hour fire resistance rated loadbearing walls are required for most residential and office buildings, while 2-hour fire resistance rated loadbearing walls are required for residential and office buildings greater than 6 storeys in height, and for shorter buildings with large areas (e.g. more than 1800 $m^2$ in a 4-storey residential building) (Clauses 3.2.2.47 to 3.2.2.53 of Division B of NBCC) (NRCC 2010). According to the Underwriters Laboratories of Canada (ULC), one way to provide 1-hour fire resistance to a steel assembly is to affix a single layer of 15.9 mm ($^5/_8$") Type X fire resistant gypsum on both sides of the steel frame (ULC Design No. W424, 2006). To obtain a 2-hour fire resistant assembly, two layers of 15.9 mm ($^5/_8$") Type X fire resistant gypsum would need to be attached to both sides of the steel frame (ULC Design No. W424, 2006). CFS walls constructed with this thickness and number of layers of gypsum have not been tested in terms of their ability to carry lateral in-plane loads. Since gypsum can provide significant strength, it is essential to quantify its influence on the behaviour of the wall and the building. As will be described in the Literature Review (Section 1.5), some researchers have investigated the influence of gypsum panels on the resistance of shear walls and bearing walls, but little testing has been done on strap-braced walls that can resist high lateral load and walls that can provide a 1 or 2-hour fire resistance.

Furthermore, according to the NBCC (2010), the sound class transmission (SCT) rating between dwelling units should be superior to 50 and the SCT rating between a dwelling unit and an elevator hoist way should be superior to 55 (Clause 5.9.1.2 of Division B of NBCC). According to Table 9.10.3.1 of the NBCC (2010), these SCT ratings can be reached by using resilient channels spaced at 600 mm o/c. These channels are installed between the gypsum panels and the steel frame; thus, they will likely influence the contribution of the panels to a wall's shear resistance and stiffness.

## 1.3 Research objectives

The main objectives of this research are:

- To review previous research conducted on CFS strap-braced walls and gypsum-sheathed CFS walls;

- To develop and conduct a testing program in order to investigate the contribution of gypsum panels in 1-hour and 2-hour fire resistance rated and soundproofed strap-braced and shear walls designed according to capacity design principles, and in 1-hour and 2-hour fire resistance rated bearing walls;

- To improve the understanding of the behaviour of CFS structural walls sheathed with gypsum;

- To obtain design values with respect to the nominal and maximum in-plane shear strengths as well as the stiffness of strap-braced shear walls sheathed with gypsum, shear walls sheathed with gypsum and gravity-carrying walls sheathed with gypsum;

- To construct a numerical model of walls sheathed with gypsum in OpenSees (McKenna,1997) and to calibrate this model using the laboratory test data.

## 1.4 Scope of study

Thirty-five CFS framed walls were tested under lateral in-plane displacement-based monotonic and reversed cyclic protocols in order to complement the gypsum-sheathed walls test data available in the literature. The aspect ratio of all the walls was 2:1. Two main types of walls were included: twenty-seven shear walls and eight bearing walls. All the shear walls had a steel thickness of 1.37 mm and had hold-downs in order to transfer lateral load and uplift from the frame to the foundation. The shear walls were designed according to capacity based principles accounting for the anticipated strength of the gypsum panels. Most of the shear wall configurations (16) included strap braces and gypsum panels (1-hour and 2-hour fire rated configurations). Amongst them, four walls were built using resilient channels in order to provide improved sound-proofing. Two bare steel strap braced shear wall were tested in order to provide a reference for the resistance of the steel straps. One bare steel unstrapped walls was tested in order to provide a reference resistance for the steel frame. Eight shear walls were tested without straps but with gypsum in order to understand the influence of the gypsum alone on the resistance of the walls and to know if the gypsum panels could be used as a lateral resisting element. The bearing walls were composed of 1.09 mm thick steel framing members. Hold-downs were not installed for these gravity-carrying (bearing) walls since they are typically not expected to resist lateral in-plane loads. Walls with both a 1-hour and a 2-hour fire resistance rating were tested. This thesis contains a presentation of the results obtained during the wall testing. Nominal properties of the tested walls as well as factors to take into account the over-strength for capacity-based design are provided. The experimental data obtained were used to calibrate the numerical model of CFS walls sheathed with gypsum in OpenSees (McKenna,1997).

## 1.5 Literature review

A comprehensive review of the behaviour of light-frame walls under lateral loading is provided herein. The standards regarding seismic design in Canada and design of CFS framed walls are summarized, as well as previous testing and modelling of light-frame walls. Relevant full-scale tests of CFS strap-braced walls and CFS sheathed walls are presented. Since the influence of gypsum sheathing on wood frame walls has been evaluated in several past studies, some results are included here for comparison purpose. Small-scale tests of sheathing connections are also described in order to understand the local behaviour of the connections in a wall. Representative analytical and numerical models of CFS walls are also presented.

### 1.5.1 Design standards

The 2010 National Building Code of Canada (NBCC), which is published by the National Research Council of Canada (NRCC), and the 2009 Canadian Standards Association (CSA) S16 Standard for Steel Structures allow the designer to consider the inelastic behaviour of the building during earthquake loading. Thus, buildings are designed for seismic forces less than those they would experience if they behaved elastically. To obtain the seismic design forces on the building, the elastic shear demand is divided by the ductility factor $R_d$ and the over-strength factor $R_o$.

The 2010 NBCC prescribes a method, the Equivalent Static Force Procedure, to estimate the force applied on a regular building due to a dynamic earthquake. For buildings with irregularities, dynamic analysis is necessary. For regular buildings, the static base shear force equivalent to the dynamic loading applied on the building can be estimated by Equation ( 1.1 ), which cannot be inferior to the force calculated with Equations ( 1.2 ) or ( 1.3 ) (NRCC 2010). The base shear is distributed over the storeys according to their height and weight. The 2010 NBCC gives formulae to estimate the building's fundamental period of vibration according to its height and type of lateral load resisting system (Equations ( 1.4 ), ( 1.5 ) and ( 1.6 )).

$$V = \frac{S(T_a) \cdot M_v \cdot I_E \cdot W}{R_d \cdot R_o} \tag{1.1}$$

$$V \geq \frac{S(2.0) \cdot M_v \cdot I_E \cdot W}{R_d \cdot R_o} \quad \text{for moment resisting frames and braced frames} \tag{1.2}$$

$$V \geq \frac{S(4.0) \cdot M_v \cdot I_E \cdot W}{R_d \cdot R_o} \quad \text{for steel panel shear walls} \tag{1.3}$$

where:

$V$ is the seismic base shear;

$S(T_a)$ is the design spectral response acceleration;

$T_a$ is the fundamental lateral period of vibration;

$M_v$ is the factor to account for effects of higher mode vibrations;

$I_E$ is the importance factor;

$W$ is the seismic weight;

$R_d$ is the ductility-related seismic force modification factor;

$R_o$ is the over-strength-related seismic force modification factor.

$$T_a = 0.085\, h_n^{3/4} < 0.1275\, h_n^{3/4} \qquad \text{for moment frames} \tag{1.4}$$

$$T_a = 0.025\, h_n < 0.05\, h_n \qquad \text{for braced frames} \tag{1.5}$$

$$T_a = 0.05\, h_n^{3/4} < 0.1\, h_n^{3/4} \qquad \text{for shear walls} \tag{1.6}$$

where:

$T_a$ is the fundamental lateral period of vibration;

$h_n$ is the building height (m).

The 2010 NBCC and 2009 CSA S16 Standard require the use of a capacity-based design philosophy for hot-rolled steel framed structures subjected to lateral loading. Selected members of the frame are designed to resist lateral loading and perform as a fuse. Lateral resisting elements have to be ductile in order to dissipate energy. The steel used for the lateral resisting elements can be stronger than expected; thus, the nominal resistance of the elements is multiplied by a factor $R_y$ that accounts for the possibility that the actual steel resistance is greater than the nominal value. The other elements in the lateral load carrying path must be able to resist forces that correspond to the probable resistance of the fuse element combined with the related companion gravity loads such that the expected ductile response can be achieved.

The current CSA S136 Standard (2012) published by the Canadian Standards Association (CSA) contains information about the design of cold-formed steel members and connections approved in Canada, the United States and Mexico. It takes into account the particular properties of CFS, such as elastic local buckling, post-buckling resistance, torsional buckling, distortional buckling, residual stress due to the forming process, etc.

The 2010 NBCC provides information on lateral loading, while the CSA S136 Standard describes how to design CFS members and connections; but neither contains information specific to the lateral design of CFS framing systems. The American Iron and Steel Institute (AISI) S213 Standard (2007) and its soon to be available replacement AISI S400 (2015) address this lack of information. Amongst other design aspects, the AISI S213 and S400 Standards cover the capacity-based design of CFS strap-braced walls, as well as wood, gypsum, fibreboard and steel-sheathed walls. The design of the diagonal braced walls is based mainly on the work of Al-Kharat and Rogers (2008). The nominal in-plane lateral strengths of shear walls sheathed on one side with wood panels or steel sheets of different thickness and fastener spacing are provided in the standards. The nominal shear strengths of walls sheathed with $^1/_2$" gypsum board or $^1/_2$" fibreboard on one side are also listed. The over-strength factors to consider for capacity-based design are given; an over-strength factor of 1.33 is recommended to design gypsum-sheathed shear walls. Nevertheless, there is no information provided for walls with thicker gypsum, gypsum on both sides or multiple layers of gypsum. Moreover, there is no requirement that the gypsum panels in sheathed structural (bearing and strap-braced) or non-structural (partition) walls be considered in the capacity design calculations. Nevertheless, given the anticipated resistances of gypsum-sheathed walls, it is postulated that they will offer significant resistance to a CFS framed lateral force resisting system and affect the overall building response to seismic loads. In the following subsections, a review is provided of past research on CFS strap-braced walls and the influence of structural and non-structural sheathing on CFS walls.

### 1.5.2 Cold-formed steel strap-braced walls

CFS strap-bracing can be screw-connected or welded on a wall frame in order to provide lateral resistance to a building (Figure 1.1). To achieve a capacity design for CFS strap-braced walls, the straps must be the main lateral resisting element and yield before the surrounding members and connections in the lateral load carrying path reach their factored resistance. They also must have a ductile behaviour in order to dissipate energy.

Serrette and Ogunfunmi (1996) tested two 2.44 m x 2.44 m CFS strap-braced walls. The straps were 50.8 mm wide x 0.88 mm thick and were pre-tensioned during installation. The walls were subjected to monotonic loading and failed by yielding of the braces in tension. They found that the studs did not provide significant flexural resistance. Tian *et al.* (2004) evaluated the lateral performance 2.45 m x 1.25 m CFS walls with single and double X-strap bracing under monotonic 1-step and 3-step loadings. The braces were 60 mm wide × 1.0 mm thick or 60 mm wide × 1.2 mm thick. They showed that walls with single strap-bracing on both sides were the most efficient. Nevertheless, the modes of failure observed (track buckling and rivet failure) showed that the walls were not designed according to capacity-based principles. They also tested walls without straps and found that the frame contributed less than 5% in the resistance of the strap-braced walls.

Several researchers including Gad *et al.* (1999a), Fulop and Dubina (2004), Al-Kharat and Rogers (2008), Moghimi and Ronagh (2009), Velchev *et al.* (2010), Macillo *et al.* and Iuorio *et al.* (2014) tested walls with both monotonic and cyclic protocols. Using different wall and strap sizes, they showed that CFS strap-braced walls exhibited a significant pinching behaviour when loaded cyclically. Thus, the dissipation of lateral energy is reduced when the structure is subjected to earthquake loads.

Barton (1997) and Gad *et al.* (1999a) investigated the behaviour of different configurations of a 2.3 m x 2.4 m x 2.4 m high CFS domestic structure with shake table tests. One of the configurations consisted of an unlined wall frame with strap bracing (25 mm x 1 mm) on all four walls. Tensioner units were installed on the straps. The straps yielded and ultimately failed by fracture at the tensioner unit or at the bottom corner connection location. Kim *et al.* (2006) tested dynamically a two-storey one-bay CFS structure made of strap-braced walls. The straps (102 mm x 1.4 mm) were larger than those tested by Barton and Gad *et al.*. These two studies showed that strap-braced walls can also exhibit a ductile behaviour under dynamic loading.

Casafont *et al.* (2006) investigated the behaviour of common screw connections used to attach the straps in CFS walls. They recommended that the connection be designed to fail in a tilting-net section fracture mode because it allows the straps to yield and maintain their strength for large displacements.

Al-Kharat and Rogers (2008) evaluated the inelastic performance of 2.44 m x 2.44 m screw-connected cold-formed steel strap-braced walls that were designed following a capacity-based design approach. In all the tests, straps reached the yielding level. However, walls without extended tracks also showed damage in the tracks (compression and bearing at the hold-down's anchor rod location) and the chord studs (compression). On the other hand, the tests showed that using walls with extended tracks and additional shear anchors in the track extensions could allow the track to work in tension and lead to a more efficient capacity-designed CFS braced wall. Indeed, the track was not subjected to extensive damage due to compressive loads; thus, inelastic deformations were limited to tension yielding of the braces, which is a ductile mode of failure. They observed that wall performance depends on the strain rate of loading. It has been found that $F_u/F_y$ must be superior to 1.2 in order to maintain ductile behaviour of the strap and limit the possibility of brace fracture under seismic loading.

Velchev *et al.* (2010) tested welded and screw-connected strap braced walls under monotonic and reversed cyclic loadings. The walls ranged in size from 0.61 m x 2.44 m to 2.44 m x 2.44 m and had varying strap dimensions (63.5 mm x 1.09 mm, 69.9 mm x 1.37 mm, 101.6 mm x 1.73 mm). Walls with an aspect ratio less than or equal to 2:1 were able to reach and maintain their yield resistance. Both welded and screw-connected straps respected the capacity design behaviour.

In order to achieve a proper capacity-based design of a braced wall, one must ensure that the braces in tension yield and maintain their strength while the other elements of the frame remain elastic. It has been seen that this can be achieved for frames with aspect ratios less than 2:1 (Velchev *et al.*, 2010), by using a proper hold-down system, ductile steel and extended tracks (Al-Kharat and Rogers, 2008).

### 1.5.3 Gypsum sheathed cold-formed steel walls

Gypsum board, also known as drywall or plaster board (Figure 1.4), is a panel made of a gypsum (hydrous calcium sulfate) core stranded between two paper faces (Allen and Thallon, 2006). Gypsum wallboard is commonly used to sheath CFS framed structures in North-American residential construction (Figure 1.5). Indeed, it can provide fire resistance, sound-proofing (Gypsum Association (GA), 2007) and is easy to install.

Gypsum panels are usually affixed to the studs with self-drilling drywall screws (Allen and Thallon, 2006). The spacing of the fasteners on the edge and in the field of the panel varies according to the fire resistance and sound-proofing requirements if the gypsum is used as a non-structural element and according to the structural design if the gypsum is used to resist in-plane lateral loads or to stabilize gravity load carrying members such as well studs.


**Figure 1.4 Type X gypsum boards**

**Figure 1.5 Gypsum sheathed walls (Peterman, 2014)**

Gypsum boards can provide additional in-plane shear strength to CFS walls thus, it is essential to understand how gypsum panels and their fasteners behave under lateral loading in order to predict their influence on the overall wall's, as well as building's, resistance and stiffness. This Subsection contains a review of the results of several experimental programs of gypsum-sheathed walls and their modelling and gives a better understanding of their behaviour.

#### *1.5.3.1 Cold formed steel gypsum sheathed non-structural walls*

CFS gypsum-sheathed walls are often used as partition walls in order to create smaller spaces usually in a commercial or institutional building. In residential buildings, all the walls usually carry gravity or in-plane lateral loads. Partition walls are non-structural walls, i.e. they are not designed to carry gravity or in-plane shear loads. Nonetheless, there exist research programs in which the influence of partition walls on the overall building resistance has been investigated.

Several experimental studies have been conducted to evaluate the resistance of CFS gypsum-sheathed non-structural walls (Bersofsky, 2004; Lee *et al.*, 2007 and Memari *et al.*, 2008). The walls differed in size, stud and gypsum thickness and sheathing connections pattern. Indeed, the fabrication of non-structural walls depends largely on the common practices in the region. The walls were tested with monotonic and cyclic protocols. Davies et al. (2011) complemented those studies by testing numerous configurations of non-structural walls as part of a research program on the seismic performance of non-structural systems. They tested commercial (Figure 1.6) and institutional (Figure 1.7) slip track (Figure 1.8) walls, commercial and institutional full connection (Figure 1.9) walls, partial height walls and walls with improved wall intersection detail (space between perpendicular gypsum boards). They modelled an existing four-storey medical facility in California. The structural frame was made with hot rolled steel and moment frames were present to resist lateral forces. They found that including CFS partition walls in the model increased the fundamental period of the building from 1% to 11% depending on the wall configuration. Wood and Hutchinson (2012) developed an OpenSees model of partition walls thanks to the experimental data obtained by Davies et al. They modelled nine representative buildings with concrete and steel moment frames and gypsum-sheathed CFS partition walls. Partition walls were found to increase the building period by a maximum of 14%, which was slightly higher than the increase found by Davies et al.

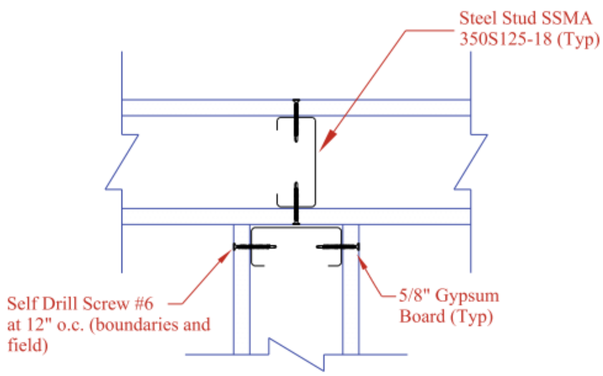



**Figure 1.6 Typical commercial partition wall intersection detail (Davies et al., 2011)**

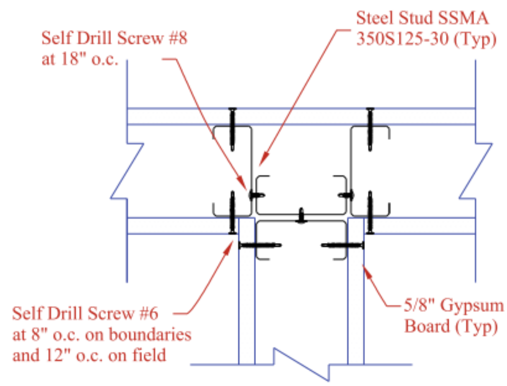



**Figure 1.7 Typical industrial partition wall intersection detail (Davies et al., 2011)**

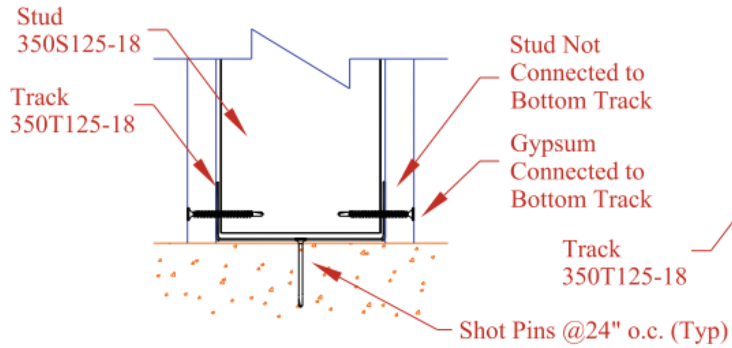



**Figure 1.8 Typical framing and sheathing basic connection (Davies et al., 2011)**

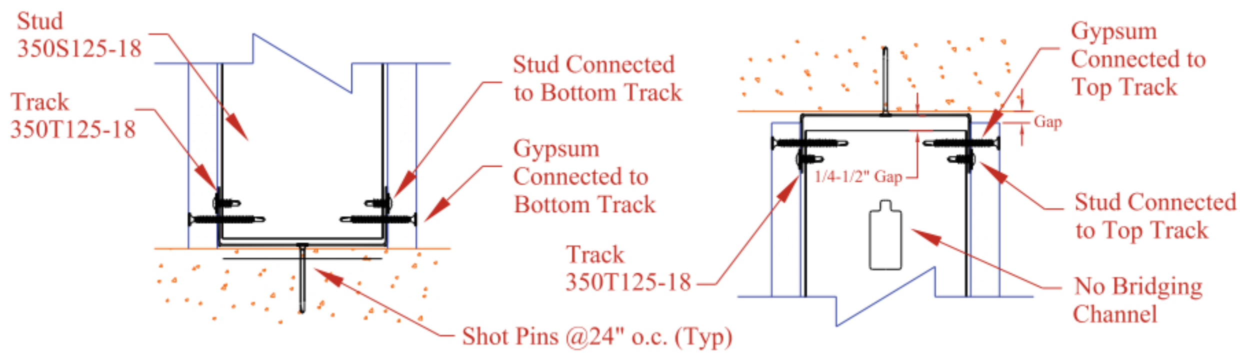



**Figure 1.9 Typical framing and sheathing full connection (Davies et al., 2011)**

Studies have shown that non-structural gypsum CFS walls can provide additional lateral strength and stiffness to the building. They also show the importance of considering all the non-structural components of a building in order to obtain a representative model that accounts for sources of lateral stiffness and strength.

#### *1.5.3.2 Cold formed steel gypsum sheathed bearing walls*

CFS framed bearing walls are meant to resist gravity loadings. When designing bearing walls, only the resistance of the steel studs is considered. But the sheathing can help to brace the studs and thus increase the resistance of the wall. Several research programs were carried out to better understand the behaviour of sheathed bearing CFS walls under vertical loads.

Miller and Pekoz (1994) showed that sheathing panels on CFS studs did not act exactly as diaphragms. Indeed, unlike a diaphragm, deformation in gypsum panels was concentrated in the corners and around the fasteners. Vieira Jr and Schafer (2013) clarified the understanding of the behaviour of sheathed bearing walls under compressive loads. They showed that the bracing provided by the sheathing comes from two sources: local fastener stiffness and global panel stiffness. Vieira Jr and Schafer developed an analytical method to take into account both local and global sources of deformation. They relied on past experiments by Vieira Jr *et al.* (2011) to validate their model.

Some research also focused on the lateral resistance of sheathed bearing walls. Bearing walls are only designed to resist vertical load and thus do not have hold-downs. Nevertheless, sheathing on the walls can provide lateral resistance and stiffness, as shown in studies conducted by Fulop and Dubina (2004) and Pan and Shan (2011).

As part of one of their experimental studies, Fulop and Dubina (2004) investigated the influence of gypsum sheathing on corrugated sheet sheathed walls. They did not use hold-down devices. They carried out one monotonic and two cyclic tests of shear walls sheathed with corrugated sheets on one side and compared them to one monotonic and two cyclic tests of walls sheathed with corrugated sheets on one side and gypsum (12.5 mm thick) on the other side. Reparable damage (mostly screw tilting and pull through) was observed in the gypsum panels. Deformation of the track occurred due to uplift forces followed by profile-end distortion. Gradual deformation and failure occurred at the seam fasteners linking the corrugated sheets together. The failure of the fasteners induced overall failure of the panel. The presence of gypsum panels in the corrugated sheet sheathed walls provided an increase in strength of 17 %. The influence of the gypsum on the stiffness is difficult to quantify with the values given by Fulop and Dubina because the stiffness in the walls with and without gypsum were both taken at 40% of the ultimate strength of the wall. Since the ultimate strength of the walls with gypsum was greater than that for the walls without gypsum, the stiffness were not calculated at the same load level.

Pan and Shan (2011) tested with monotonic and reversed cyclic protocols CFS wall frames having different sheathings including 9 mm and 12 mm thick gypsum boards. The studs and the tracks were subjected to severe deformation due to uplift forces. Gypsum panels were damaged due to screw bearing and pull-through. In some gypsum-sheathed specimens, screws in the corners of the walls failed in shear. Walls with a 1:1 aspect ratio and sheathed on one side had a resistance between 7.0 kN/m (9 mm-thick panel) and 7.7 kN/m (12 mm-thick panel). Walls sheathed on both sides had a resistance between 11.9 kN/m (9 mm-thick panel) and 15.3 kN/m (12 mm-thick panel). One wall with a 2:1 aspect ratio was tested with 12 mm-thick panels on both sides; it had a lateral resistance of 9.7 kN/m. The stiffness of the walls (at 40% of the ultimate strength) ranged between 0.8 kN/mm to 1.6 kN/mm.

The main failures observed in the gypsum-sheathed bearing walls were screw tilting, screw bearing, screw pull-through and stud and track deformation. The presence of gypsum panels on bearing walls modifies the overall building behaviour during seismic events by increasing the expected shear strength and stiffness of the building.

#### *1.5.3.3 Cold formed steel gypsum-sheathed shear walls*

By using hold-downs, the uplift forces can be transferred from the chord studs to the supporting foundation or wall, which prevents the tracks and studs from deforming. Furthermore, the lateral resistance of the gypsum-sheathed shear wall will be increased compared with a bearing wall configuration. In this thesis, "shear walls" are defined as walls with hold-downs, which have been specifically designed to resist in-plane lateral loads.

When gypsum-sheathed CFS shear walls are subjected to lateral loading, the frame deforms as a parallelogram while the gypsum panel rotates as a rigid body (Lange and Naujoks, 2006). This differential deformation initiates tension in the diagonal of the panel as well as a differential displacement demand on the sheathing fasteners. Several tests reported in the literature describe the modes of failure of gypsum-sheathed shear walls (Klippstein and Tarpy, 1992; Serrette *et al.*, 1997; Salenikovich *et al.*, 2000; Landolfo *et al.*, 2006; Moghimi and Ronagh, 2009; Morello, 2009; Peck *et al.*, 2012 and Liu *et al.*, 2012). Damage in the gypsum panels is initiated by screw tilting in the direction of the shear stress and bearing. Gypsum panels can then fail by cracking in the tension corners and on the edges or by screws pulling through the gypsum both leading to the unzipping of the sheathing from the wall frame and the redistribution of stress. The overall wall failure can be due to gypsum panel connection failure or framing failure.

Klippstein and Tarpy (1992) tested shear walls with CFS studs and different sheathings (gypsum wallboard, gypsum sheathing board, Stucco, cement plaster, plywood). Most of the walls were sheathed on both sides with 12.7 mm-thick gypsum. To investigate the effect of gypsum thickness, one of the specimen had two layers of 15.9 mm-thick gypsum on both sides. Different details were used in the walls to investigate the influence of the anchorage details, loading conditions, gypsum fastener spacing, stud spacing. The failure of all the walls initiated at the bottom track (bending), in the tension corner. Cracking of the gypsum panel occurred at this corner and expanded to the edge of the panel. Klippstein and Tarpy found that the wall panel anchorage has a significant influence on the shear strength of the wall; the shear resistance of the wall was increased by 98% when clip angles were used at the corners of the wall. Using two layers of 15.9 mm-thick gypsum wallboard instead of one layer of 12.7 mm-thick gypsum wallboard resulted in an increase in lateral strength of 16 % (6.6 kN/m instead of 5.7 kN/m). Decreasing the fastener spacing from 305 mm o/c on the perimeter to 152 mm o/c resulted in a 78% increase in ultimate test load (9.8 kN/m instead of 5.5 kN/m). When studs were closer, panels were attached with more fasteners to the frame, which resulted in an increase of the wall strength.

Serrette *et al.* (1997) tested four gypsum-sheathed walls under monotonic load controlled loading. All the walls were 2.44 m x 2.44 m and were sheathed on both sides with two 12.7 mm-thick 1.22 m x 2.44 m gypsum panels. Double chord studs were used as well as external hold-downs. To quantify the influence of screw spacing, three walls sheathed with vertical gypsum panels with different screw spacing (178 mm on edges/178 mm in the field, 152 mm/305 mm and 102 mm/102 mm) were tested. In the last wall, gypsum panels were placed horizontally and affixed in the middle of the wall height to strap blocking. The maximum lateral load that the walls resisted ranged from 10.7 kN/m to 14.7 kN/m.

Salenikovich *et al.* (2000) tested monotonically 12.2 m-long shear walls sheathed with oriented strand board (11.1 mm-thick) on one side and gypsum (12.7 mm-thick) on the other side. Gypsum panels' fasteners were spaced at 178 mm on perimeter and 254 mm in the field. Severe local buckling occurred in the tracks and studs. They found that gypsum sheathing had a simple additive effect on the strength and stiffness of the shear wall and contributed up to 24 % (2.8 kN/m) in the resistance of the walls.

Landolfo *et al.* (2006) tested, under vertical and lateral loading, shear walls sheathed with oriented strand board (OSB) on one side and gypsum panels on the other side. Hold-downs were specifically designed for the wall specimens. Local buckling of the web occurred in the tracks, which may indicate that the hold-downs were under-designed. In both monotonic and cyclic tests, the behaviour of the OSB connections was characterized by tilting and pulling though; gypsum panel connections failed by bearing and pulling through. The strength degradation for walls under cyclic loads was greater than that of the walls under monotonic loads because after the sheathing was unfastened due to screw pulling through, distortional buckling in the studs occurred. The post-peak response was different for each cyclically loaded wall; so it seems difficult to foresee the post-peak behaviour of the walls under cyclic loading. This may due to the local buckling of the tracks.

During their experimental program, Moghimi and Ronagh (2009) tested one specimen sheathed on one side with 10 mm-thick gypsum panels installed horizontally. The wall had a lateral resistance of 1.35 kN/m. Damage was mostly concentrated in the gypsum-to-frame connections.

Morello (2009) tested six (three monotonic and three reversed cyclic) shear walls sheathed with fire-rated type X gypsum panels and two (one monotonic and on reversed cyclic) shear walls sheathed with regular gypsum panels. All the panels were 12.7 mm-thick and walls were sheathed on one side only. Different fastener schedules were used (200 mm / 300 mm, 150 mm / 300 mm and 100 mm / 300 mm). Gypsum panels were in contact with the test frame on both top and bottom of the wall. The regular gypsum panels were not attached on the top edge on the wall whereas all the fire-rated gypsum panels were connected along their entire perimeter. Walls sheathed with fire-rated gypsum were stronger (6.5 kN/m) than those sheathed with regular gypsum (4.2 kN/m) for the same fastener schedule (150 mm / 300 mm). The resistance of the one-side fire-rated gypsum sheathed walls ranged between 5.7 kN/m (200 mm / 300 mm) and 8.4 kN/m (100 mm / 300 mm).

Peck *et al.* (2012) tested twenty-one 12.7 mm-thick gypsum-sheathed shear walls with monotonic or reversed cyclic loadings. The walls were all 2.44 m high and were either 1.22 m long (aspect ratio of 2:1) or 2.44 m long (aspect ratio of 1:1). The walls were sheathed on one side only. They tested blocked vertically installed gypsum panels and mid-height unblocked horizontally installed gypsum panels. Peck *et al.* showed that unblocked walls had a resistance ranging between 40% to 57% of the capacity of blocked walls. The resistance of unblocked walls can be significantly improved by reducing intermediate screw spacing from 305 mm to 152 mm. They also found that the walls with an aspect ratio of 2:1 and a single vertical gypsum panel had roughly the same behaviour though slightly weaker (15%) than the walls with an aspect ratio of 1:1 and two vertical gypsum panels linked by a vertical joint. Fastener spacing on field has little influence on the resistance of blocked walls. Blocked wall resistance ranged from 2.5 kN/m (203 mm / 305 mm) to 4.7 kN/m (102 mm / 305 mm). By comparing their results to previous tests (Morgan *et al.*, 2002) with the same wall configurations except the steel thickness, Peck *et al.* hypothesised that thicker steel framing members limit screw tilting by offering a greater restraint and thus increase the shear wall strength.

Liu *et al.* (2012) investigated the influence of 12.5 mm-thick regular gypsum panels on 11.1 mm-thick OSB sheathed shear walls. They compared the cyclic behaviour of shear walls (1.22 m x 2.74 m and 2.44 m x 2.74 m) sheathed with OSB on one side and interior gypsum board on the other side and shear walls sheathed with OSB alone on one side. They also tested cyclically one wall sheathed with gypsum alone on one side. Gypsum panels were not fastened on the top of the wall because of the presence of a ledger and screws were spaced at 152 mm o/c. The addition of gypsum increased the lateral resistance of the wall by up to 6% (1.1 kN/m) and the resistance of the wall with gypsum alone was 3.4 kN/m.

#### *1.5.3.4 Cold-formed steel strap-braced gypsum sheathed shear walls*

When strap braces are used in shear walls to resist the lateral loading, gypsum sheathing is usually considered as a non-structural element and is only used for aesthetic purposes, fire rating and soundproofing. Nevertheless, it has been shown in the previous subsections that the gypsum could provide lateral strength and stiffness to the wall and thus contribute to the overall resistance and stiffness of the building. The added resistance is beneficial to the structure since the wall can resist higher load, but on the other hand, the increased stiffness of the structure attracts more load. Several research projects that were conducted in order to improve the understanding of the effect of non-structural gypsum panels on strap-braced walls are presented herein. In all the lateral tests of CFS strap-braced gypsum-sheathed shear walls reported here, the straps yielded and the gypsum panels failed as described in the previous Subsections.

Adham *et al.* (1990) tested six 2.44 m x 2.44 m shear walls with CFS strap bracing and one 15.9 mm-thick type X gypsum board on both sides of the wall under combined vertical and lateral cyclic loadings. One specimen was braced by gypsum panels only and the other specimens had varying strap sizes (50.8 mm x 0.91 mm, 76.2 mm x 1.21 mm, 76.2 mm x 1.52 mm). The wall with gypsum only had a lateral resistance of 11.7 kN/m. They observed that area of strap was almost proportional with the contribution from the strap to the overall wall resistance.

During their test program, Serrette and Ogunfunmi (1996) tested a total of thirteen 2.44 m x 2.44 m shear walls with three different configurations. The three configurations were one strap-braced wall, one wall sheathed with 12.5 mm-gypsum wallboard on one side and 12.5 mm-gypsum sheathing board on the other side and one wall with both gypsum sheathing and steel straps. The straps were pre-tensioned during their installation. They showed that the use of straps in the gypsum-sheathed walls did not increase the stiffness of the walls. Moreover, they found that the resistance of the wall with straps and gypsum (14.1 kN/m) was smaller than the sum of the resistances of the wall with straps only (4.7 kN/m) and the wall with gypsum only (11.2 kN/m). By adding the resistance of the wall with straps and the resistance of the wall with gypsum to get the resistance of the wall with straps and gypsum, the resistance is overestimated by 13%.

Gad *et al.* (1999b) tested a one-storey house statically with a displacement-based lateral loading. By adding the resistance of the wall with straps (4 kN/m) and the resistance of the wall with gypsum (8 kN/m) to get the resistance of the wall with straps and gypsum (11 kN/m), the resistance is overestimated by 9%. Contrary to Serrette and Ogunfunmi (1996) , they found that the stiffness of the wall with straps and sheathing was simply the addition of the stiffness of the wall with straps only and the wall with sheathing only. This difference may be due to a different way of calculating the stiffness or because of a different pre-tensioning of the straps.

After testing a 1-storey 2.4 m x 2.4 m house, Barton (1997) created a finite element model using ANSYS to represent the test house and to extend the results to other domestic structures. Gad *et al.* (1999a) used this model to demonstrate the importance of taking into account the effect of return walls, which increased significantly the lateral resistance of walls.

### 1.5.4 Other-than-gypsum sheathed cold-formed steel walls

#### *1.5.4.1 Cold-formed steel wood-sheathed shear walls*

Wood panels are often used as sheathing and bracing material for CFS frames because of their high lateral resistance. Numerous experimental programs focussed on the effect of plywood or oriented strandboard (OSB) panels on CFS walls in order to determine design values for different configurations of walls. Amongst them, Klippstein and Tarpy (1992) Serrette *et al.* (1997), Salenikovich *et al.* (2000), CoLA-UCI (2001), Fulop and Dubina (2004), Branston *et al.* (2006), Morello (2009), Pan and Shan (2011) and Liu *et al.* (2014) provided a significant database covering many configurations differing on steel framing members thickness, thickness of the panel, sheathing fastener spacing, panel orientation, aspect ratio and lateral loading protocols.

Fulop and Dubina (2004) and Branston *et al.* (2006) showed that the lateral deformation of the panel mainly depends on the deformation of the screws between the sheathing and the studs, which is a similar behaviour to a gypsum-sheathed wall. Hikita (2006) and Branston *et al.* (2006) have found that the addition of vertical loading did not change the shear resistance of the wood-sheathed wall if the chords were designed to resist the combination of the vertical and horizontal forces.

Peterman (2014) tested a full scale two-storey CFS house with OSB-sheathed shear walls in order to distinguish the different system level behaviours in the overall behaviour of a building. She highlighted the necessity to take into account non-structural partition walls and bearing walls into the seismic design of a building.

#### *1.5.4.2 Cold-formed steel steel-sheathed shear walls*

To provide lateral stiffness to the wall, engineers can also use thin steel sheets affixed the CFS frame. Steel sheets have the advantage of being made of a ductile and resistant material. Thus, the panel can deform in the direction of the diagonal of the wall, where a tension field forms as shown by Shamim *et al.* (2013), while maintaining its strength. . Several researchers have contributed to a deeper understanding of steel sheet sheathed walls and have provided design values.

Yu (2010) investigated the influence of the thickness of the steel sheathing. DaBreo *et al.* (2014) showed that the ultimate shear resistance of the walls was directly linked to the failure of the sheathing-to-framing connections and, for walls with unblocked stud members, to the twisting of chord members. The chord stud deformation was likely the consequence of the concentrated tension field, which leads to the application of a horizontal force on the chord studs and a torsional moment. When closer spaced sheathing panel fasteners and thicker panels were used, the shear resistance of the wall was higher, if the stud members were designed correctly. More precisely, Javaheri-Tafti *et al.* (2014) showed that when distance between the screws was decreased, shear force increased until a certain screw spacing limit depending on the wall configuration. When the screw spacing was below this limit, no increase in strength was observed. After testing two different positions of hold-down devices, DaBreo *et al.* (2014) showed that there was no influence of their position on the resistance of the walls. Shakibanasab *et al.* (2014) provided a less conservative reduction factor for walls with high aspect ratios (greater than 2:1) than the one found in AISI S213-07. More recently, Balh *et al.* (2014) used the results of previous shear wall tests and the EEEP model to provide a method to design CFS steel sheathed walls.

#### *1.5.4.3 Cold-formed steel calcium-silicate sheathed shear walls*

Calcium-silicate or cement board can be used to provide lateral bracing to a shear wall. Indeed, it has a higher strength and stiffness than gypsum (Pan and Shan, 2011). One main concern about calcium silicate board is that explosive spalling at high temperature can occur and thus safety during a fire can be limited (Chen *et al.*, 2012).

Lange and Naujoks (2006) tested shear walls, with CFS studs and different sheathings (chipboard, gypsum fibreboard, cement bonded fibreboard, trapezoidal sheet). They give a design method based on the ultimate displacement of the edge screws, which is related to the ultimate horizontal load.

Nithyadharan and Kalyanaraman (2012) have tested CFS walls sheathed with calcium silicate board under monotonic and reversed cyclic loading. They designed the walls so that the failure of the screws was controlling. During the experiments, the screws first underwent tilting, then the sheathing exhibited bearing damage and finally the screws were pulled through the sheathing. The thicker the board was and the further the screws were from the edge of the sheathing, the greater the ultimate strength and energy dissipation were. When two boards were used instead of one single board (same total dimensions), the deformation was higher even though the ultimate strength was the same. The ultimate strength is the same because the same number of screws was used. The deformation is higher because at the middle stud, there is a higher relative shear deformation between the two boards. A design equation based on the screw connection shear strength is provided to evaluate the resistance of the CFS wall.

Baldassino *et al.* (2014) tested braced walls sheathed with different cement boards and combinations of cement board and gypsum board. The cement board seemed to provide most of the strength and stiffness of the wall since sheathed walls with and without straps had approximately the same behaviour. These tests showed the importance of the sheathing properties and the sheathing-to-frame fasteners in the overall wall behaviour.

Other researchers (Lin *et al.*, 2014; Shahi *et al.*, 2014 and Zeynalian and Ronagh, 2015) carried out experimental programs to obtain complementary design values for cement board sheathed shear walls. They also found that failure was concentrated in the sheathing-to-frame fasteners.

### 1.5.5 Wood frame gypsum-sheathed shear wall

CFS framing has similar dimensions and resistance to wood light-framing. Thus, it is relevant to summarize the research that has been conducted on the effect of gypsum sheathing on the lateral behaviour of wood light-framed walls.

Wolfe (1983) conducted a test program in order to understand the contribution of gypsum wallboard in the shear resistance of wood light-framed walls. He found that bracing and gypsum panels acted in a parallel manner, not interacting with each other, which means that resistances and stiffness can be simply added. It appeared that the panel orientation and wall length had an influence on the contribution of gypsum in shear resistance. McCutcheon (1985) showed that the behaviour of full-scale walls up to a certain drift ratio can be predicted with the behaviour of small-scale sheathing-to-frame connections. Several other experimental programs focussed on the contribution of gypsum panels in the resistance of wood-framed shear walls (Oliva, 1990; Karacabeyli and Ceccotti, 1996; Uang and Gatto, 2003). The FEMA P-807 guidelines (Federal Emergency Management Agency (FEMA), 2012) recommend, in the general case, to add the load-drift curves of each layer of sheathing to get the global load-drift curve of the assembly. For assemblies including wood structural panels, the global load-drift curve of the assembly is the lowest of:

- the sum of 50% of the load-drift curve of wood structural panel layers and 100% of the load-drift curve of the other sheathing materials;
- the sum of 100% of the load-drift curve of wood structural panel layers and 50% of the load-drift curve of the other sheathing materials.

Some investigations such as the one done by Kawai *et al.* (1999) specifically focused on the difference between wood and CFS framing. Kawai *et al.* tested and modeled the behaviour of CFS bearing wall sheathed with plywood and gypsum and subjected to lateral load. They compared it to a wood-framed bearing wall with the same sheathing. They found that even though wood frame and CFS frame had similar general response, the failure modes were not the same. Steel walls had greater initial stiffness and resistance and showed greater pinching behaviour than the same size wood wall.

The CUREE-Caltech Woodframe Project, initiated in 1998, allowed for the improvement of the seismic performance of wood frame construction (Hall, 2000). Following this large project, a user-friendly software, the Seismic Analysis Package for Woodframe structures (SAPWood), was developed to provide a tool to perform nonlinear seismic structural analysis and loss analysis for wood frame structures (van de Lindt and Pei, 2010). This software is mainly based on the Seismic Analysis of Woodframe Structures (SAWS) and Computer Program for the Cyclic Analysis of Shear Walls (CASHEW) concepts (Folz and Filiatrault, Folz and Filiatrault 2004a; Folz and Filiatrault, 2004b).

### 1.5.6 Analytical and numerical models of CFS walls

Some analytical models were created in order to foresee the strength and stiffness a sheathed CFS wall can provide without resorting to experimental data or finite element analysis. For instance, Xu and Martínez (2006) developed an analytical method to determine the shear strength and stiffness in CFS walls sheathed with OSB or gypsum. They based their model on the analogy between the sheathing-to-framing connections and an eccentrically loaded steel bolted connection. Their predictions result in less than a 10% error compared with experimental results, and thus are recommended for use in engineering practice.

Most of the sheathed walls tested under lateral load in the literature failed at the sheathing connections location (Serrette *et al.*, 1997; Fulop and Dubina, 2004; Branston *et al.*, 2006; Morello, 2009). Since sheathing connections seem to provide most of the lateral resistance and stiffness, several researchers have investigated the link that exists between the local behaviour of connections between the sheathing and the CFS framing and the overall behaviour of the sheathed wall. Numerous experimental values of sheathing connection resistance are available in the literature (Miller and Pekoz, 1994; Serrette *et al.*, 1997; Fülöp and Dubina, 2006; Fülöp and Dubina, Fiorino *et al.*, 2007; Nithyadharan and Kalyanaraman, 2011; Baldassino *et al.*, 2014; Peterman and Schafer, 2013).

Since numerous parameters affect the overall behaviour of sheathed CFS walls, it is difficult for analytical models to capture them all. On the other hand, semi-empirical or empirical numerical models allow for a reasonably accurate representation of the behaviour of the wall. This is conditioned by extensive testing on sheathing connections (semi-empirical) or sheathed full scale walls (empirical).

Lange and Naujoks (2006) gave a design method for walls under horizontal loading based on the ultimate displacement of the corner screws, which is related to the ultimate horizontal load. The resistance of the connection is needed for the design.

Corte *et al.* (2006) created a numerical model of wood-sheathed walls based on experimental data from previous studies. Nithyadharan and Kalyanaraman (2013) have numerically modeled the hysteretic behaviour of calcium-silicate sheathed CFS walls. Bian *et al.* (2014) developed an OpenSees model to represent wood-sheathed CFS walls. They based their numerical model on the experimental values of sheathing connection resistance and the Pinching4 (Lowes *et al.*, 2004) material response. Their model of a full-scale wood-sheathed wall was able to approximate conservatively the results obtained by experiments. In their model, the peak resistance was inferior to that obtained by experiments, and the post-peak degradation was faster than the degradation observed during experiments. Thus, this model can be used for design purposes. This team of researchers used local empirical behaviour of connections to deduce numerically the global behaviour. This type of modelling based on the explicit modelling of the screw fasteners allows more flexibility in the configurations of the wall modelled and less experimental efforts (small-scale tests), but the computational efforts are greater than for a wall model with implicit representation of the sheathing and sheathing fasteners with a unique element. Moreover, the overall behaviour of the wall modelled can be adjusted as needed so that it is close to the real overall behaviour.

Lee and Foutch (2010) used a numerical model to evaluate the performance of CFS strap-braced framed walls and non-structural gypsum walls in a CFS building. Drain-2DX was used for their model. The columns were modeled with elastic beam elements and the beams were considered to be rigid. Plastic hinges were used at the end of the columns and the steel straps were modeled using inelastic truss elements.

Shamim and Rogers (2013) tested steel sheathed/CFS framed shear walls on a shake table and numerically modeled them with OpenSees.

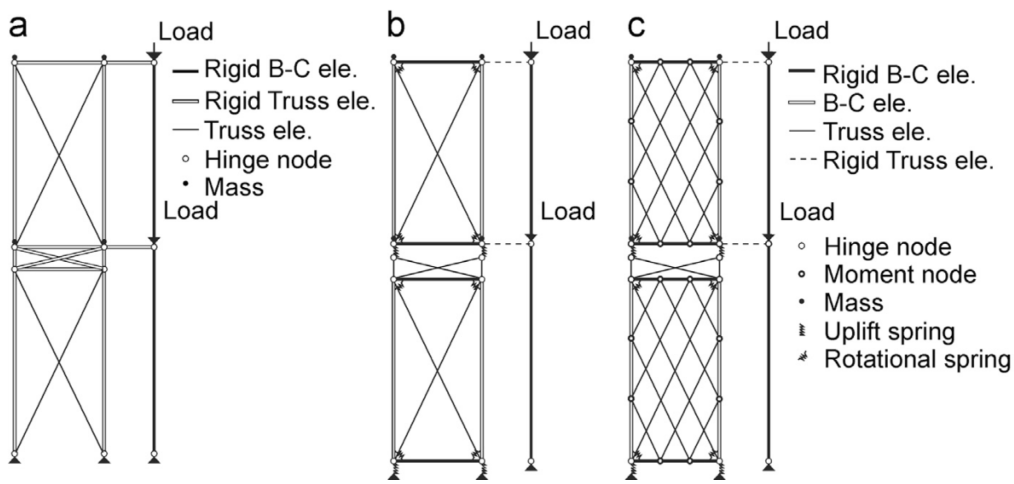



**Figure 1.10 OpenSees dynamic models for double-storey walls: (a) predictive model prior to shake table test, (b) developed model based on shake table test data, and (c) developed model with the brace net system (Shamim and Rogers, 2013)**

At first, they used existing reversed cyclic shear wall test data to calibrate their non linear model (Figure 1.10a). These preliminary results were used to predict the force and displacement of the structure and to establish the loading protocol for the dynamic test program (Ong-Tone, 2009; Balh, 2010; El-Saloussy, 2010; DaBreo, 2012). Then, they tested single and double storey shear walls and additional ancillary components. A second numerical model (Figure 1.10b) was created in OpenSees to reproduce the shear strength and displacement time history and hysteretic response of the dynamically tested shear walls. This model took into account the inelastic behaviour of the shear-wall segment as well as the elastic stiffness of the floor framing, hold-downs and CFS frame. Shear walls were represented using the Pinching4 hysteretic material. The influence of the CFS frame, blocking, floor framing, P-delta force and anchor rods was considered using beam-column, truss and elastic spring elements. The OpenSees models with the applied Rayleigh damping ratio were able to predict the dissipated energy appropriately both under the elastic and enhanced level ground motions. This model was used to represent twelve archetype buildings subjected to several ground motions (Shamim and Rogers (2015)). It has been demonstrated that the model could be used to represent CFS framed buildings located in seismic zones.

### 1.5.7 Summary

Nowadays, the capacity-design of strap-braced CFS bare frame walls is well known (Subsection 1.5.2) and implemented in North-American Standards (Subsection 1.5.1). Nevertheless, CFS walls are not left bare in residential and office buildings, and are often sheathed with gypsum for aesthetics, fire protection and sound-proofing. 1-hour to 2-hour fire resistance rating are often required in those buildings (NRCC, 2010). This can be achieved by using one or two layers of 15.9 mm Type X Gypsum (ULC, 2006). Resilient channels can also be added between the steel frame and the gypsum panels so that gypsum is not directly in contact with the frame and does not transmit the sound directly; they could influence the contribution of gypsum to the overall wall behaviour. Numerous tests of gypsum-sheathed walls were carried as reported in Subsection 1.5.3. These experimental programs allowed a better understanding of the behaviour of gypsum-sheathed walls and showed that gypsum panels could contribute significantly to the wall strength and stiffness. The increase in strength is beneficial to the overall wall behaviour but the increase in stiffness generates higher load demand on the structure. In the capacity design point of view, the added strength of gypsum to the shear wall results in a more resistant fuse element;

thus, the other elements in the lateral load carrying path need to be designed stronger than this more resistant fuse element. It is important to quantify the increase of strength and stiffness due to gypsum sheathing whether it is in a bearing wall, a sheathed shear wall or a strap-braced shear wall. Since a lot of variation of strength and stiffness in previous tests has been observed, it is difficult to extrapolate the results and foresee how thicker framing and sheathing can affect the load sharing between the steel framing and the sheathing. Very few tests (e.g. Klippstein and Tarpy, 1992) with 1 or 2 layers of 15.9 mm gypsum panels were carried out to investigate the influence of those thickness of gypsum panels on the behaviour of strap-braced walls, shear walls or bearing walls. Thus, in this thesis an experimental program to complement the numerous tests on gypsum-sheathed walls is described and more design values for gypsum-sheathed walls are to be provided. The results of the full-scale tests will be used to create a numerical model of the gypsum-sheathed walls with OpenSees that can later be implemented in a complete building model.

# Chapter 2. Test program

In the Literature Review (Section 1.5), we have seen that gypsum sheathing can provide additional lateral in-plane shear strength and stiffness to walls. If the additional strength provided by the gypsum is considered during design, it may allow for the construction of more economical buildings. Nevertheless, if a building is stiffer than expected, it will have a smaller period of vibration and will be subjected to higher shear force demands under seismic loading. Moreover, if the lateral resisting elements are stronger than expected, the other elements in the load carrying path might fail before them even if the current capacity protection design procedures are followed. Thus, for seismic design, a good estimation of a wall's lateral strength and stiffness accounting for the gypsum sheathing is crucial. In this chapter, the design of the walls will be presented as well as the construction details and the test setup and loading protocols. The results of the test program will be presented in Chapter 3.

## 2.1 Description of test program

During the summer of 2014, thirty-five single storey walls were tested in the Jamieson Structures Laboratory at McGill University with monotonic and reversed cyclic displacement-based lateral loading protocols in order to investigate the effect of 1 to 2-hour fire resistance rated gypsum configuration on the shear behaviour. We have seen (Section 1.2) that one easy way to provide a 1-hour fire resistance rating to a load-bearing steel assembly is to affix one layer of 15.9 mm ($^5/_8$") Type X fire resistant gypsum on both sides of the steel frame (Underwriters Laboratories of Canada (ULC) (2006)). To construct a 2-hour fire resistant assembly, two layers of 15.9 mm ($^5/_8$") Type X fire resistant gypsum can be affixed to both sides of the steel frame (ULC, 2006). Both of the configurations were tested. The screws in each gypsum panel were spaced at 305 mm (12") o/c. Two main categories of walls were tested: shear walls and bearing walls. Shear walls are designed to resist lateral load and thus have hold-downs to anchor the studs to the ground. Bearing walls carry gravity loads along, hence are not designed to resist lateral load, and thus do not have hold-downs. Nonetheless, previous tests (see Subsection 1.5.3.2) have shown that gypsum-sheathed bearing walls can provide lateral resistance.

**Figure 2.1 Strap-braced gypsum-sheathed shear wall in the test frame**

**Figure 2.2 Test set-up**

All the walls were 2.44 m high and 1.22 m long (aspect ratio of 2:1) and the studs were spaced at 406 mm (16”) o/c (Figure 2.1). The walls were installed in a test frame specifically designed for in-plane shear loading (Figure 2.2). The test frame is equipped with a 250kN MTS dynamic loading actuator with a ±125mm stroke. Out-of-plane movements of the walls were resisted with lateral supports (Figure 2.3) that braced the load beam. Teflon plates were used between the lateral supports and the load beam to limit friction.

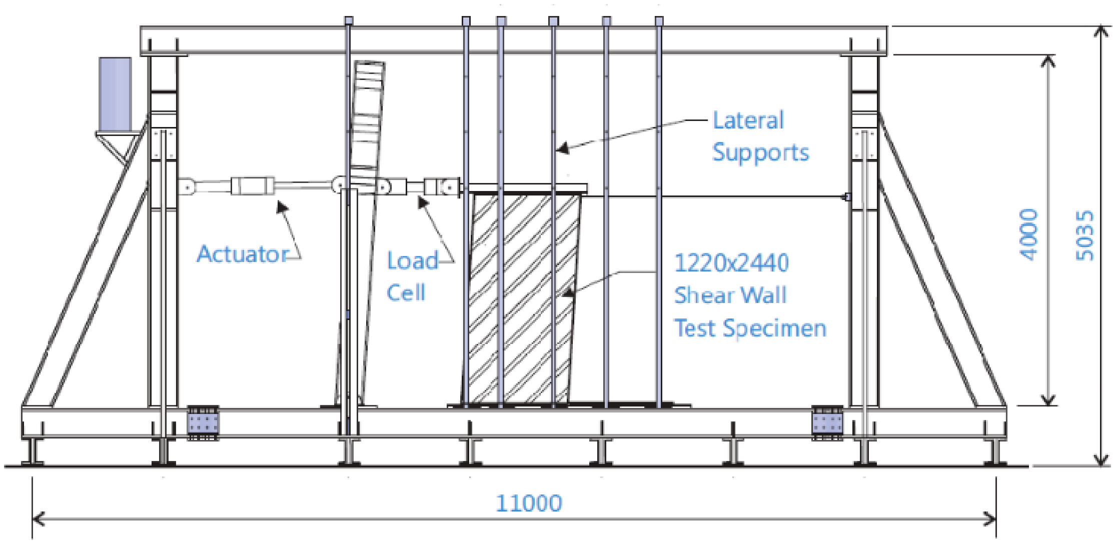



**Figure 2.3 Shear wall test frame**

In the shear walls, hold-downs were screw-connected to both ends of the chord studs (i.e. exterior studs) in order to counteract the uplift force due to lateral loading. Tracks were affixed to the test frame by means of bolts to transfer shear loads and to avoid slipping. Since the chord studs had to resist high axial force, they were made with two 1.37 mm-thick C-section studs put back-to-back. The interior studs were 1.09 mm-thick single C-section studs. In a gypsum-sheathed shear wall, shear resistance can be provided by the gypsum panels alone or by the association of straps and gypsum panels. The straps are screw-connected to gusset plates, which in turn are screw fastened to the frame, in order to have enough area to transfer the lateral load to the frame. Eight shear walls were sheathed with gypsum only and had no straps or gussets (Figure 2.6). 1-hour and 2-hour fire-resistance rated configurations were tested. Sixteen shear walls had straps, gusset plates and gypsum panels (Figure 2.7). Different gypsum configurations were tested in order to quantify the effect of 1 and 2-hour fire resistance rated configurations and resilient channels for sound-proofing configuration. One steel frame with hold-downs but no gussets plates or straps (Figure 2.4) was tested in order to quantify the frame contribution in the lateral resistance of shear walls. Two strap-braced wall with no sheathing (Figure 2.5) were tested monotonically and cyclically for comparison purposes.

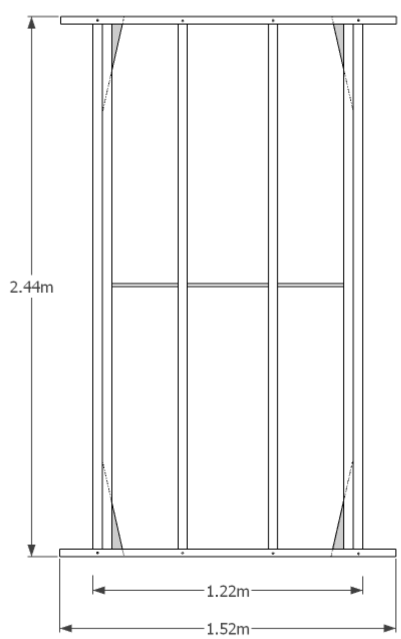



**Figure 2.4 Steel frame with hold-downs**

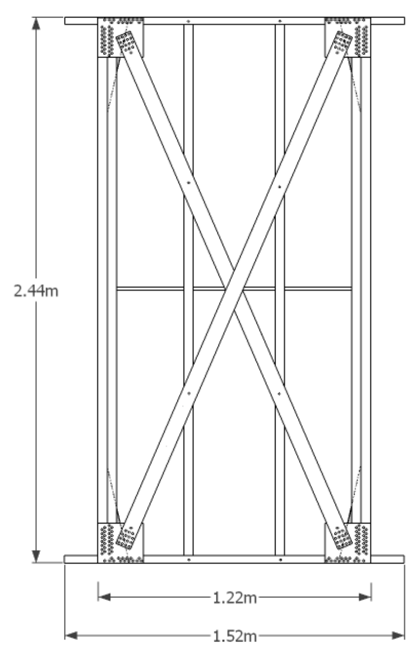
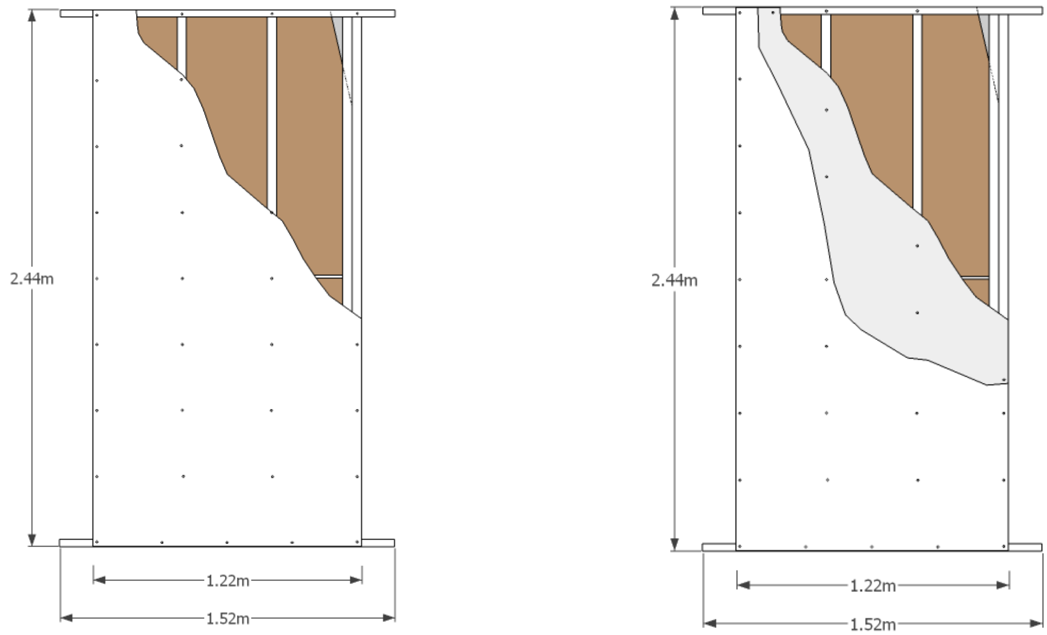
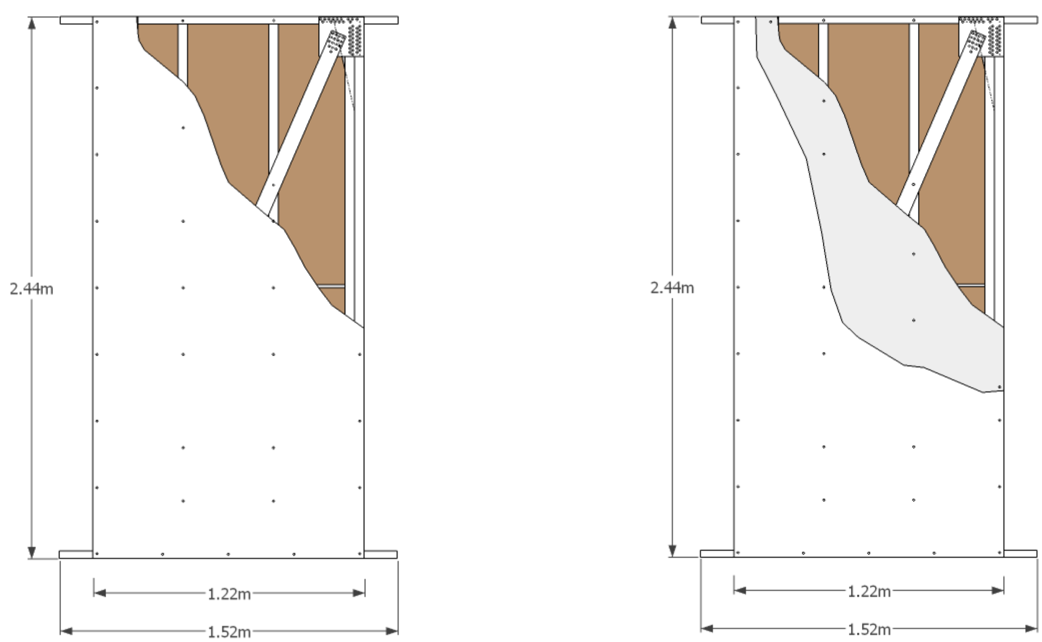



**Figure 2.5 Strap-braced shear frame**

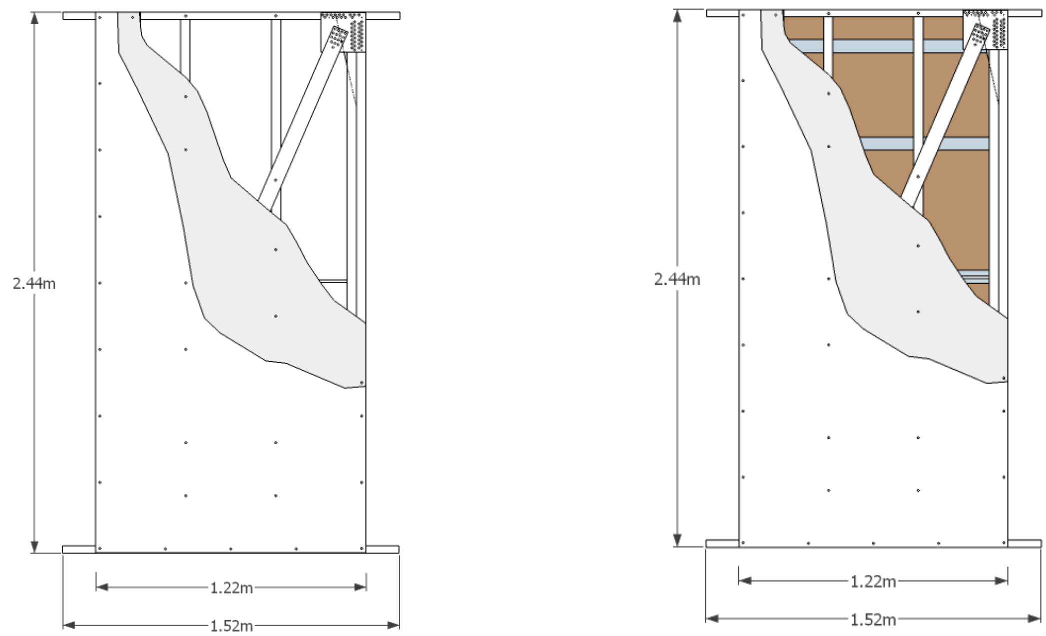



**(a)** **(b)**

**Figure 2.6 Gypsum-sheathed shear wall with (a) one layer of gypsum on both sides and (b) two layers of gypsum on both sides**

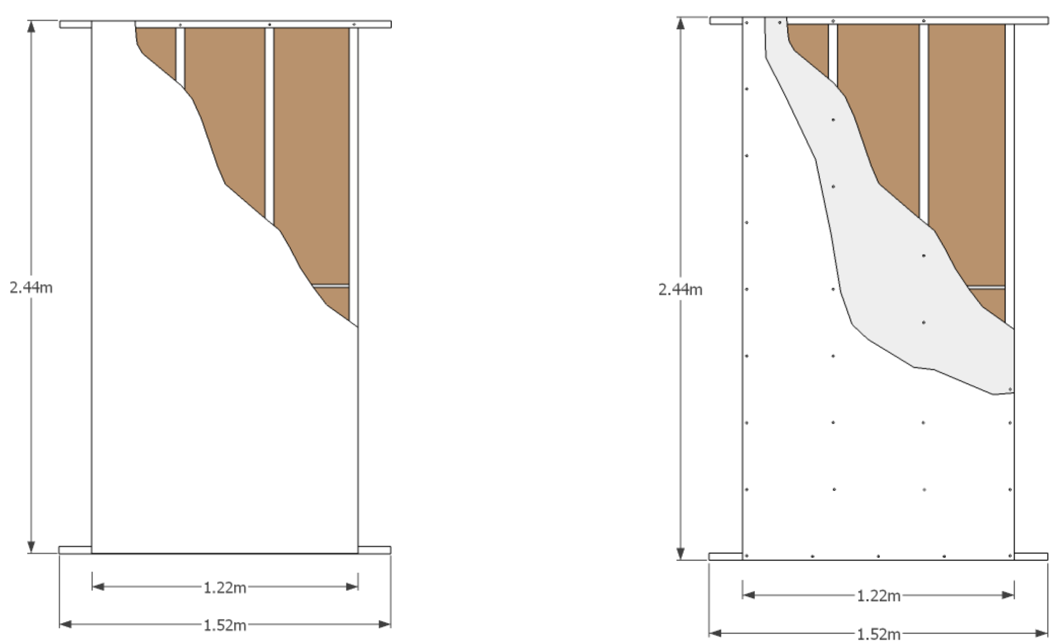



**(a)** **(b)**




**(c)** **(d)**

**Figure 2.7 Gypsum-sheathed strap-braced walls with (a) one layer of gypsum on both sides, (b) two layers of gypsum on both sides (c) two layers of gypsum on one side and (d) two layers of gypsum on one side and two layers of gypsum and resilient channels on the other side**




**(a)** **(b)**

**Figure 2.8 Gypsum-sheathed bearing walls with (a) one layer of gypsum on both sides and (b) two layers of gypsum on both sides**

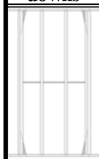
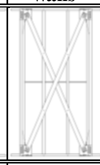
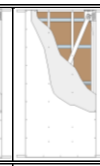
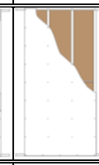
In bearing walls (Figure 2.8), no hold-downs were used. The tracks were affixed to the test frame by means of bolts to transfer shear forces and to avoid slipping. The “chord studs” were the same as the two interior studs since bearing walls usually spread over long distances. Thus, both the exterior and interior studs were made of 1.09 mm-thick single studs. 1 and 2-hour fire resistance rated bearing walls were tested.

In all the walls, the screws in each layer of gypsum were spaced at 300 mm o/c. For walls with one layer or for the inner layer of double layer sheathed walls, #6x25 mm (1”) type S drywall screws were used. In the outer layer of double layer sheathed walls, #6x41 mm (1”-$^{5}/_{8}$) type S drywall screws were used and were staggered with respect to the screws of the inner layer. Since the screws from the outer layer penetrated through the inner layer as well, the inner layer was attached to the frame every 150 mm.

A detailed matrix of all the test specimens is presented in Table 2.1. The numbering of each wall specimen was chosen as follows: ## X – Y with:

- ## the number of the wall configuration, beginning at 65;
- X the letter associated to the specimen tested (A, B or C);
- Y the letter corresponding to the type of loading, M meaning that the specimen was tested with monotonic loading and C meaning that the specimen was tested with cyclic loading.

## Table 2.1 Matrix of wall test specimens

| | Test specimens | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Steel frame with hold-downs** | **Strap-braced shear walls** | **Gypsum-sheathed shear walls** | | **Gypsum-sheathed strap-braced shear walls** | | | | **Gypsum-sheathed bearing wall** | |
| |  |  |  |  |  |  |  |  |  |  |
| **Name of the specimen** | 82 A-M | 65 A-M<br>83 A-C | 66 A-M<br>66 B-M<br>67 A-C<br>67 B-C | 68 A-M<br>68 B-M<br>69 A-C<br>69 B-C | 70 A-M<br>70 B-M<br>71 A-C<br>71 B-C | 72 A-M<br>72 B-M<br>73 A-C<br>73 B-C | 74 A-M<br>74 B-M<br>75 A-C<br>75 B-C | 76 A-M<br>76 B-M<br>77 A-C<br>77 B-C | 78 B-M<br>78 C-M<br>79 A-C<br>79 B-C | 80 A-M<br>80 B-M<br>81 A-C<br>81 B-C |
| **Straps**<br>- Thickness: 1.37 mm<br>- Width: 69.9 mm<br>- Grade: 340 MPa | No | Yes | No | | Yes | | | | No | |
| **Gusset plates**<br>- 177.8 mm x 203.2 mm<br>- Thickness: 1.37 mm<br>- Grade: 340 MPa | No | Yes | No | | Yes | | | | No | |
| **Type X Gypsum**<br>- 2.44 m x 1.22 m<br>- Thickness: 15.9 mm | NA | NA | 1 layer on both sides | 2 layers on both sides | 1 layer on both sides | 2 layers on both sides | 2 layers on 1 side | 2 layers on 1 side; 2 layers + resilient channel on other side | 1 layer on both sides | 2 layers on both sides |
| **Chord studs**<br>152 mm x 41 mm x 12.7 mm | Double chord studs put back-to-back<br>- Thickness: 1.37 mm<br>- Grade: 340 MPa | | | | | | | | Single chord stud<br>- Thickness: 1.09 mm<br>- Grade: 230 MPa | |
| **Hold-downs**<br>Simpson Strong Tie S/HD15S | Yes | | | | | | | | No | |
| **Interior studs**<br>- 152 mm x 41 mm x 12.7 mm<br>- Thickness: 1.09 mm<br>- Grade: 230 MPa | Spaced at 406 mm o/c | | | | | | | | | |
| **Tracks**<br>- 152 mm x 31.8 mm<br>- Thickness: 1.37 mm<br>- Grade: 340 MPa | Extended tracks (1.52 m long) | | | | | | | | | |

## 2.2 Design of the wall specimens

CFS shear walls need to be designed according to capacity based design principles. To begin with, the fuse elements need to be chosen so that they fail in a ductile fashion. Then, their probable resistance needs to be estimated in order to design all the non-fuse elements so that they are able to resist the loads associated with yielding of the braces. The same steel frame will be used for all the shear walls. We would like the straps and the gypsum panels to act as the fuse elements. Since the non-fuse members of the frame need to be stronger than the fuse elements in all the configurations, they were designed according to the largest fuse configuration resistance, which corresponds to the sum of the probable resistances of the straps and the two layers of gypsum on both sides of the frame.

Since bearing walls are not intended to resist lateral load, no capacity design was made. The same tracks as the shear walls were used and all the studs were 1.09 mm-thick studs.

### 2.2.1 Estimation of the maximum resistance of the fuse elements in shear walls

#### *2.2.1.1 Estimation of the resistance of the strap braces*

The strap braces used in the test walls had the same cross-section and grade as those used in the medium walls tested by Velchev *et al.* (2010) for comparison purposes. They were designed by Velchev *et al.* according to CSA S136 (2007) to resist a factored lateral load of 40 kN in 1:1 aspect ratio walls. Because of the high slenderness of the straps, only the straps in tension were considered to provide lateral resistance. The factored tension resistances based on the gross section yielding (Equation ( 2.1 )) and the net section fracture (Equation ( 2.2 )) were used. The straps were 69.9 mm (2 - $^{3}/_{4}$”) wide and 1.37 mm ($^{3}/_{64}$”) thick. The steel used had a nominal yield strength of 340 MPa (50 ksi) and a nominal ultimate tensile strength of 450 MPa (65 ksi).

$$T_r = \phi_t A_g F_y \tag{2.1}$$

$$T_r = \phi_u A_n F_u \tag{2.2}$$

where:

$\phi_t$ is the resistance factor for gross section yielding;

$\phi_u$ is the resistance factor for the net section fracture;

$A_g$ is the gross cross section area;

$A_n$ is the net cross section area;

$F_y$ is the yield strength;

$F_u$ is the ultimate strength.

For capacity design, the maximum force that the brace can transfer to the frame is needed to design the non-fuse elements. Since the actual strength of the steel can be greater than the nominal strength given by the manufacturer, the probable steel strength needs to be identified. Thus, once the size and grade of the straps is chosen, the probable resistance in tension of the brace (S213-07) is as determined using Equation ( 2.3 ), which corresponds to the yielding of the gross section.

$$T_n = A_g R_y F_y \tag{2.3}$$

$$T_n = A_n R_T F_u \tag{2.4}$$

where:

$A_g$ is the gross section area;

$A_n$ is the net section area;

$R_y$ is the yielding over-strength factor equal to 1.1 for 340 MPa steels (AISI S213-07);

$R_T$ is the ultimate over-strength factor equal to 1.1 for 340 MPa steels (AISI S213-07);

$F_y$ is the yield strength equal to 340 MPa in our specimens;

$F_u$ is the ultimate strength equal to 450 MPa in our specimens

In order for the braces to fail in a ductile fashion, yielding must occur before they fracture through the net section (Equation ( 2.4 )). This requirement leads to the Equation ( 2.5 ), which is given in the AISI S213-07 Standard.

$$A_n R_T F_u \geq A_g R_y F_y \quad (2.5)$$

The net area is calculated after the screw pattern of the brace connection has been determined. The two critical net section areas are represented on Figure 2.9. The probable resistance to fracture of one brace as per Equation ( 2.4 ) is 44.0 kN.

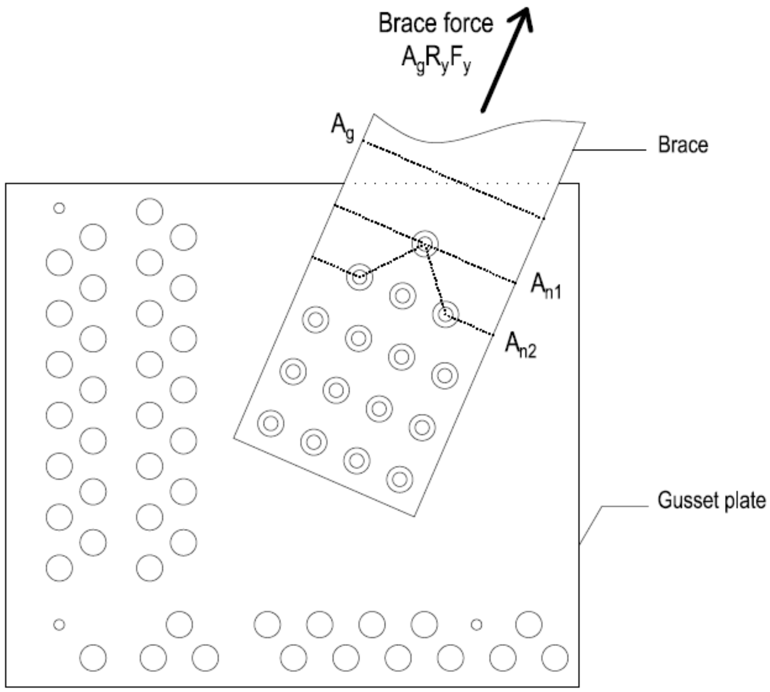



**Figure 2.9 Definition of gross section area and critical net section areas of the brace**

The probable gross yielding resistance in tension of one brace is *35.8 kN* (Equation ( 2.3 )). Thus, the ductility requirement as denoted by Equation ( 2.5 ) is verified.

Once the probable tension resistance of one strap is calculated, the total probable lateral load (Equation ( 2.6 )) and the total probable vertical load (Equation ( 2.7 )) that will occur on the shear wall can be determined; note two straps are accounted for in Equations ( 2.6 ) and ( 2.7 ) because the tested specimens have straps on both sides.

$$Total\ horizontal\ force = 2 \cdot cos\ \theta \cdot A_g R_y F_y \quad (2.6)$$

$$Total\ vertical\ force = 2 \cdot sin\ \theta \cdot A_g R_y F_y \quad (2.7)$$

where $\theta$ is the angle between the straps and the horizontal direction.

The probable horizontal resistance of the straps is 32.0 kN and the probable vertical resistance of the straps is 64.0 kN.

#### *2.2.1.2 Estimated gypsum resistance*

The described estimate of the gypsum resistance is an attempt to predict the forces in the test walls. Given this information, a capacity design calculation of the non-fuse elements in the wall specimens can be carried out accounting for both the straps and gypsum panels. The AISI S213 Standard (2007) lists the nominal shear strength provided by one layer of 12.7 mm gypsum sheathed on one side of a CFS wall (Table C 2.1.5 reproduced in Table 2.2). The results are based on tests of walls with unblocked gypsum panels and clip angles that were connected to the studs to act as hold-downs. To determine the probable resistance of the gypsum for capacity design, the Clause C 5.1.5 of AISI S213 recommends factoring the nominal resistance provided by the gypsum by 1.33.

Morello (2009) tested walls sheathed with one layer of 12.7 mm thick gypsum. The difference with the walls reported in AISI S213 is that gypsum panels were blocked on top and bottom of the wall and standard industry hold-downs were installed. These differences explain the larger resistances found in Morello (2009) compared to those reported in AISI S213. The results of the experiments are presented in Table 2.3.

**Table 2.2 Nominal shear resistance for wind and seismic loads for shear walls sheathed with gypsum board (kN/m) (according to Table C2.1-5 in AISI S213 (2007))**

| Assembly description | Maximum aspect ratio (h/w) | Fastener spacing at panel edges/field (mm) | | |
|---|---|---|---|---|
| | | 100/300 | 150/300 | 200/300 |
| | | Notation | | |
| | | $R_{100/300}$ | $R_{150/300}$ | $R_{200/300}$ |
| 12.5 mm unblocked gypsum board on one side of wall; studs max. 600 mm o.c.; clip angles used as hold-downs | 2:1 | 3.4 | 3.1 | 2.7 |

**Table 2.3 Nominal shear resistance for wind and seismic loads for shear walls sheathed with blocked gypsum board and hold-downs devices (kN/m) (according to Morello (2009))**

| Assembly description | Aspect ratio (h/w) | Fastener spacing at panel edges/field (mm) | | |
|---|---|---|---|---|
| | | 100/300 | 150/300 | 200/300 |
| | | Notation | | |
| | | $R_{100/300}$ | $R_{150/300}$ | $R_{200/300}$ |
| 12.5 mm blocked gypsum board on one side of wall; studs at 600 mm o.c.; industrial hold-down devices | 2:1 | 8.4 | 6.5 | 5.7 |

The walls tested for the experimental program described herein were constructed with industrial hold-down devices similar to those used by Morello (2009), however, the gypsum panels were not blocked at the top and the bottom of the wall, which is a similar configuration to the shear walls described in AISI S213.

In the tests reported in AISI S213 (2007) and Morello (2009), the walls had a screw spacing of either 150 mm or 200 mm along panel edges and 300 mm for interior connections. Since the screw spacing for the edge and interior screws of the test specimens for this project was selected as 300 mm, a conservative estimate of the expected gypsum resistance corresponding to the $R_{300/300}$ detail can be made with the resistance of the gypsum sheathed walls having a screw spacing of 200 mm for edge screws and 300 mm for interior screws, $R_{200/300}$. (Equation ( 2.8 )).

$$R_{300/300} = R_{200/300} \qquad (2.8)$$

When two layers of gypsum are connected with screws at 300 mm, the inner layer has screws every 150 mm. Thus, the $R_{150/300}$ resistance for the inner layer and the $R_{300/300}$ resistance for the outer layer were used to estimate the contribution of the gypsum. Since most of the failures of the gypsum included screw bearing (Subsection 1.5.3), it was postulated that the resistance provided by the gypsum was proportional to the panel thickness, and thus the tabulated values could be adjusted to account for the 15.9 mm-thick gypsum panels used for testing. To sum, the estimation of the resistance of a wall sheathed on both sides with two layers of 15.9 mm-thick gypsum panels was made with Equation ( 2.9 ). Using the resistances recommended in AISI S213 and the overstrength factor of 1.33, a predicted resistance for the test walls of $R_{gypsum} = 19\ kN/m$ was obtained. Using the resistances of the walls tested by Morello (2009) (Table 2.3) a larger value of $R_{gypsum}$ = *31 kN/m* was determined.

$$R_{gypsum} = (2 \cdot R_{150/300} + 2 \cdot R_{300/300}) \cdot \frac{t_{test}}{t_{reference}} \qquad (2.9)$$

where:

$t_{test}$ is the thickness of the gypsum equal to *15.9 mm* ;

$t_{reference}$ is the thickness of the gypsum in the reference tests equal to *12.7 mm* (AISI S213 or Morello, 2009)

Thus, the total horizontal load the gypsum wall can resist is given by Equation ( 2.10 ). The probable resistance of walls sheathed on both sides with two layers of 15.9 mm-thick gypsum is between *24 kN* (based on AISI S213) and *37 kN* (based on Morello, 2009).

$$Total\ horizontal\ force = R_{gypsum} \cdot L \qquad (2.10)$$

where $L$ is the length of the wall equal to 1.22 m.

To be conservative in the capacity design calculations, the highest predicted resistance of the gypsum panels (37 kN) was used. The braces and the gypsum panels were considered to act in combination as the fuse element in the lateral force resisting system. For a capacity based design, the other elements of the shear wall need to remain elastic when subjected to the force transferred by the fuse elements. The maximum of the horizontal force that can be transferred by the fuse elements is the sum of the horizontal resistance of the braces and the gypsum, equal to *69 kN*. The maximum of the vertical force that can be transferred by the fuse elements is the sum of the vertical resistance of the braces and the gypsum, equal to *101 kN*.

### 2.2.2 Design of the non-fuse elements in the shear walls

#### *2.2.2.1 Design of the back-to-back chord studs*

The chord studs were composed of two C-section studs placed back-to-back and connected together with screws spaced at 305 mm o/c. They were designed according to CSA S136 (2012) so that their nominal resistance (Clauses C5.1.2 and C5.2.2 of AISI S213 (2007)) to a concentric compression load is greater than the maximum probable vertical load transferred from the lateral resisting elements, equal to *101 kN*. Several tests have shown that it would be too conservative to consider the chord studs as pinned (Miller and Pekoz, 1993; Telue and Mahendran, 2001). The effective length factors for the buckling about the strong axis $K_x$ and the buckling about the weak axis $K_y$ were chosen based on the recommendations made by Hikita (2006) and are equal to $K_x = K_y = 0.9$. To be conservative, the effective length factor for torsion $K_t$ was chosen to be equal to $K_t = 1$. To be conservative, even though the walls were braced with the gypsum sheathing, only the bracing provided by the steel frame was considered in the design of the chord studs. The unbraced length in the strong axis was 2.44 m and the unbraced length in the weak axis was 1.22 m because flexural buckling about the weak axis was restrained by the bridging channel at the middle height of the wall. Chord studs with the same thickness (1.37 mm) and grade (340 MPa) as the straps were used.

When full composite action between the two studs placed back-to-back is assumed and when the web holes are not considered, the nominal resistance is *121.1 kN*. In reality, the two chord studs do not exactly act as one member and have their webs linked by screws spaced at 305 mm o/c. Moreover, the webs of the studs have holes to permit the passage of utilities. When screw connections of the webs at 305 mm o/c and web holes (36 mm wide) are considered, the calculated nominal resistance is *102.8 kN*.

Both of the calculated chord stud capacities are superior to the maximum probable vertical load transferred from the lateral resisting elements, equal to *101 kN*. Thus, the choice of the chord stud section was considered to be appropriate.

#### *2.2.2.2 Design of the hold-downs*

Hold-downs are used to transfer the uplift forces from the chord studs directly to the foundation. According to AISI S213 (Clauses C5.1.2 and C5.2.2), their nominal strength need to resist the uplift effect from the lateral load that the system can deliver, which is equal to *101 kN*. When used on steel with a thickness of 1.37 mm, Simpson Strong Tie S/HD 15 S hold-downs have a nominal capacity of *100.7 kN* (Simpson Strong-Tie, 2014). This is slightly inferior to the vertical force that the system can deliver but the estimation of the uplift was conservative since gypsum panels were considered to bear on the test frame, which will not be the case in the test program. Thus, Simpson Strong Tie S/HD 15 S hold-downs were used in the test walls.

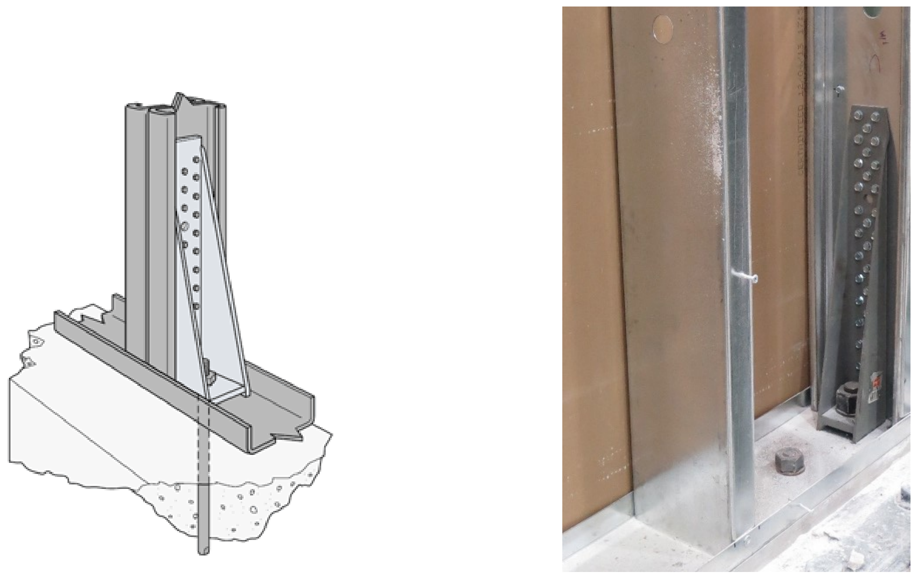


**Figure 2.10 Simpson Strong Tie Hold-down device installed on back-to-back chord studs (drawing on the left from Simpson Strong-Tie, 2014)**

#### *2.2.2.3 Design of the tracks*

The tracks had the same thickness (1.37 mm) and grade (340 MPa) as the chord studs and the straps. The extended parts of the tracks are subjected to tension due to the force transfer from the braces in tension. The parts of the tracks between the chord studs are subjected to compression due to the force transfer from the gypsum. The tracks are also subjected to bearing at shear anchor and anchor rod locations. The extended part of the track (in tension) only needed to resist the horizontal shear force from the braces (32.0 kN). The part of the track between the chord studs (in compression) needs to resist the distributed force from the gypsum (31.0 kN/m). The length to consider for the lateral force transfer from the gypsum to the track can be approximated by the length between the shear anchors (maximum of 330 mm). Thus, the parts of the tracks between the chord studs need to resist a load of 10.2 kN.

The nominal axial tension and axial compression and bearing capacity of the track were calculated following the CSA S136 provisions. The axial compression capacity of the track was determined assuming that it was fully braced. The nominal axial tension resistance of the track is equal to 99.4 kN and the nominal compression resistance of the track is equal to 47.7 kN. The shear anchors consist of $^{3}/_{4}$" ASTM A325 bolts and the anchor rods maintaining the hold-downs consist of 1" ASTM A193 threaded rods. The track bearing capacity is equal to 30.6 kN at shear anchor holes and to 33.6 kN at anchor rod holes.

#### *2.2.2.4 Design of the screw connections*

Gusset plates were installed between the frame and the straps in order to have a bigger area for lateral load transfer from the strap to the frame. The screw connections to connect the brace to the gusset plate and the gusset plate to the frame were designed according to CSA S136. Following AISI S213 (Clause C5.2.1), the factored resistance of the connections for straps must exceed the probable resistance of the fuse elements; in this case the strap brace. The factored shear resistance of one screw connection is determined by Equation ( 2.11) and is equal to *2.26 kN* for the 5 mm diameter fasteners that were used.

$$P_r = \phi P_{ss} \qquad \textbf{( 2.11)}$$

where:

$\phi$ is the screw safety factor equal to *0.4*;

$P_{ss}$ is the screw nominal shear resistance for one screw, equal to *5.64 N* for #10 screws in 1.37 mm-thick steel.

The number of screws *n* was chosen so that the brace-to-gusset plate screw connection resisted the probable yielding load of the brace (Equation ( 2.12 ))

$$n \cdot P_r \geq A_g R_y F_y \qquad \textbf{( 2.12 )}$$

The screw connections between the gusset plate and the straps transfer the tension load coming from the straps, equal to *35.8 kN* (Subection 2.2.1.1). Thus, sixteen screws were needed to transfer the load from the strap to the gusset plate.

The screw connections between the gusset plate and the frame need to resist the horizontal and vertical component of force from the brace. The conservative assumption that the screws placed vertically carried the entire vertical load from the brace and the screws placed horizontally carried the entire horizontal load from the brace was made. Thus, the screws placed vertically had to resist a probable force of *64 kN* and the screws placed horizontally had to resist a probable force of *32 kN* (Subsection 2.2.1.1). Fifteen #10 x 19 mm ($^3/_4$) screws were needed to transfer the horizontal load to the track and twenty-nine screws were needed to transfer the vertical load to the chord studs. The screws need to be separated from each other by at least 3 times the diameter of the screw (14.5 mm). In order for all the screws to fit on the studs, the tracks and the gusset plate while respecting this condition, a 178 mm x 203 mm gusset plate was used (Figure 2.11).

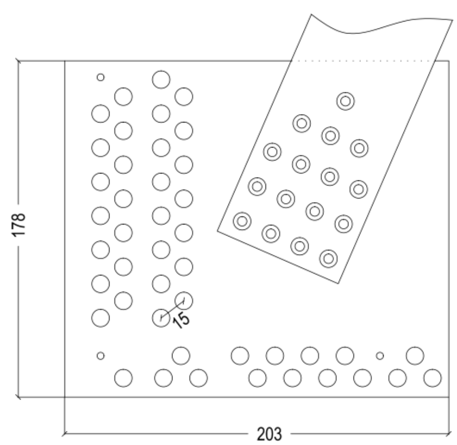



**Figure 2.11 Screw configuration in the gusset plate**

### *2.2.2.5 Design of the gusset plates*

Once the size of the gusset plate had been chosen, the resistance of the gusset plate needed to be checked. The nominal tension resistances based on the yielding of the gross area (Equation ( 2.13 )) and the fracture of the net area (Equation ( 2.14 )) were checked for the effective cross-sectional area at the end of a connection limited by the Whitmore section (Whitmore, 1952). The definition of the Whitmore section is presented in Figure 2.12. The capacity of the gusset plate calculated with its effective cross-sectional area needs to be superior to the probable force transferred by the brace, equal to *35.8 kN* (Subsection 2.2.1.1).

$$T_r = A_g F_y \quad (2.13)$$

$$T_r = A_n F_u \quad (2.14)$$

where:

$A_g$ is the gross section area;

$A_n$ is the net section area;

$F_y$ is the yield strength;

$F_u$ is the ultimate strength.

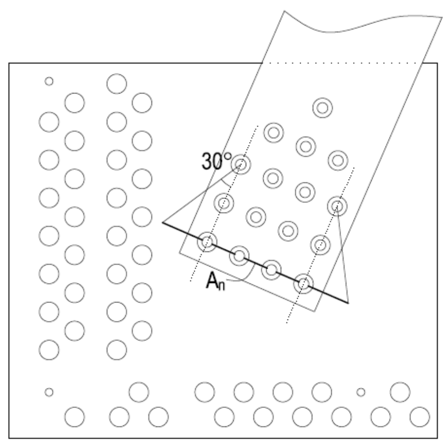



**Figure 2.12 Definition of the Whitmore section $A_n$**

The nominal tension resistance calculated based on the yielding of the gross area is equal to *44.7 kN* and the one calculated based on the fracture of the net area is equal to *46.8 kN*.

## 2.3 General fabrication and construction details

Tracks were drilled so that they could be affixed with the appropriate number of shear anchors and anchor rods to the loading beam (top track) and the test frame (bottom track). The anchors were spaced at 200 mm o/c on average. The shear anchor and anchor rod locations are represented in Figure 2.13.

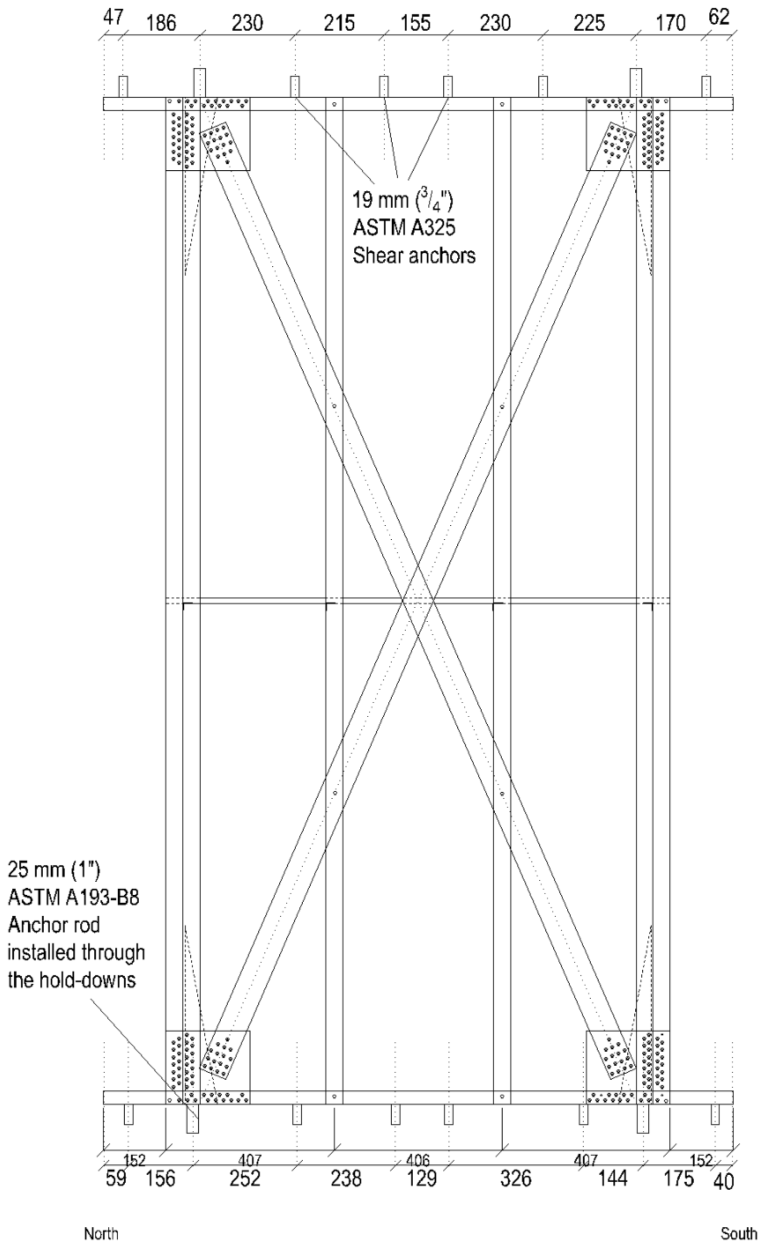



**Figure 2.13 Shear anchor and anchor rod locations**

The two C-studs put back-to-back to form the chord studs were fastened with two #10 x 19.1 mm ($^{3}/_{4}$") self-drilling hex washer head screws (Figure 2.14) spaced at 305 mm (12") o/c. S/HD 15S Simpson Strong-Tie hold-downs were attached at the top and bottom of the chord studs with thirty-three #14 x 25.4 mm (1") self-drilling hex washer head screws (Figure 2.14).

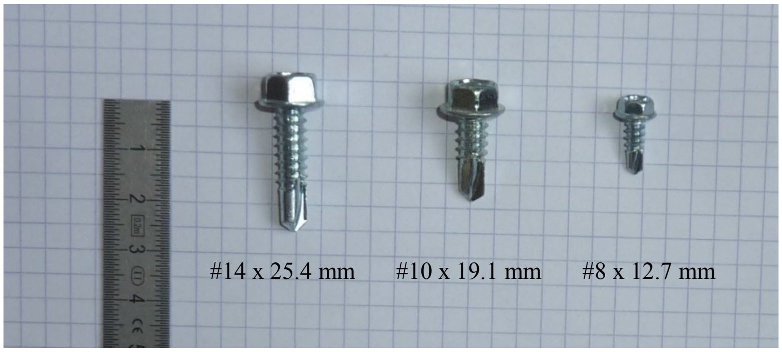



**Figure 2.14 Self-drilling hex washer head screws used in the specimens (scale in cm)**

The interior studs were oriented so that their open face was facing south (Figure 2.15). In bearing walls, all the studs were also oriented so that their open face was facing south.

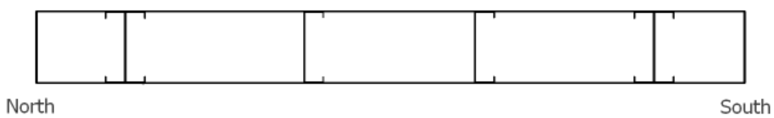



**Figure 2.15 Top view of the studs in the track in shear walls**

Clip angles were screw-connected on all the studs (interior and exterior) at mid-height with two #8 x 12.7 mm ($^{1}/_{2}$”) self-drilling hex washer head screws (Figure 2.14). They were used to attach the horizontal bridging channel (Figure 2.16).

**Figure 2.16 Clip angles and bridging channel**

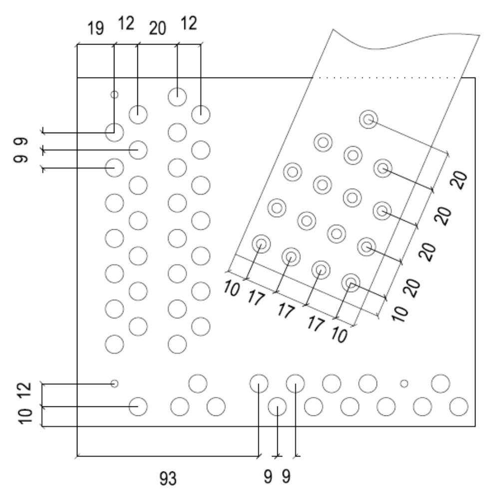



**Figure 2.17 Screw fastener locations in the gusset plates**

After the tracks and studs were prepared, they were assembled on the floor using several clamps. The interior studs were spaced at 406 mm (16”) o/c. The studs were screw-connected to the tracks using one #8 x 12.7 mm (1/2”) self-drilling wafer head screw (Figure 2.18) on each flange. A bridging channel was introduced through the holes in the web of the studs at mid-height and fastened to the clip angles with two #8 x 12.7 mm (1/2”) self-drilling hex washer head screws.

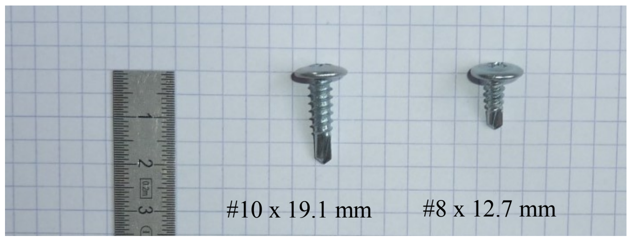



**Figure 2.18 Self-drilling wafer head screws used in the specimens (scale in cm)**

For strap-braced walls, gusset plates were screw-connected to the corners of the frame with forty-four #10 x 19.1 mm ($^3/_4$”) self-drilling wafer head screws (Figure 2.17 and Figure 2.18). Afterwards, strap-braces were fastened to one gusset plate with the same size screws. Then, while being hand-tensioned, the straps were connected with one #8 x 12.7 mm ($^1/_2$”) self-drilling wafer head screw to the interior stud and fastened to the second gusset plate. In all the walls, the straps connected to the bottom south corner and the top north corner were placed under the strap oriented in the other direction. The Figure 2.19 shows the overall dimensions and details of a strap-braced wall specimen.

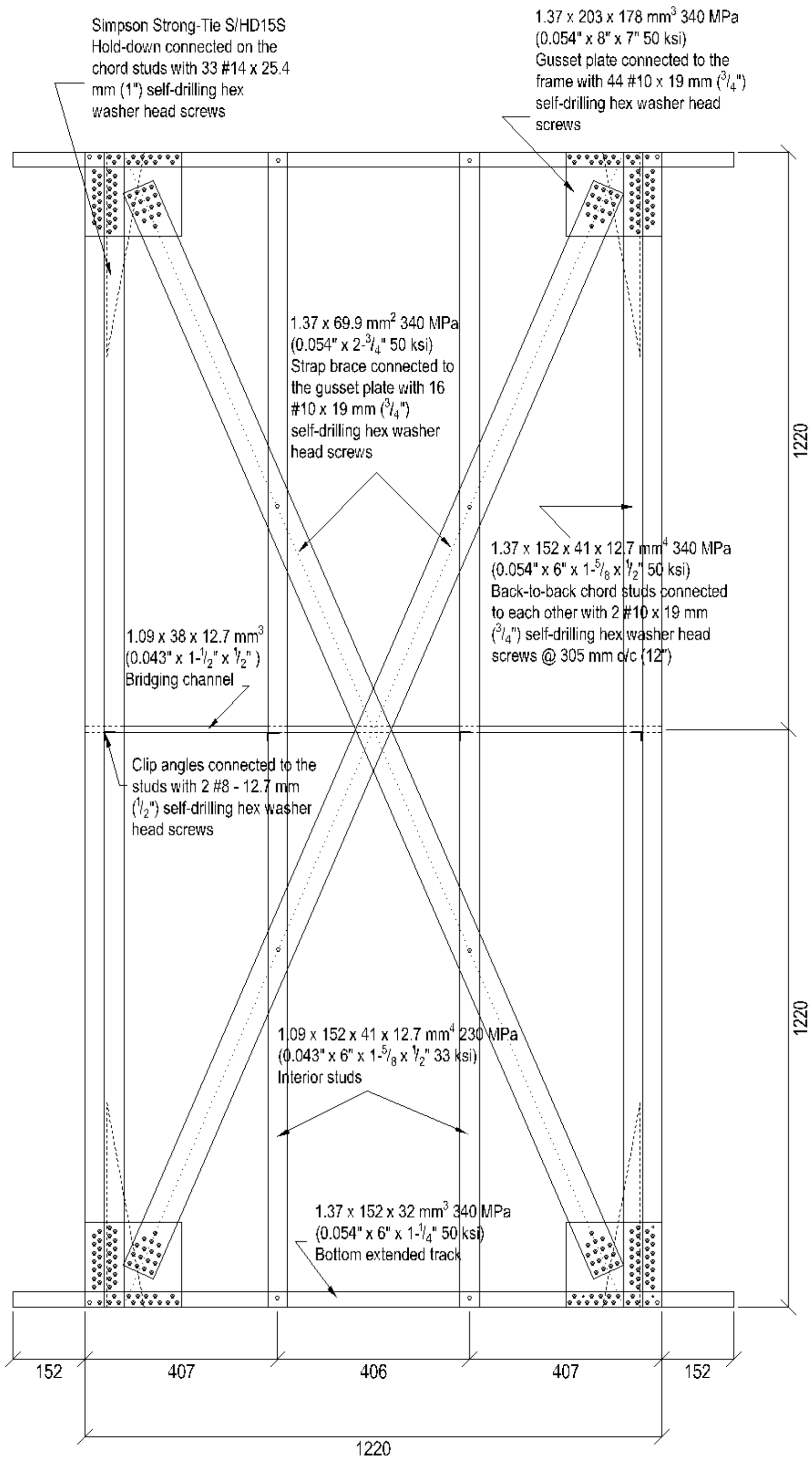



**Figure 2.19 Details of the frame of strap-braced walls**

For gypsum-sheathed walls, the panels were screw-connected on one side of the wall while the wall was horizontal (Figure 2.21.a). For the walls that were sheathed on both sides, the second side of the wall was sheathed after the wall had been installed in the frame (Figure 2.21.b). As recommended by the Underwriters Laboratories of Canada (ULC) (2006) for load bearing walls, the single layer or inner layer of a double layer assembly were fastened to the studs and the tracks with #6 25.4 mm (1”) long Type S drywall screws (Figure 2.20), spaced at approximately 300 mm o/c on the perimeter and in the field. The outer layers of a double layer assembly were screw-connected to the studs and the tracks with #6 41.3 mm (1-$^{5}/_{8}$”)long Type S drywall screws (Figure 2.20), spaced at approximately 300 mm (12”) o/c on the perimeter and in the field. In strap-braced walls, the spacing of the screws in the field was adapted so that no gypsum screws were fastened to the straps. The resilient channels, when specificed, were attached with screws at 270 mm o/c with one #8 12.7 mm ($^{1}/_{2}$”) on each chord or interior stud (Figure 2.22). The resilient channels were cut around the gusset plates so that the floating part of the resilient channel did not touch the gusset plate, allowing for efficient sound proofing. The gypsum panels were then connected to the resilient channels (Figure 2.23) with drywalls screws spaced at 300 mm o/c in each layer; the screws of the inner layer and outer layer of gypsum were staggered.

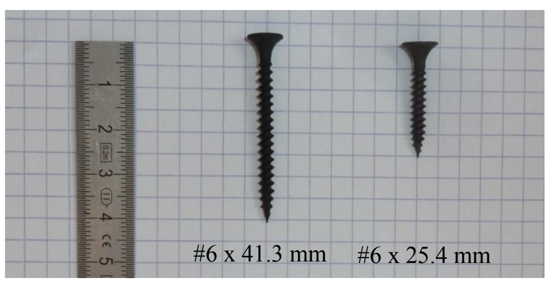



**Figure 2.20 Self-drilling Type S drywall screws used in the specimens (scale in cm)**

**(a)** **(b)**

**Figure 2.21 Gypsum installation: (a) First side of the wall placed in horizontal position; (b) Second side of the wall placed in vertical position**

**Figure 2.22 Resilient channels installed on the frame**

**Figure 2.23 Double layer gypsum fastened to the resilient channels**

## 2.4 Test setup and data acquisition instrumentation

Once each wall was built, it was affixed to the frame with shear anchors ($^3/_4$" ASTM A325 bolts) and, for shear walls the hold-downs were attached with anchor rods (1" ASTM A193-B7 threaded rods). The nuts were hand-tightened with a ratchet. In bearing walls, 1"-thick steel plates were used as washers in the two exterior bottom shear anchors in order to have a better distribution of the uplift load in the tracks.

A string potentiometer was installed to measure the in-plane lateral displacement of the top corner of the wall. It was affixed to the test frame and the string was hooked to a steel plate attached to the top of the chord-stud (Figure 2.24). The load cell inside the actuator was used to measure the lateral in-plane loading applied to the specimen. Steel plates were screw-connected to the frame so that the linear variable differential transformers (LVDT) could have a reference point to measure the uplift and in-plane slip at the bottom corners of the walls (Figure 2.25). In strap-braced walls, strain gauges (Figure 2.26) were installed on one side of the wall only. One strain gauge was installed on the east side strap in tension for monotonic tests and two strain gauges were installed on the two east side straps for cyclic tests. LVDTs and string potentiometers were installed to record the in-plane deformations of the test wall, including; slip, uplift and top of wall displacement. The measurement instruments were connected to Vishay Model 5100B scanners, which were used to record data using the Vishay System 5000 StrainSmart software

**Figure 2.24 String potentiometer installed on the top south of the wall**

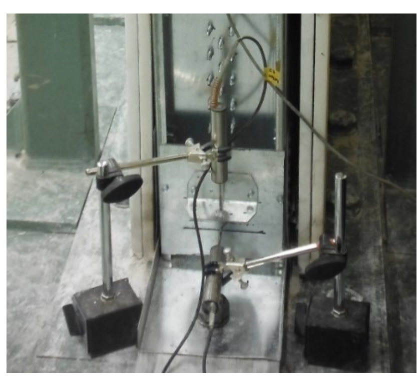


**Figure 2.25 LVDTs set up at the south corner of the wall**

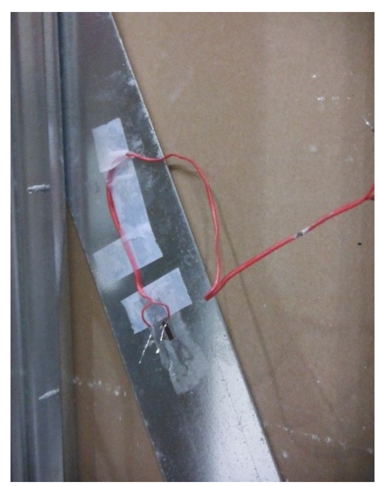


**Figure 2.26 Strain gauge installed on a brace**

## 2.5 Loading protocol

### 2.5.1 Monotonic testing

The monotonic testing protocol was used to simulate static lateral loading typical of wind loading. Moreover, the observed behaviour of the wall and the backbone curve do not depend on the history of the loading. The walls were subjected to a monotonic lateral loading at a constant rate of 5 mm/min. The specimens were tested until the gypsum panels began to bear on the loading frame or when the maximum stroke of the actuator (125 mm) was reached.

### 2.5.2 Reversed cyclic testing

The CUREE (Consortium of Universities for Research in Earthquake Engineering) reversed cycling protocol for ordinary ground motions (Krawinkler *et al.*, 2000) was used to represent the displacements that the specimens would experience if they were subjected to an earthquake with a probability of exceedance of 10 % in 50 years. Since a structure can be subjected to several earthquakes in its lifetime, the protocol takes into account the cumulative damage effects by imputing several cycles prior to the largest deformation amplitude.

The protocol depends on the specimen tested. Indeed, the amplitudes of the cycles are proportional to a reference displacement obtained from the monotonic tests of the same configuration wall specimen. For gypsum-sheathed bearing walls, the monotonic displacement capacity corresponds to the displacement, $\Delta_m$, at which the wall resistance is equal to 80% of the maximum resistance after it has reached its maximum capacity under monotonic loading (Figure 2.27). This displacement is then reduced to obtain the reference displacement for the CUREE reversed cyclic protocol corresponding to the maximum expected displacement taking into account the cumulative damage under cyclic loading (Equation ( 2.15 )). The monotonic test of one of the bearing walls sheathed with one layer of gypsum on both sides (78B-M) was used to determine the reference displacement for the CUREE protocol of the same configuration walls. Because of a set-up problem, the other monotonic test of the same configuration (specimen 78C-M) was done after the cyclic tests. The monotonic tests of the bearing walls sheathed with two layers of gypsum on both sides (80A-M and 80B-M) were used to obtain the reference displacement for the CUREE protocol of the same configuration walls.

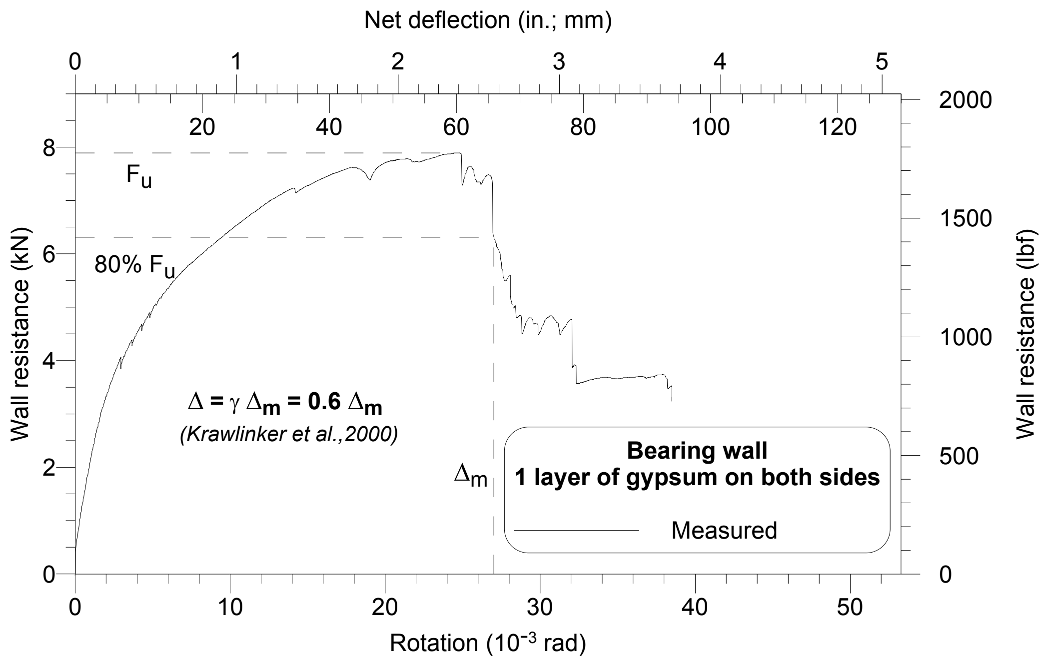



**Figure 2.27 Example of determination of the CUREE reference displacement *Δ* for sheathed bearing walls (based on 78B-M)**

$$\Delta = \gamma \Delta_m \quad (2.15)$$

where:

$\Delta$ is the reference displacement corresponding to the expected maximum displacement;

$\gamma$ is the reduction factor accounting for the difference of damage between monotonic and cyclic loading, equal to *0.6* according to Krawlinker *et al.* (2000).

For comparison purposes, the monotonic test of the strap-braced wall without gypsum panel (65A-M) was used to determine the reference displacement of the CUREE reversed cyclic protocols for all the shear walls (Figure 2.28). This is adequate for gypsum-sheathed strap-braced walls since in those walls, gypsum is considered as being non-structural. Moreover, using the same CUREE protocol for all the shear walls allows the direct comparison between strap-braced gypsum-sheathed shear walls and gypsum-sheathed shear walls

Since the strap-braced wall without gypsum panels (65A-M) maintained its strength up to the maximum stroke of the actuator (125 mm), the method mentioned above to calculate the reference displacement $\Delta$ cannot be used. Instead, the reference displacement was deduced from the yielding displacement $\Delta_Y$ as recommended in Al-Kharat and Rogers (2007). The yielding displacement was estimated by dividing the yielding strength (deduced from coupons tests) by the elastic stiffness. The reference displacement was obtained by factoring the yielding displacement by *2.667* to pass the displacement corresponding to the peak strength.

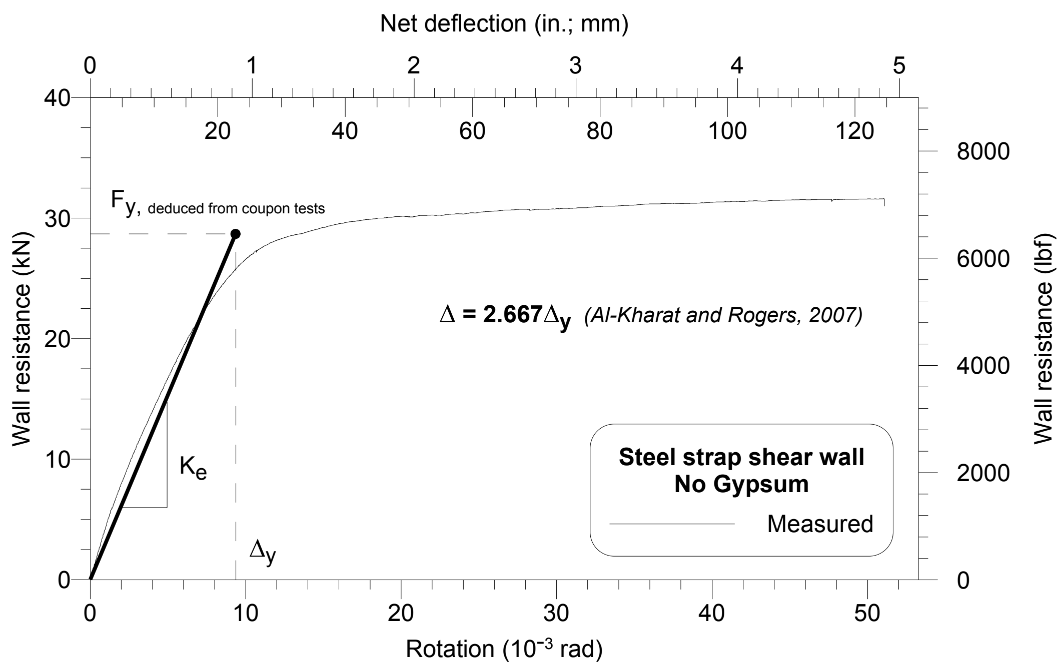



**Figure 2.28 Determination of the CUREE reference displacement $\Delta$ for shear walls**

The reference displacement calculated with Equation ( 2.15 ) is factored to obtain the different displacement values of the cyclic input. The cycles had a constant frequency of 0.25 Hz. Values and shape of a typical reversed cyclic protocol are presented in Figure 2.29. The other reversed cyclic protocols used can be found in Appendix A.

| Cycle Displacements | Target Displacement (mm) | Actuator input (mm) | Number of Cycles |
|---|---|---|---|
| 0.050 Δ | 3.0 | 4.2 | 6 |
| 0.075 Δ | 4.6 | 5.7 | 1 |
| 0.056 Δ | 3.4 | 4.6 | 6 |
| 0.100 Δ | 6.1 | 7.2 | 1 |
| 0.075 Δ | 4.6 | 5.7 | 6 |
| 0.200 Δ | 12.2 | 13.3 | 1 |
| 0.150 Δ | 9.1 | 10.3 | 3 |
| 0.300 Δ | 18.3 | 19.4 | 1 |
| 0.225 Δ | 13.7 | 14.9 | 3 |
| 0.400 Δ | 24.4 | 25.5 | 1 |
| 0.300 Δ | 18.3 | 19.4 | 2 |
| 0.700 Δ | 42.6 | 43.8 | 1 |
| 0.525 Δ | 32.0 | 33.1 | 2 |
| 1.000 Δ | 60.9 | 62.0 | 1 |
| 0.750 Δ | 45.7 | 46.8 | 2 |
| 1.500 Δ | 91.4 | 92.5 | 1 |
| 1.125 Δ | 68.5 | 69.7 | 2 |
| 2.000 Δ | 121.8 | 122.9 | 1 |
| 1.500 Δ | 91.4 | 92.5 | 2 |
| 2.500 Δ | - | 125.0 | 1 |
| 1.875 Δ | 114.2 | 115.3 | 2 |

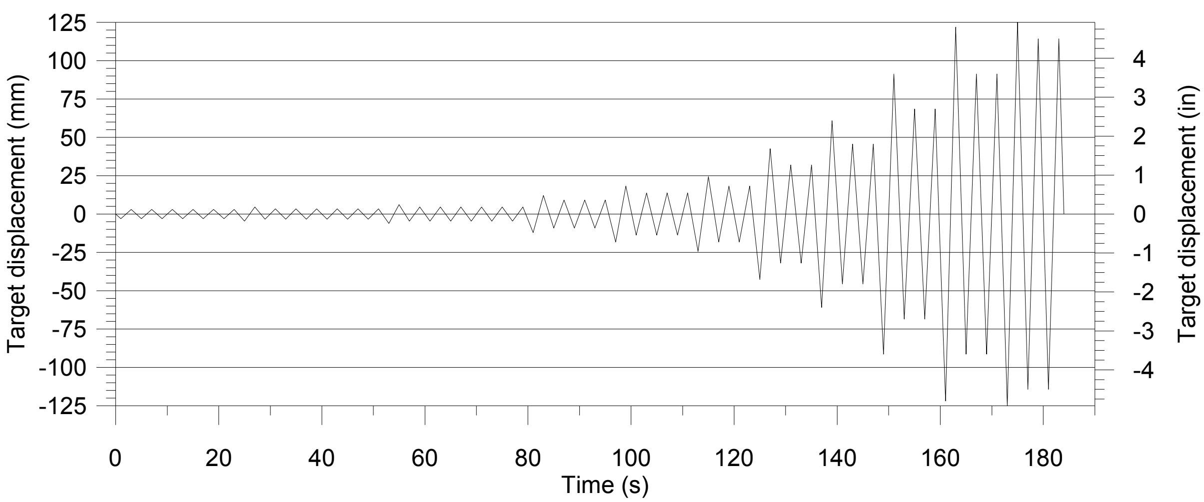



**Figure 2.29 Target displacements for the reversed cyclic protocol of strap-braced walls**

# Chapter 3. Test results and observations

This chapter contains the test results and observations of the experimental program. Different methods to estimate the resistance of the gypsum-sheathed walls and comparisons between the predicted resistance and the experimental results are presented.

## 3.1 Material properties

### 3.1.1 Steel members

The cold-formed steel products used in the test program were made from three different zinc-coated coils. One of them had a nominal thickness of 1.09 mm and a nominal grade of 230 MPa (ASTM A653, 2013); it was used to roll interior studs. The tracks, the gusset plates, the strap braces and the majority of the chord studs were produced from a coil with a nominal thickness of 1.37 mm and a nominal grade of 340 MPa (ASTM A653, 2013). Twenty-four chord studs (twelve double-chord studs) were rolled from another coil with the same nominal thickness and grade. Since the chord studs were not expected to buckle on the side of the wall in tension, the studs from this second coil were used on the uplift side of the monotonically tested specimens; and as such their response to loading had a minimal effect on the wall's response.

All the coils were zinc-coated to avoid steel oxidation. Since the actual thickness of the steel was not directly measureable, the coating from one coupon of each coil was removed with a water / hydrochloric acid solution; after which the uncoated thickness of the coils was measured (Table 3.1).

The material properties of each coil were determined by testing three coupons of each coil according to ASTM A370 (American Society for Testing and Materials (ASTM), 2014). Before beginning the test, gauge marks spaced at 50.4 mm (gauge length) were punched on the coupons in order to measure the elongation at the end of the test. An extensometer placed on the coupons was used to monitor their elongation; it was removed just before the coupons broke, at necking. In the elastic range, the cross-head rate was 0.002 mm/s. In the plateau region, the speed was increased to 0.01 mm/s. The rate was further increased to 0.1 mm/s until the end of the test. The results of the tests are presented in Table 3.1.

**Table 3.1 Material properties of interior studs, double chord studs, tracks, gusset plates and straps**

| Member | Interior stud | Chord stud, track, gusset plate, strap (first 1.37 mm-thick coil) | Chord stud (second 1.37 mm-thick coil) |
|---|---|---|---|
| Nominal thickness, $t_n$ | 1.09 mm | 1.37 mm | 1.37 mm |
| Nominal yield strength, $F_{yn}$ | 230 MPa | 340 MPa | 340 MPa |
| Uncoated thickness, $t_{uc}$ | 1.11 mm | 1.38 mm | 1.35 mm |
| Cross-head rate | 0.002 mm/s | 0.002 mm/s | 0.002 mm/s |
| Measured yield strength, $F_y$ | 297 MPa | 362 MPa | 394 MPa |
| Measured ultimate strength, $F_u$ | 383 MPa | 453 MPa | 480 MPa |
| $F_u$ / $F_y$ | 1.29 | 1.25 | 1.22 |
| Elongation | 38.6 % | 36.1 % | 31.8 % |
| $F_y$ / $F_{yn}$ | 1.29 | 1.06 | 1.16 |

### 3.1.2 Gypsum panels

The moisture content of the gypsum in each specimen was obtained with the Method B of ASTM D4442 (ASTM, 2007) using circular samples from each layer (Data sheets in Appendix B). The average volume of the circular samples was 119 $cm^3$. The moisture contents ranged between 17.4% and 22.6% and the average moisture content measured with this method was 21.4%.

## 3.2 Observed behaviour of walls under lateral loading

The test program was conducted to better understand the influence of gypsum panels on shear walls and bearing walls subjected to lateral in-plane loading. The shear walls of the test program were designed according to capacity based design principles, as described in Section 2.2. The components of the steel frame for the shear walls were designed so that they would remain elastic when the braces and drywall connections reached their ultimate resistance. In contrast, even though it was known beforehand that bearing walls with gypsum panels would likely provide lateral resistance, the steel frame of these walls was not specifically designed with this in mind because typically a bearing wall is not intended to resist in-plane lateral force. Taking this background information into account, a review of the observed behaviour during testing is presented in this section; the detailed specimen-by-specimen observations can be found in Appendix B.

### 3.2.1 Behaviour of cold-formed-steel components

#### *3.2.1.1 Shear walls*

In all the shear walls, the steel frame was globally undamaged, which is consistent with the design assumption. All the CFS components and their fasteners remained elastic except at some localized areas. The lips in the chord studs (Figure 3.1) and interior studs (Figure 3.2) exhibited some minor local buckling. Local web buckling was also observed at the bottom of the interior studs. Some distortional buckling in the chord studs (Figure 3.3) due to bending was also observable.

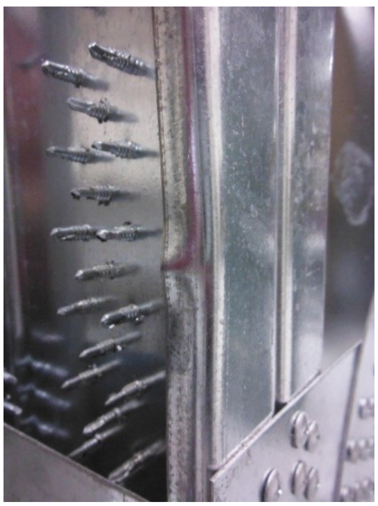


**Figure 3.1 Chord stud lip local buckling**

**Figure 3.2 Interior stud lip local buckling**

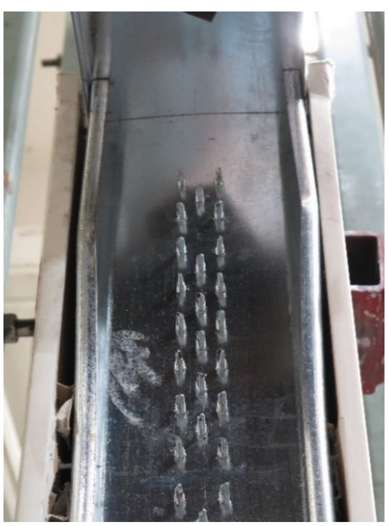


**Figure 3.3 Chord stud flange distortional buckling**

**Figure 3.4 Yielding of the straps in tension and buckling of the straps in compression**

In all the strap-braced shear walls, the straps subjected to tension have yielded (Figure 3.4), the straps subjected to compression have buckled and have provided effectively no resistance, while the steel frame mainly remained elastic. These were the expected member behaviours for the strap-braced walls. None of the braces has fractured.

### *3.2.1.2 Bearing walls*

In bearing walls, uplift was not restrained by means of hold-downs; as such, the tracks and stud-to-track connections were subjected to higher loads than they were in the shear walls. In the bottom corners in tension of some walls this led to the screw bearing failure of the flanges of the tracks (Figure 3.5) or the shear failure of the screw connection between the studs and the track (Figure 3.6). Localized damage to the tracks (Figure 3.5) and their flanges (Figure 3.7) were also observable in the bearing walls. Distortion of the section was also observable at the bottom of the interior studs (Figure 3.8).

**Figure 3.5 Bearing failure of the flanges of the track and localized damage of the track**

**Figure 3.6 Shear failure of the screw**

**Figure 3.7 Localized damage of the flanges of the track**

**Figure 3.8 Section distortion of the interior studs**

### 3.2.2 Behaviour of gypsum-sheathing components

#### *3.2.2.1 General description of the sheathing behaviour*

When lateral in-plane displacement is imposed on the walls, for the most part, the gypsum panels rotate as rigid bodies while the steel frame deforms in shear. The connections between the gypsum panels and the steel frame accommodated this differential displacement by means of bearing / pull through damage in the gypsum and bearing damage in the steel frame, as well as fastener tilting. Due to the differential displacement between the gypsum panels and the steel frame, the holes through which the screws were attached were enlarged (Figure 3.9). This failure mode is referred to as screw tilting (ST). As the displacements of the wall became larger, the screw head carved into the gypsum (Figure 3.10) and in some cases pulled entirely through the panel. This failure mode is referred to as pull-through (PT); it was more evident at the screw connections along the perimeter of the wall since they were subjected to higher differential displacement.

Figure 3.9 Screw tilting

Figure 3.10 Screw pull-through

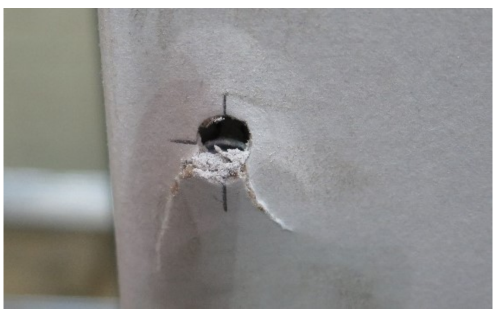


Figure 3.11 Screw bearing

Figure 3.12 Gypsum cracking

Figure 3.13 Gypsum crushing

Figure 3.14 Screw shear

Differential displacement between the steel frame and the gypsum also yielded bearing (B) of the screw shank on the gypsum (Figure 3.11). When high displacements were reached, the portions of the gypsum panels subjected to tension cracked. Gypsum cracking (GC) mostly happened in the corners in tension of the walls. (Figure 3.12) and along the edges. In some cases, the gypsum failed by crushing (GCu) on the screws (Figure 3.13). Screw shear failure (SS) (Figure 3.14) of the drywall fasteners was also observed near the panel corners in compression because the gypsum did not crack in tension, and as such, greater force demand was placed on the fastener.

*3.2.2.2 Shear walls*

The behaviours described above were all observed during the shear walls tests. Furthermore, in the specimens tested with a reversed cyclic protocol, the shear failure of the screws was not limited to the corners of the walls; rather, several screws failed in shear along the edges of the walls. In the walls with two layers of gypsum on one side and two layers of gypsum and resilient channels on the other side, the side with resilient channels had a different behaviour; failure was concentrated in the resilient channels (Figure 3.15 and Figure 3.16) and gypsum sheathing; the sheathing-to-resilient channel and the resilient channel-to-frame connections remained relatively undamaged.

**Figure 3.15 Damaged resilient channel**

**Figure 3.16 Close up of a damaged resilient channel**

#### *3.2.2.3 Bearing walls*

In bearing walls, damage of the sheathing was limited to some screw locations along the perimeter of the panels. In the one-layer gypsum-sheathed bearing walls, screw tilting, screw pull-through, gypsum bearing, gypsum cracking and screw shear were observable. In the two-layer gypsum-sheathed bearing walls, screw pull-through and bearing were visible, along with some screw tilting.

## 3.3 Method of analysis of measured test data

### 3.3.1 Lateral resistance properties

Different lateral resistance parameters, $S_u$, $S_{0.4u}$, $S_{0.8u}$ and $S_y$, were obtained for each specimen when it was possible. In this thesis, the wall resistances (kN) will be designated with an identifier beginning with the letter *F*. The wall resistance per unit length (kN/m), which is calculated by dividing *F* by the length of the wall (1.22 m), will be designated with an identifier beginning with the letter *S*.

In all the specimens, the ultimate resistance $S_u$ was defined as the highest load reached during the test. $S_{0.4u}$ and $S_{0.8u}$ (post-peak) were defined respectively as being equal to 40% and 80% of $S_u$.

A small plateau region was observed for the monotonic test of the unsheathed strap-braced shear wall specimen (65 A-M). In this specimen, the yielding force, $S_y$, was taken as the lowest value in the post-yield plateau region (Figure 3.17).

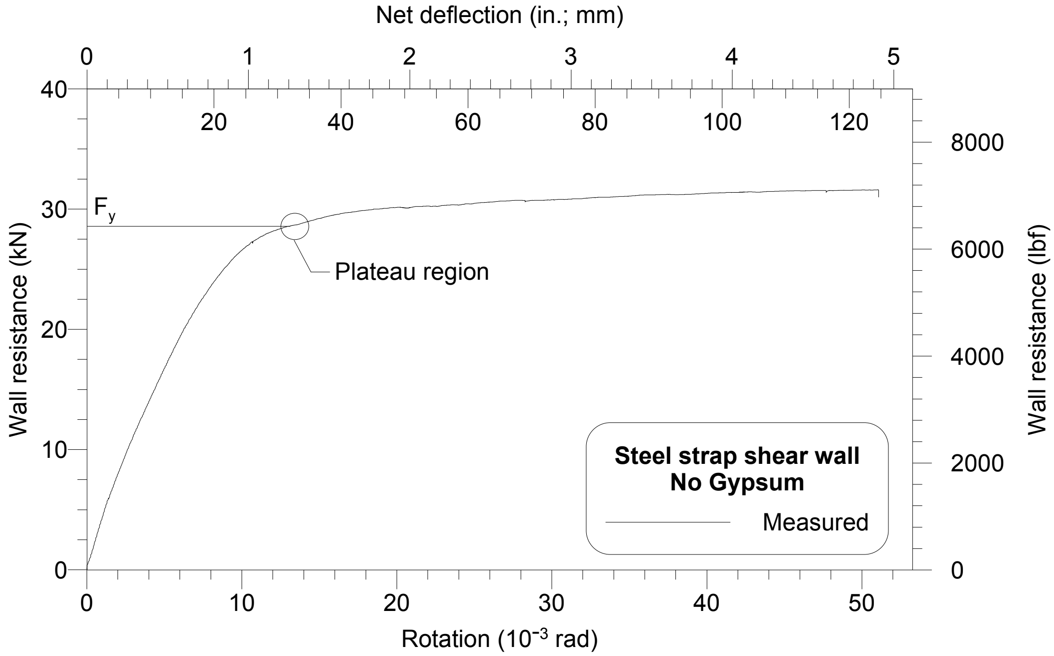



**Figure 3.17 Plateau region and definition of the yielding force $F_y$ for the specimen 65A-M**

In gypsum-sheathed walls, no yield plateau region was observable. Park (1989) developed the equivalent energy elastic-plastic (EEEP) method to estimate the yield resistance $S_y$ of structures subjected to lateral loading. This equivalent energy approach, later modified by Foliente (1996), is based on the assumption that the energy dissipated up to ultimate failure can be represented by a simplified bilinear elastic-plastic curve with the same energy dissipation. This is equivalent to defining the yield resistance $S_y$ such as the areas $A_1$ and $A_2$ of the graph in Figure 3.18 are equal.

The maximum displacement $\Delta_{net,max}$ corresponding to the ultimate failure needs to be defined because a wall in a building cannot deform indefinitely. There were three cases depending on the maximum code-based storey drift ratio $\Delta_{max,code}$ and the values of the lateral in-plane displacements $\Delta_{net,u}$ and $\Delta_{net,0.8u}$ corresponding respectively to $S_u$ and to $S_{0.8u}$ (post-peak). In the NBCC (NRCC, 2010), the maximum inelastic seismic storey drift ratio is 2.5%, which corresponds to a lateral displacement $\Delta_{max,code}$ of 61 mm in the specimens tested. Nevertheless, some wall specimens degraded significantly and their resistance went below $S_{0.8u}$ before reaching $\Delta_{max,code}$ . In these cases (Case 1), the displacement $\Delta_{net,max}$ corresponding to the ultimate failure was taken equal to $\Delta_{net,0.8u}$. Conversely, several walls maintained their resistance way beyond the maximum code-based storey drift ratio $\Delta_{max,code}$ and choosing the ultimate failure at this storey drift ratio was considered too conservative. Thus, for the walls which reached their maximum capacity $S_u$ for storey drift greater than 2.5%, showing that they still had a significant lateral resistance (Figure 3.20), a less conservative maximum displacement ($\Delta_{net,max}$ = 100 mm) was chosen (Case 3). For all the other cases, the displacement $\Delta_{net,max}$ corresponding to the ultimate failure was taken equal to code-based drift limit $\Delta_{max,code}$ (Case 2) (Figure 3.19). In summary:

- Case 1: if $\Delta_{net,0.8u} < \Delta_{max,code}$, $\Delta_{net,max} = \Delta_{net,0.8u}$ ;
- Case 2: if $\Delta_{net,u} < \Delta_{max,code} < \Delta_{net,0.8u}$, $\Delta_{net,max} = \Delta_{max,code}$ = 61 mm;
- Case 3: if $\Delta_{net,u} > \Delta_{max,code}$, $\Delta_{net,max}$ = 100 mm.

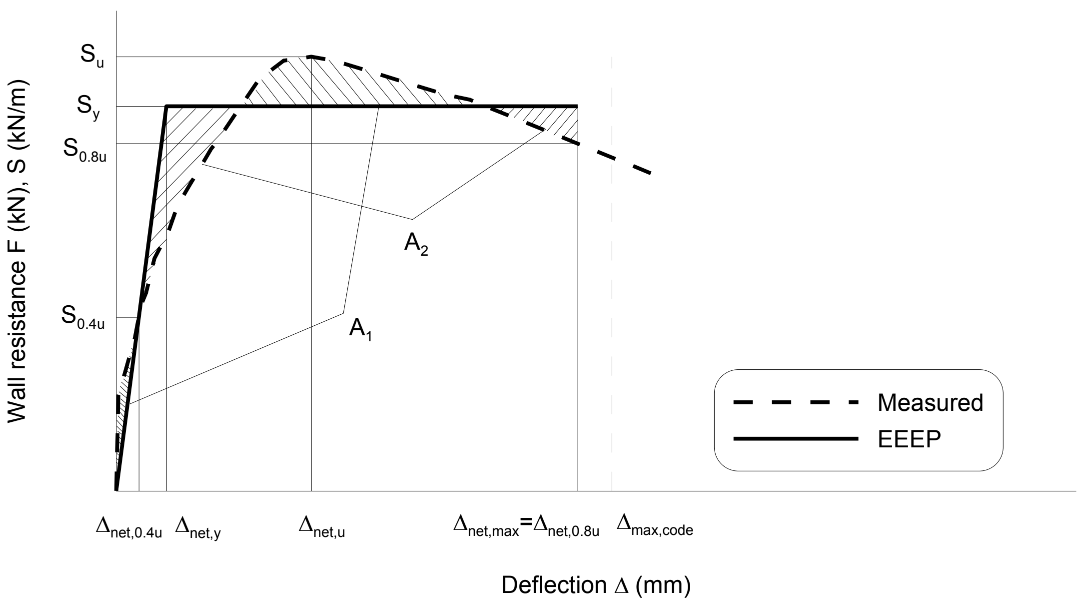



**Figure 3.18 EEEP model and definition of $\Delta_{net,max}$ for Case 1 wall specimens**

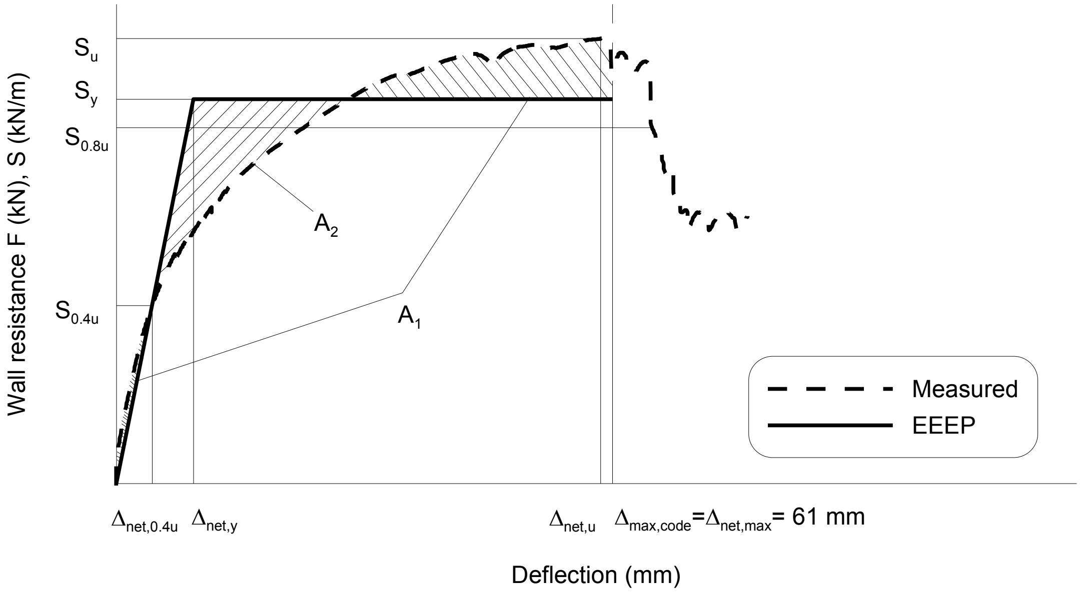



**Figure 3.19 EEEP model and definition of $\Delta_{net,max}$ for Case 2 wall specimens**

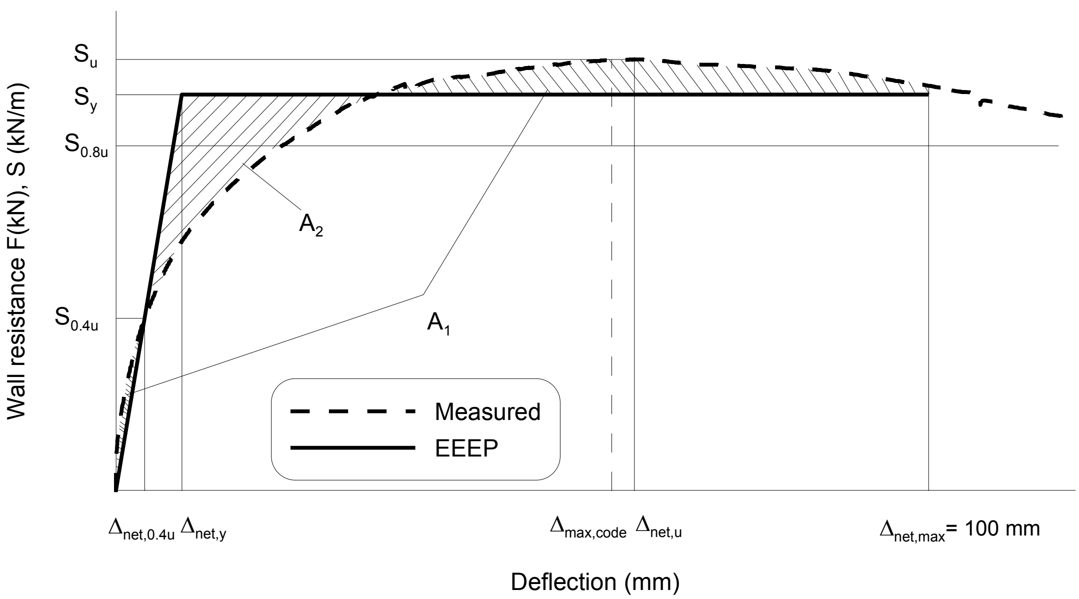



**Figure 3.20 EEEP model and definition of $\Delta_{net,max}$ for Case 3 wall specimens**

### 3.3.2 Stiffness properties

According to ASTM E2126 (American Society for Testing and Materials (ASTM), 2011), the in-plane lateral elastic stiffness, $K_e$, of the wall can be calculated with the Equation ( 3.1 ).

$$K_e = \frac{F_{0.4u}}{\Delta_{net,0.4u}} \quad (3.1)$$

where:

$F_{0.4u}$ is equal to 40% of the ultimate load $F_u$;

$\Delta_{net,0.4u}$ is the in-plane lateral displacement of the wall corresponding to $F_{0.4u}$.

This definition of $K_e$ allows a simple way to estimate the elastic stiffness, since one can find it by hand. It is accurate for elements that behave elastically for small displacements and reach their ultimate resistances well within the 2.5% inelastic drift limit. However, when subjected to lateral in-plane loading, gypsum-sheathed walls tend to behave non-linearly at relatively low drifts and the maximum resistance may be reached at high drifts. Thus, an alternate definition for the in-plane lateral elastic stiffness $K_e$, which takes into account the ductile behaviour of the walls, was considered. This alternate $K_e$ was based on an EEEP model where the perfectly plastic region is at the level of $F_u$, which differs from the EEEP model presented in the Subsection 3.3.1. Thus, knowing $F_u$, one could determine $K_{e,mod.EEEP}$ and $\Delta_{y,mod.EEEP}$ so that the areas $A_1$ and $A_2$ on the Figure 3.21 were equal.

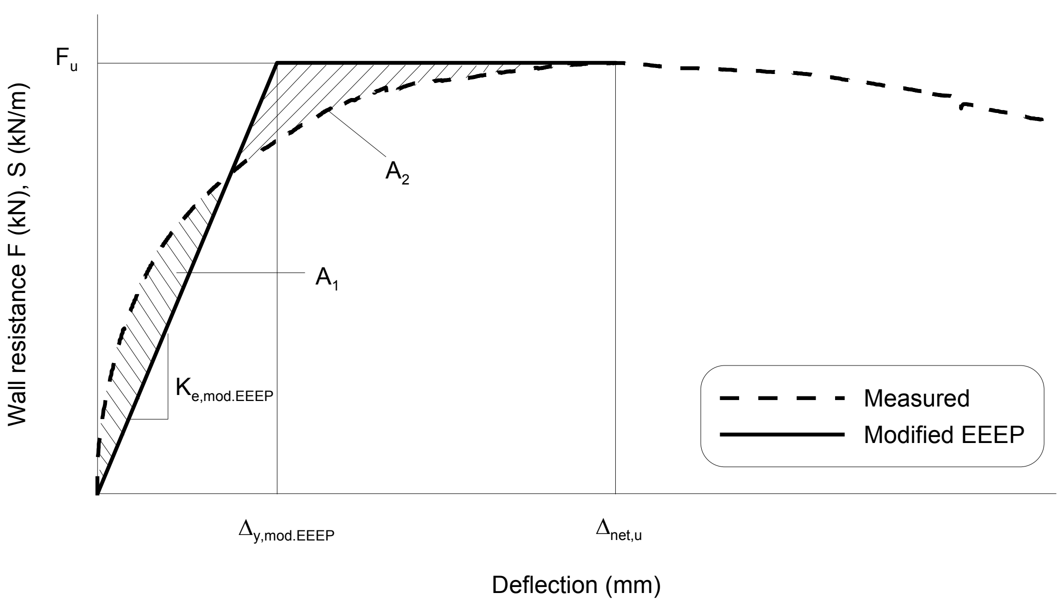



**Figure 3.21 Determination of $K_{e.mod.EEEP}$ with a modified EEEP model**

The shear bare frame (82A-M) had almost a linear behaviour. Thus, instead of using the previous definitions, the elastic stiffness, $K_e$, was obtained with a linear regression fitted using the least square method (Figure 3.22).

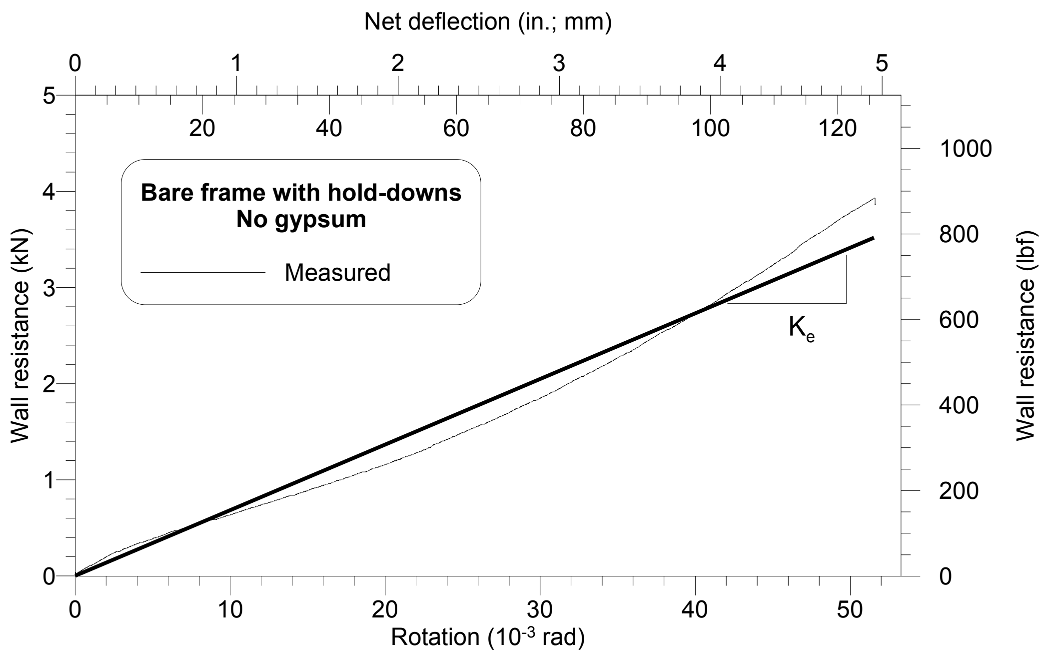



**Figure 3.22 Elastic stiffness of the shear bare frame obtained with a linear regression**

### 3.3.3 Seismic design properties

The ductility factor $\mu$ can be determined with the Equation ( 3.2 ) described in ASTM E2126 (2011).

$$\mu = \frac{\Delta_{max}}{\Delta_{net,y}} \quad (3.2)$$

where:

$\mu$ is the ductility factor;

$\Delta_{max}$ is the displacement corresponding to the failure limit state and;

$\Delta_{net,y}$ is the ideal elastic yield displacement; $\Delta_{net,y} = F_y / K_e$ , with $F_y$ the yield resistance and $K_e$ the elastic stiffness.

In the unstrapped shear walls and the bearing walls, $F_y$ was determined as described in Subsection 3.3. For sheathed strap-braced walls, $F_y$ could not be determined because no yield plateau was observable. Thus, the predicted yielding force $F_{yp}$ of the straps using their actual dimensions was used instead of $F_y$ to determine $\Delta_{net,y}$.

The test-based ductility-related force modification factor $R_d$ was calculated with the Equation ( 3.3 ) (Newmark and Hall, 1982).

$$R_d = \sqrt{2\mu - 1} \qquad (3.3)$$

where:

$R_d$ is the ductility-related force modification factor;

$\mu$ is the ductility factor.

### 3.3.4 Energy

The energy dissipated by the wall was determined by adding the area under the monotonic curve or the backbone curve of walls tested cyclically at all the time steps up to the maximum displacement. (Equation ( 3.4 )).

$$\mathrm{E} = \sum_{i=1}^{n-1} \frac{F_i + F_{i+1}}{2} \cdot (\Delta_{i+1} - \Delta_i) \qquad (3.4)$$

where:

$E$ is the total energy dissipated by the wall up to the maximum displacement $\Delta_{net,max}$;

$F_i$ is the shear resistance of the wall at recording step $i$;

$n$ is the number of recorded steps up to the maximum displacement $\Delta_{net,max}$.

The normalised energy is equal to the energy dissipated by the wall up to the maximum displacement $\Delta_{net,max}$ divided by $\Delta_{net,max}$ (Equation ( 3.5 )).

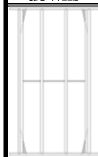
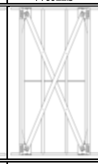
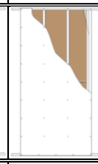
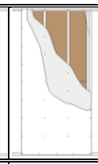
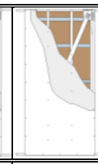
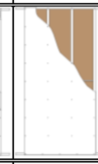
$$\text{Normalised Energy} = \frac{E}{\Delta_{net,max}} \qquad (3.5)$$

## 3.4 Comparison of the test results and predictions

### 3.4.1 Observed performance of wall test specimens

The measured properties of each wall specimen were found with the methods presented in Section 3.3 for both monotonic (Table 3.2) and reversed cyclic (Table 3.3) tests. When multiple specimens of a particular wall configuration and load protocol were tested, the average of the lateral loading response properties were determined.

**Table 3.2 Observed performance of wall specimens under monotonic loading**

| | Test specimens | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Steel frame with hold-downs | Strap-braced shear walls | Gypsum-sheathed shear walls | | Gypsum-sheathed strap-braced shear walls | | | | Gypsum-sheathed bearing wall | |
| |  |  |  |  |  |  |  |  |  |  |
| **Name of the specimen** | 82 A-M | 65 A-M | 66 A-M<br>66 B-M | 68 A-M<br>68 B-M | 70 A-M<br>70 B-M | 72 A-M<br>72 B-M | 74 A-M<br>74 B-M | 76 A-M<br>76 B-M | 78 B-M<br>78 C-M | 80 A-M<br>80 B-M |
| **$F_u$ (kN)** | 3.93 | 31.61 | 9.60 | 21.91 | 37.70 | 50.04 | 38.91 | 40.92 | 7.64 | 8.00 |
| **$\Delta_{net,u}$ (mm)** | 125.7 | 124.5 | 36.7 | 64.0 | 46.6 | 49.8 | 53.3 | 54.0 | 48.9 | 38.5 |
| **$K_e$ (kN/mm)** | 0.028 | 1.48 | 2.24 | 2.25 | 2.27 | 2.71 | 2.26 | 2.13 | 0.810 | 0.962 |
| **$\Delta_{net,max}$ (mm)** | 100.0 | 100.0 | 61.0 | 100.0 | 61.0 | 61.0 | 61.0 | 61.0 | 53.2 | 48.7 |
| **Normalized energy, Energy / Lateral drift (J/mm)** | 1.29 | 26.70 | 8.35 | 19.27 | 30.69 | 39.66 | 31.55 | 32.63 | 6.02 | 6.49 |
| **$F_y$ (kN)** | 2.03 (2) | 28.58 (1) | 8.63 (2) | 20.18 (2) | 35.17 (2) | 46.07 (2) | 36.35 (2) | 38.33 (2) | 6.53 (2) | 7.04 (2) |
| **$\Delta_{net,y}$ (mm)** | 75.52 (4) | 31.9 (3) | 4.0 (4) | 9.1 (4) | 15.6 (4) | 17.0 (4) | 16.1 (4) | 18.1 (4) | 8.2 (4) | 7.4 (4) |
| **Ductility, μ** | 1.38 | 3.14 | 15.88 | 11.08 | 3.94 | 3.59 | 3.79 | 3.39 | 6.50 | 6.73 |
| **$R_d$** | 1.33 | 2.30 | 5.52 | 4.59 | 2.62 | 2.49 | 2.56 | 2.40 | 3.46 | 3.51 |
| **$\Delta_{y,mod.EEEP}$ (mm)** | - | 31.24 (5) | 13.7 | 22.9 | 22.5 | 25.2 | 23.0 | 24.8 | 22.1 | 16.4 |
| **$K_{e,mod.EEEP}$ (kN/mm)** | - | 1.01 (5) | 0.71 | 0.96 | 1.68 | 1.99 | 1.69 | 1.65 | 0.35 | 0.49 |

(1) Yielding force obtained by determining the plateau region

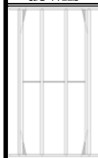
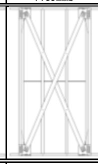
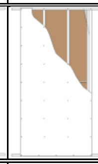
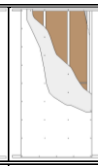
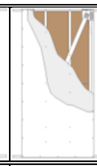
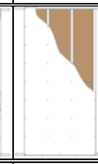
(2) Yielding force obtained with the EEEP method (Subsection 3.3.1)

(3) Yielding displacement corresponding to the point where the plateau region is reached

(4) Yielding displacement defined in the EEEP method (Subsection 3.3.1)

(5) Obtained with the modified EEEP method (Subsection 3.3.2) up to the displacement corresponding to the maximum stroke of the actuator

**Table 3.3 Observed performance of wall specimens under reversed cyclic loading**

| | Test specimens | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Steel frame with hold-downs | Strap-braced shear walls | Gypsum-sheathed shear walls | | Gypsum-sheathed strap-braced shear walls | | | | Gypsum-sheathed bearing wall | |
| |  |  |  |  |  |  |  |  |  |  |
| **Name of the specimen** | NA | 83 A-C | 67 A-C<br>67 B-C | 69 A-C<br>69 B-C | 71 A-C<br>71 B-C | 73 A-C<br>73 B-C | 75 A-C<br>75 B-C | 77 A-C<br>77 B-C | 79 A-C<br>79 B-C | 81 A-C<br>81 B-C |
| **$F_u$ (kN)** | NA | 33.54 | 9.05 | 21.07 | 37.46 | 49.36 | 41.04 | 41.86 | 6.23 | 8.73 |
| **$\Delta_{net,u}$ (mm)** | NA | 103.26 | 41.23 | 58.48 | 52.71 | 44.25 | 48.26 | 76.82 | 32.83 | 30.45 |
| **$K_e$ (kN/mm)** | NA | 1.49 | 3.57 | 2.25 | 1.94 | 2.30 | 1.96 | 2.05 | 1.18 | 1.05 |
| **$\Delta_{net,max}$ (mm)** | NA | 100.00 | 61.00 | 61.00 | 61.00 | 61.00 | 61.00 | 80.50 | 61.00 | 53.27 |
| **Normalized energy, Energy / Lateral drift (J/mm)** | NA | 28.6 | 8.1 | 17.5 | 29.9 | 38.7 | 32.6 | 34.8 | 6.4 | 7.2 |
| **$F_y$ (kN) [(1)]** | NA | 32.0 | 8.3 | 18.9 | 35.2 | 46.5 | 39.1 | 39.8 | 6.8 | 7.8 |
| **$\Delta_{net,y}$ (mm) [(1)]** | NA | 21.56 | 2.96 | 8.64 | 18.21 | 20.50 | 20.03 | 19.63 | 6.40 | 7.45 |
| **Ductility, $\mu$** | NA | 4.64 | 27.22 | 7.34 | 3.37 | 3.02 | 3.07 | 4.05 | 10.82 | 7.26 |
| **$R_d$** | NA | 2.88 | 7.04 | 3.68 | 2.39 | 2.24 | 2.26 | 2.65 | 4.46 | 3.65 |
| **$\Delta_{y,mod.EEEP}$ (mm)** | NA | 29.74 | 11.11 | 20.21 | 24.42 | 26.06 | 24.92 | 26.06 | 21.79 | 14.91 |
| **$K_{e,mod.EEEP}$ (kN/mm)** | NA | 1.13 | 0.86 | 1.05 | 1.54 | 1.90 | 1.65 | 1.61 | 0.36 | 0.59 |

[(1)] Obtained with the EEEP method (Subsection 3.3.1)

### 3.4.2 Design values of the yielding resistances of the walls

If they are used as structural elements, the resistance of the strap-braced and gypsum-sheathed walls needs to be calculated so that it is greater than the applied factored load. In the following subsections, methods to determine the nominal design resistance values of the walls are described.

#### *3.4.2.1 Yielding resistance for design: Strap-braced bare frame*

The design for the nominal and factored resistance of the CFS strap-braced walls can be calculated according to CSA S136 (2007), as described in Subsection 2.2.1.1. This design only relies on the lateral wall resistance provided by the strap-braces.

#### *3.4.2.2 Yielding resistance for design: Gypsum-sheathed shear wall*

If gypsum panels are relied on to resist in-plane lateral load, one can use the nominal shear resistance values tabulated in AISI S213 (2007) and AISI S400 (2015) for 12.7 mm-thick gypsum panels, as described in Subsection 2.2.1.2. These nominal yielding resistance values were obtained with the EEEP method. For 15.9 mm-thick gypsum panels with screws spaced at 300 mm o/c in the field and along the perimeter, the nominal yielding resistance values in Table 3.4 can be used for the design of the lateral force resisting gypsum-sheathed shear walls. The nominal yielding lateral resistances, $S_{ya}$, of the walls account for the resistance of the frame with hold-downs, but without the strap-braces. They were determined by averaging the yielding resistance obtained by the EEEP method of each configuration of wall (Subsection 3.3.1). The yielding resistance of each test, $S_y$, and the test over nominal resistance, $S_y/S_{ya}$, ratios for each test are listed in Table 3.5 (1-layer gypsum-sheathed shear walls) and Table 3.6 (2-layer gypsum-sheathed shear walls). A resistance factor of 0.60 (LSD) for gypsum-sheathed walls is recommended by the AISI S213 (2007) and AISI S400 (2015) standards.

**Table 3.4 Contribution of 1 or 2 layers of 15.9mm gypsum panels installed on both sides of the wall**

| | Nominal resistance $S_{ya}$ (kN/m) |
|---|---|
| 1 layer of 15.9 mm Type X Firecode C Core gypsum board on both sides Screw pattern: 300mm/300mm | 6.9 |
| 2 layers of 15.9 mm Type X Firecode C Core gypsum board on both sides Screw pattern: 300mm/300mm for both layers | 16.0 |

**Table 3.5 Test results for 1-layer gypsum sheathed shear walls and comparison to the nominal yielding resistance $S_{ya}$**

| Gypsum-sheathed (1 layer) shear wall tests | | $S_y$ (kN/m) | $S_y/S_{ya}$ with $S_{ya}$ = 6.9 kN/m |
|---|---|---|---|
| **66A-M** | | 7.04 | 1.020 |
| **66B-M** | | 7.10 | 1.030 |
| **67A-C** | *Positive* | *6.89* | *0.998* |
| | *Negative* | *-7.28* | *1.055* |
| | **Average** | 7.08 | 1.027 |
| **67B-C** | *Positive* | *6.10* | *0.884* |
| | *Negative* | *-6.90* | *1.000* |
| | **Average** | 6.50 | 0.942 |
| **Configuration average** | | **6.93** | **1.005** |
| **Standard deviation** | | | 0.0363 |
| **Coefficient of variation** | | | 0.0361 |

**Table 3.6 Test results for 2-layer gypsum-sheathed shear walls and comparison to the nominal yielding resistance $S_{ya}$**

| Gypsum-sheathed (2 layers) shear wall | | $S_y$ (kN/m) | $S_y/S_{ya}$ with $S_{ya}$ = 16.0 kN/m |
|---|---|---|---|
| **68A-M** | | 17.59 | 1.099 |
| **68B-M** | | 15.50 | 0.969 |
| **69A-C** | *Positive* | *14.66* | *0.916* |
| | *Negative* | *-16.29* | *1.018* |
| | **Average** | 15.47 | 0.967 |
| **69B-C** | *Positive* | *15.00* | *0.937* |
| | *Negative* | *-15.96* | *0.998* |
| | **Average** | 15.48 | 0.967 |
| **Configuration average** | | **16.01** | **1.001** |
| **Standard deviation** | | | 0.0569 |
| **Coefficient of variation** | | | 0.0568 |

#### *3.4.2.3 Yielding resistance for design: Gypsum-sheathed strap-braced wall*

During the design process of gypsum-sheathed walls, if the gypsum panels are used as structural elements along with the strap braces, one could estimate the nominal yielding resistance of the wall assembly by adding the nominal resistance of the gypsum-sheathed shear walls and the yielding resistance of the steel strap braces (Subsection 3.4.2.1). When considering walls sheathed on both sides, the nominal values listed in Table 3.4 can be used to obtain the contribution of the gypsum panels and to account for the resistance of the steel frame and the hold-downs.

When considering walls sheathed on one side only, a simple way to estimate the contribution of the gypsum sheathing and its connections is to divide the values of $S_{ya}$ from Table 3.4 by 2. However, because $S_{ya}$ includes the resistance of the frame this method results in the contribution of the frame being divided by two, which in strict terms is not correct. Thus, the contribution of the gypsum for a single sided wall corresponds to the contribution of the gypsum panels and half of the steel frame and the hold-downs.

Walls with gypsum on one side and gypsum and resilient channels on the other side can be considered as walls with gypsum on one side only. This observation holds true because the resilient channels are flexible and do not allow for the transfer of substantial lateral load to the gypsum panel, which is affixed to the channels not the steel frame.

Table 3.7 contains a summary of the results of the predictions of the yielding shear resistance of the test walls constructed with both strap bracing and gypsum panels, as well as the test/predicted ratios. The detailed values are available in Table D.1 (Appendix D). The yielding resistance of the walls are overestimated except for the walls with resilient channels. To take into account this overestimation, a reduction factor can be applied when combining the yielding resistance of the gypsum and the strap-braces. Since the test/predicted ratios are always superior to 0.9 (Table 3.7), the reduction factor 0.9 can be applied to the sum of the gypsum panels resistance and the straps resistance to obtain a conservative estimate of the nominal resistance of gypsum combined to strap-braced.

**Table 3.7 Prediction of the yielding lateral shear resistance of the complete strap-braced gypsum-sheathed walls**

| Gypsum-sheathed strap-braced wall tests | Values | | | |
|---|---|---|---|---|
| | 70A-M<br>70B-M<br>71A-C<br>71B-C | 72A-M<br>72B-M<br>73A-C<br>73B-C | 74A-M<br>74B-M<br>75A-C<br>75B-C | 76A-M<br>76B-M<br>77A-C<br>77B-C |
| **Number of layers of gypsum** | 1 | 2 | 2 | 2 |
| **Number of sheathed sides** | 2 | 2 | 1 | 2 (1) |
| **Average $S_y$ (kN/m)** | 28.84 | 37.95 | 30.91 | 32.01 |
| **$A_gS_y$' nominal brace yielding resistance (kN/m)** | 23.87 | | | |
| **$S_{va}$ nominal gypsum resistance of the shear walls** | 6.9 | 16.0 | 16.0/2 | 16.0/2 |
| **$S_{va}$+$A_gS_y$' prediction of the yielding resistance (kN)** | 30.77 | 39.87 | 31.87 | 31.87 |
| **Test/Predicted ratio** | 0.937 | 0.952 | 0.970 | 1.004 |
| **Statistical informations** | AVG=0.966 ; SD=0.0339 ; COV=0.0351 | | | |

(1) 2 layers of gypsum on one side and 2 layers of gypsum with resilient channels on the other side

### 3.4.3 Capacity design values of the ultimate resistances of the wall

If the walls are required to resist earthquake loading, a capacity design philosophy is needed to protect the non-fuse members and connections in the lateral load carrying path. Thus, the maximum probable capacity of the fuse element(s) is required. The following subsections describe how to obtain the ultimate resistances of the strap-braced walls, the gypsum-sheathed shear walls and the strap-braced gypsum-sheathed shear walls.

#### *3.4.3.1 Probable lateral resistance for capacity design: Strap-braced bare frame*

Two predictions of the lateral yielding resistance of a strap-braced bare steel wall were made based on the yielding force of the straps. The first prediction, $F_{yp}$ , is based on the measured properties of the two tension braces, and was calculated according to Equation ( 3.6 ). The second prediction, $F_{yn}$ , is based on the nominal properties of the two tension braces, and was calculated according to Equation ( 3.7 ) as provided in AISI S213 (2007) and AISI S400 (2015). Table 3.8 lists the measured yielding resistance of the strap-braced walls and the test/predicted ratios.

$$F_{yp} = 2 \cdot \cos\theta_{actual} \cdot A_{g,measured} F_{y,measured} \quad (3.6)$$

where:

$\theta_{actual}$ is the angle between the strap and the frame taking into account that the centreline of the brace goes through the hold-downs and not though the corners of the frame;

$A_{g,measured}$ is the measured gross section area obtained by multiplying the uncoated thickness and the strap width measured before each test;

$F_{y,measured}$ is the yield strength obtained from coupon tests (Table 3.1).

$$F_{yn} = 2 \cdot cos\, \theta_{actual} \cdot A_{g,nominal} R_y F_y \quad (3.7)$$

where:

$\theta_{actual}$ is the angle between the strap and the frame taking into account that the centreline of the brace goes through the hold-downs and not though the corners of the frame;

$A_{g,nominal}$ is the nominal gross section area;

$R_y$ is the yielding over-strength factor equal to 1.1 for 340 MPa steels (AISI S213, 2007; AISI S400. 2015);

$F_y$ is the nominal yield strength equal to 340 MPa in the tested specimens.

**Table 3.8 Test results for the strap-braced walls and comparison to the predicted yielding resistances *$S_{yp}$* and *$S_{yn}$***

| Strap-braced bare wall tests | | $S_y$ (kN/m) | $S_y/S_{yp}$ (3) | $S_y/S_{yn}$ (4) |
|---|---|---|---|---|
| **65A-M** | | 23.42 (1) | 0.997 | 1.005 |
| **83A-C** | *Positive* | *26.19* (2) | *1.091* | *1.124* |
| | *Negative* | *-26.31* (2) | *1.102* | *1.129* |
| | **Average** | 26.25 | 1.096 | 1.126 |
| **Configuration average** | | **26.25** | **1.047** | **1.066** |
| **Standard deviation** | | | 0.0494 | 0.0606 |
| **Coefficient of variation** | | | 0.0472 | 0.0569 |

(1) Yielding force corresponding to the plateau

(2) Yielding force obtained with the EEEP analysis (Subsection 3.3.1)

(3) $S_{yp}$ calculated with the Equation (3.8); the result is devided by the length of the wall (1.22m)

(4) $S_{yn}$ calculated with the Equation (3.9); the result is devided by the length of the wall (1.22m)

### 3.4.3.2 Probable lateral resistance for capacity design: Gypsum-sheathed shear wall

Gypsum sheathed shear walls with hold-downs can be used to transfer lateral load to the foundation. For a capacity based design, the probable capacity of the energy dissipating element (here the gypsum-to-steel framing connections) is needed in order to design all the other elements of the wall. The nominal yielding resistance of the gypsum-sheathed shear walls used in design can be obtained as described in Subsection 3.4.2.2 with the EEEP method. Because this nominal resistance is less than the ultimate resistance, an overstrength factor is needed to determine the probable resistance of the shear wall. This factor was obtained by dividing the ultimate resistance of each tested shear wall by the nominal resistance of the walls $S_{ya}$ as listed in Table 3.4. By using the average value of the ratios an overstrength factor of *1.1* was found. Table 3.9 and Table 3.10 list the test results and the test/predicted ratios with an overstrength factor of *1.1* . An example of prediction of the probable shear capacity for gypsum-sheathed shear walls without straps is presented in Figure 3.23.

**Table 3.9 Test results for 1-layer gypsum sheathed shear walls and comparison to the predicted probable resistance $S_{u,predlicted}$**

| Gypsum-sheathed (1 layer) shear wall tests | | $S_u$ (kN/m) | $S_u/S_{u,predicted}$ with $S_{u,predicted} = 1.1S_{ya}$ |
|---|---|---|---|
| **66A-M** | | 7.75 | 1.021 |
| **66B-M** | | 7.99 | 1.052 |
| **67A-C** | *Positive* | *7.51* | *0.990* |
| | *Negative* | *-8.10* | *1.067* |
| | **Average** | 7.81 | 1.028 |
| **67B-C** | *Positive* | *6.48* | *0.854* |
| | *Negative* | *-7.59* | *1.000* |
| | **Average** | 7.03 | 0.927 |
| **Configuration average** | | **7.64** | **1.007** |
| **Standard deviation** | | | 0.0479 |
| **Coefficient of variation** | | | 0.0475 |

**Table 3.10 Test results for 2-layer gypsum-sheathed shear walls and comparison to the predicted probable resistance $S_{u,predicted}$**

| Gypsum-sheathed (2 layers) shear wall tests | | $S_u$ (kN/m) | $S_u/S_{u,predicted}$ with $S_{u,predicted} = 1.1S_{ya}$ |
|---|---|---|---|
| **68A-M** | | 19.15 | 1.088 |
| **68B-M** | | 16.77 | 0.953 |
| **69A-C** | *Positive* | *16.32* | *0.927* |
| | *Negative* | *-18.20* | *1.034* |
| | **Average** | 17.26 | 0.981 |
| **69B-C** | *Positive* | *16.63* | *0.945* |
| | *Negative* | *-17.93* | *1.019* |
| | **Average** | 17.28 | 0.982 |
| **Configuration average** | | **17.62** | **1.001** |
| **Standard deviation** | | | 0.0517 |
| **Coefficient of variation** | | | 0.0517 |

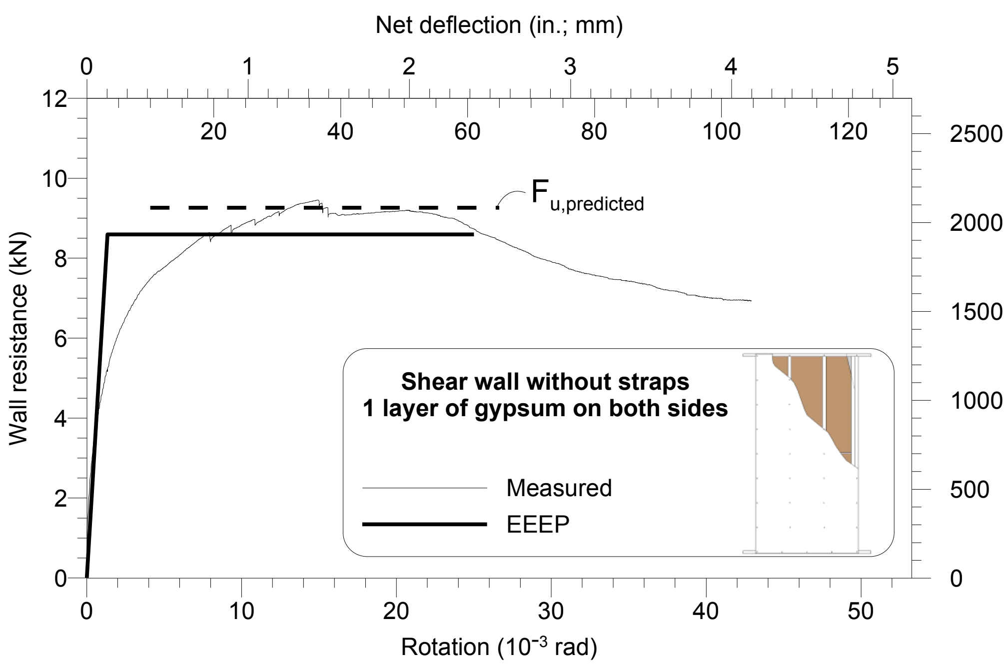



**Figure 3.23 Comparison of the measured resistance of wall 66A-M with the predicted resistance of the wall**

### *3.4.3.3 Probable lateral resistance for capacity design: Gypsum-sheathed strap-braced wall*

Four different configurations of gypsum-sheathed strap-braced walls were tested:

- strap-braced wall with 1 layer of gypsum on both sides;

- strap-braced wall with 2 layers of gypsum on both sides;
- strap-braced wall with 2 layers of gypsum on one side;
- strap-braced wall with 2 layers of gypsum on one side and 2 layers of gypsum over resilient channels on the other side.

In the following subsections, different methods to predict the probable resistance of these test wall configurations are presented. The simple methods (Subsections 3.4.3.3.1 and 3.4.3.3.2) allow for a quick estimate of the shear resistance of a wall. Nevertheless, in order to estimate the probable resistance of different untested configurations of strap-braced sheathed walls with these methods, one should make sure that the displacements corresponding to the ultimate resistance of the different fuse components are compatible. If it is not the case, an alternative method (Subsection 3.4.3.3.3) allows one to predict the shear resistance of a wider range of wall configurations, for which the displacements corresponding to the ultimate resistance of the different components added are not necessarily close.

##### *3.4.3.3.1 Simple prediction of combined probable capacity*

The contribution of the steel braces to the lateral resistance of a wall can be estimated as described in Subsection 3.4.3.1. The nominal contribution of the gypsum panels can be estimated as described in Subsection 3.4.2.3. For the walls sheathed on both sides, the nominal values listed in Table 3.4 can be used to estimate the nominal strength $S_{ya}$ of the gypsum panels. For the walls sheathed on one side only or sheathed on both sides with resilient channels on one side, the nominal strengths in Table 3.4 can be reduced by half. To determine the probable shear resistance of the wall, the nominal resistance of the gypsum can be factored by: 1.1. This is a simple prediction because the listed nominal resistance of the gypsum panels, $S_{ya}$, not only includes the resistance of the gypsum panels but also implicitly accounts for the resistance of the steel frame and the hold-downs. Thus, the contribution of the gypsum $S_g$ corresponds, in fact, to the lateral resistance of the gypsum panels, the steel frame and the hold-downs.

Table 3.11 contains a summary of the results of the predictions of the probable lateral shear resistance of the test walls constructed with both strap bracing and gypsum panels, as well as the test/predicted ratios. The detailed values are available in Table D.2 (Appendix D). As examples, the results for a wall sheathed on both sides is presented in Figure 3.24 and the results for a wall with resilient channels is presented in Figure 3.25. The resistance *F* (kN), which is equal to *S* (kN/m) multiplied by the length of the wall (1.22 m), is represented in the graphs. For the walls sheathed on both sides, the prediction was accurate with test/predicted ratios close to 1.0. For the walls sheathed on one side only, the prediction underestimated the measured resistance of the wall, which was expected since only half of the contribution of the steel frame and hold-downs was considered. The difference is greater for walls with resilient channels because the contribution of the side with resilient channels and gypsum has been neglected.

**Table 3.11 Simple prediction of the ultimate lateral shear resistance of the complete strap walls**

| | | Values | | | | |
|---|---|---|---|---|---|---|
| **Strap-braced wall tests** | | 65A-M<br>83A-C | 70A-M<br>70B-M<br>71A-C<br>71B-C | 72A-M<br>72B-M<br>73A-C<br>73B-C | 74A-M<br>74B-M<br>75A-C<br>75B-C | 76A-M<br>76B-M<br>77A-C<br>77B-C |
| **Number of layers of gypsum** | | - | 1 | 2 | 2 | 2 |
| **Number of sheathed sides** | | - | 2 | 2 | 1 | 2 [1] |
| **Average $S_u$ (kN/m)** | | 26.70 | 30.80 | 40.73 | 32.77 | 33.93 |
| **$S_{yn}$ (kN/m) braces resistance predicted with nominal properties [2]** | | 23.31 | | | | |
| **$S_{yp}$ (kN/m) braces resistance predicted with measured properties [3]** | | 23.72 | 23.29 | 23.38 | 23.35 | 23.41 |
| **$S_{ya}$ (kN/m) nominal added resistance due to gypsum [4]** | | - | 6.9 | 16.0 | 16.0/2 | 16.0/2 |
| **Simple prediction of the resistance of the walls $S_g = 1.1S_{ya}$** | **$S_{u,n1} = S_{yn} + 1.1S_{ya}$ (kN/m)** | 23.31 | 30.9 | 40.91 | 32.11 | 32.11 |
| | **Test/Predicted ratio** | - | 0.997 | 0.996 | 1.020 | 1.056 |
| | **Statistical informations** | - | AVG=1.017 ; SD=0.0308 ; COV=0.0303 | | | |
| | **$S_{u,p1} = S_{yp} + 1.1S_{ya}$ (kN/m)** | 23.72 | 30.88 | 40.98 | 32.15 | 32.21 |
| | **Test/Predicted ratio** | - | 0.998 | 0.994 | 1.019 | 1.053 |
| | **Statistical informations** | - | AVG=1.016 ; SD=0.0293 ; COV=0.0288 | | | |

(1) 2 layers of gypsum on one side and 2 layers of gypsum with resilient channels on the other side

(2) $S_{yn}$ calculated with the Equation (3.7)

(3) $S_{yp}$ calculated with the Equation (3.6)

(4) $S_{ya}$ from Table 3.4 includes the gypsum panels resistance and the steel frame resistance

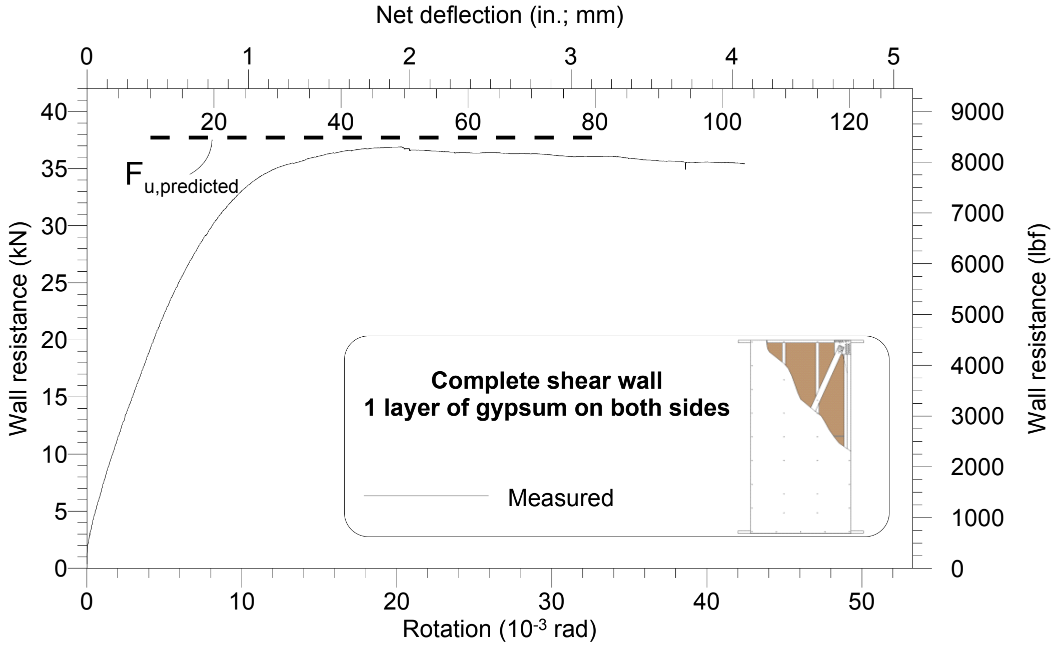



**Figure 3.24 Comparison of the measured lateral resistance of wall 70A-M with the predicted probable lateral resistance based on nominal properties of the wall with $S_g = 1.1S_{ya}$**

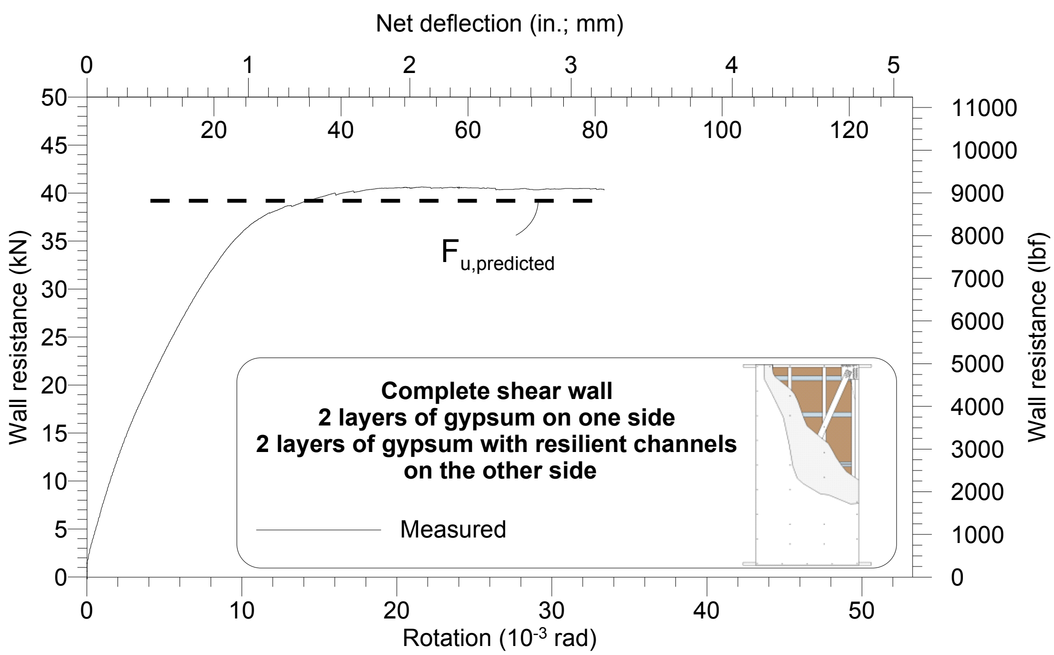



**Figure 3.25 Comparison of the measured lateral resistance of wall 76A-M with the predicted probable lateral resistance based on nominal properties of the wall with $S_g = 1.1S_{ya}$**

#### *3.4.3.3.2 Conservative simple prediction of combined probable capacity*

In Subsection 3.4.3.3.1, it was noted that for the strap-braced walls sheathed on one side only and for the walls with resilient channels on one side, the simple prediction was not accurate because when dividing the gypsum resistance $S_{ya}$ by two, the frame contribution to the resistance was also reduced by half. An overstrength factor of 1.2 or 1.3 could be used for the gypsum contribution to take into account the neglected part of the frame and gypsum panel on resilient channels resistances. In this fashion, one would obtain a more conservative prediction of the probable force in the strap-braced / gypsum-sheathed shear wall. Nevertheless, this approach will be less accurate for walls sheathed on both sides because the contribution of the steel frame was already taken into account and accurately estimated with the simple prediction $S_g = 1.1 \cdot S_{ya}$ .

The results of the predictions are listed in Table 3.12 and the graphs of the predictions for Tests 70A-M and 76A-M are presented in Figure 3.26 and Figure 3.27. The resistance *F* (kN), which is equal to *S* (kN/m) multiplied by the length of the wall (1.22 m), is represented in the graphs. The detailed values can be found in Table D.2 (Appendix D). For the walls sheathed on both sides, the prediction overestimated the resistance of the wall, which is conservative in a capacity-design philosophy. For the walls sheathed on one side only and the walls with resilient channels, the conservative predictions compensated the neglected part of the frame action.

**Table 3.12 Conservative simple prediction of the probable lateral shear resistance of the complete strap walls**

| | | Values | | | | |
|---|---|---|---|---|---|---|
| Strap-braced wall tests | | 65A-M<br>83A-C | 70A-M<br>70B-M<br>71A-C<br>71B-C | 72A-M<br>72B-M<br>73A-C<br>73B-C | 74A-M<br>74B-M<br>75A-C<br>75B-C | 76A-M<br>76B-M<br>77A-C<br>77B-C |
| Number of layers of gypsum | | - | 1 | 2 | 2 | 2 |
| Number of sheathed sides | | - | 2 | 2 | 1 | 2 (1) |
| Average $S_u$ (kN/m) | | 26.70 | 30.80 | 40.73 | 32.77 | 33.93 |
| $S_{yn}$ (kN/m) braces resistance predicted with nominal properties (2) | | 23.31 | | | | |
| $S_{yp}$ (kN/m) braces resistance predicted with measured properties (3) | | 23.72 | 23.29 | 23.38 | 23.35 | 23.41 |
| $S_{ya}$ (kN/m) nominal added resistance due to gypsum (4) | | - | 6.9 | 16.0 | 16.0/2 | 16.0/2 |
| Simple prediction of the resistance of the walls $S_g = 1.2S_{ya}$ | $S_{u,n2} = S_{yn} + 1.2S_{ya}$ (kN/m) | 23.31 | 31.59 | 42.51 | 32.91 | 32.91 |
| | Test/Predicted ratio | - | 0.975 | 0.958 | 0.996 | 1.031 |
| | Statistical informations | - | AVG=0.990 ; SD=0.0325 ; COV=0.0329 | | | |
| | $S_{u,p2} = S_{yp} + 1.2S_{ya}$ (kN/m) | 23.72 | 31.57 | 42.58 | 32.95 | 33.01 |
| | Test/Predicted ratio | - | 0.976 | 0.957 | 0.995 | 1.028 |
| | Statistical informations | - | AVG=0.989 ; SD=0.0312 ; COV=0.0316 | | | |
| Simple prediction of the resistance of the walls $S_g = 1.3S_{ya}$ | $S_{u,n3} = S_{yn} + 1.3S_{ya}$ (kN/m) | 23.31 | 32.28 | 44.11 | 33.71 | 33.71 |
| | Test/Predicted ratio | - | 0.954 | 0.923 | 0.972 | 1.006 |
| | Statistical informations | - | AVG=0.964 ; SD=0.0348 ; COV=0.0361 | | | |
| | $S_{u,p3} = S_{yp} + 1.3S_{ya}$ (kN/m) | 23.72 | 32.26 | 44.18 | 33.75 | 33.81 |
| | Test/Predicted ratio | - | 0.955 | 0.922 | 0.971 | 1.003 |
| | Statistical informations | - | AVG=0.963 ; SD=0.0337 ; COV=0.0350 | | | |

(1) 2 layers of gypsum on one side and 2 layers of gypsum with resilient channels on the other side

(2) $S_{yn}$ calculated with the Equation (3.7)

(3) $S_{yp}$ calculated with the Equation (3.6)

(4) $S_{ya}$ from Table 3.4 includes the gypsum panels resistance and the steel frame resistance

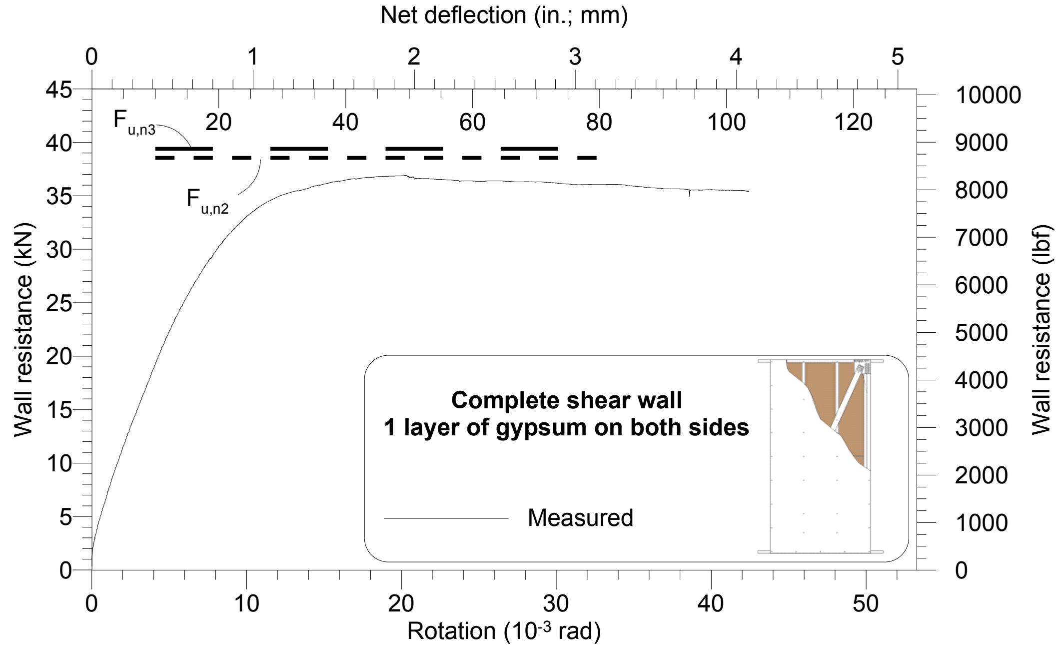



**Figure 3.26 Comparison of the measured lateral resistance of wall 70A-M with the predicted probable lateral resistances based on nominal properties of the wall**

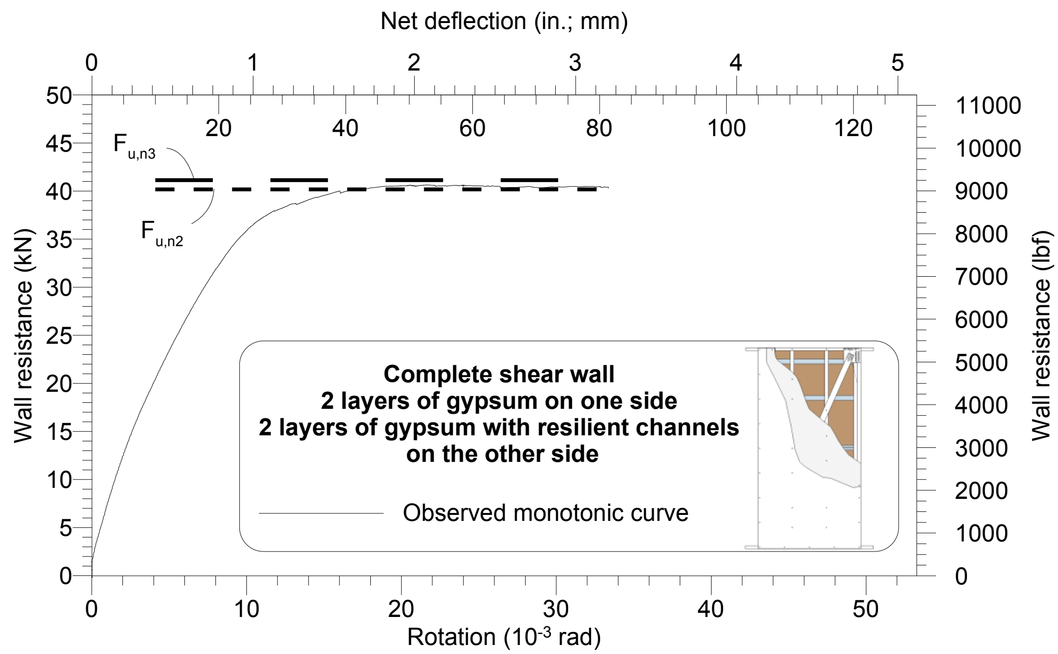



**Figure 3.27 Comparison of the measured lateral resistance of wall 76A-M with the predicted probable lateral resistances $S_{u,n2}$ and $S_{u,n3}$ based on nominal properties of the wall**

#### *3.4.3.3.3 Alternative prediction method of combined probable capacity*

The simple predictions presented in Subsections 3.4.3.3.1 and 3.4.3.3.2 provided a good estimate of the ultimate lateral resistance of the strap-braced / gypsum-sheathed test walls. The measured ultimate resistance of the strap-braced / gypsum-sheathed walls was approximately equal to the sum of the predicted yielding resistance of the tension strap-braces and the predicted ultimate resistance of the gypsum-sheathed shear wall. Nevertheless, the displacement corresponding to the yielding resistance of the strap-braced frame is not necessarily the same as the displacement corresponding to the ultimate resistance of the gypsum sheathed shear wall. Thus, the ultimate resistance of the strap-braced sheathed walls is not necessarily equal to the sum of the resistance provided by the straps and gypsum. Consequently, in order to obtain a more general and accurate prediction of the behaviour of the strap-braced gypsum-sheathed walls, the approach adopted in the FEMA P-807 (Federal Emergency Management Agency (FEMA), 2012) guidelines can be used. Instead of adding the ultimate shear resistances of the two systems independent of drift compatibility, the loads at each drift level can be added. Adding the total load-drift curves allows one to determine at which displacement the ultimate resistance is reached for the assembly, which may lead to a lower and more accurate estimate. The resistance estimates $S_{u,p4}$ were made at each displacement increment with Equation ( 3.8 ) .

$$S_{u,p4} = S_{sbf} + n \cdot (S_g - S_{bf}) \tag{3.8}$$

where:

$S_{u,p4}$ is the predicted resistance of the strap-braced/gypsum-sheathed wall at the displacement *d*;

$S_{sbf}$ is the average resistance of the strap-braced frames (65A-M and 83A-C) at the displacement *d,* including the resistance of the steel frame and the hold-downs;

$S_g$ is the average resistance of the shear walls sheathed on both sides with one or two layers of gypsum at the displacement *d,* including the resistance of the steel frame and the hold-downs;

$S_{bf}$ is the resistance of the bare shear frame with hold-downs (82A-M) at the displacement *d*;

$n = 1$ if the strap-braced/gypsum-sheathed wall is sheathed on both sides and $n = 1/2$ if the strap-braced/gypsum-sheathed wall is sheathed on one side only.

The predicted ultimate resistance for each type of wall is provided in Table 3.13. The detailed values are available in Table D.2 (Appendix D). The predictions were made up to the smallest maximum drift, $\Delta_{net,max}$, defining the failure modes of the walls (Subsection 3.3.1). An example of prediction using the load-drift curve method is presented in Figure 3.28 and Figure 3.29. The resistance *F* (kN), which is equal to *S* (kN/m) multiplied by the length of the wall (1.22 m), is represented in the graphs. In all the tests, the predictions of the resistance using the method described overestimate the resistance of the walls (Table 3.13). This is due to the fact that the contribution of the frame, $S_{bf}$, is underestimated because the resistance of the bare shear frame is used to estimate the contribution of the frame. In the sheathed walls, the frame is braced by the gypsum panels; as such, it has a slightly greater shear resistance than the bare frame. Therefore, if this method is to be used, a greater frame contribution $S_{bf}$ will have to be deduced from the sheathed shear wall resistance $S_g$ in Equation ( 3.8 ) to have a more accurate prediction of the resistance.

**Table 3.13 Load-drift curve prediction of the resistance of the complete strap walls**

| | Values | | | |
|---|---|---|---|---|
| **Gypsum-sheathed strap-braced wall tests** | 70A-M<br>70B-M<br>71A-C<br>71B-C | 72A-M<br>72B-M<br>73A-C<br>73B-C | 74A-M<br>74B-M<br>75A-C<br>75B-C | 76A-M<br>76B-M<br>77A-C<br>77B-C |
| **Number of layers of gypsum** | 1 | 2 | 2 | 2 |
| **Number of sheathed sides** | 2 | 2 | 1 | 2 (1) |
| **Average $S_u$ (kN/m)** | 30.80 | 40.73 | 32.77 | 33.93 |
| **Average $\Delta_{net,u}$ (mm)** | 49.6 | 47.0 | 50.8 | 65.4 |
| **$S_{u,p4}$ (kN/m)** | 32.09 | 42.74 | 34.11 | 34.11 |
| **$\Delta_{u,p4}$ (mm) (2)** | 45.5 | 64.5 | 60.0 | 60.0 |
| **Resistance Test/Predicted ratio** | 0.960 | 0.953 | 0.961 | 0.994 |
| **Statistical informations** | AVG=0.967 ; SD=0.0238 ; COV=0.0246 | | | |

(1) 2 layers of gypsum on one side and 2 layers of gypsum with resilient channels on the other side

(2) Displacement at which $S_{u,p4}$ is reached

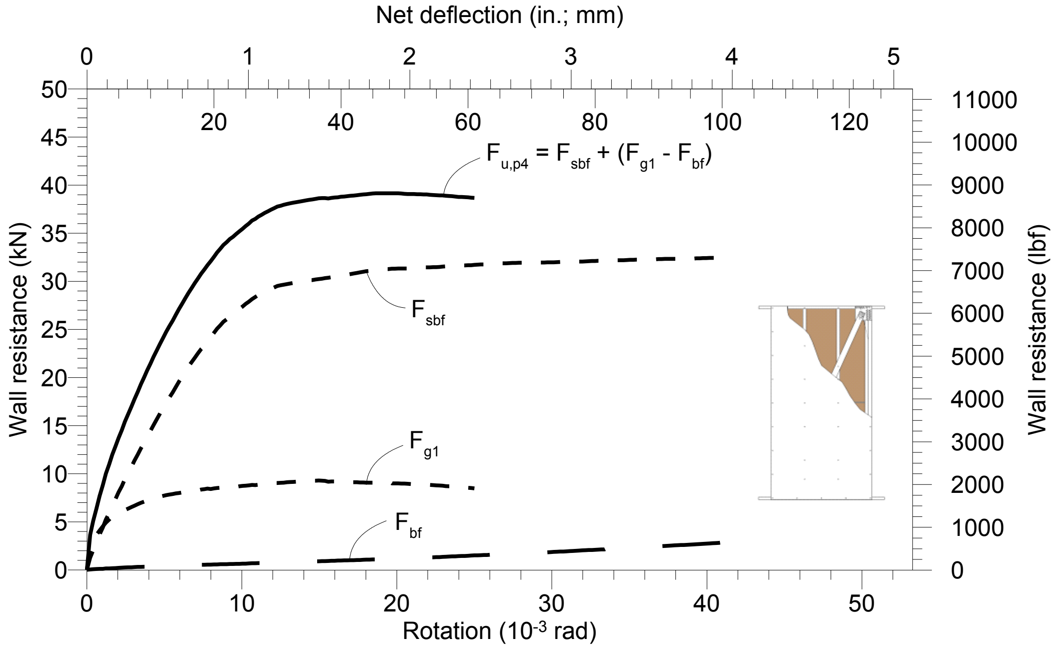



**Figure 3.28 Shear resistance – Predicted drift curves of a strap-braced wall sheathed with one layer of gypsum on both side up to $\Delta_{max}$ = *61 mm***

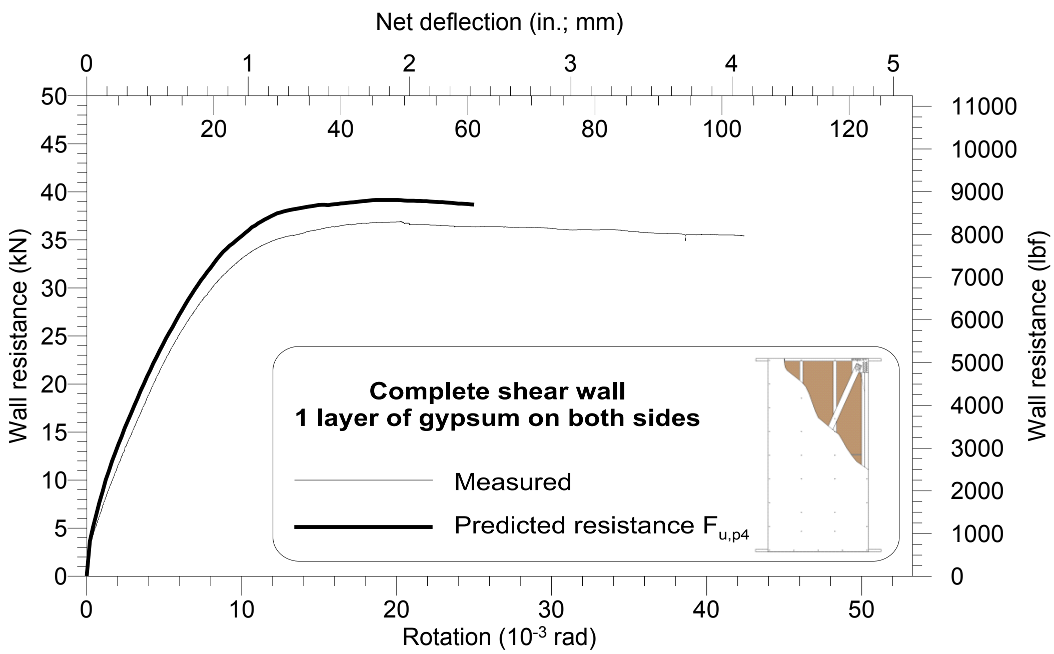



**Figure 3.29 Comparison of the measured and predicted load-drift curve for wall specimen 70A-M**

### 3.4.4 Lateral in-plane resistance of the bearing walls

One-layer and two-layer gypsum-sheathed bearing walls exhibited similar ultimate shear resistances because in both cases the steel frame failed at the stud to track connection (Subsection 3.2.1.2), while the gypsum and the drywall screws suffered only minor damage (Subsection 3.2.2.3). In design, bearing walls are assumed incapable of efficiently transferring lateral load (and uplift forces) to the ground since they are constructed without hold-downs. Therefore, gypsum-sheathed bearing walls cannot be used as lateral resisting systems. Nevertheless, if the lateral resistance of the bearing walls needs to be considered for the evaluation of the overall performance of a building subjected to earthquake ground motions, then one can use the mean value of the test-based yielding resistances obtained by the EEEP method (Figure 3.30) for one-layer and two-layer gypsum walls: $S_{yn}$ = 5.8 kN/m. Table 3.14 presents the test over nominal yielding resistance ratio for each specimen, as well as the average and the coefficient of variation of the ratios.

**Table 3.14 Comparison of the test and nominal resistance of bearing walls**

| Bearing wall tests | | $S_y$ (kN/m) | $S_y/S_{yn}$ with $S_{yn}$ = 5.8 kN/m |
|---|---|---|---|
| **78B-M** | | 5.59 | 0.963 |
| **78C-M** | | 5.11 | 0.881 |
| **79A-C** | *Positive* | *5.50* | *0.948* |
| | *Negative* | *-5.90* | *1.018* |
| | **Average** | 5.70 | 0.983 |
| **79B-C** | *Positive* | *5.29* | *0.913* |
| | *Negative* | *-5.91* | *1.020* |
| | **Average** | 5.60 | 0.966 |
| **Configuration average** | | **5.50** | **0.948** |
| **80A-M** | | 5.87 | 1.012 |
| **80B-M** | | 5.67 | 0.977 |
| **81A-C** | *Positive* | *5.60* | *0.966* |
| | *Negative* | *-6.80* | *1.172* |
| | **Average** | 6.20 | 1.069 |
| **81B-C** | *Positive* | *5.58* | *0.962* |
| | *Negative* | *-7.47* | *1.287* |
| | **Average** | 6.52 | 1.125 |
| **Configuration average** | | **6.06** | **1.046** |
| | | **Average of $S_y$ / $S_{yn}$** | 0.997 |
| | | **Standard deviation** | 0.0687 |
| | | **Coefficient of variation** | 0.0689 |

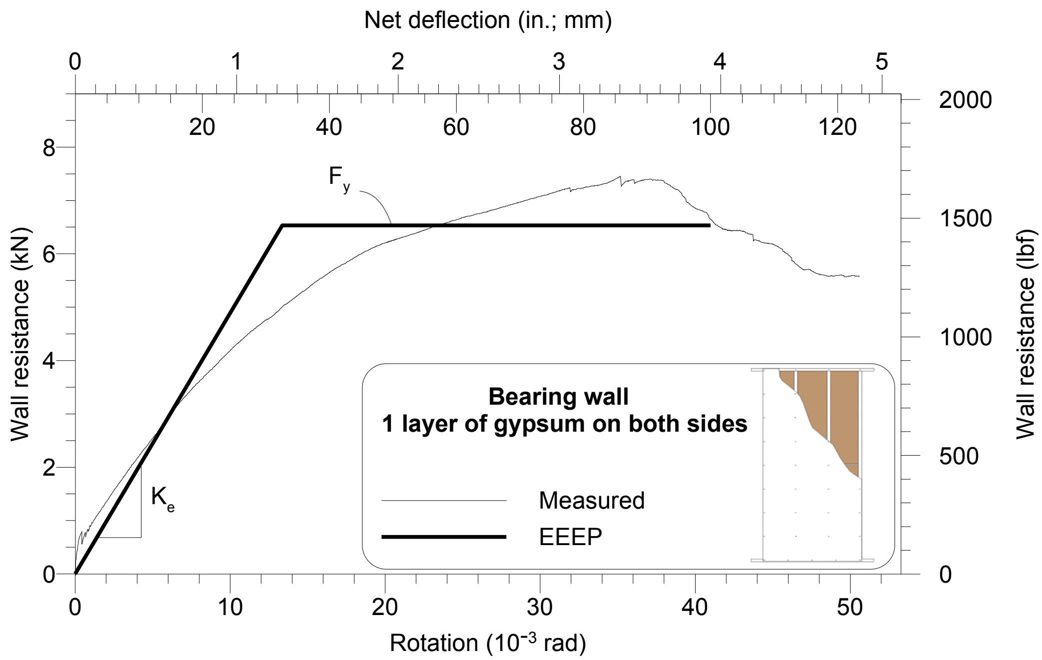



**Figure 3.30 Measured and EEEP curves for bearing test wall 78A-M**

### 3.4.5 Predictions of the lateral in-plane stiffness of the strap-braced bare frame

A prediction of the elastic lateral in-plane stiffness based on an equivalent spring model was made for the strap-braced bare frames. Each brace was represented by two springs in series respectively modelling the stiffness of the brace itself $K_{b'}$ (Equation ( 3.9 )) and the stiffness of the screw connections $K_c$ between the brace and the two gusset plates. $K_c$ was composed of several springs working in parallel, each spring $K_{ss}$ representing one screw (Equation ( 3.10 )) (Velchev *et al.*, 2010).

$$K_{b'} = \frac{E \cdot A_b}{L_b} \tag{3.9}$$

where:

$K_{b'}$ is the predicted stiffness of the brace;

$E$ is the modulus of elasticity equal to 203 000 MPa;

$A_b$ is the measured cross-section area of the brace;

$L_b$ is the length of the brace.

$$K_c = \frac{n \cdot K_{ss}}{2} \tag{3.10}$$

where:

$K_c$ is the stiffness of the all the connections between the brace and the two gusset plates;

$n$ is the number of screws in the connection between a brace and one gusset-plate, equal to *16* in this research program;

$K_{ss}$ is the stiffness of a single fastener, approximately equal to *1.775 kN/mm* (value deduced from a connection test and consequent calculations by Velchev *et al.*, 2010).

One brace and the two gusset plates that are used to affix it were in series (Figure 3.31). Consequently, the global stiffness of one brace and its gusset plates was calculated with the Equation ( 3.11 ).

$$\frac{1}{K_b} = \frac{1}{K_{b\prime}} + \frac{1}{K_c} \quad \textbf{( 3.11 )}$$

where:

$K_b$ is the global stiffness of brace including the connections to the gusset plates;

$K_{b'}$ is the stiffness of the brace;

$K_c$ is the stiffness of the connections between the brace and the two end gusset plates.

The axial stiffness of the hold-downs and the anchor rods was determined with Equation ( 3.12 ). The highest allowable design load and the corresponding deflection were found in the catalogue of the manufacturer (Simpson Strong-Tie, 2014) and the deflection included the fasteners slip, the hold-down elongation and the anchor rod elongation for a 100 mm (4”) long rod. The global stiffness of a hold-down was equal to $21.47 \cdot 10^6$ N/m.

$$K_{hd} = \frac{T_{hd}}{\delta_{hd}} \quad \textbf{( 3.12 )}$$

where:

$K_{hd}$ is the global stiffness of a hold-down connection including the anchor rod;

$T_{hd}$ is the highest allowable design load;

$\delta_{hd}$ is the hold-down and anchor rod deflection corresponding to the highest allowable design load.

Before each test was run, the strap widths were measured to obtain the actual cross section of each brace. These measurements were used to calculate the predicted stiffness of the braces $K_b$. Then, the predicted horizontal stiffness of the strap-braced frame $K_p$ based on measured strap-braces properties was calculated with the Equation ( 3.13 ). The hold-down and anchor rod horizontal stiffness was obtained by assuming a rigid body motion of the wall rotating about the bottom compression corner. It takes into account that there are braces on both sides of the wall and that the two braces in tension act in parallel (Figure 3.31). The compression braces do not contribute to the in-plane stiffness of the wall given their high slenderness.

$$\frac{1}{K_p} = \frac{1}{2 \cdot K_b \cdot cos^2\theta} + \frac{1}{K_{hd} \cdot tan^2\theta} \quad (3.13)$$

where:

$K_p$ is the global horizontal stiffness of the strap-braced wall;
$\theta$ is the angle of the brace to the horizontal direction.

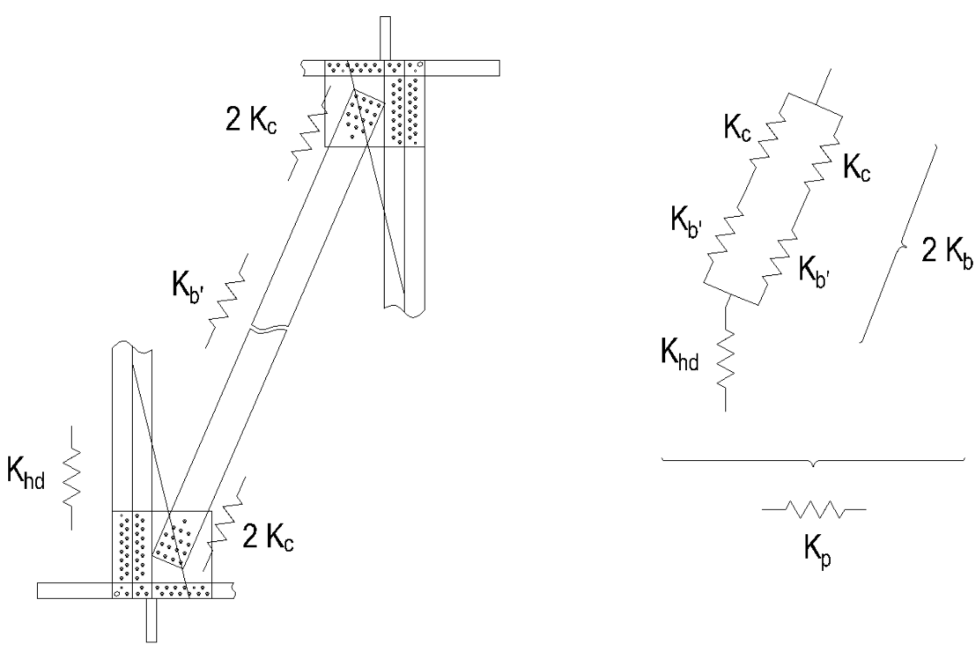



**Figure 3.31 Components contributing to the predicted stiffness of the strap-braced frame**

The predicted lateral stiffness of the strap-braced bare frame $K_n$ based on nominal strap-braces properties was also calculated with Equation ( 3.13 ), except that $K_b$ was obtained using the nominal properties of the braces.

### 3.4.6 Prediction of the lateral in-plane stiffness of the gypsum sheathed walls

#### *3.4.6.1 Gypsum-sheathed shear walls*

The stiffness of the gypsum-sheathed shear walls were evaluated with the modified EEEP method presented in Subsection 3.3.2. Table 3.15 provides the nominal values of the stiffness of gypsum panels, which was evaluated by taking the average of the stiffness of the specimens of each wall configuration. Table 3.16 and Table 3.17 list the stiffness values obtained for each shear wall and display the test/nominal stiffness ratios.

**Table 3.15 Nominal stiffness of the gypsum-sheathed shear walls**

| | Gypsum-sheathed shear wall elastic stiffness, $K_{e,g}$ (kN/mm) |
|---|---|
| 1 layer of 15.9 mm Type X Firecode C Core gypsum board on both sides<br>Screw pattern: 300mm/300mm | 0.79 |
| 2 layers of 15.9 mm Type X Firecode C Core gypsum board on both sides<br>Screw pattern: 300mm/300mm for both layers | 1.0 |

**Table 3.16 Comparison of the test and nominal stiffness of the 1-layer gypsum-sheathed shear walls**

| Gypsum-sheathed (1 layer) shear wall tests | | $K_{e,EEEP}$ (kN/mm) | $K_{e,EEEP}/K_{e,g}$ with $K_{e,g}$ = 0.79 kN/mm |
|---|---|---|---|
| **66A-M** | | 0.77 | 0.975 |
| **66B-M** | | 0.65 | 0.823 |
| **67A-C** | *Positive* | *0.92* | *1.165* |
| | *Negative* | *0.65* | *0.823* |
| | **Average** | 0.79 | 0.994 |
| **67B-C** | *Positive* | *1.12* | *1.418* |
| | *Negative* | *0.76* | *0.962* |
| | **Average** | 0.94 | 1.190 |
| **Configuration average** | | **0.79** | **0.995** |
| **Standard deviation** | | | 0.1304 |
| **Coefficient of variation** | | | 0.1311 |

**Table 3.17 Comparison of the test and nominal stiffness of the 2-layer gypsum-sheathed shear walls**

| Gypsum-sheathed (2 layers) shear wall | | $K_{e,EEEP}$ (kN/mm) | $K_{e,EEEP}/K_{e,g}$ with $K_{e,g}$ = 1.0 kN/mm |
|---|---|---|---|
| **68A-M** | | 1.06 | 1.060 |
| **68B-M** | | 0.86 | 0.860 |
| **69A-C** | *Positive* | *1.10* | *1.100* |
| | *Negative* | *1.02* | *1.020* |
| | **Average** | 1.06 | 1.060 |
| **69B-C** | *Positive* | *1.08* | *1.080* |
| | *Negative* | *0.98* | *0.980* |
| | **Average** | 1.03 | 1.030 |
| **Configuration average** | | **1.00** | **1.003** |
| **Standard deviation** | | | 0.0832 |
| **Coefficient of variation** | | | 0.0830 |

#### *3.4.6.2 Gypsum-sheathed strap-braced walls*

The stiffness of the strap-braced walls were obtained with the modified EEEP method presented in Subsection 3.3.2. It was hypothesized that the gypsum panels and the strap-braces act in parallel. This is consistent with the approach of adding the load-drift curves of the different components (FEMA P-807, 2012). Moreover, several past studies (Wolfe (1983), Gad *et al.* (1999), Salenikovich *et al.* (2000)) found that the stiffness of the different components of a shear wall could be added.

The contribution of the gypsum panels and the strap-braces were considered. The stiffness provided by the gypsum panels was estimated using the values presented in Table 3.15 and included the frame action. The stiffness of the strap-braces was estimated by different methods. The two first methods used were the ones presented in Subsection 3.4.5 based on analytical calculations and the nominal and measured properties of the steel components. Nevertheless, the stiffness calculated with the analytical methods were based on the actual elastic behaviour, which differs from the measured stiffness to which it was compared. Indeed, the measured stiffness of the gypsum-sheathed strap-braced walls with the EEEP method takes into account some ductile behaviour. Therefore, if the analytical estimation of the stiffness of the strap-braces is used, the contribution of the strap-braces in the overall measured stiffness will be over-estimated ($K_{e,n1}$ and $K_{e,p1}$ in Table 3.18). In order to better estimate the contribution of the strap-braces, one can use the modified EEEP method (Subsection 3.3.2) to estimate the stiffness of the strap-braced bare frames. Thus, the stiffness of the strap-braces also includes some inelastic behaviour. The predicted overall wall stiffness with this method ($K_{e,p2}$) is presented in Table 3.18. In all the predictions, the frame action is included in both the stiffness of the strap-braces as well as of the gypsum panels; thus, the frame action is accounted for twice, which may lead to an overestimation of the predicted stiffness.

As examples, the results for a wall sheathed on both sides are presented in Figure 3.32 and the results for a wall with resilient channels are presented in Figure 3.33. For the walls sheathed on both sides, the predictions overestimated the stiffness. This was expected since the frame action was accounted for twice in the predictions. For the walls sheathed on one side only and for the walls with resilient channels on one side, the predictions were more accurate. Indeed, when the contribution of the gypsum $K_{e,g}$, which includes the frame action, was divided by two, the frame action was also divided by two. Thus, the frame action was considered 1.5 times instead of 2 times.

**Table 3.18 Prediction of the in-plane lateral stiffness of the gypsum-sheathed strap-braced walls**

| | Values | | | | |
|---|---|---|---|---|---|
| **Strap-braced wall tests** | 65A-M<br>83A-C | 70A-M<br>70B-M<br>71A-C<br>71B-C | 72A-M<br>72B-M<br>73A-C<br>73B-C | 74A-M<br>74B-M<br>75A-C<br>75B-C | 76A-M<br>76B-M<br>77A-C<br>77B-C |
| **Number of layers of gypsum** | - | 1 | 2 | 2 | 2 |
| **Number of sheathed sides** | - | 2 | 2 | 1 | 2 (1) |
| **Average $K_{e,mod.EEEP}$ (kN/mm)** | 1.07 | 1.61 | 1.94 | 1.67 | 1.63 |
| **$K_n$ strap-braced frame predicted stiffness with nominal properties (kN/mm) (2)** | 1.62 | | | | |
| **$K_p$ average strap-braced frame predicted stiffness with measured properties (kN/mm) (3)** | 1.62 | 1.65 | 1.66 | 1.66 | 1.66 |
| **$K_{e,g}$ gypsum stiffness (kN/mm) (4)** | - | 0.79 | 1.0 | 1.0/2 | 1.0/2 |
| **$K_{e,n1} = K_{e,g} + K_n$ (kN/mm)** | 1.62 | 2.41 | 2.6 | 2.12 | 2.12 |
| **Test/Predicted ratio** | - | 0.667 | 0.741 | 0.787 | 0.770 |
| **Statistical informations** | - | AVG=0.741 ; SD=0.0535 ; COV=0.0721 | | | |
| **Average $K_{e,p1} = K_{e,g} + K_p$ (kN/mm)** | 1.62 | 2.44 | 2.7 | 2.16 | 2.16 |
| **Test/Predicted ratio** | - | 0.658 | 0.730 | 0.774 | 0.756 |
| **Statistical informations** | - | AVG=0.730 ; SD=0.0517 ; COV=0.0709 | | | |
| **Average $K_{e,p2} = K_{e,g} + K_{e,mod.EEEP,b}$ (kN/mm)** | 1.07 | 1.86 | 2.07 | 1.57 | 1.57 |
| **Test/Predicted ratio** | - | 0.864 | 0.938 | 1.063 | 1.040 |
| **Statistical informations** | - | AVG=0.976 ; SD=0.0875 ; COV=0.0896 | | | |

(1) 2 layers of gypsum on one side and 2 layers of gypsum with resilient channels on the other side

(2) $K_n$ calculated with the Equation (3.13) and the nominal properties of the braces

(3) $K_p$ calculated with the Equation (3.13) and the measured properties of the braces

(4) $K_{e,g}$ from Table 3.14 includes the gypsum panels resistance and the steel frame resistance

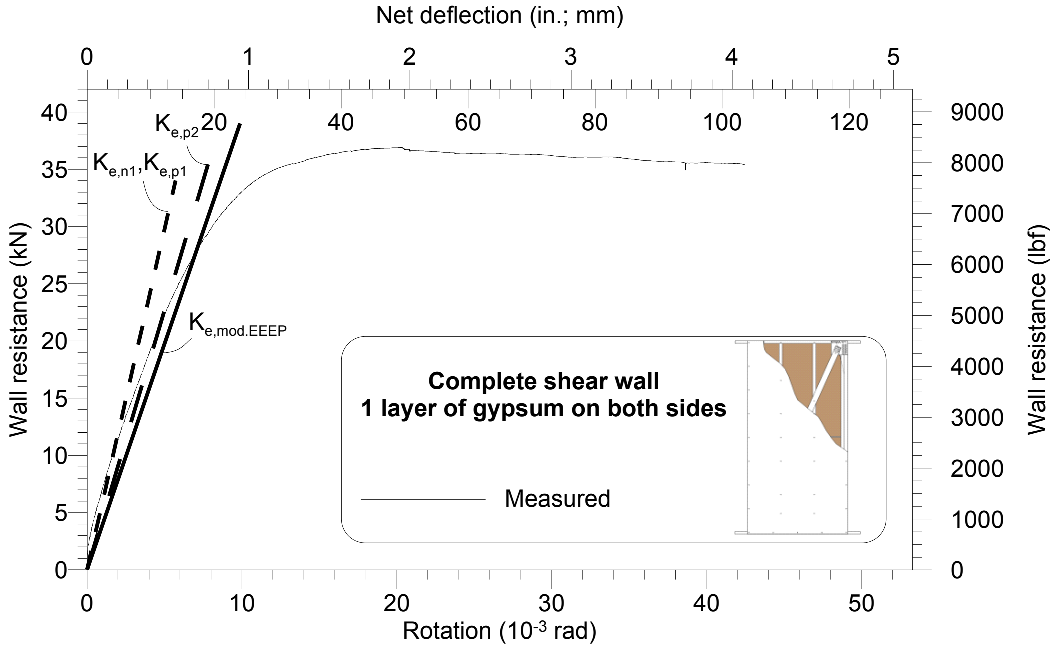



**Figure 3.32 Comparison of the measured stiffness of wall 70A-M with the predicted stiffness**

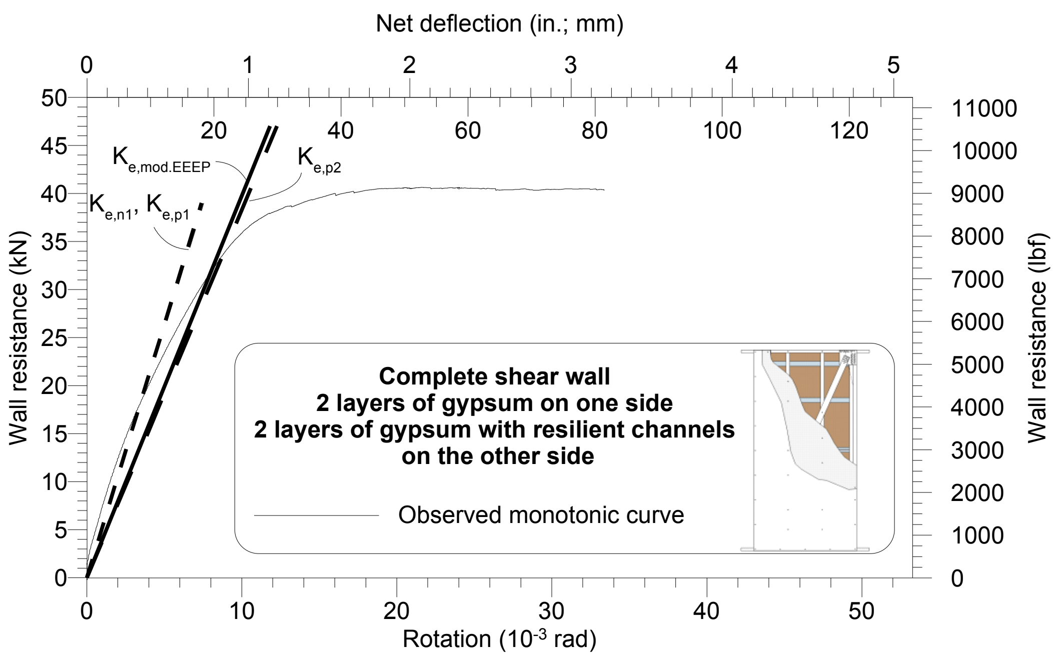



**Figure 3.33 Comparison of the measured stiffness of wall 76A-M with the predicted stiffness**

### 3.4.6.3 Gypsum-sheathed bearing walls

When evaluating the stiffness of a building, one may need an estimate of the stiffness of the gypsum-sheathed bearing walls. By using the modified EEEP method presented in Subsection 3.3.2, the stiffness for each bearing wall was obtained and all the values were averaged to obtain the nominal stiffness of one-layer and two-layer gypsum-sheathed bearing walls (Table 3.19). Table 3.20 and Table 3.21 list the stiffness values obtained for each shear wall and display the test/nominal stiffness ratios.

**Table 3.19 Nominal stiffness of the gypsum-sheathed bearing walls**

| | Gypsum-sheathed bearing wall elastic stiffness, $K_{e,n}$ (kN/mm) |
|---|---|
| 1 layer of 15.9 mm Type X Firecode C Core gypsum board on both sides<br>Screw pattern: 300mm/300mm | 0.36 |
| 2 layers of 15.9 mm Type X Firecode C Core gypsum board on both sides<br>Screw pattern: 300mm/300mm for both layers | 0.5 |

**Table 3.20 Comparison of the test and nominal stiffness of the 1-layer gypsum-sheathed bearing walls**

| **Gypsum-sheathed (1 layer) bearing wall tests** | | **$K_{e,mod.EEEP}$ (kN/mm)** | **$K_{e,mod.EEEP}/K_{e,n}$ with $K_{e,n}$ = 0.36 kN/mm** |
|---|---|---|---|
| **78B-M** | | 0.32 | 0.889 |
| **78C-M** | | 0.38 | 1.056 |
| **79A-C** | *Positive* | *0.35* | *0.972* |
| | *Negative* | *0.38* | *1.056* |
| | **Average** | 0.37 | 1.014 |
| **79B-C** | *Positive* | *0.35* | *0.972* |
| | *Negative* | *0.36* | *1.000* |
| | **Average** | 0.36 | 0.986 |
| **Configuration average** | | **0.36** | **0.986** |
| **Standard deviation** | | | 0.0613 |
| **Coefficient of variation** | | | 0.0622 |

**Table 3.21 Comparison of the test and nominal stiffness of the 2-layer gypsum-sheathed bearing walls**

| Gypsum-sheathed (2 layers) bearing wall tests | | $K_{e,mod.EEEP}$ (kN/mm) | $K_{e,mod.EEEP}/K_{e,n}$ with $K_{e,n}$ = 0.54 kN/mm |
|---|---|---|---|
| **80A-M** | | 0.48 | 0.889 |
| **80B-M** | | 0.49 | 0.907 |
| **81A-C** | *Positive* | *0.61* | *1.130* |
| | *Negative* | *0.56* | *1.037* |
| | **Average** | 0.59 | 1.083 |
| **81B-C** | *Positive* | *0.62* | *1.148* |
| | *Negative* | *0.56* | *1.037* |
| | **Average** | 0.59 | 1.093 |
| **Configuration average** | | **0.54** | **0.993** |
| **Standard deviation** | | | 0.0952 |
| **Coefficient of variation** | | | 0.0959 |

## 3.5 Summary

The capacity design of the shear wall test specimens (with hold-downs) lead to the desired behaviour: the fuse elements were able to maintain their strength in the inelastic range while the other structural members in the lateral load carrying path remained mainly elastic (Section 3.2). In the bearing wall test specimens, for which no capacity design calculations were implemented, the gypsum panels remained mainly undamaged, while the damage was mostly concentrated in the steel frame (Section 3.2).

The test results (Subsection 3.4.1) showed that attaching 15.9 mm-thick gypsum panels to a strap-braced wall could provide 15% (one layer of gypsum on both sides) to 53% (two layers of gypsum on both sides) additional strength. Figure 3.34 shows the additional strength provided by the gypsum panels to a CFS strap-braced wall.

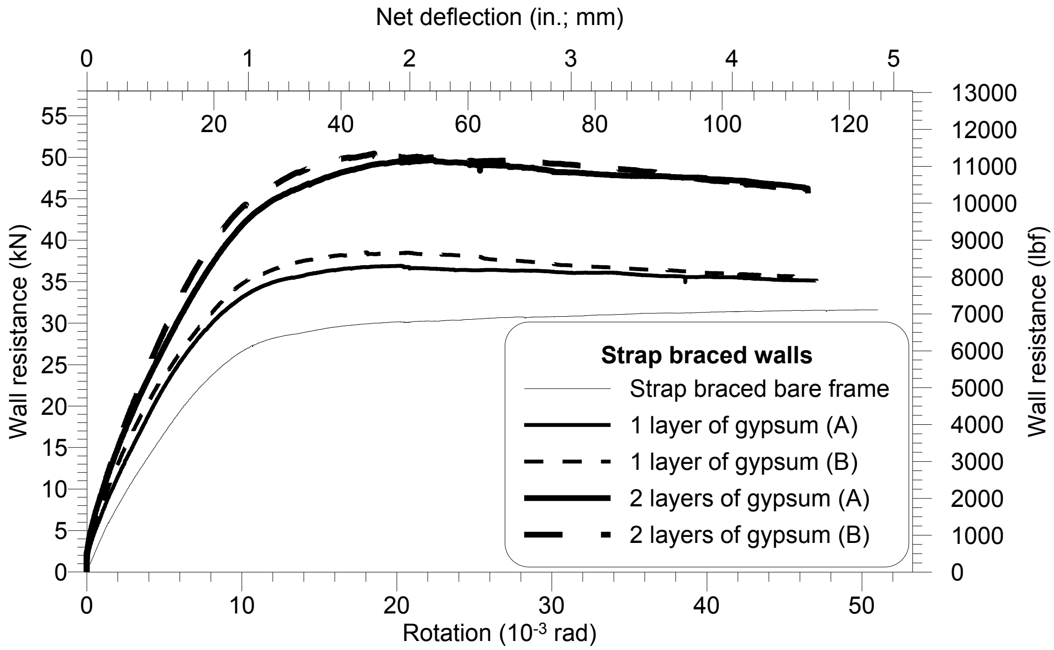



**Figure 3.34 Additional strength provided by the gypsum panels to a CFS strap-braced wall**

Values to be used for the design of gypsum-sheathed shear walls and gypsum-sheathed strap-braced shear walls were provided (Subsection 0). This allows the designer to account for the lateral in-plane resistance of the gypsum panels and use them as structural elements. For the capacity-based design, values and factors to be used for the sheathed shear walls were provided and methods of prediction of the probable force for the strap-braced sheathed shear walls were presented (Subsection 3.4.3).

A method to predict analytically the elastic stiffness of the strap-braced frames is presented (Subsection 3.4.5). Values to evaluate the stiffness (including some ductile behaviour) of the sheathed shear walls, the sheathed strap-braced walls and the bearing walls were obtained (Subsection 3.4.6).

# Chapter 4. Numerical modeling of the tests

In the previous chapters, it has been shown that gypsum panels could provide additional lateral in-plane resistance and stiffness to a building. In hot-rolled steel building or concrete buildings, the lateral resistance and stiffness of the structural members are greater than those of a gypsum-sheathed CFS wall. However, in CFS framed buildings, gypsum panels can add 15% to 53% of strength to a strap-braced wall (Section 3.5). Thus, it is essential to take into account the influence of gypsum panels on the overall response of a CFS framed building when subjected to lateral loading. The objective of this chapter is to provide a sheathed wall phenomenological numerical model that can be used to evaluate the influence of gypsum on the behaviour of a building. For this purpose, the test walls were numerically modelled using OpenSees (McKenna, 1997).

## 4.1 Model components

### 4.1.1 Shear wall model

In this thesis the shear walls were designed to resist lateral load and therefore have hold-downs. The shear walls can be braced with gypsum panels alone, with CFS strap-braces alone or with both gypsum panels and strap braces. The model was based on the sheathed wall model developed by Shamim (2013). The components used to model the shear walls, as well as the numbering of the elements and nodes used in the OpenSees model, are represented in Figure 4.1.

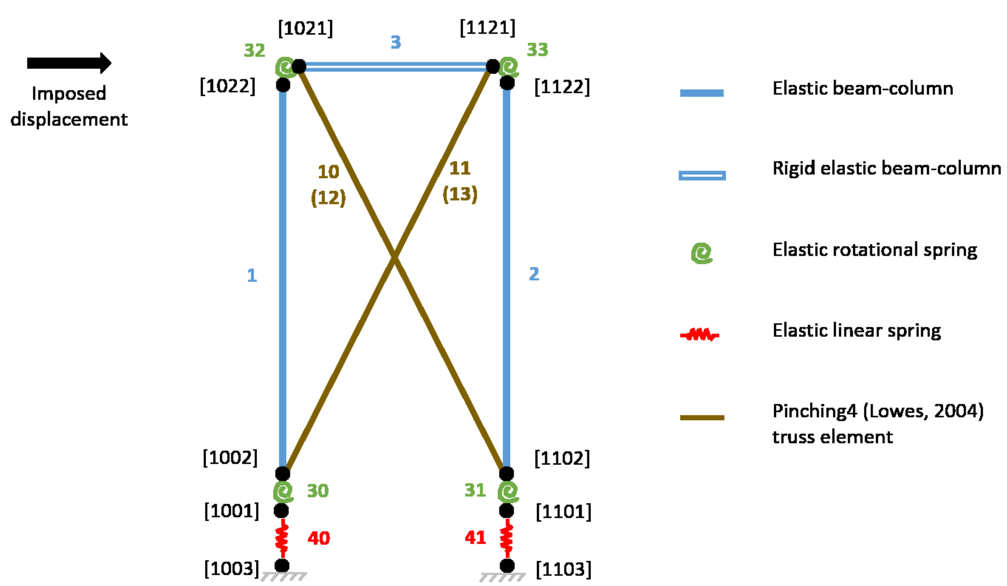



**Figure 4.1 Model of the shear walls in OpenSees**

The chord studs (1 and 2 in Figure 4.1) and the tracks (3 in Figure 4.1) were modeled with elastic beam-column elements. The tracks were defined as rigid beam-column elements because in the specimens tested, the tracks were connected to the test frame, which is rigid. The hold-downs were modeled with linear elastic springs (40 and 41 in Figure 4.1). They were constrained to deform only along the vertical direction.

The connections between the double chord studs and the tracks are not perfectly pinned since the double chord studs cannot rotate freely around the screw connection to the track. Elastic rotational springs (30, 31, 32 and 33 in Figure 4.1) were used to represent the connections between the chord studs and the tracks, i.e. the frame action of the wall.

The gypsum panels and the straps are both modeled with a pair of diagonal truss elements (10 and 11 in Figure 4.1) with Pinching4 (Lowes *et al.*, 2004) material, which allowed a good behaviour fitting (Section 4.3). When the walls were braced with both gypsum panels and straps, two pairs of diagonal truss elements were used; one pair of truss elements (10 and 11) represented the gypsum panels and the other pair of truss elements (12 and 13) represented the strap braces. Even though the straps were made of steel, Steel02 material was not used for the behaviour of the straps because it could not capture the pinched behaviour of the straps.

### 4.1.2 Bearing wall model

The bearing walls are only designed to carry gravity loads and do not have hold-downs. Nevertheless, in Chapter 1 and Chapter 3, it has been shown that when bearing walls are sheathed with gypsum panels, they can also provide in-plane lateral resistance and stiffness to a structure. Without sheathing, the frame of the bearing walls did not have any in-plane lateral resistance; thus, the connections between the studs and the tracks can be considered as pinned. The model of the bearing walls was similar to that of the shear walls but did not have the linear springs representing the hold-downs and the rotational springs at the chord stud-to-track connection locations. The components used to model the bearing walls, as well as the numbering of the elements and nodes used in the OpenSees model, are represented in Figure 4.2.

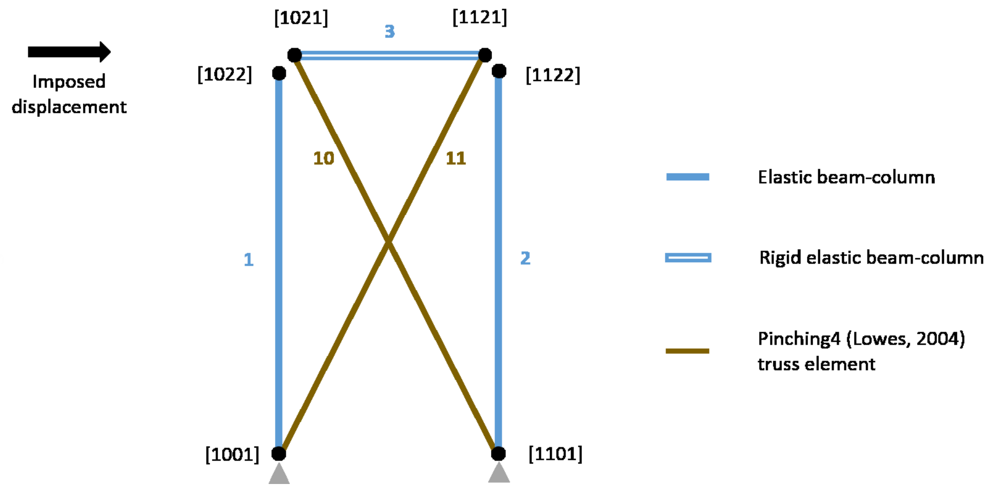



**Figure 4.2 Model of the bearing walls in OpenSees**

## 4.2 Material properties and calibration of the model

### 4.2.1 Elastic beam-columns elements

The modulus of elasticity of the elements representing the double chord studs was taken equal to 203 MPa. The gross section area and modulus of inertia of the double chord studs were calculated and implemented in the corresponding beam-column element in the shear wall model. The gross section area and modulus of inertia of the single chord studs were calculated and implemented in the corresponding beam-column element in the bearing wall model. The track was supposed to be rigid; thus, the Young's modulus, the cross-section area and the moment of inertia of the tracks were greater than the actual properties of the tracks.

### 4.2.2 Elastic linear springs

The stiffness of the linear springs representing the hold-downs and 100 mm (4") long anchors rods was taken equal to $21.47 \cdot 10^6$ N/m, value given in the catalogue of the manufacturer (Simpson Strong-Tie, 2014) (see Subsection 3.4.5).

### 4.2.3 Elastic rotational springs

The elastic stiffness of the rotational springs were determined with a model representing a shear bare frame (specimen 82A-M). The model comprised of elastic beam-column elements (chord studs), rigid elastic beam-column elements (track), linear spring (hold-downs) and rotational springs. The stiffness of the rotational springs was chosen so that the OpenSees model pushover curve fitted the 82A-M test curve (Figure 4.3).

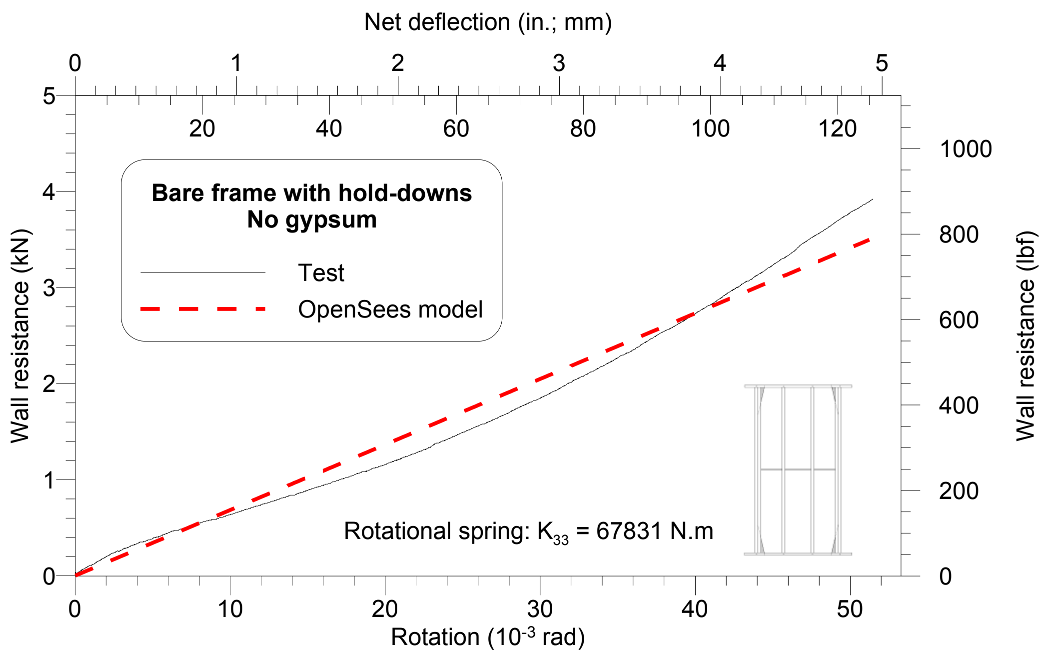



**Figure 4.3 OpenSees model of the shear bare frame (82A-M) and determination of the stiffness of the rotational springs**

### 4.2.4 Pinching4 truss elements

The Pinching4 (Lowes *et al.*, 2004) material was created to represent a material exhibiting pinching behaviour and degradation under cyclic loading. The parameters of the model are shown in Figure 4.4. The backbone curve of the material can be defined with four points. The pinching properties are defined with three factors uForce, rForce and rDisp. Three types of cyclic degradation can be combined in the model: unloading stiffness degradation, reloading stiffness degradation, strength degradation. Each type of degradation is defined with four parameters ($g_1$ to $g_4$ in Figure 4.4), to account for the influence of drift and dissipated energy. A fifth parameter ($g_{lim}$) allows limiting the degradation level for each type of degradation.

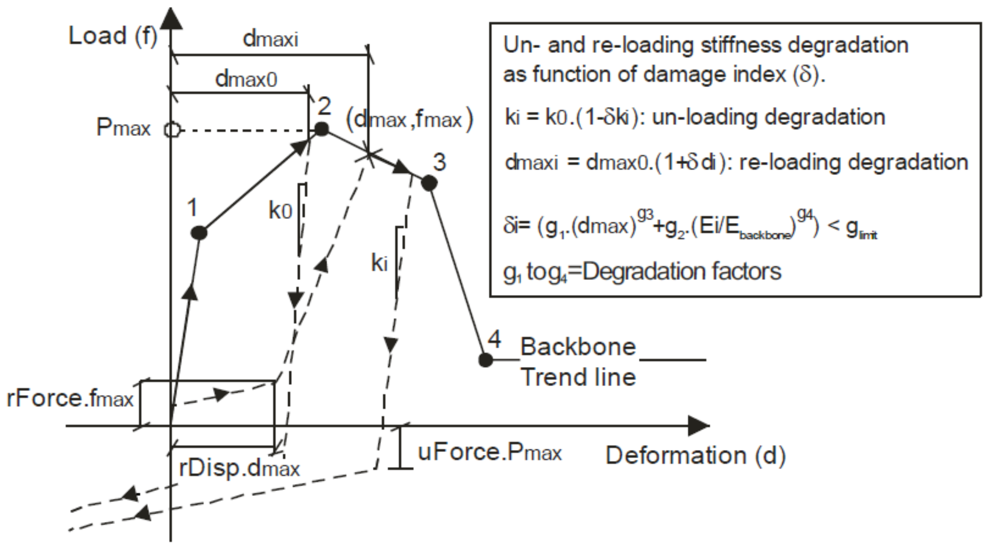



**Figure 4.4 Definition of Pinching4 (Lowes *et al.*, 2004) parameters (figure from Shamim, 2011)**

For the modelling of strap-braces, the parameters defining the backbone curve of the Pinching4 model were chosen based on the measured properties of the steel coupons. No resistance in compression was considered for the straps. The other parameters of the model were chosen such that they fitted the results of the tested unsheathed strap-braced wall (83A-C).

For the modelling of the gypsum panels, the parameters were chosen such that the results of the model fitted the test results of the gypsum-sheathed shear walls without straps. The diagonal truss elements representing the gypsum panels were considered to have a symmetrical behaviour; thus they had the same resistance in compression and tension. The parameters defining the backbone curve were chosen such that the wall model fitted the average of the monotonic and cyclic backbones of the corresponding specimens (Figure 4.5). The energy dissipated under the backbone curve obtained with the pushover analysis of the model was the same as the average of the energy dissipated under the monotonic and cyclic curves of the tested walls. The other parameters (Figure 4.4) of the Pinching4 model were chosen so that the reversed cyclic analysis of the model fitted the cyclically tested gypsum-sheathed shear wall specimens without straps.

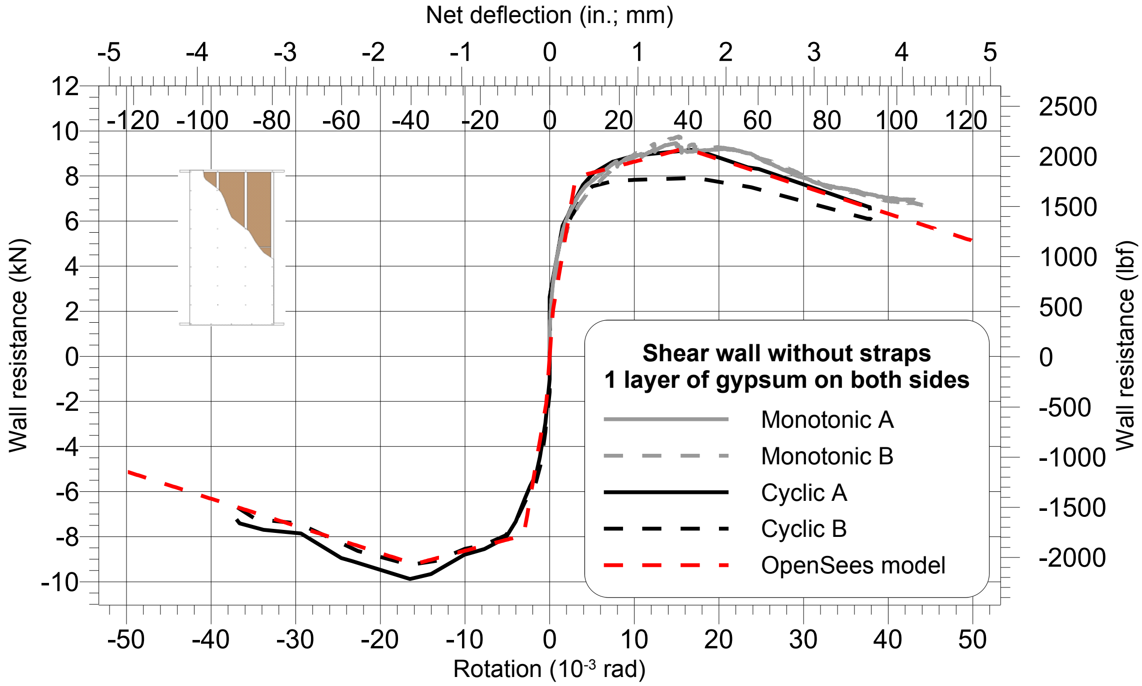



**Figure 4.5 Example of comparison of the pushover analysis result with the monotonic curves and the backbone curve obtained from the cyclic tests of the shear walls (66A-M, 66B-M, 67A-C and 67B-C)**

For the strap-braced gypsum sheathed walls, two pairs of truss elements were used. The first pair represented the gypsum panels. For the strap-braced walls sheathed on both sides with one or two layers of gypsum, the parameters of the Pinching4 material representing the gypsum panels were the same as the parameters found for the corresponding shear wall without straps. For the strap-braced walls sheathed on one side only or sheathed on both sides with resilient channels on one side, the parameters were the same as that of the model of the 2-layer gypsum-sheathed shear walls except for the parameters defining the backbone curve. The stresses were half of the ones found for the 2-layer gypsum-sheathed shear walls.

## 4.3 Comparison between numerical model and experimental results

The parameters of the Pinching4 material were calibrated such that the energy dissipated by the numerical models during pushover analysis was the same as the energy dissipated by the monotonically tested walls. The pinching and degradation parameters were chosen such that the energy dissipated by the cyclically tested walls was the same as the energy dissipated by the numerical model subjected to the same reversed cyclic loading. The behaviour of the steel straps (Figure 4.6) as well as the gypsum panels (Figure 4.7 and Figure 4.8) were well represented by the Pinching4 material. Overall, the OpenSees models and the tests agree very well (Figure 4.6 to Figure 4.14). The parameters are available in Appendix E.

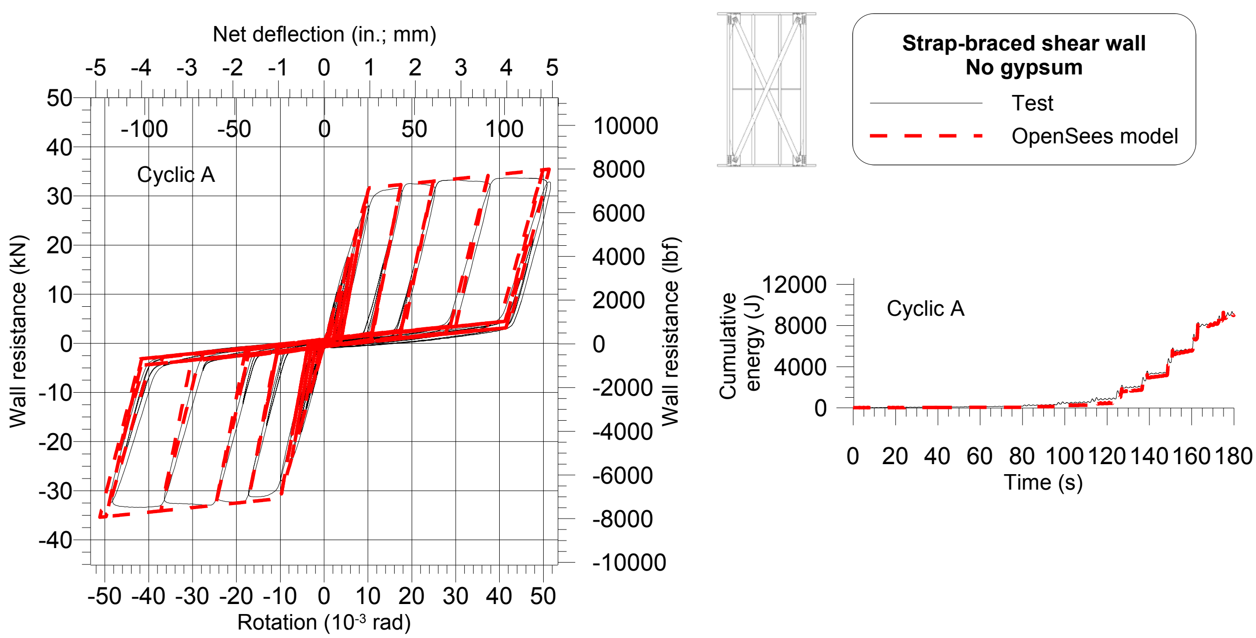



**Figure 4.6 Comparison between the numerical model and the results of the corresponding cyclic test for the strap-braced wall frame (83A-C)**

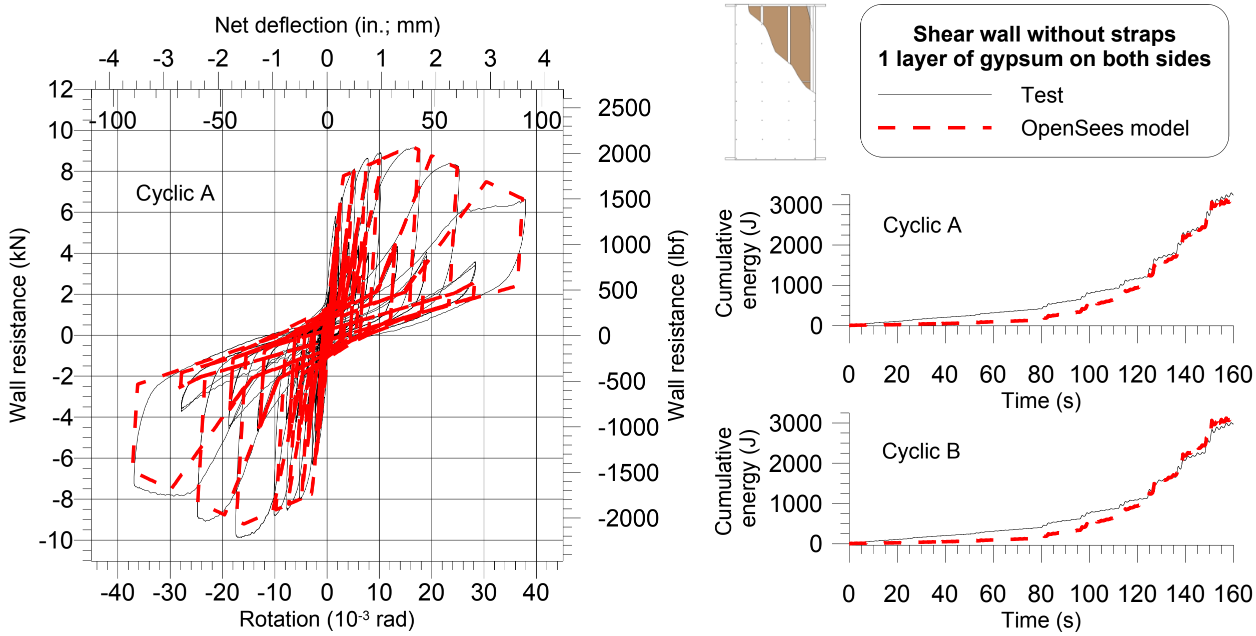



**Figure 4.7 Comparison between the numerical model and the results of the corresponding cyclic tests for the shear walls sheathed with one layer of gypsum on both sides (67A-C and 67B-C)**

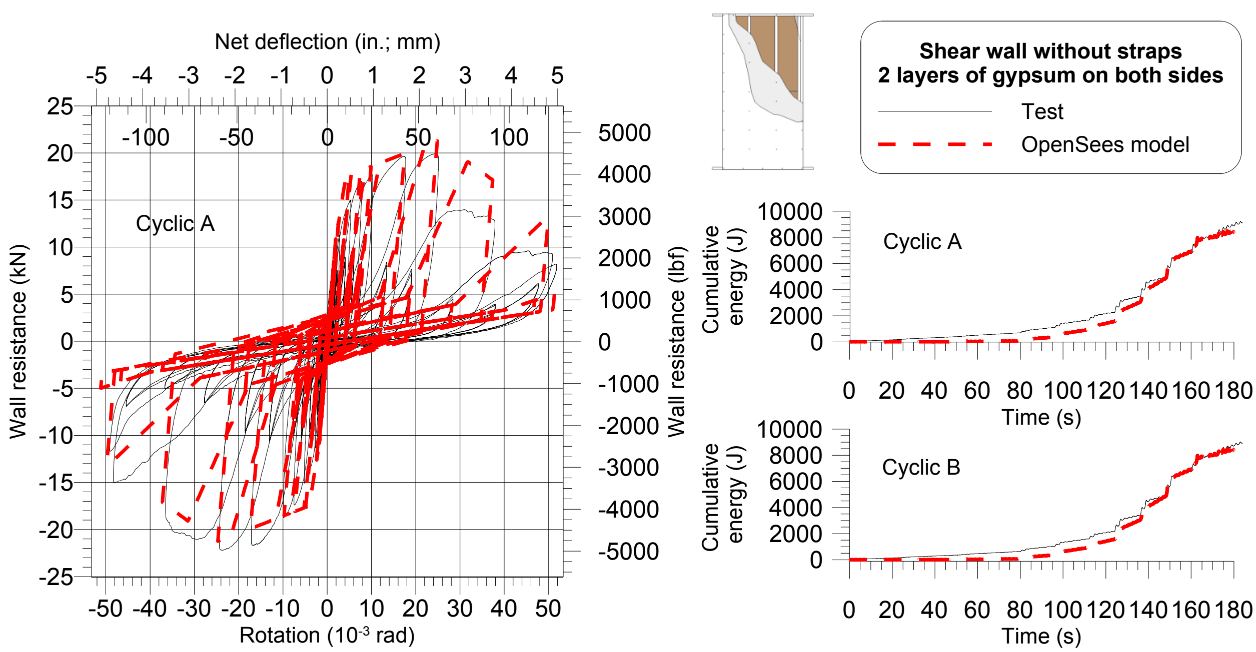



**Figure 4.8 Comparison between the numerical model and the results of the corresponding cyclic tests for the shear walls sheathed with two layers of gypsum on both sides (69A-C and 69B-C)**

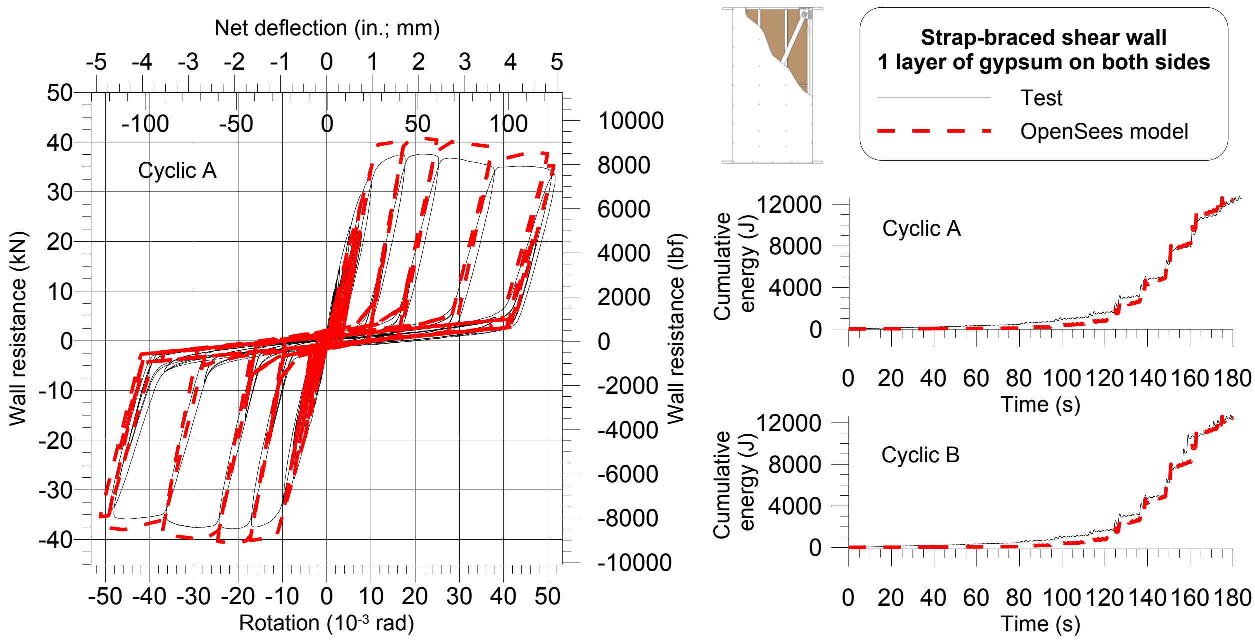



**Figure 4.9 Comparison between the numerical model and the results of the corresponding cyclic tests for the strap-braced walls sheathed with one layer of gypsum on both sides (71A-C and 71B-C)**

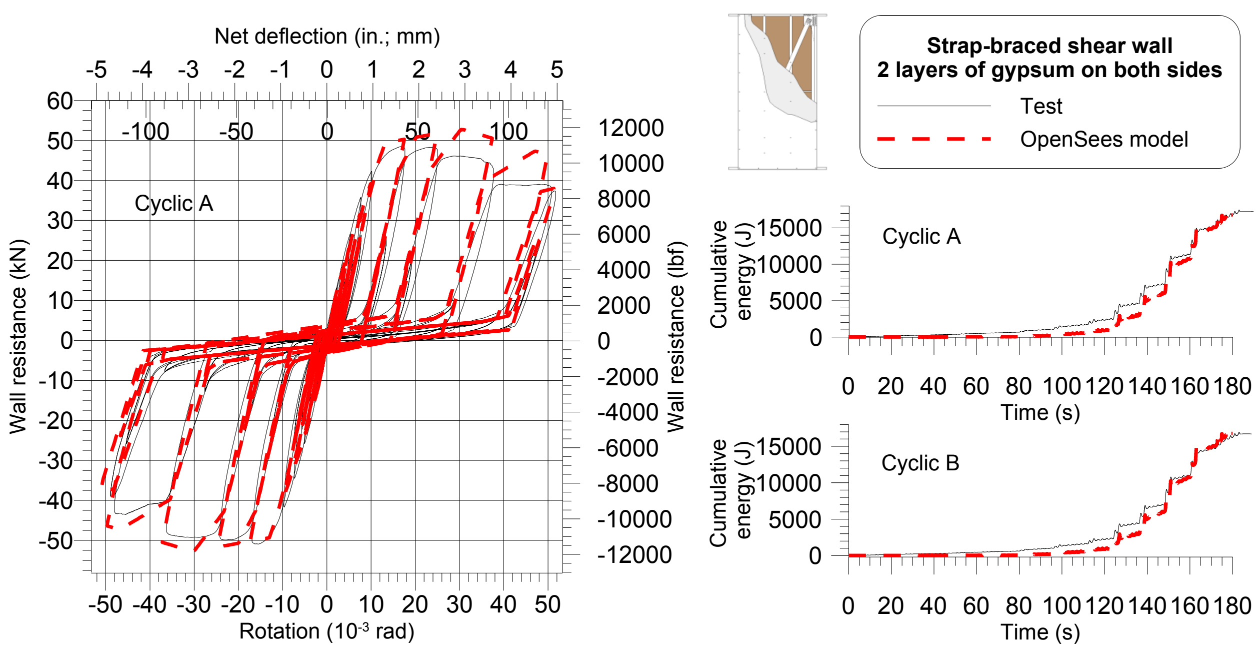



**Figure 4.10 Comparison between the numerical model and the results of the corresponding cyclic tests for the strap-braced walls sheathed with two layers of gypsum on both sides (73A-C and 73B-C)**

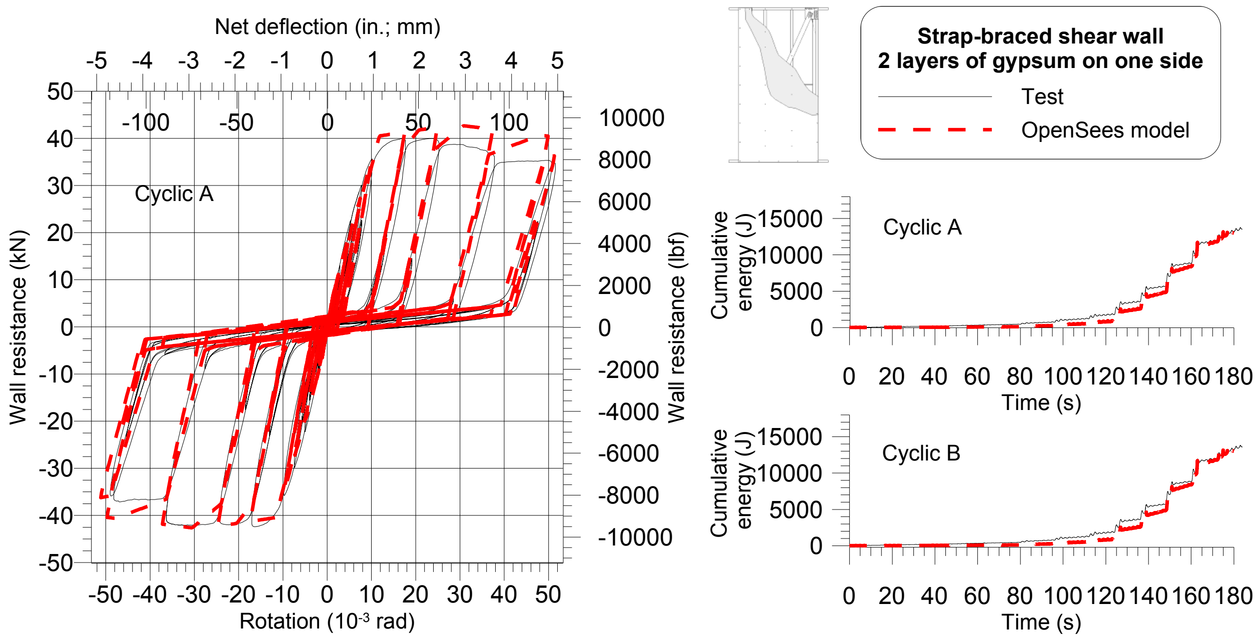



**Figure 4.11 Comparison between the numerical model and the results of the corresponding cyclic tests for the strap-braced walls sheathed with two layers of gypsum on one side only (75A-C and 75B-C)**

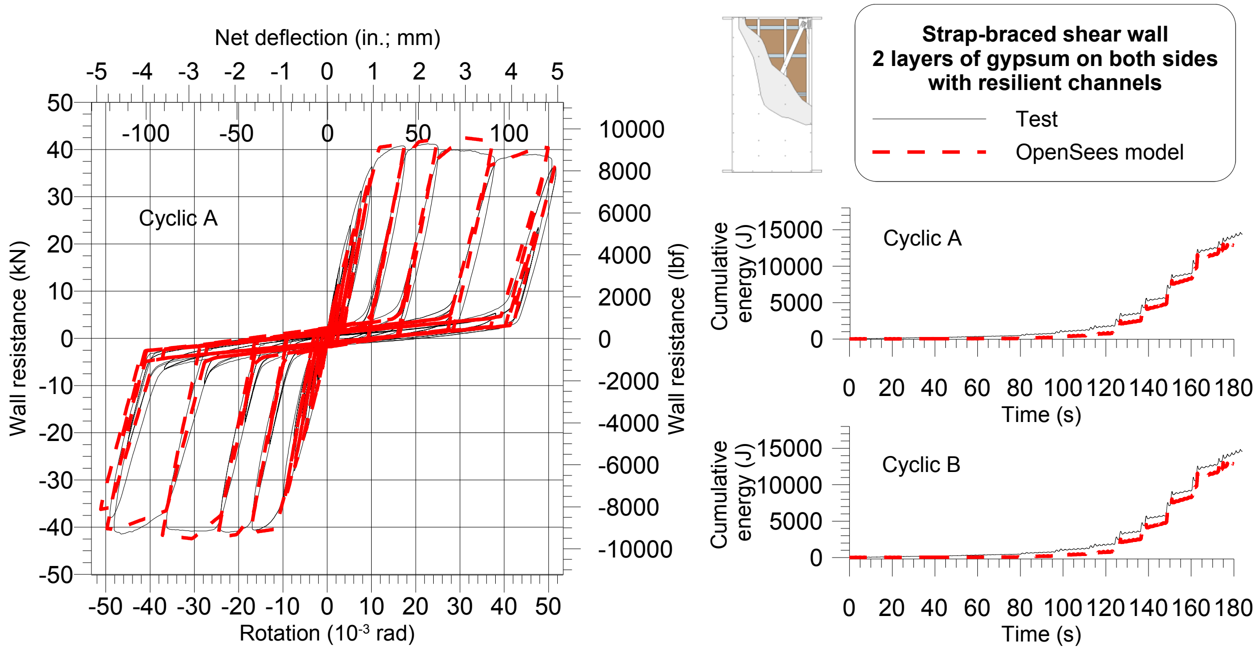



**Figure 4.12 Comparison between the numerical model and the results of the corresponding cyclic tests for the strap-braced walls sheathed with two layers of gypsum on both sides with resilient channels on one side (77A-C and 77B-C)**

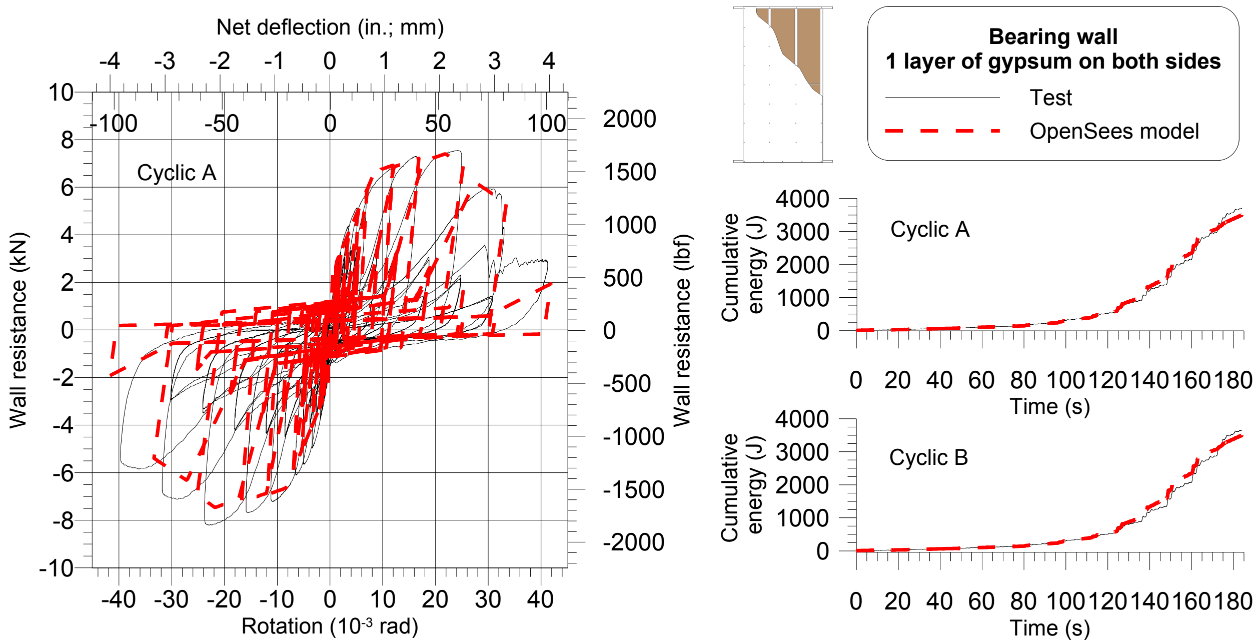



**Figure 4.13 Comparison between the numerical model and the results of the corresponding cyclic tests for the bearing walls sheathed with one layer of gypsum on both sides (79A-C and 79B-C)**

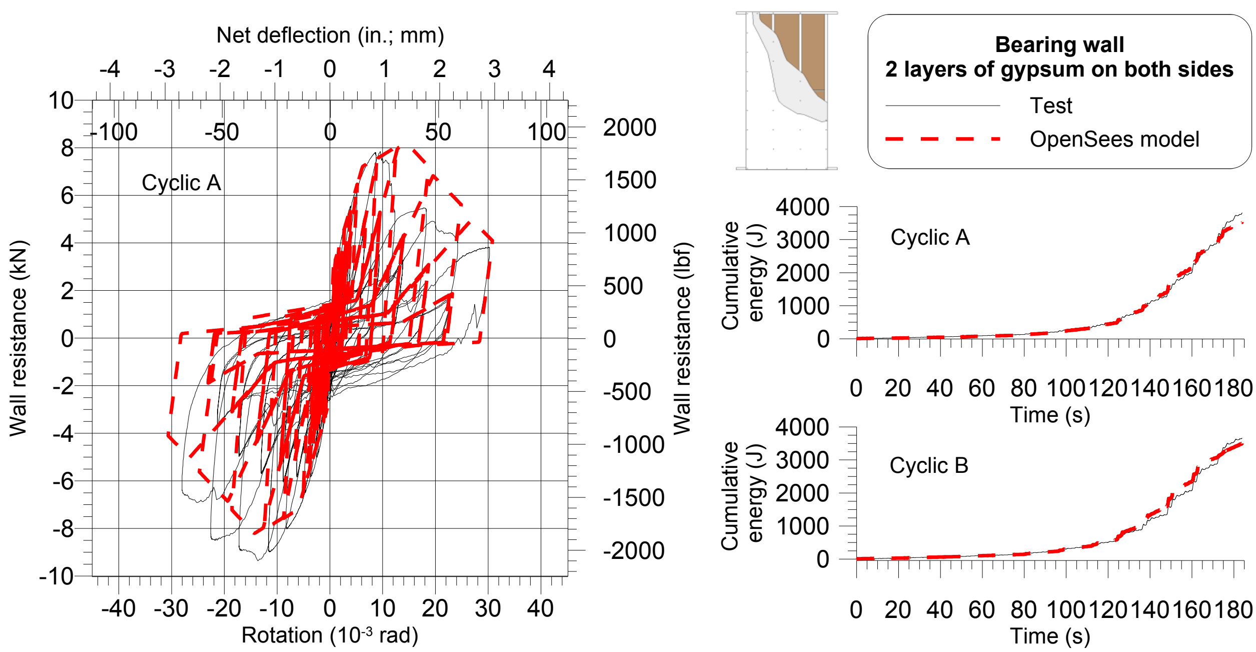



**Figure 4.14 Comparison between the numerical model and the results of the corresponding cyclic tests for the bearing walls sheathed with two layers of gypsum on both sides (81A-C and 81B-C)**

# Chapter 5. Conclusions and recommendations

## 5.1 Conclusions

The first objective of this research project was to investigate the effect of gypsum panels on the response of CFS shear walls, strap-braced shear walls and bearing walls and to provide recommendations for the design and the capacity design of gypsum-sheathed walls. The second objective was to create numerical models of the tested walls with OpenSees (McKenna, 1997) that can be used to incorporate the effect of gypsum panels on walls in a full building model. For these purposes, thirty-five 2.44 m x 1.22 m walls sheathed with different gypsum and strap-brace configurations were tested under in-plane lateral loading. All the gypsum panels were 15.9 mm-thick and were affixed with screws spaced at 300 mm o/c in the field and on the perimeter. Thus, in the walls sheathed with two layers of gypsum, the inner layer was screw connected every 150 mm.

The shear wall test specimens (walls with hold-downs) were designed according to capacity-based principles with conservative assumptions to estimate gypsum panels contribution. The recommended capacity design method is a modified version of the initial method and was based on the results of the walls tested for this research. In all the shear walls, the CFS frame remained mainly undamaged while any damage that did occur was concentrated in the gypsum panels and the sheathing-to-frame connections, which is the desired ductile mode of failure. Drywall screw tilting, pull-through, bearing and shear, as well as gypsum cracking and crushing were observed during the tests of the shear walls. In a building, bearing walls are only designed to carry gravity loads and no capacity check is done. Thus, the bearing walls in the test program were not designed with a capacity-based philosophy. During the bearing wall tests, the gypsum panels and the sheathing-to-frame connections remained undamaged whereas the CFS frame was distorted and some framing screws failed in shear.

The nominal yielding resistance of strap-braced frames can be calculated according to CSA S136 (2007). The nominal yielding resistance obtained for the tested gypsum-sheathed shear walls are provided and can be used for design. It has to be noted that all the gypsum-sheathed shear walls tested were sheathed on both sides. It has been found that the yielding resistance of gypsum-sheathed strap-braced walls can be estimated by adding the nominal yielding resistance of the corresponding gypsum-sheathed shear wall and the strap-braced frame and reducing the sum with a 0.9 factor. For walls sheathed with gypsum on one side only, the nominal resistance of the gypsum-sheathed shear wall provided can be divided by two.

A method to calculate the probable resistance of strap-braces is provided in AISI S213 (2007) and AISI S400 (2015). The probable resistance of the gypsum-sheathed shear walls can be estimated by factoring the nominal yielding resistance provided in the thesis with 1.1. Different methods to predict the probable resistance of gypsum-sheathed strap-braced walls are also presented. For the strap-braced walls sheathed on both sides, a simple way to predict the resistance of those walls is to add the probable resistance of strap-braced and the probable resistance of gypsum-sheathed wall. For the strap-braced walls sheathed on one side only, a simple way to predict the resistance of those walls is to add the probable resistance of strap-braced and half of the probable resistance of gypsum-sheathed wall. Nevertheless, this method can underestimate the probable resistance of walls sheathed on one side only. Thus, more conservative factors (1.2 or 1.3) can be used when estimating the probable resistance of the gypsum panels. An alternative method to estimate the probable strength of gypsum-sheathed strap-braced walls using the load-drift curves of strap-braced walls and gypsum-sheathed shear walls is presented.

Even if a bearing wall cannot be used as a lateral load resisting elements due to its non-ductile behaviour, it can provide lateral resistance; an estimate of this resistance is provided in this thesis for the evaluation of the overall performance of a building subjected to earthquake ground motions.

The OpenSees software (McKenna, 1997) was used to create phenomenological numerical models of the tested specimens. The parameters of the material Pinching4 (Lowes, 2004) were calibrated. A good agreement was obtained between the numerical models and the tested wall specimens.

## 5.2 Recommendations for future research

Walls sheathed with 15.9 mm-thick gypsum can provide 1-hour (one layer on both sides) to 2-hour (two layers on both sides) fire resistance rating which is often required in the buildings. In the current standards, the only recommendations available are for 12.7 mm-thick gypsum panels. In this research, walls with different configuration of 15.9 mm-thick gypsum panels were tested.

Nevertheless, only one sheathing-to-frame connection spacing was investigated. Gypsum-sheathed walls with 15.9 mm-thick gypsum and other screw configurations should be tested so that a wider database can be obtained and implemented in the design standards.

In this research, the gypsum panels were not restrained at the top, the bottom or the sides, i.e. no bearing type contact of the panel edges was simulated. Different boundary conditions will modify the influence of the gypsum panels on the response of the CFS wall. If the wall had more restraints, it would be able to transmit load through these restraints and the wall would likely be able to carry higher lateral loads. Thus, the capacity design methods and the numerical models should include a consideration for the boundary conditions of the gypsum-sheathed walls.

In order to be able to model numerically various buildings, a wider offer of OpenSees wall configurations needs to be provided. A lot of testing was done throughout the world and large amount of data is already available. Thus, creating a program that automatically fits the parameters of the Pinching4 material to the tested curves would allow one to obtain the numerical model of a greater variety of walls.

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# Appendix A. CUREE reversed cyclic protocols

**Table A.1 Reversed cyclic CUREE test protocol for strap walls**

| Cycle Displacements | Target Displacement (mm) | Actuator input (mm) | Number of Cycles |
|---|---|---|---|
| 0.050 Δ | 3.045 | 4.203 | 6 |
| 0.075 Δ | 4.568 | 5.726 | 1 |
| 0.056 Δ | 3.426 | 4.584 | 6 |
| 0.100 Δ | 6.091 | 7.248 | 1 |
| 0.075 Δ | 4.568 | 5.726 | 6 |
| 0.200 Δ | 12.182 | 13.337 | 1 |
| 0.150 Δ | 9.136 | 10.292 | 3 |
| 0.300 Δ | 18.272 | 19.426 | 1 |
| 0.225 Δ | 13.704 | 14.859 | 3 |
| 0.400 Δ | 24.363 | 25.515 | 1 |
| 0.300 Δ | 18.272 | 19.426 | 2 |
| 0.700 Δ | 42.635 | 43.781 | 1 |
| 0.525 Δ | 31.977 | 33.126 | 2 |
| 1.000 Δ | 60.908 | 62.048 | 1 |
| 0.750 Δ | 45.681 | 46.826 | 2 |
| 1.500 Δ | 91.362 | 92.493 | 1 |
| 1.125 Δ | 68.521 | 69.660 | 2 |
| 2.000 Δ | 121.816 | 122.938 | 1 |
| 1.500 Δ | 91.362 | 92.493 | 2 |
| 2.500 Δ | - | 125.000 | 1 |
| 1.875 Δ | 114.202 | 115.327 | 2 |

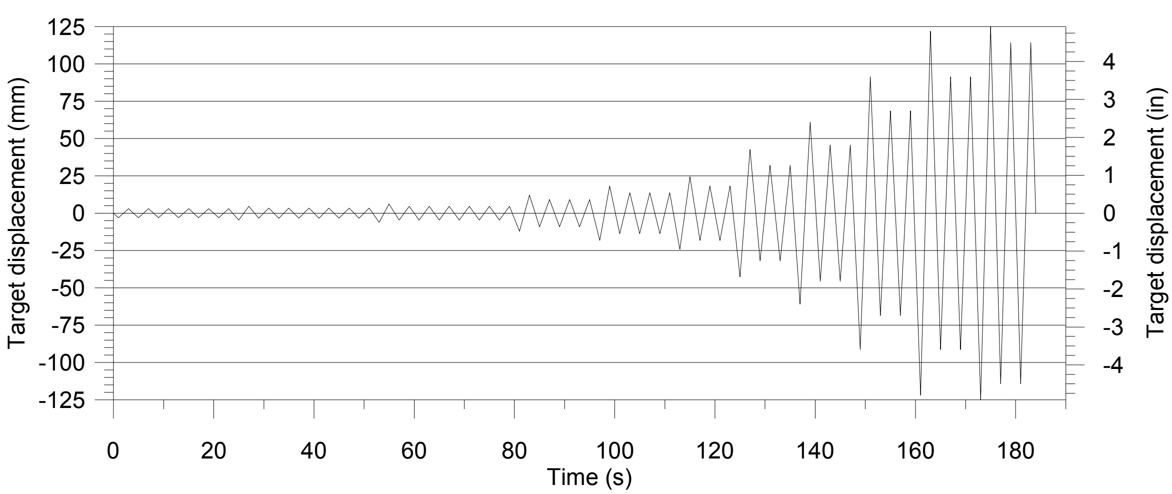



**Figure A-1 CUREE displacement time history for strap walls**

**Table A.2 Reversed cyclic CUREE test protocol for bearing walls with one layer of gypsum**

| Cycle Displacements | | Target Displacement (mm) | Actuator input (mm) | Number of Cycles |
|---|---|---|---|---|
| 0.050 | Δ | 1.977 | 2.914 | 6 |
| 0.075 | Δ | 2.965 | 3.925 | 1 |
| 0.056 | Δ | 2.224 | 3.167 | 6 |
| 0.100 | Δ | 3.953 | 4.936 | 1 |
| 0.075 | Δ | 2.965 | 3.925 | 6 |
| 0.200 | Δ | 7.907 | 8.982 | 1 |
| 0.150 | Δ | 5.930 | 6.959 | 3 |
| 0.300 | Δ | 11.860 | 13.027 | 1 |
| 0.225 | Δ | 8.895 | 9.993 | 3 |
| 0.400 | Δ | 15.813 | 17.073 | 1 |
| 0.300 | Δ | 11.860 | 13.027 | 2 |
| 0.700 | Δ | 27.673 | 29.209 | 1 |
| 0.525 | Δ | 20.755 | 22.129 | 2 |
| 1.000 | Δ | 39.533 | 41.345 | 1 |
| 0.750 | Δ | 29.650 | 31.232 | 2 |
| 1.500 | Δ | 59.299 | 61.572 | 1 |
| 1.125 | Δ | 44.474 | 46.402 | 2 |
| 2.000 | Δ | 79.066 | 81.799 | 1 |
| 1.500 | Δ | 59.299 | 61.572 | 2 |
| 2.500 | Δ | 98.832 | 102.026 | 1 |
| 1.875 | Δ | 74.124 | 76.742 | 2 |
| 3.000 | Δ | 118.598 | 122.253 | 1 |
| 2.250 | Δ | 88.949 | 91.912 | 2 |
| 3.500 | Δ | - | 125.000 | 1 |
| 2.625 | Δ | 103.774 | 107.083 | 2 |

**Table A.3 Reversed cyclic CUREE test protocol for bearing walls with two layers of gypsum**

| Cycle Displacements | | Target Displacement (mm) | Actuator input (mm) | Number of Cycles |
|---|---|---|---|---|
| 0.050 | Δ | 1.462 | 2.428 | 6 |
| 0.075 | Δ | 2.192 | 3.173 | 1 |
| 0.056 | Δ | 1.644 | 2.614 | 6 |
| 0.100 | Δ | 2.923 | 3.919 | 1 |
| 0.075 | Δ | 2.192 | 3.173 | 6 |
| 0.200 | Δ | 5.846 | 6.900 | 1 |
| 0.150 | Δ | 4.385 | 5.409 | 3 |
| 0.300 | Δ | 8.770 | 9.881 | 1 |
| 0.225 | Δ | 6.577 | 7.645 | 3 |
| 0.400 | Δ | 11.693 | 12.862 | 1 |
| 0.300 | Δ | 8.770 | 9.881 | 2 |
| 0.700 | Δ | 20.462 | 21.805 | 1 |
| 0.525 | Δ | 15.347 | 16.588 | 2 |
| 1.000 | Δ | 29.232 | 30.748 | 1 |
| 0.750 | Δ | 21.924 | 23.296 | 2 |
| 1.500 | Δ | 43.848 | 45.654 | 1 |
| 1.125 | Δ | 32.886 | 34.475 | 2 |
| 2.000 | Δ | 58.464 | 60.559 | 1 |
| 1.500 | Δ | 43.848 | 45.654 | 2 |
| 2.500 | Δ | 73.080 | 75.465 | 1 |
| 1.875 | Δ | 54.810 | 56.833 | 2 |
| 3.000 | Δ | 87.696 | 90.370 | 1 |
| 2.250 | Δ | 65.772 | 68.012 | 2 |
| 3.500 | Δ | 102.312 | 105.276 | 1 |
| 2.625 | Δ | 76.734 | 79.191 | 2 |
| 4.000 | Δ | 116.928 | 120.181 | 1 |
| 3.000 | Δ | 87.696 | 90.370 | 2 |
| 4.500 | Δ | - | 125.000 | 1 |
| 3.375 | Δ | 98.658 | 101.549 | 2 |

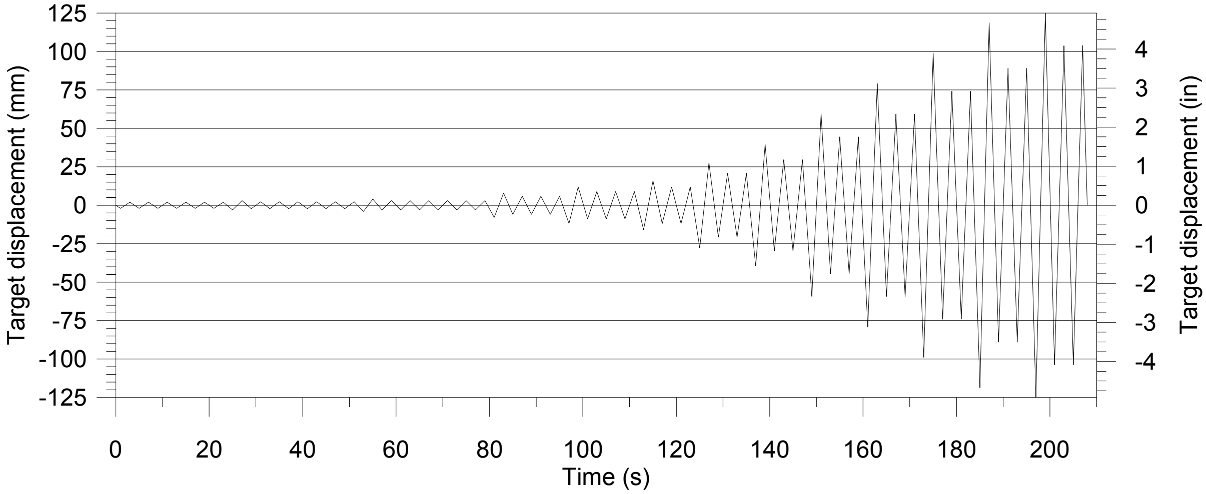



**Figure A-2 CUREE displacement time history for bearing walls with one layer of gypsum**

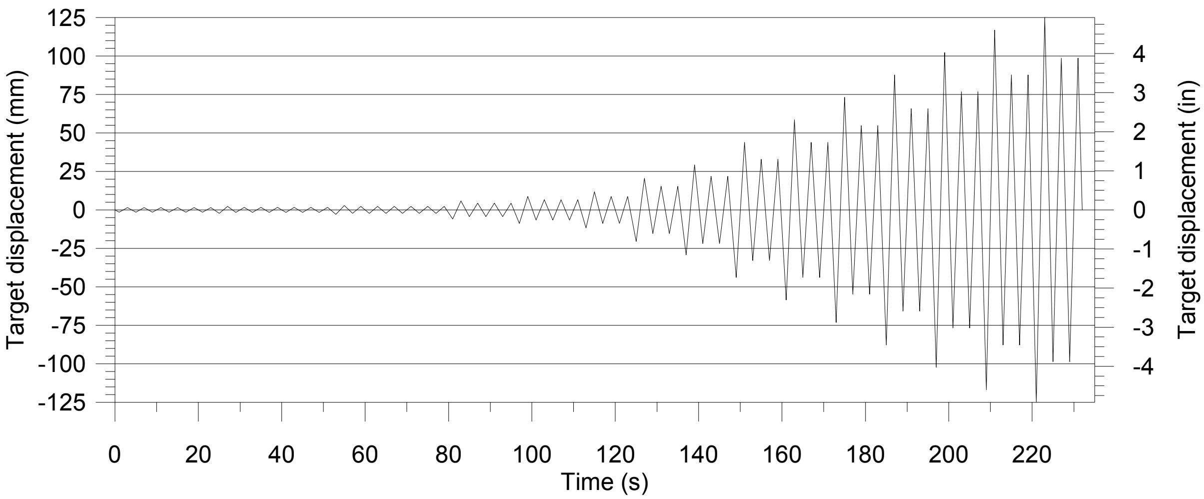



**Figure A-3 CUREE displacement time history for bearing walls with two layers of gypsum**

# Appendix B. Test data sheets and observed behaviour

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 65 A-M

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 10, 2014  **TIME:** 10:45 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [x] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | | 32mm type S drywall screw |
| Top layer | | 50mm type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic  5mm/min
- [ ] Cyclic  CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | x | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,7 | 72,8 | 72,2 | 72,5 |
| 72,0 | 72,1 | 72,0 | 71,5 |
| 71,7 | 71,4 | 72,4 | 72,0 |
| AVG 72,1 mm | AVG 72,1 mm | AVG 72,2 mm | AVG 72,0 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | NA | NA |
| Wd= | NA | NA | NA | NA |
| m.c.= | NA | NA | NA | NA |

AVG m.c. #DIV/0!

**DATA ACQ. RECORD RATE:** 2 scan/sec  **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

| | |
|---|---|
| Test name: | 65 A-M |
| Date tested: | June 10th, 2014 |
| # of gypsum layers per side: | ∅ |
| # of sheathed sides: | ∅ |
| Resilient channel: | ☐ yes ☑ no |
| Test mode: | ☑ monotonic ☐ cyclic |

## Observations of the steel frame

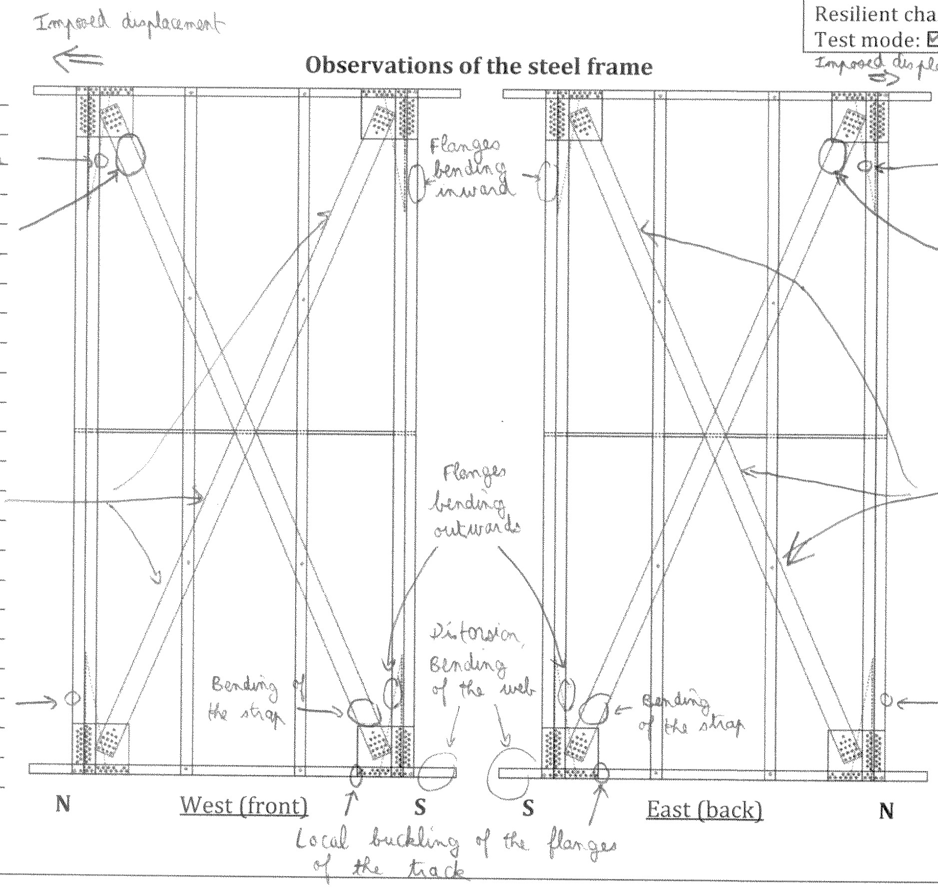
West side notes:

Local buckling of the lips

Bending of the strap

Buckling of the ~~comp~~ strap in compression

Local buckling of the lips




East side notes:

Local buckling of the lip

Bending of the strap

Buckling of the strap in compression

Local buckling of the lip

General notes:

Flexure of the 2 chord studs

Straps (in tension) have yielded

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 66 A-M

**RESEARCHER:** Sophie LU

**ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 10, 2014

**TIME:** 5:15 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| | | | |
| | | | |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NM | NM | NM | NM |
| Wd= | | | | |
| m.c.= | NM | NM | NM | NM |

AVG m.c. NM

**DATA ACQ. RECORD RATE:** 2 scan/sec

**MONITOR RATE:** 10 scan/sec

**COMMENTS:** Gypsum West side: paper ripped at points I1, K1, C4a

McGill

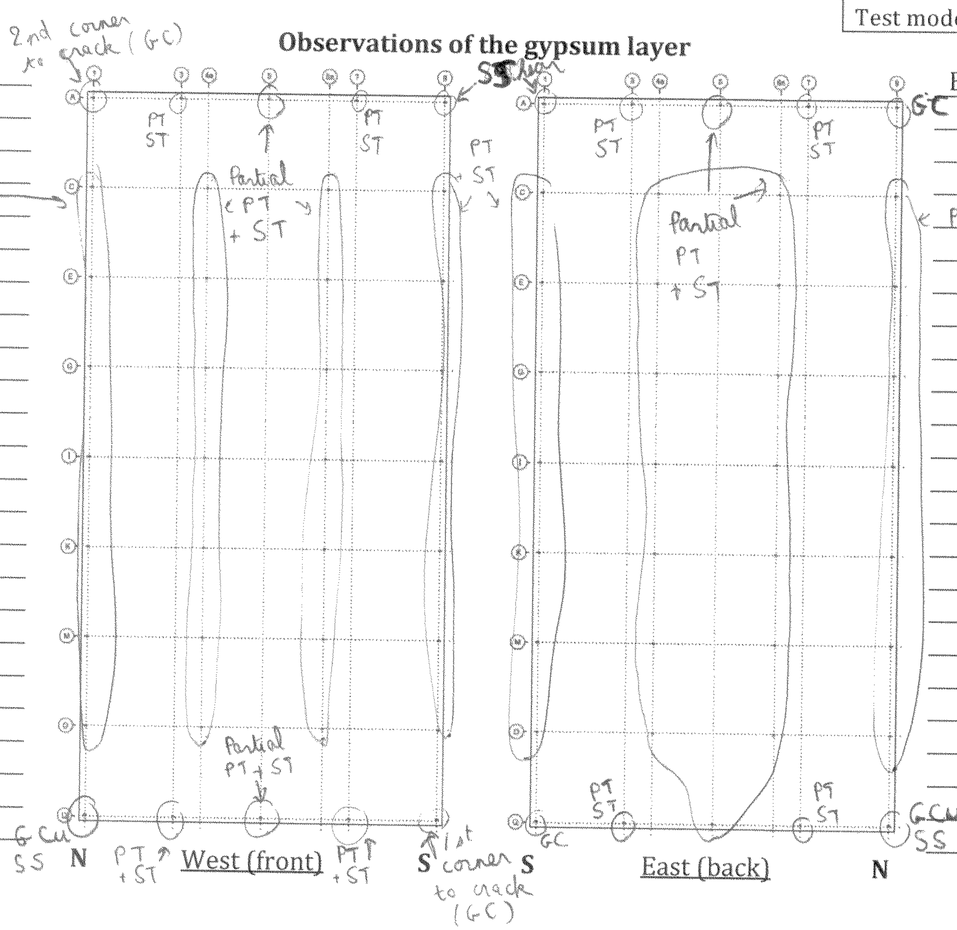
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

| | |
|---|---|
| Test name: | 66 A-M |
| Date tested: | June 10th 2014 |
| # of gypsum layers per side: | 1 |
| # of sheathed sides: | 2 |
| Resilient channel: | ☐ yes ☒ no |
| Test mode: | ☒ monotonic ☐ cyclic |

**Observations of the gypsum layer**

West side notes:

PT + ST




East side notes:

PT + ST

General notes:

McGill

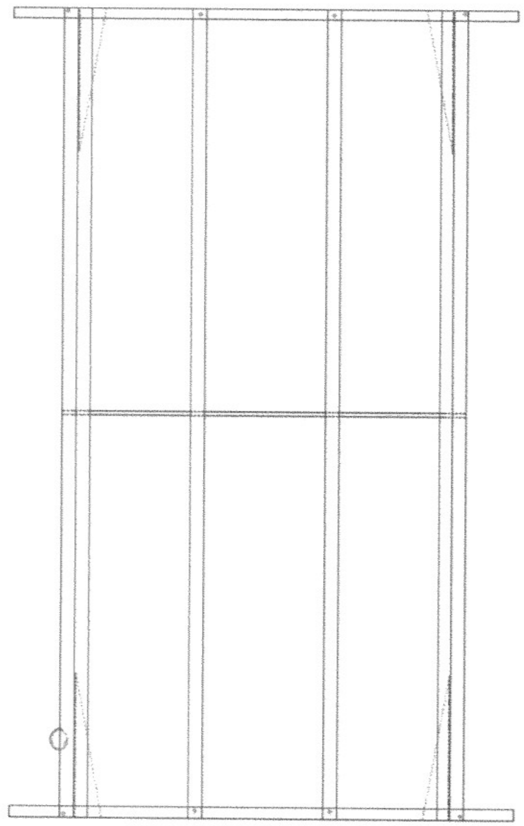
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 66 A-M
Date tested: June 10th, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

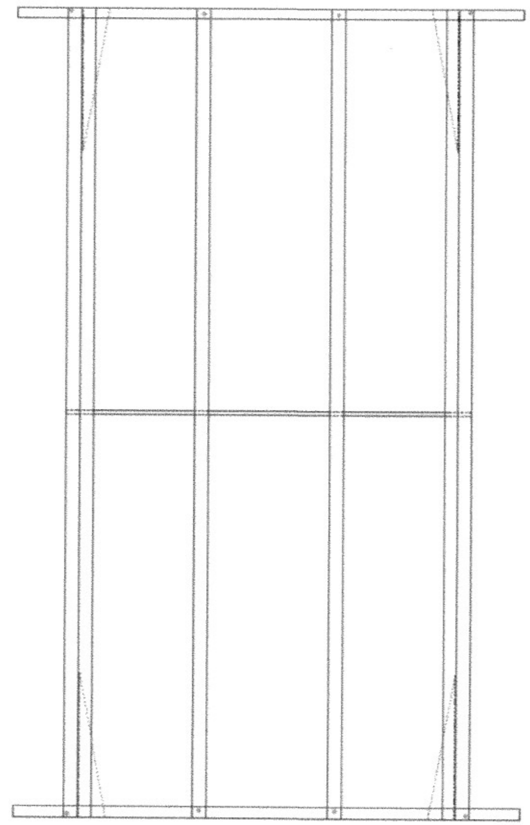
## Observations of the steel frame

West side notes:

Lip local buckling



N West (front) S



S East (back) N

East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 66 B-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 11, 2014 **TIME:** 4:50 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NM | NM | NM | NM |
| Wd= | | | | |
| m.c.= | NM | NM | NM | NM |

AVG m.c. NM

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**
Screws at bottom corners on west side: holes next to the Screws
C4a: paper ripped

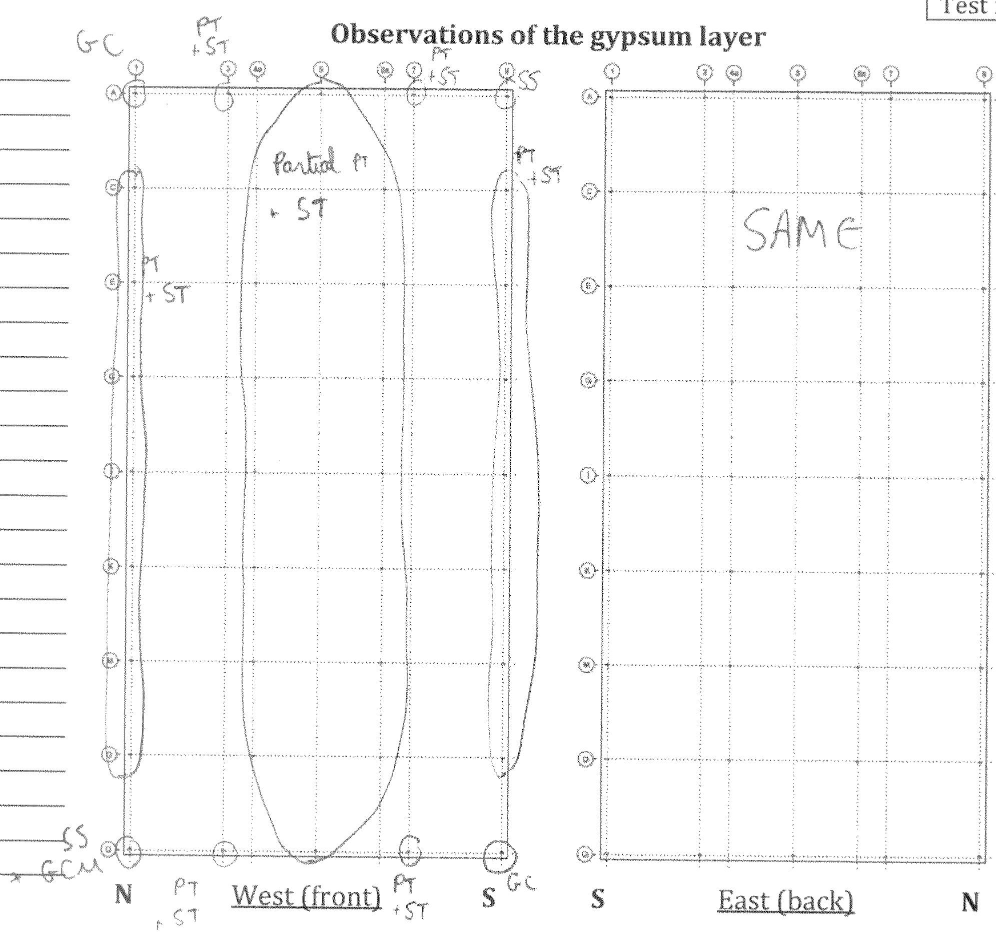
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 66 B-M
Date tested: June 11, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

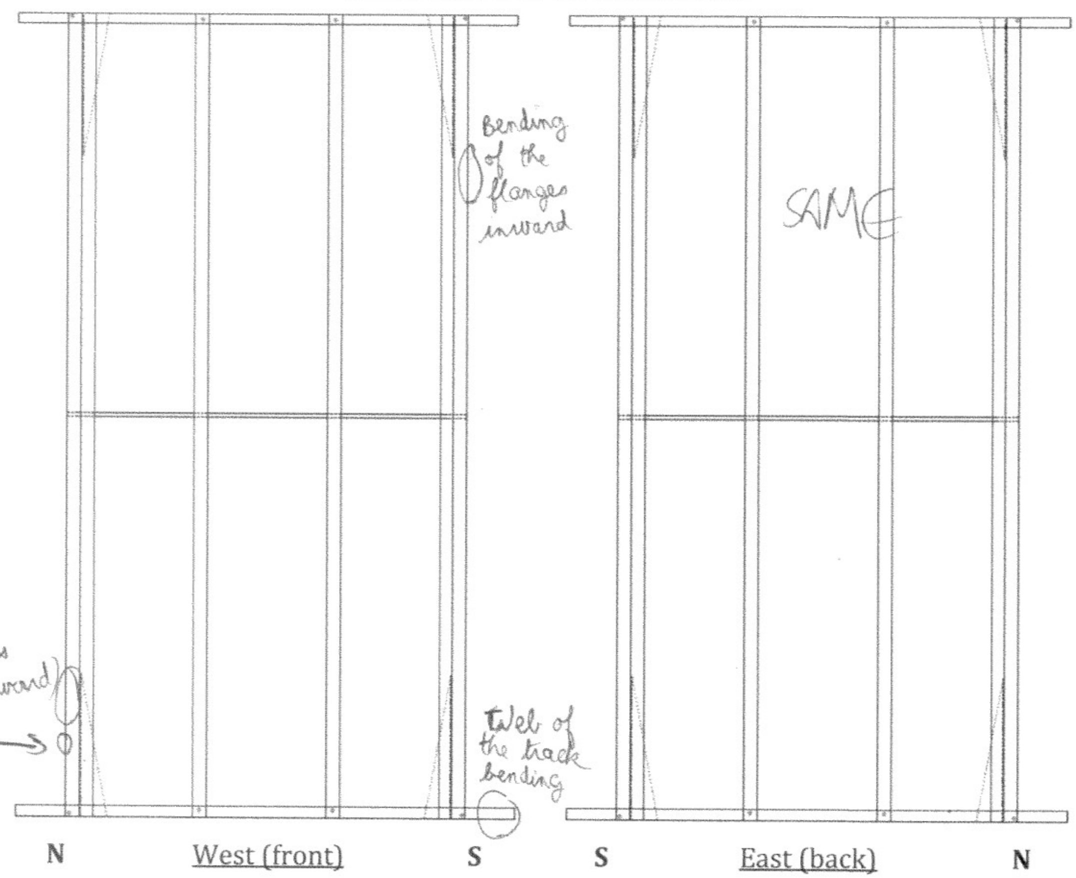
| | |
|---|---|
| Test name: | 66 B-M |
| Date tested: | June 11, 2014 |
| # of gypsum layers per side: | 1 |
| # of sheathed sides: | 2 |
| Resilient channel: | ☐ yes ☑ no |
| Test mode: | ☑ monotonic ☐ cyclic |

**Observations of the steel frame**

West side notes:

Distorsion of the flanges (bending inward)

local buckling of the lip →




East side notes:

General notes: 2 chord studs bending

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 67 A-C

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 17, 2014 **TIME:** 9:25 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic — 5mm/min
- [x] Cyclic — CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 79,67 | NA | 80,51 |
| Wd= | | 66,58 | | 66,2 |
| m.c.= | NA | 19,66 | NA | 21,62 |

AVG m.c. 20,64

**DATA ACQ. RECORD RATE:** 100 scan/sec **MONITOR RATE:** 200 scan/sec

**COMMENTS:** Gypsum on East side: at C9, the drywall screw pulled trhough during installation

McGill

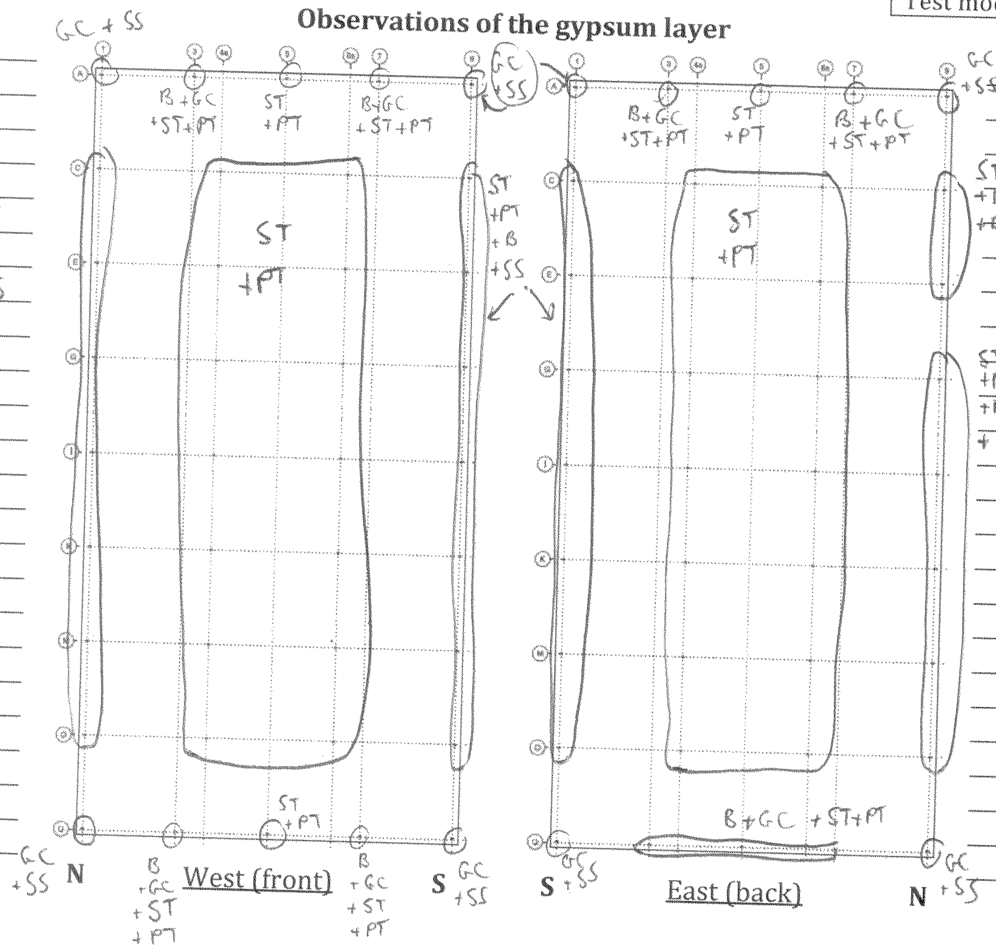
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 67 A-C
Date tested: July 17, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the gypsum layer

West side notes:

ST
+PT
+B
+SS




East side notes:

ST
+PT
+B

ST
+PT
+B
+SS

General notes:

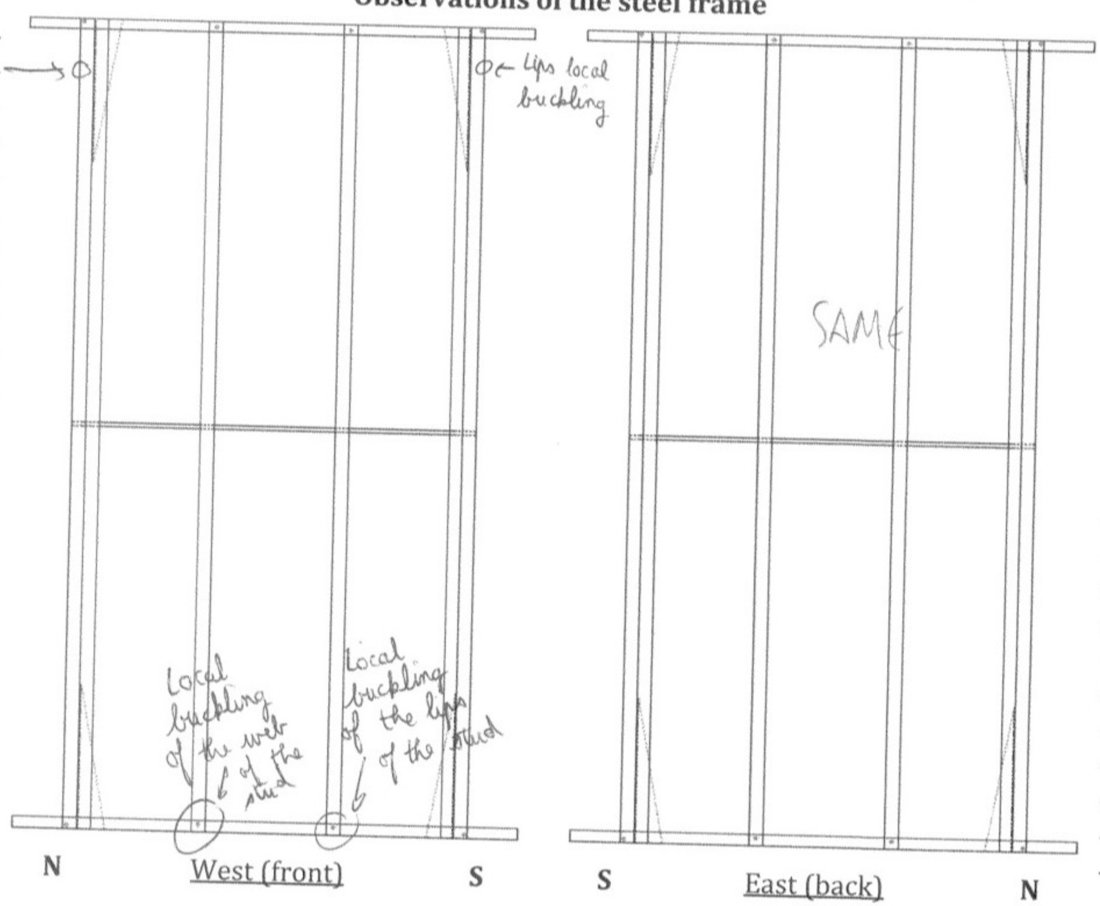
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 67 A-C
Date tested: July 17, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:
Lips local buckling




East side notes:

General notes: Bending of the chord studs

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 67 B-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 17, 2014  **TIME:** 3:15 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 80,11 | NA | 78,98 |
| Wd= | | 65,89 | | 65,14 |
| m.c.= | NA | 21,58 | NA | 21,25 |

AVG m.c. 21,41

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:** East C9: screw pulled through during installation

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 67 B-C
Date tested: July 17, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the gypsum layer

West side notes:

GC +SS

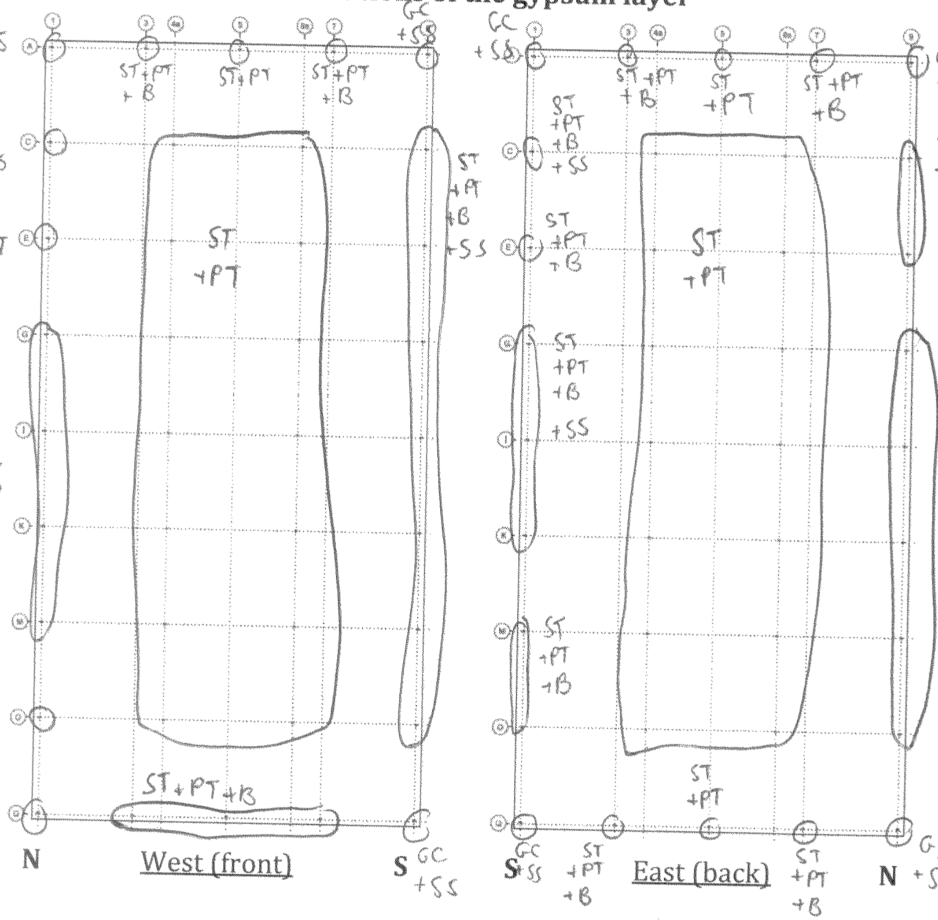
ST +PT +B +SS

ST +PT +B

ST +PT +B +SS

ST +PT +B

GC +SS




East side notes:

GC +SS

ST +PT +B

ST +PT +B +SS

GC +SS

General notes:

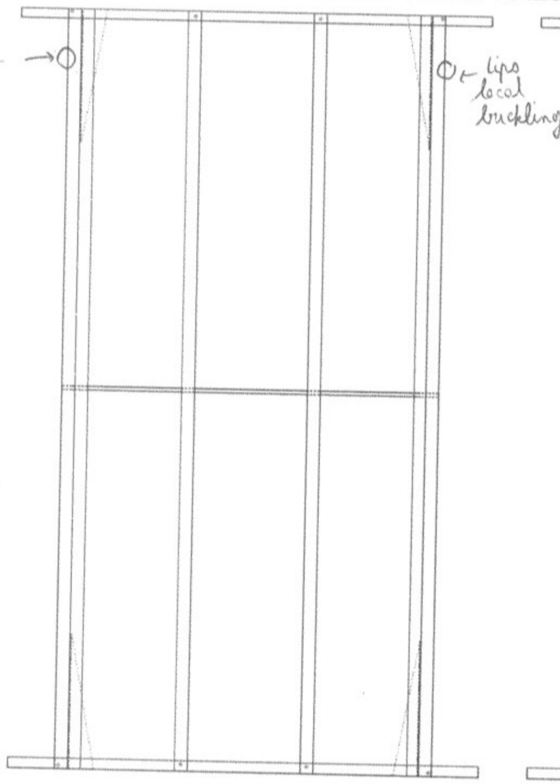
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

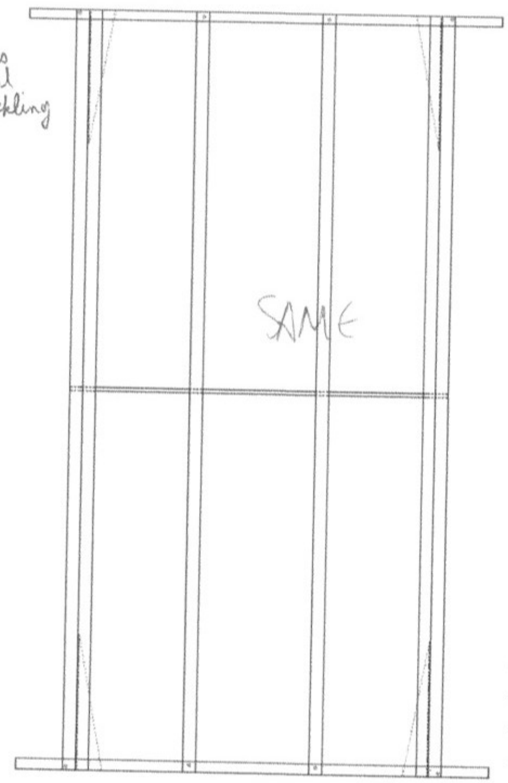
Test name: 67 B-C
Date tested: July 17, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:
lips local buckling




N West (front) S




S East (back) N

East side notes:

General notes: Bending of the chord studs

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 68 A-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 16, 2014 **TIME:** 1:52 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 82.92 | 83.61 | 82.95 | 83.43 |
| Wd= | 68.39 | 68.93 | 68.03 | 68.55 |
| m.c.= | 21,246 | 21,3 | 21,93 | 21,71 |

AVG m.c. 21,55 %

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

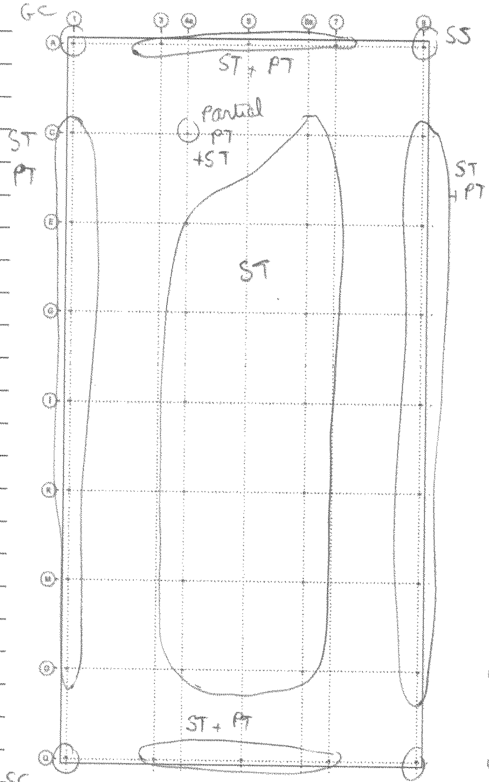
McGill

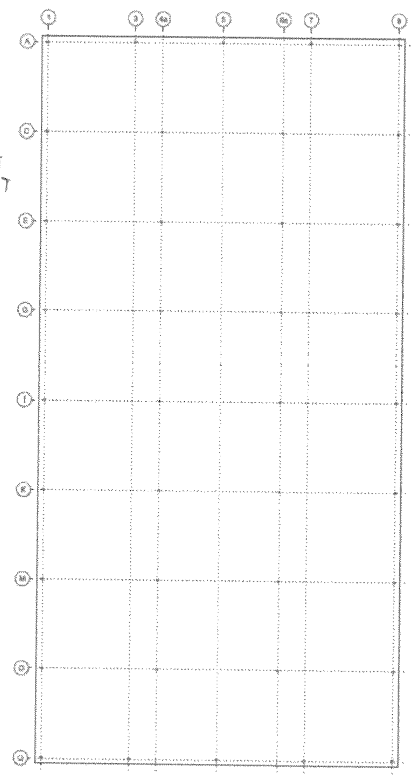
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 68 A-M
Date tested: June 16, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer

West side notes:




East side notes:

General notes:

McGill

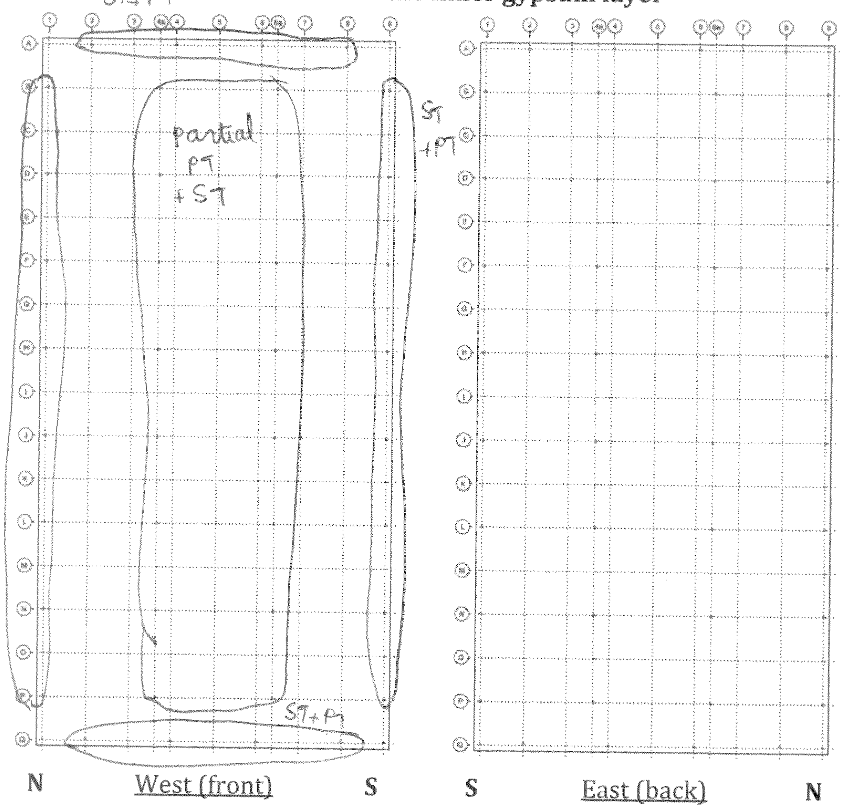
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 68 A-M
Date tested: June 16, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer

West side notes:

ST +PT




East side notes:

General notes: Screws in inner layer gypsum

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

| | |
|---|---|
| Test name: | 68 A-M |
| Date tested: | June 16, 2014 |
| # of gypsum layers per side: | 2 |
| # of sheathed sides: | 2 |
| Resilient channel: | ☐ yes ☑ no |
| Test mode: | ☑ monotonic ☐ cyclic |

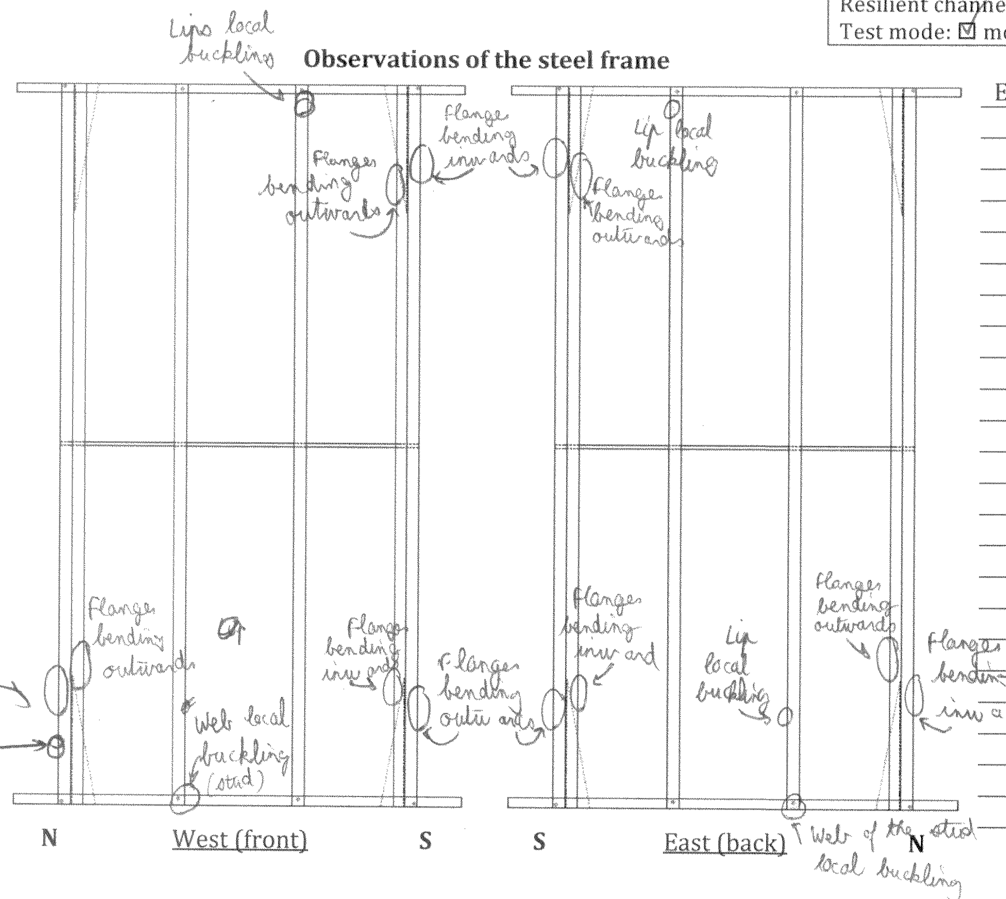
## Observations of the steel frame

West side notes:

Flanges bending inward

Lip local buckling

wall here plate for LVDT's was screwed




East side notes:

General notes:

**Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls**
**McGill University, Montreal**

**TEST:** 68 B-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 12, 2014 **TIME:** 4:50 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NM | NM | NM | NM |
| Wd= | | | | |
| m.c.= | NM | NM | NM | NM |

AVG m.c. NM

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

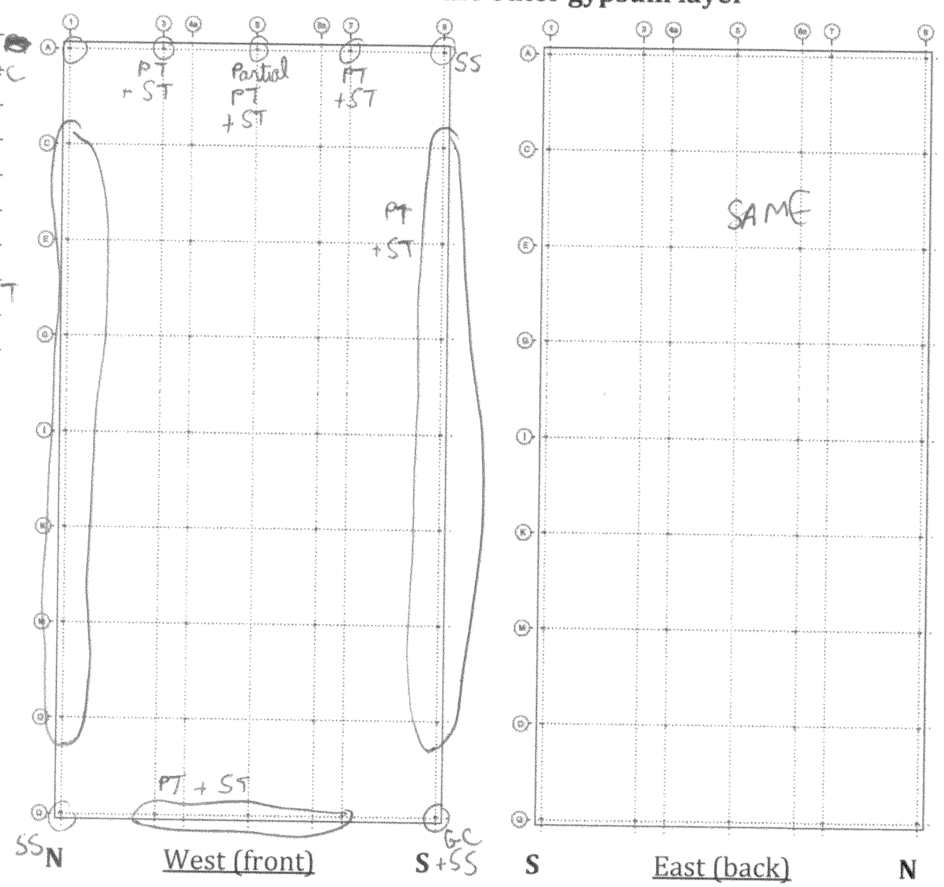
Test name: 68 B-M
Date tested: June 12, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer

West side notes:

GC

PT
+ST




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

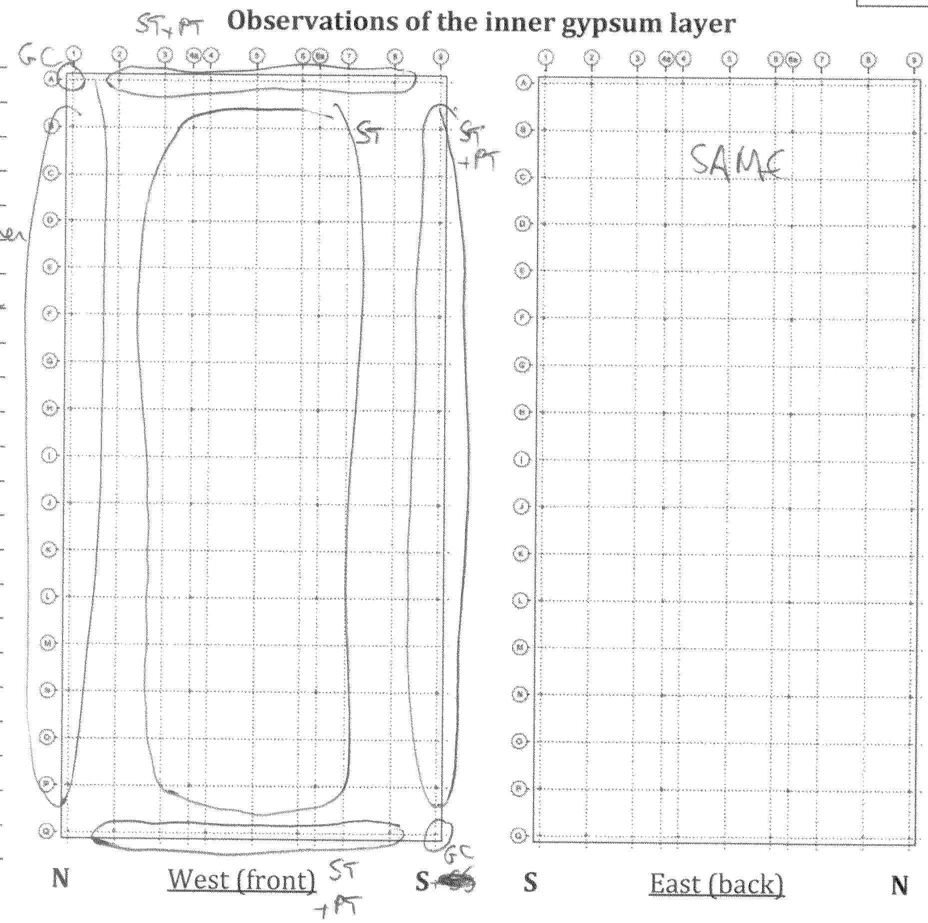
Test name: 68 B-M
Date tested: June 12 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer

West side notes:

ST +PT

- pull through of the inner layer screws
- no pull through of the outer layer screws




East side notes:

General notes:

McGill

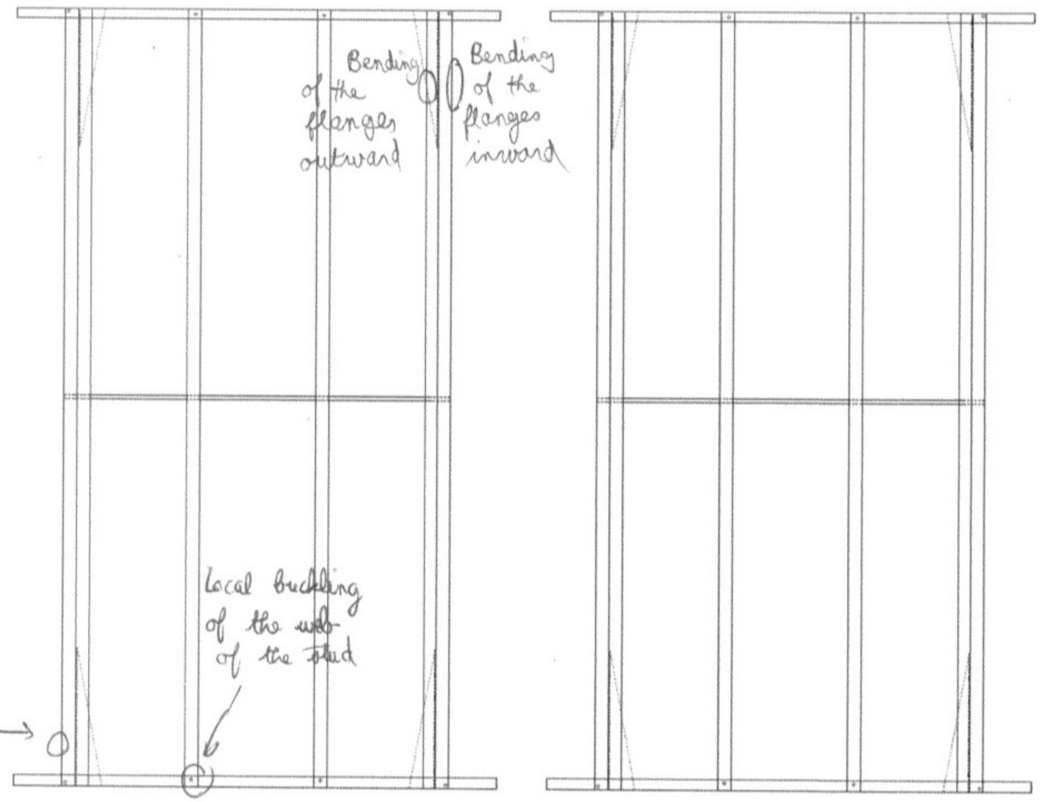
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 68 B-M
Date tested: June 12, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:

Lip local buckling where plate for LVDT's was screwed




N West (front) S S East (back) N

East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 69 A-C

**RESEARCHER:** Sophie LU　　**ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 21, 2014　　**TIME:** 10:00 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson　　number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic　　5mm/min
- [x] Cyclic　　CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 80,17 | 81,31 | 79,44 | 79,8 |
| Wd= | 65,92 | 66,78 | 65,61 | 65,59 |
| m.c.= | 21,617 | 21,76 | 21,08 | 21,66 |

AVG m.c. 21,53 %

**DATA ACQ. RECORD RATE:** 100 scan/sec　　**MONITOR RATE:** 200 scan/sec

**COMMENTS:** Gypsum on east side: at K9 (outer layer), paper around the srew damaged

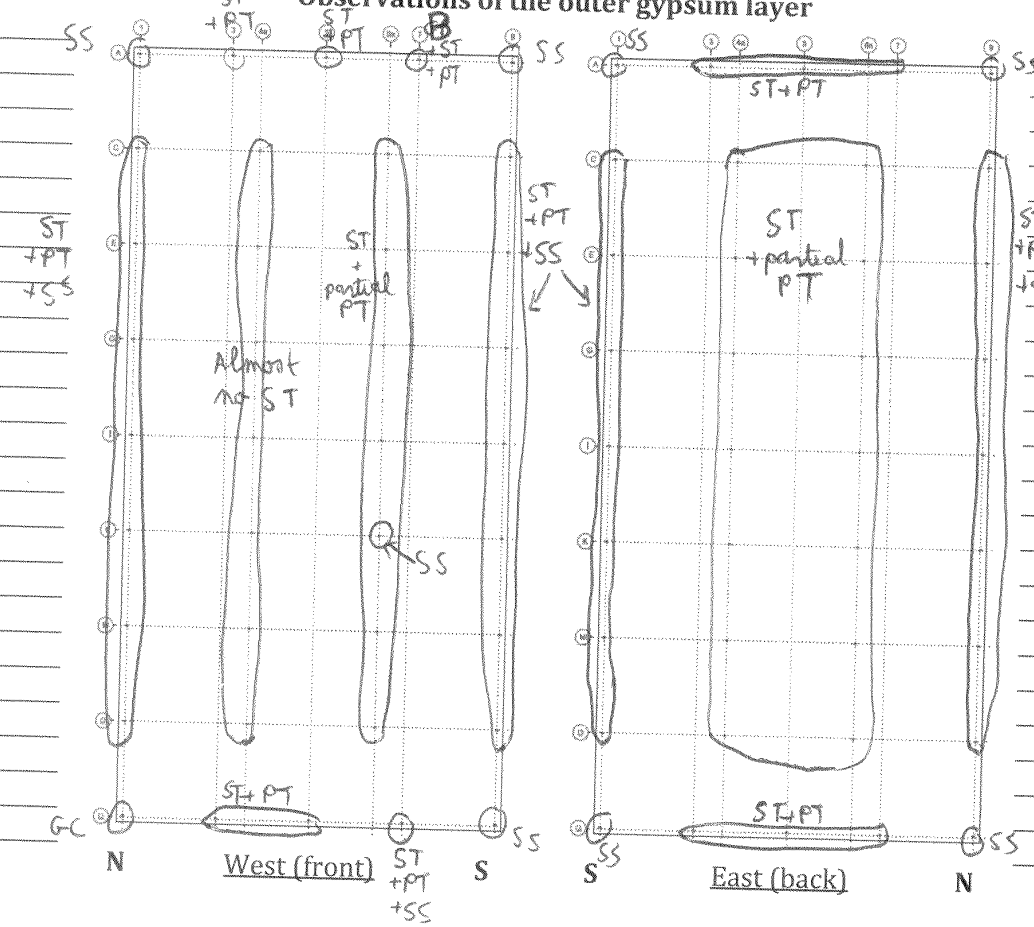
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 6J A-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

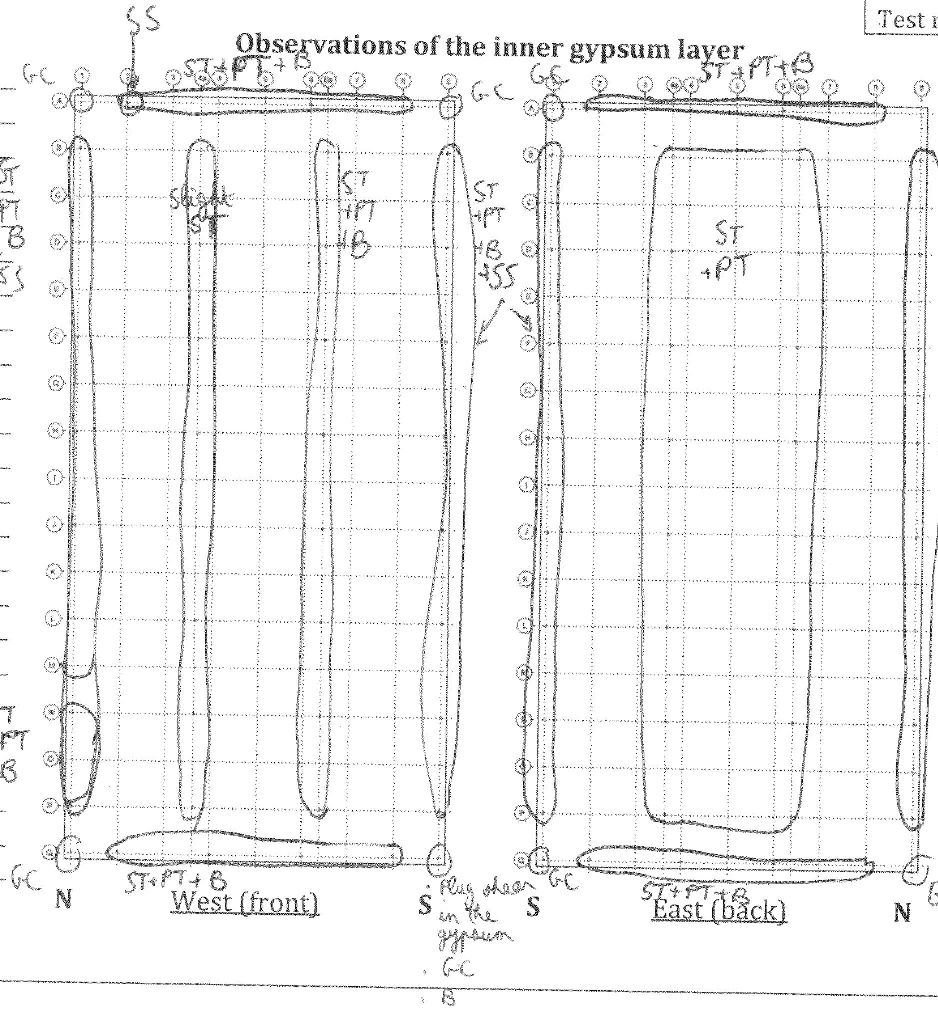
Test name: 69 A-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer

West side notes:

ST +PT +B +SS

ST +PT +B




East side notes:

ST +PT +B +SS

General notes:

McGill

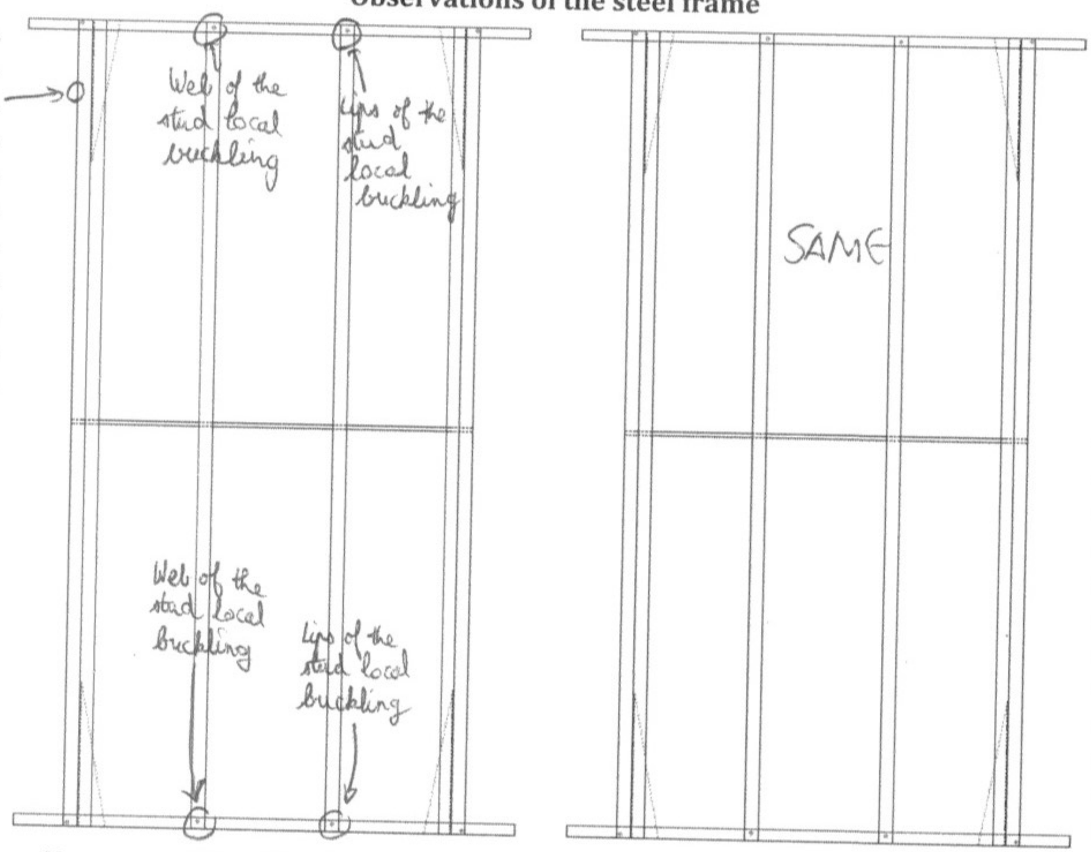
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 69 A-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:

lips local buckling




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 69 B-C

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 29, 2014 **TIME:** 10:25 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic — 5mm/min
- [x] Cyclic — CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | NA | NA | NA | NA |
| | NA | NA | NA | NA |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 78,44 | 81,32 | 81,16 | 79,55 |
| Wd= | 64,71 | 66,82 | 66,8 | 65,58 |
| m.c.= | 21,218 | 21,7 | 21,50 | 21,3 |

AVG m.c. 21,43 %

**DATA ACQ. RECORD RATE:** 100 scan/sec **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

McGill

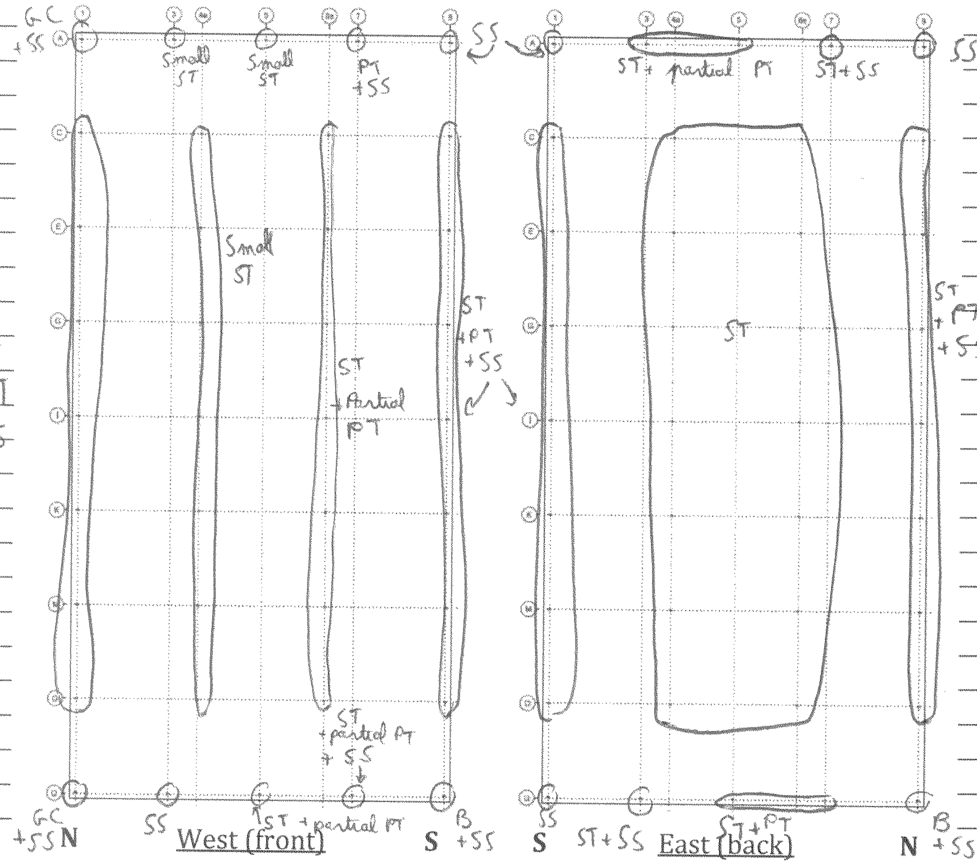
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 69 B-C
Date tested: July 29, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer

West side notes:

ST
+PT
+SS




East side notes:

General notes:

# McGill

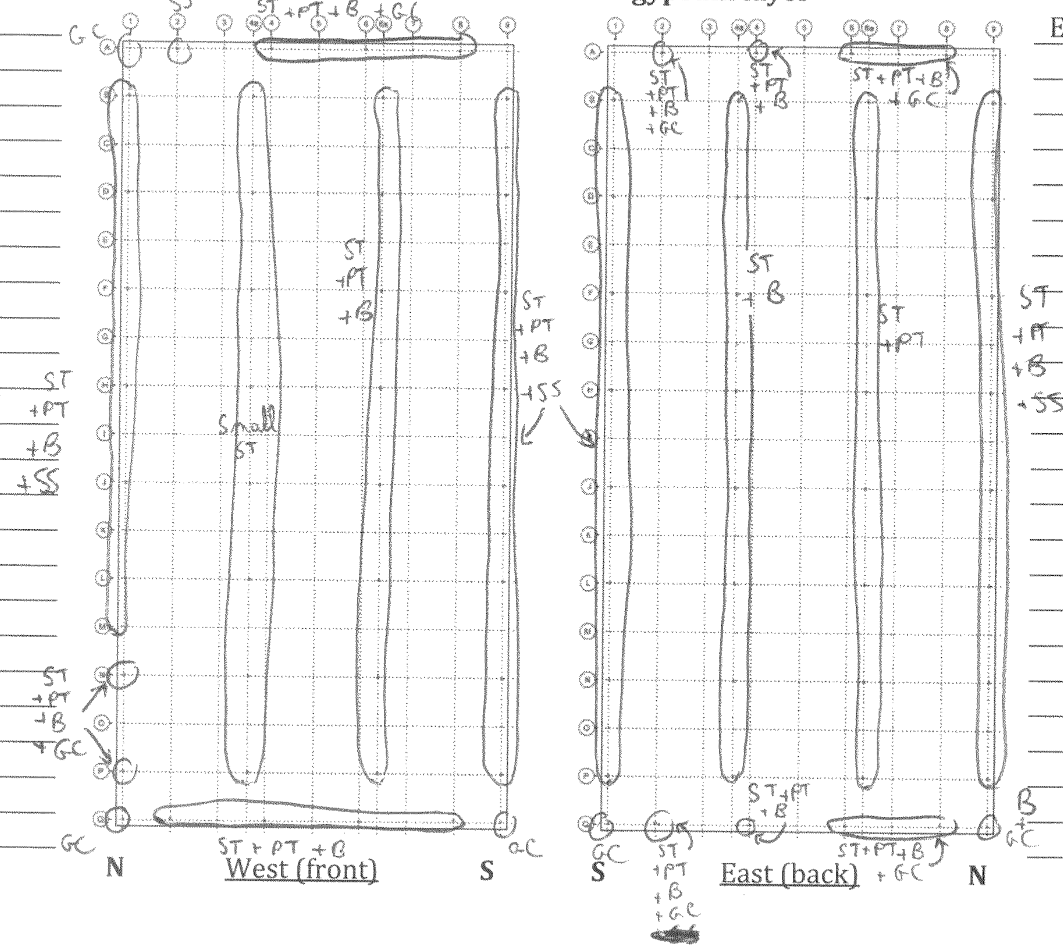
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: C9 B-C
Date tested: July 29, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer

West side notes:

East side notes:




General notes:

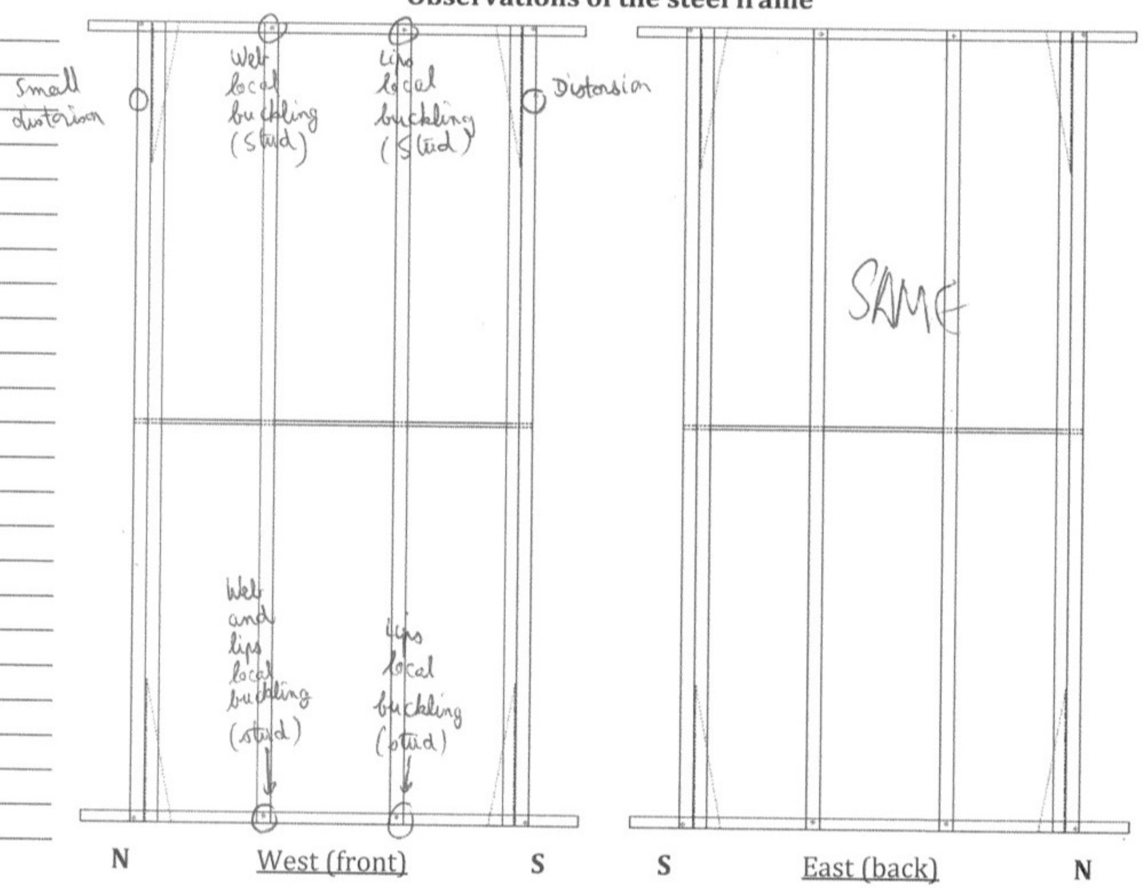
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 69 B-C
Date tested: July 29, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:




East side notes:

General notes:

Bending of the chord studs

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 70 A-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 13, 2014 **TIME:** 4:10 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Loose |
| West | Tight | Loose |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,7 | 71,1 | 71,3 | 70,8 |
| | 72,1 | | 72,5 |
| 68,5 | 73,1 | 72,5 | 72,3 |
| AVG 70,6 mm | AVG 72,1 mm | AVG 71,9 mm | AVG 71,9 mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 83.17 | NA | 83.55 |
| Wd= | NA | 68.55 | NA | 68.76 |
| m.c.= | NA | 21,33 | NA | 21,51 |

AVG m.c. 21,42

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**
Wall not perfectly square
Strap widths taken after the test: on the 2 gusset plates at each end of the strap for the straps in tension (no deformation)
and on the ends and the middle of the strap for the straps in compression

McGill

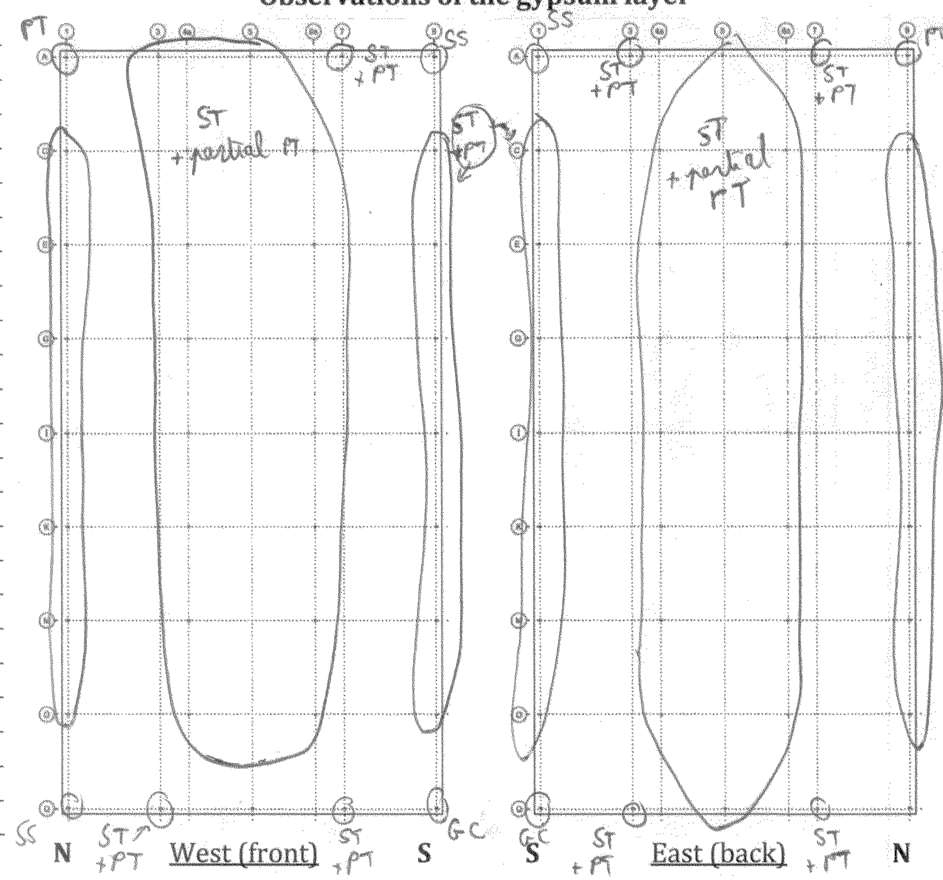
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 70 A-M
Date tested: June 13, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:

ST +PT




East side notes:

ST +PT

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 70 A-M
Date tested: June 13, 2014
\# of gypsum layers per side: 1
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

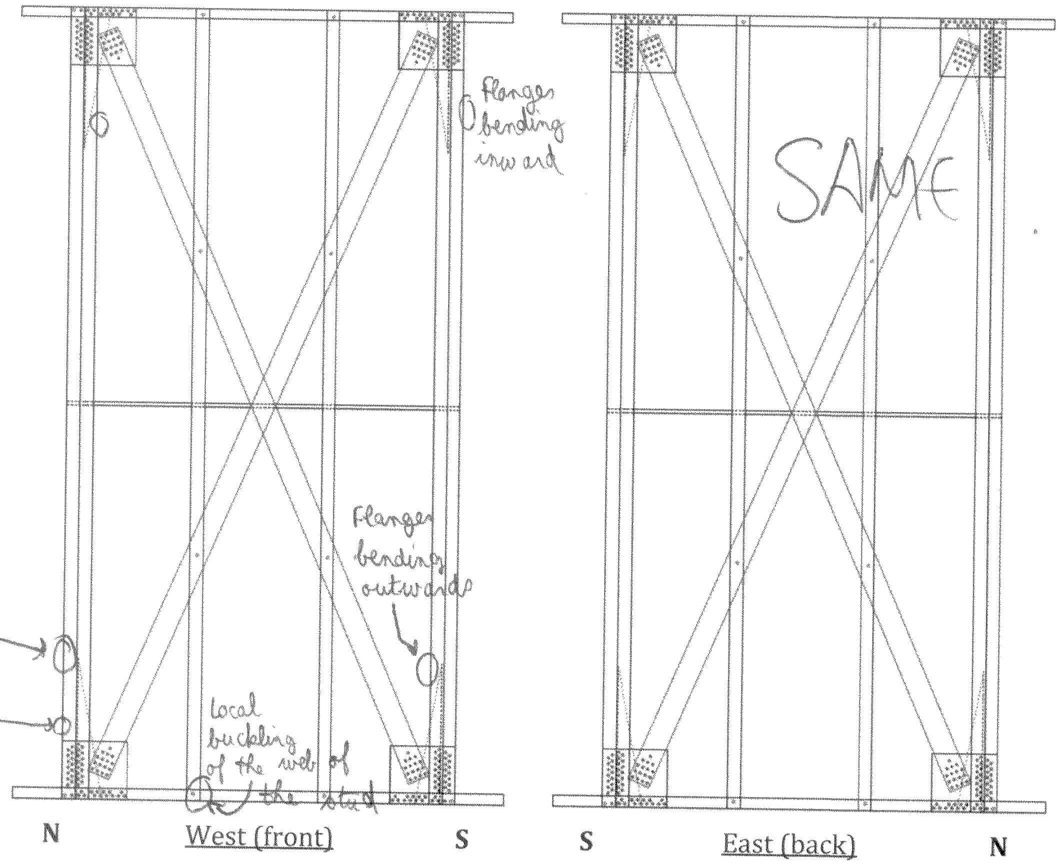
**Observations of the steel frame**

West side notes:

Lip and flange local buckling

Local buckling of the flange (bending inwards)

Local buckling of the lip




East side notes:

General notes: Straps in tension have yielded

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 70 B-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 20, 2014 **TIME:** 4:05 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | x | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,2 | 69,2 | 72,2 | 70,8 |
| 71,9 | 71,2 | 71,5 | 71,8 |
| 72,5 | 73,6 | 72,0 | 71,6 |
| AVG 71,9 mm | AVG 71,3 mm | AVG 71,9 mm | AVG 71,4 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 83,35 | NA | 82,74 |
| Wd= | NA | 68,51 | NA | 68,03 |
| m.c.= | NA | 21,66 | NA | 21,62 |

AVG m.c. 21,64

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:** Wall a little bit twisted

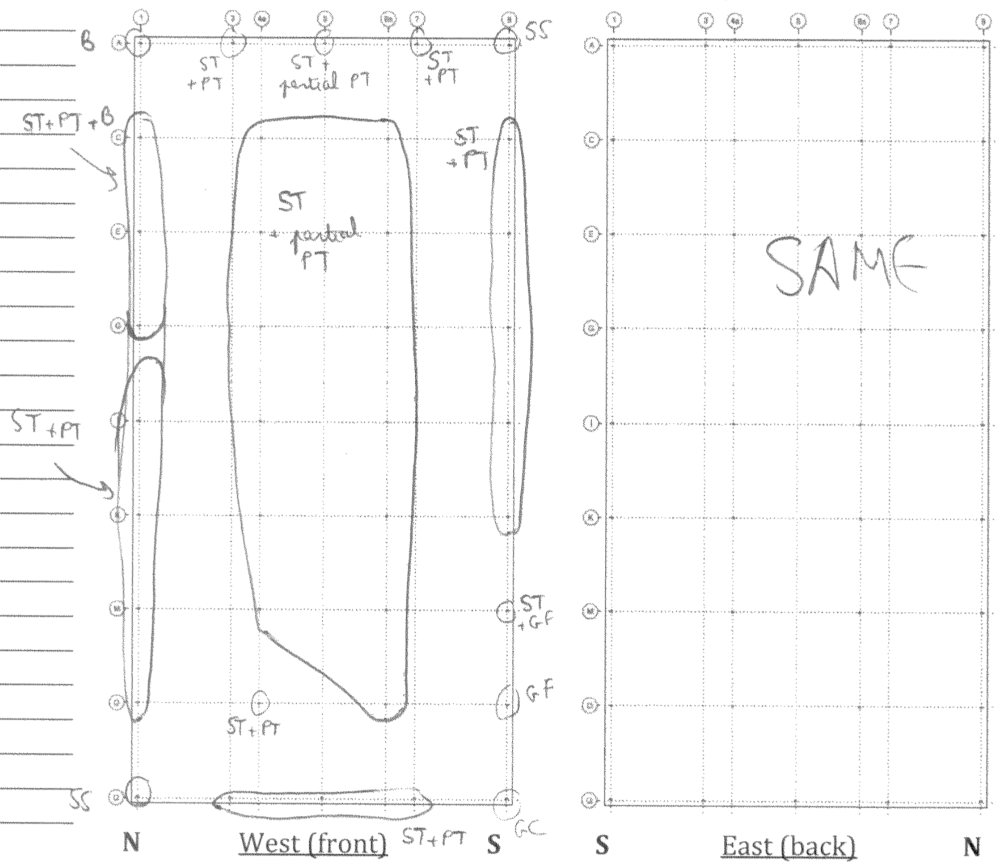
**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 20 B-M
Date tested: June 20, 2014
\# of gypsum layers per side: 1
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 70 B-M
Date tested: June 20, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

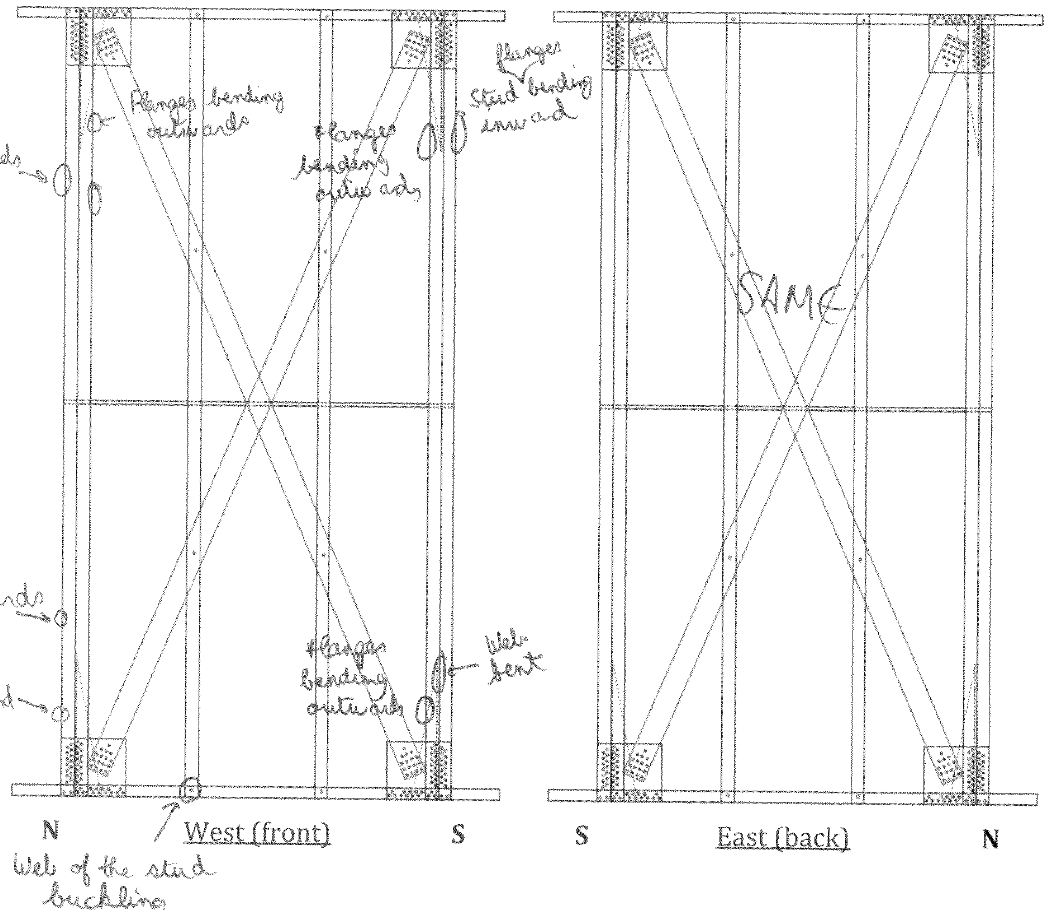
## Observations of the steel frame

West side notes:

Flanges bending outwards

Flanges bending outwards

Flanges bending inward




East side notes:

General notes:

- Straps in tension have yielded

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 71 A-C

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built June 2014; Tested July 9, 2014 **TIME:** 11:23 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**
- Sheathing: Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Sheathing: Top layer [ ] 48mm (1''-7/8) type S drywall screw
- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [x] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [x] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic 5mm/min
- [x] Cyclic CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [x] Bot north- Top south brace

Total: 9

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,2 | 72,8 | 72,8 | 68,8 |
| 71,5 | 72,1 | 71,4 | 71,6 |
| 72,7 | 71,8 | 72,0 | 72,5 |
| AVG 71,8 mm | AVG 72,2 mm | AVG 72,1 mm | AVG 71,0 mm |

71,9333333
71,6

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 80,16 | NA | 79,81 |
| Wd= | NA | 66,33 | NA | 65,72 |
| m.c.= | NA | 20,85 | NA | 21,44 |

AVG m.c. 21,14

**DATA ACQ. RECORD RATE:** 100 scan/sec **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

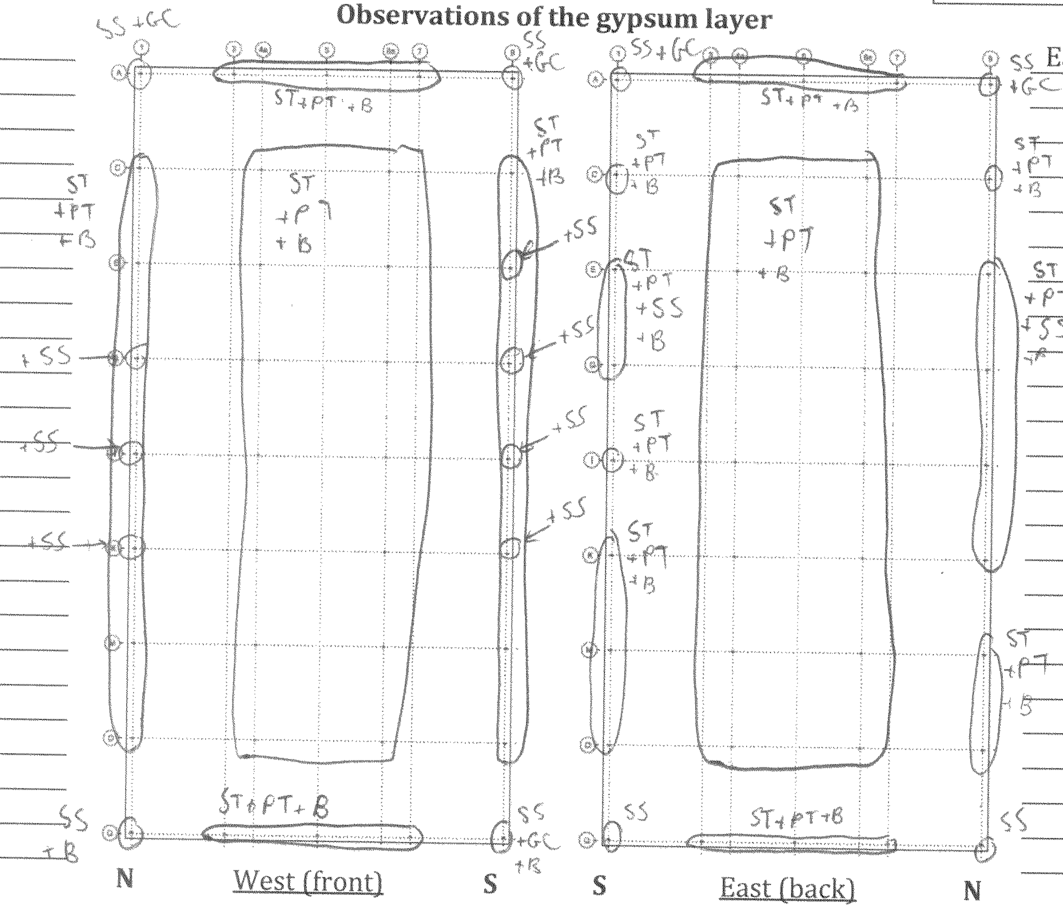
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 71 A-C
Date tested: July 9, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

McGill

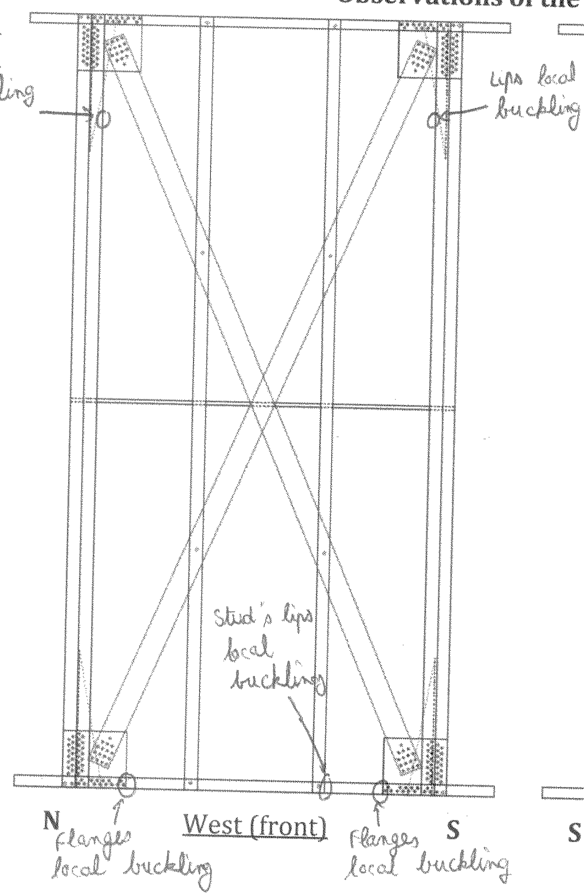
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

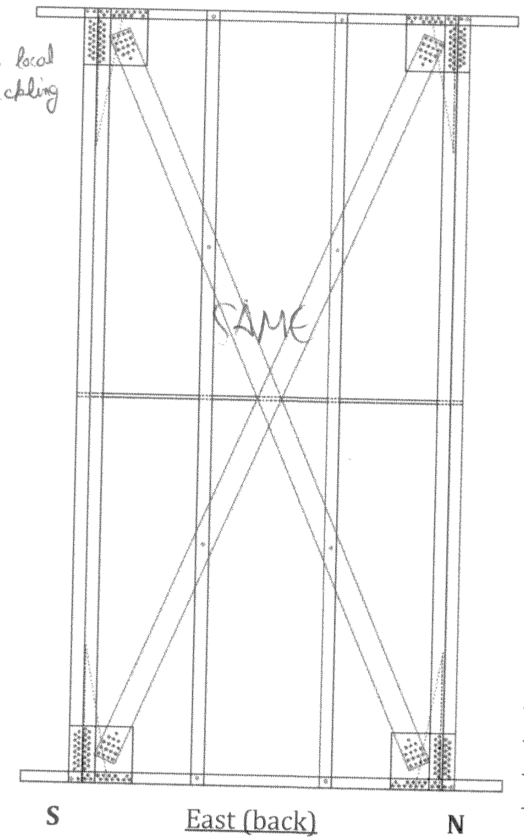
Test name: 71 A-C
Date tested: July 9, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Lips local buckling




East side notes:

General notes:

- Bending of the chord studs
- Straps yielding

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 71 B-C

**RESEARCHER:** Sophie LU

**ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built June 2014; Tested July 7, 2014

**TIME:** 3:00 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

Sheathing:
- Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [ ] 48mm (1''-7/8) type S drywall screw

- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [x] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [x] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic — 5mm/min
- [x] Cyclic — CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [x] Bot north- Top south brace

Total: 9

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,5 | 70,9 | 70,0 | 71,3 |
| 71,8 | 71,5 | 70,9 | 71,9 |
| 72,4 | 72,7 | 70,5 | 70,3 |
| AVG 71,9 mm | AVG 71,7 mm | AVG 70,5 mm | AVG 71,2 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 81,83 | NA | 79,54 |
| Wd= | NA | 67,24 | NA | 65,2 |
| m.c.= | NA | 21,7 | NA | 21,99 |

AVG m.c. 21,85

**DATA ACQ. RECORD RATE:** 100 scan/sec

**MONITOR RATE:** 200 scan/sec

**COMMENTS:** West A7, West C8, East C8: Gypsum cracked near the screw

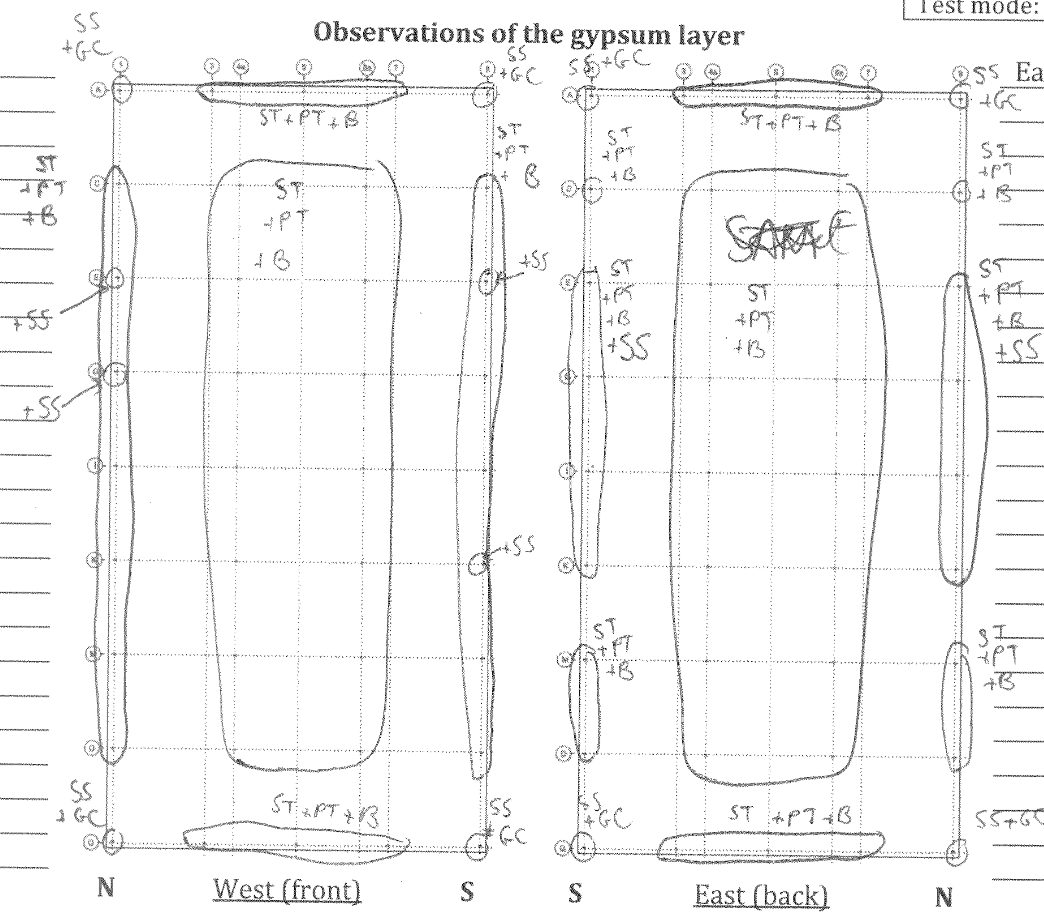
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 71 B-C
Date tested: July 7, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

McGill

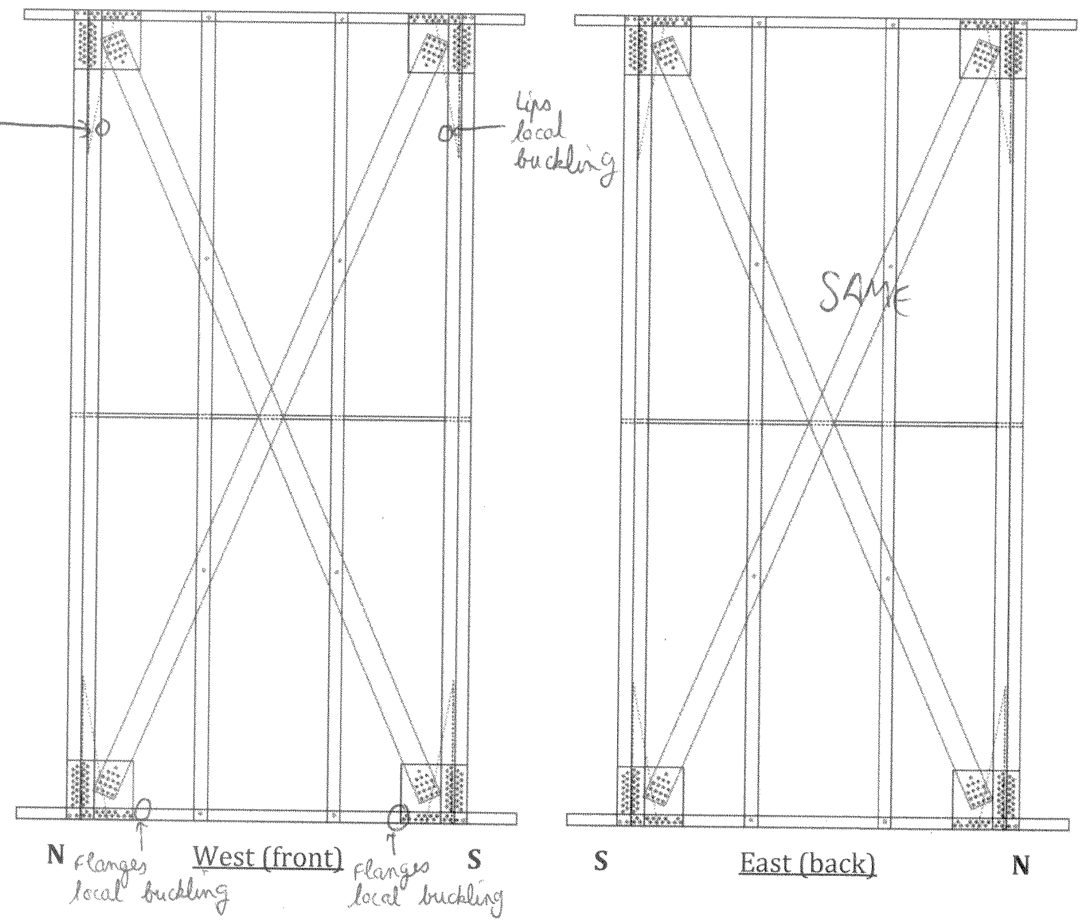
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 71 B-C
Date tested: July 7, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Lips local buckling




East side notes:

General notes:

- All the straps have yielded
- Bending of the chord studs

# Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 72 A-M

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 24, 2014  **TIME:** 4:43 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic  5mm/min
- [ ] Cyclic  CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | 71,2 | 74,3 | 71,6 | 69,1 |
| | 71,9 | 72,1 | 72,0 | 71,0 |
| | 72,5 | 69,8 | 72,5 | 72,5 |
| AVG | 71,9 mm | 72,1 mm | 72,0 mm | 70,9 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 79,93 | 81,38 | 79,53 | 81,3 |
| Wd= | 65,68 | 65,87 | 65,5 | 67,01 |
| m.c.= | 21,696 | 23,55 | 21,42 | 21,33 |

AVG m.c. 22,00 %

**DATA ACQ. RECORD RATE:** 2 scan/sec  **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

McGill

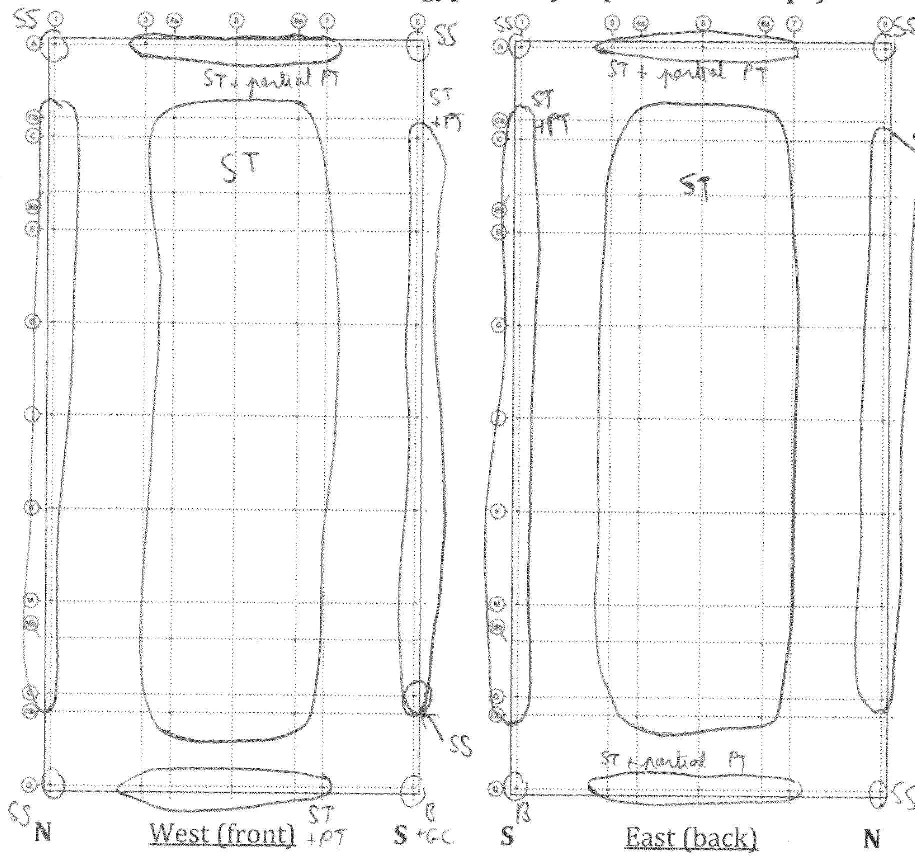
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 72 A-M
Date tested: June 24, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:

ST +PT




East side notes:

General notes:

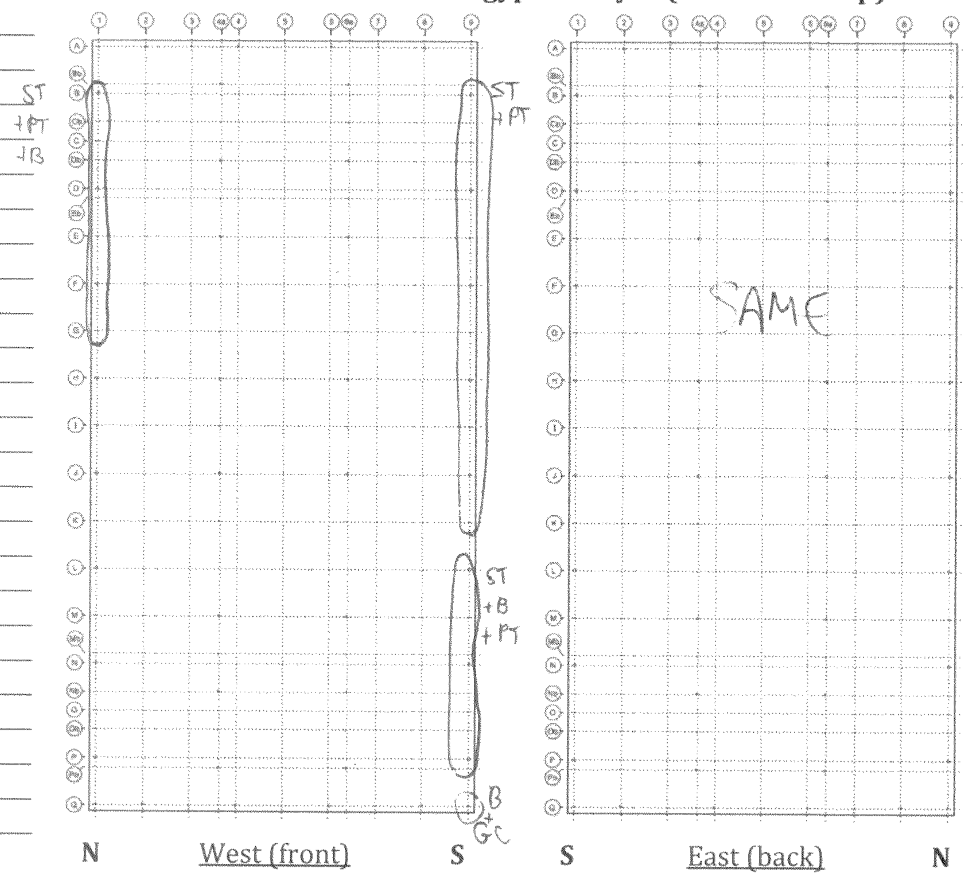
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 72 A-M
Date tested: June 24, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer (wall with strap)

West side notes:




East side notes:

General notes:

McGill

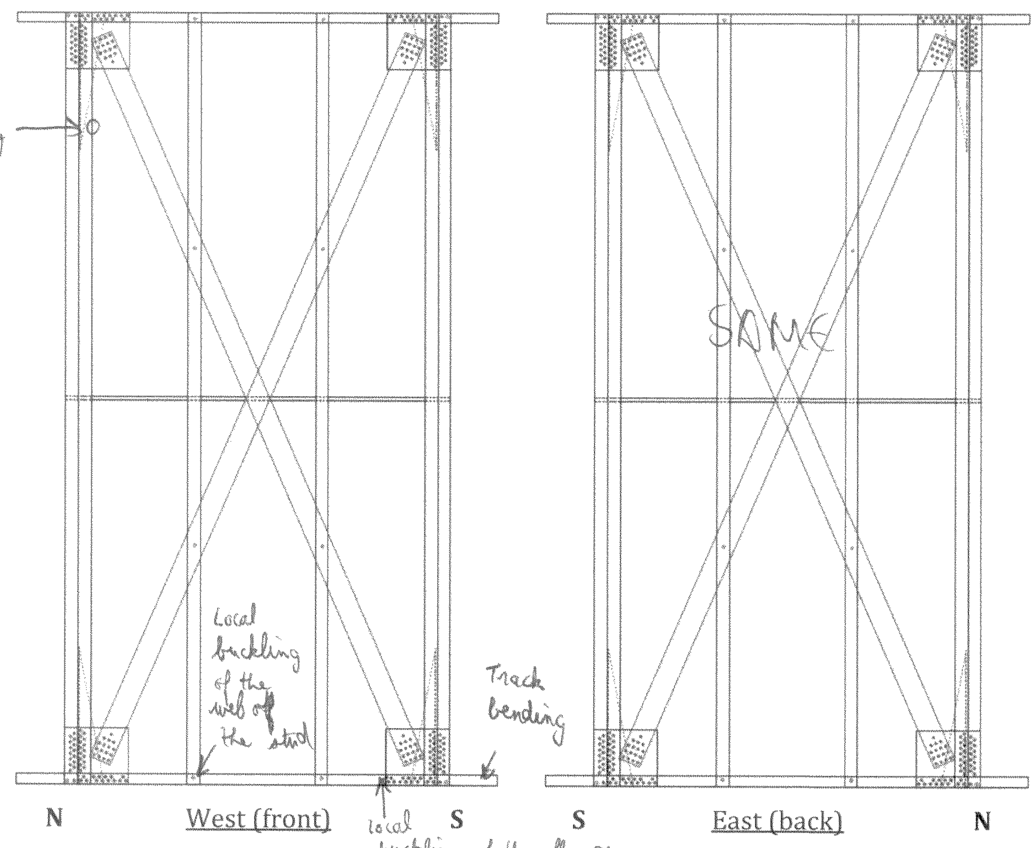
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 22A-M
Date tested: June 24, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☒ no
Test mode: ☒ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:

Lip local buckling




East side notes:

General notes:
- Bending of the chord studs (flanges bending inward and outward
- Straps have yielded

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 72 B-M

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 23, 2014  **TIME:** 3:45 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**
- Sheathing: Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [x] 48mm (1''-7/8) type S drywall screw
- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [x] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [x] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic  5mm/min
- [ ] Cyclic  CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | 72,2 | 69,3 | 70,6 | 69,2 |
| | 72,0 | 72,0 | 71,5 | 71,4 |
| | 70,8 | 74,9 | 72,7 | 74,1 |
| AVG | 71,7 mm | 72,1 mm | 71,6 mm | 71,6 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 81,96 | 79,96 | 81,87 | 84,17 |
| Wd= | 67,53 | 66,01 | 67,25 | 69,14 |
| m.c.= | 21,368 | 21,13 | 21,74 | 21,74 |

AVG m.c. 21,49 %

**DATA ACQ. RECORD RATE:** 2 scan/sec  **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

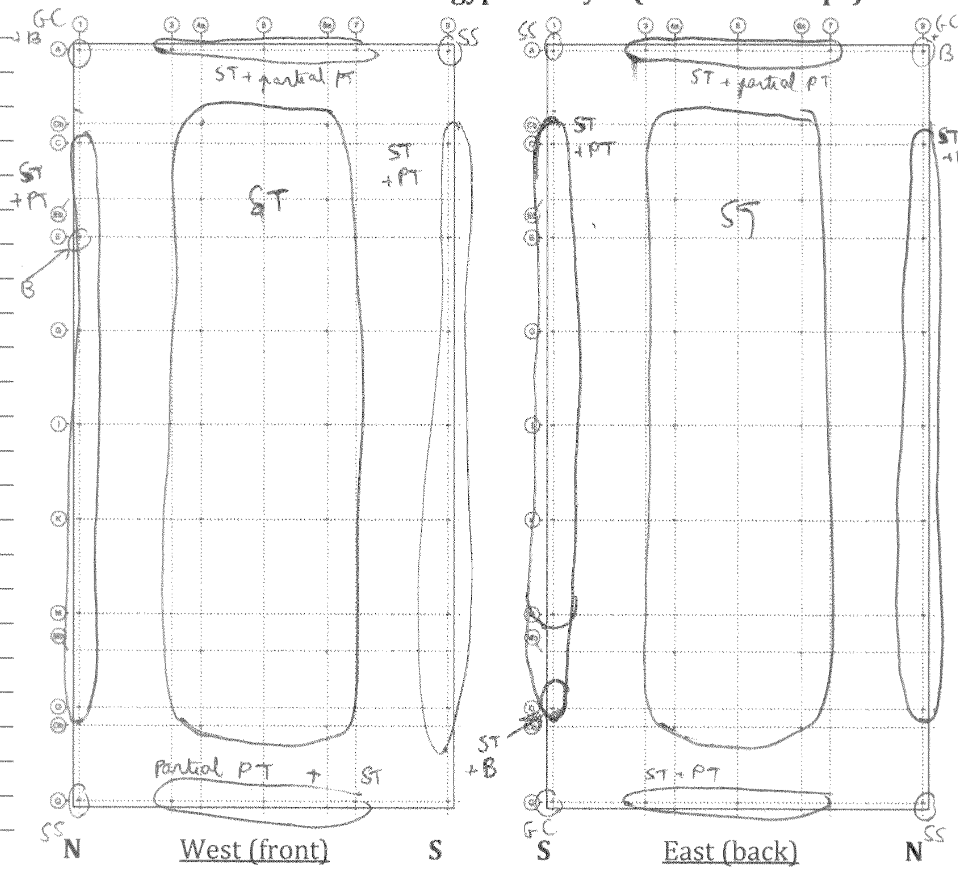
# McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: #2 B-M
Date tested: June 23, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

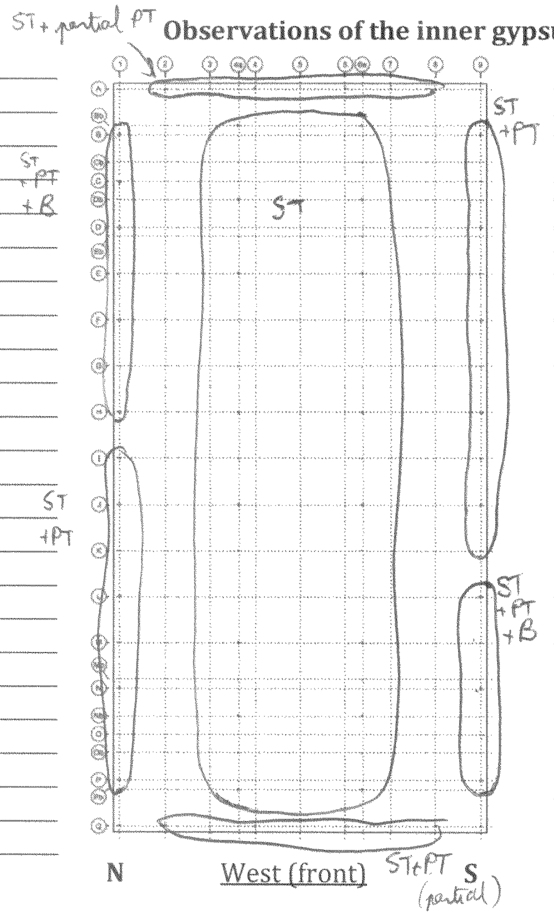
Test name: 72 8-M
Date tested: June 23, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

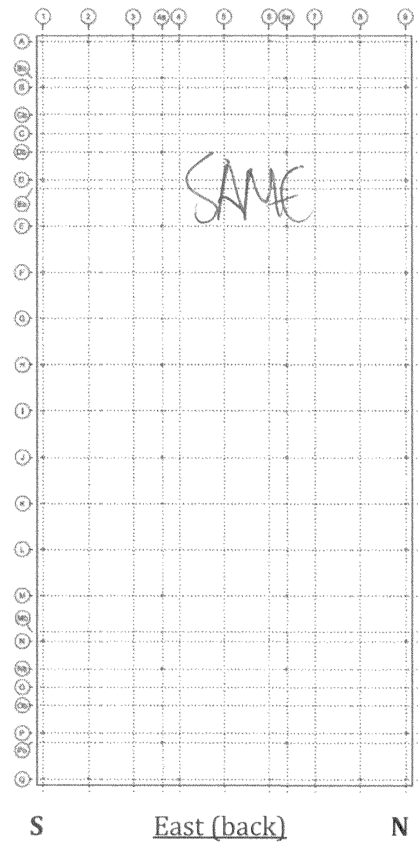
**Observations of the inner gypsum layer (wall with strap)**

West side notes:

ST + PT + B

ST + PT




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

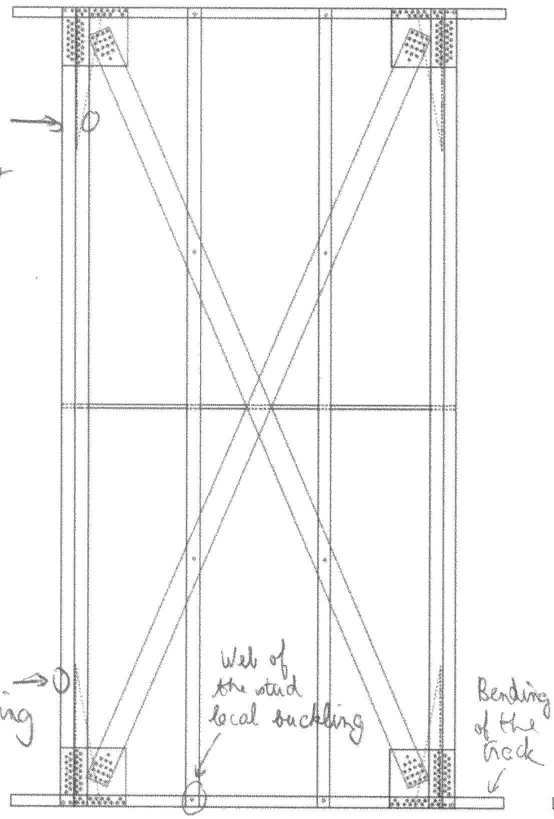
Test name: 72 B-M
Date tested: June 23, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

**Observations of the steel frame**

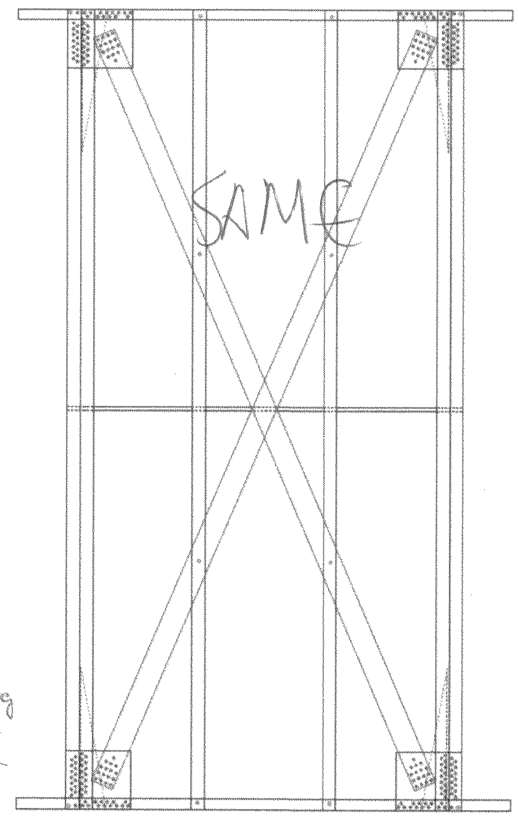
West side notes:

- Flanges ~~tips~~ bending outwards
- Lip local buckling

- ~~Flanges~~ bending inward
- Lip local buckling




West (front)




East (back)

East side notes:

General notes:
- Chord studs bending
- Straps have yielded

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 73 A-C

**RESEARCHER:** Sophie LU

**ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built June 2014; Tested July 9, 2014

**TIME:** 4:33 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

Sheathing:
- Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [x] 48mm (1''-7/8) type S drywall screw

- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [x] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [x] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic — 5mm/min
- [x] Cyclic — CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [x] Bot north- Top south brace

Total: 9

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | 72,9 | 71,8 | 72,6 | 71,7 |
| | 72,1 | 72,1 | 72,0 | 71,9 |
| | 71,3 | 72,2 | 71,7 | 72,3 |
| AVG | 72,1 mm | 72,0 mm | 72,1 mm | 72,0 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 80,79 | 81,14 | 80,89 | 80,81 |
| Wd= | 66,7 | 66,8 | 66,5 | 66,54 |
| m.c.= | 21,124 | 21,47 | 21,64 | 21,45 |

AVG m.c. 21,42 %

**DATA ACQ. RECORD RATE:** 100 scan/sec

**MONITOR RATE:** 200 scan/sec

**COMMENTS:**

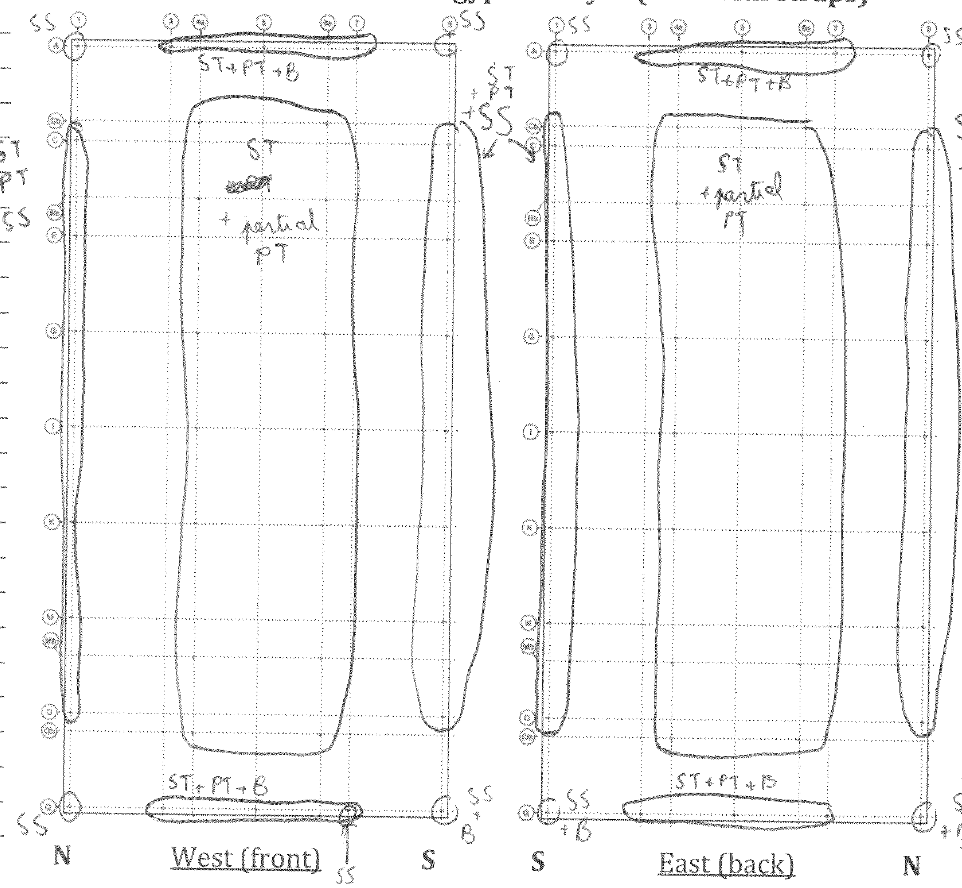
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 73 A-C
Date tested: July 9, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:
ST
+PT
+SS




East side notes:
ST
+PT
+SS

General notes:

McGill

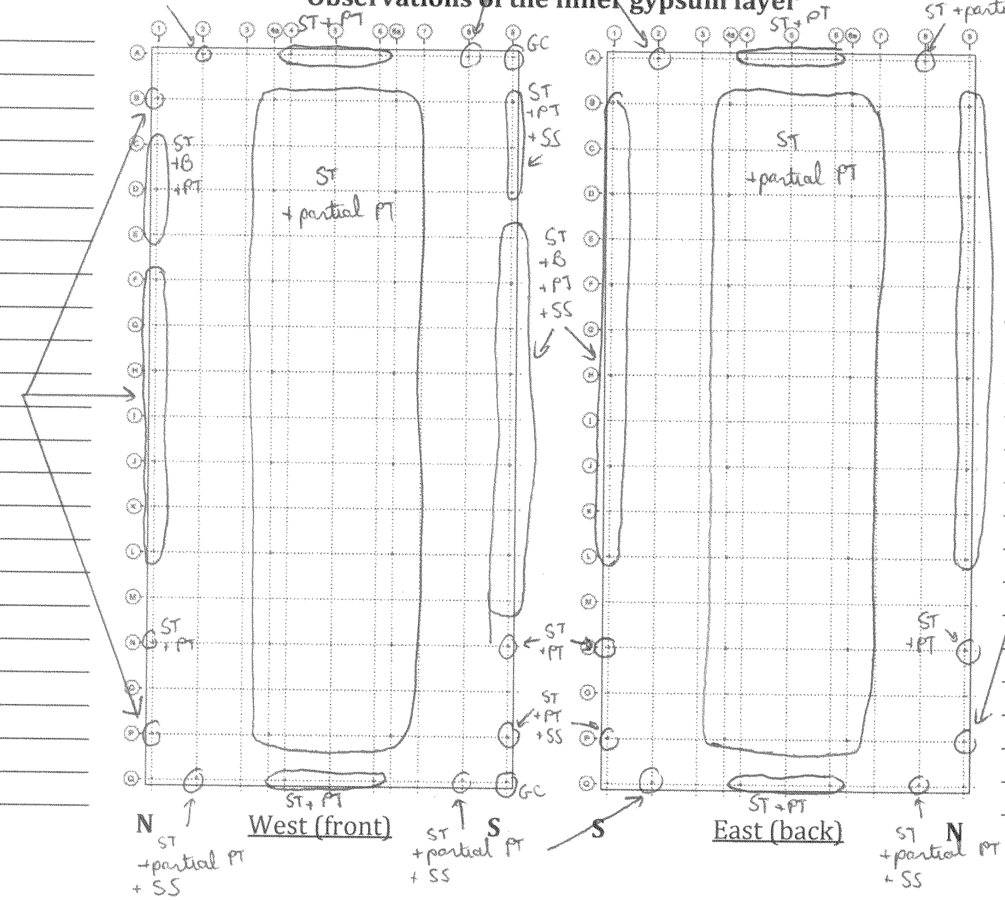
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

| | |
|---|---|
| Test name: | 73 A-C |
| Date tested: | July 9, 2014 |
| # of gypsum layers per side: | 2 |
| # of sheathed sides: | 2 |
| Resilient channel: | ☐ yes ☑ no |
| Test mode: | ☐ monotonic ☑ cyclic |

## Observations of the inner gypsum layer

West side notes:

ST + B + PT + SS




East side notes:

ST + B + PT + SS

General notes:

McGill

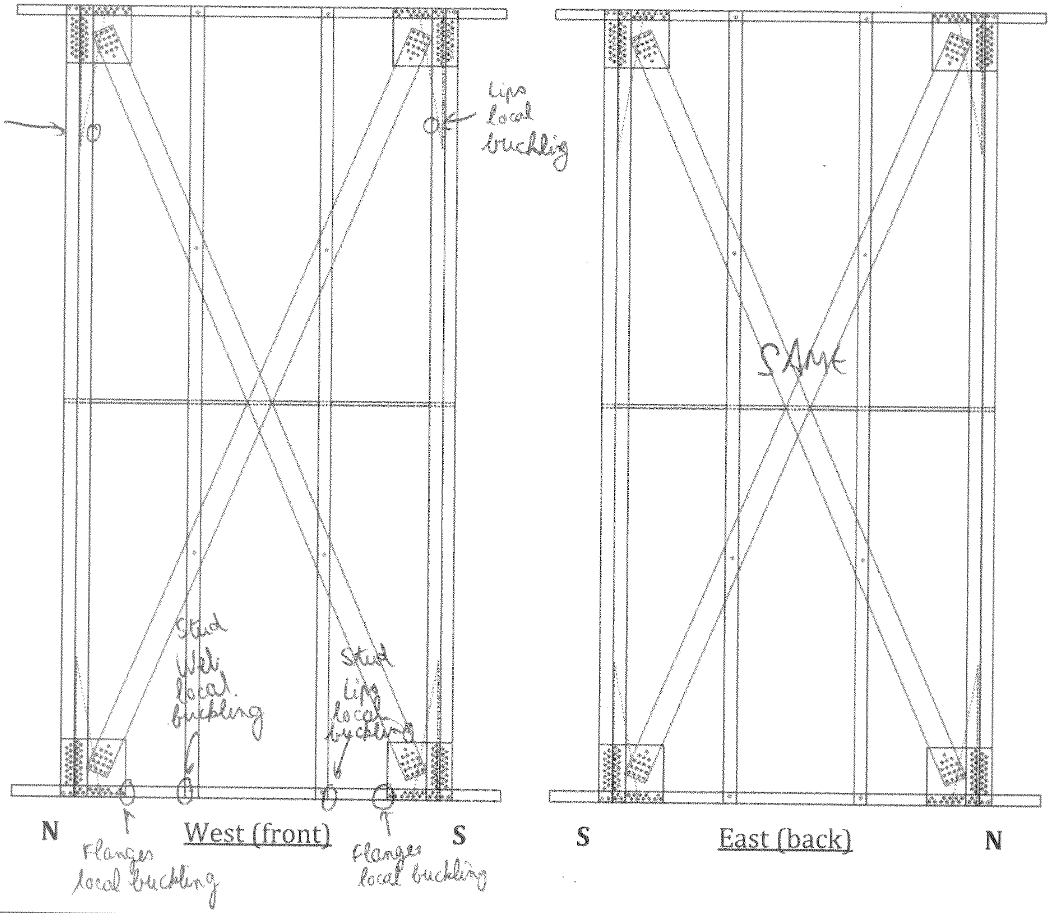
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 73 A-C
Date tested: July 9, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:

Lips local buckling




East side notes:

General notes:

- Chord studs bending (induces distorsion of the flanges)
- Straps yielding

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 73 B-C

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 8, 2014 **TIME:** 2:00 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Loose | Loose |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic 5mm/min
- [x] Cyclic CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [x] Bot north- Top south brace

Total: 9

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,0 | 72,8 | 72,3 | 71,3 |
| 72,0 | 71,9 | 71,9 | 71,9 |
| 70,7 | 71,8 | 71,7 | 72,7 |
| AVG 71,2 mm | AVG 72,2 mm | AVG 72,0 mm | AVG 72,0 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 78,62 | 80,93 | 81,79 | 80,56 |
| Wd= | 64,3 | 66,18 | 66,44 | 65,81 |
| m.c.= | 22,271 | 22,29 | 23,10 | 22,41 |

AVG m.c. 22,52 %

**DATA ACQ. RECORD RATE:** 100 scan/sec **MONITOR RATE:** 200 scan/sec

**COMMENTS:** East bottom north corner outer gypsum: hole 1.4 cm of diameter

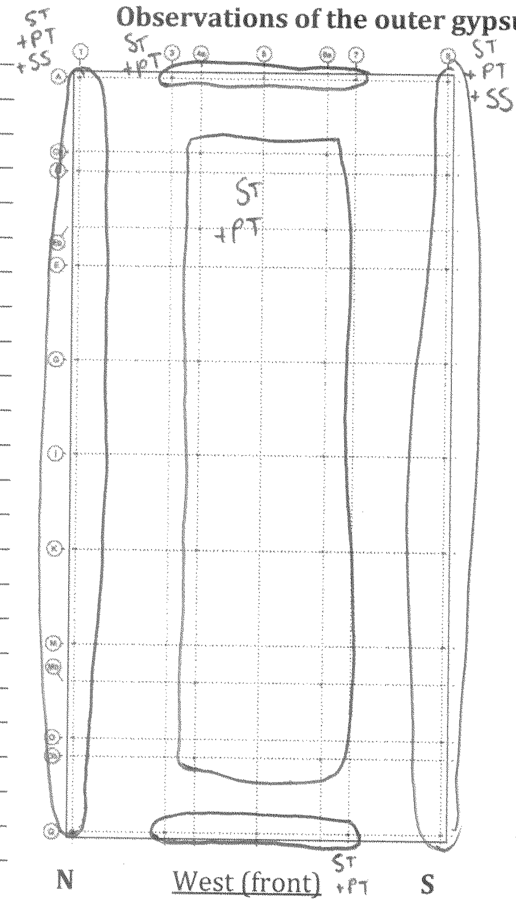
McGill

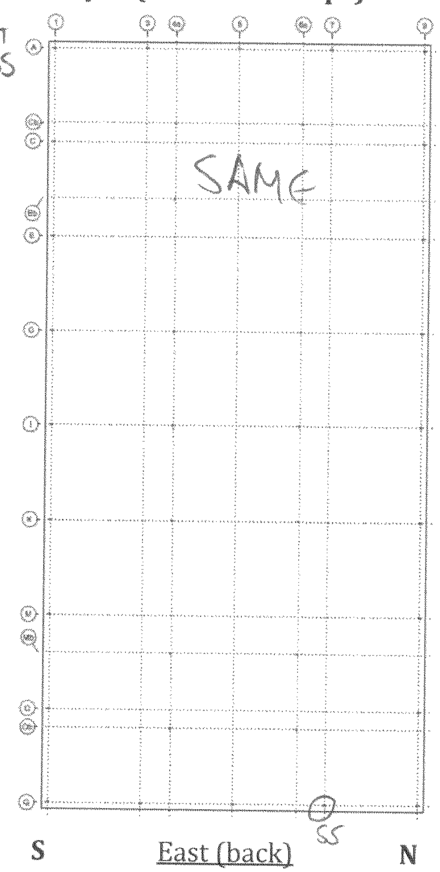
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 73 B-C
Date tested: July 8, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the outer gypsum layer (wall with straps)**

West side notes:




East side notes:

Same as west side except @7 (screw sheared)

General notes:

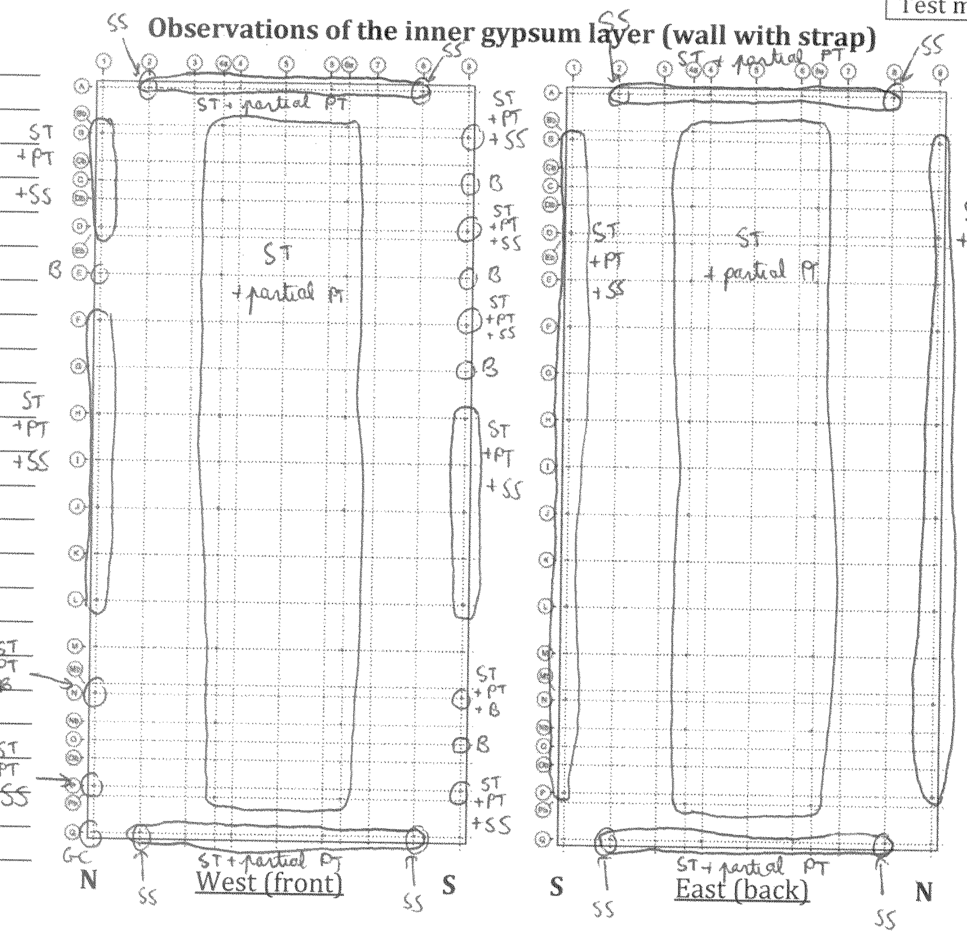
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 13 B-C
Date tested: July 8, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer (wall with strap)

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

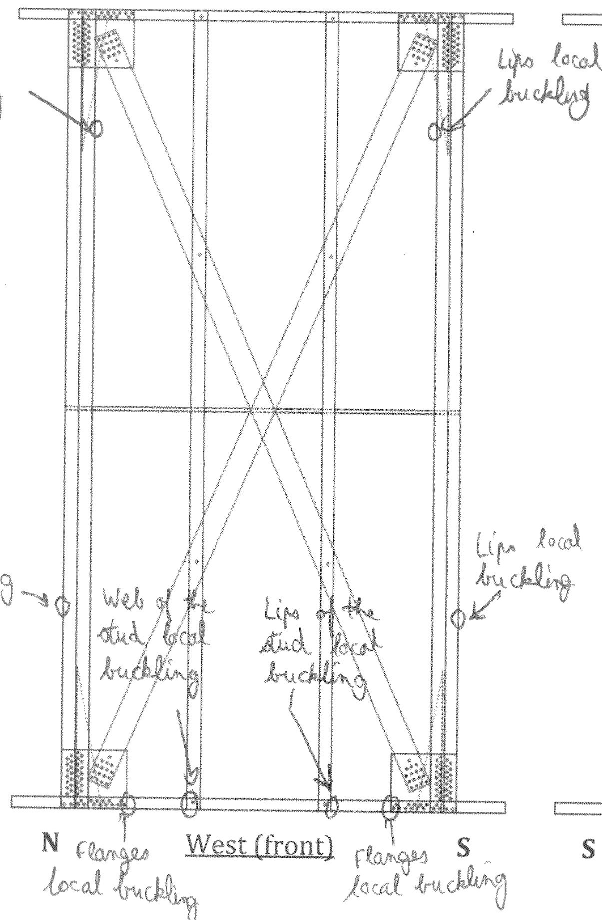
Test name: 73 B.C
Date tested: July 8, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

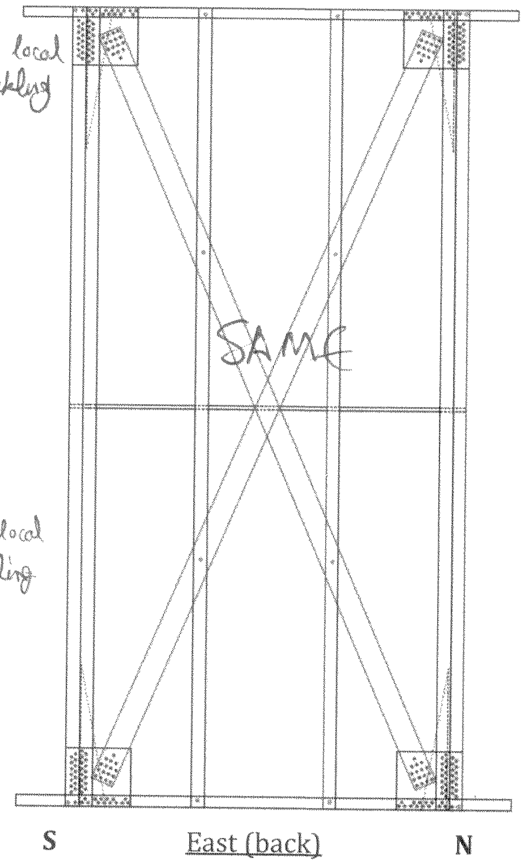
## Observations of the steel frame

West side notes:

Lips local buckling

Lips local buckling




East side notes:

General notes:

Straps have yielded

Bending of the chord studs

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 74 A-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 25, 2014 **TIME:** 3:27 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,1 | 72,7 | 72,5 | 72,3 |
| 71,8 | 71,9 | 71,8 | 71,7 |
| 71,0 | 71,2 | 71,3 | 69,4 |
| AVG 71,3 mm | AVG 71,9 mm | AVG 71,9 mm | AVG 71,1 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | 81,64 | 83,41 |
| Wd= | NA | NA | 67,43 | 68,69 |
| m.c.= | NA | NA | 21,07 | 21,43 |

AVG m.c. 21,25

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:** 1 screw in the field of the gypsum has been forgotten (location Ob 3)

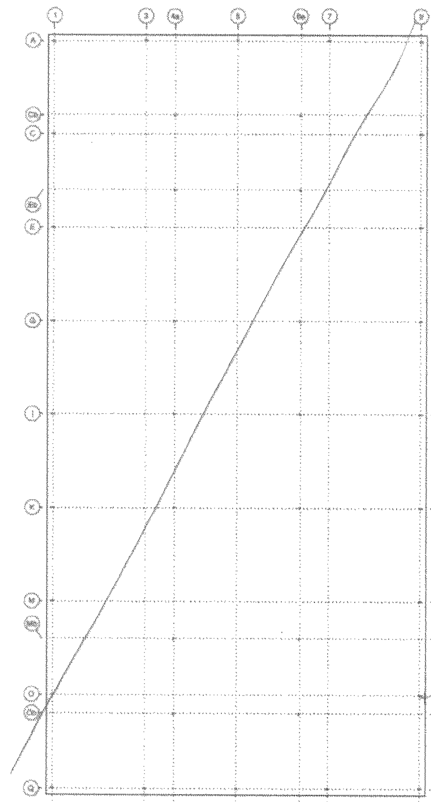
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

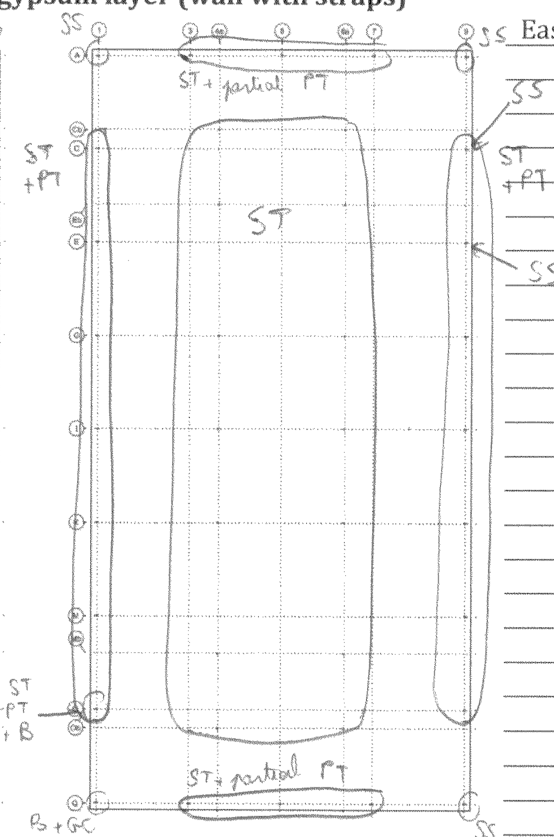
| | |
|---|---|
| Test name: | 74 A-M |
| Date tested: | June 25, 2014 |
| # of gypsum layers per side: | 2 |
| # of sheathed sides: | 1 |
| Resilient channel: | ☐ yes ☑ no |
| Test mode: | ☑ monotonic ☐ cyclic |

## Observations of the outer gypsum layer (wall with straps)

West side notes:



N West (front) S




S East (back) N

East side notes:

General notes:

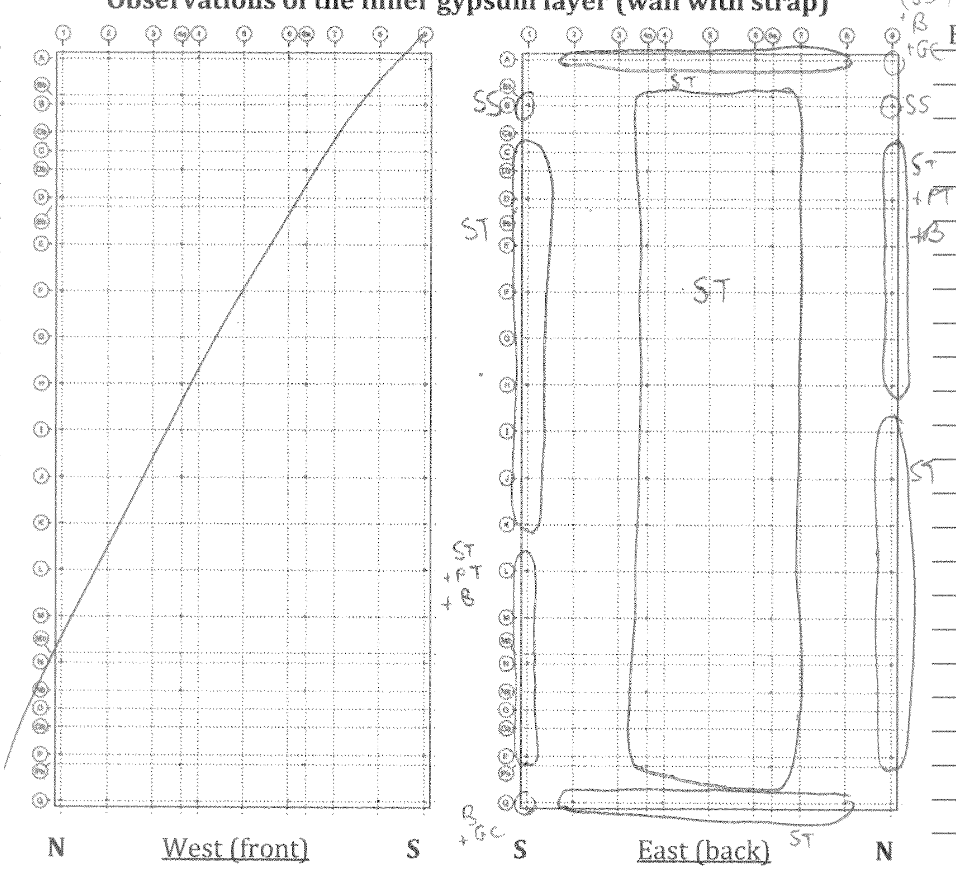
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 74 A-M
Date tested: June 25, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer (wall with strap)

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

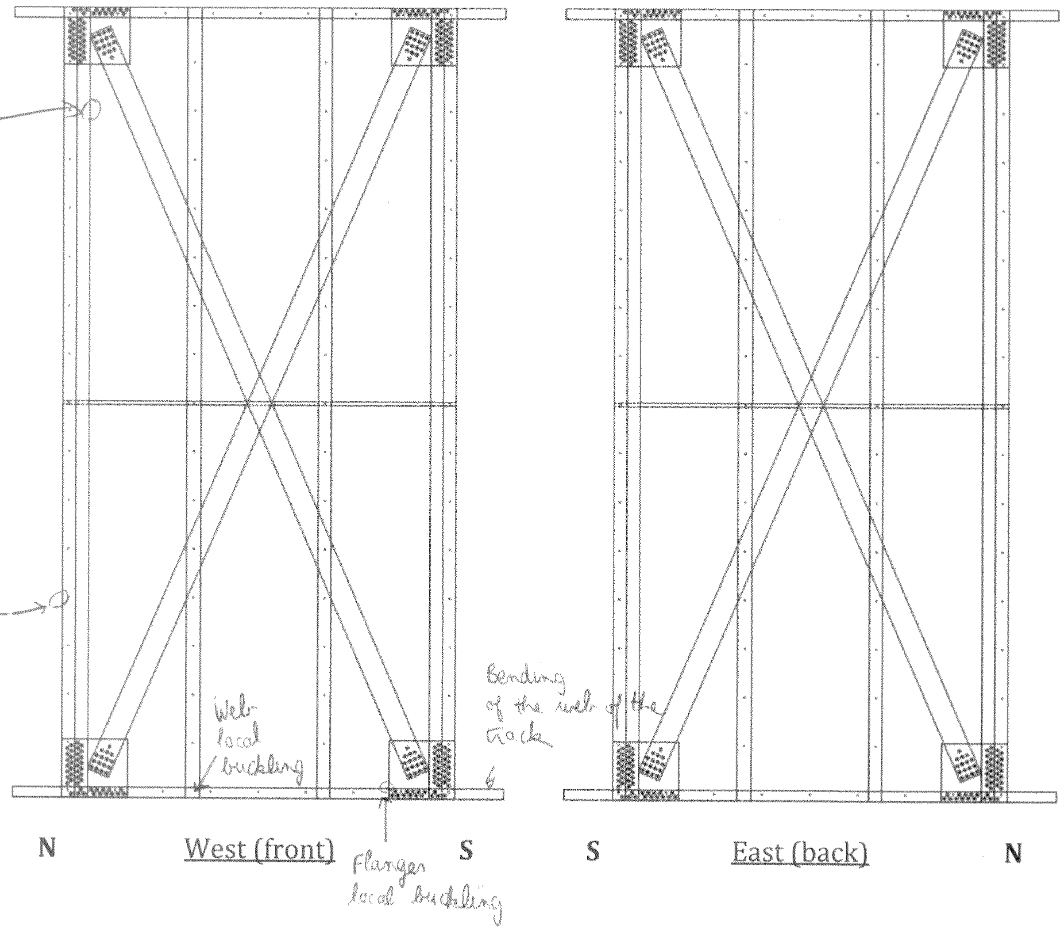
Test name: 74 A-M
Date tested: June 25, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 1
Resilient channel: ☐ yes ☒ no
Test mode: ☒ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:

lip local buckling

lip local buckling




East side notes:

General notes:

· Chord studs bending

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 74 B-M

**RESEARCHER:** Sophie LU | **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 26, 2014 | **TIME:** 2:10 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,5 | 71,9 | 72,1 | 71,7 |
| 71,9 | 71,7 | 71,1 | 71,8 |
| 69,5 | 71,9 | 72,5 | 72,1 |
| AVG 71,3 mm | AVG 71,8 mm | AVG 71,9 mm | AVG 71,9 mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | 80,93 | 81,55 |
| Wd= | NA | NA | 69,9 | 68,51 |
| m.c.= | NA | NA | 15,78 | 19,03 |

AVG m.c. 17,41

**DATA ACQ. RECORD RATE:** 2 scan/sec | **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

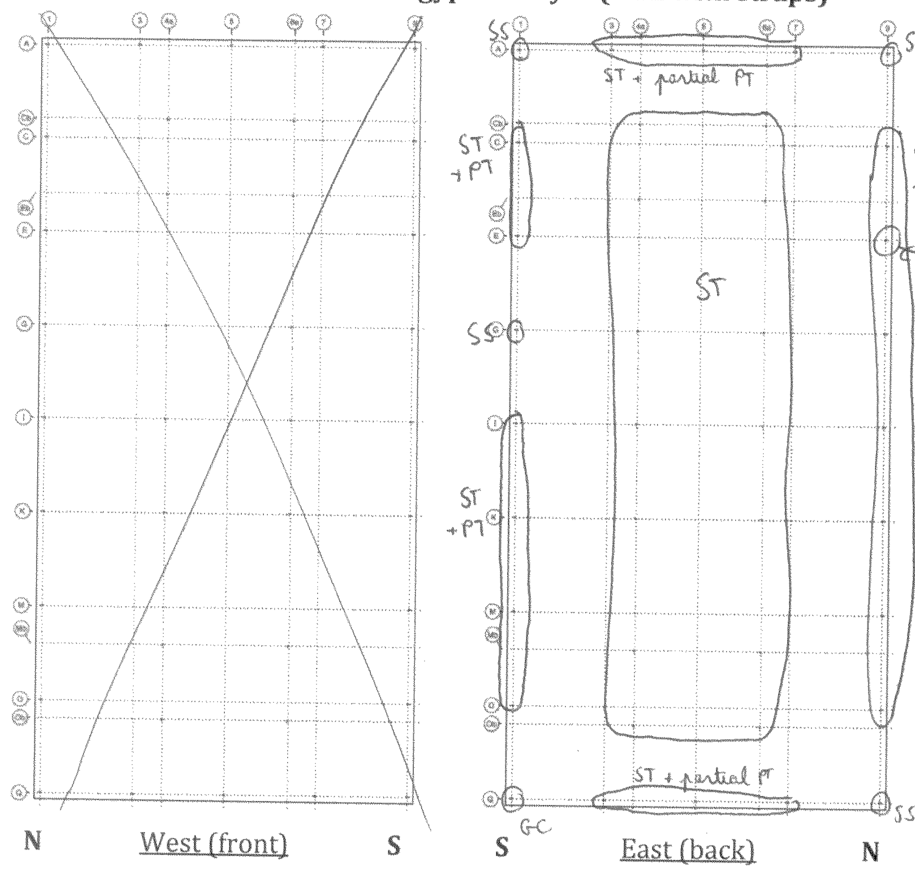
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 74 B-M
Date tested: June 26, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:




East side notes:

General notes:

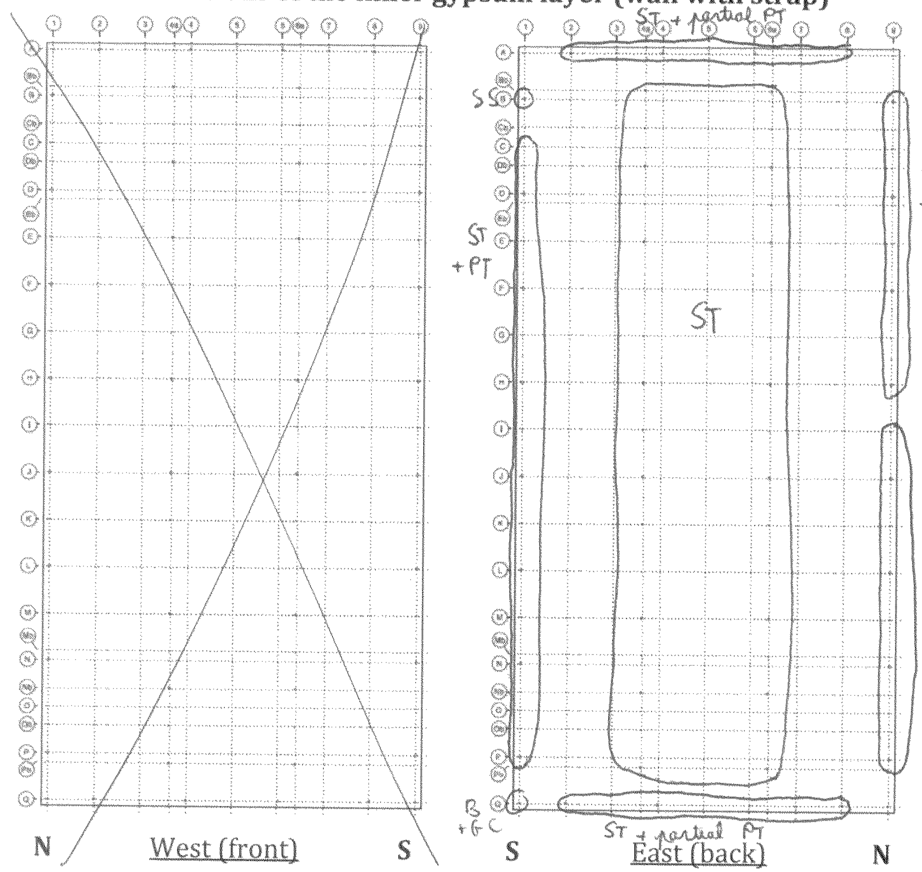
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 74 B-M
Date tested: June 26, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer (wall with strap)

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

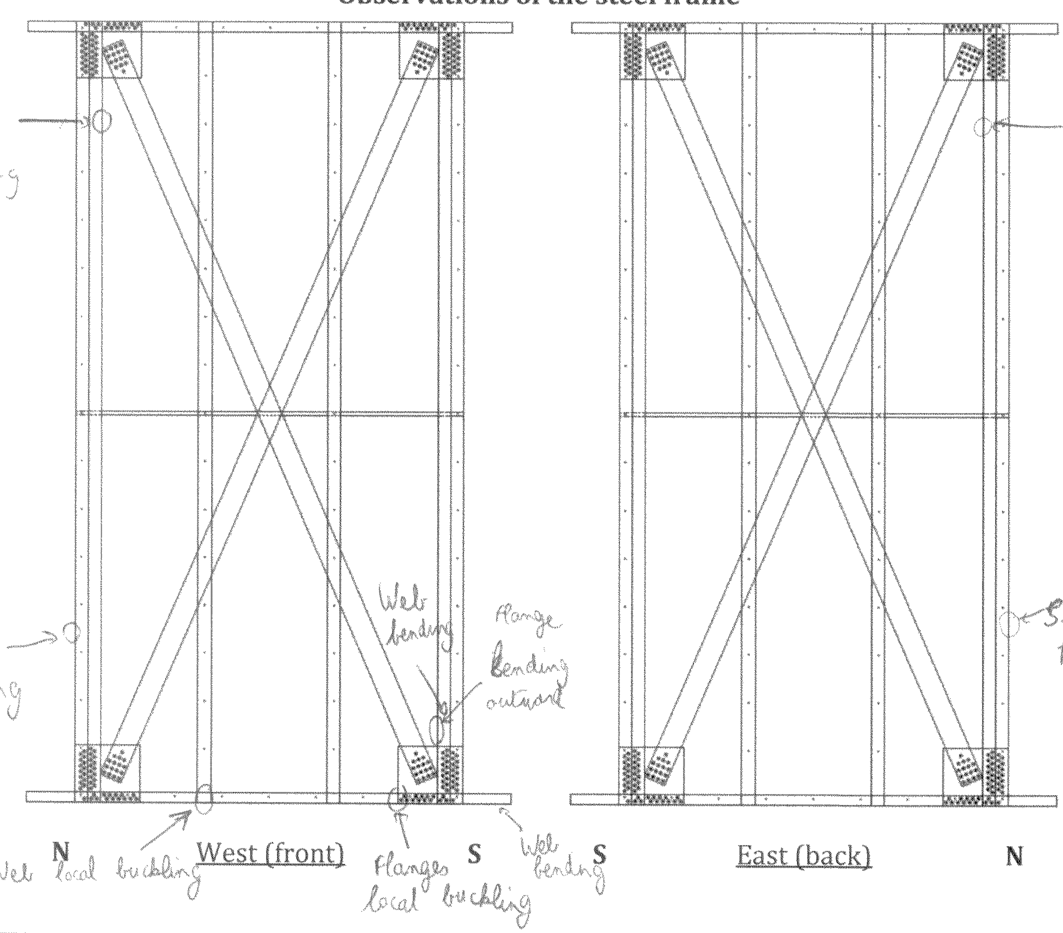
Test name: 24 B-M
Date tested: June 26, 2014
\# of gypsum layers per side: ________
\# of sheathed sides: ________
Resilient channel: ☐ yes ☐ no
Test mode: ☐ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:

- Distortional buckling
- → lip local buckling
- → flange local buckling

- Distortional buckling
- → lip local buckling
- → flange local buckling




East side notes:

- Distortional buckling
- Small bending of the flange

General notes:

- Bending of the chord studs
- Yielding of the straps

**Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls**
**McGill University, Montreal**

**TEST:** 75 A-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 16, 2014  **TIME:** 1:20 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | x | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | x | Bot north- Top south brace |

Total: 9

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | 72,8 | 72,7 | 70,4 | 72,2 |
| | 71,8 | 72,0 | 71,7 | 71,9 |
| | 71,9 | 71,1 | 72,4 | 71,3 |
| AVG | 72,2 mm | 71,9 mm | 71,5 mm | 71,8 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | 81,88 | 78,82 |
| Wd= | | | 67,42 | 64,56 |
| m.c.= | NA | NA | 21,45 | 22,09 |

AVG m.c. 21,77

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

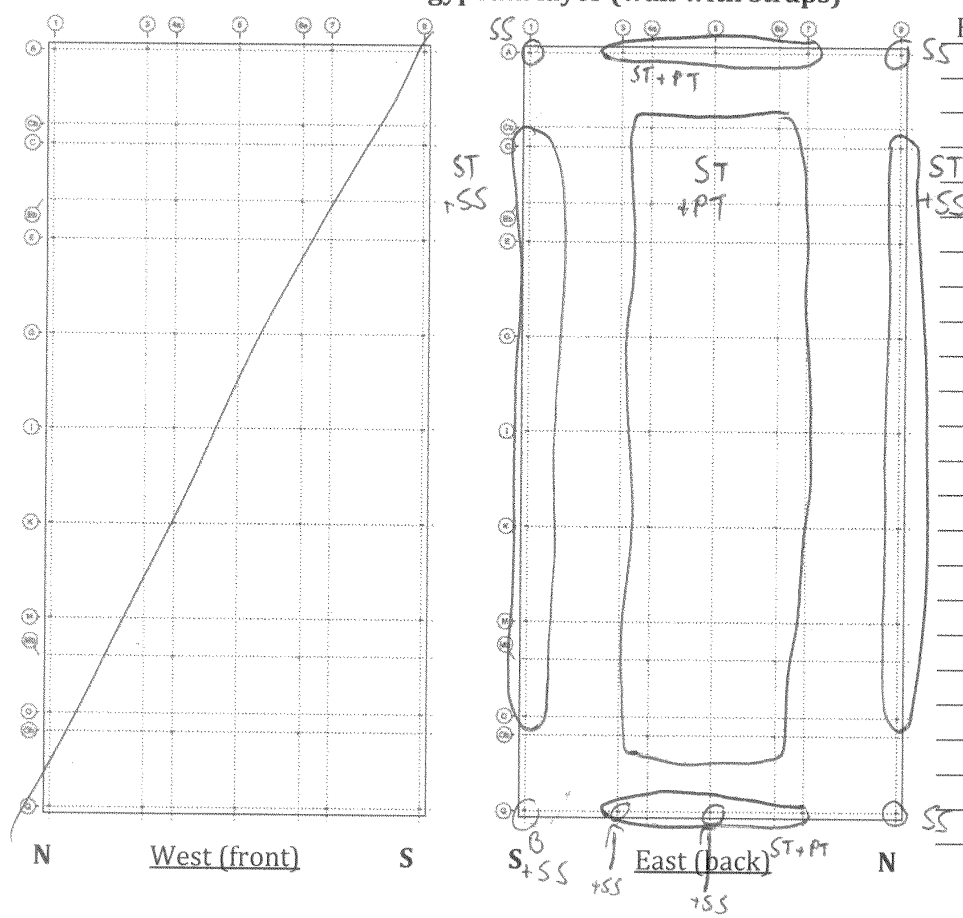
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 45 A-C
Date tested: July 16, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:




East side notes:

General notes:

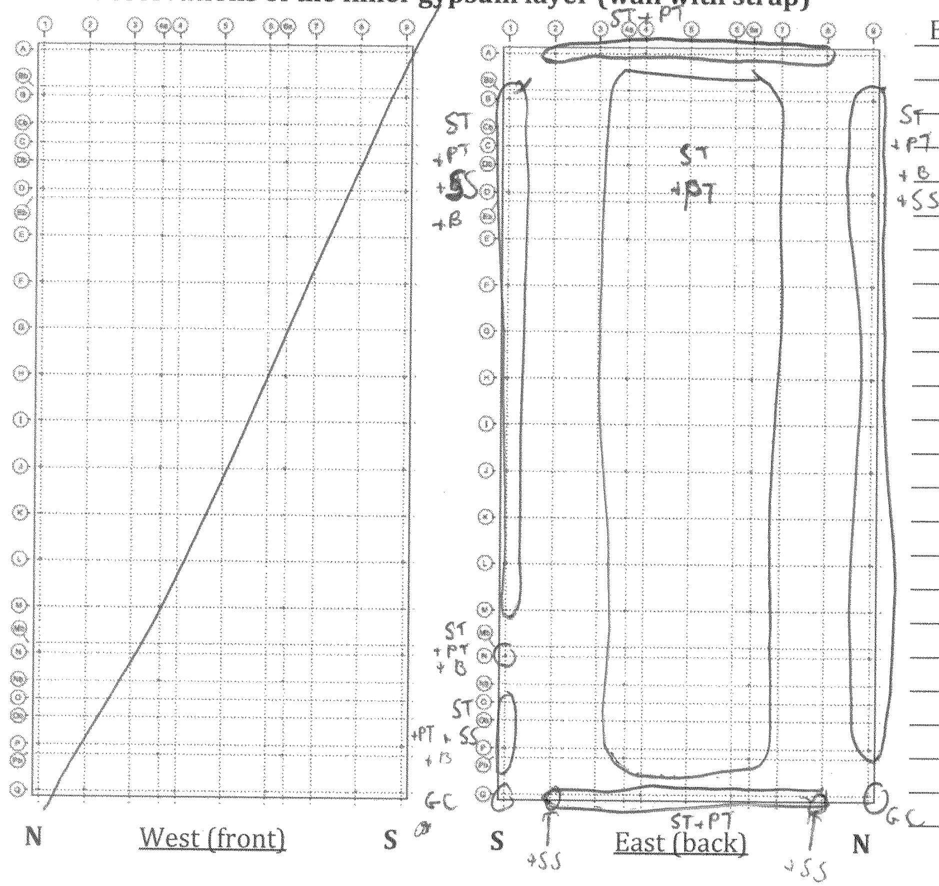
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 75 A-C
Date tested: July 16, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer (wall with strap)

West side notes:




East side notes:

General notes:

McGill

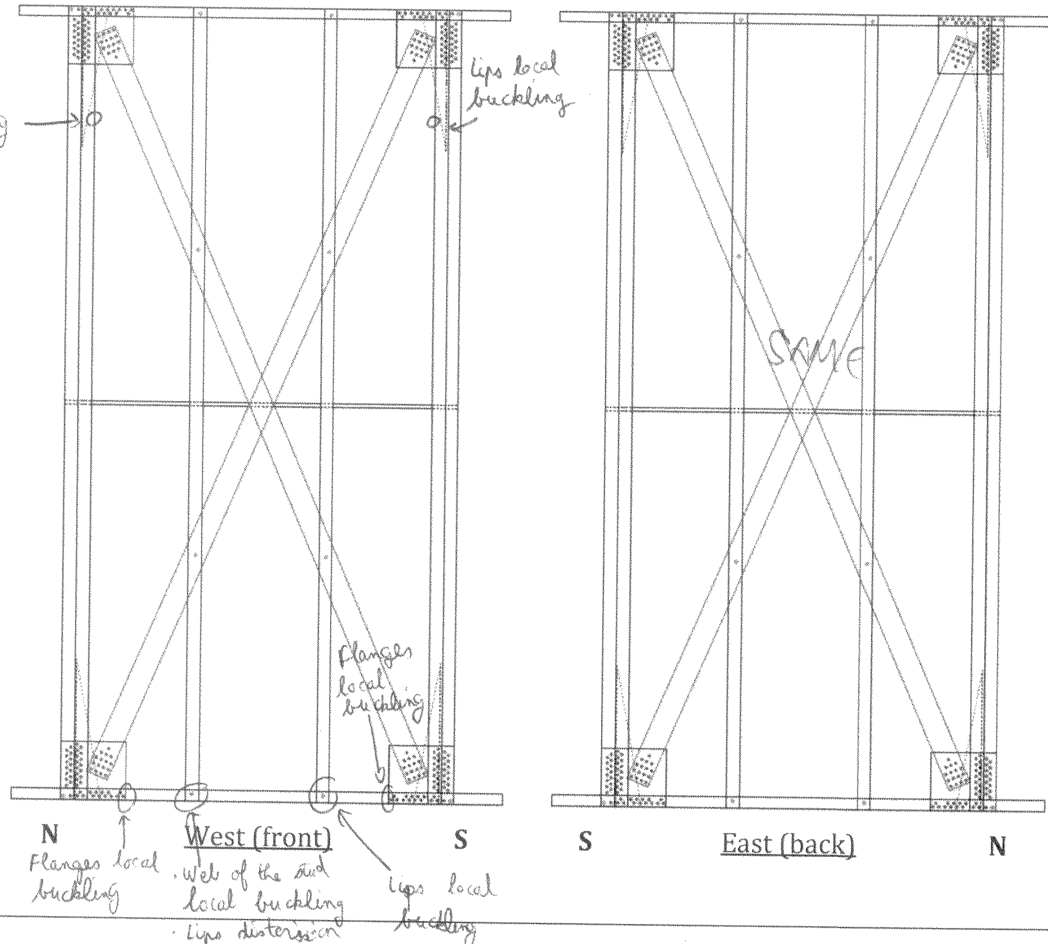
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 75 A-C
Date tested: July 16, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Lips local buckling




East side notes:

General notes:

- Chord studs bending
- Straps yielding

# Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 75 B-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 21, 2014  **TIME:** 3:00 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | x | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | x | Bot north- Top south brace |

Total: 9

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 71,4 | 72,6 | 69,8 | 69,6 |
| 71,9 | 72,4 | 71,8 | 71,5 |
| 72,4 | 69,7 | 74,8 | 74,3 |
| AVG 71,9 mm | AVG 71,6 mm | AVG 72,1 mm | AVG 71,8 mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | 80,62 | 80,78 |
| Wd= | | | 66,4 | 66,75 |
| m.c.= | NA | NA | 21,42 | 21,02 |

AVG m.c. 21,22

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

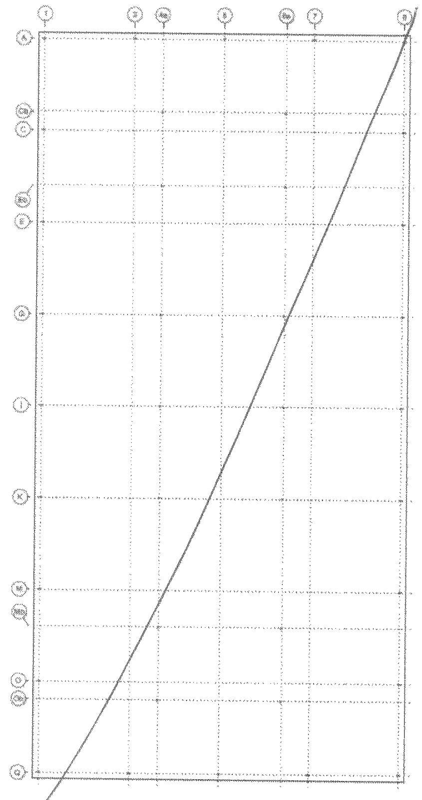
McGill

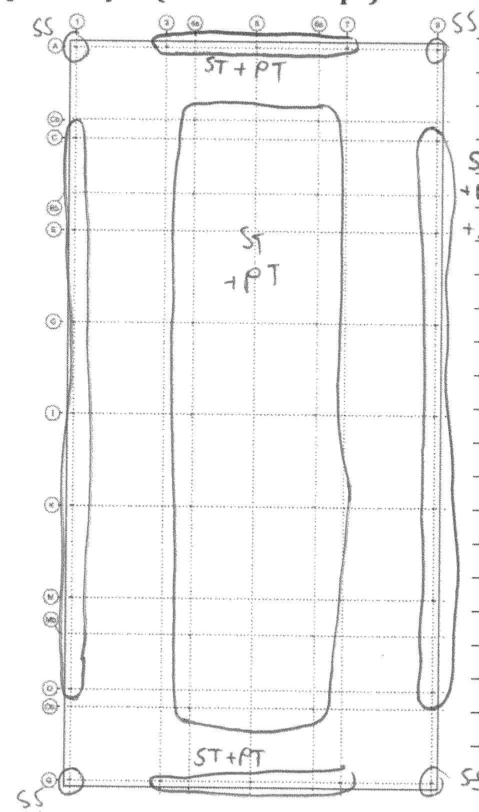
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 75 B-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer (wall with straps)

West side notes:




East side notes:

General notes:

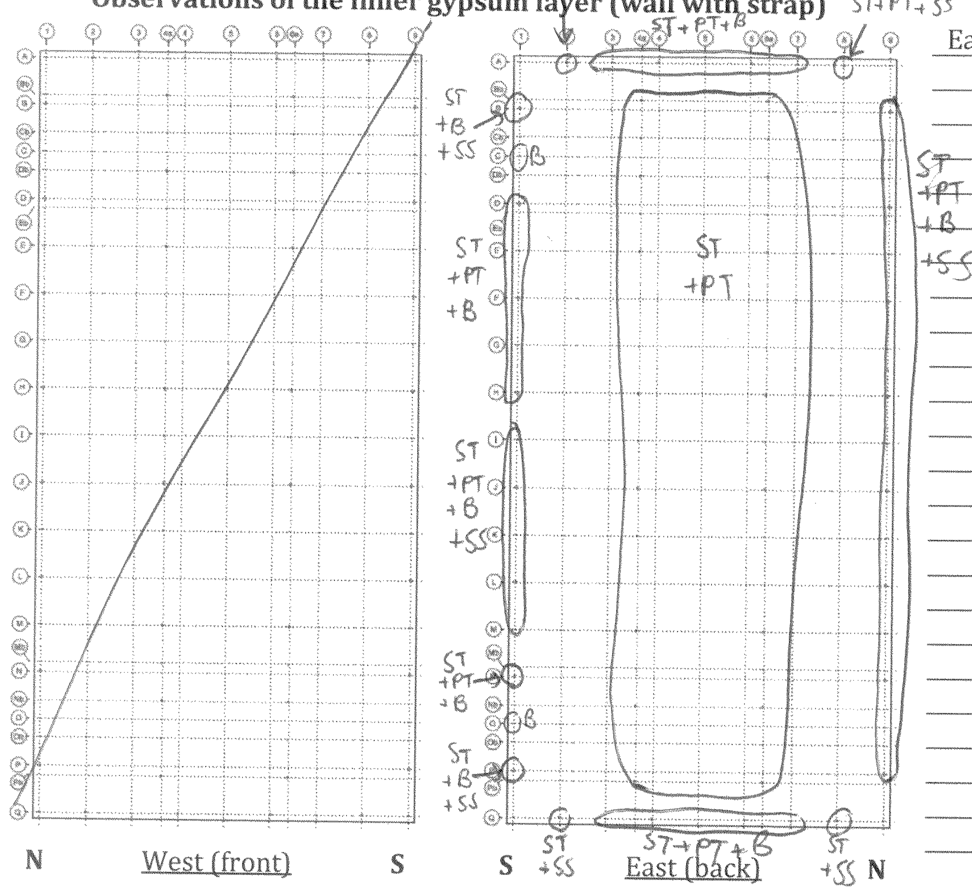
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 75 B-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the inner gypsum layer (wall with strap)**

West side notes:




East side notes:

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

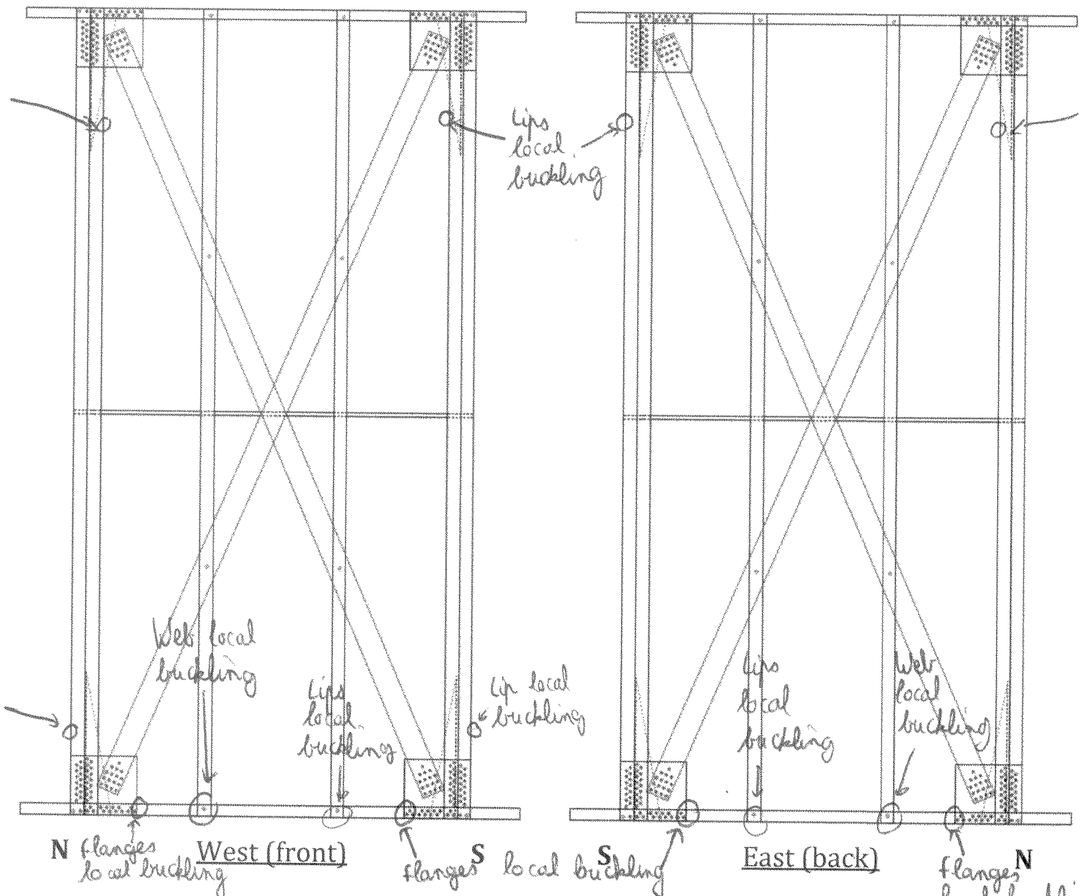
Test name: 75 B-C
Date tested: July 21, 2014
# of gypsum layers per side: 2
# of sheathed sides: 1
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Lips local buckling

Lip local buckling




East side notes:

Lips local buckling

General notes:
- Bending of the chord studs
- Yielding of the straps

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 76 A-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built June 2014; Tested July 3, 2014 **TIME:** 3:15 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | x | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | x | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,0 | 72,5 | 72,4 | 72,2 |
| 72,1 | 71,9 | 71,2 | 71,8 |
| 71,8 | 70,7 | 72,1 | 71,5 |
| AVG 72,0 mm | AVG 71,7 mm | AVG 71,9 mm | AVG 71,8 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 81,18 | 83,77 | 80,25 | 86,13 |
| Wd= | 66,75 | 68,77 | 65,59 | 72,94 |
| m.c.= | 21,618 | 21,81 | 22,35 | 18,08 |

AVG m.c. 20,97 %

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:** West side: bottom north corner of the Inner layer gypsumis slightly damaged

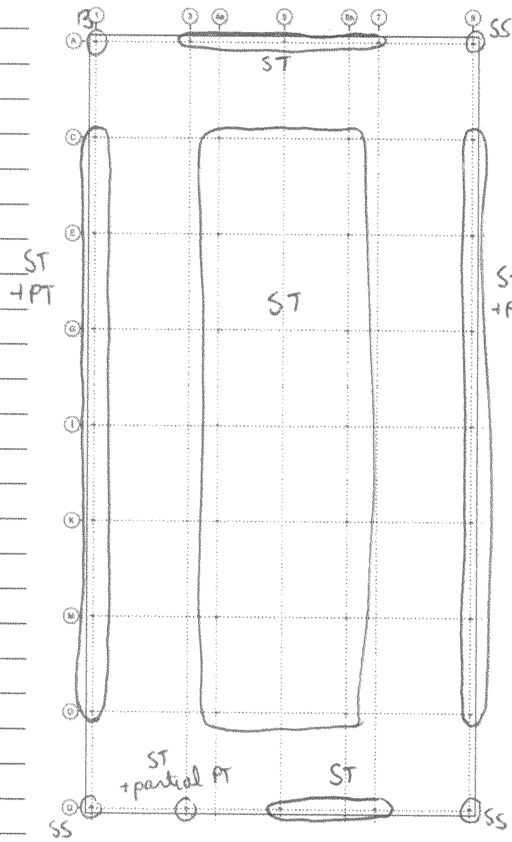
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

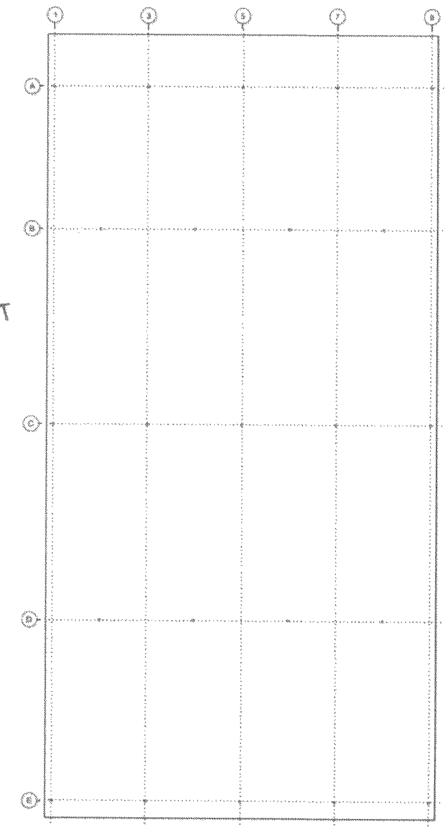
Test name: 76 A-M
Date tested: July 3, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the outer gypsum layer

West side notes:




N West (front) S



S East (back) N

East side notes:

- After 105 mm disp, bearing on bottom north (east) corner.
- No failure in the gypsum

General notes:

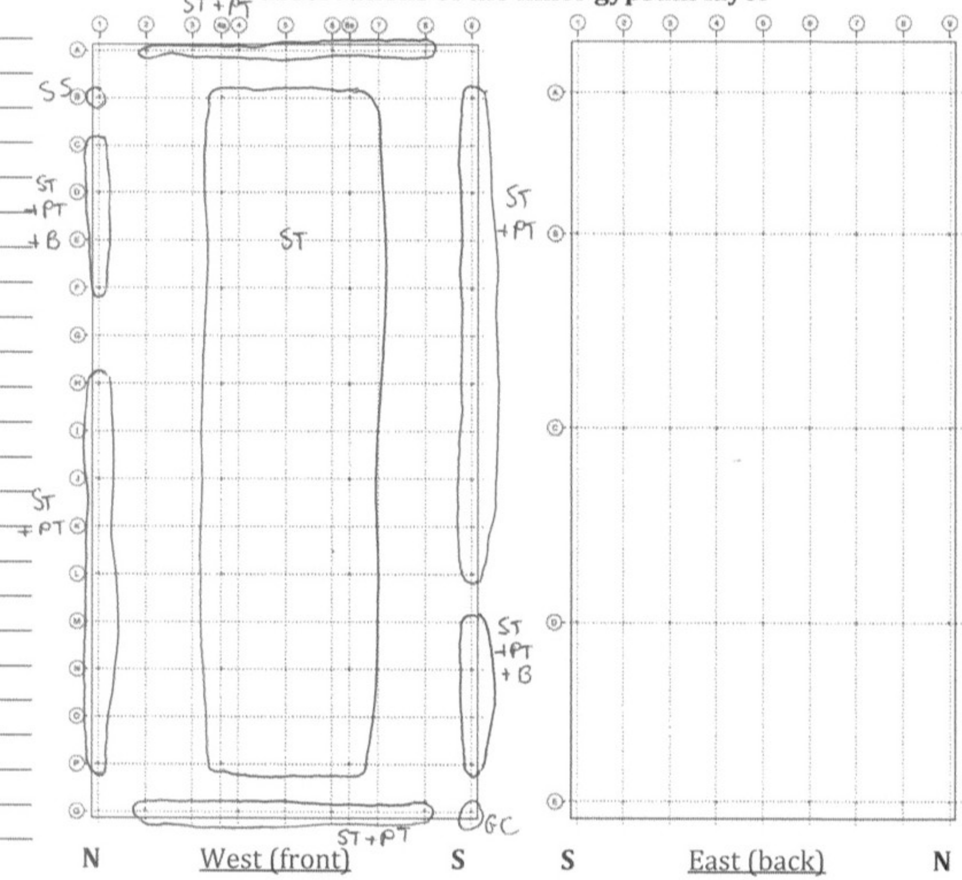
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 76 A-M
Date tested: July 3, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer

West side notes:




East side notes:

No damage in the gypsum.

General notes:

**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

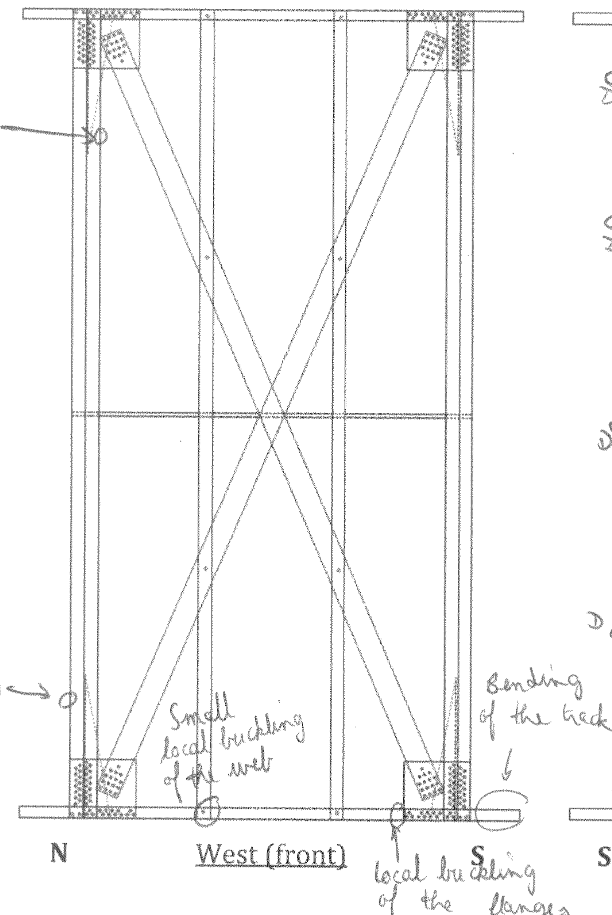
Test name: 76 A-M
Date tested: July 3, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the steel frame

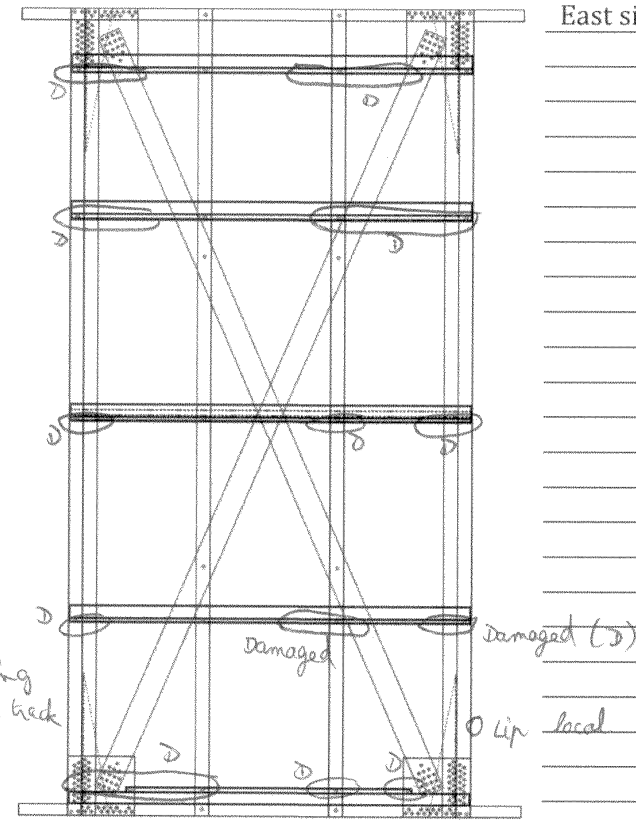
West side notes:

Lip local buckling

Lip local buckling




N West (front) S




S East (back) N

East side notes:

General notes:

. Bending of the chord studs
. Yielding of the braces in tension

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 76 B-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built June 2014; Tested July 4, 2014 **TIME:** 3:40 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**
- Sheathing: Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [x] 48mm (1''-7/8) type S drywall screw
- Resilient channel: [x]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [x] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [x] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,7 | 71,3 | 72,5 | 73,7 |
| 72,6 | 72,0 | 71,5 | 71,8 |
| 71,3 | 72,3 | 72,0 | 69,3 |
| AVG 72,2 mm | AVG 71,9 mm | AVG 72,0 mm | AVG 71,6 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 84,53 | 86,38 | 83,09 | 80,41 |
| Wd= | 68,4 | 70,38 | 68 | 65,9 |
| m.c.= | 23,582 | 22,73 | 22,19 | 22,02 |

AVG m.c. 22,63 %

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

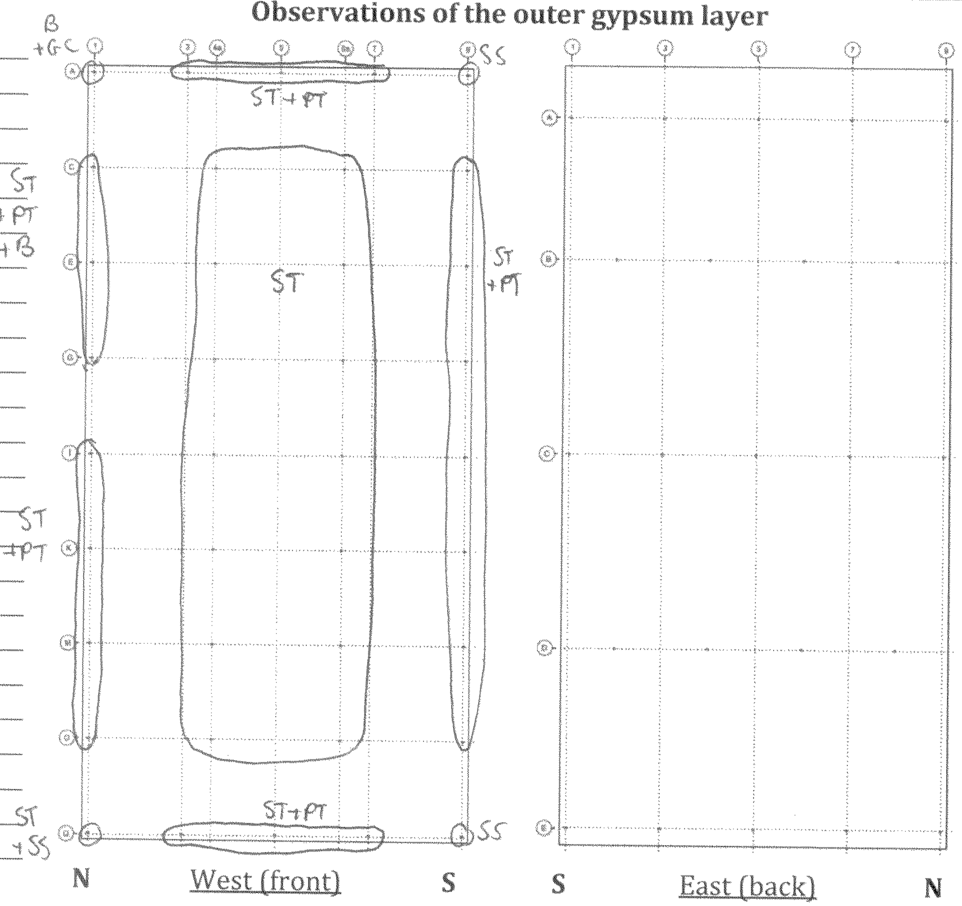
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 76 B-M
Date tested: July 4, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

**Observations of the outer gypsum layer**

West side notes:




East side notes:

No failure in the gypsum

General notes:

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 76 B-M
Date tested: July 4, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

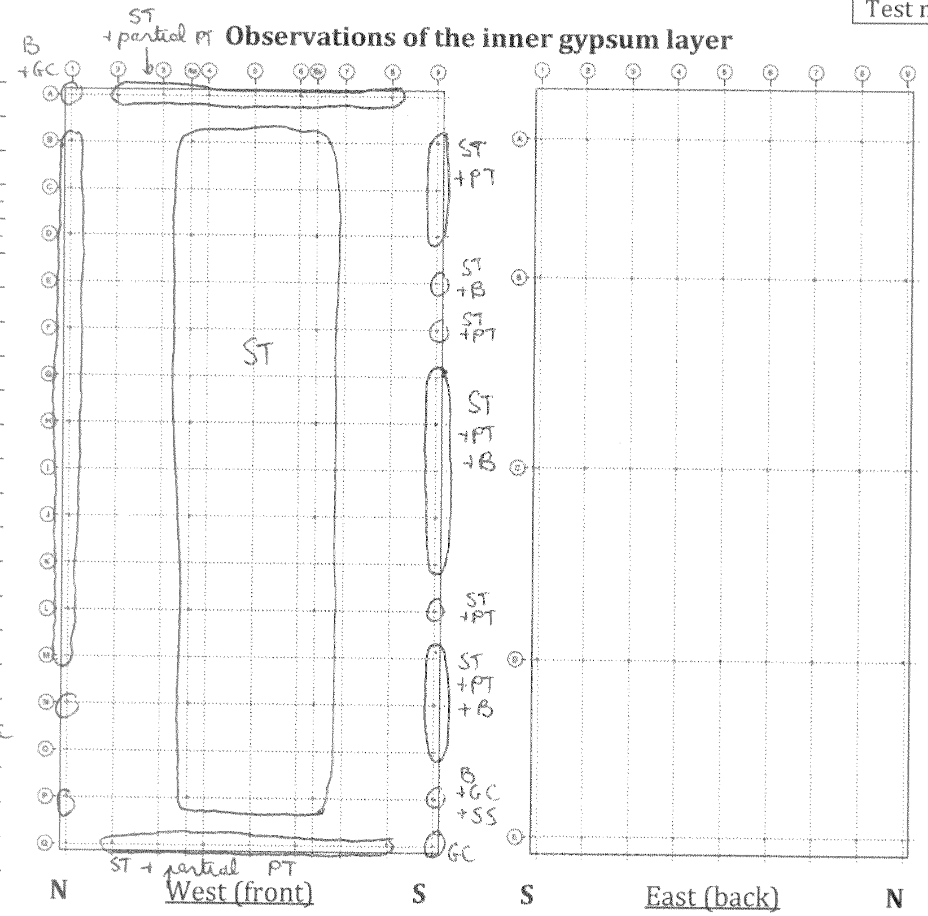
## Observations of the inner gypsum layer

West side notes:

ST
+ PT
+ B

ST
+ PT
+ GC

ST
+ PT




East side notes:

No damage in the gypsum

General notes:

**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

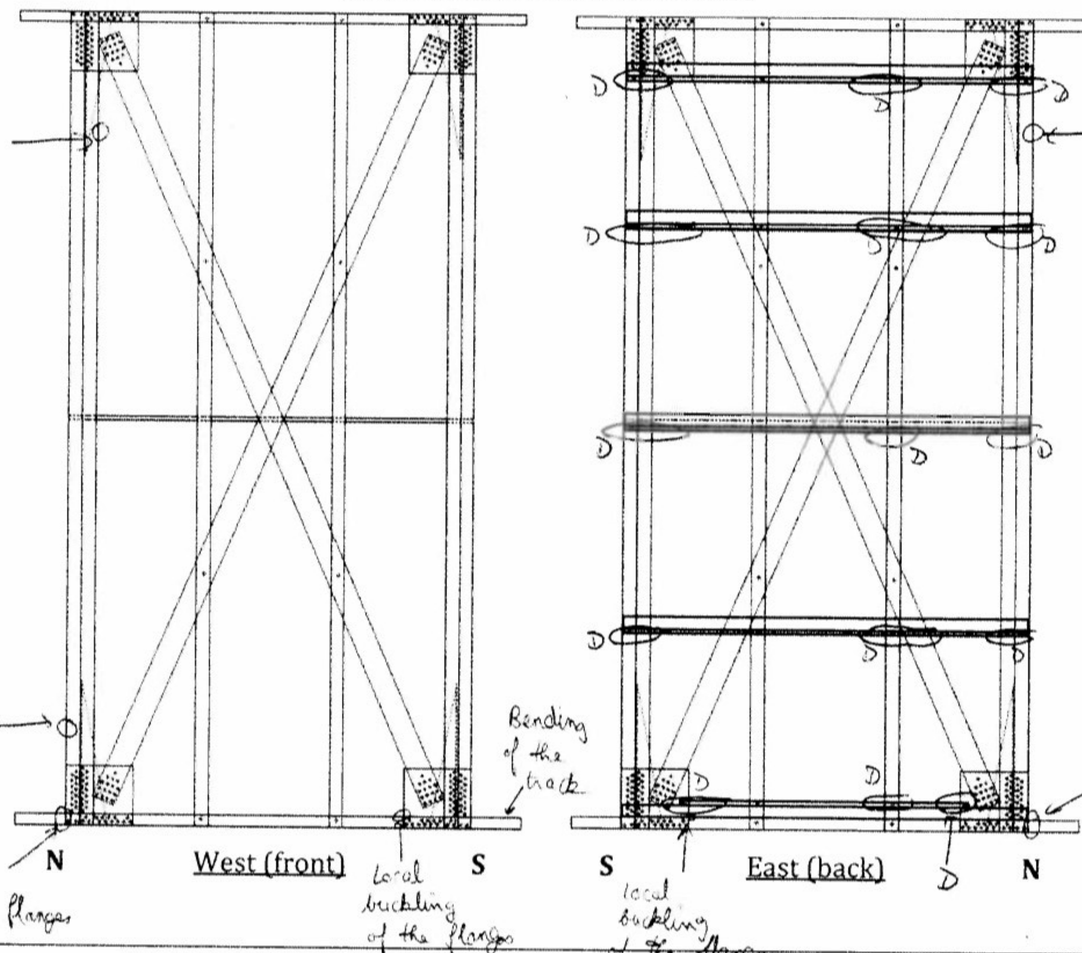
Test name: 76 B-M
Date tested: July 4, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:

lip local buckling

lip local buckling




East side notes:

lip local buckling

local buckling of the flanges

General notes:

Local buckling of the flanges

- Bending of the chord studs
- Yielding of the straps in tension

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 77 A-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 28, 2014  **TIME:** 2:00 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Loose |
| West | Tight | Loose |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | x | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | |
|---|---|---|
| [x] MTS Actuator LVDT | [x] South Slip LVDT | [x] String potentiometer |
| [x] MTS Actuator load cell | [x] North Uplift LVDT | [x] Bot south-Top north brace |
| [x] North Slip LVDT | [x] South Uplift LVDT | [x] Bot north- Top south brace |

Total: 9

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 72,6 | 70,3 | 70,8 | 71,6 |
| 72,2 | 71,3 | 71,7 | 71,4 |
| 71,2 | 71,2 | 73,2 | 72,3 |
| AVG 72,0 mm | AVG 70,9 mm | AVG 71,9 mm | AVG 71,8 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 80,14 | 78,81 | 80,81 | 78,88 |
| Wd= | 65,9 | 65,3 | 66,4 | 64,92 |
| m.c.= | 21,608 | 20,69 | 21,70 | 21,5 |

AVG m.c. 21,38 %

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:** Gypsum east side: at D4 (outer layer), screw not all the way through the resilient channel

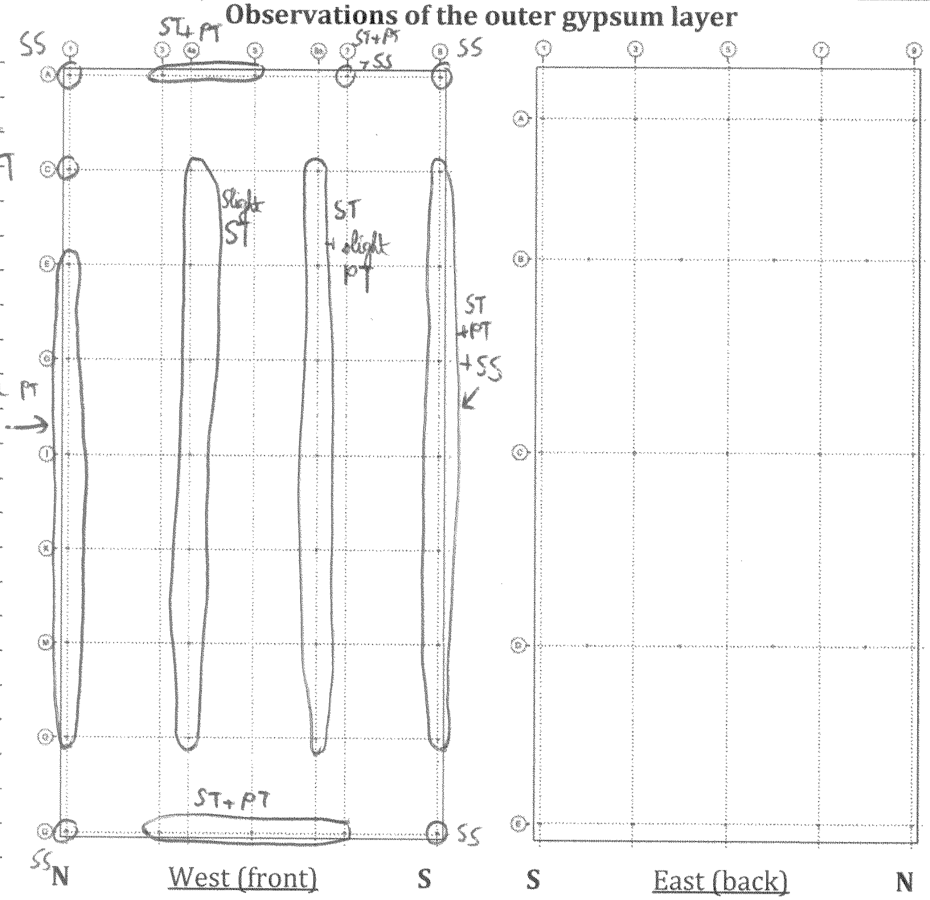
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 77 A-C
Date tested: July 28, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the outer gypsum layer**

West side notes:




East side notes:

No damage in the gypsum.

General notes:

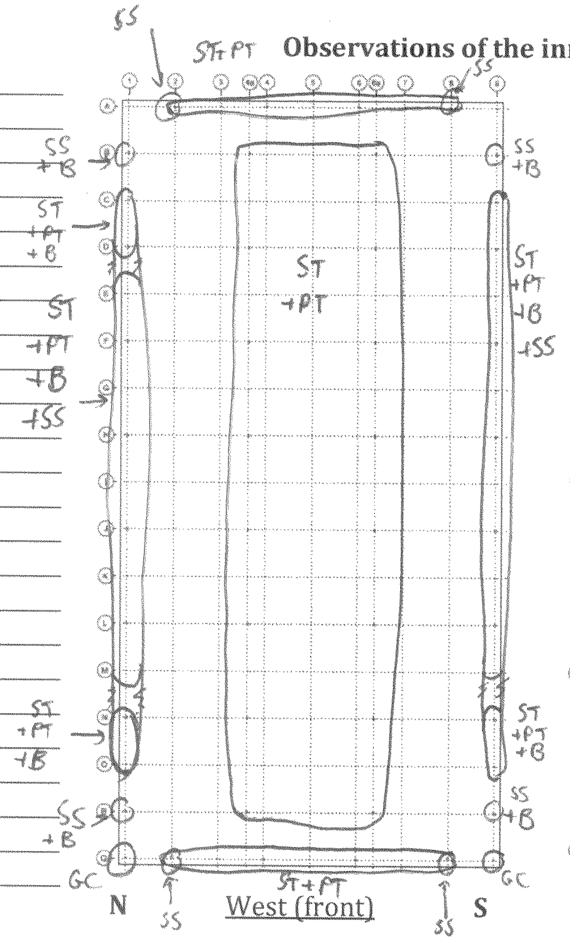
McGill

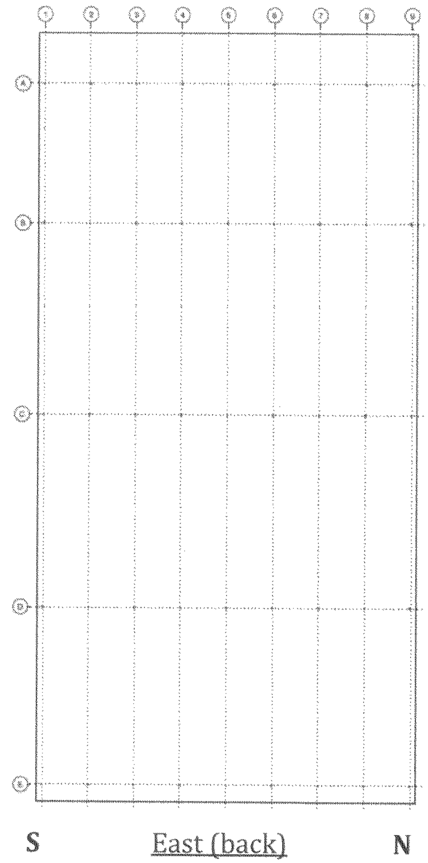
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 77 A-C
Date tested: July 28, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer

West side notes:




East side notes:

No damage in the gypsum

General notes:

McGill

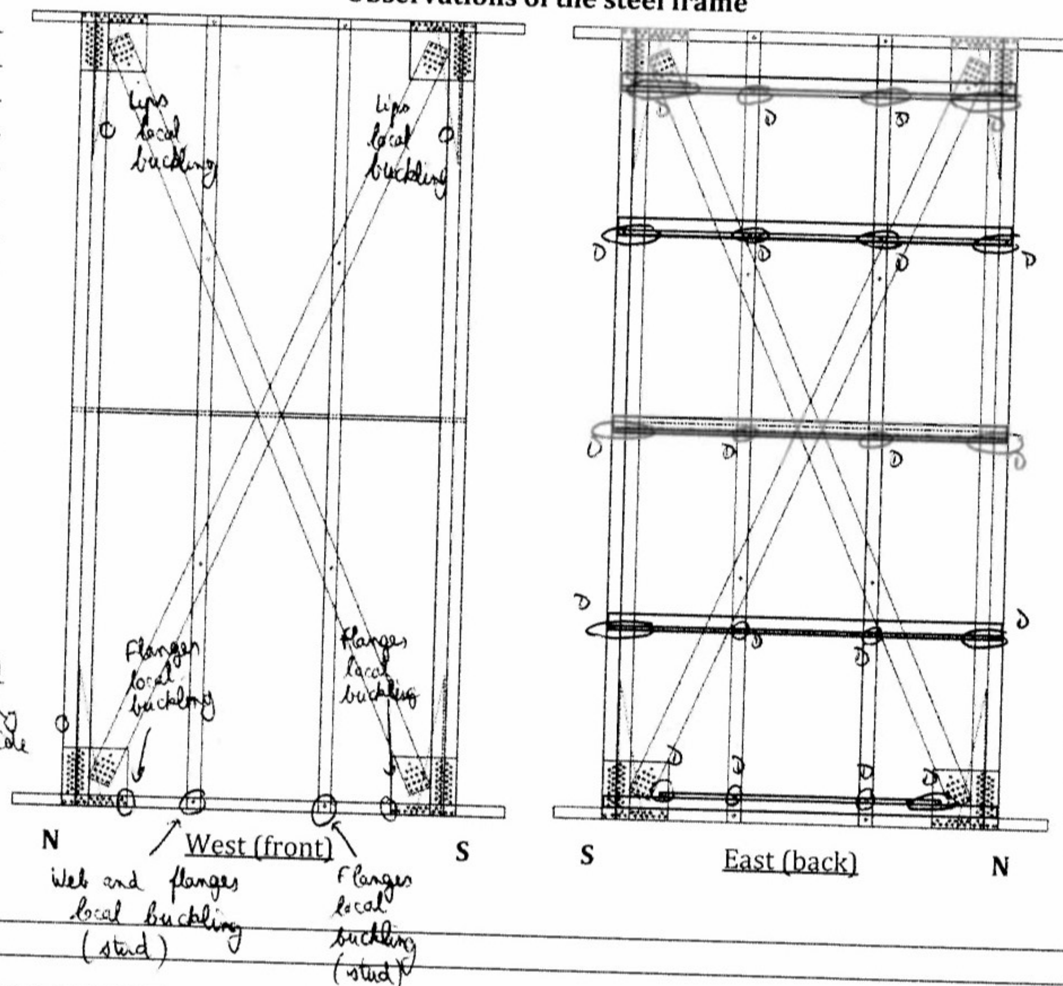
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 77 A-C
Date tested: July 28, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:

lip local buckling (west side only)




East side notes:

General notes:

- Bending of the chord studs
- Yielding of the straps

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 77 B-C

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 29, 2014 **TIME:** 4:20 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Loose | Tight |
| West | Tight | Loose |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | x | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | x | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic 5mm/min
- [x] Cyclic CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [x] Bot north- Top south brace

Total: 9

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | 70,0 | 69,6 | 73,8 | 69,3 |
| | 71,9 | 71,7 | 71,9 | 71,8 |
| | 74,5 | 74,5 | 69,9 | 75,2 |
| AVG | 72,1 mm | 71,9 mm | 71,9 mm | 72,1 mm |

**MOISTURE CONTENT OF SHEATHING:** OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 79,48 | 78,55 | 82,49 | 80,45 |
| Wd= | 65,35 | 64,54 | 67,78 | 66,46 |
| m.c.= | 21,622 | 21,71 | 21,70 | 21,05 |

AVG m.c. 21,52 %

**DATA ACQ. RECORD RATE:** 100 scan/sec **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

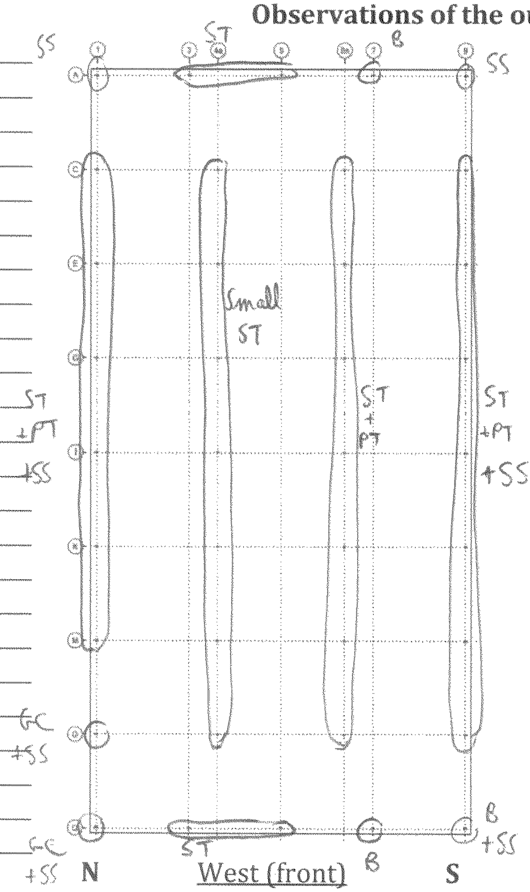
McGill

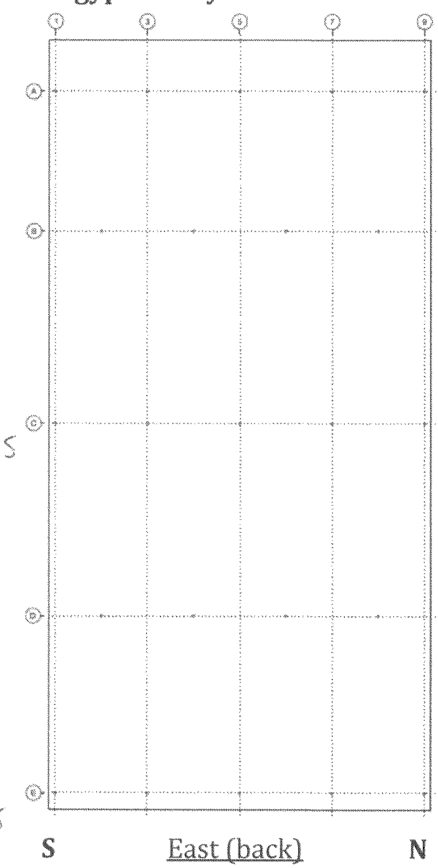
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 77 B-C
Date tested: July 29, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer

West side notes:




East side notes:

NO DAMAGE IN THE GYPSUM

General notes:

McGill

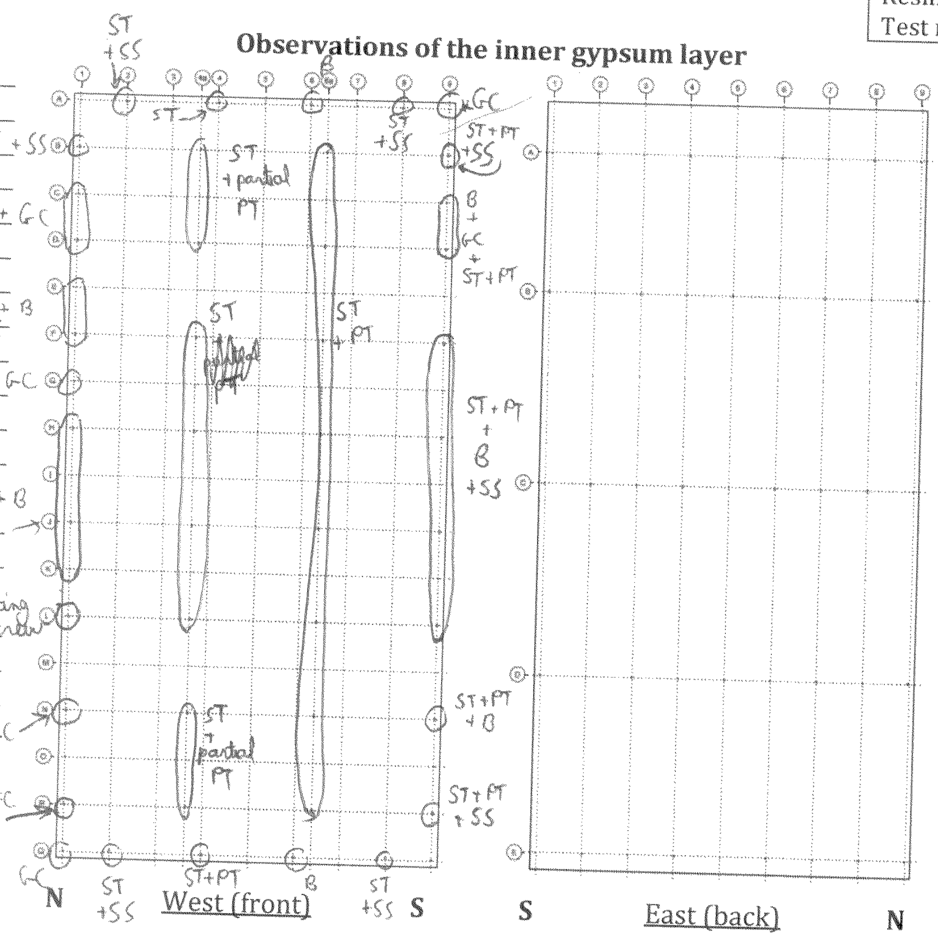
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

| | |
|---|---|
| Test name: | 77 B-C |
| Date tested: | July 29 2014 |
| # of gypsum layers per side: | 2 |
| # of sheathed sides: | 2 |
| Resilient channel: | ☑ yes ☐ no |
| Test mode: | ☐ monotonic ☑ cyclic |

## Observations of the inner gypsum layer

West side notes:

- ST + PT + SS
- ST + PT B + GC
- ST + PT + B + SS
- ~~ST + PT~~ + B + GC
- ST + PT + B + SS
- ST + PT + B + GC + bending of screw
- ST + PT + B + GC
- ST + PT + B + GC + SS




East side notes:

NO DAMAGE IN THE GYPSUM

General notes:

McGill

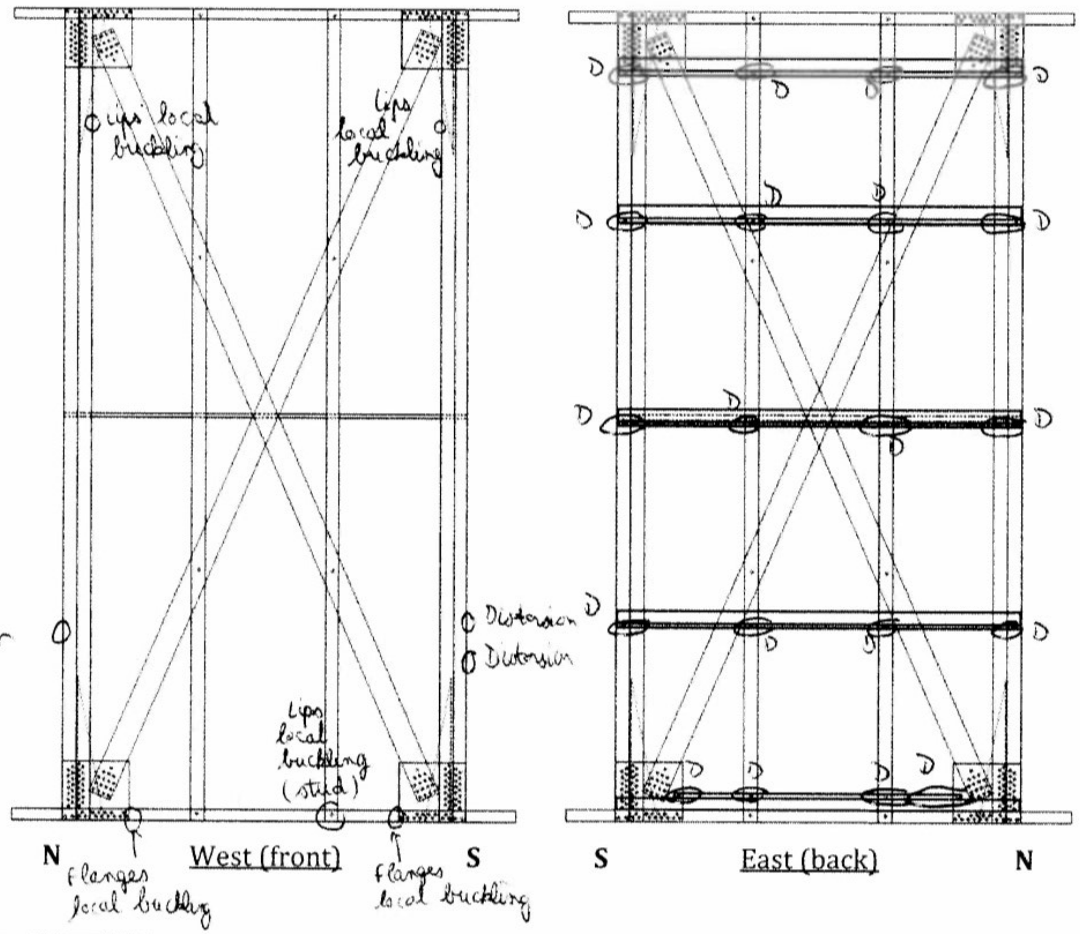
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 77 B-C
Date tested: July 29, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☑ yes ☐ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Distorsion




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 78 A-M

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 17, 2014  **TIME:** 1:10 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic  5mm/min
- [ ] Cyclic  CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| | | | |
| | | | |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 85.27 | NA | 84.21 |
| Wd= | NA | 70.10 | NA | 69.07 |
| m.c.= | NA | 21,64 | NA | 21,92 |

AVG m.c. 21,78

**DATA ACQ. RECORD RATE:** 2 scan/sec  **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

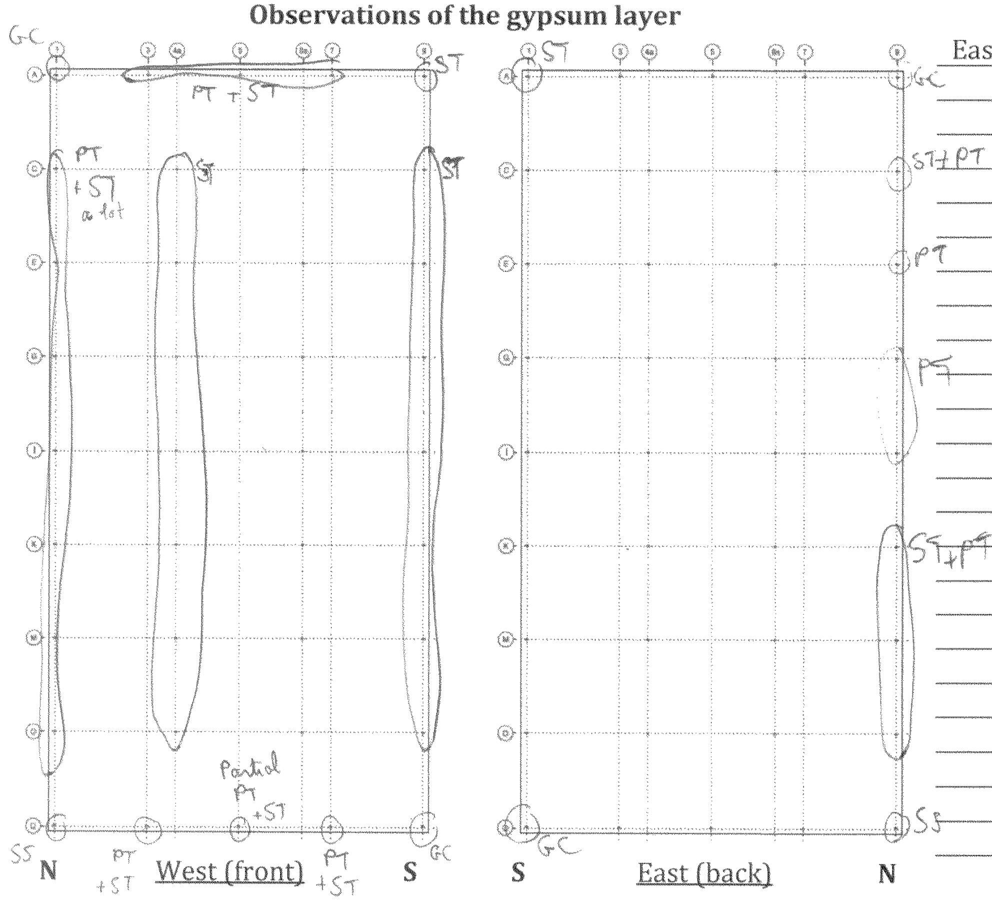
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 38 A-M
Date tested: June 17, 2014
\# of gypsum layers per side: 1
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

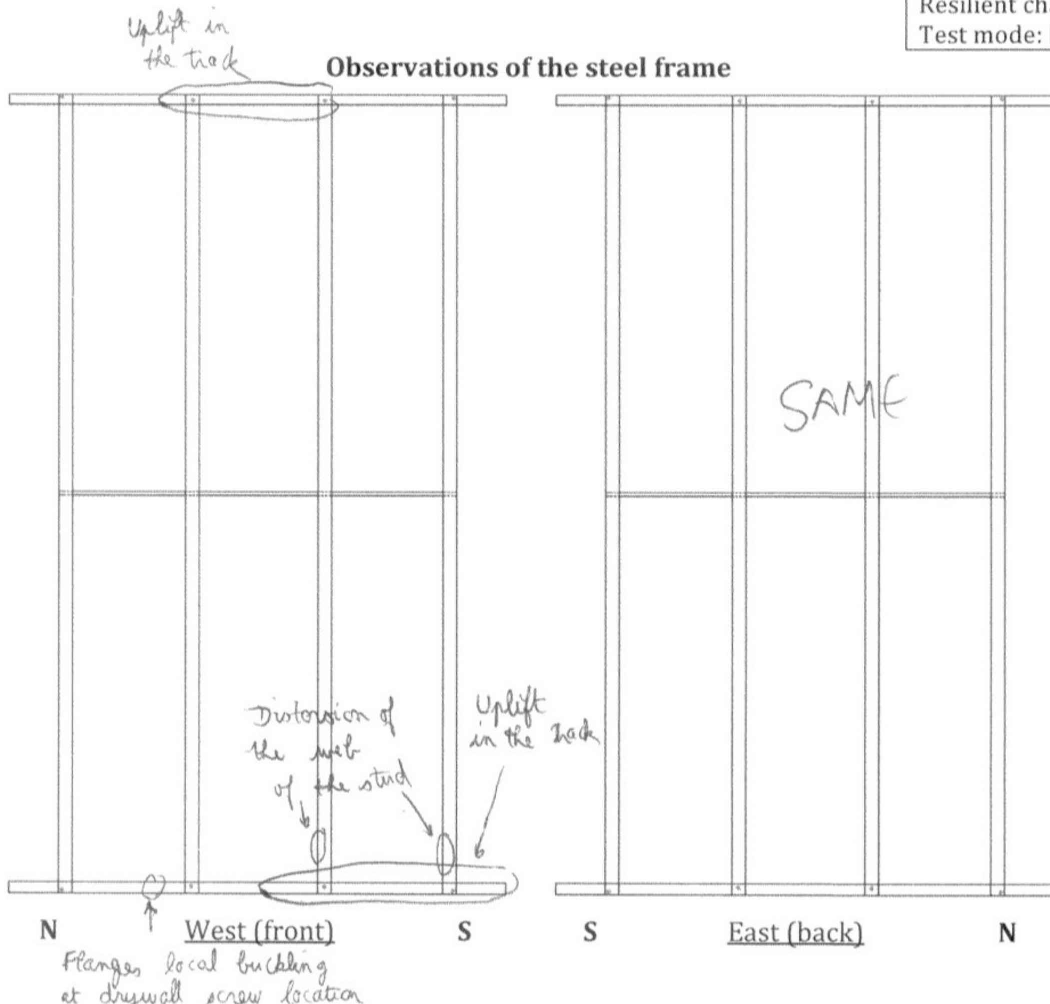
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 78 A-M
Date tested: June 17, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

**Observations of the steel frame**

West side notes:




East side notes:

General notes:

Because of the uplift of the track, the plate to put the LVDT on the south side bended

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 78 B-M

**RESEARCHER:** Sophie LU — **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 19, 2014 — **TIME:** 3:16 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| | | | |
| | | | |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 83,25 | NA | 81,18 |
| Wd= | NA | 68,41 | NA | 67,13 |
| m.c.= | NA | 21,69 | NA | 20,93 |

AVG m.c. 21,31

**DATA ACQ. RECORD RATE:** 2 scan/sec — **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

Gypsum is cracked on the West side, North bottom corner

Plate washer used in the most southerly bottom track connection

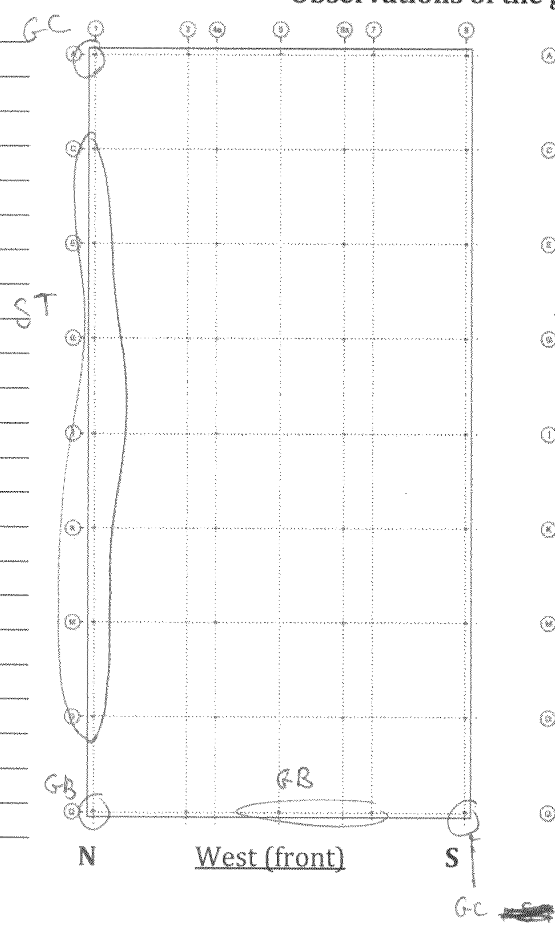
McGill

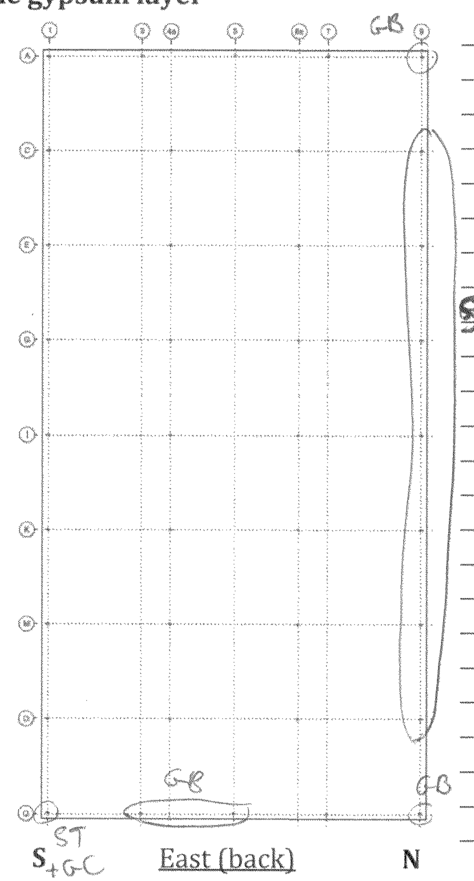
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 78 B-M
Date tested: June 19, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

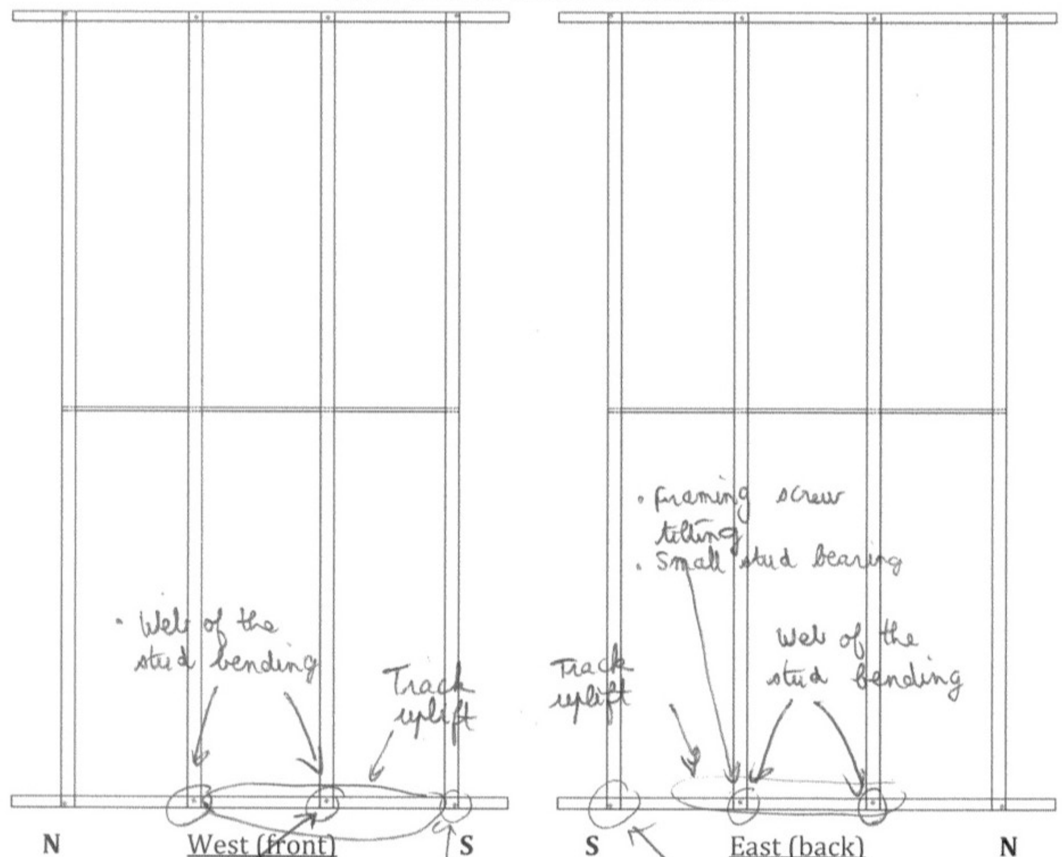
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 78 B-M
Date tested: June 19, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:




East side notes:

General notes:

- Framing screw tilting
- Small stud bearing
- ~~Stud and~~ track bearing (plug shear)
- Tilting of the framing screw
- Small stud bearing
- Stud bearing
- Tilting of the gypsum screw

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 78 C-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 31, 2014 **TIME:** 9:35 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 7

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| NA | NA | NA | NA |
| NA | NA | NA | NA |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 82,51 | NA | 81,03 |
| Wd= | NA | 67,6 | NA | 66,98 |
| m.c.= | NA | 22,06 | NA | 20,98 |

AVG m.c. 21,52

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:**
Small cracks in the gypsum on the East side, South corners and top north corner
Plate washer used in the most southerly bottom track connection

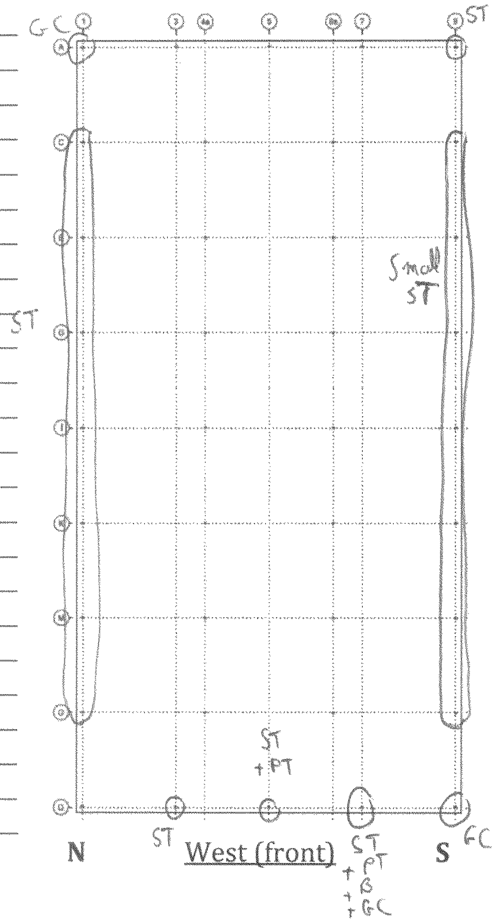
McGill

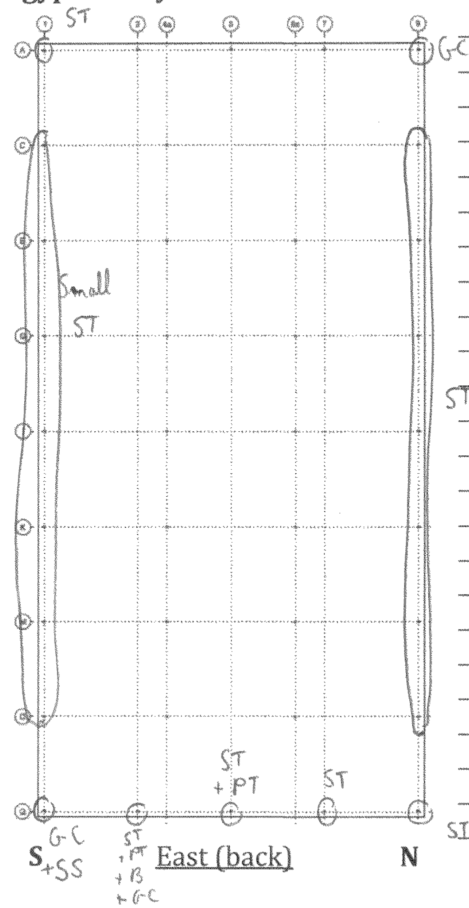
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 78 C-M
Date tested: July 31, 2014
\# of gypsum layers per side: 1
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the gypsum layer

West side notes:




East side notes:

General notes:

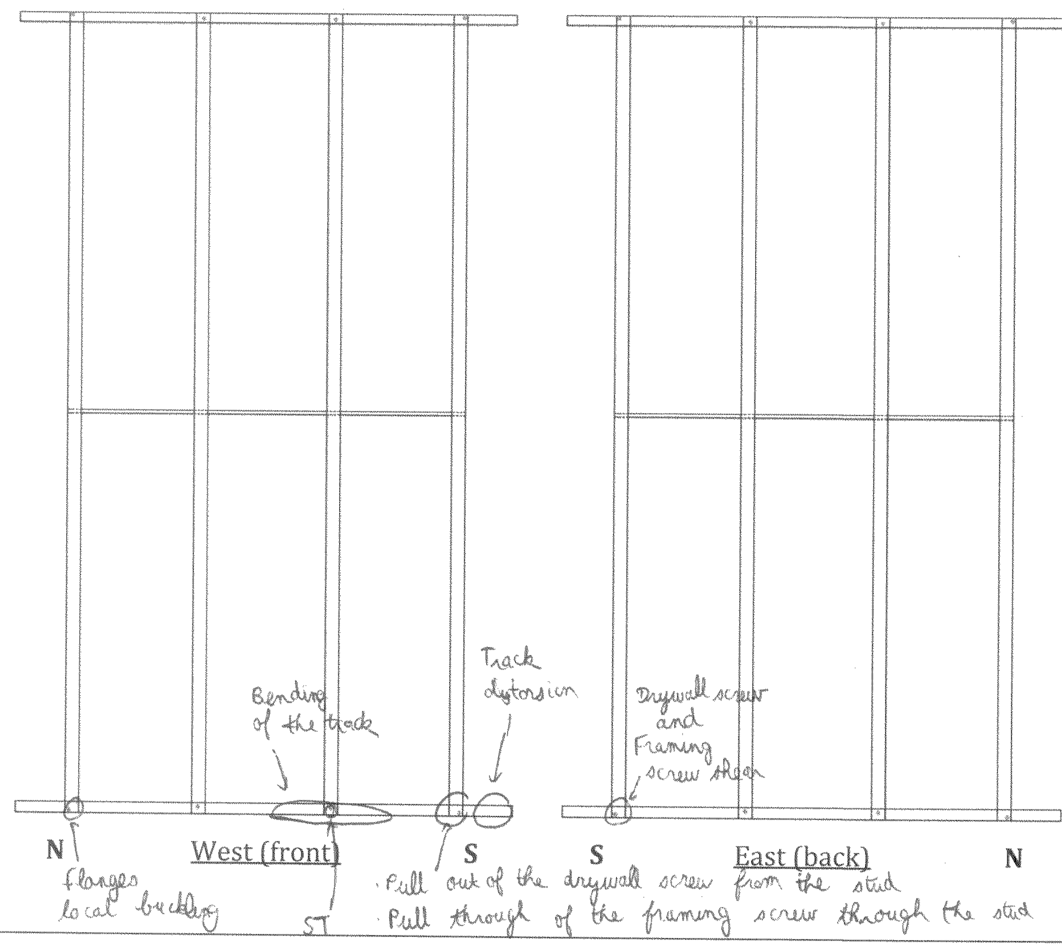
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 28 C-M
Date tested: July 31, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 79 A-C

**RESEARCHER:** Sophie LU    **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested July 11, 2014    **TIME:** 9:40 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson    number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic    5mm/min
- [x] Cyclic    CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | | North Uplift LVDT | | Bot south-Top north brace |
| x | North Slip LVDT | | South Uplift LVDT | | Bot north- Top south brace |

Total: 5

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 79,34 | NA | 82,05 |
| Wd= | | 65,38 | | 67,53 |
| m.c.= | NA | 21,35 | NA | 21,5 |

AVG m.c. 21,43

**DATA ACQ. RECORD RATE:** 100 scan/sec    **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

McGill

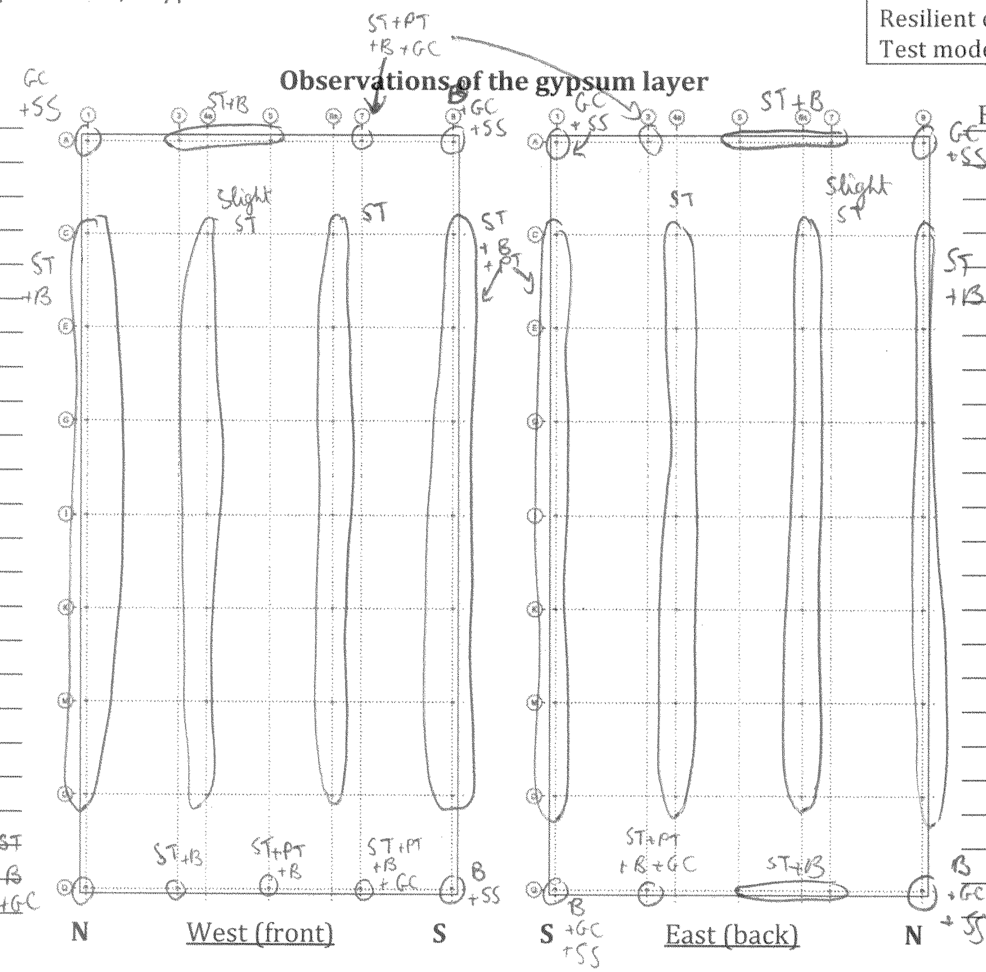
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 79 A-C
Date tested: July 11, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☒ no
Test mode: ☐ monotonic ☒ cyclic

## Observations of the gypsum layer

West side notes:

East side notes:




General notes:

McGill

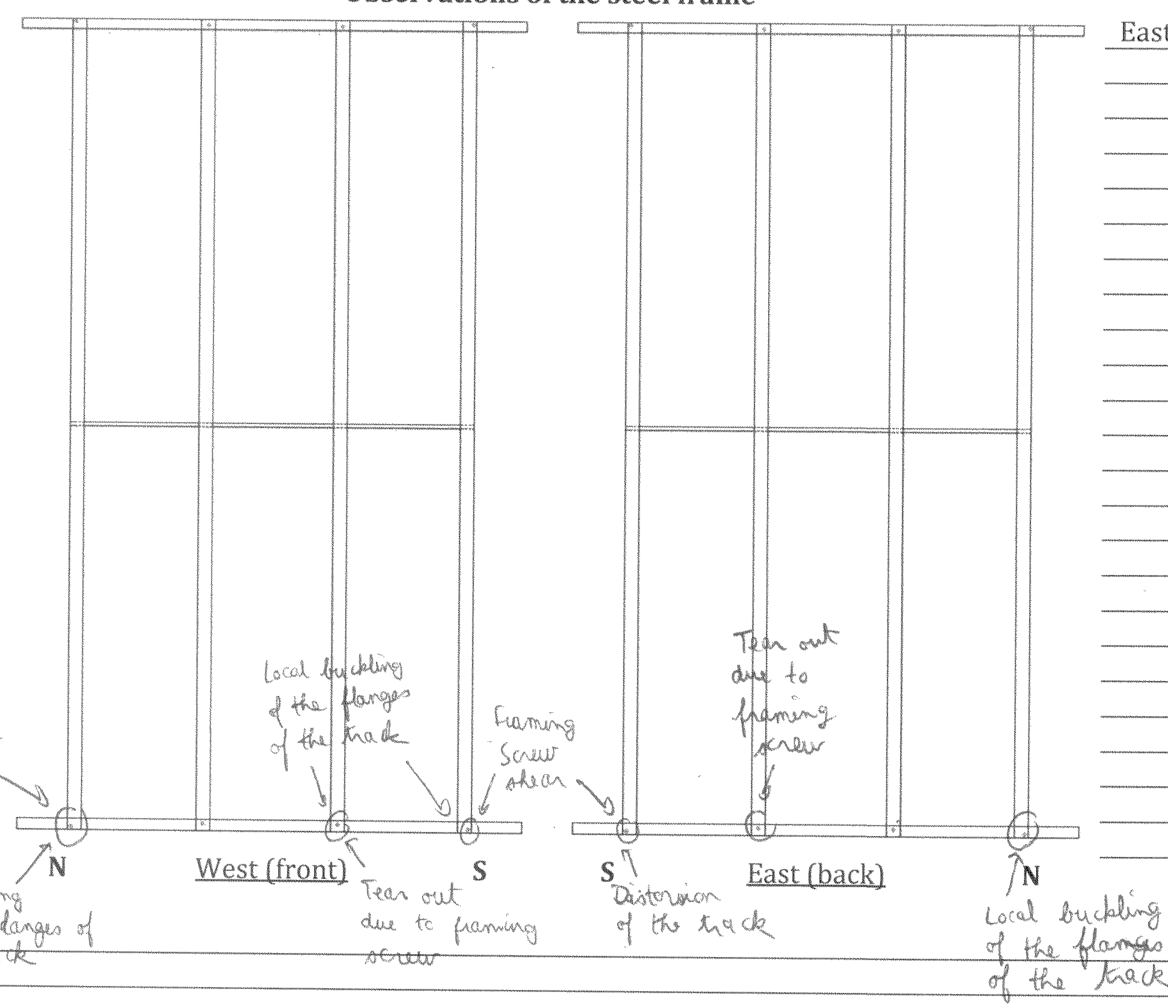
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 79 A-C
Date tested: July 11, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Tearing of the flange of the track due to drywall screw




East side notes:

General notes: Local buckling of the flanges of the track

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 79 B-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested July 11, 2014  **TIME:** 1:55 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [x] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | | |
|---|---|---|---|
| Sheathing: | Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| | Top layer | | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | | |
| Straps: | | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | | 1" Rod |
| Loading beam: | | x | A325 3/4" bolts |
| Base: | | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [ ] North Uplift LVDT
- [ ] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 5

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| | | | |
| | | | |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | 80,02 | NA | 79,71 |
| Wd= | | 66,33 | | 65,85 |
| m.c.= | NA | 20,64 | NA | 21,05 |

AVG m.c. 20,84

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 79 B-C
Date tested: July 11, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

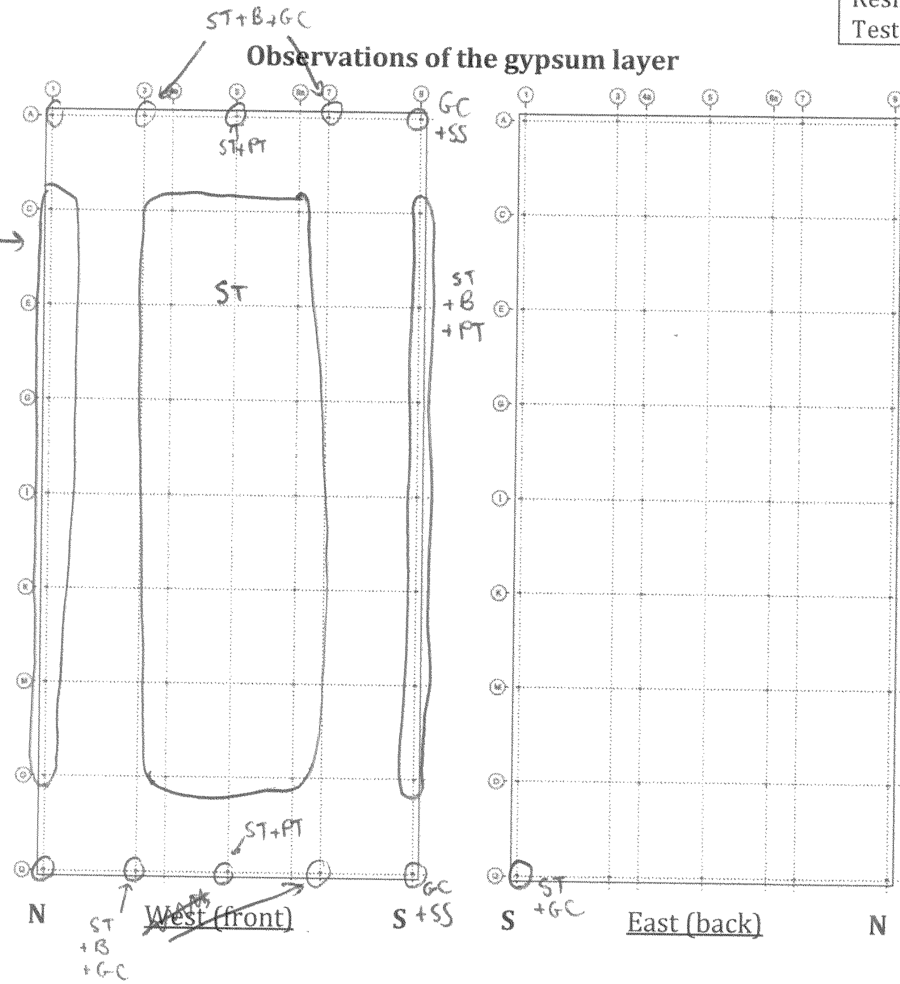
## Observations of the gypsum layer

West side notes:

GC +SS

ST + B + PT

ST + GC




East side notes:

Same failures as west side except Q1

General notes:

**McGill**

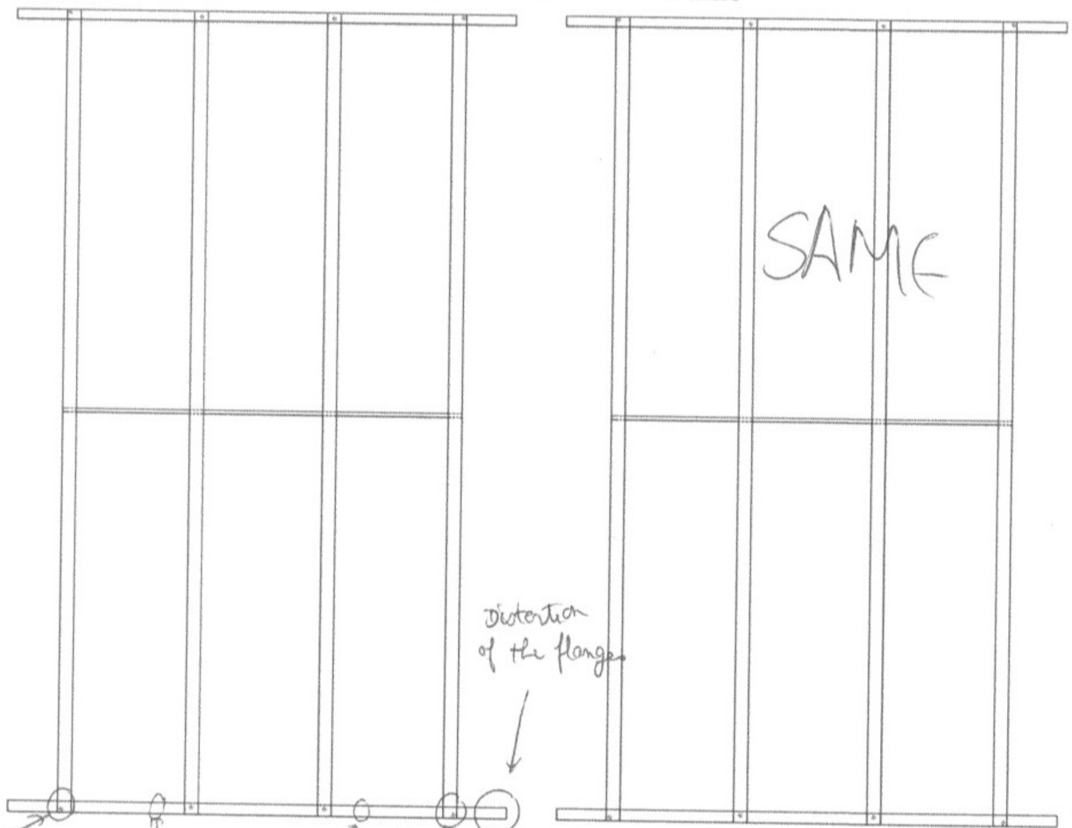
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 79 B-C
Date tested: July 11, 2014
# of gypsum layers per side: 1
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the steel frame**

West side notes:

Flanges local buckling




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 80 A-M

**RESEARCHER:** Sophie LU **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 18, 2014 **TIME:** 10:55 AM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic 5mm/min
- [ ] Cyclic CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**

| | | | | | |
|---|---|---|---|---|---|
| x | MTS Actuator LVDT | x | South Slip LVDT | x | String potentiometer |
| x | MTS Actuator load cell | x | North Uplift LVDT | | Bot south-Top north brace |
| x | North Slip LVDT | x | South Uplift LVDT | | Bot north- Top south brace |

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 83,9 | 83,64 | 83,19 | 83,33 |
| Wd= | 68,67 | 68,54 | 68,26 | 68,37 |
| m.c.= | 22,179 | 22,03 | 21,87 | 21,88 |

AVG m.c. 21,99 %

**DATA ACQ. RECORD RATE:** 2 scan/sec **MONITOR RATE:** 10 scan/sec

**COMMENTS:** Plate washer used in the most southerly bottom track connection

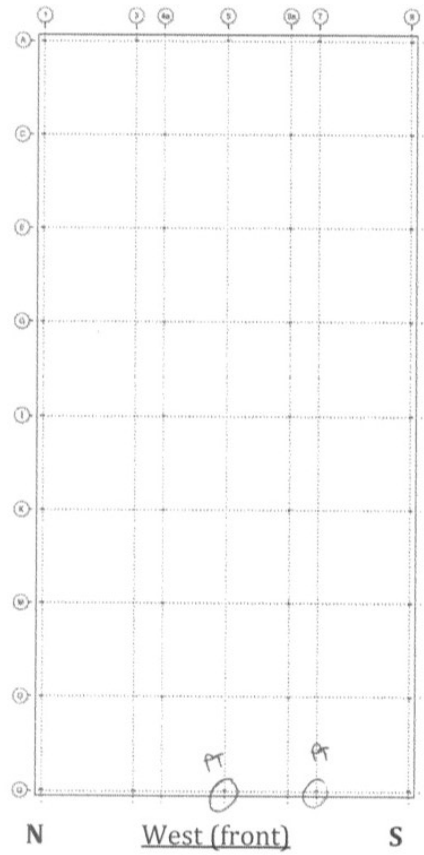
McGill

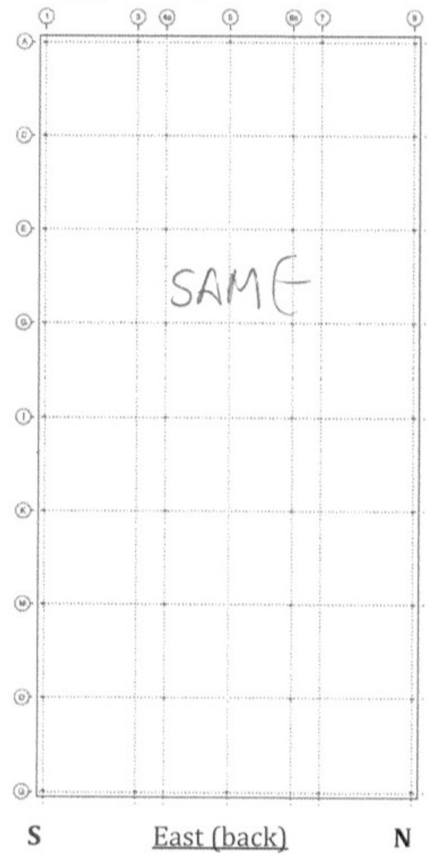
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 90 A-M
Date tested: June 18, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

**Observations of the outer gypsum layer**

West side notes:




East side notes:

General notes:

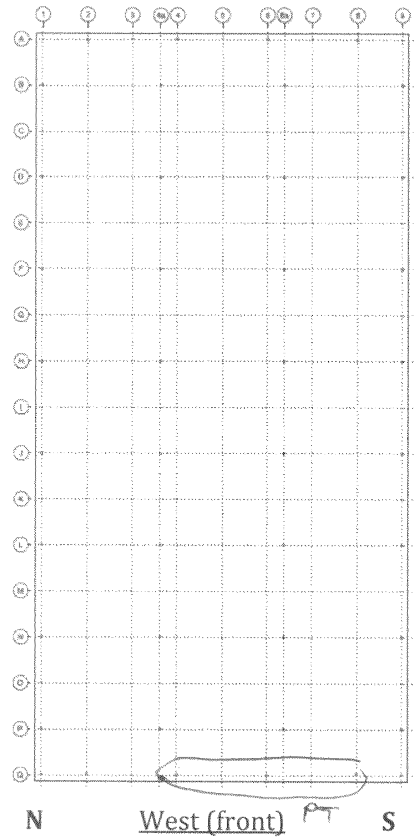
McGill

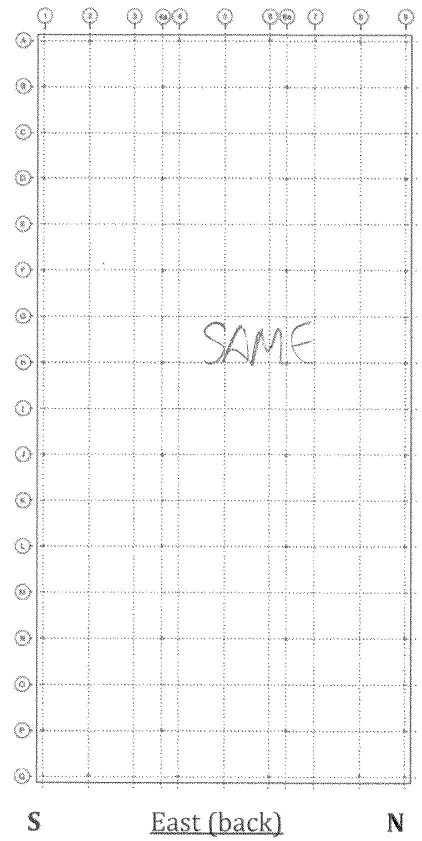
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 80 A-M
Date tested: June 18, 2016
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer

West side notes:




East side notes:

General notes:

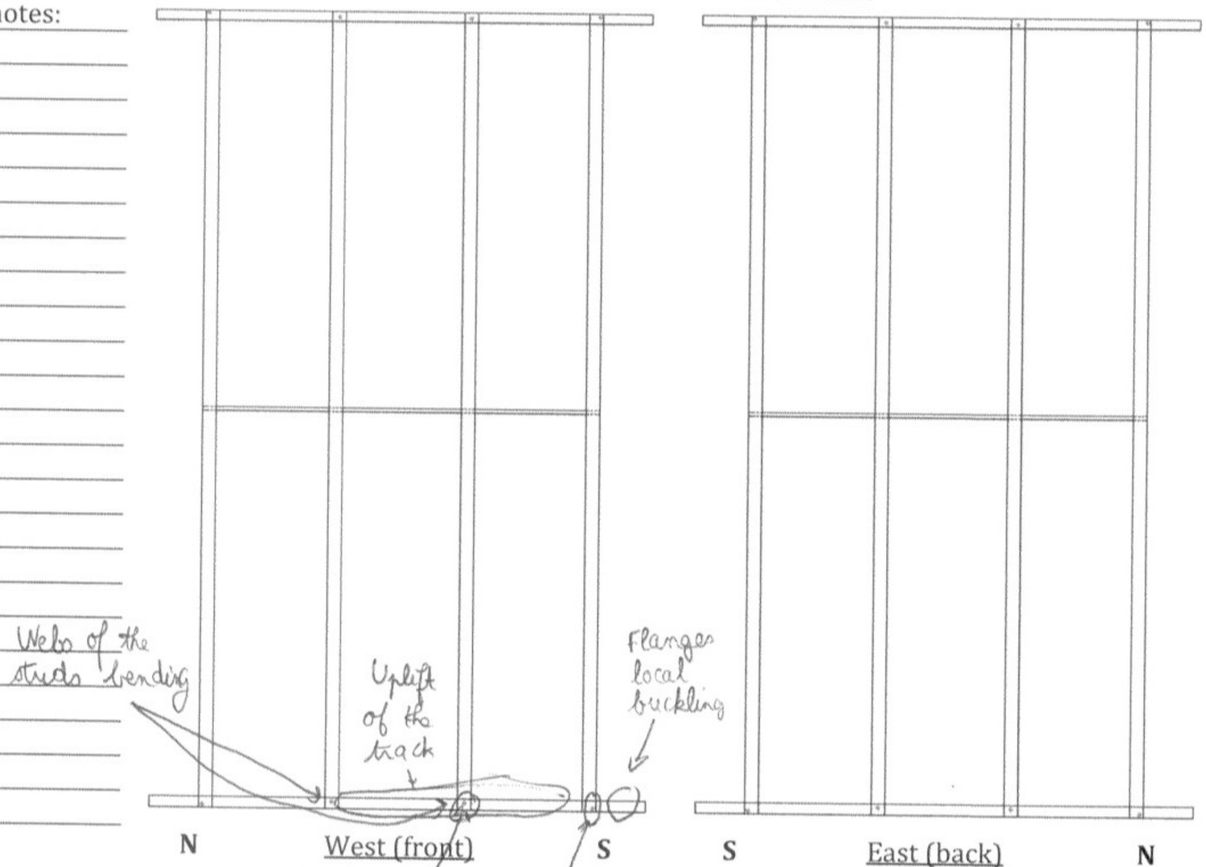
**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 80 A-M
Date tested: June 18, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☒ no
Test mode: ☒ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:




East side notes:

General notes:
- Framing screw tilting
- Flanges of the track local buckling
- Framing screw bearing

Screws bearing (drywall screw and framing screw going through the flanges of the track)

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 80 B-M

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 18, 2014  **TIME:** 4:20 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | x | 32mm (1''-1/4) type S drywall screw |
| Sheathing: Top layer | x | 48mm (1''-7/8) type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 83,77 | 83,52 | 83,9 | 83,83 |
| Wd= | 68,74 | 68,77 | 68,94 | 68,65 |
| m.c.= | 21,865 | 21,45 | 21,70 | 22,11 |

AVG m.c. 21,78 %

**DATA ACQ. RECORD RATE:** 2 scan/sec  **MONITOR RATE:** 10 scan/sec

**COMMENTS:** Plate washer used in the most southerly bottom track connection

McGill

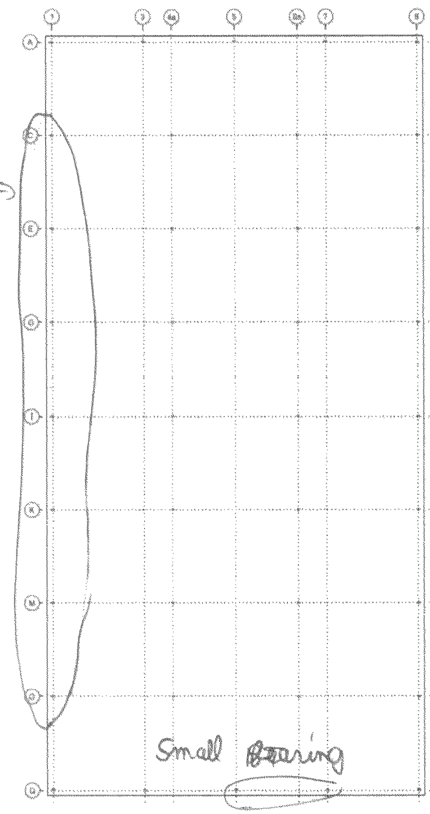
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 80 B-M
Date tested: June 18 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

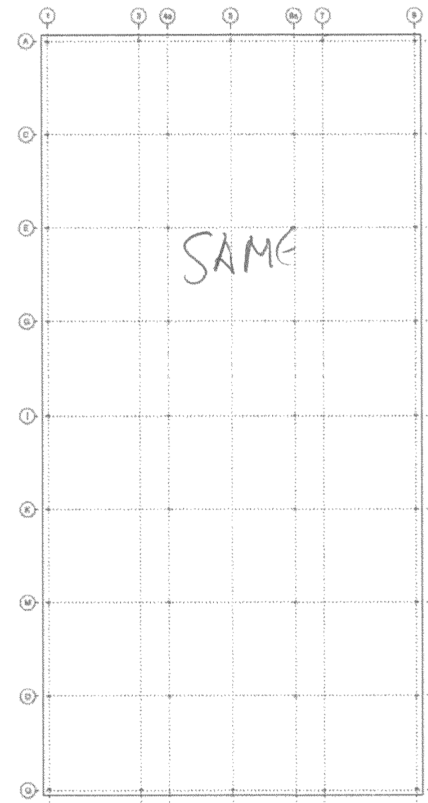
**Observations of the outer gypsum layer**

West side notes:

Screws slightly tilted →




N West (front) S




S East (back) N

East side notes:

General notes:

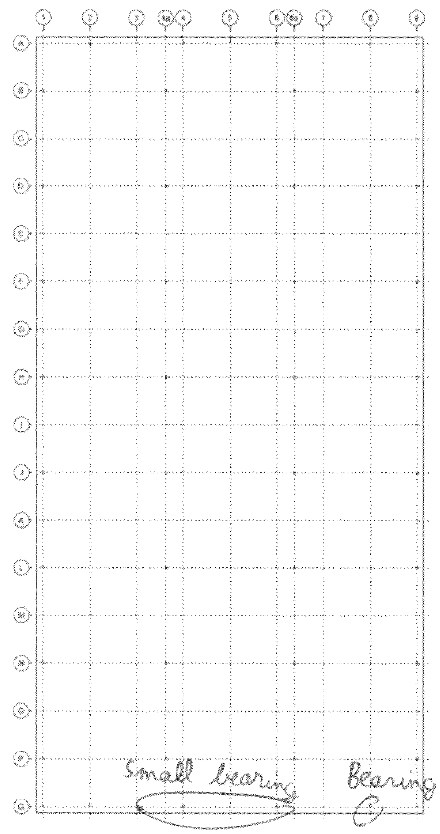
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

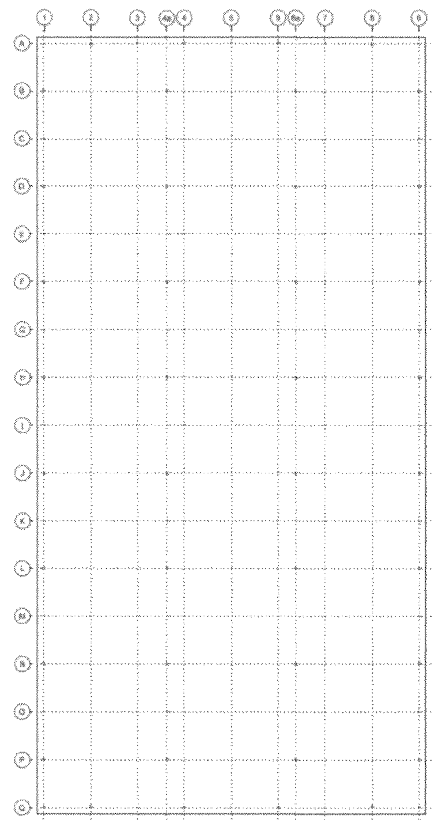
Test name: 80 B-M
Date tested: June 18, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

## Observations of the inner gypsum layer

West side notes:




N West (front) S



S East (back) N

East side notes:

General notes:

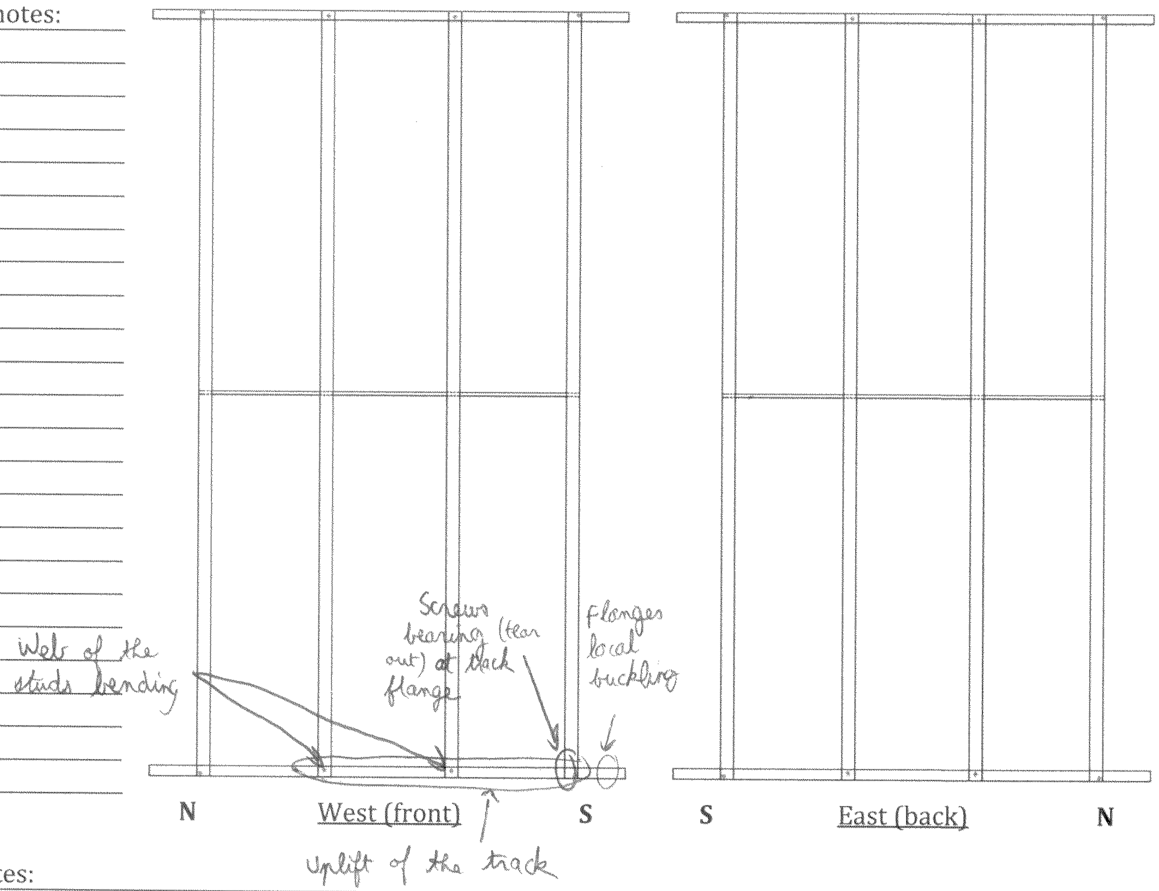
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 80 B-M
Date tested: June 18, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☒ no
Test mode: ☒ monotonic ☐ cyclic

## Observations of the steel frame

West side notes:




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 81 A-C

**RESEARCHER:** Sophie LU
**ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested July 14, 2014
**TIME:** 2:15 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**

Sheathing:
- Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [x] 48mm (1''-7/8) type S drywall screw

- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [ ] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [ ] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic — 5mm/min
- [x] Cyclic — CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [ ] North Uplift LVDT
- [ ] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 5

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 80,05 | 81,98 | 81,3 | 81,61 |
| Wd= | 66,2 | 67,91 | 66,53 | 66,59 |
| m.c.= | 20,921 | 20,72 | 22,20 | 22,56 |

AVG m.c. 21,60 %

**DATA ACQ. RECORD RATE:** 100 scan/sec
**MONITOR RATE:** 200 scan/sec

**COMMENTS:**

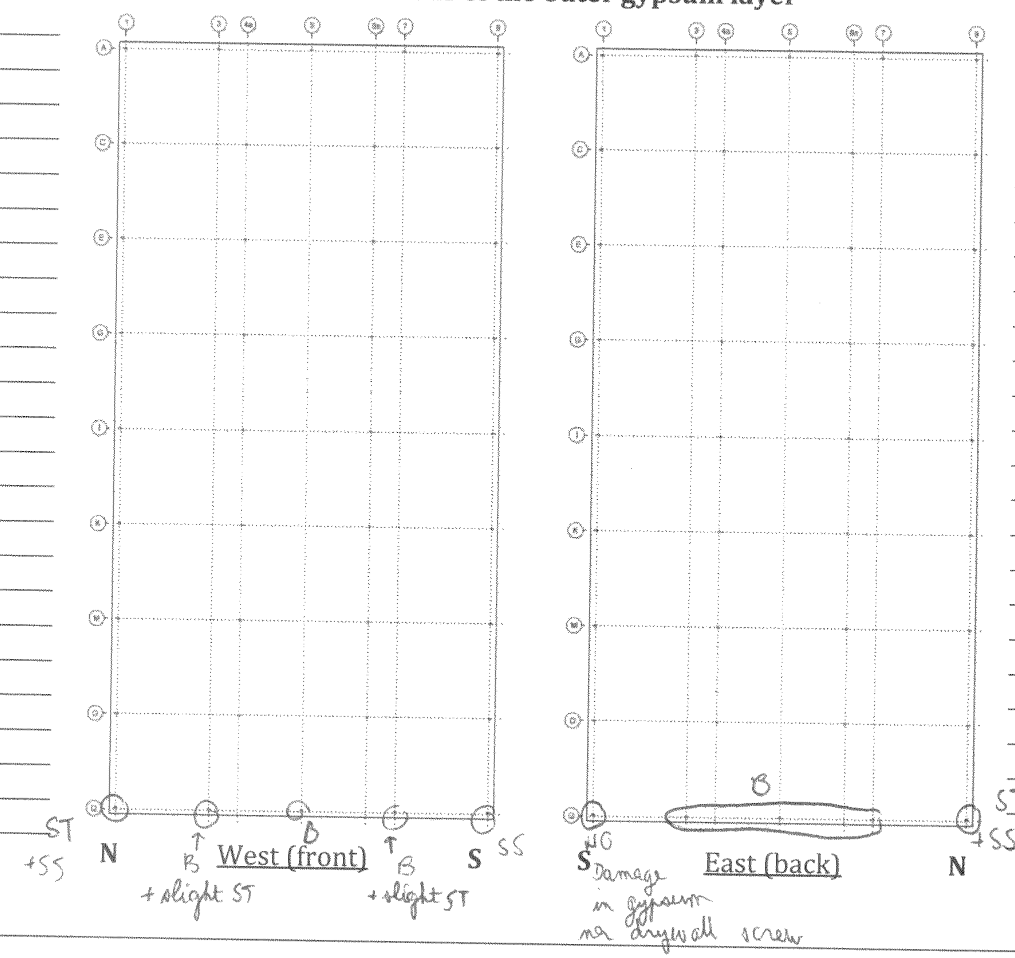
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 81 A-C
Date tested: July 14, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer

West side notes:




East side notes:

General notes:

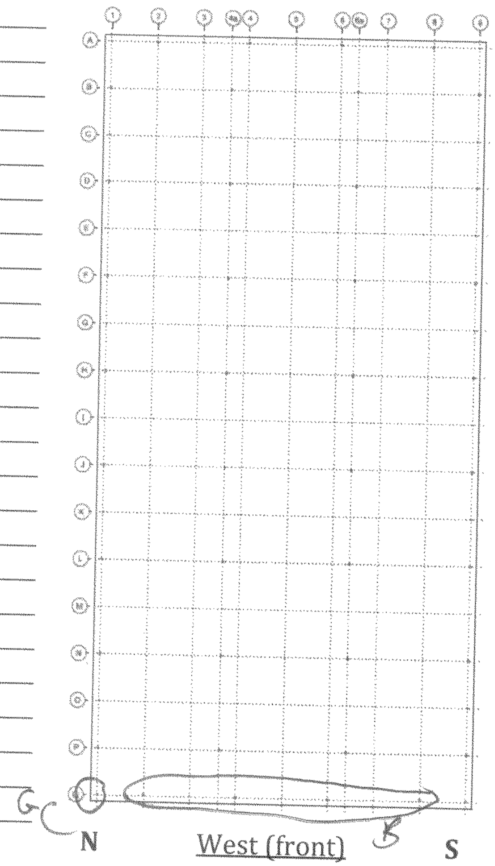
McGill

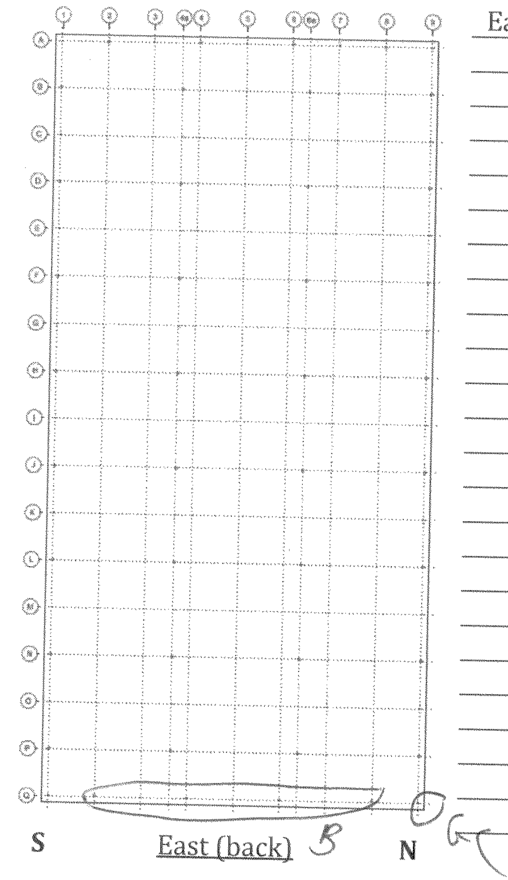
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 81 A-C
Date tested: July 14, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

**Observations of the inner gypsum layer**

West side notes:




East side notes:

General notes:

McGill

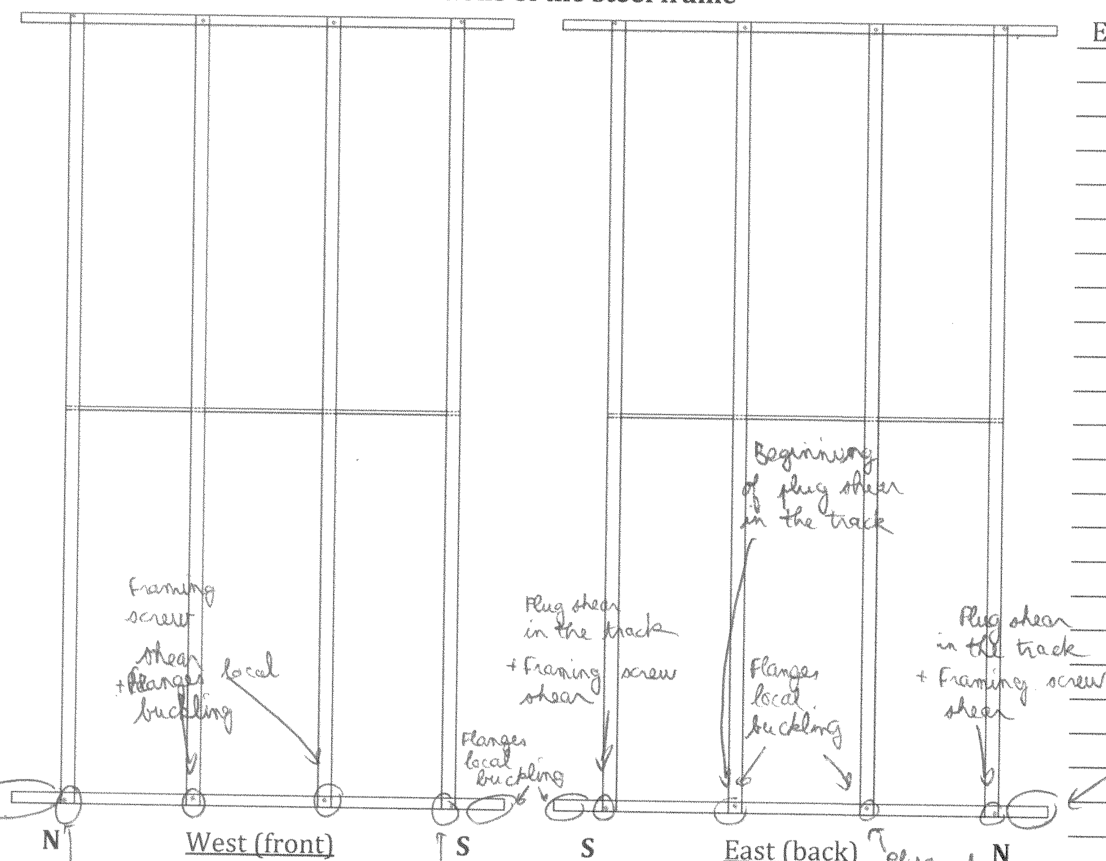
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 81 A-C
Date tested: July 14, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Flanges local buckling




East side notes:

Flanges local buckling

General notes:

Plug shear in the track (Framing screw and drywall screw) + Flanges local buckling + Framing screw shear

Framing screw shear + flanges distorsion (track) + Distorsion of the stud

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 81 B-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested July 15, 2014  **TIME:** 4:35 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [x] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [ ] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [x] No hold down
- [ ] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [ ] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [x] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS AND BOLTS:**
- Sheathing: Inner layer [x] 32mm (1''-1/4) type S drywall screw
- Top layer [x] 48mm (1''-7/8) type S drywall screw
- Resilient channel: [ ]
- Straps: [x] No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive
- Framing: [x] No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive
- Hold downs: [ ] No. 14 gauge 1" self-drilling hex washer head
- Back-to-back chord studs: [x] No. 10 gauge 0.5" self-drilling hex head
- Anchor rods: [ ] 1" Rod
- Loading beam: [x] A325 3/4" bolts
- Base: [x] A325 3/4" bolts

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [ ] North Uplift LVDT
- [ ] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 5

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| NA | NA | NA | NA |
| | | | |
| | | | |
| AVG NA mm | AVG NA mm | AVG NA mm | AVG NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | 83,09 | 81,64 | 80,61 | 78,91 |
| Wd= | 68,15 | 67,22 | 66,58 | 64,9 |
| m.c.= | 21,922 | 21,45 | 21,07 | 21,59 |

AVG m.c. 21,51 %

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:**

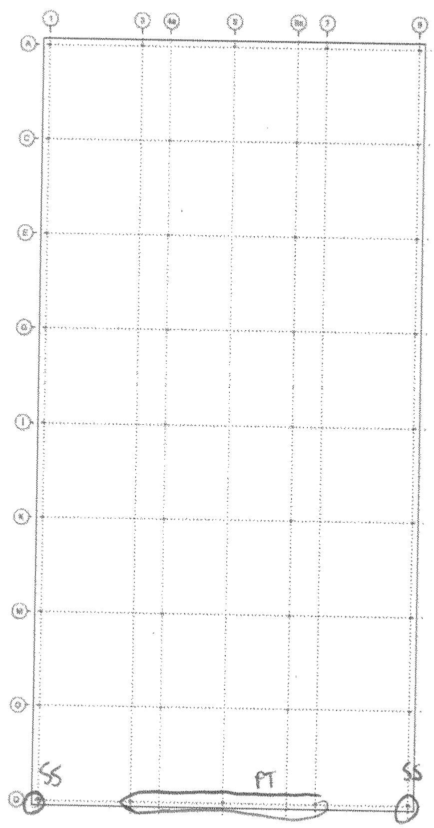
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

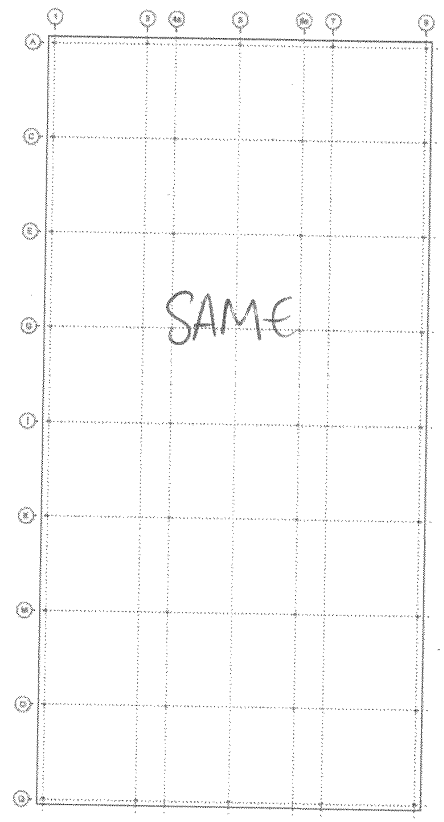
Test name: 81 B-C
Date tested: July 15, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the outer gypsum layer

West side notes:




West (front)




East (back)

East side notes:

General notes:

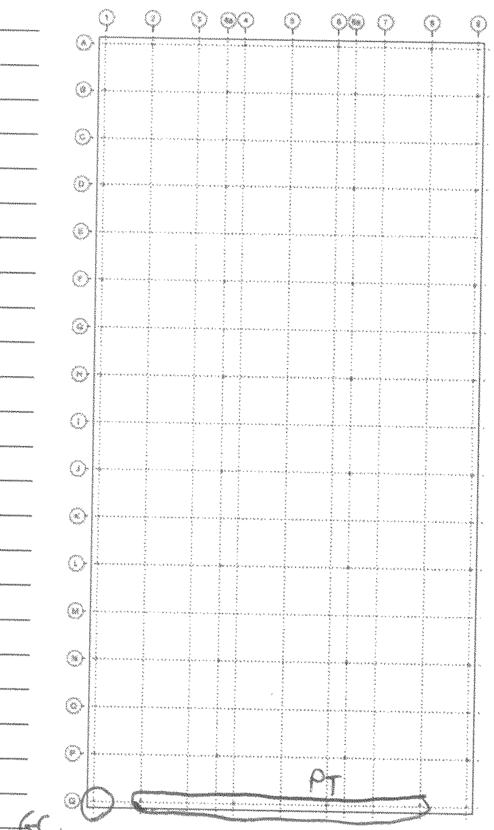
**McGill**

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

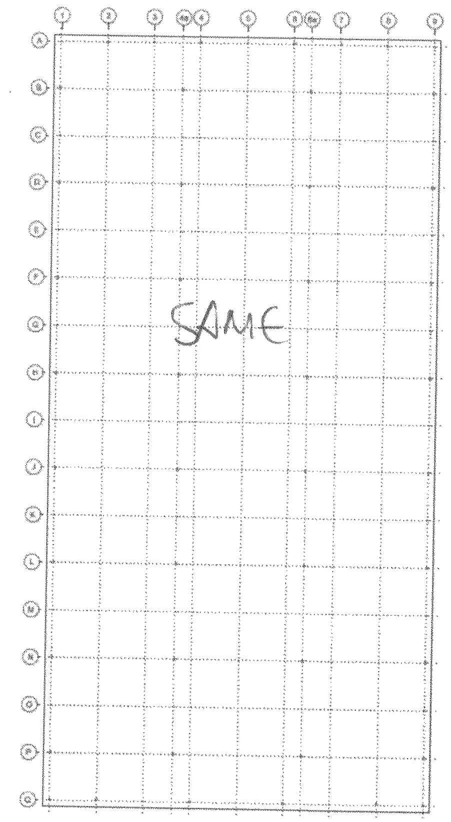
Test name: 81 B-C
Date tested: July 15, 2014
# of gypsum layers per side: 2
# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the inner gypsum layer

West side notes:




**N** West (front) **S**




**S** East (back) **N**

East side notes:

General notes:

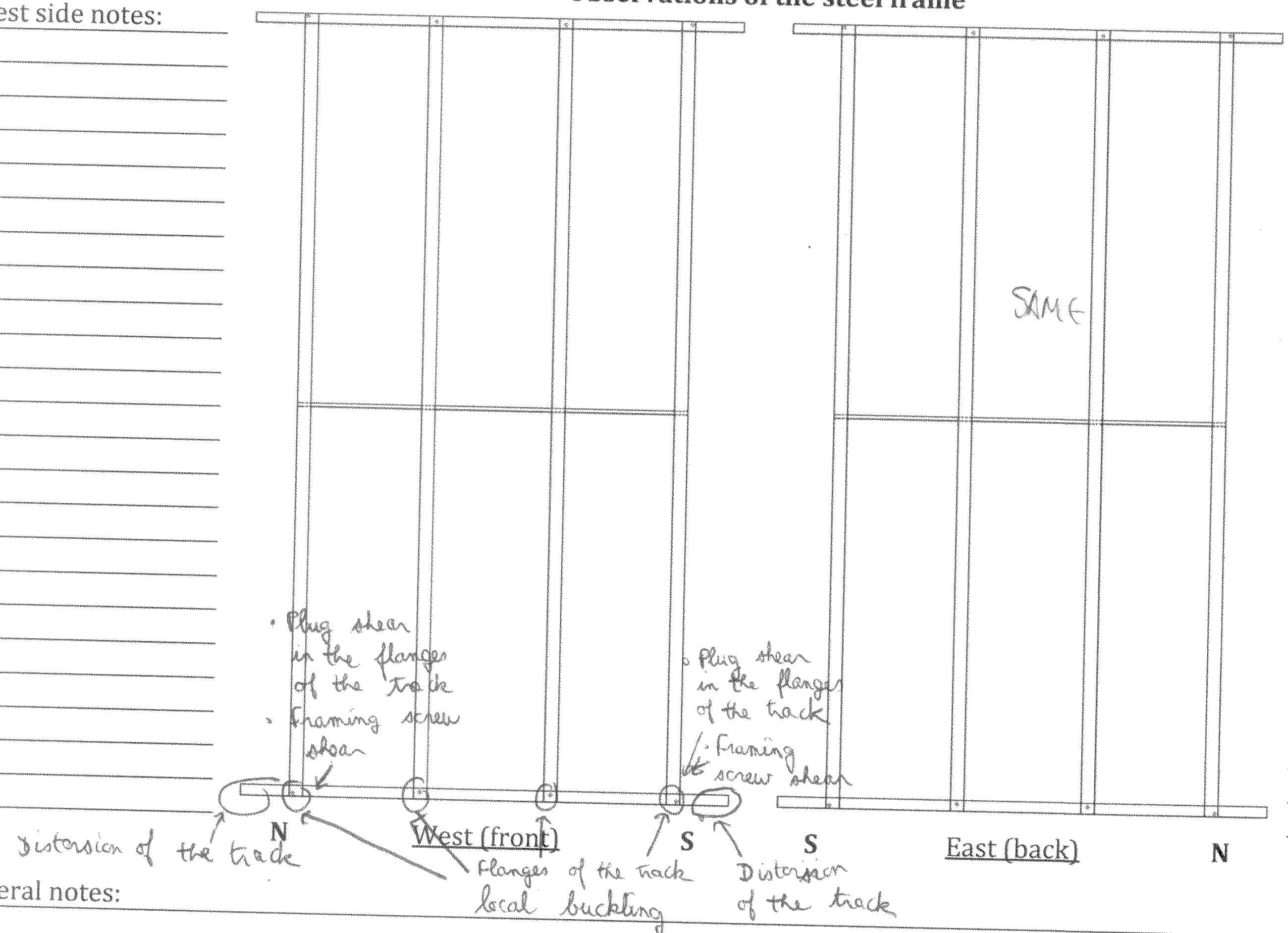
McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 81B-C
Date tested: July 15, 2014
\# of gypsum layers per side: 2
\# of sheathed sides: 2
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 82 A-M

**RESEARCHER:** Sophie LU — **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built May 2014; Tested June 16, 2014 — **TIME:** 4:20 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | NA | NA |
| West | NA | NA |

**STRAP:**
- [x] No strap
- [ ] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [x] No gusset plate
- [ ] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson — number of screws: 33

**SHEATHING:**
- [x] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | | 32mm type S drywall screw |
| Sheathing: Top layer | | 50mm type S drywall screw |
| Resilient channel: | | |
| Straps: | | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [x] Monotonic — 5mm/min
- [ ] Cyclic — CUREE reversed cyclic

**MEASUREMENT INSTRUMENTS**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [ ] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 7

**STRAP WIDTH BEFORE TEST:**

| | West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|---|
| | NA | NA | NA | NA |
| | | | | |
| | | | | |
| AVG | NA mm | NA mm | NA mm | NA mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | NA | NA |
| Wd= | | | | |
| m.c.= | NA | NA | NA | NA |

AVG m.c. #DIV/0!

**DATA ACQ. RECORD RATE:** 2 scan/sec — **MONITOR RATE:** 10 scan/sec

**COMMENTS:**

Steel frame from wall 68 A-M:

> the web and lib of the north interior stud suffered loacl buckling

> the bridging channel was damaged in the middle when the gypsum was taken off

McGill

Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

Test name: 82 A-M
Date tested: June 16, 2014
# of gypsum layers per side: Ø
# of sheathed sides: Ø
Resilient channel: ☐ yes ☑ no
Test mode: ☑ monotonic ☐ cyclic

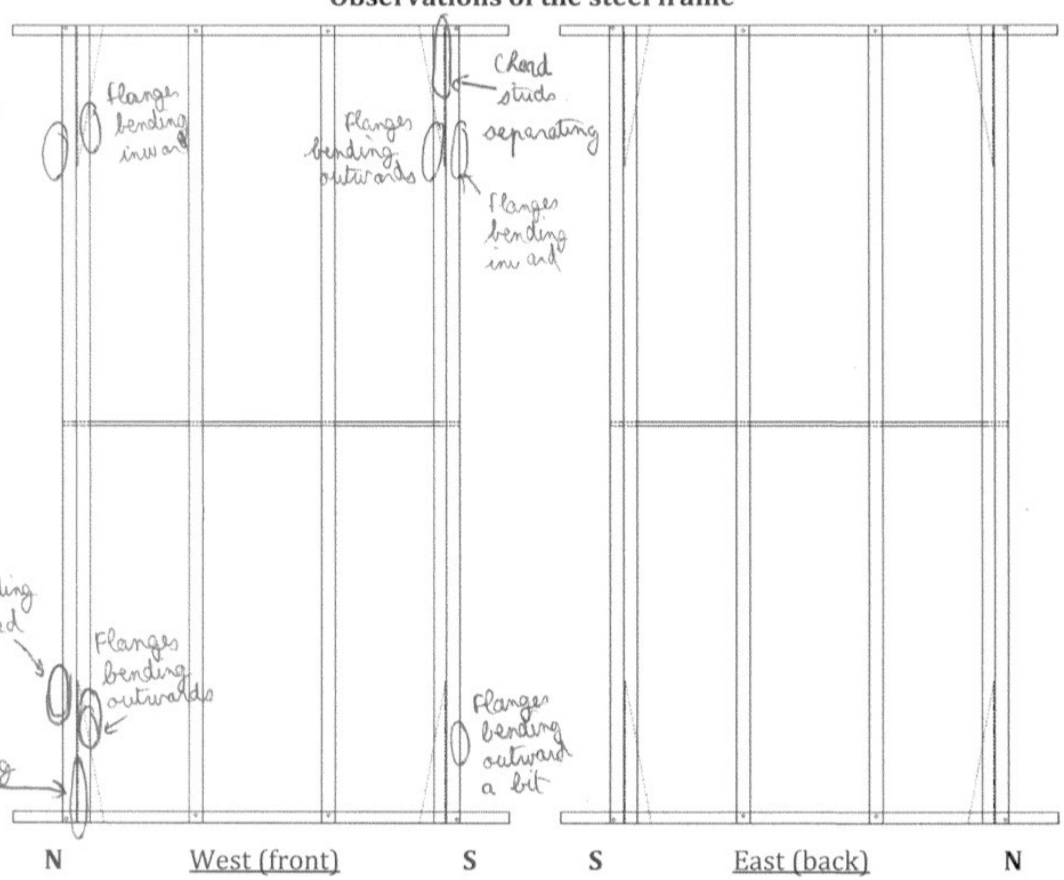
**Observations of the steel frame**

West side notes:

flanges bending outwards

flanges bending inward

Chord studs separating




East side notes:

General notes:

## Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls
## McGill University, Montreal

**TEST:** 83 A-C

**RESEARCHER:** Sophie LU  **ASSISTANTS:** Siriane LAWLESS, Milad FORADI, David PIZZUTO

**DATE:** Built July 2014; Tested July 31, 2014  **TIME:** 12:05 PM

**DIMENSIONS OF WALL:** 2.44 m x 1.22 m

**INITIAL STRAP SURVEY:**

| | Bot south | Bot north |
|---|---|---|
| East | Tight | Tight |
| West | Tight | Tight |

**STRAP:**
- [ ] No strap
- [x] 69.9mm x 1.37mm (2.75" x 0.054") 340 MPa (50 ksi)

**GUSSET:**
- [ ] No gusset plate
- [x] 177.8mm x 203.2mm (7"x8") 1.37mm (0,054") 340 MPa (50 ksi)

**INTERIOR STUDS:**
- [x] 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi) - Spaced at 410mm (16")

**CHORD STUDS:**
- [ ] Simple chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,09mm (0.043") 230 MPa (33 ksi)
- [x] Back-to-back chord studs - 152mm web x 41mm flange x 12,7mm lip (6" x 1-5/8" x 1/2") 1,37mm (0.054") 340 MPa (50 ksi)

**EXTENDED TRACKS:**
- [x] 1.52 m long, 152mm web x 31.8mm flange (6" x 1-1/4") 1,37mm (0.054") 340 MPa (50 ksi)

**HOLD DOWNS:**
- [ ] No hold down
- [x] S/HD15S Simpson  number of screws: 33

**SHEATHING:**
- [x] No sheathing
- [ ] 1 layer on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on each side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side - 15,9mm (5/9") Gypsum FireCode C Type X
- [ ] 2 layers on one side / Resilient channels spaced at 600mm + 2 layers on the other side - 15,9mm (5/9") Gypsum FireCode C Type X

**SCREWS:**

| | | |
|---|---|---|
| Sheathing: Inner layer | | 32mm type S drywall screw |
| Sheathing: Top layer | | 50mm type S drywall screw |
| Resilient channel: | | |
| Straps: | x | No. 10 gauge 0.75" self-drilling wafer head (mod. Truss) Phillips drive |
| Framing: | x | No. 8 gauge 0.5" self-drilling wafer head (mod. Truss) Phillips drive |
| Hold downs: | x | No. 14 gauge 1" self-drilling hex washer head |
| Back-to-back chord studs: | x | No. 10 gauge 0.5" self-drilling hex head |
| Anchor rods: | x | 1" Rod |
| Loading beam: | x | A325 3/4" bolts |
| Base: | x | A325 3/4" bolts |

**TEST PROTOCOL AND DESCTIPTION:**
- [ ] Monotonic  5mm/min
- [x] Cyclic  CUREE reversed cyclic - 0.25 Hz

**MEASUREMENT INSTRUMENTS:**
- [x] MTS Actuator LVDT
- [x] MTS Actuator load cell
- [x] North Slip LVDT
- [x] South Slip LVDT
- [x] North Uplift LVDT
- [x] South Uplift LVDT
- [x] String potentiometer
- [x] Bot south-Top north brace
- [ ] Bot north- Top south brace

Total: 8

**STRAP WIDTH BEFORE TEST:**

| West Bot South (mm) | West Bot North (mm) | East Bot South (mm) | East Bot North (mm) |
|---|---|---|---|
| 74,0 | 73,7 | 71,0 | 72,8 |
| 71,6 | 71,5 | 72,7 | 72,0 |
| 69,1 | 69,4 | 75,0 | 71,3 |
| AVG 71,6 mm | AVG 71,5 mm | AVG 72,9 mm | AVG 72,0 mm |

**MOISTURE CONTENT OF SHEATHING:**

OVEN DRIED ACCORDING TO APA TEST METHOD P-6

| | West Inner | West Outer | East Inner | East Outer |
|---|---|---|---|---|
| Ww= | NA | NA | NA | NA |
| Wd= | NA | NA | NA | NA |
| m.c.= | NA | NA | NA | NA |

AVG m.c. #DIV/0!

**DATA ACQ. RECORD RATE:** 100 scan/sec  **MONITOR RATE:** 200 scan/sec

**COMMENTS:** Bottom track dented near the chord studs

McGill

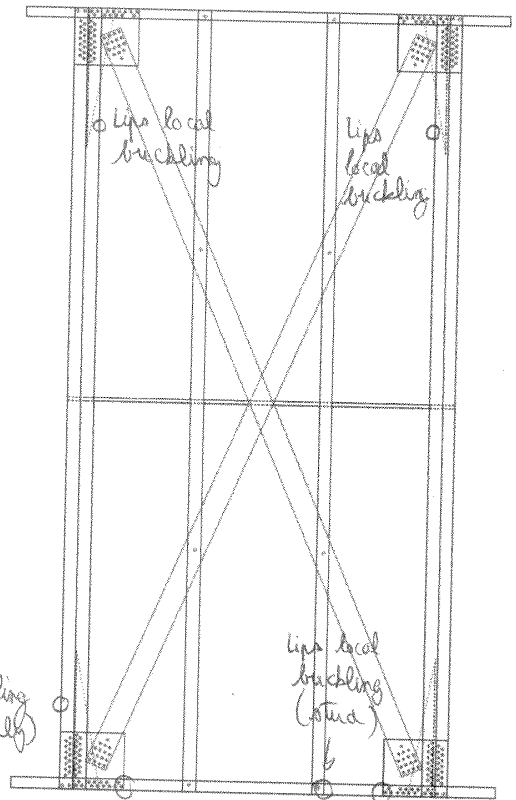
Cold-Formed Steel Strap Braced / Gypsum Sheathed Walls

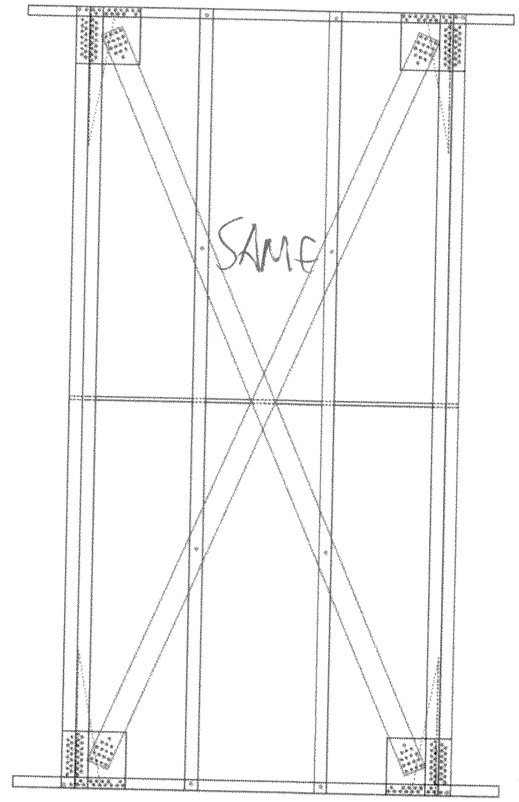
Test name: 83 A.C
Date tested: July 31 2014
# of gypsum layers per side: ∅
# of sheathed sides: ∅
Resilient channel: ☐ yes ☑ no
Test mode: ☐ monotonic ☑ cyclic

## Observations of the steel frame

West side notes:

Lip local buckling (west side only)




East side notes:

General notes:

Bending of the chord studs
Yielding of the straps

# Appendix C. Analysis of the test results

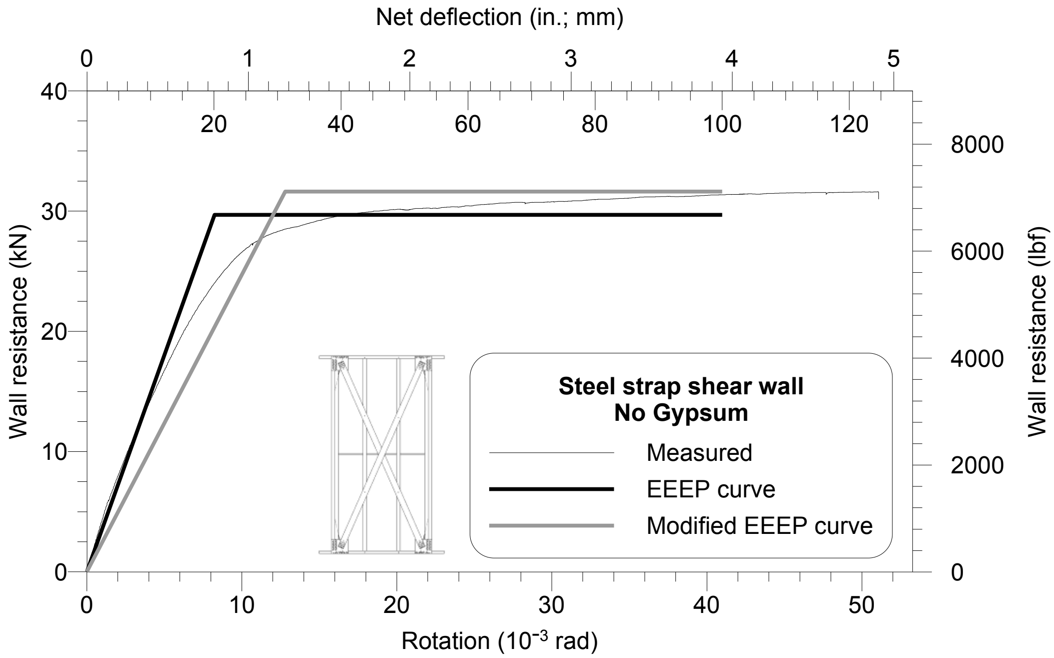



**Figure C-1 Measured and EEEP curves for test 65A-M**

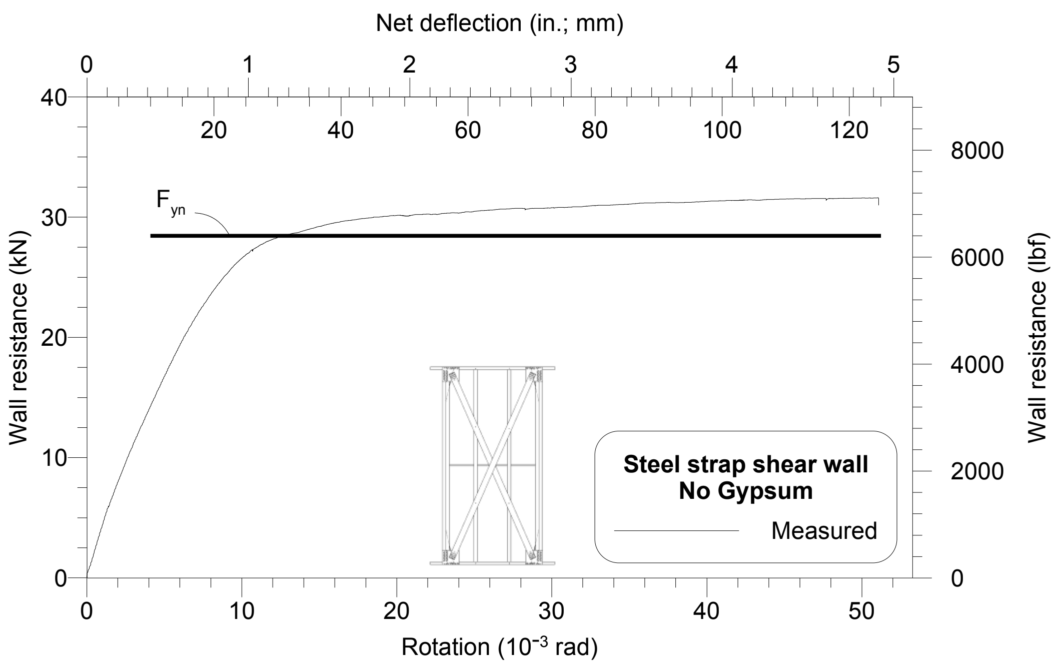



**Figure C-2 Comparison of the predicted probable yielding strength (calculated according AISI S213 and AISI S400) and the test measurements for test 65A-M**

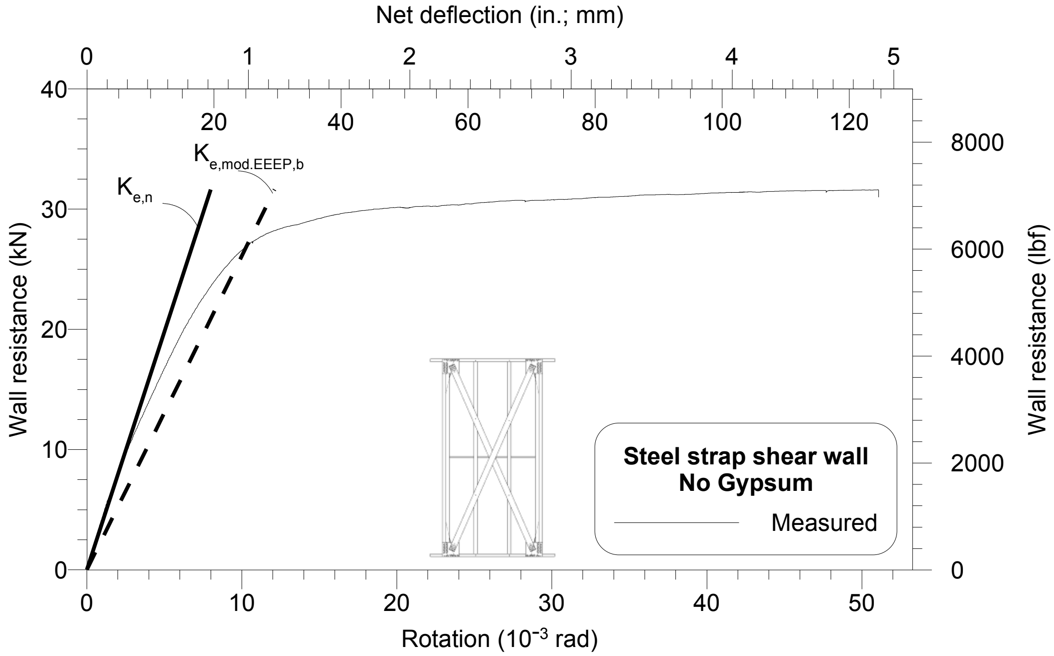



**Figure C-3 Comparison of the different stiffness predictions for test 65A-M**

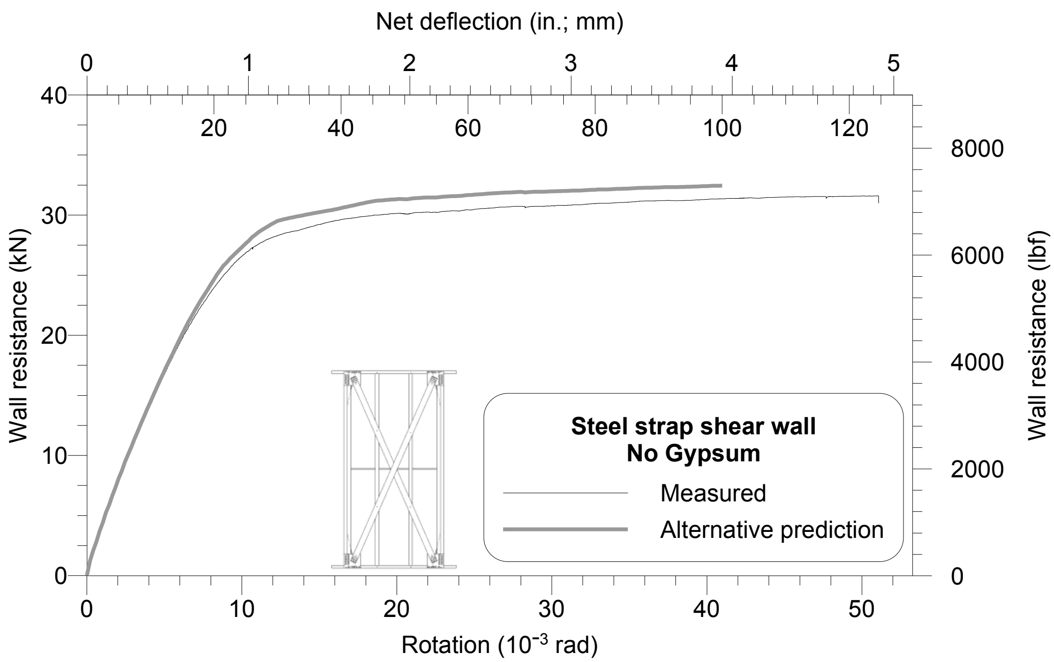



**Figure C-4 Load-drift curve to be used in the alternative prediction of strap-braced walls compared to the test results**

**Table 4 Monotonic test results for test 65A-M**

| | Parameters | Specimen 65A-M | Units |
|---|---|---|---|
| Test Results | $F_u$ | 31.61 | kN |
| | $\Delta_{net,u}$ | 124.48 | mm |
| | $F_{0.4u}$ | 12.64 | kN |
| | $\Delta_{net,0.4u}$ | 8.56 | mm |
| | $K_e$ | 1.48 | kN/mm |
| | $F_{0.8u}$ | 25.29 | kN |
| | $\Delta_{net,0.8u}$ | - | mm |
| | $\Delta_{net,max}$ | 100 | mm |
| | Normalized energy [(1)] | 26.70 | J/mm |
| EEEP analysis | $F_y$ | 29.68 | kN |
| | $\Delta_y$ | 20.10 | mm |
| | Ductility (μ) | 4.98 | - |
| | $R_d$ | 2.99 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 31.24 | mm |
| | $K_{e,mod.EEEP}$ | 1.01 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.65 | kN |
| | $K_p$ | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | kN |
| | $K_n$ | 1.62 | kN/mm |
| Strain gauge results | Max strain | 15459 | - |
| | Yielding strain | 1617 | - |
| | Yielding status | OK | |

[(1)] Ratio of energy dissipated under the measured curve by maximum displacement

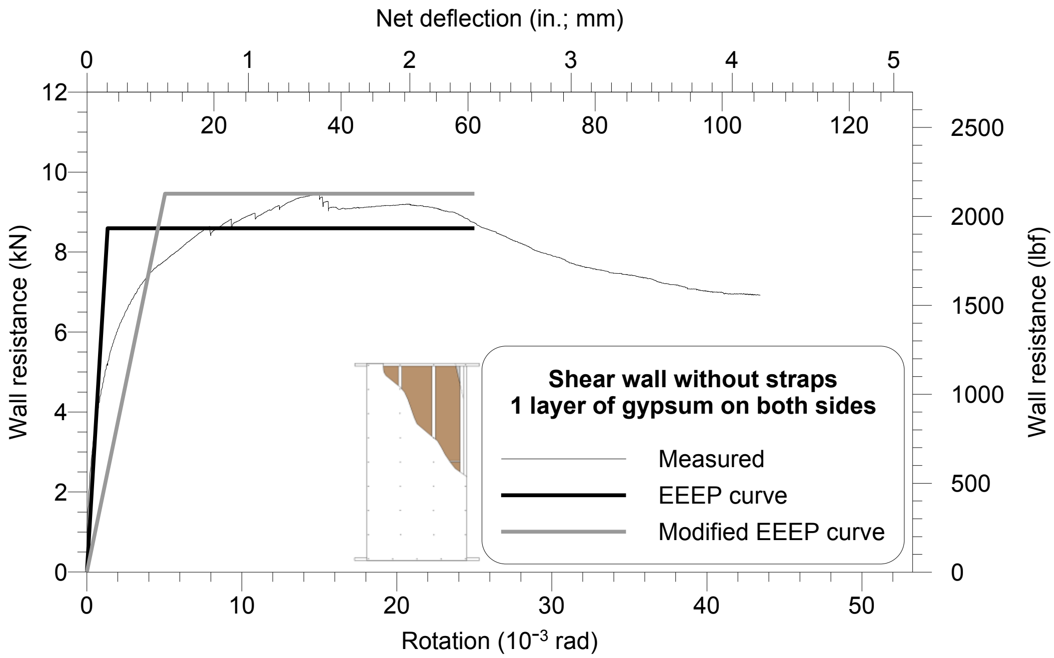



**Figure C-5 Measured and EEEP curves for test 66A-M**

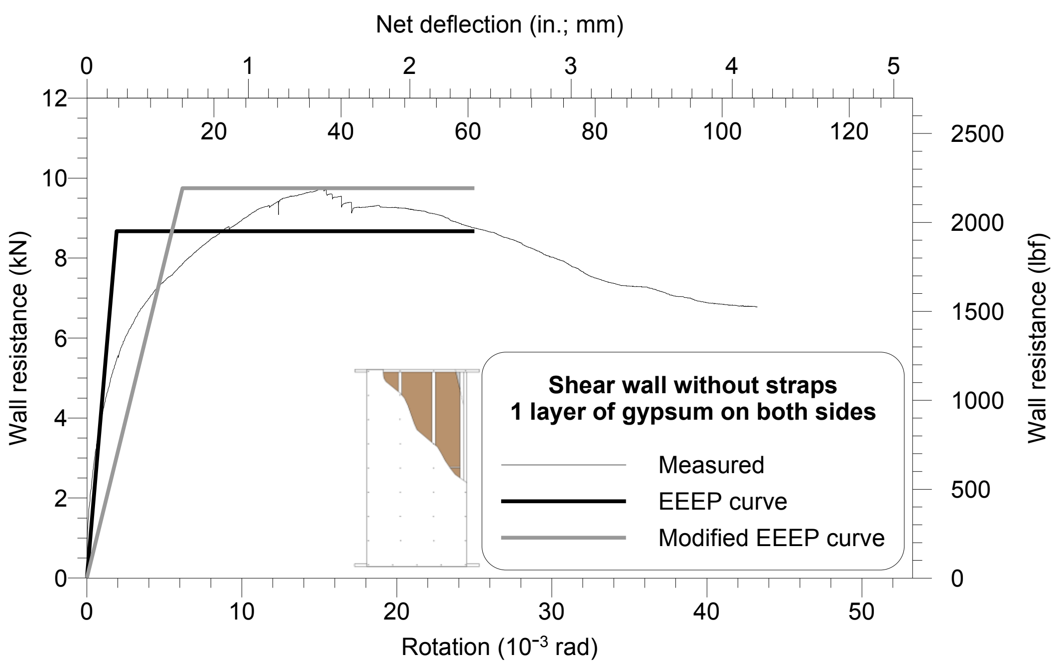



**Figure C-6 Measured and EEEP curves for test 66B-M**

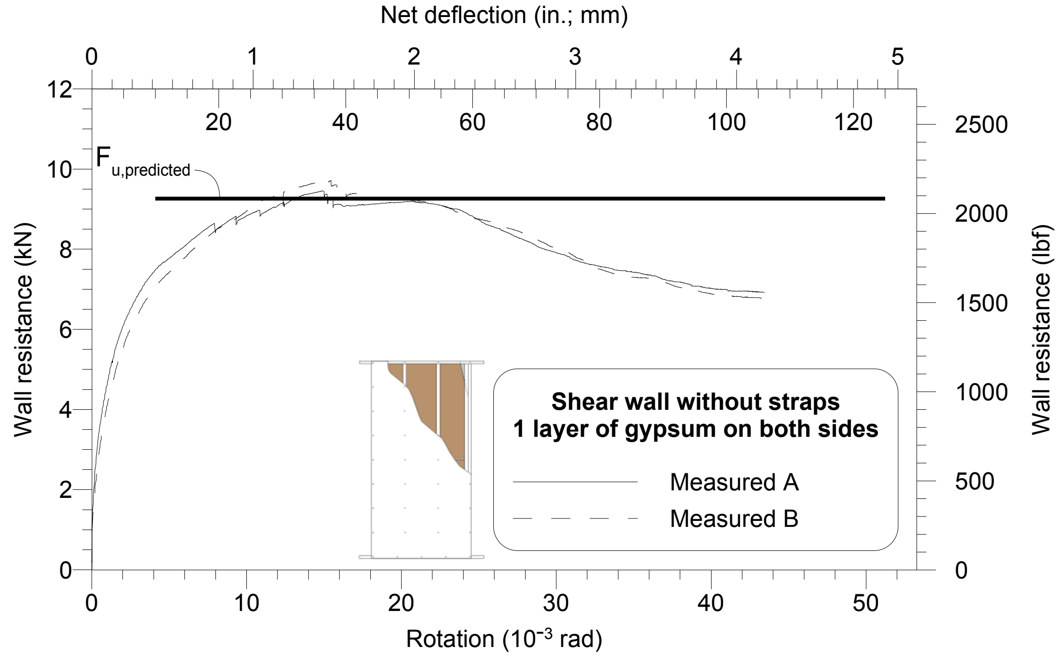



**Figure C-7 Comparison of the recommended probable strength of the wall and the test measurements for tests 66A-M and 66B-M**

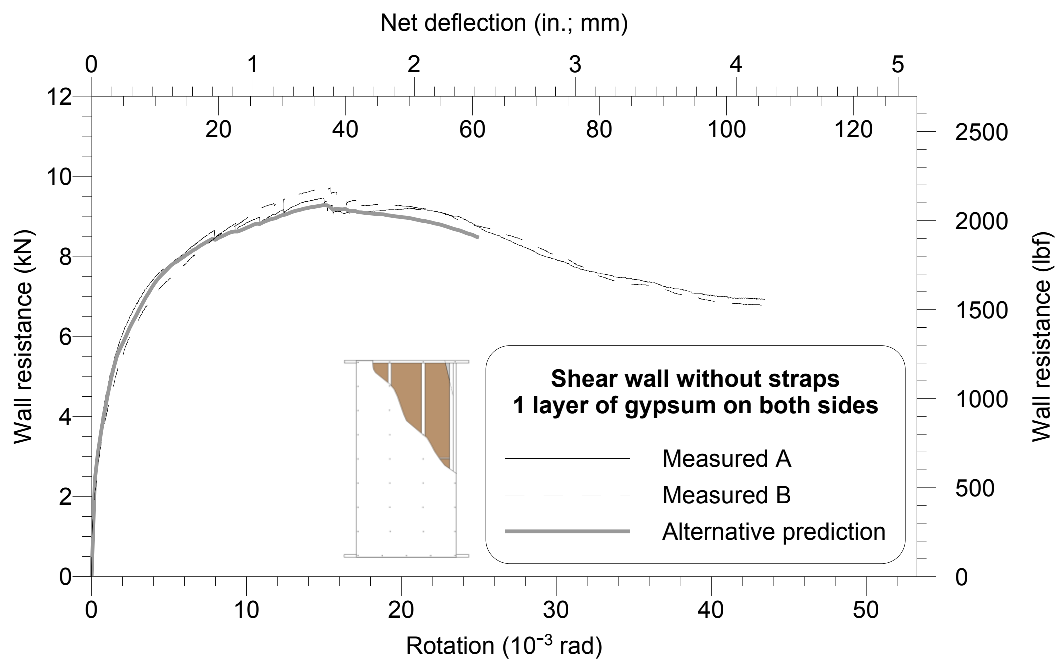



**Figure C-8 Comparison of the load-drift curve to be used in the alternative prediction of gypsum-sheathed walls and the test results for tests 66A-M and 66B-M**

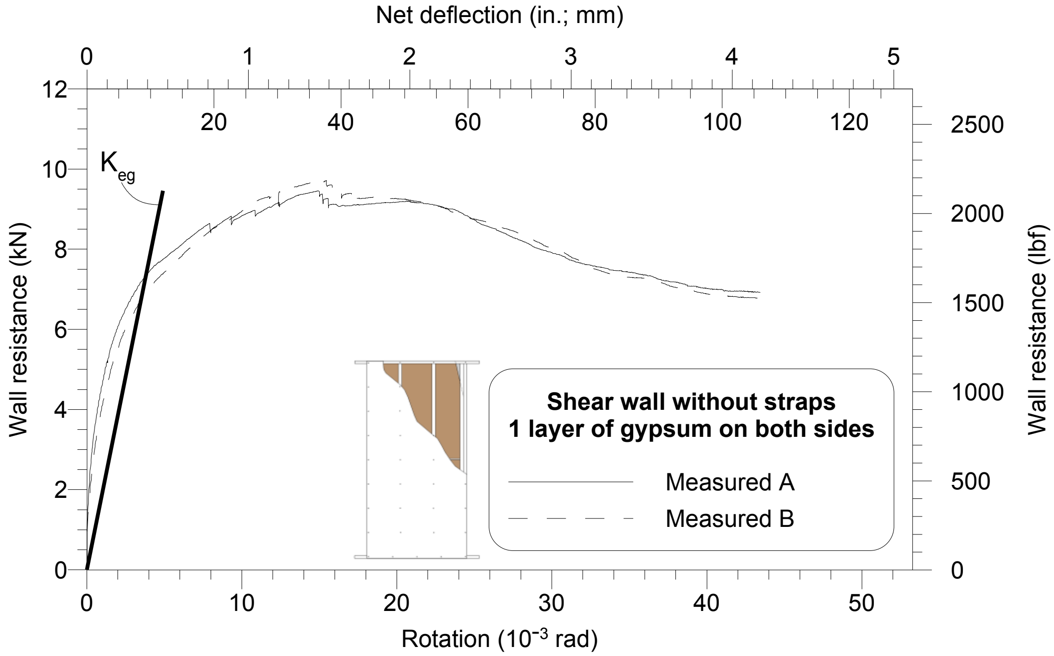
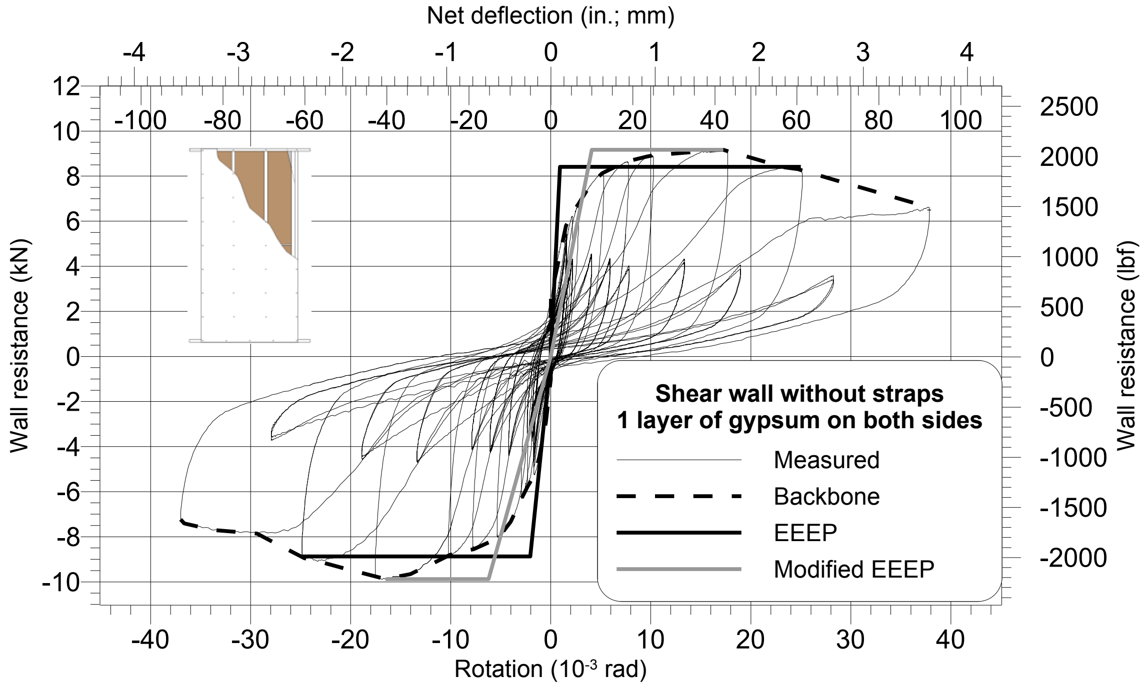



**Figure C-9 Comparison of the recommended stiffness of the wall with the test results for tests of the wall with the test results 66A-M and 66B-M**

**Table 5 Monotonic test results for tests 66A-M and 66B-M**

| | Parameters | Specimens 66A-M | Specimens 66B-M | Units |
|---|---|---|---|---|
| Test Results | $F_u$ | 9.45 | 9.74 | kN |
| | $\Delta_{net,u}$ | 36.23 | 37.07 | mm |
| | $F_{0.4u}$ | 3.78 | 3.90 | kN |
| | $\Delta_{net,0.4u}$ | 1.44 | 2.10 | mm |
| | $K_e$ | 2.63 | 1.85 | kN/mm |
| | $F_{0.8u}$ | 7.56 | 7.80 | kN |
| | $\Delta_{net,0.8u}$ | 80.12 | 76.24 | mm |
| | $\Delta_{net,max}$ | 61.00 | 61.00 | mm |
| | Normalized energy (1) | 8.36 | 8.33 | J/mm |
| EEEP Analysis | $F_y$ | 8.59 | 8.67 | kN |
| | $\Delta_{net,y}$ | 3.26 | 4.67 | mm |
| | Ductility ($\mu$) | 18.71 | 13.06 | - |
| | $R_d$ | 6.03 | 5.01 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 12.30 | 15.04 | mm |
| | $K_{e,mod.EEEP}$ | 0.77 | 0.65 | kN/mm |

(1) Energy dissipated under the EEEP curve



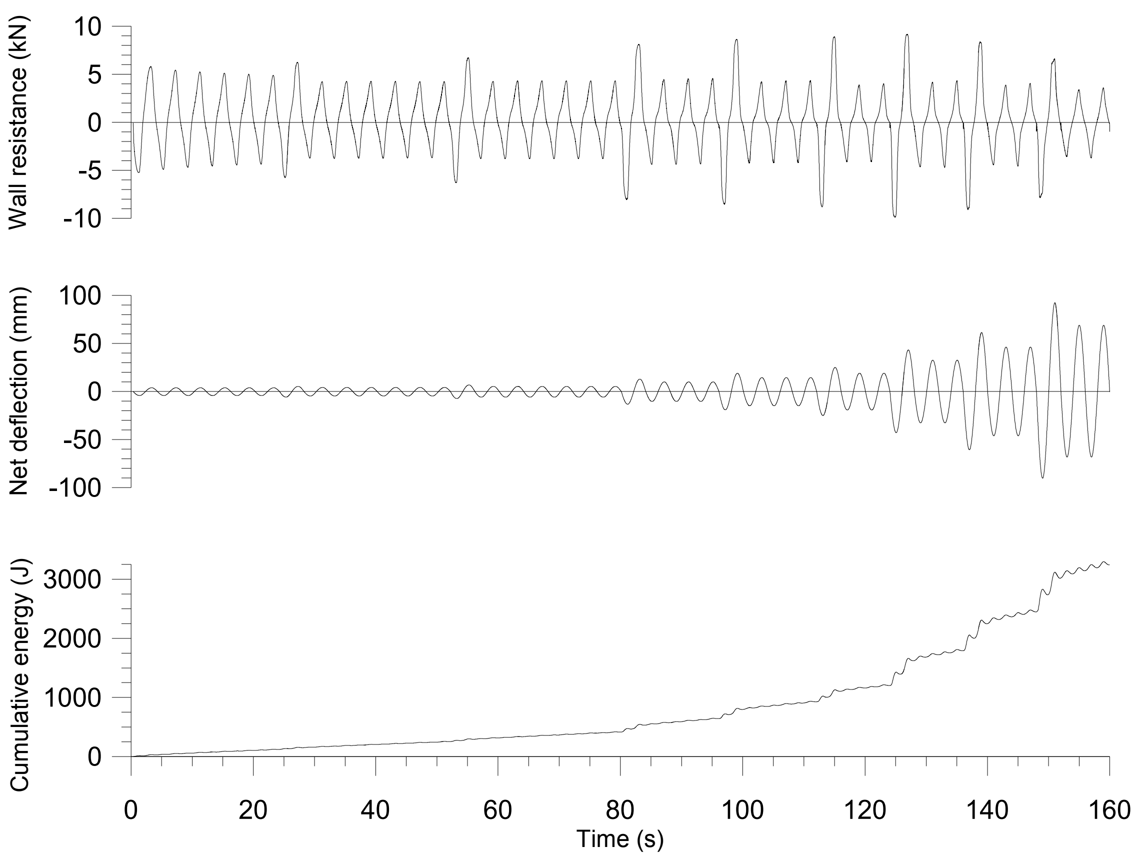




**Figure C-10 Measured and EEEP curves and time history for test 67A-C**

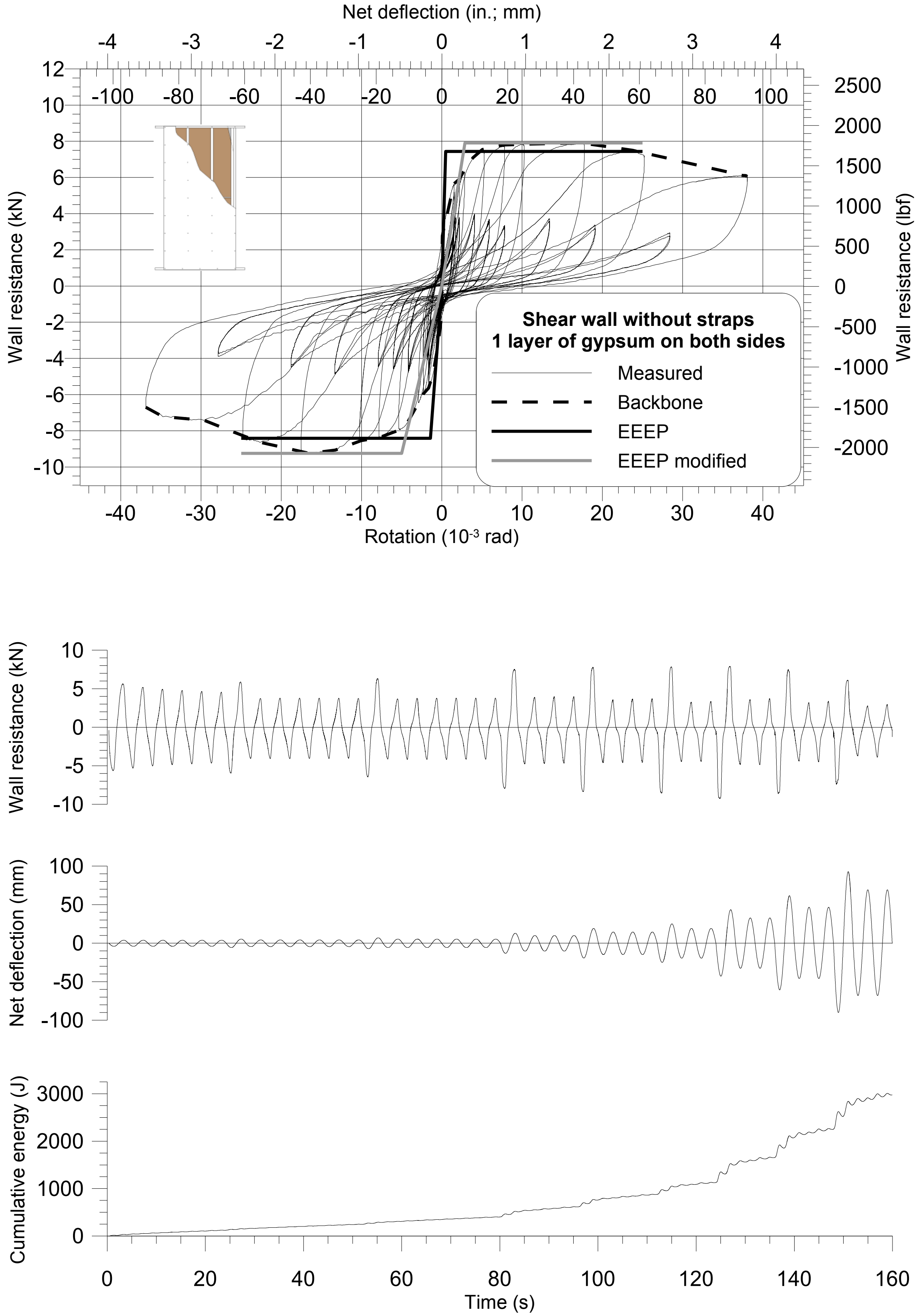



**Figure C-11 Measured and EEEP curves and time history for test 67 BC**

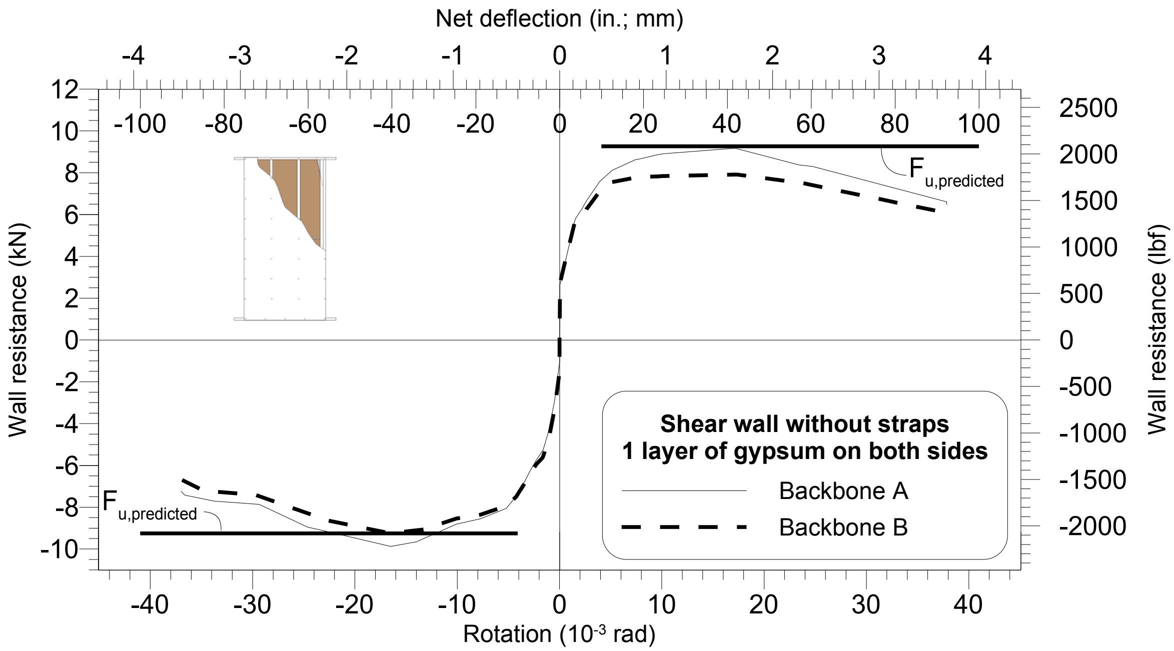



**Figure C-12 Comparison of the recommended probable strength of the wall and the test measurements for tests 67A-C and 67B-C**

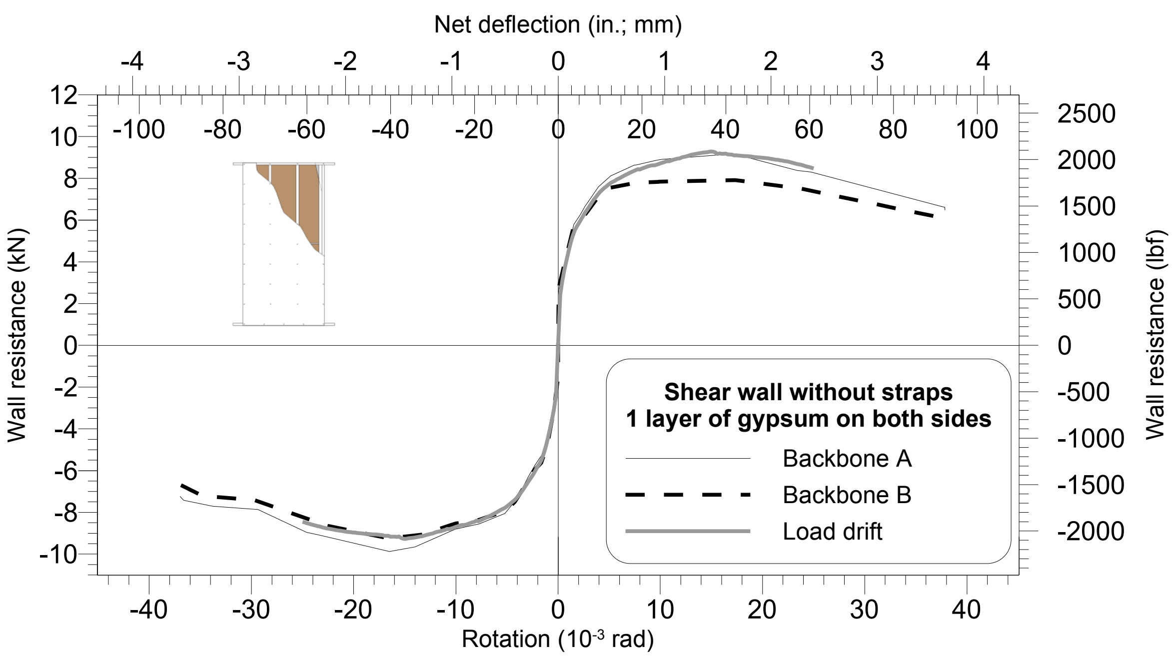



**Figure C-13 Comparison of the load-drift curve to be used in the alternative prediction of gypsum-sheathed walls and the test results for tests 67A-C and 67B-C**

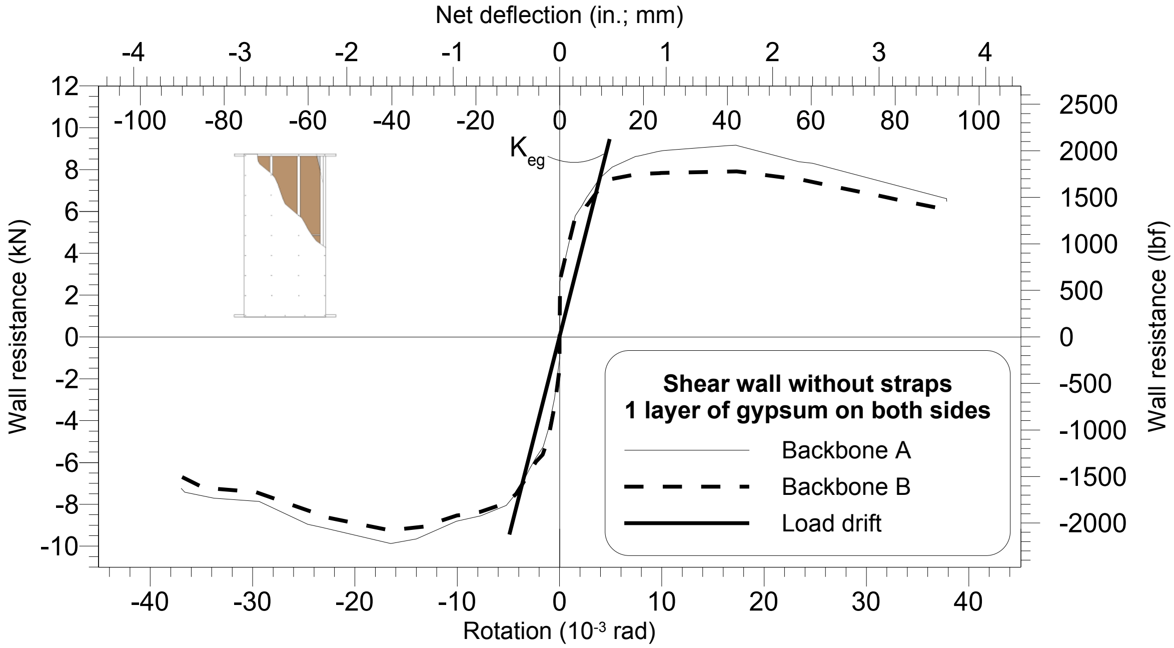



**Figure C-14 Comparison of the recommended stiffness of the wall with the test results for tests of the wall with the test results 67A-C and 67B-C**

**Table 6 Cyclic test results for tests 67A-C and 67B-C**

| | Parameters | Specimens 67A-C | | Specimens 67B-C | | Units |
|---|---|---|---|---|---|---|
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 9.16 | -9.88 | 7.91 | -9.26 | kN |
| | $\Delta_{net,u}$ | 42.07 | -40.28 | 42.27 | -40.27 | mm |
| | $F_{0.4u}$ | 3.67 | -3.95 | 3.16 | -3.70 | kN |
| | $\Delta_{net,0.4u}$ | 0.97 | -2.22 | 0.50 | -1.52 | mm |
| | $K_e$ | 3.77 | 1.78 | 6.30 | 2.44 | kN/mm |
| | $F_{0.8u}$ | 7.33 | -7.90 | 6.32 | -7.40 | kN |
| | $\Delta_{net,0.8u}$ | 78.60 | -71.28 | 86.18 | -73.51 | mm |
| | $\Delta_{net,max}$ | 61.00 | -61.00 | 61.00 | -61.00 | mm |
| | Normalized energy (1) | 8.25 | -8.52 | 7.37 | -8.18 | J/mm |
| EEEP Analysis | $F_y$ | 8.40 | -8.88 | 7.44 | -8.42 | kN |
| | $\Delta_{net,y}$ | 2.23 | -4.99 | 1.18 | -3.46 | mm |
| | Ductility ($\mu$) | 27.4 | 12.2 | 51.6 | 17.6 | - |
| | $R_d$ | 7.33 | 4.84 | 10.11 | 5.86 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 10.01 | -15.18 | 7.03 | -12.24 | mm |
| | $K_{e,mod.EEEP}$ | 0.92 | 0.65 | 1.12 | 0.76 | kN/mm |

(1) Energy dissipated under the EEEP curve

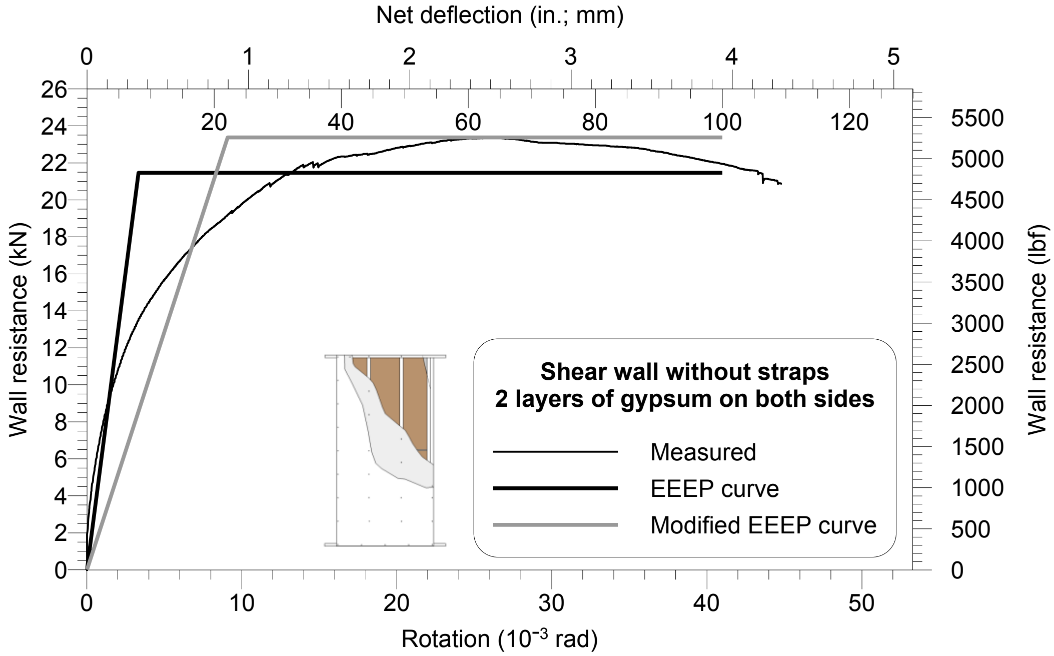



**Figure C-15 Measured and EEEP curves for test 68AM**

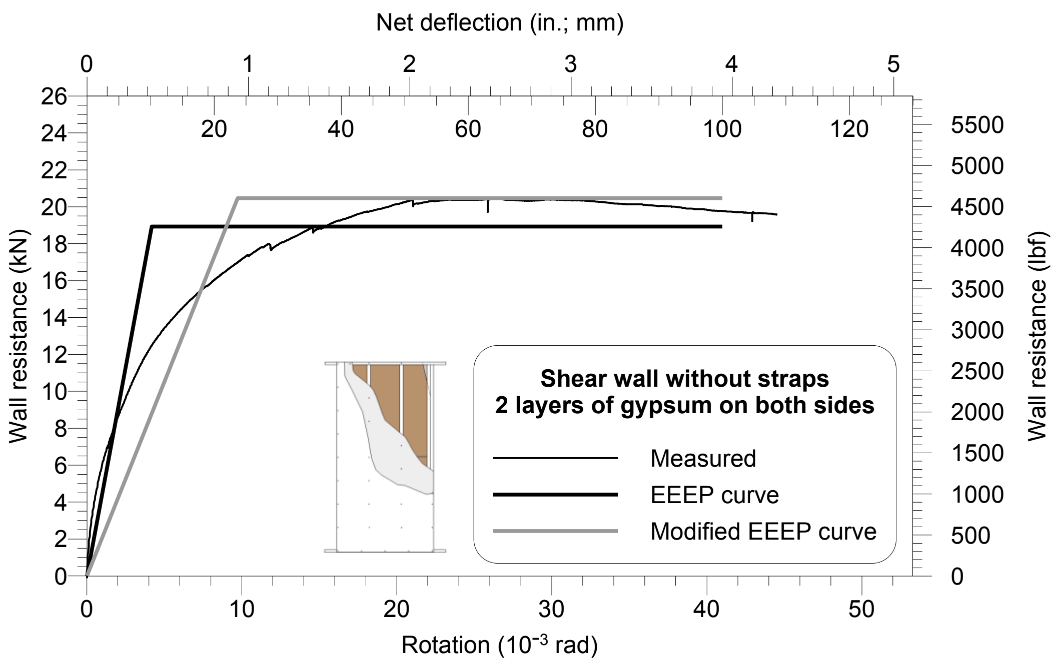



**Figure C-16 Measured and EEEP curves for test 68BM**

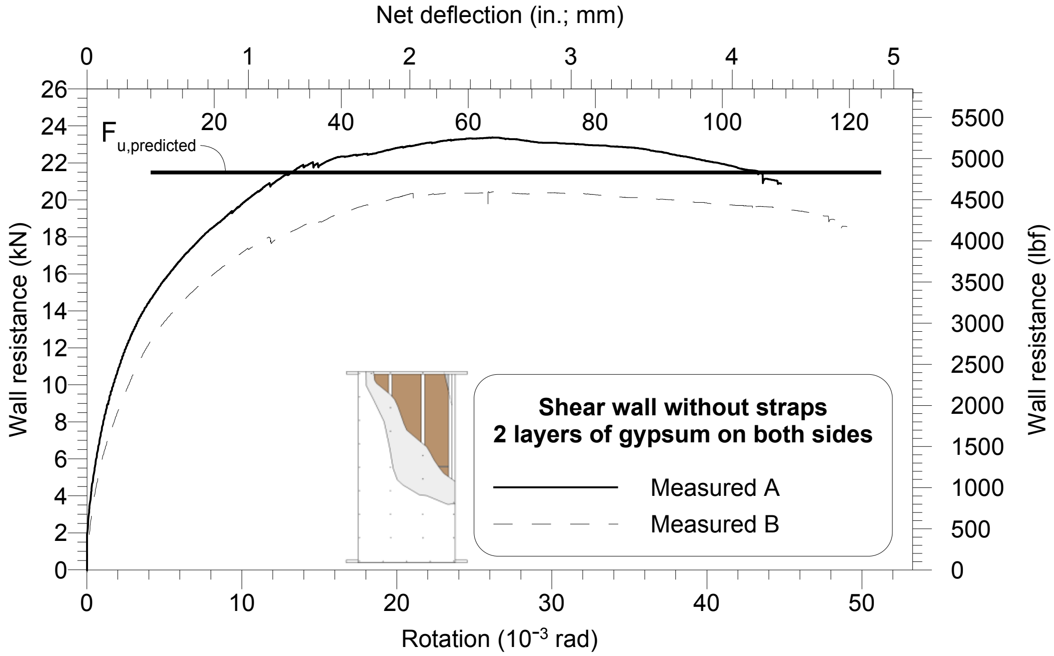



**Figure C-17 Comparison of the recommended probable strength of the wall and the test measurements for tests 68A-M and 68B-M**

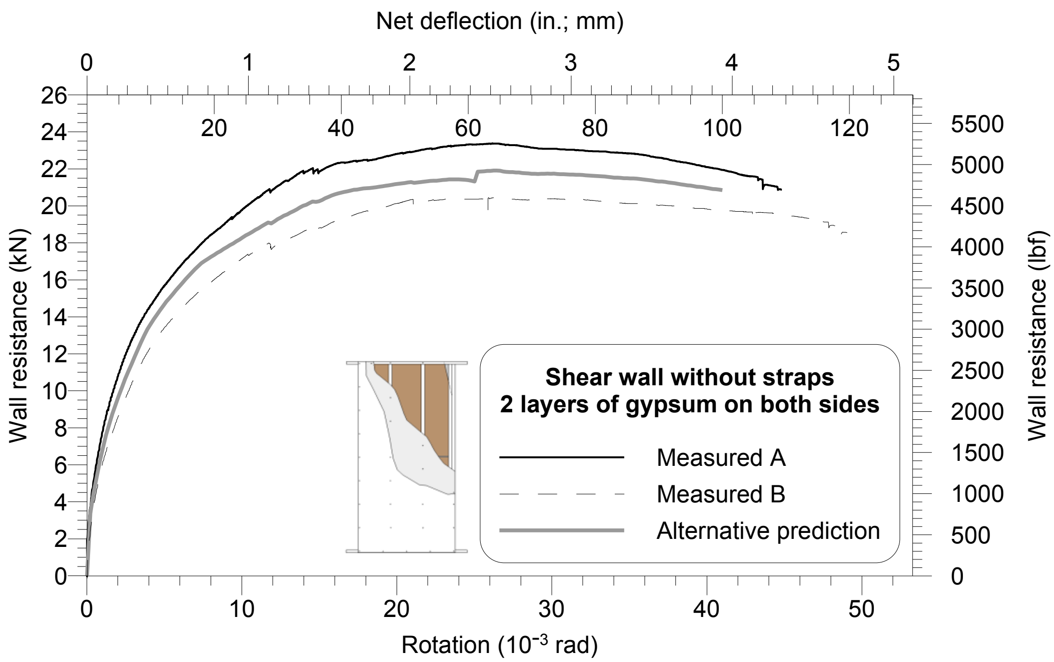



**Figure C-18 Comparison of the load-drift curve to be used in the alternative prediction of gypsum-sheathed walls and the test results for tests 68A-M and 68B-M**

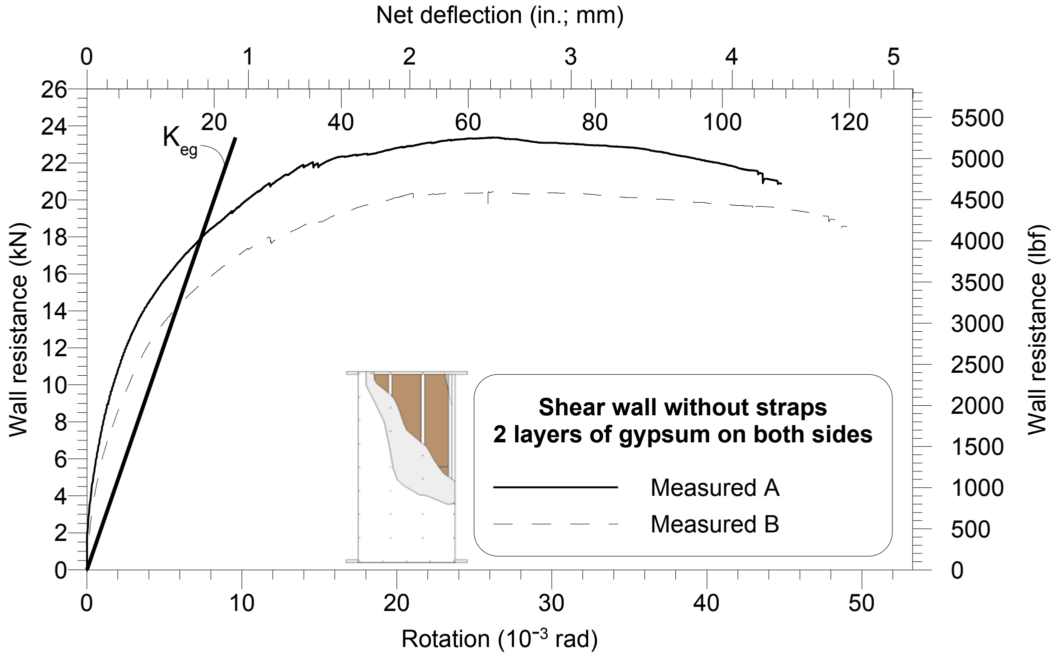
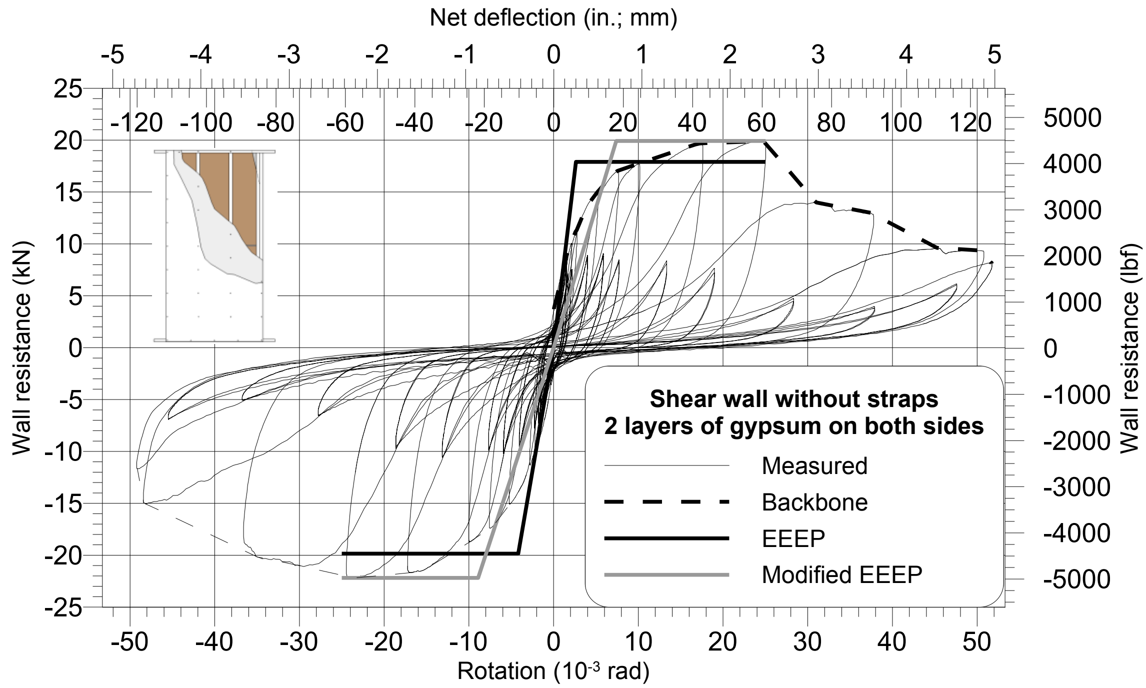



**Figure C-19 Comparison of the recommended stiffness of the wall with the test results for tests of the wall with the test results 68A-M and 68B-M**

**Table 7 Monotonic test results for tests 68A-M and 68B-M**

| | Parameters | Specimens 68A-M | Specimens 68B-M | Units |
|---|---|---|---|---|
| Test Results | $F_u$ | 23.36 | 20.46 | kN |
| | $\Delta_{net,u}$ | 63.79 | 64.30 | mm |
| | $F_{0.4u}$ | 9.35 | 8.18 | kN |
| | $\Delta_{net,0.4u}$ | 3.53 | 4.40 | mm |
| | $K_e$ | 2.65 | 1.86 | kN/mm |
| | $F_{0.8u}$ | 18.69 | 16.37 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 100.00 | 100.00 | mm |
| | Normalized energy (1) | 20.59 | 17.95 | J/mm |
| EEEP Analysis | $F_y$ | 21.45 | 18.91 | kN |
| | $\Delta_{net,y}$ | 8.10 | 10.18 | mm |
| | Ductility ($\mu$) | 12.35 | 9.82 | - |
| | $R_d$ | 4.87 | 4.32 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 22.13 | 23.69 | mm |
| | $K_{e,mod.EEEP}$ | 1.06 | 0.86 | kN/mm |

(1) Energy dissipated under the EEEP curve



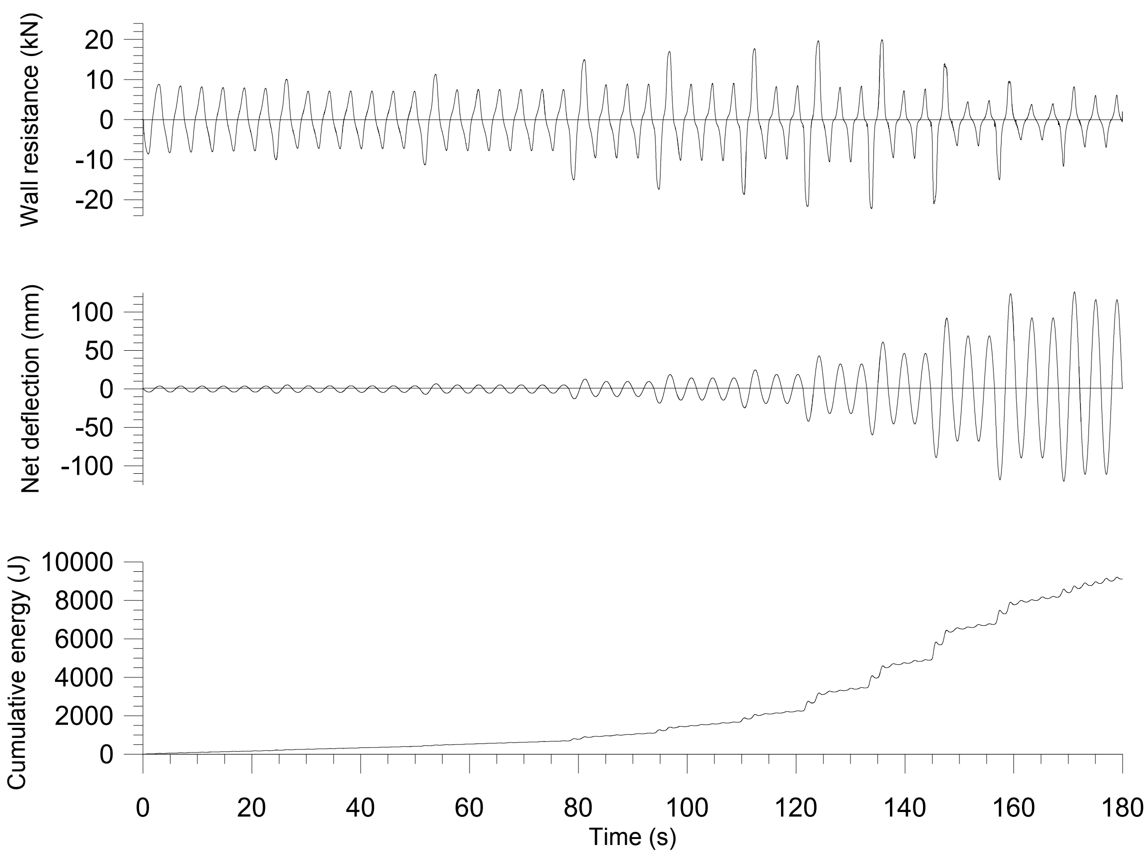
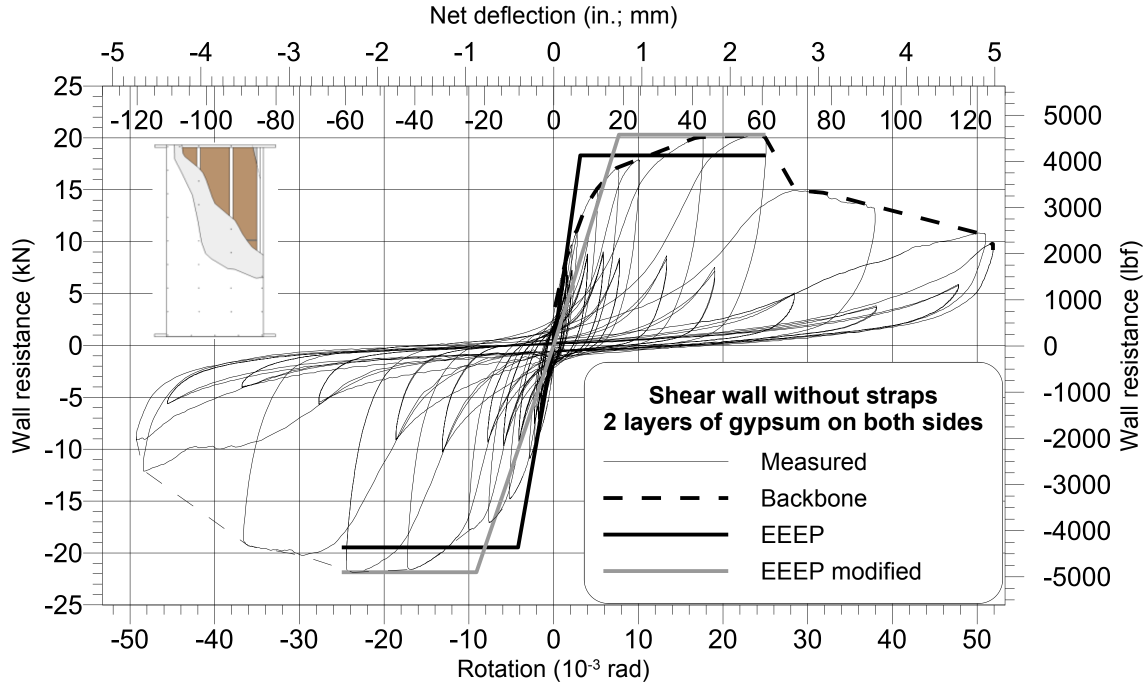




**Figure C-20 Measured and EEEP curves and time history for test 69A-C**



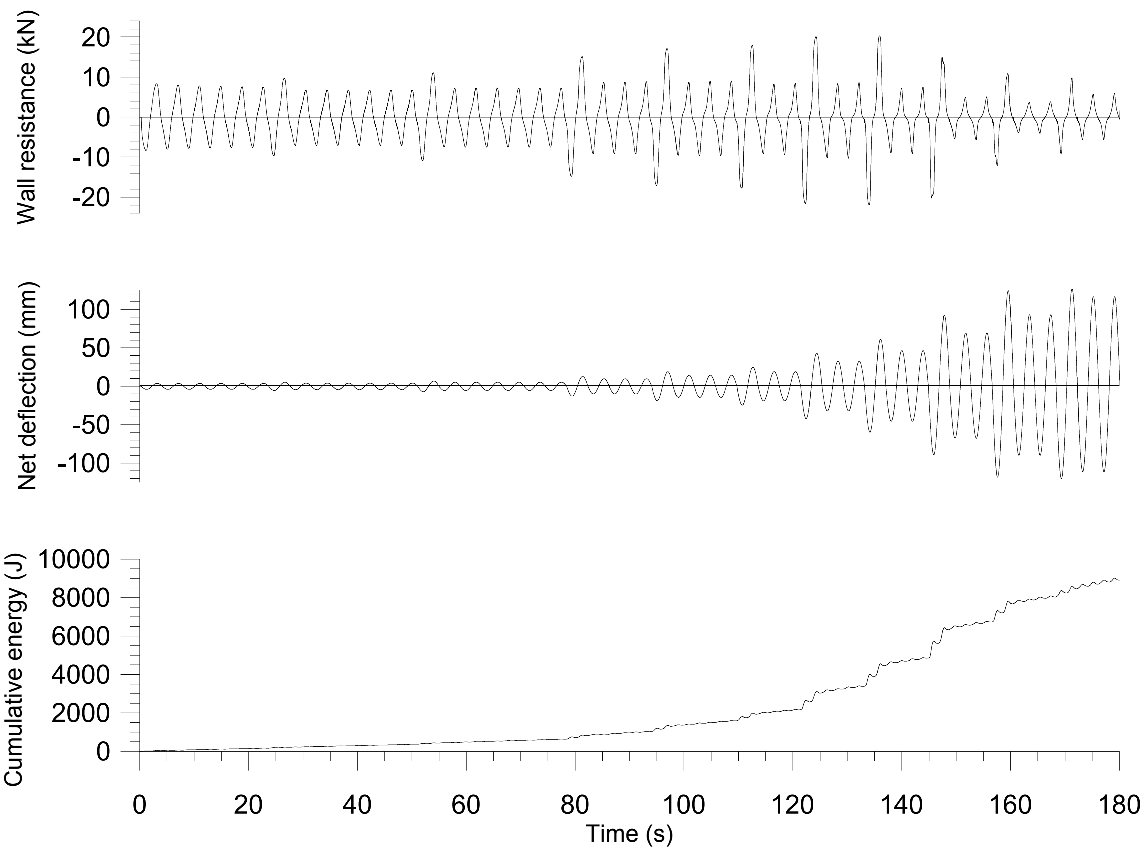




**Figure C-21 Measured and EEEP curves and time history for test 69B-C**

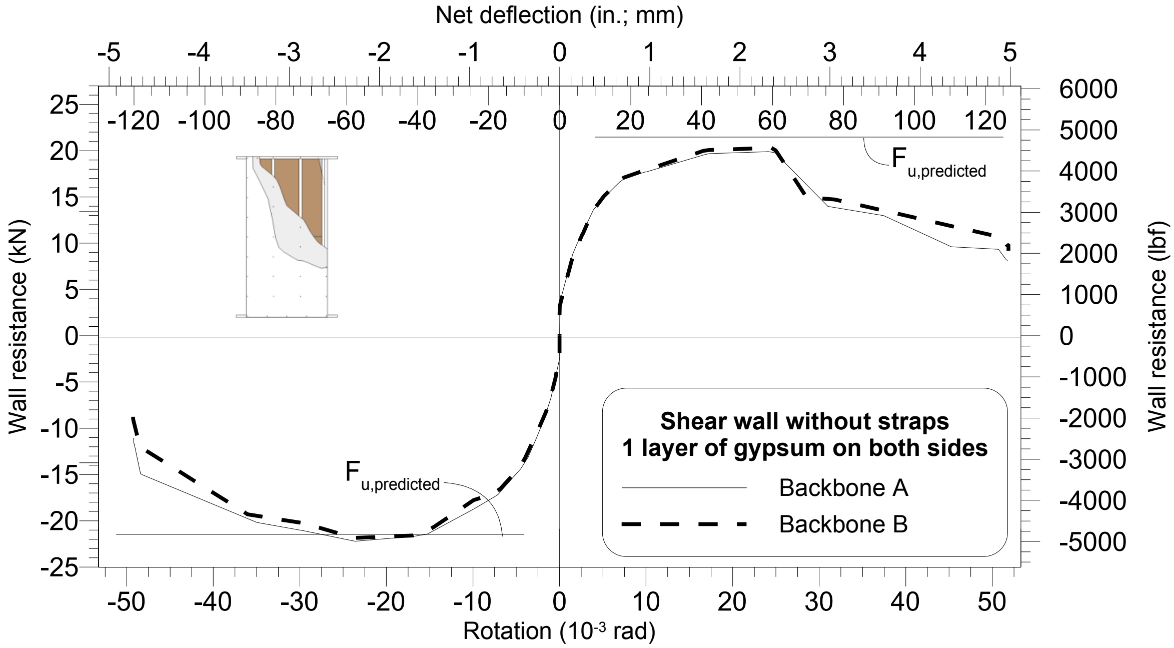



**Figure C-22 Comparison of the recommended probable strength of the wall and the test measurements for tests 69A-C and 69B-C**

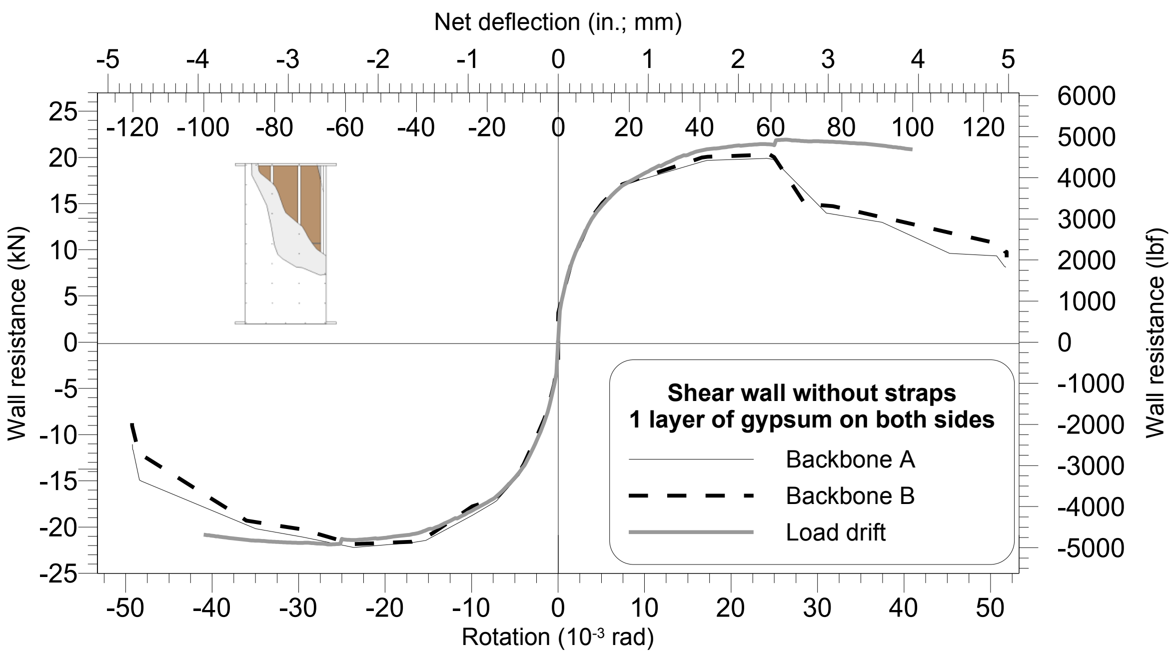



**Figure C-23 Comparison of the load-drift curve to be used in the alternative prediction of gypsum-sheathed walls and the test results for tests 69A-C and 69B-C**

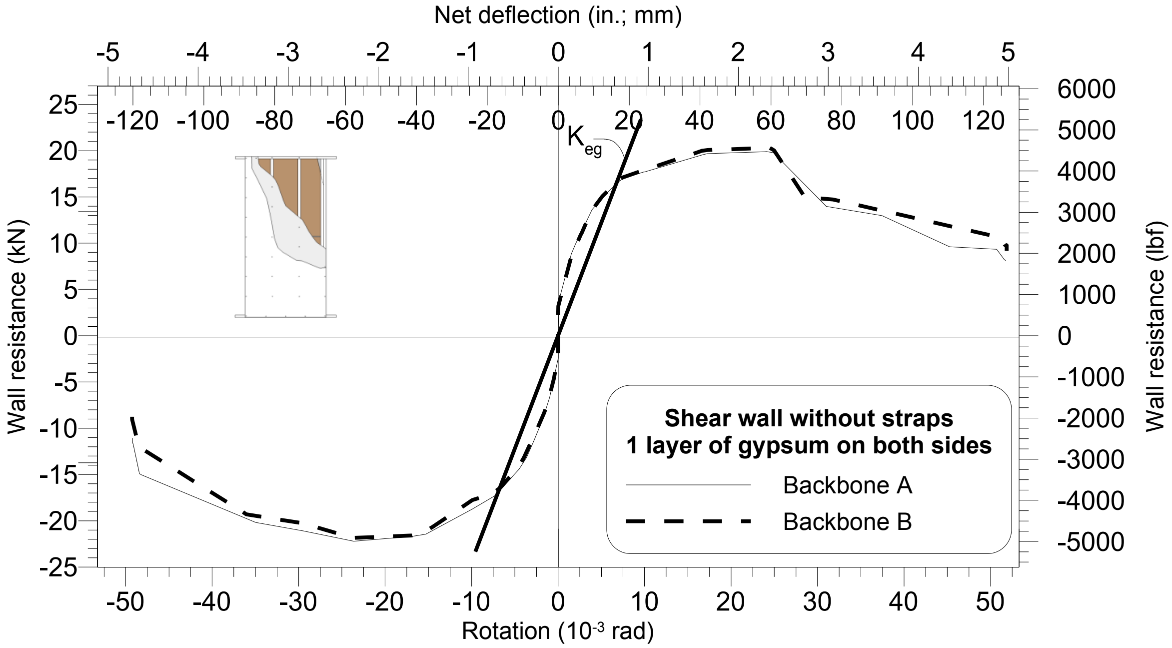



**Figure C-24 Comparison of the recommended stiffness of the wall with the test results for tests of the wall with the test results 69A-C and 69B-C**

**Table 8 Cyclic test results for tests 69A-C and 69B-C**

| | Parameters | Specimens | | | | Units |
|---|---|---|---|---|---|---|
| | | 69A-C | | 69B-C | | |
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 19.92 | -22.20 | 20.29 | -21.88 | kN |
| | $\Delta_{net,u}$ | 58.67 | -57.67 | 59.72 | -57.86 | mm |
| | $F_{0.4u}$ | 7.97 | -8.88 | 8.12 | -8.75 | kN |
| | $\Delta_{net,0.4u}$ | 2.87 | -4.54 | 3.42 | -4.60 | mm |
| | $K_e$ | 2.78 | 1.95 | 2.37 | 1.90 | kN/mm |
| | $F_{0.8u}$ | 15.93 | -17.76 | 16.23 | -17.50 | kN |
| | $\Delta_{net,0.8u}$ | 70.58 | -100.48 | 67.45 | -95.48 | mm |
| | $\Delta_{net,max}$ | 61.00 | -61.00 | 61.00 | -61.00 | mm |
| | Normalized energy (1) | 16.94 | -18.21 | 17.14 | -17.84 | J/mm |
| EEEP Analysis | $F_y$ | 17.88 | -19.87 | 18.30 | -19.47 | kN |
| | $\Delta_{net,y}$ | 6.44 | -10.16 | 7.72 | -10.23 | mm |
| | Ductility ($\mu$) | 9.5 | 6.0 | 7.9 | 6.0 | - |
| | $R_d$ | 4.24 | 3.32 | 3.85 | 3.31 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 18.03 | -21.74 | 18.80 | -22.26 | mm |
| | $K_{e,mod.EEEP}$ | 1.10 | 1.02 | 1.08 | 0.98 | kN/mm |

(1) Energy dissipated under the EEEP curve

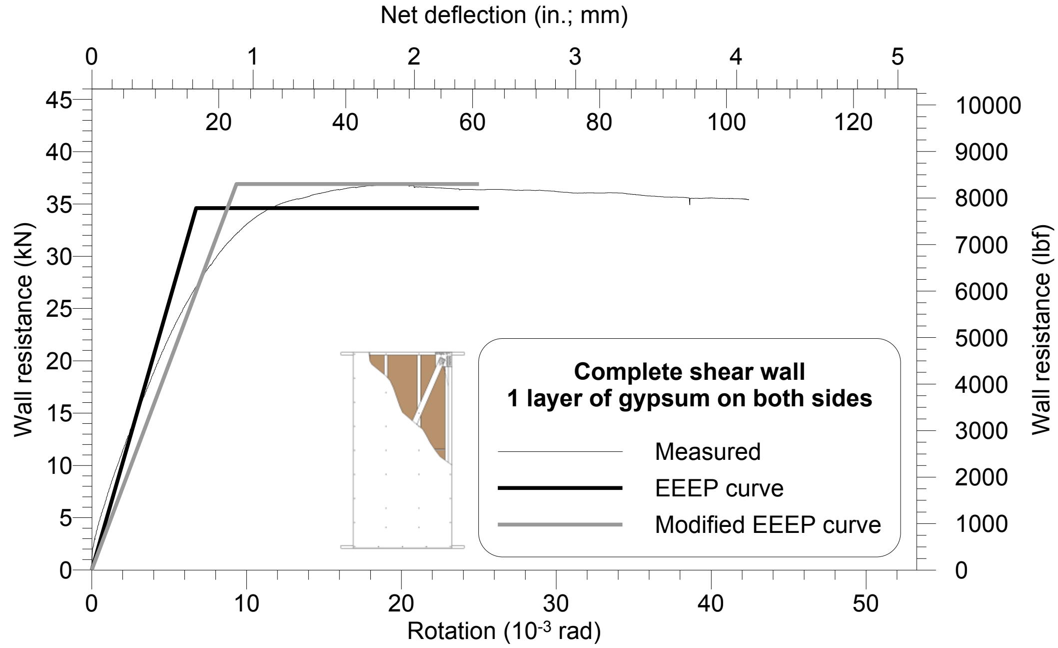



**Figure C-25 Measured and EEEP curves for test 70A-M**

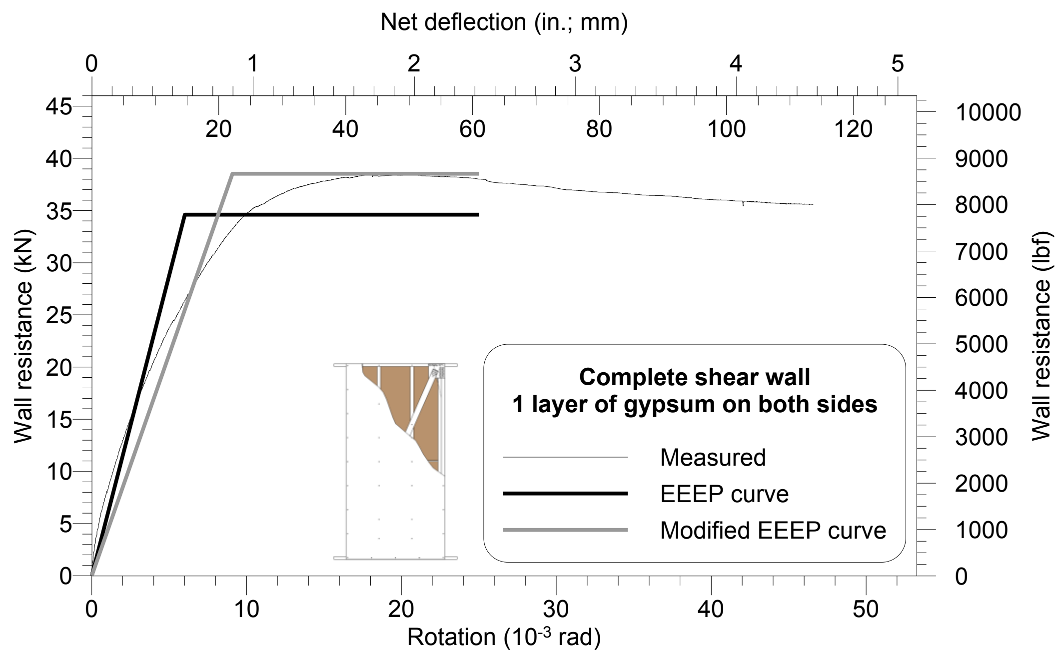



**Figure C-26 Measured and EEEP curves for test 70B-M**

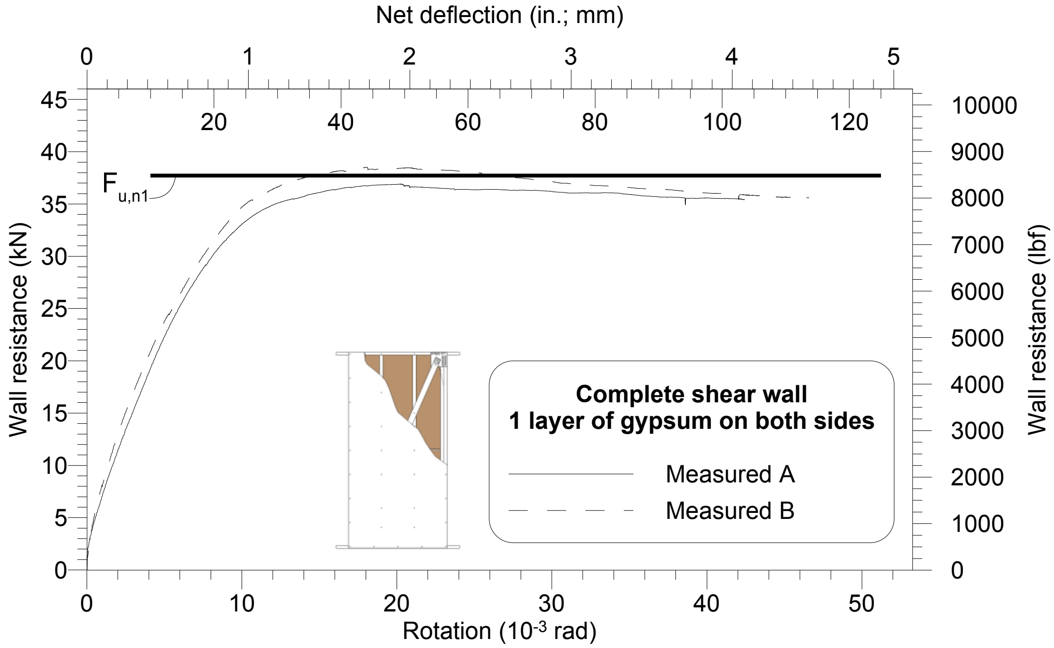



**Figure C-27 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 70A-M and 70B-M**

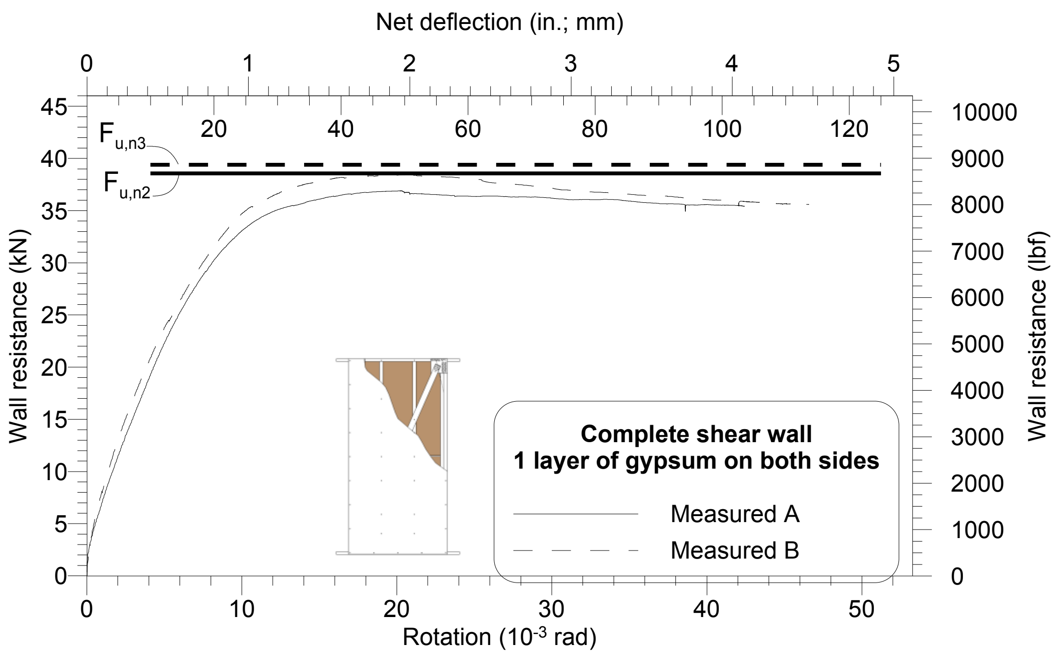



**Figure C-28 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 70A-M and 70B-M**

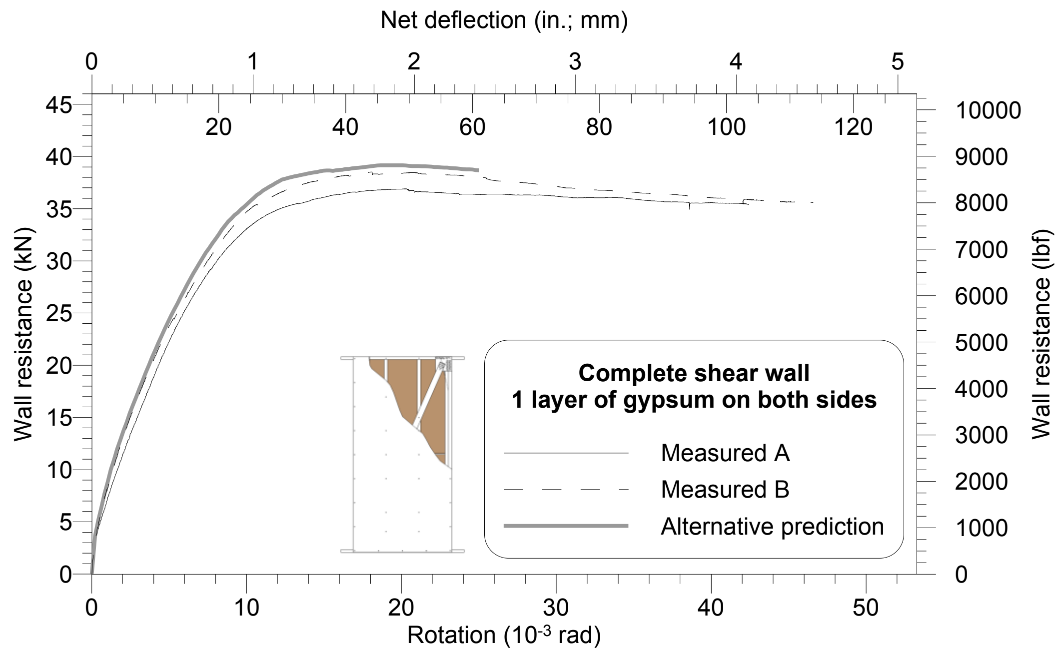



**Figure C-29 Comparison of the predicted load-drift curve and the test results for tests 70A-M and 70B-M**

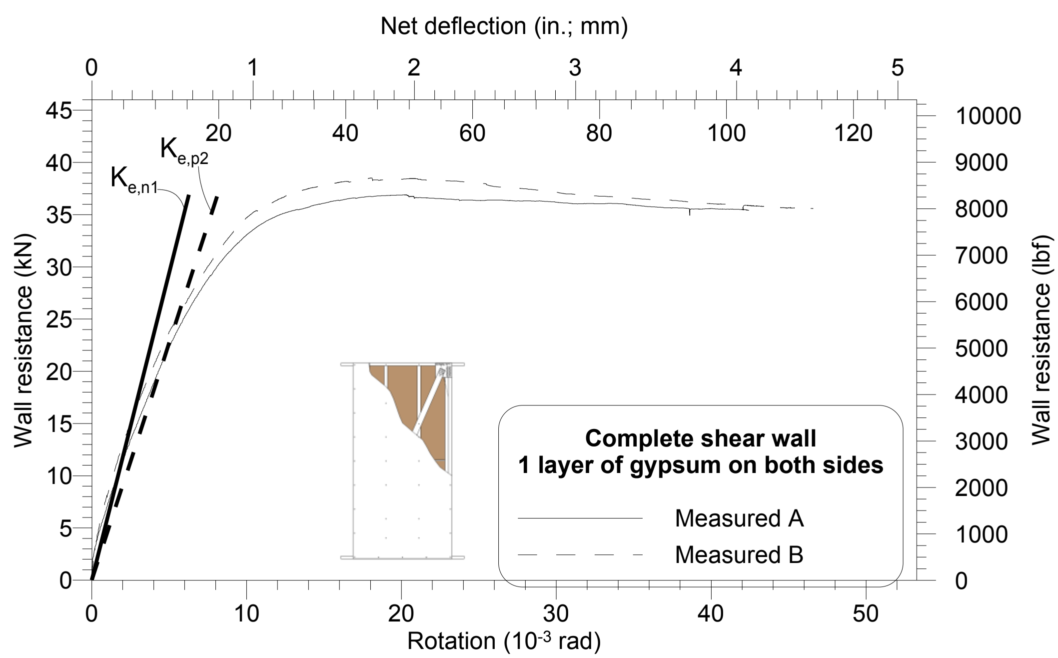



**Figure C-30 Comparison of the different stiffness predictions for tests 70A-M and 70B-M**

**Table 9 Monotonic test results for tests 70A-M and 70B-M**

| | Parameters | Specimens 70A-M | Specimens 70B-M | Units |
|---|---|---|---|---|
| Test Results | $F_u$ | 36.89 | 38.51 | kN |
| | $\Delta_{net,u}$ | 49.30 | 43.85 | mm |
| | $F_{0.4u}$ | 14.76 | 15.40 | kN |
| | $\Delta_{net,0.4u}$ | 7.01 | 6.32 | mm |
| | $K_e$ | 2.10 | 2.44 | kN/mm |
| | $F_{0.8u}$ | 29.51 | 30.81 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 61 | 61 | mm |
| | Normalized energy [1] | 29.93 | 31.45 | J/mm |
| EEEP analysis | $F_y$ | 34.59 | 35.75 | kN |
| | $\Delta_y$ | 16.44 | 14.66 | mm |
| | Ductility ($\mu$) | 3.71 | 4.16 | - |
| | $R_d$ | 2.53 | 2.71 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 22.81 | 22.17 | mm |
| | $K_{e,mod.EEEP}$ | 1.62 | 1.74 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.29 | 28.55 | kN |
| | $K_p$ | 1.65 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | 28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 3655 | 15949 | - |
| | Yielding strain | 1617 | 1617 | - |
| | Yielding status | OK | OK | |

[1] Ratio of energy dissipated under the measured curve by maximum displacement

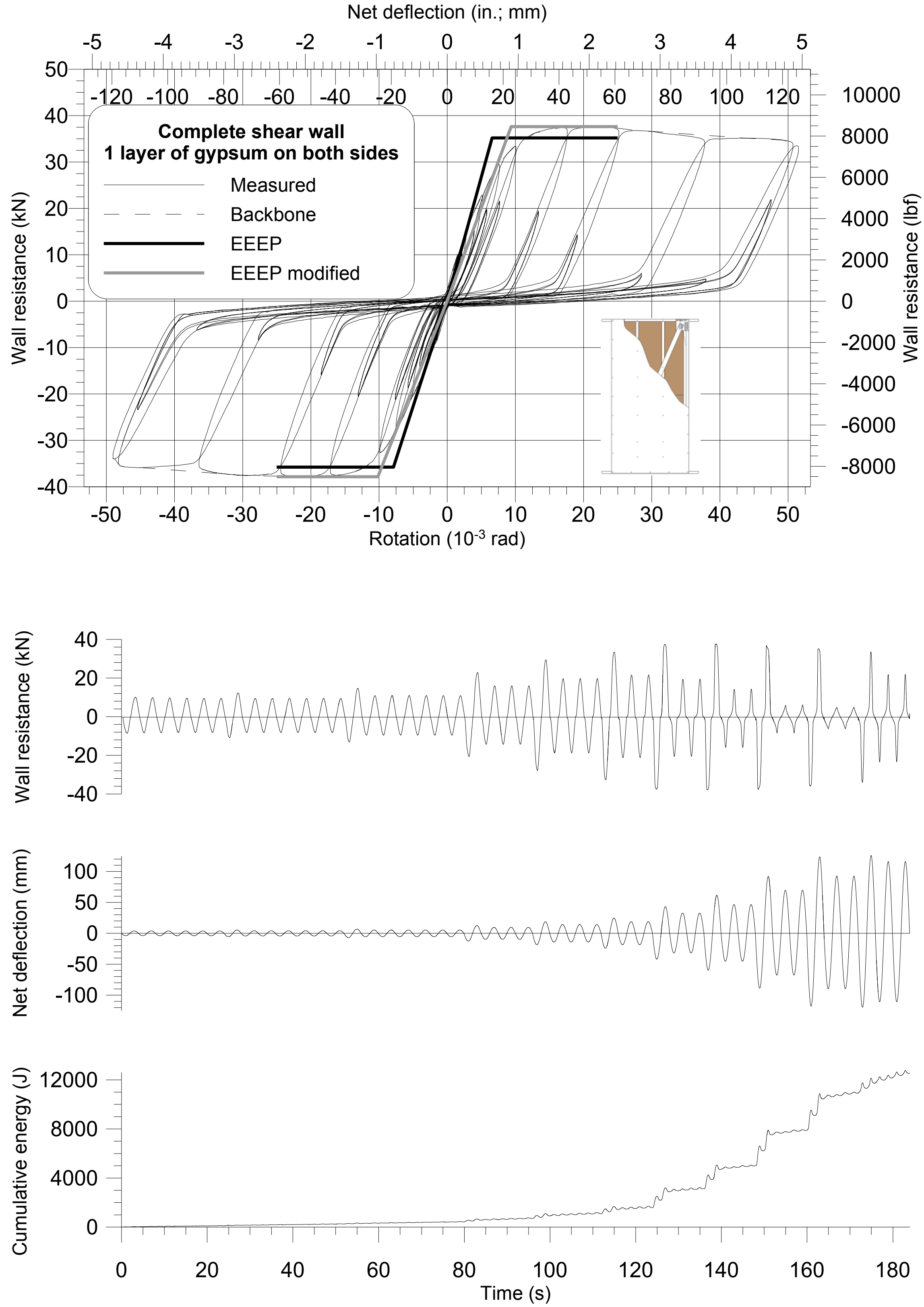
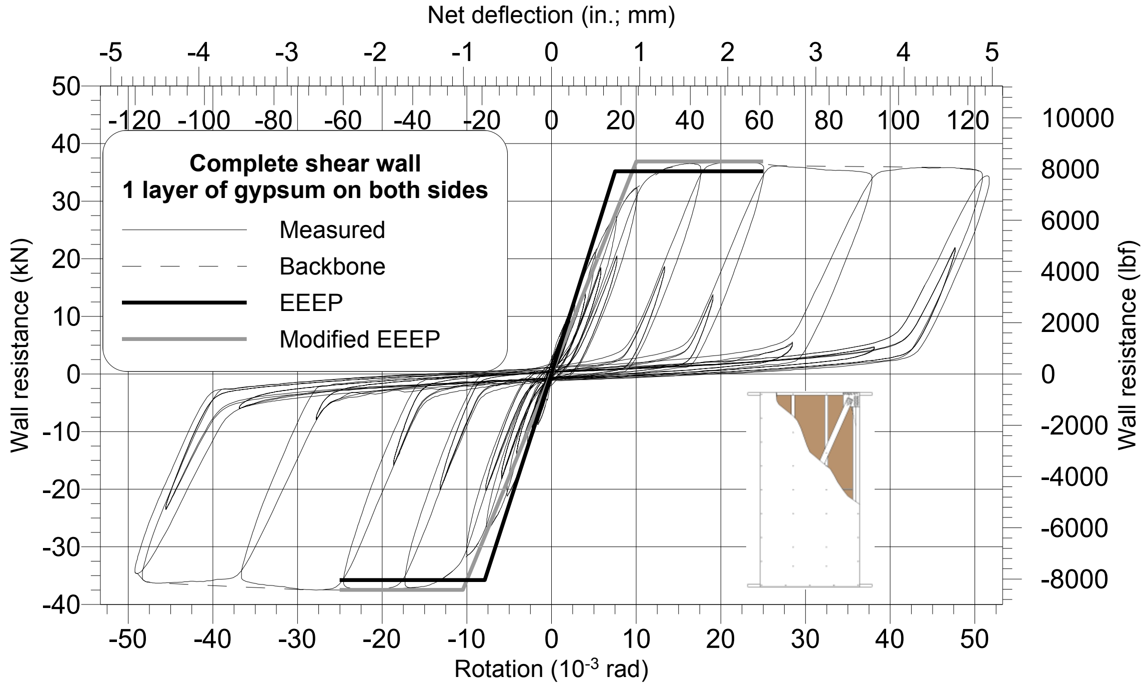



**Figure C-31 Measured and EEEP curves and time history for test 71A-C**



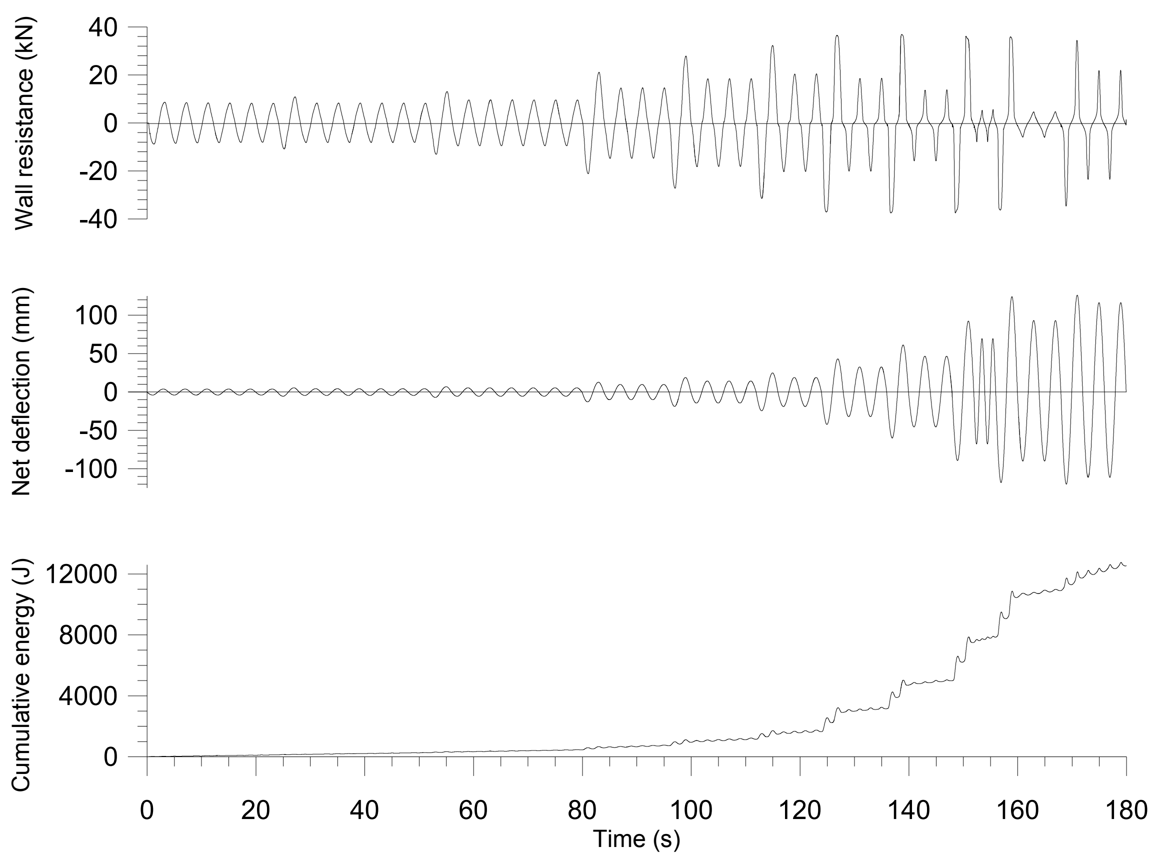




**Figure C-32 Measured and EEEP curves and time history for test 71 B-C**

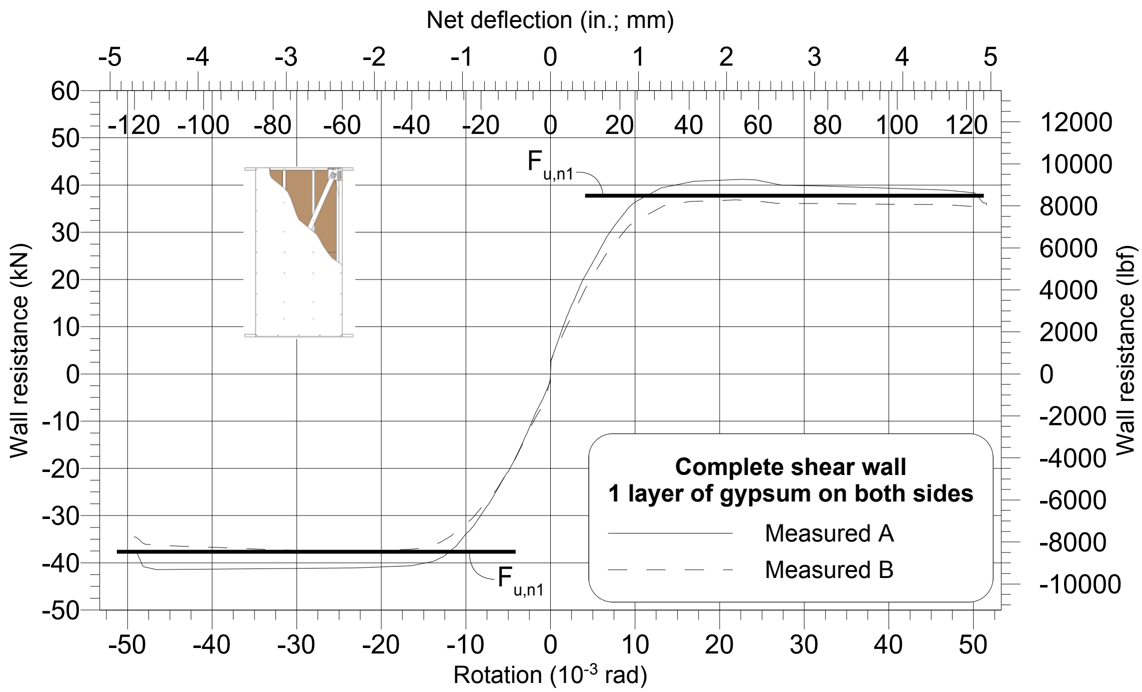



**Figure C-33 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 71A-C and 71B-C**

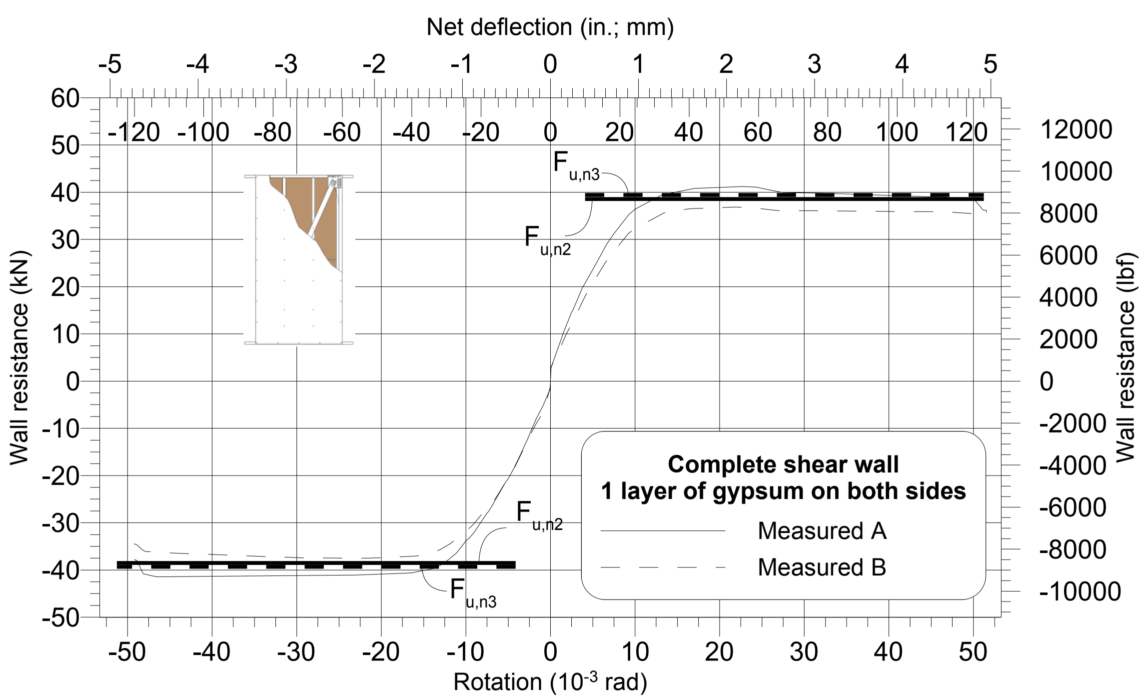



**Figure C-34 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 71A-C and 71B-C**

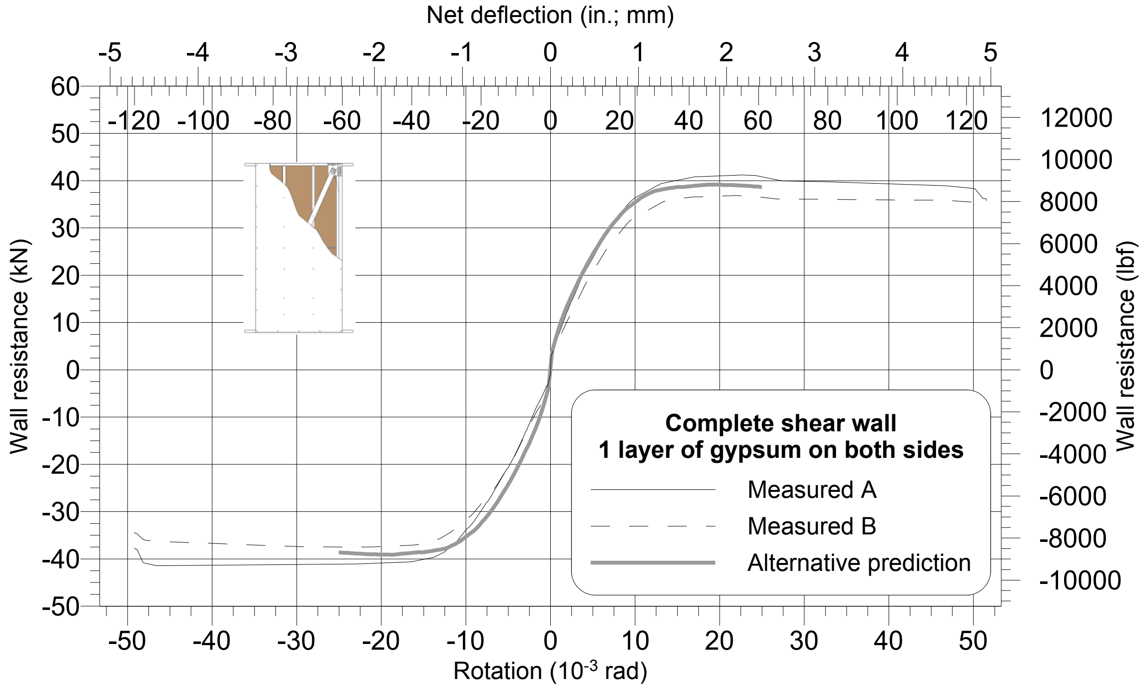



**Figure C-35 C-36 Comparison of the predicted load-drift curve and the test results for tests 71A-C and 71B-C**

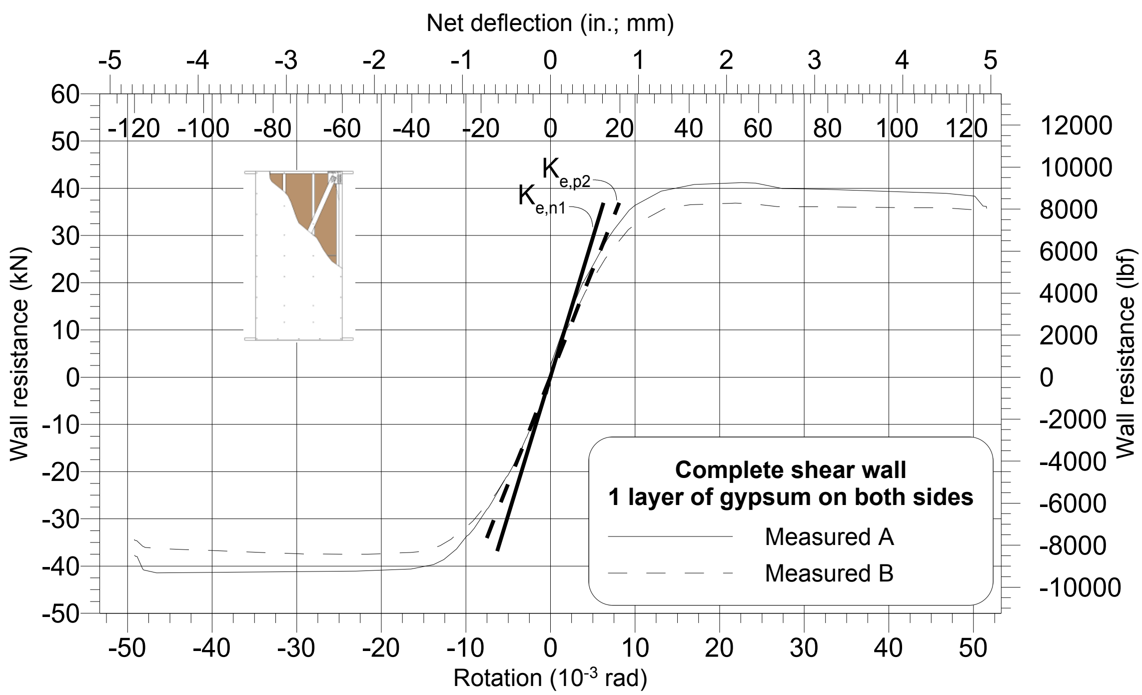



**Figure C-37 Comparison of the different stiffness predictions for tests 71A-C and 71B-C**

**Table 10 Cyclic test results for tests 71A-C and 71B-C**

| | Parameters | Specimens | | | | Units |
|---|---|---|---|---|---|---|
| | | 71A-C | | 71B-C | | |
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 37.60 | -37.85 | 36.85 | -37.51 | kN |
| | $\Delta_{net,u}$ | 52.58 | -52.35 | 53.26 | -52.66 | mm |
| | $F_{0.4u}$ | 15.09 | -15.09 | 14.87 | -14.87 | kN |
| | $\Delta_{net,0.4u}$ | 6.91 | -8.09 | 7.90 | -8.09 | mm |
| | $K_e$ | 2.18 | 1.87 | 1.88 | 1.84 | kN/mm |
| | $F_{0.8u}$ | 30.18 | -30.18 | 29.75 | -29.75 | kN |
| | $\Delta_{net,0.8u}$ | - | - | - | - | mm |
| | $\Delta_{net,max}$ | 61 | -61 | 61 | -61 | mm |
| | Normalized energy [(1)] | 30.52 | -30.18 | 29.36 | -29.71 | J/mm |
| EEEP analysis | $F_y$ | 35.16 | -35.82 | 34.56 | -35.26 | kN |
| | $\Delta_{net,y}$ | 16.11 | -19.20 | 18.35 | -19.18 | mm |
| | Ductility ($\mu$) | 3.79 | 3.18 | 3.32 | 3.18 | - |
| | $R_d$ | 2.56 | 2.31 | 2.38 | 2.32 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 22.88 | -24.77 | 24.53 | -25.49 | mm |
| | $K_{e,mod.EEEP}$ | 1.64 | 1.53 | 1.50 | 1.47 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.55 | -28.43 | 28.28 | -28.38 | kN |
| | $K_p$ | 1.66 | 1.65 | 1.65 | 1.65 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | -28.44 | 28.44 | -28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 15620 | 6735 | 14666 | 6958 | - |
| | Yielding strain | 1617 | 1617 | 1617 | 1617 | - |
| | Yielding status | OK | OK | OK | OK | |

(1) Ratio of energy dissipated under the backbone curve by maximum displacement

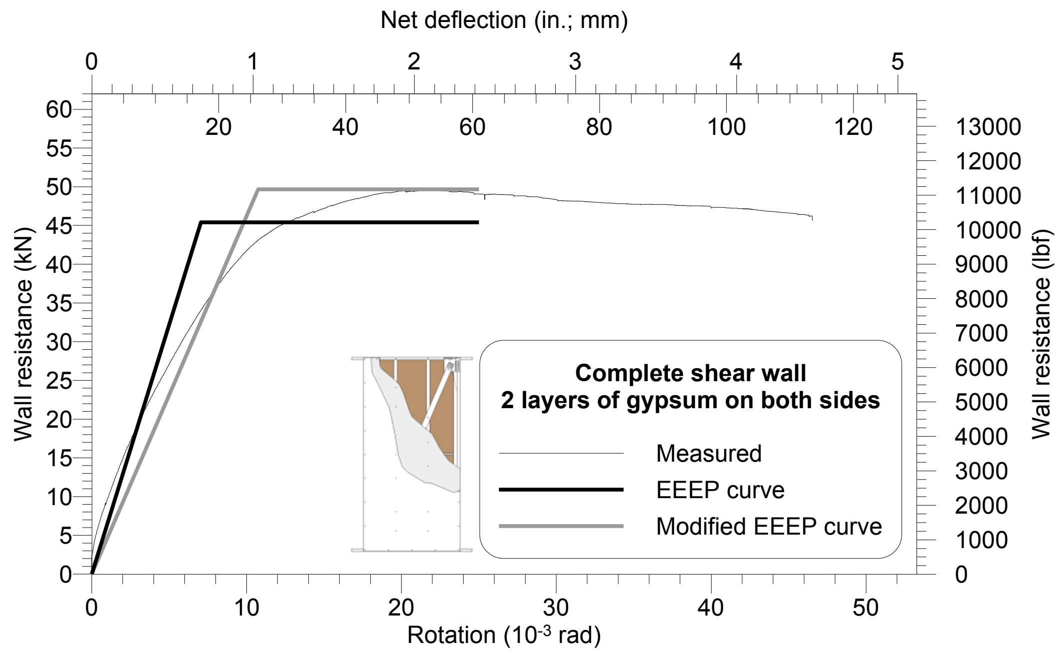



**Figure C-38 Measured and EEEP curves for test 72A-M**

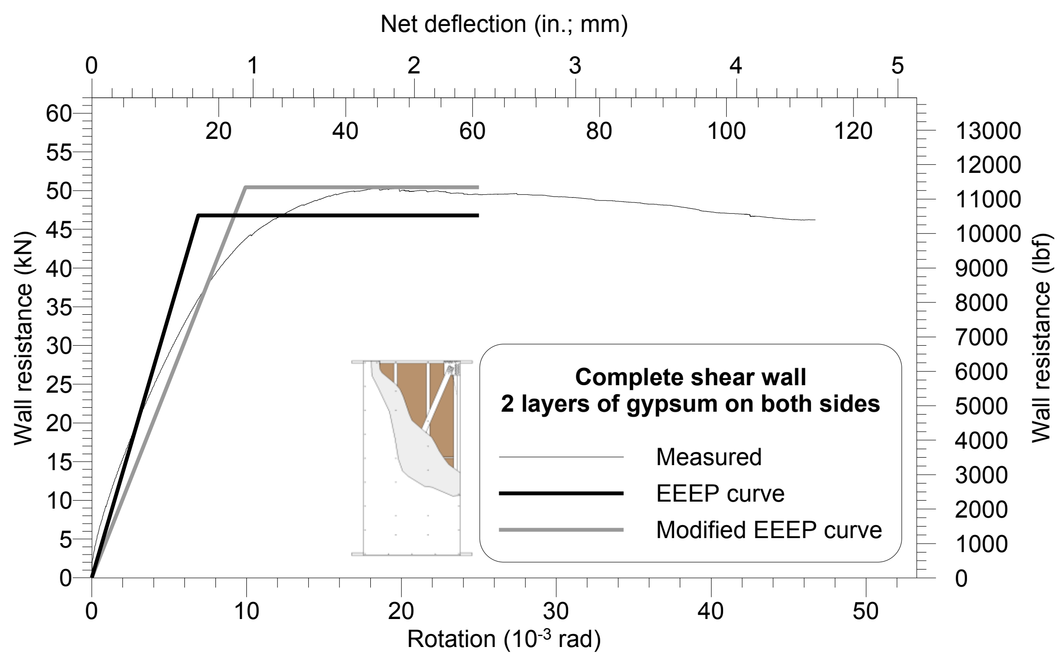



**Figure C-39 Measured and EEEP curves for test 72B-M**

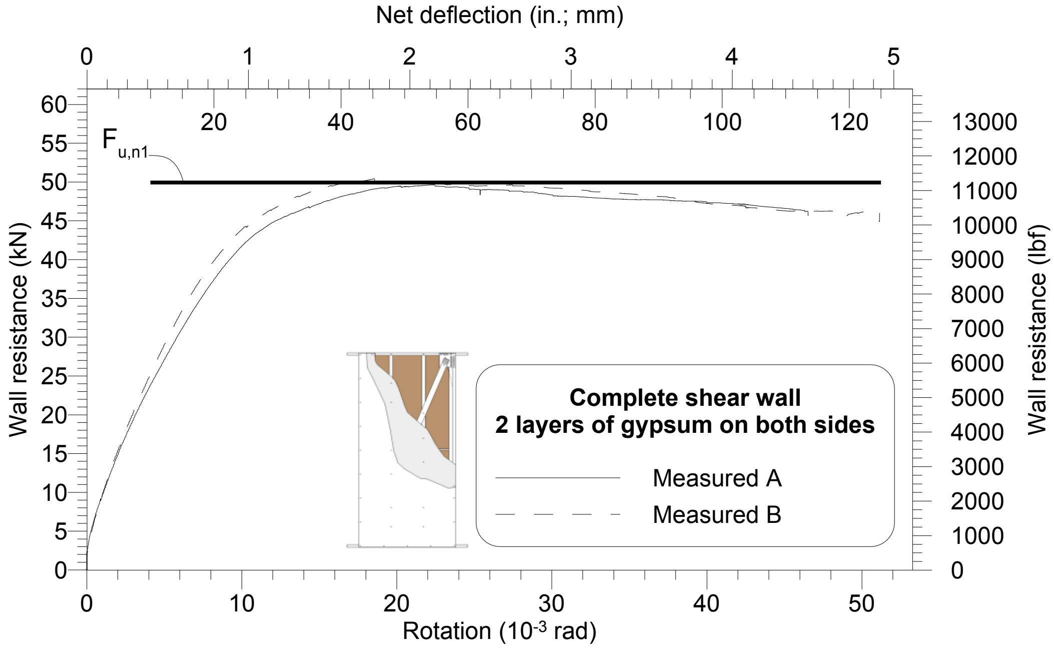



**Figure C-40 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 72A-M and 72B-M**

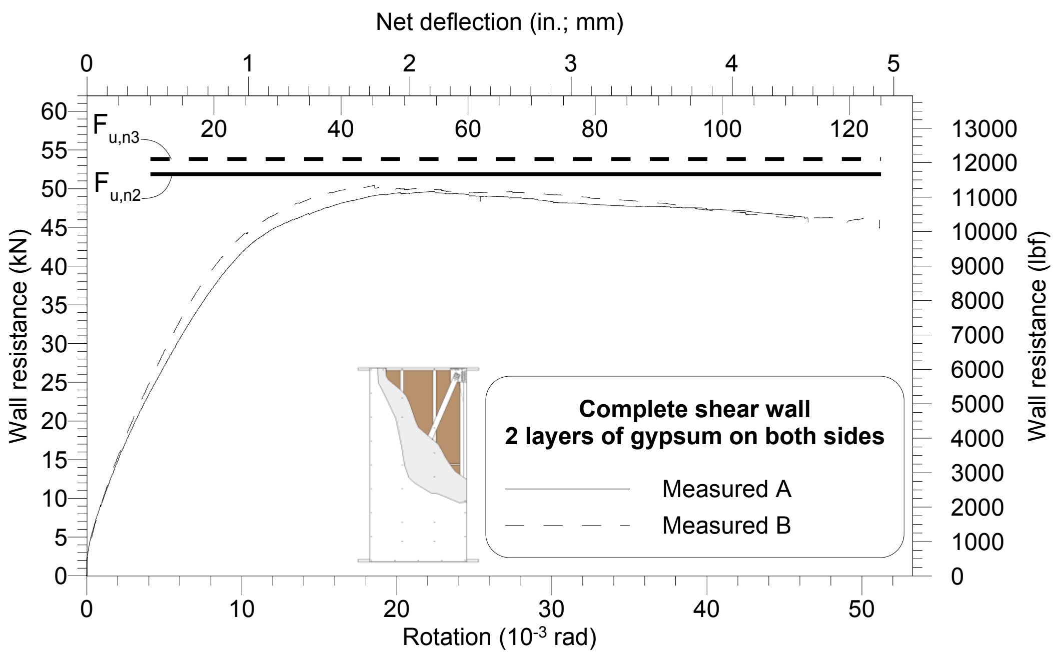



**Figure C-41 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 72A-M and 72B-M**

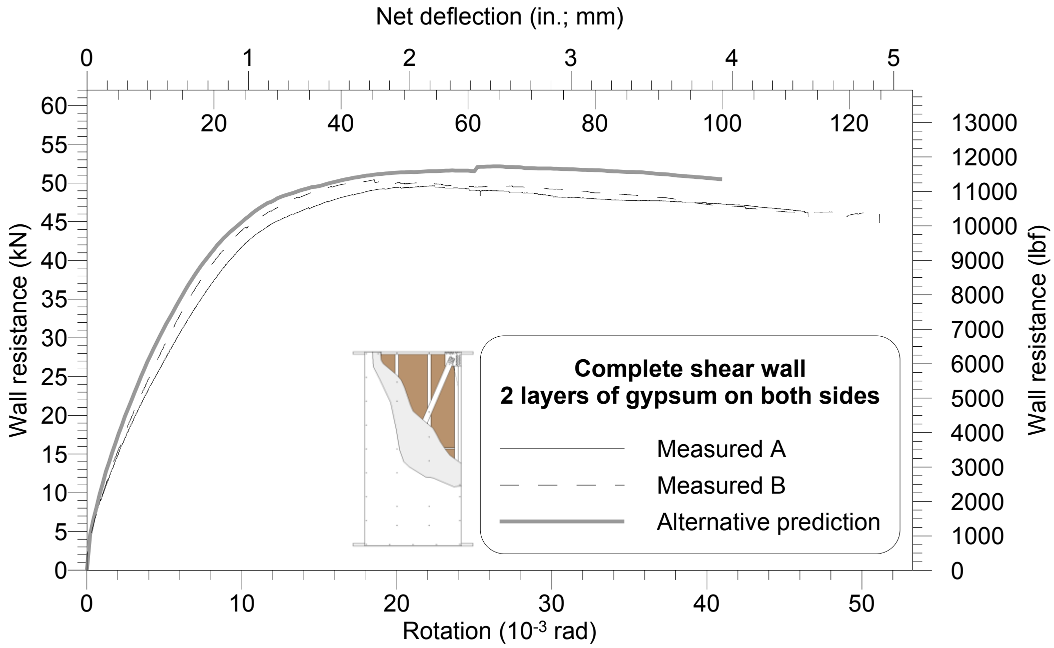



**Figure C-42 C-43 Comparison of the predicted load-drift curve and the test results for tests 72A-M and 72B-M**

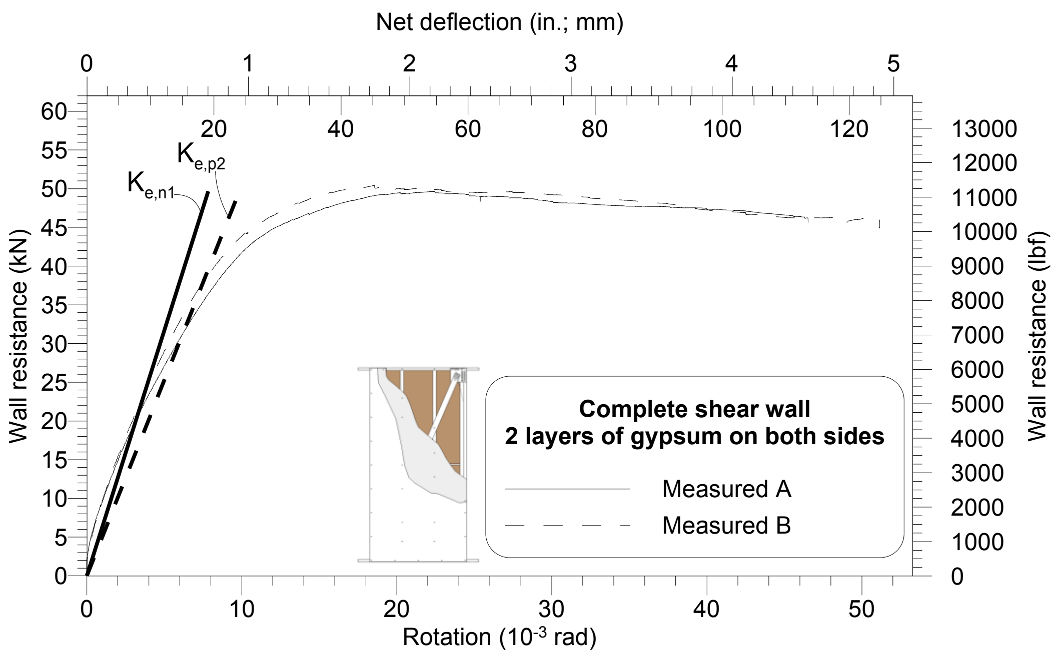



**Figure C-44 Comparison of the different stiffness predictions for tests 72A-M and 72B-M**

**Table 11 Monotonic test results for tests 72A-M and 72B-M**

| | Parameters | Specimens | | Units |
|---|---|---|---|---|
| | | 72A-M | 72B-M | |
| Test Results | $F_u$ | 49.64 | 50.43 | kN |
| | $\Delta_{net,u}$ | 54.37 | 45.24 | mm |
| | $F_{0.4u}$ | 19.86 | 20.17 | kN |
| | $\Delta_{net,0.4u}$ | 7.53 | 7.24 | mm |
| | $K_e$ | 2.64 | 2.79 | kN/mm |
| | $F_{0.8u}$ | 39.71 | 40.34 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 61 | 61 | mm |
| | Normalized energy (1) | 38.98 | 40.33 | J/mm |
| EEEP analysis | $F_y$ | 45.38 | 46.77 | kN |
| | $\Delta_y$ | 17.20 | 16.79 | mm |
| | Ductility ($\mu$) | 3.55 | 3.63 | - |
| | $R_d$ | 2.47 | 2.50 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 26.20 | 24.22 | mm |
| | $K_{e,mod.EEEP}$ | 1.89 | 2.08 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.47 | 28.45 | kN |
| | $K_p$ | 1.66 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | 28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 15684 | 15523 | - |
| | Yielding strain | 1617 | 1617 | - |
| | Yielding status | OK | OK | |

(1) Ratio of energy dissipated under the measured curve by maximum displacement

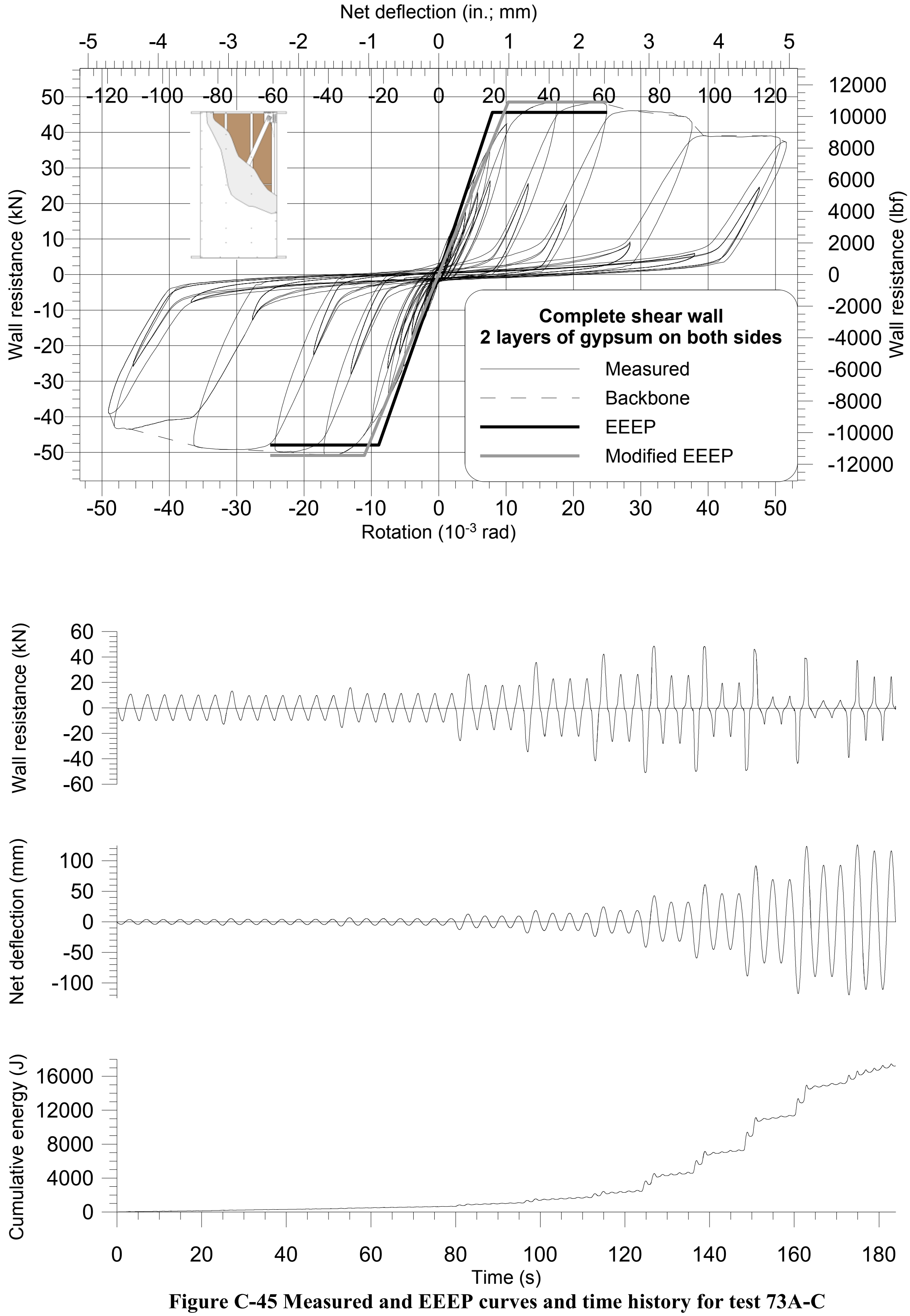



**Figure C-45 Measured and EEEP curves and time history for test 73A-C**

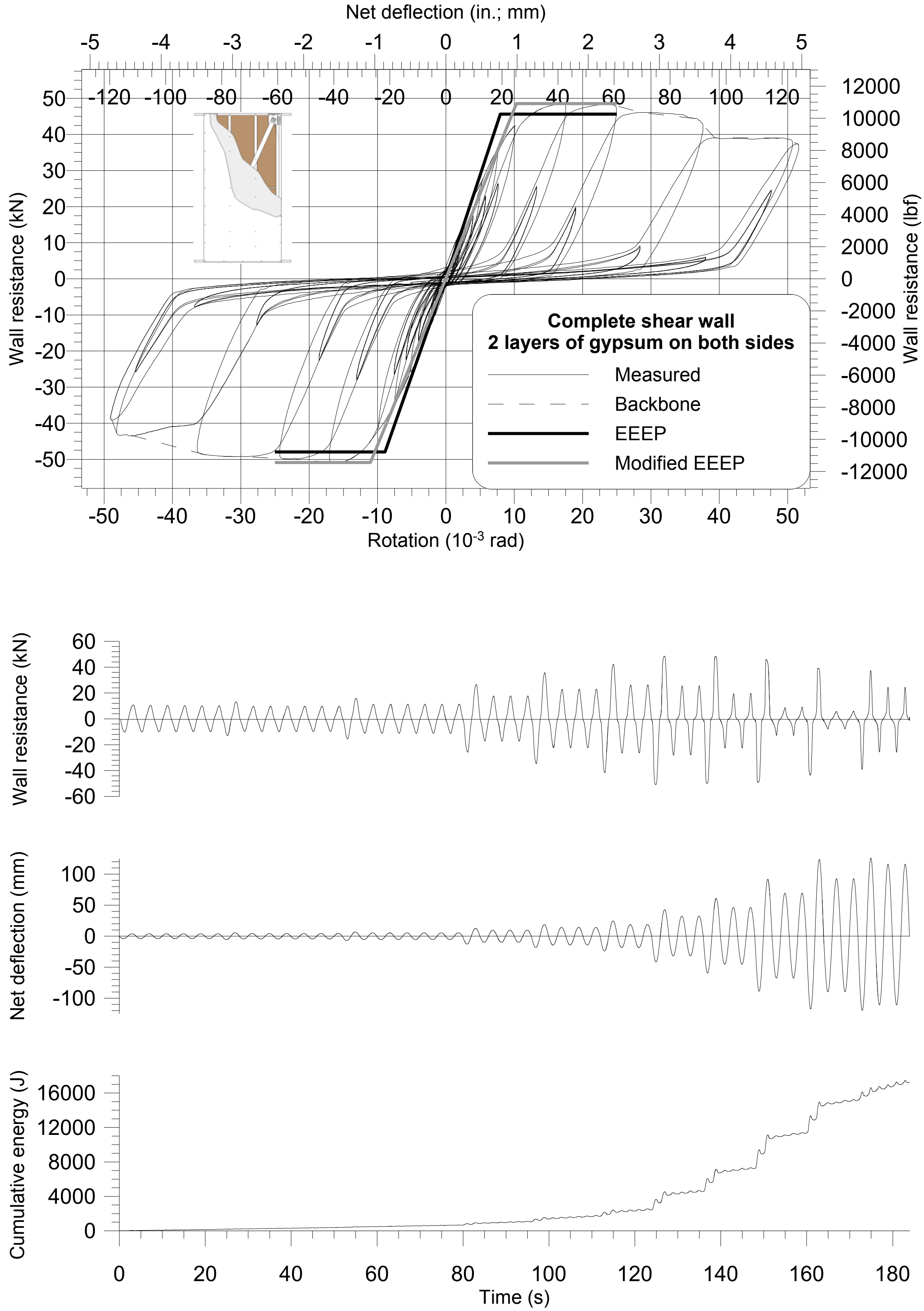



**Figure C-46 Measured and EEEP curves and time history for test 73B-C**

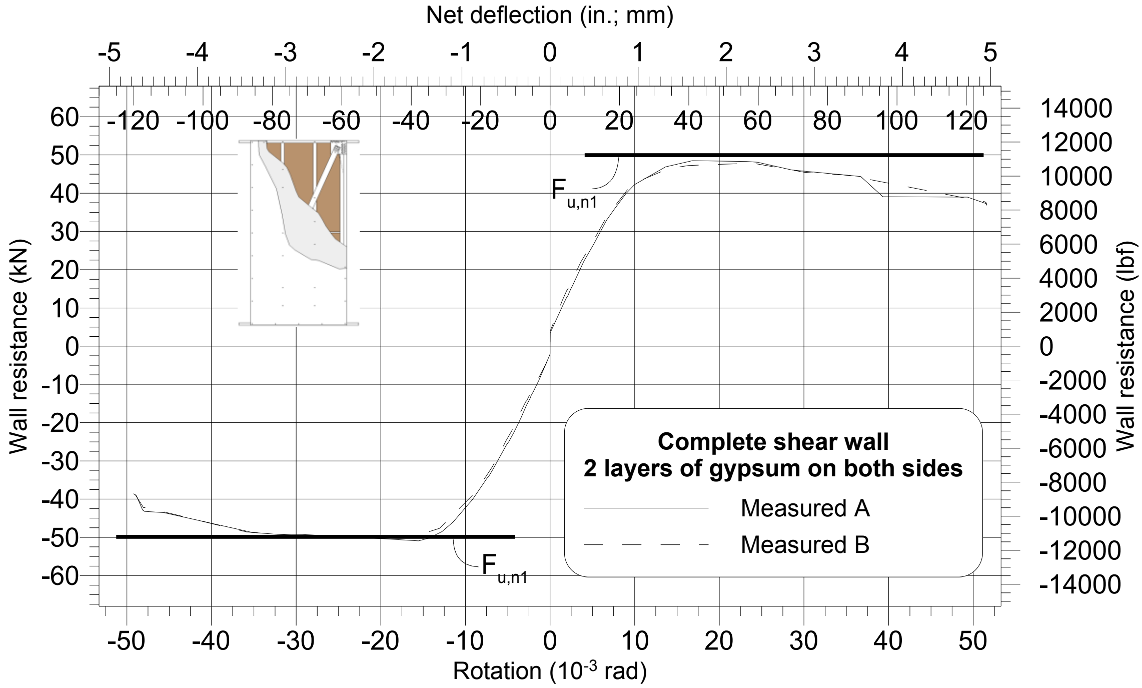



**Figure C-47 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 73A-C and 73B-C**

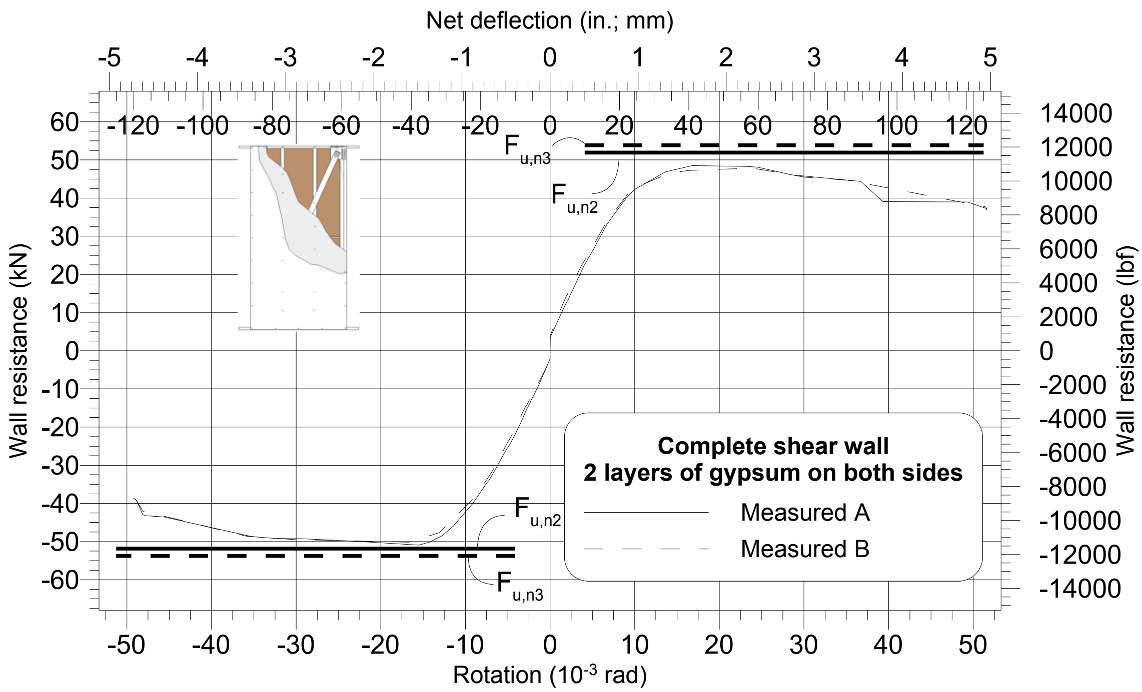



**Figure C-48 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 73A-C and 73B-C**

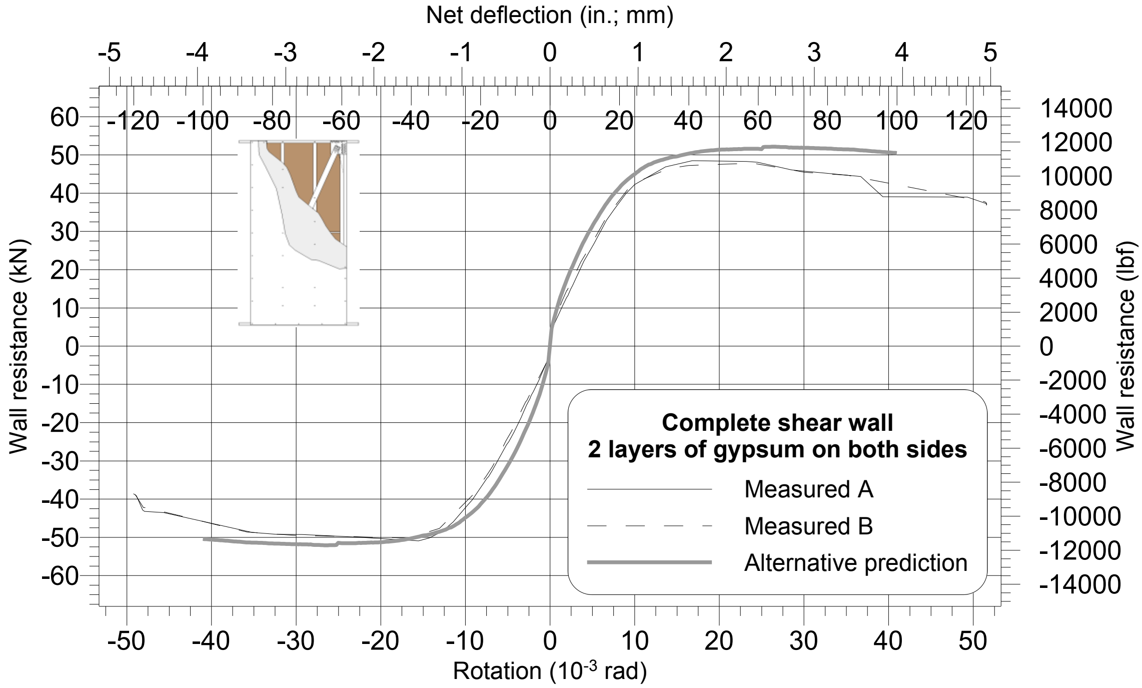



**Figure C-49 C-50 Comparison of the predicted load-drift curve and the test results for tests 73A-C and 73B-C**

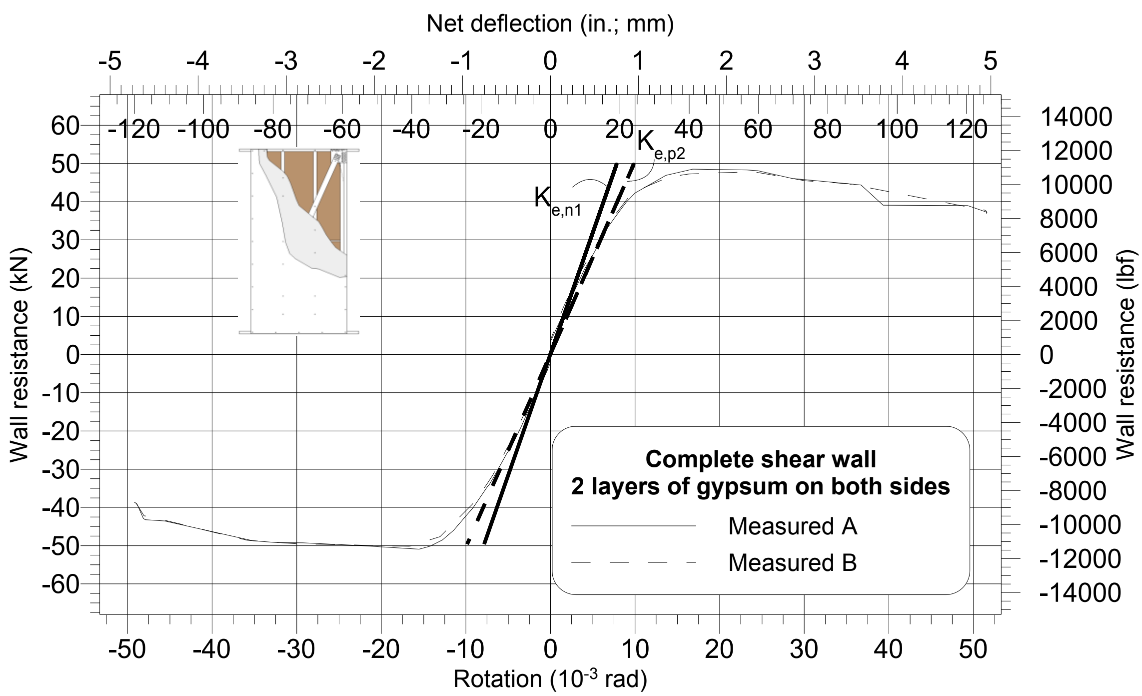



**Figure C-51 Comparison of the different stiffness predictions for tests 73A-C and 73B-C**

**Table 12 Cyclic test results for tests 73A-C and 73B-C**

| | Parameters | Specimens | | | | Units |
|---|---|---|---|---|---|---|
| | | 73A-C | | 73B-C | | |
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 48.51 | -50.92 | 47.81 | -50.19 | kN |
| | $\Delta_{net,u}$ | 40.98 | -37.90 | 57.37 | -40.74 | mm |
| | $F_{0.4u}$ | 19.89 | -19.89 | 19.60 | -19.60 | kN |
| | $\Delta_{net,0.4u}$ | 8.50 | -8.99 | 7.50 | -9.72 | mm |
| | $K_e$ | 2.34 | 2.21 | 2.61 | 2.02 | kN/mm |
| | $F_{0.8u}$ | 39.77 | -39.77 | 39.20 | -39.20 | kN |
| | $\Delta_{net,0.8u}$ | 95.06 | -118.92 | 116.98 | -119.34 | mm |
| | $\Delta_{net,max}$ | 61 | -61 | 61 | -61 | mm |
| | Normalized energy (1) | 38.30 | -39.46 | 38.40 | -38.53 | J/mm |
| EEEP analysis | $F_y$ | 45.58 | -47.99 | 44.65 | -47.83 | kN |
| | $\Delta_{net,y}$ | 19.48 | -21.70 | 17.08 | -23.72 | mm |
| | Ductility (μ) | 3.13 | 2.81 | 3.57 | 2.57 | - |
| | $R_d$ | 2.29 | 2.15 | 2.48 | 2.04 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 25.25 | -26.88 | 23.87 | -28.22 | mm |
| | $K_{e,mod.EEEP}$ | 1.92 | 1.89 | 2.00 | 1.78 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.63 | -28.59 | 28.43 | -28.63 | kN |
| | $K_p$ | 1.66 | 1.66 | 1.65 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | -28.44 | 28.44 | -28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 15489 | 11945 | 15433 | 8968 | - |
| | Yielding strain | 1617 | 1617 | 1617 | 1617 | - |
| | Yielding status | OK | OK | OK | OK | |

(1) Ratio of energy dissipated under the backbone curve by maximum displacement

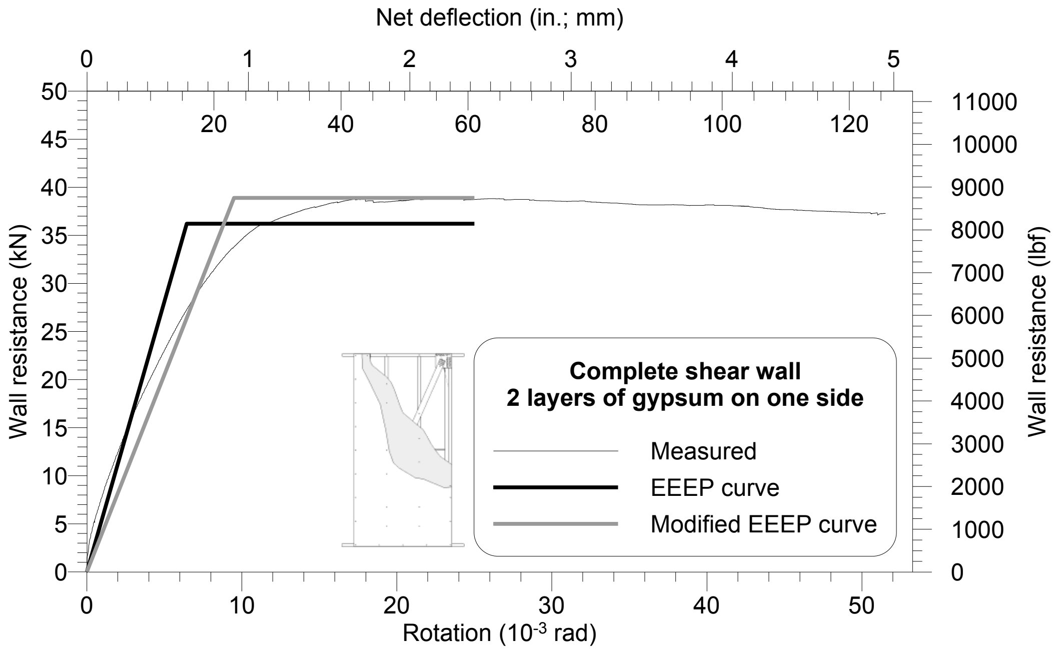



**Figure C-52 Measured and EEEP curves for test 74A-M**

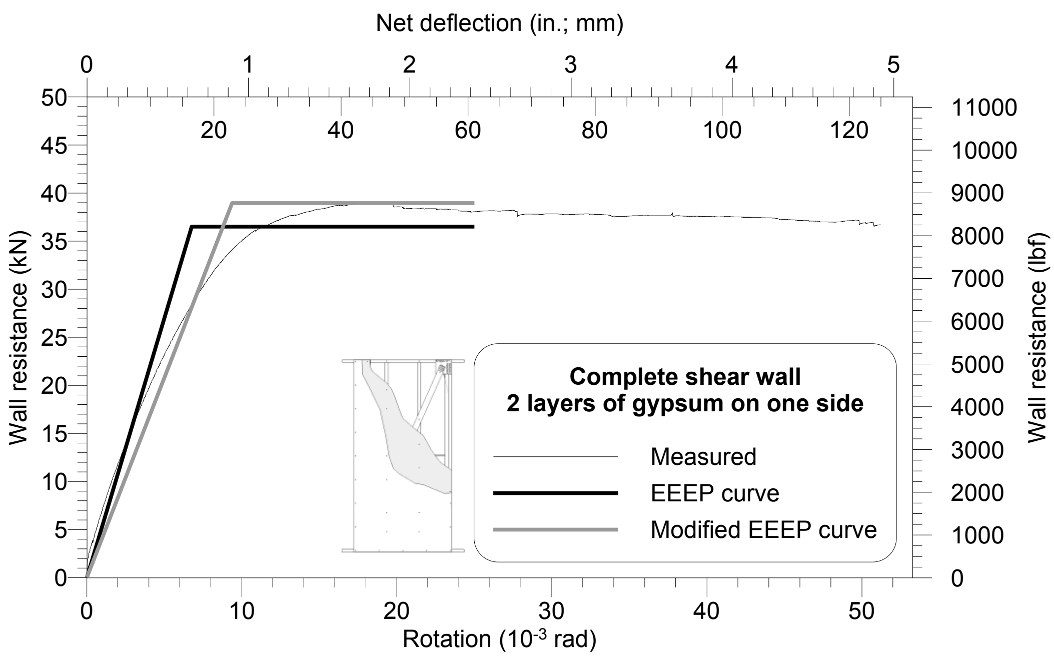



**Figure C-53 Measured and EEEP curves for test 74B-M**

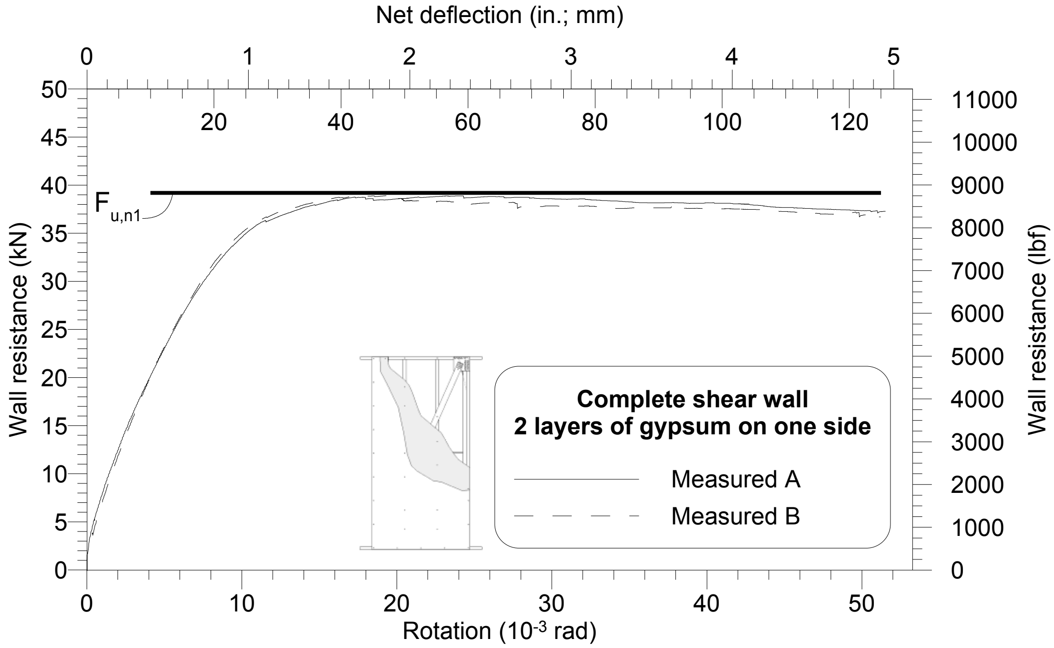



**Figure C-54 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 74A-M and 74B-M**

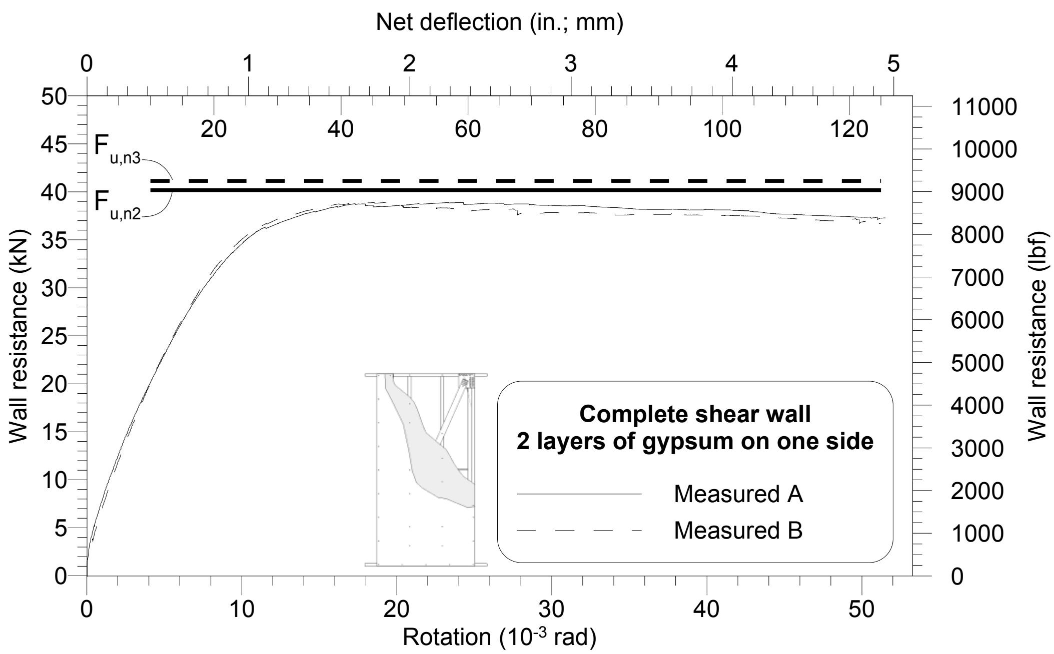



**Figure C-55 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 74A-M and 74B-M**

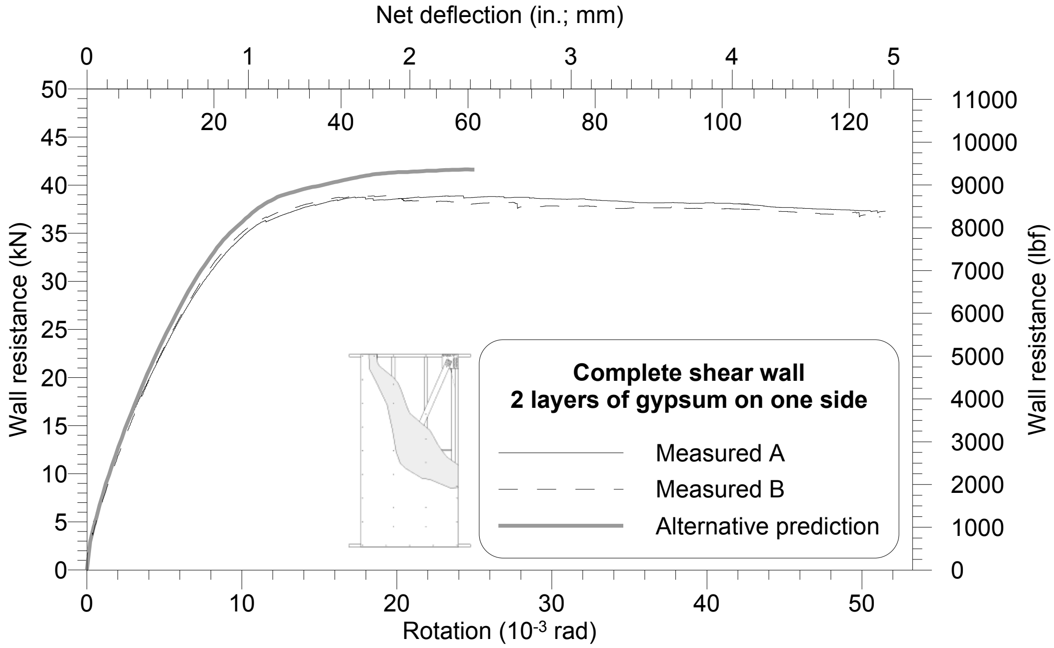



**Figure C-56 Comparison of the predicted load-drift curve and the test results for tests 74A-M and 74B-M**

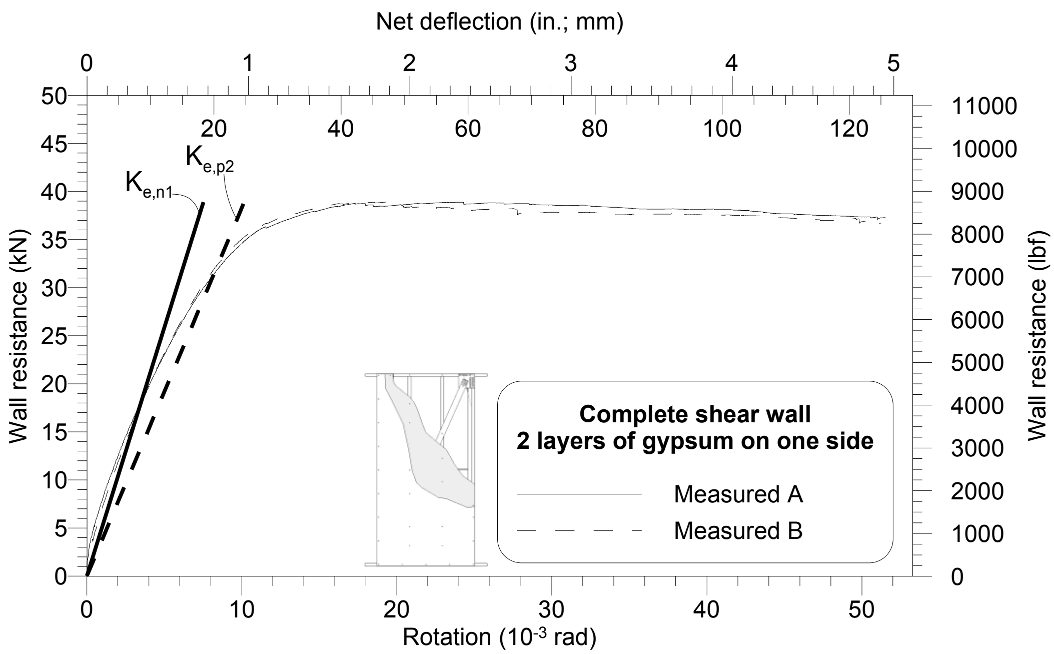



**Figure C-57 Comparison of the different stiffness predictions for tests 74A-M and 74B-M**

**Table 13 Monotonic test results for tests 74A-M and 74B-M**

| | Parameters | Specimens | | Units |
|---|---|---|---|---|
| | | 74A-M | 74B-M | |
| Test Results | $F_u$ | 38.88 | 38.94 | kN |
| | $\Delta_{net,u}$ | 58.74 | 47.87 | mm |
| | $F_{0.4u}$ | 15.55 | 15.58 | kN |
| | $\Delta_{net,0.4u}$ | 6.75 | 7.05 | mm |
| | $K_e$ | 2.30 | 2.21 | kN/mm |
| | $F_{0.8u}$ | 31.11 | 31.15 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 61 | 61 | mm |
| | Normalized energy (1) | 31.53 | 31.56 | J/mm |
| EEEP analysis | $F_y$ | 36.19 | 36.50 | kN |
| | $\Delta_y$ | 15.71 | 16.52 | mm |
| | Ductility ($\mu$) | 3.88 | 3.69 | - |
| | $R_d$ | 2.60 | 2.53 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 23.15 | 22.87 | mm |
| | $K_{e,mod.EEEP}$ | 1.68 | 1.70 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.43 | 28.43 | kN |
| | $K_p$ | 1.65 | 1.65 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | 28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 15614 | 15630 | - |
| | Yielding strain | 1617 | 1617 | - |
| | Yielding status | OK | OK | |

(1) Ratio of energy dissipated under the measured curve by maximum displacement

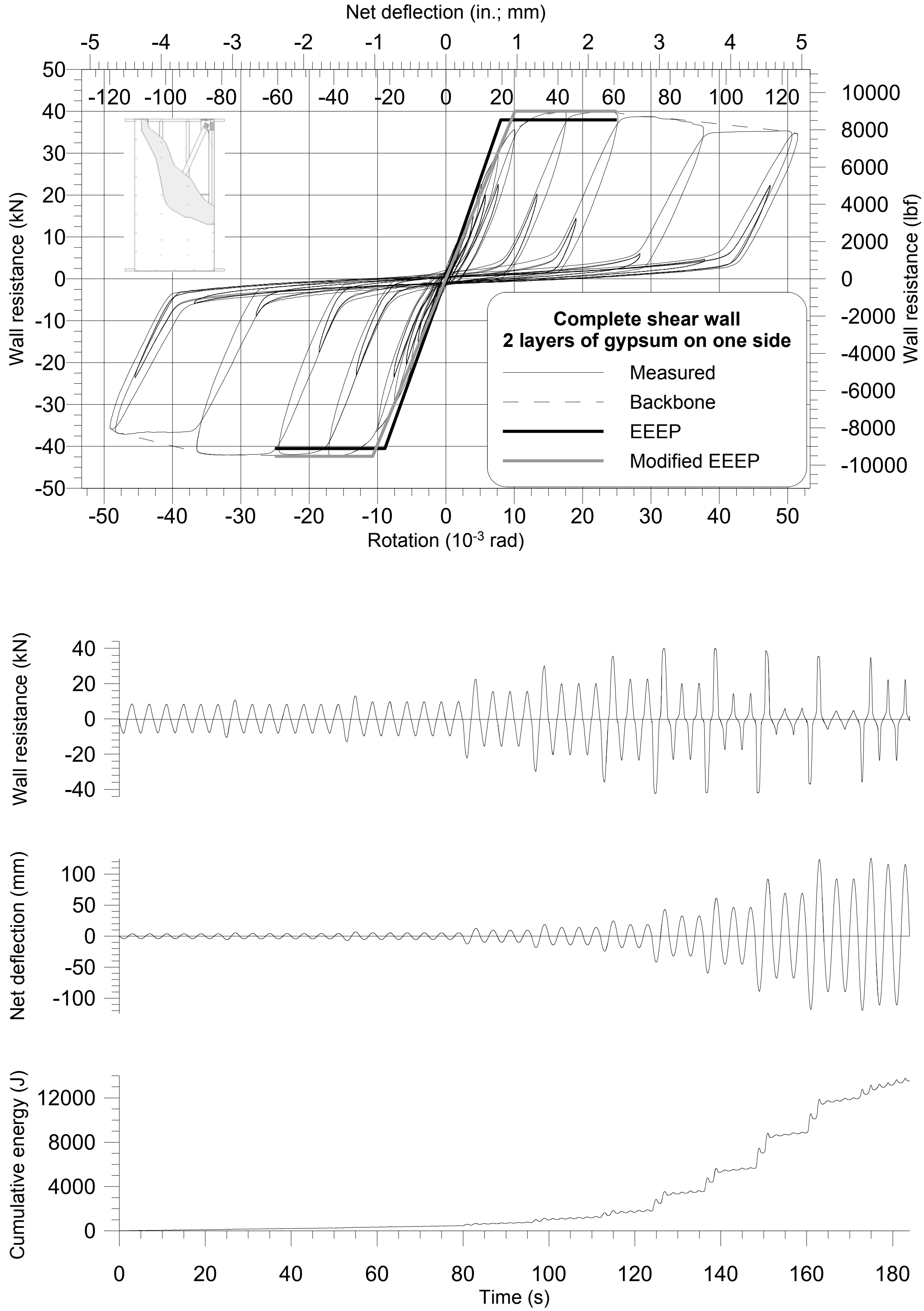
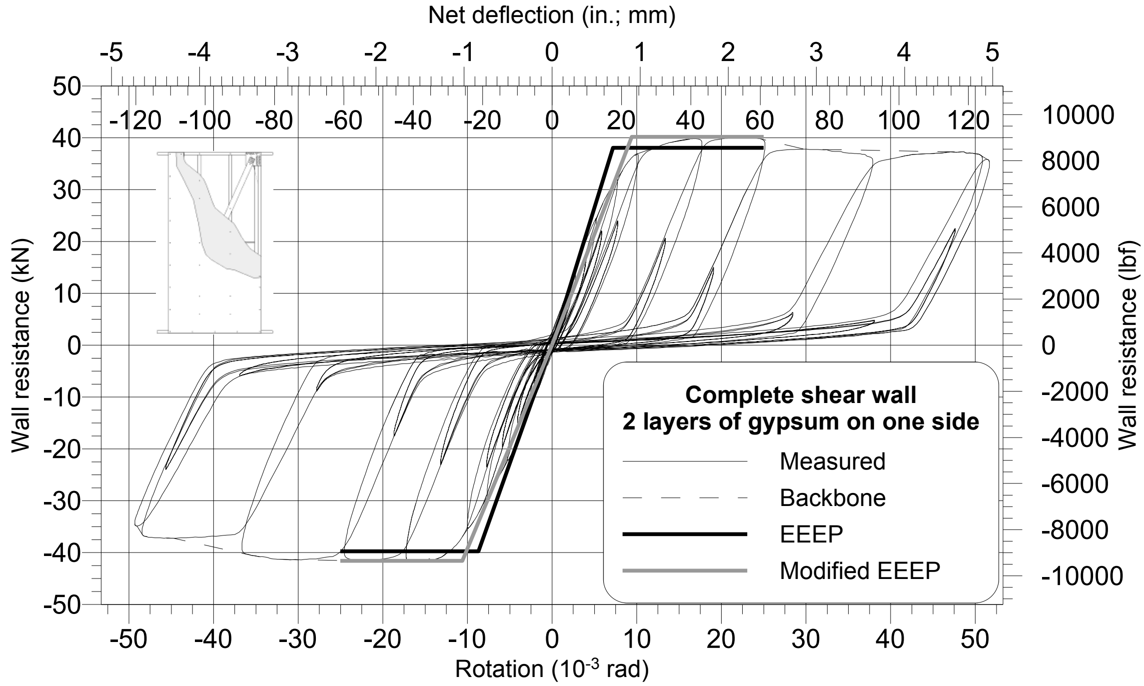



**Figure C-58 Measured and EEEP curves and time history for test 75A-C**



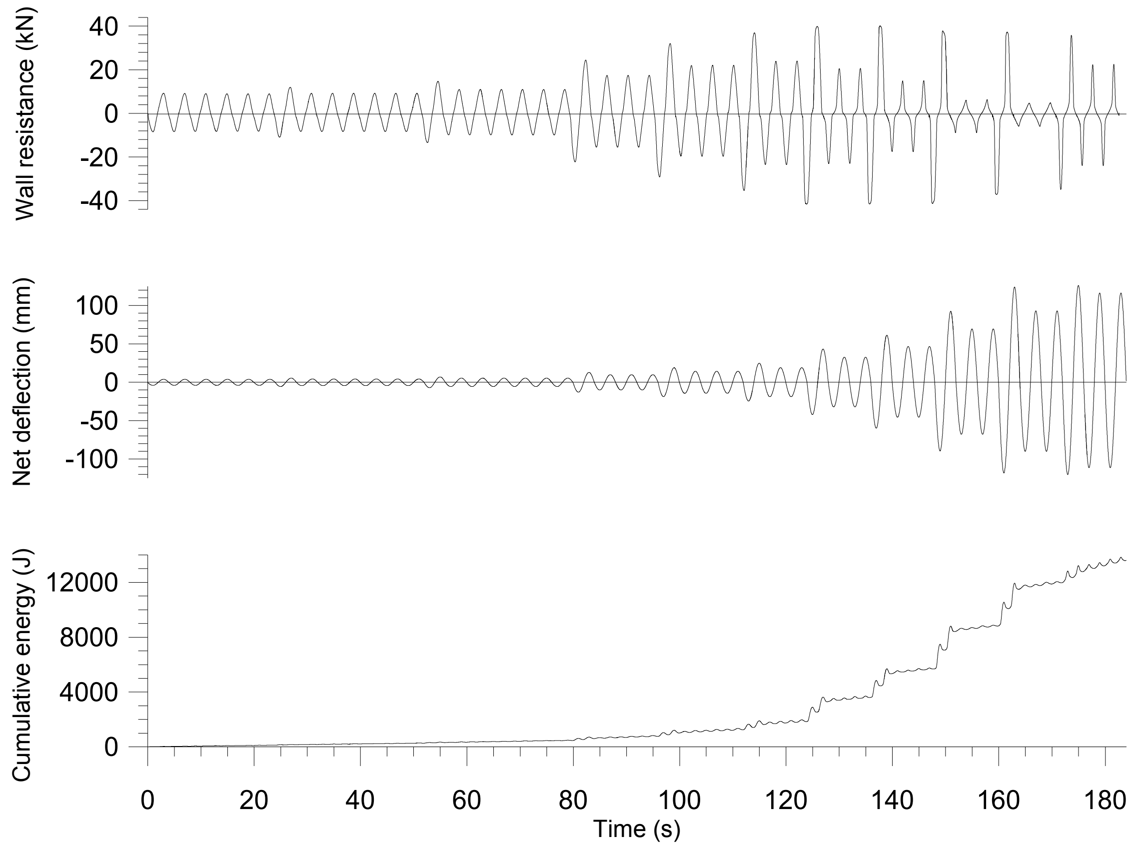




**Figure C-59 Measured and EEEP curves and time history for test 75B-C**

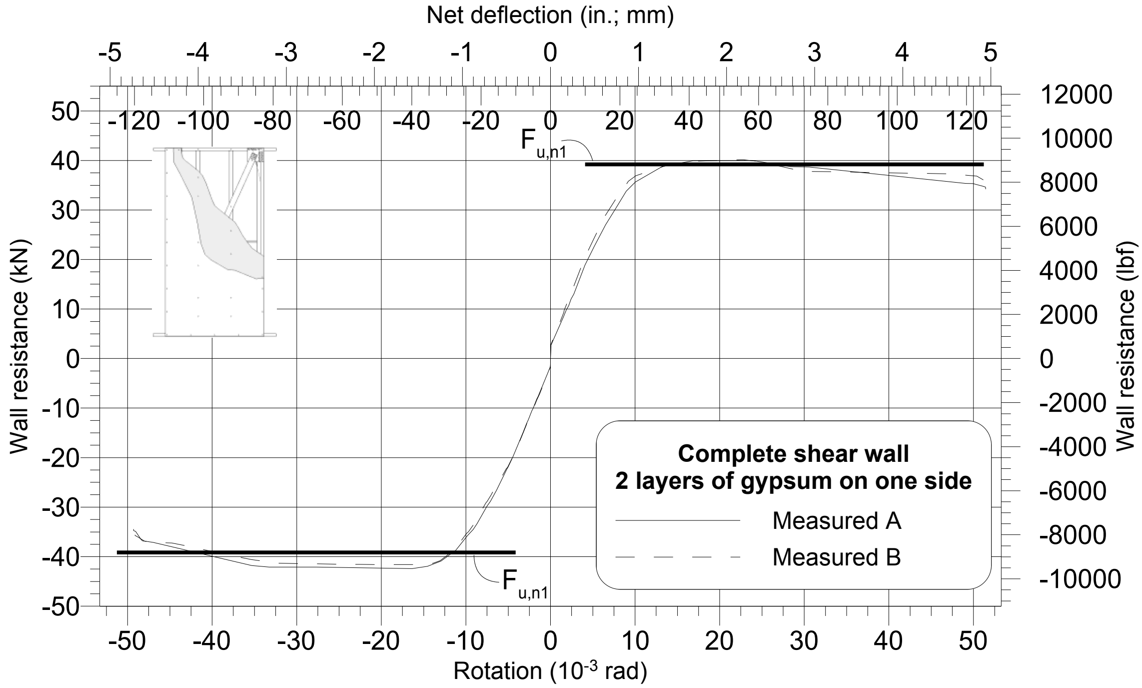



**Figure C-60 Comparison of the simple prediction with a factor of 1.1 (*$F_{u,n1}$*) and the test results for tests 75A-C and 75B-C**

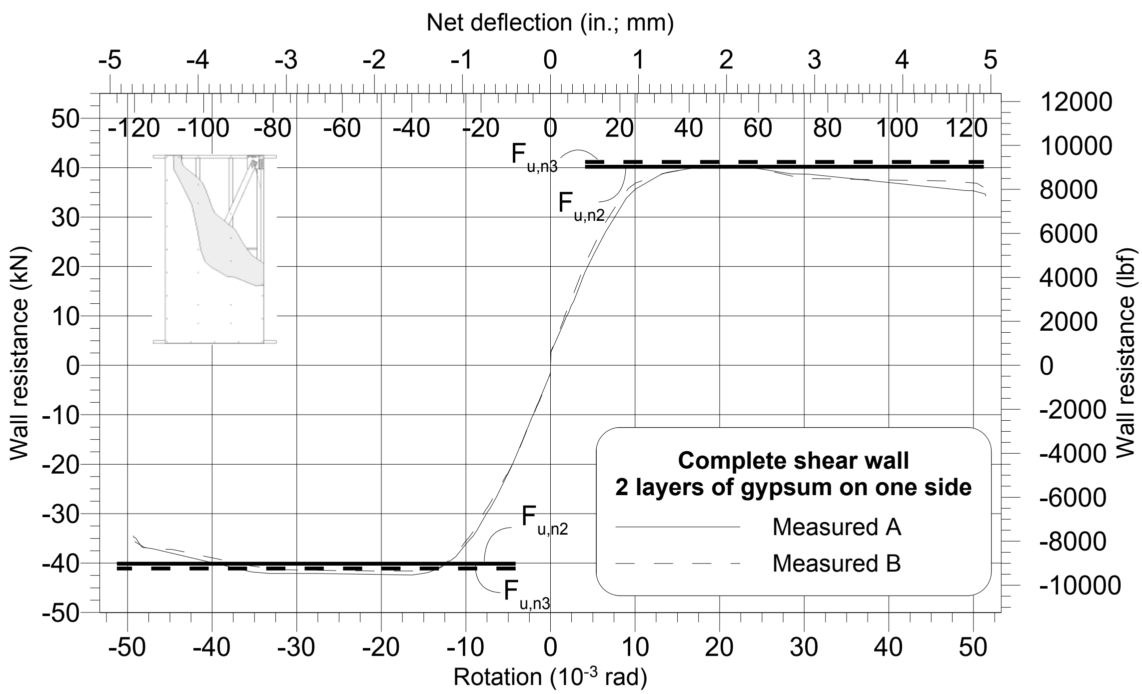



**Figure C-61 Comparison of the conservative simple predictions with a factor of 1.2 (*$F_{u,n2}$*) or 1.3 (*$F_{u,n3}$*) and the test results for tests 75A-C and 75B-C**

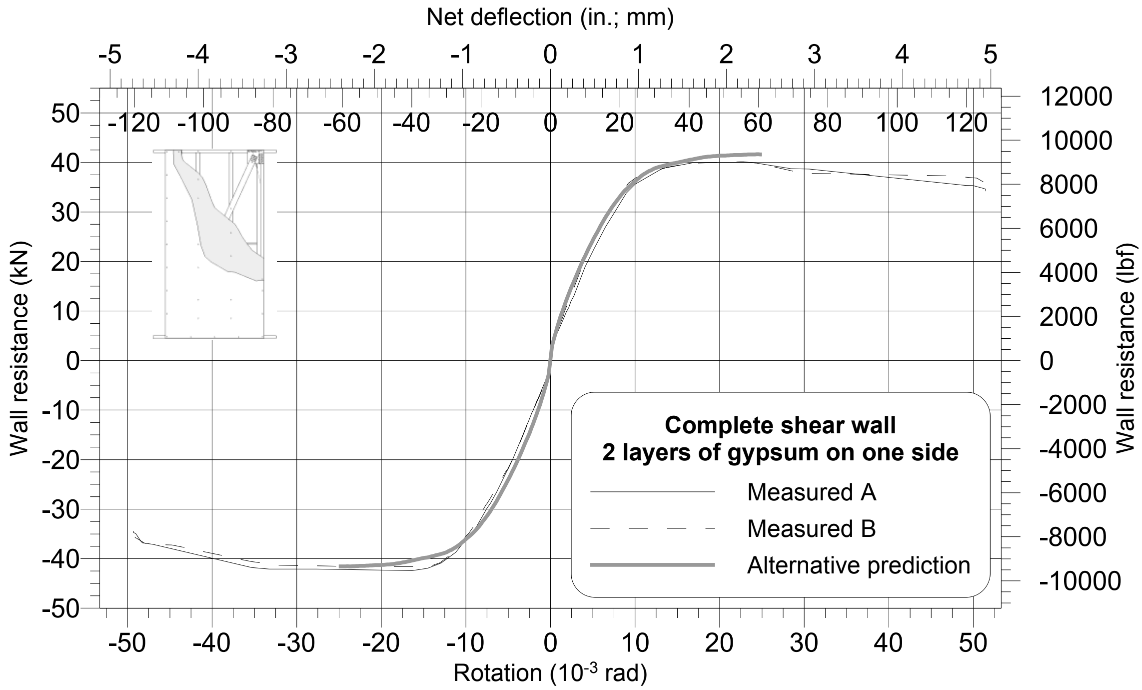



**Figure C-62 C-63 Comparison of the predicted load-drift curve and the test results for tests 75A-C and 75B-C**

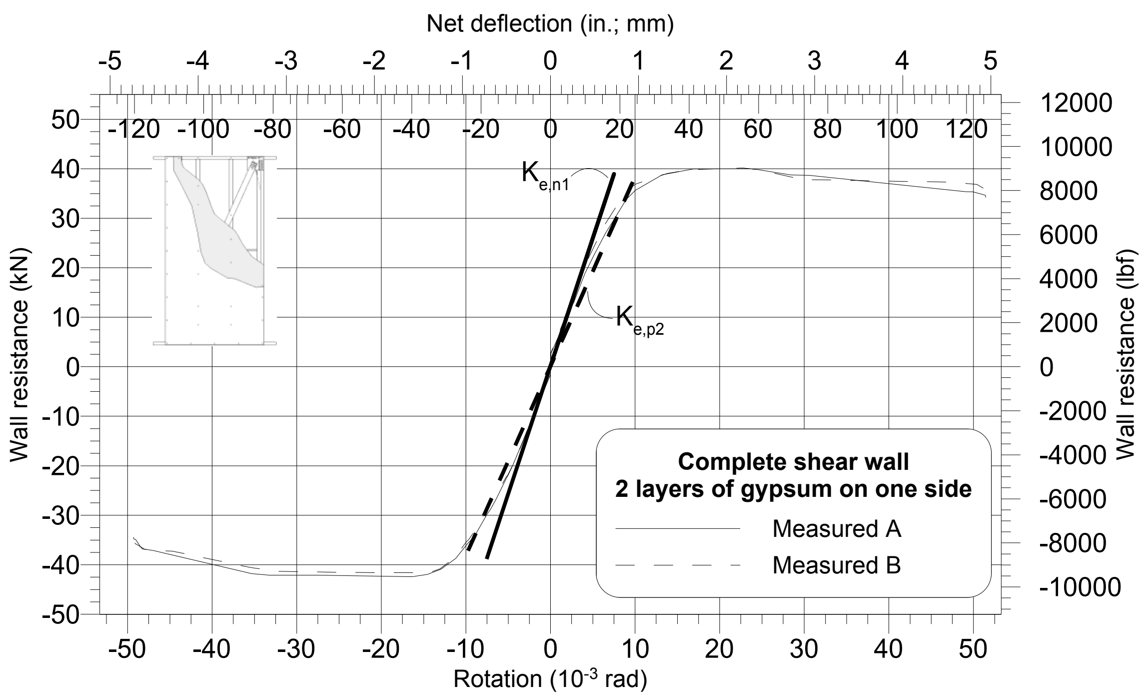



**Figure C-64 Comparison of the different stiffness predictions for tests 75A-C and 75B-C**

**Table 14 Cyclic test results for tests 75A-C and 75B-C**

| | Parameters | Specimens | | | | Units |
|---|---|---|---|---|---|---|
| | | 75A-C | | 75B-C | | |
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 39.98 | -42.40 | 40.16 | -41.62 | kN |
| | $\Delta_{net,u}$ | 57.44 | -39.90 | 55.65 | -40.03 | mm |
| | $F_{0.4u}$ | 16.48 | -16.48 | 16.35 | -16.35 | kN |
| | $\Delta_{net,0.4u}$ | 8.53 | -8.83 | 7.56 | -8.70 | mm |
| | $K_e$ | 1.93 | 1.87 | 2.16 | 1.88 | kN/mm |
| | $F_{0.8u}$ | 32.95 | -32.95 | 32.71 | -32.71 | kN |
| | $\Delta_{net,0.8u}$ | - | - | - | - | mm |
| | $\Delta_{net,max}$ | 61 | -61 | 61 | -61 | mm |
| | Normalized energy [(1)] | 31.83 | -33.32 | 32.54 | -32.88 | J/mm |
| EEEP analysis | $F_y$ | 37.94 | -40.54 | 38.02 | -39.78 | kN |
| | $\Delta_{net,y}$ | 19.63 | -21.73 | 17.58 | -21.17 | mm |
| | Ductility ($\mu$) | 3.11 | 2.81 | 3.47 | 2.88 | - |
| | $R_d$ | 2.28 | 2.15 | 2.44 | 2.18 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 24.68 | -26.13 | 23.01 | -25.85 | mm |
| | $K_{e,mod.EEEP}$ | 1.62 | 1.62 | 1.74 | 1.61 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.53 | -28.53 | 28.59 | -28.47 | kN |
| | $K_p$ | 1.66 | 1.66 | 1.66 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | -28.44 | 28.44 | -28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 7782 | 15506 | 7076 | 5472 | - |
| | Yielding strain | 1617 | 1617 | 1617 | 1617 | - |
| | Yielding status | OK | OK | OK | OK | |

(1) Ratio of energy dissipated under the backbone curve by maximum displacement

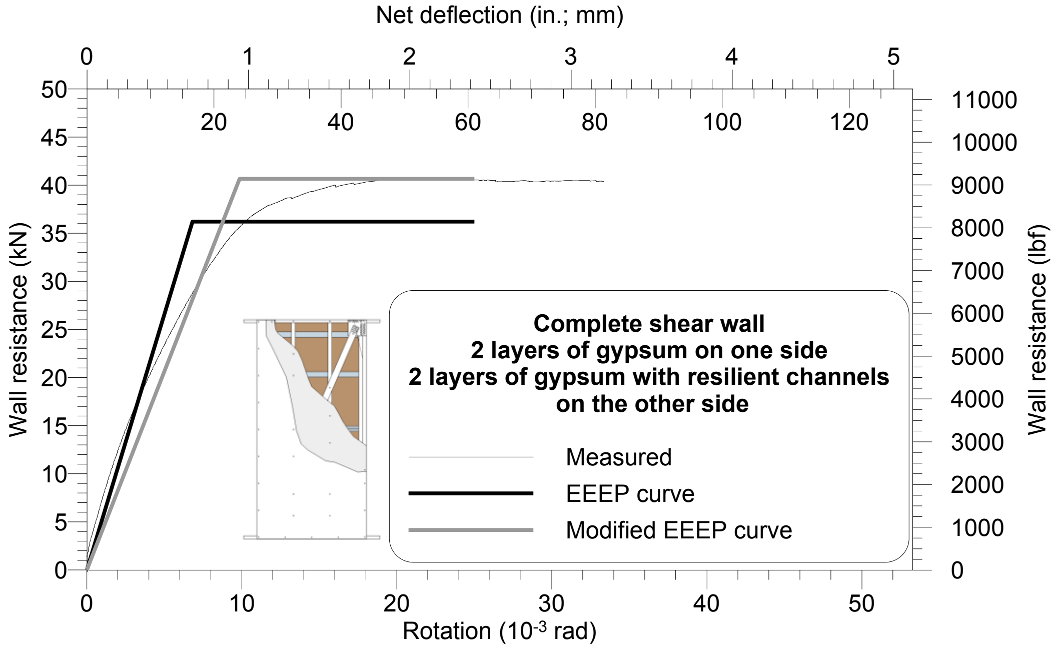



**Figure C-65 Measured and EEEP curves for test 76A-M**

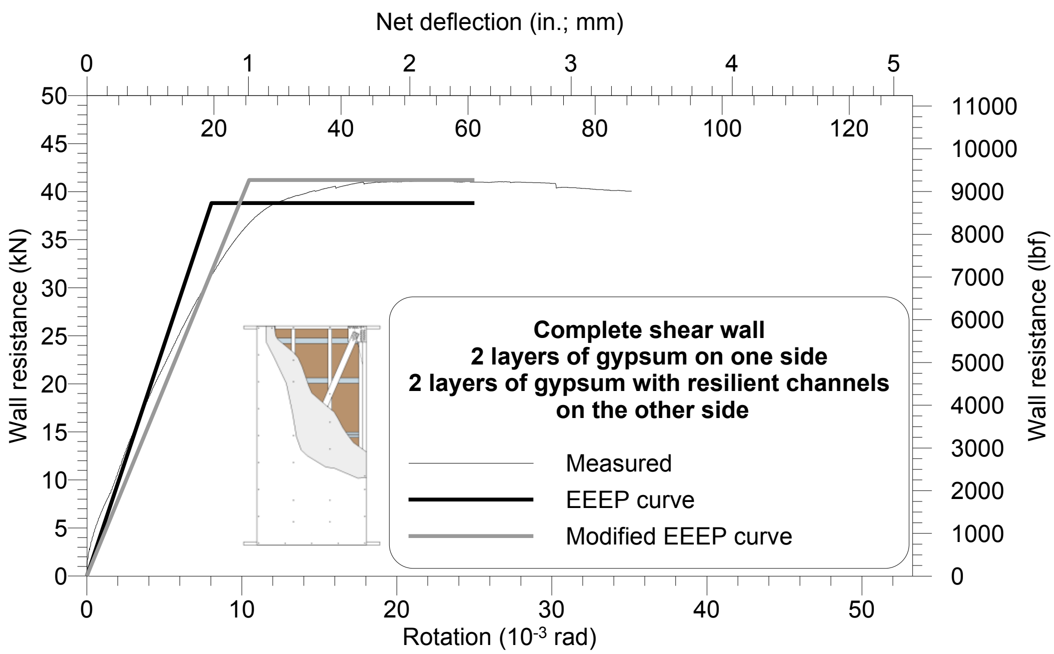



**Figure C-66 Measured and EEEP curves for test 76B-M**

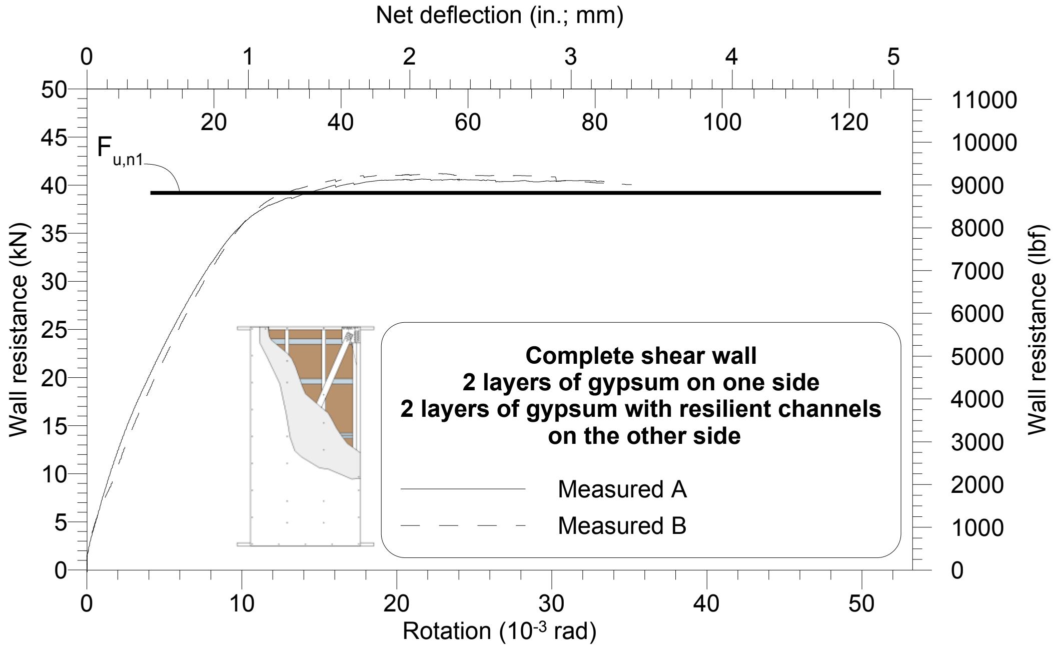



**Figure C-67 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 76A-M and 76B-M**

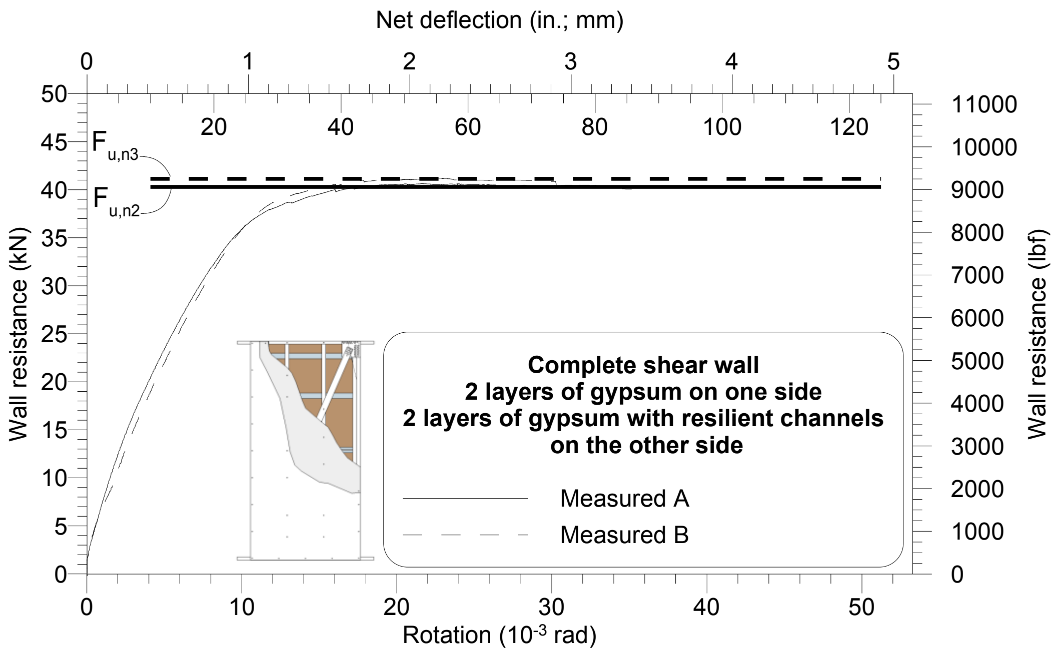



**Figure C-68 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 76A-M and 76B-M**

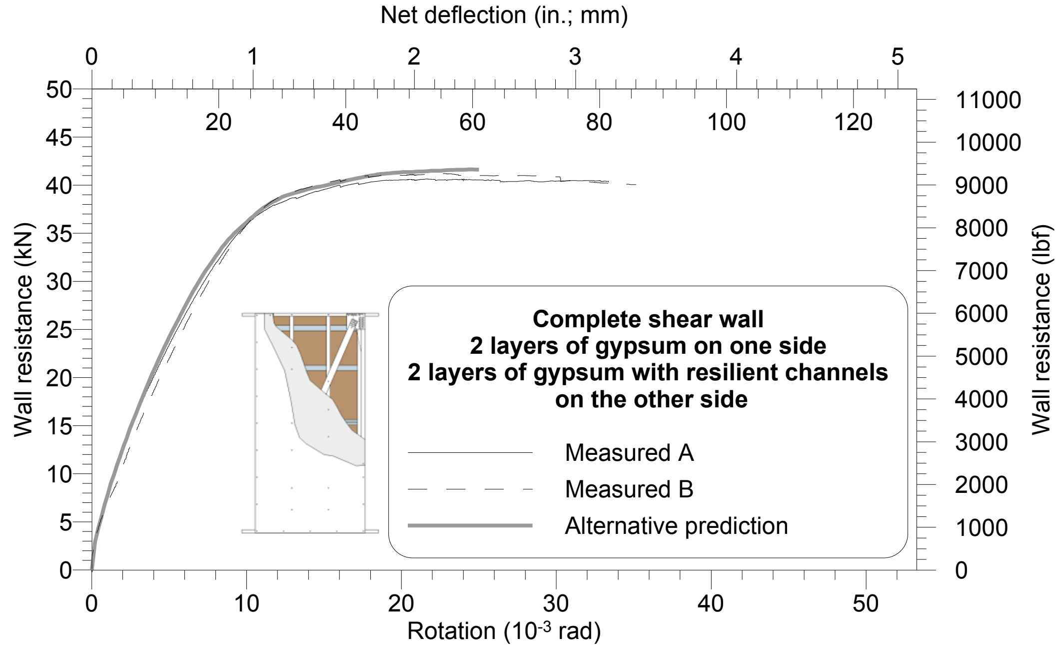



**Figure C-69 Comparison of the predicted load-drift curve and the test results for tests 76A-M and 76B-M**

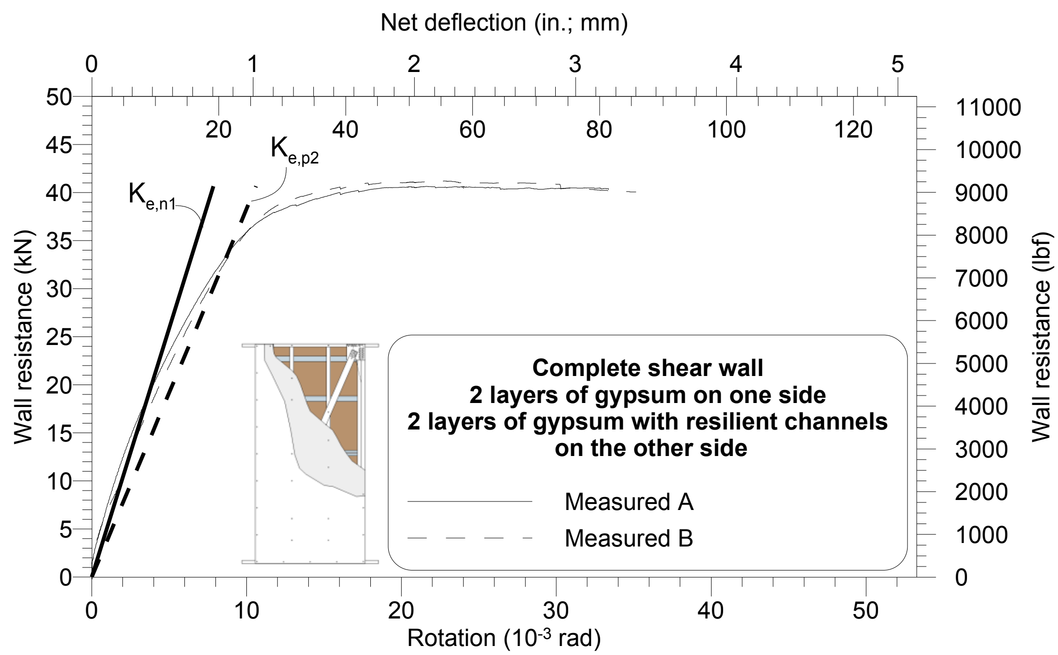



**Figure C-70 Comparison of the different stiffness predictions for tests 76A-M and 76B-M**

**Table 15 Monotonic test results for tests 76A-M and 76B-M**

| | Parameters | Specimens | | Units |
|---|---|---|---|---|
| | | 76A-M | 76B-M | |
| Test Results | $F_u$ | 40.64 | 41.20 | kN |
| | $\Delta_{net,u}$ | 52.77 | 55.23 | mm |
| | $F_{0.4u}$ | 16.26 | 16.48 | kN |
| | $\Delta_{net,0.4u}$ | 7.14 | 8.33 | mm |
| | $K_e$ | 2.28 | 1.98 | kN/mm |
| | $F_{0.8u}$ | 32.51 | 32.96 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 61 | 61 | mm |
| | Normalized energy (1) | 32.69 | 32.56 | J/mm |
| EEEP analysis | $F_y$ | 37.85 | 38.81 | kN |
| | $\Delta_y$ | 16.62 | 19.62 | mm |
| | Ductility (μ) | 3.67 | 3.11 | - |
| | $R_d$ | 2.52 | 2.28 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 24.02 | 25.55 | mm |
| | $K_{e,mod.EEEP}$ | 1.69 | 1.61 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.57 | 28.63 | kN |
| | $K_p$ | 1.66 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | 28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 3508 | 4963 | - |
| | Yielding strain | 1617 | 1617 | - |
| | Yielding status | OK | OK | |

(1) Ratio of energy dissipated under the measured curve by maximum displacement

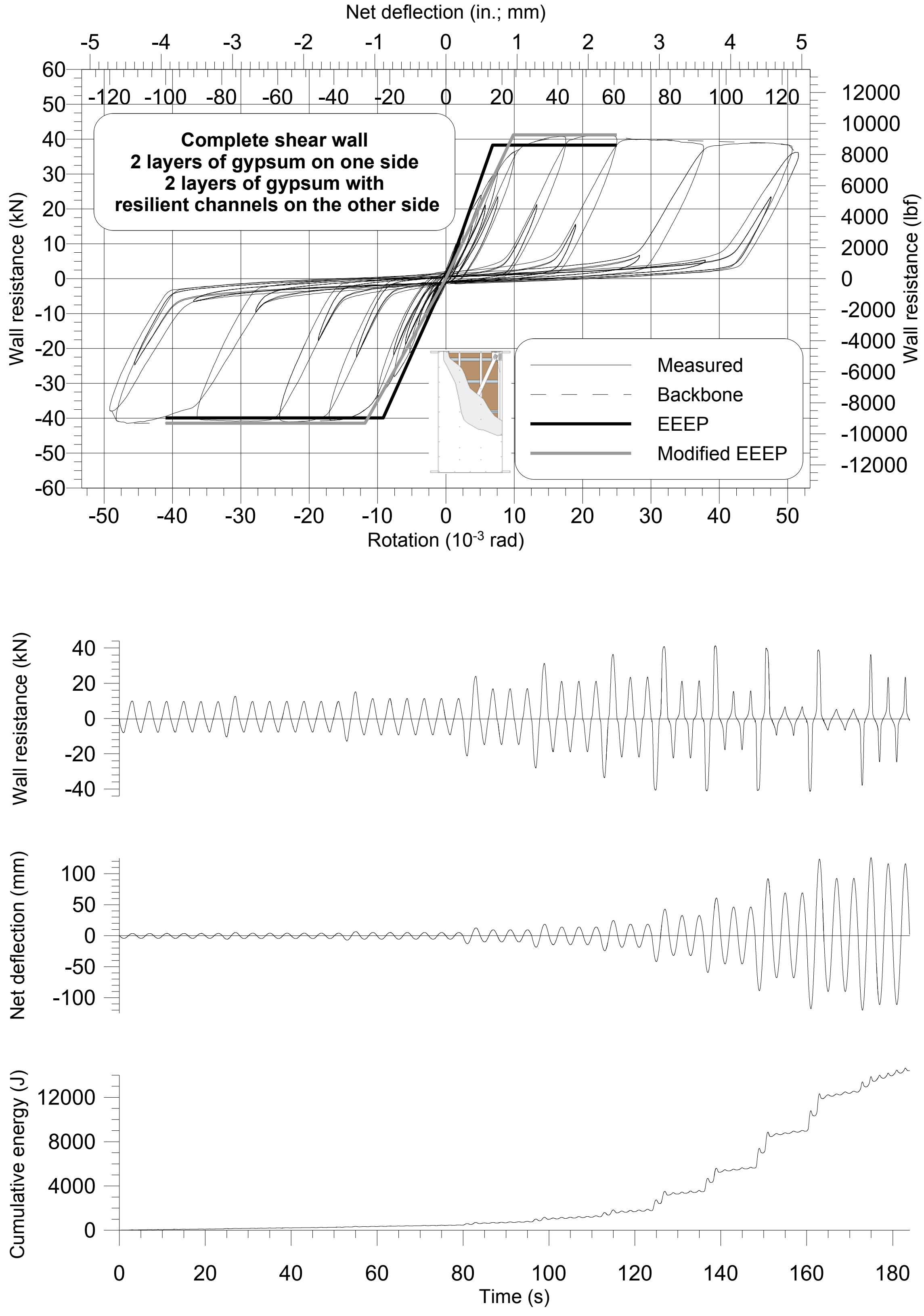



**Figure C-71 Measured and EEEP curves and time history for test 77A-C**

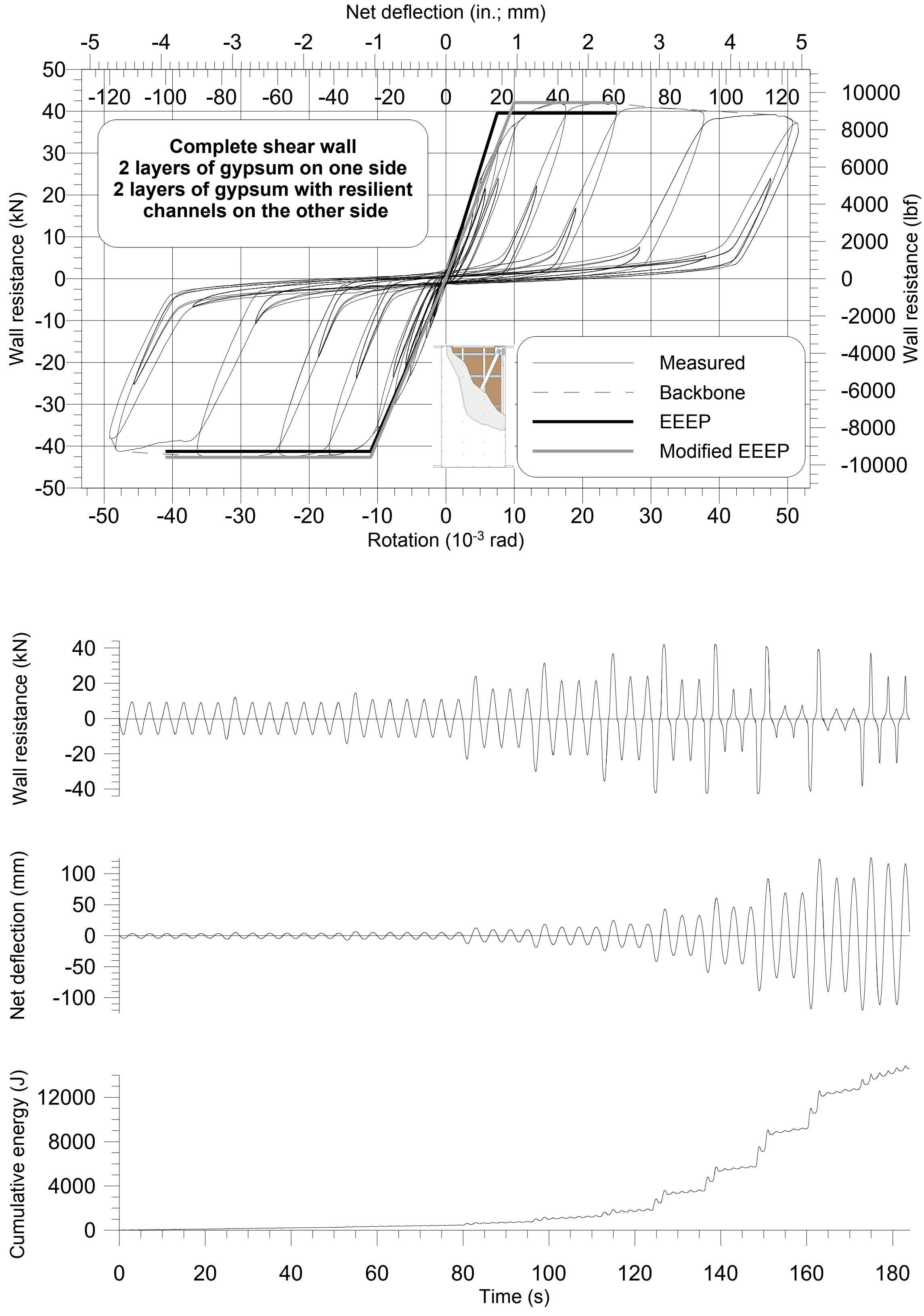



**Figure C-72 Measured and EEEP curves and time history for test 77B-C**

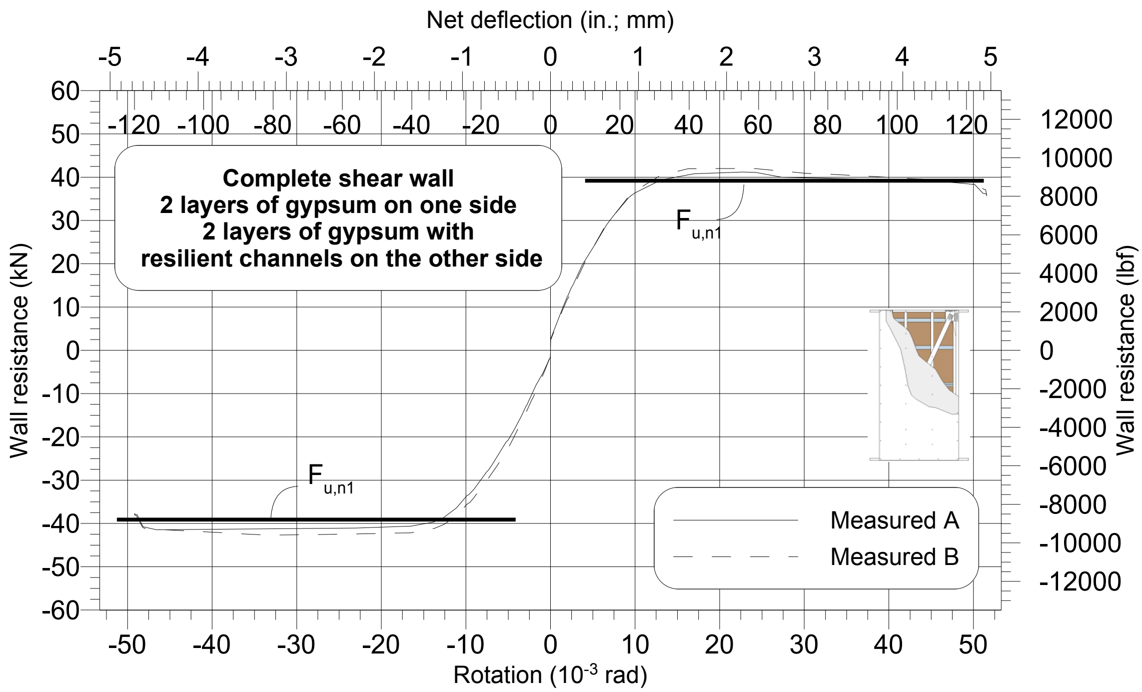



**Figure C-73 Comparison of the simple prediction with a factor of 1.1 ($F_{u,n1}$) and the test results for tests 77A-C and 77B-C**

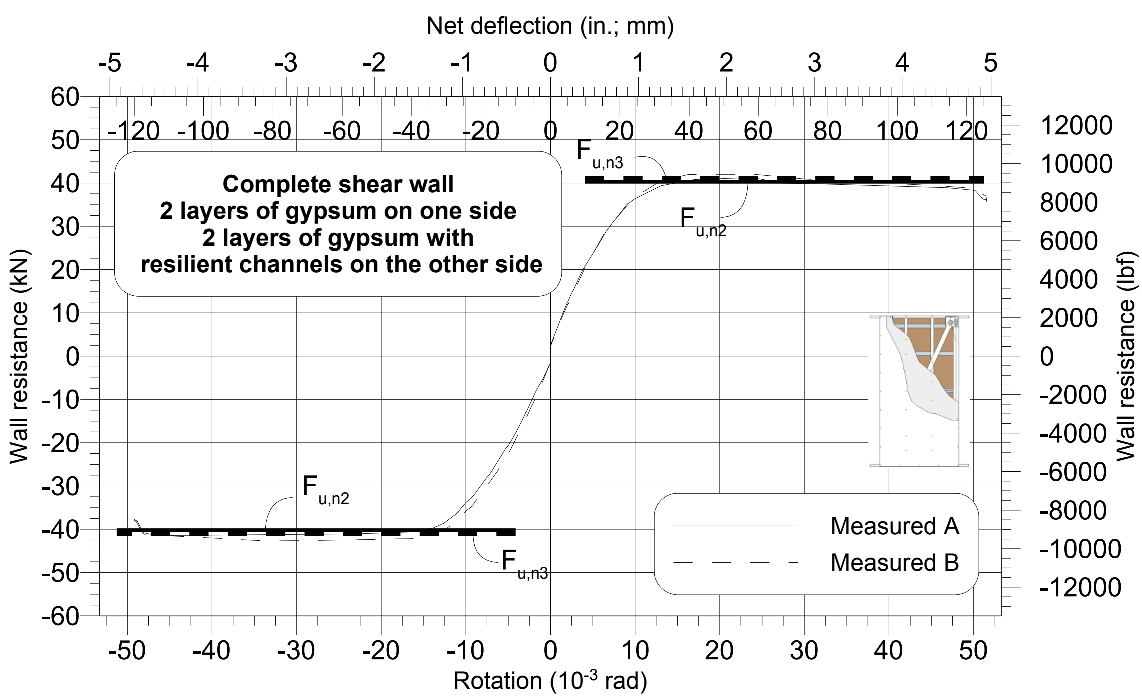



**Figure C-74 Comparison of the conservative simple predictions with a factor of 1.2 ($F_{u,n2}$) or 1.3 ($F_{u,n3}$) and the test results for tests 77A-C and 77B-C**

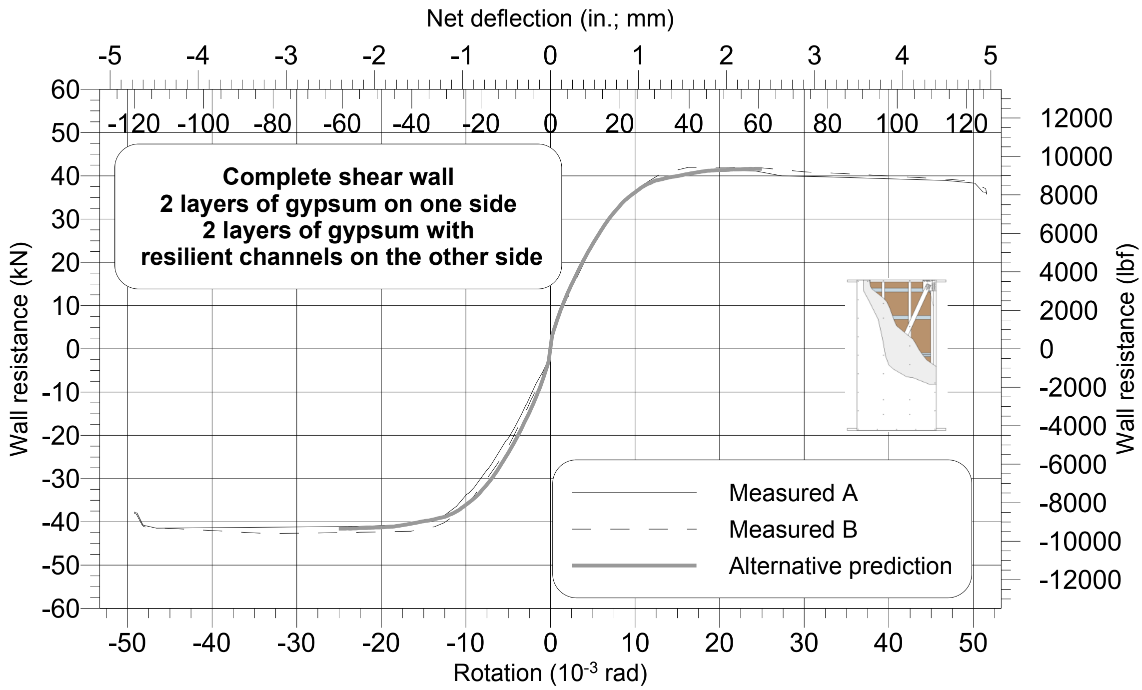



**Figure C-75 Comparison of the predicted load-drift curve and the test results for tests 77A-C and 77B-C**

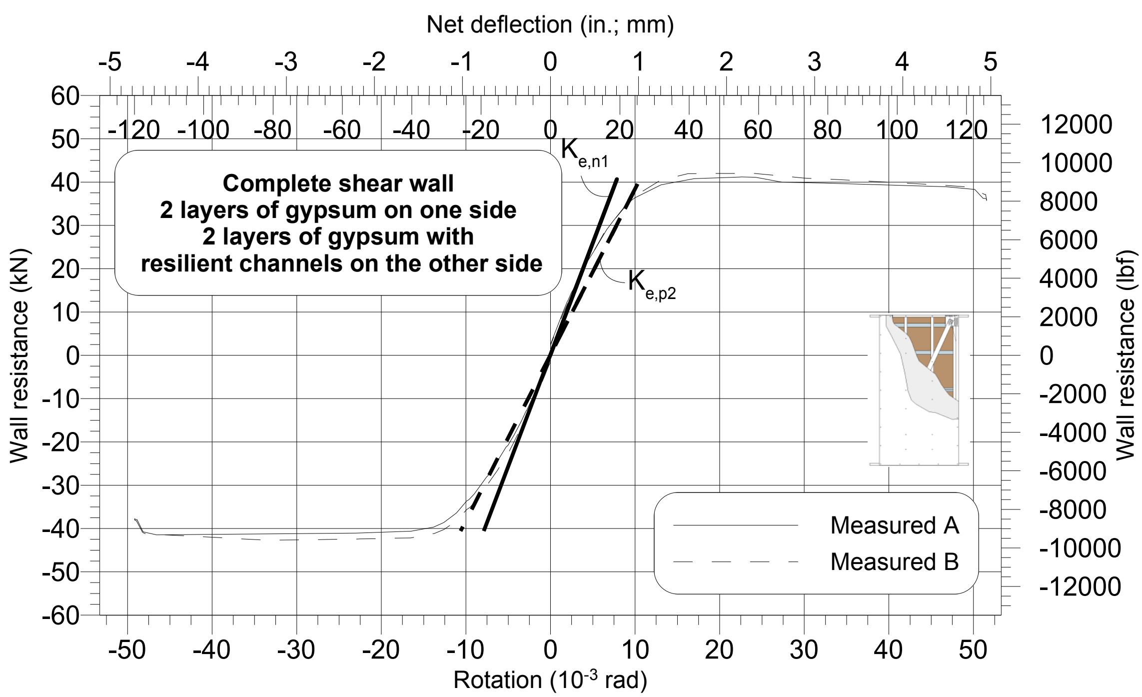



**Figure C-76 Comparison of the different stiffness predictions for tests 77A-C and 77B-C**

**Table 16 Cyclic test results for tests 77A-C and 77B-C**

| | Parameters | 77A-C Positive | 77A-C Negative | 77B-C Positive | 77B-C Negative | Units |
|---|---|---|---|---|---|---|
| Test Results | $F_u$ | 41.20 | -41.46 | 42.03 | -42.72 | kN |
| | $\Delta_{net,u}$ | 55.10 | -113.62 | 57.42 | -81.13 | mm |
| | $F_{0.4u}$ | 16.53 | -16.53 | 16.95 | -16.95 | kN |
| | $\Delta_{net,0.4u}$ | 7.22 | -9.25 | 7.88 | -8.64 | mm |
| | $K_e$ | 2.29 | 1.79 | 2.15 | 1.96 | kN/mm |
| | $F_{0.8u}$ | 33.07 | -33.07 | 33.90 | -33.90 | kN |
| | $\Delta_{net,0.8u}$ | - | - | - | - | mm |
| | $\Delta_{net,max}$ | 61 | -100 | 61 | -100 | mm |
| | Normalized energy (1) | 33.03 | -35.50 | 33.58 | -36.95 | J/mm |
| EEEP analysis | $F_y$ | 38.27 | -39.97 | 39.54 | -41.29 | kN |
| | $\Delta_{net,y}$ | 16.72 | -22.36 | 18.39 | -21.05 | mm |
| | Ductility ($\mu$) | 3.65 | 4.47 | 3.32 | 4.75 | - |
| | $R_d$ | 2.51 | 2.82 | 2.37 | 2.92 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 24.11 | -28.83 | 24.46 | -26.83 | mm |
| | $K_{e,mod.EEEP}$ | 1.71 | 1.44 | 1.72 | 1.59 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 28.57 | -28.34 | 28.59 | -28.59 | kN |
| | $K_p$ | 1.66 | 1.65 | 1.66 | 1.66 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | -28.44 | 28.44 | -28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 6051 | 8242 | 9011 | 8710 | - |
| | Yielding strain | 1617 | 1617 | 1617 | 1617 | - |
| | Yielding status | OK | OK | OK | OK | |

(1) Ratio of energy dissipated under the backbone curve by maximum displacement

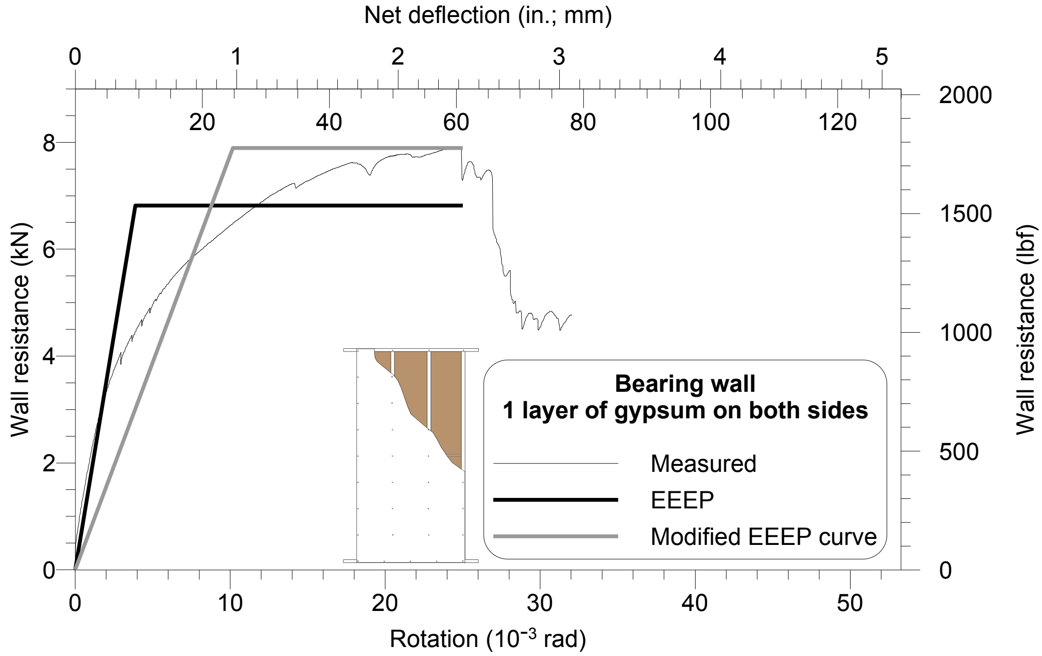



**Figure C-77 Measured and EEEP curves for test 78B-M**

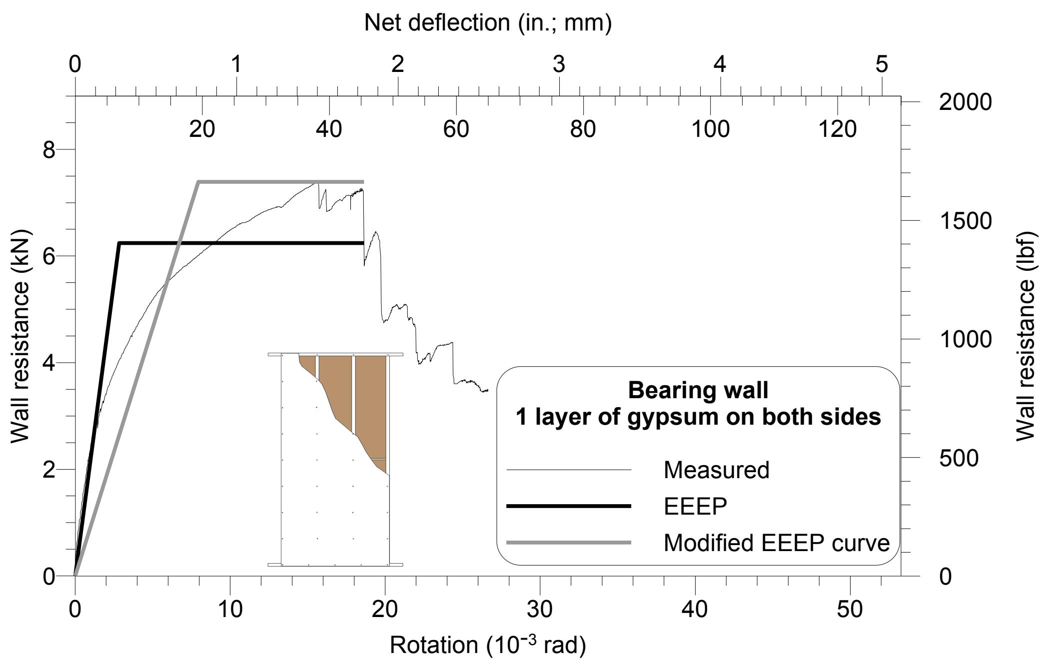



**Figure C-78 Measured and EEEP curves for test 78C-M**

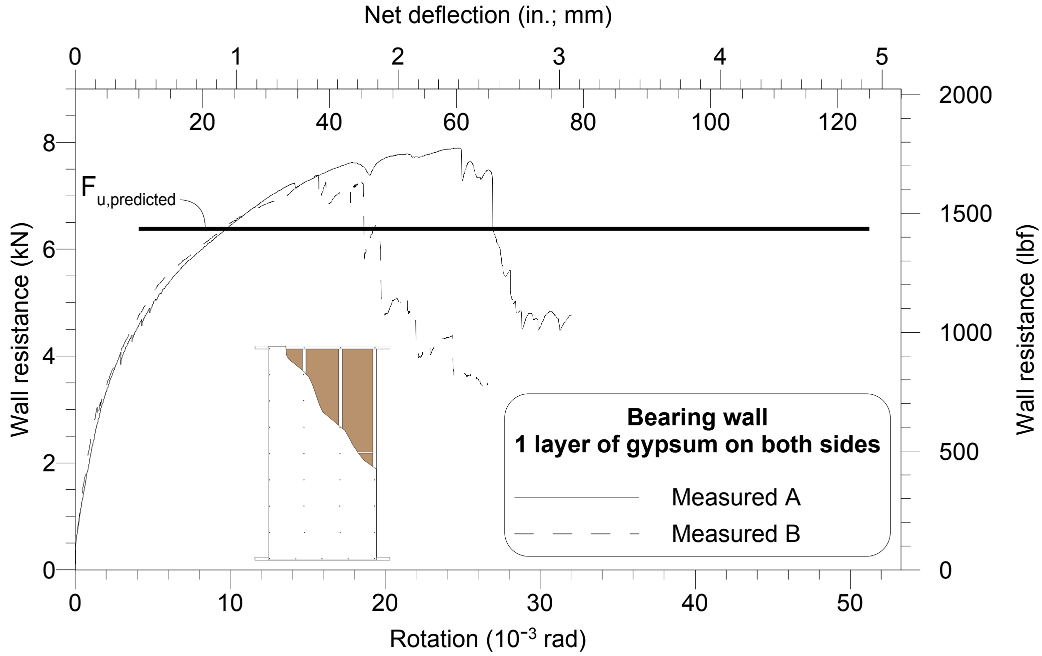



**Figure C-79 Comparison of the predicted strength and the test results for bearing wall tests 78B-M and 78C-M**

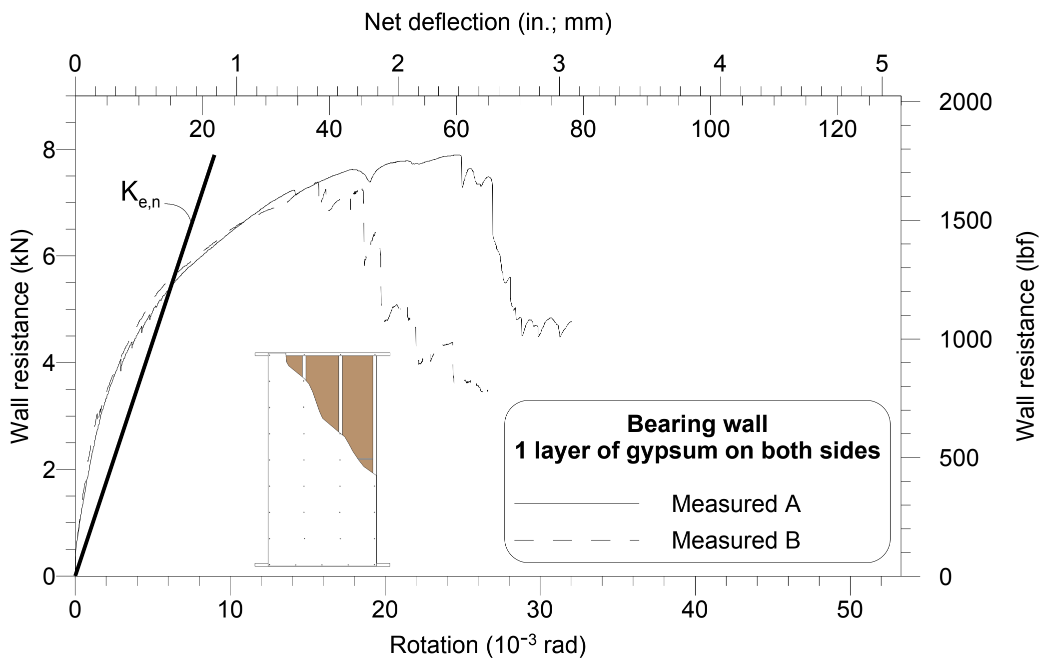
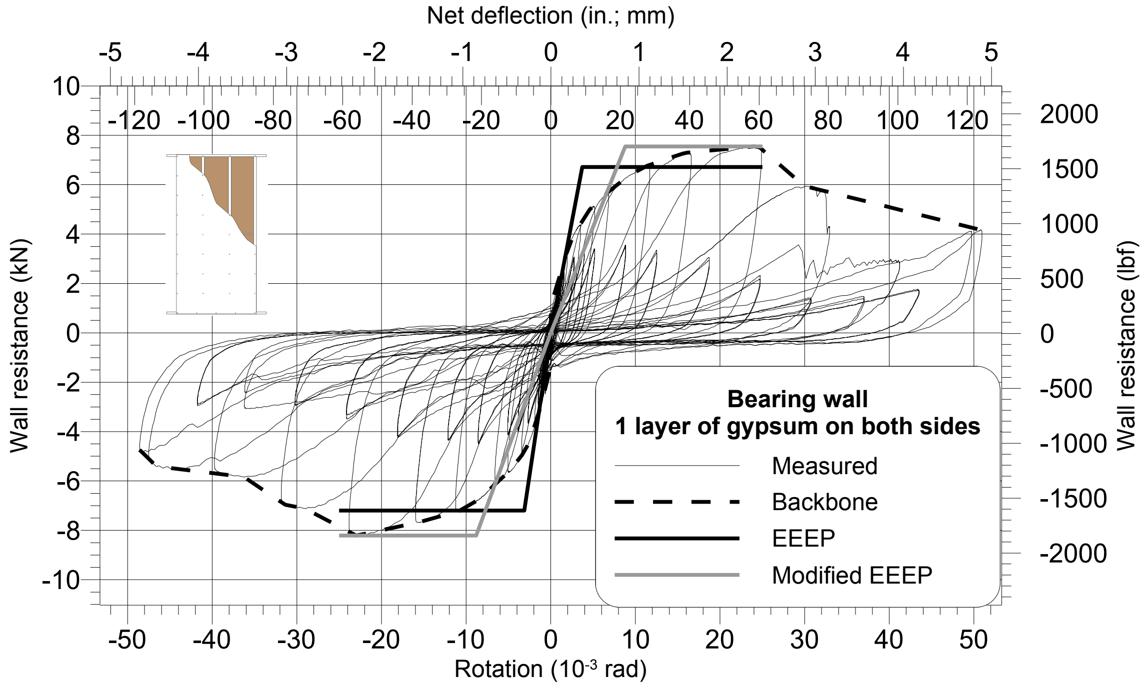



**Figure C-80 Comparison of the recommended stiffness and the test results for tests 78B-M and 78C-M**

**Table 17 Monotonic test results for tests 78B-M and 78C-M**

| | Parameters | Specimens | | Units |
|---|---|---|---|---|
| | | 78B-M | 78C-M | |
| Test Results | $F_u$ | 7.89 | 7.39 | kN |
| | $\Delta_{net,u}$ | 59.53 | 38.17 | mm |
| | $F_{0.4u}$ | 3.16 | 2.95 | kN |
| | $\Delta_{net,0.4u}$ | 4.39 | 3.28 | mm |
| | $K_e$ | 0.72 | 0.90 | kN/mm |
| | $F_{0.8u}$ | 6.31 | 5.91 | kN |
| | $\Delta_{net,0.8u}$ | 65.89 | 45.47 | mm |
| | $\Delta_{net,max}$ | 61.00 | 45.47 | mm |
| | Normalized energy [(1)] | 6.29 | 5.76 | J/mm |
| EEEP Analysis | $F_y$ | 6.81 | 6.24 | kN |
| | $\Delta_{net,y}$ | 9.47 | 6.93 | mm |
| | Ductility ($\mu$) | 6.44 | 6.56 | - |
| | $R_d$ | 3.45 | 3.48 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 24.84 | 19.38 | mm |
| | $K_{e,mod.EEEP}$ | 0.32 | 0.38 | kN/mm |

[(1)] Energy dissipated under the EEEP curve



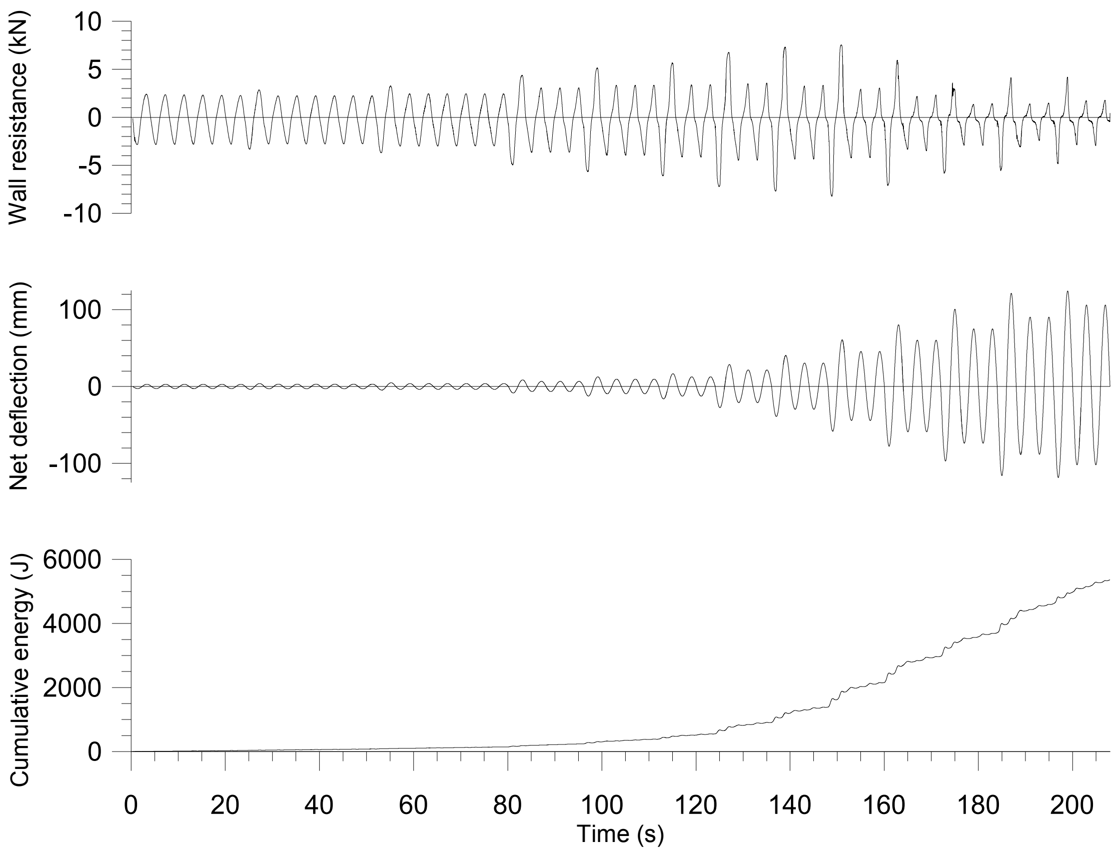




**Figure C-81 Measured and EEEP curves and time history for test 79 A-C**

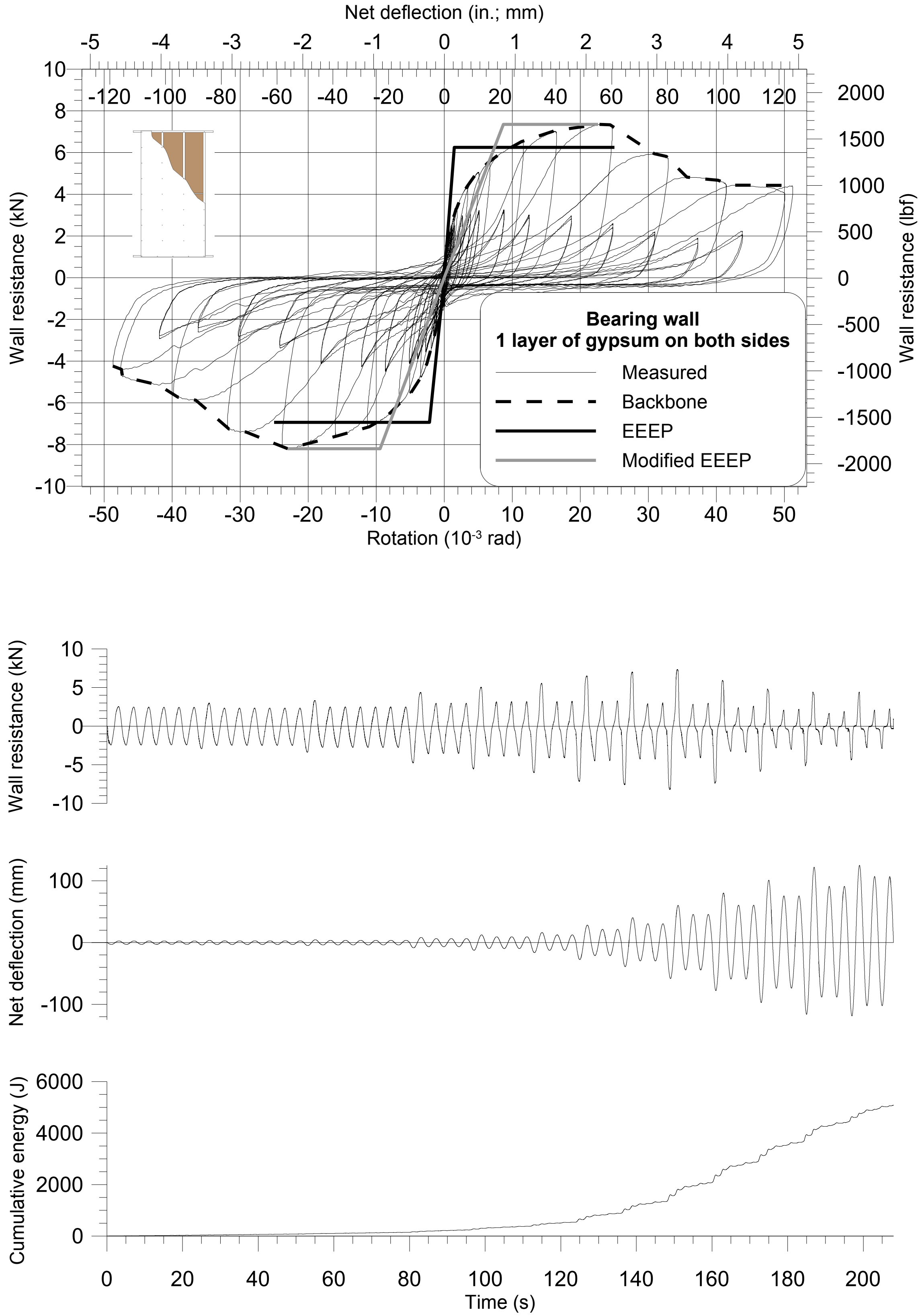



**Figure C-82 Measured and EEEP curves and time history for test 79B-C**

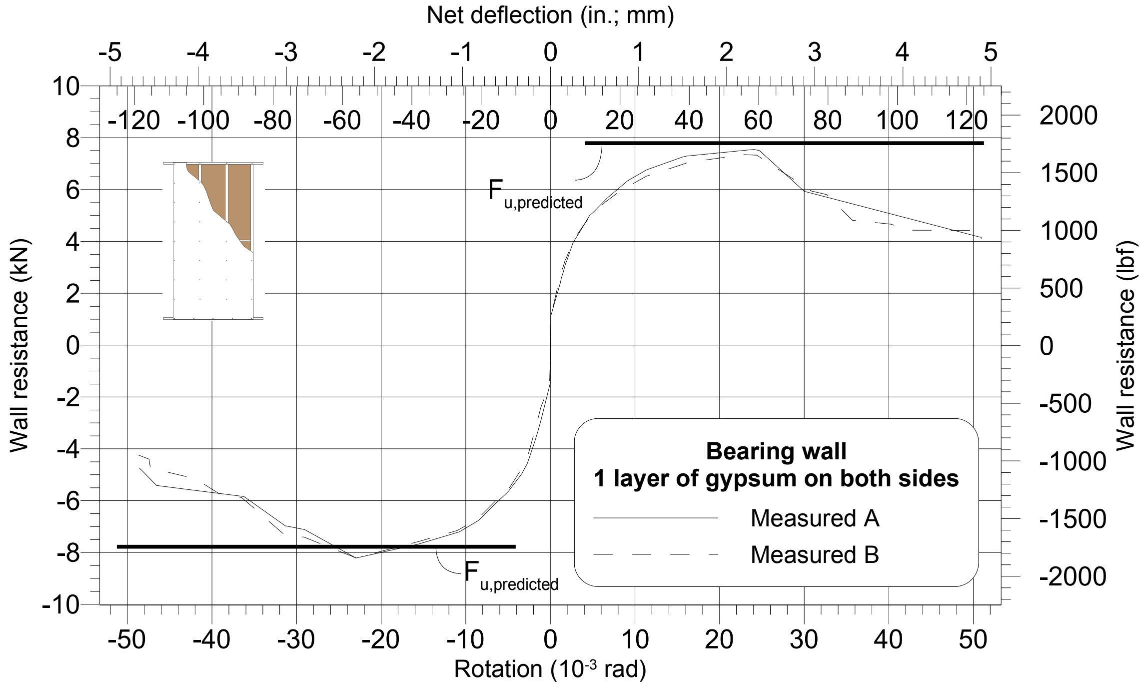



**Figure C-83 Comparison of the predicted strength and the test results for bearing wall tests 79A-C and 79B-C**

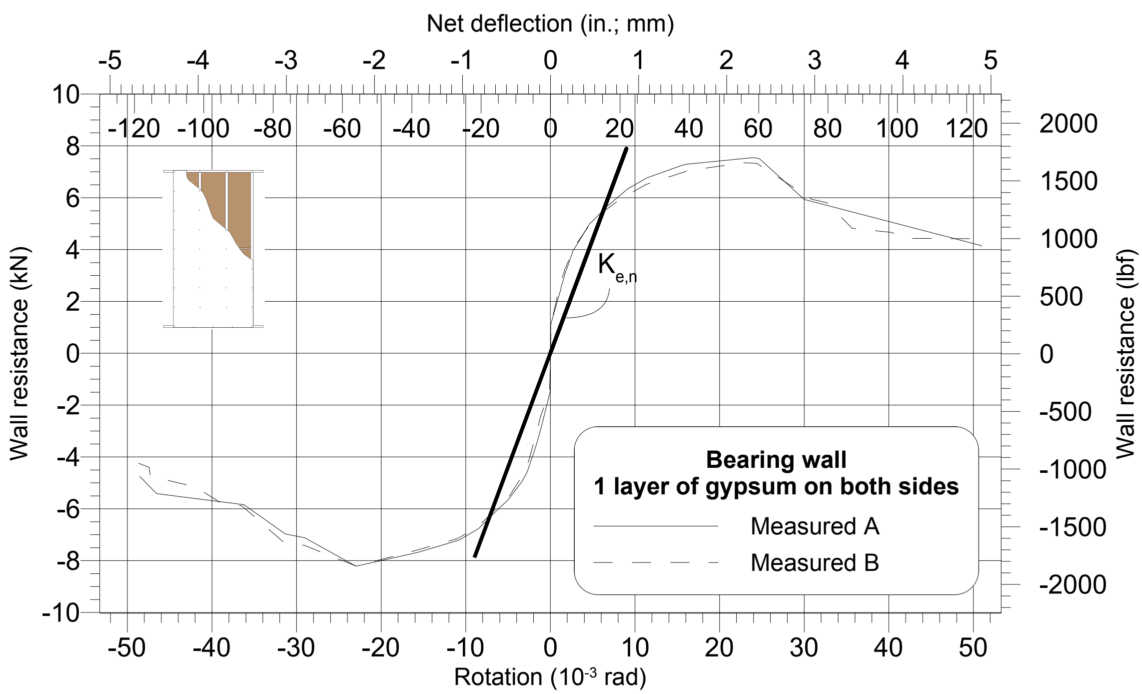



**Figure C-84 Comparison of the recommended stiffness and the test results for tests 79A-C and791B-C**

**Table 18 Cyclic test results for tests 79A-C and 79B-C**

| | Parameters | 79A-C Positive | 79A-C Negative | 79B-C Positive | 79B-C Negative | Units |
|---|---|---|---|---|---|---|
| Test Results | $F_u$ | 7.55 | -8.22 | 7.35 | -8.21 | kN |
| | $\Delta_{net,u}$ | 58.63 | -56.08 | 55.17 | -56.17 | mm |
| | $F_{0.4u}$ | 3.02 | -3.29 | 2.94 | -3.28 | kN |
| | $\Delta_{net,0.4u}$ | 4.08 | -3.48 | 3.38 | -4.40 | mm |
| | $K_e$ | 0.74 | 0.94 | 0.87 | 0.75 | kN/mm |
| | $F_{0.8u}$ | 6.04 | -6.57 | 5.88 | -6.57 | kN |
| | $\Delta_{net,0.8u}$ | 72.29 | -80.72 | 101.18 | - | mm |
| | $\Delta_{net,max}$ | 61.00 | -61.00 | 61.00 | -61.00 | mm |
| | Normalized energy (1) | 6.21 | -6.75 | 6.06 | -6.64 | J/mm |
| EEEP Analysis | $F_y$ | 6.71 | -7.20 | 6.25 | -6.94 | kN |
| | $\Delta_{net,y}$ | 9.08 | -7.63 | 3.59 | -5.29 | mm |
| | Ductility (μ) | 6.7 | 8.0 | 17.0 | 11.5 | - |
| | $R_d$ | 3.53 | 3.87 | 5.75 | 4.70 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 21.46 | -21.51 | 21.17 | -23.02 | mm |
| | $K_{e,mod.EEEP}$ | 0.35 | 0.38 | 0.35 | 0.36 | kN/mm |

(1) Energy dissipated under the EEEP curve

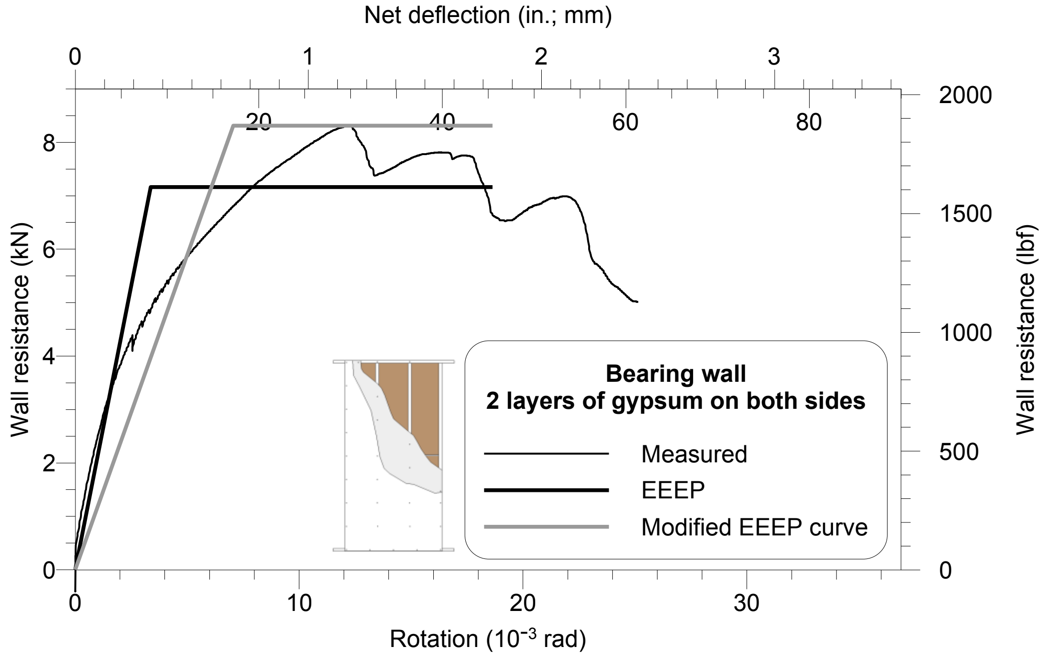



**Figure C-85 Measured and EEEP curves for test 80A-M**

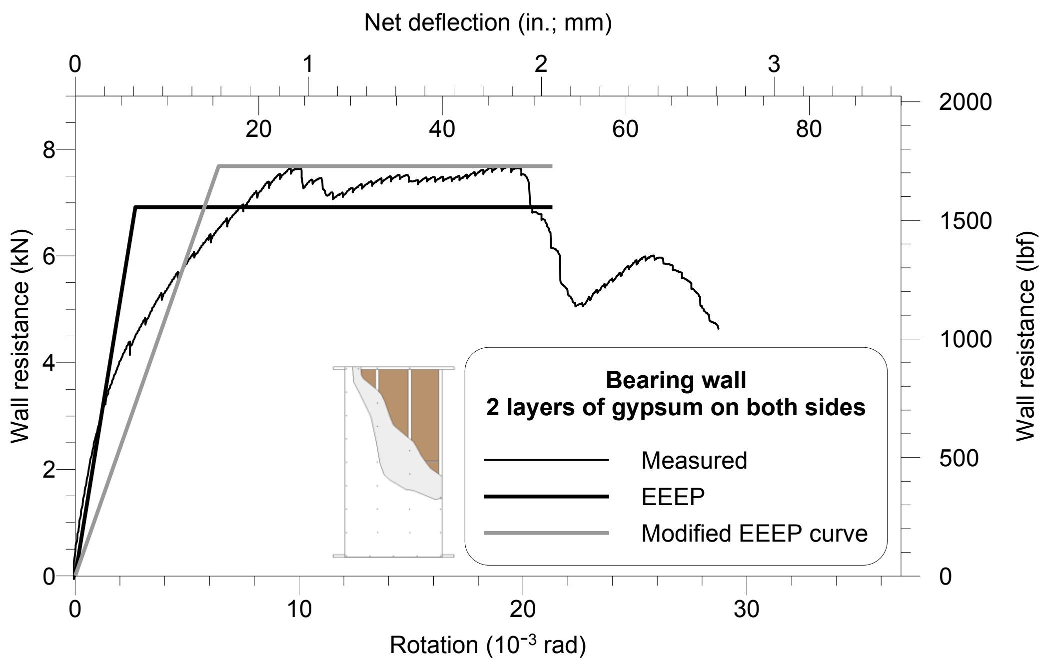



**Figure C-86 Measured and EEEP curves for test 80B-M**

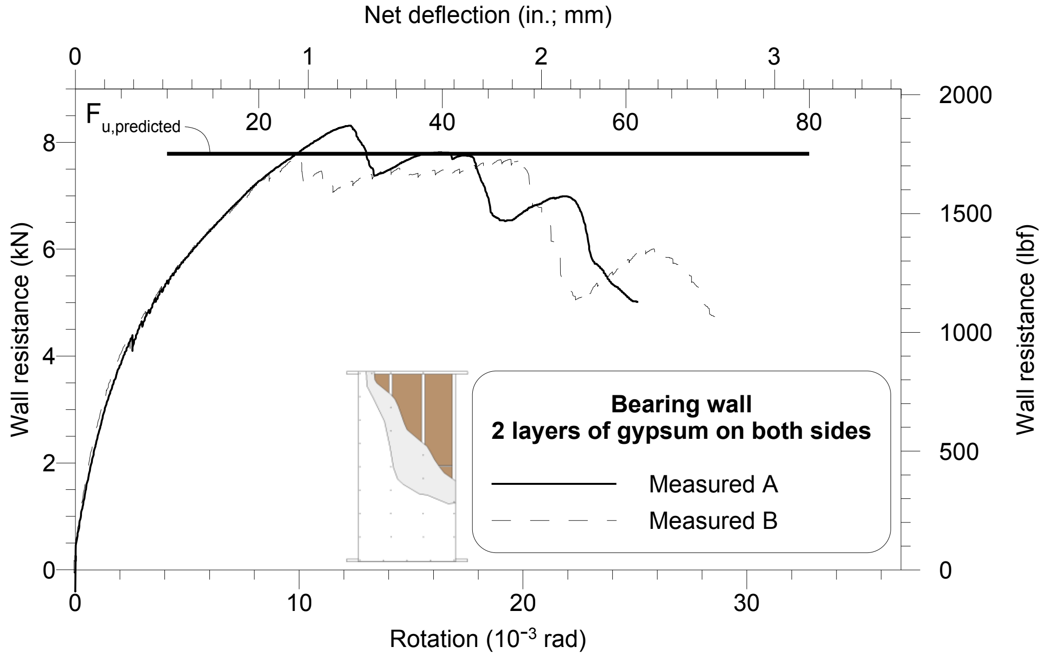



**Figure C-87 Comparison of the predicted strength and the test results for bearing wall tests 80A-M and 80B-M**

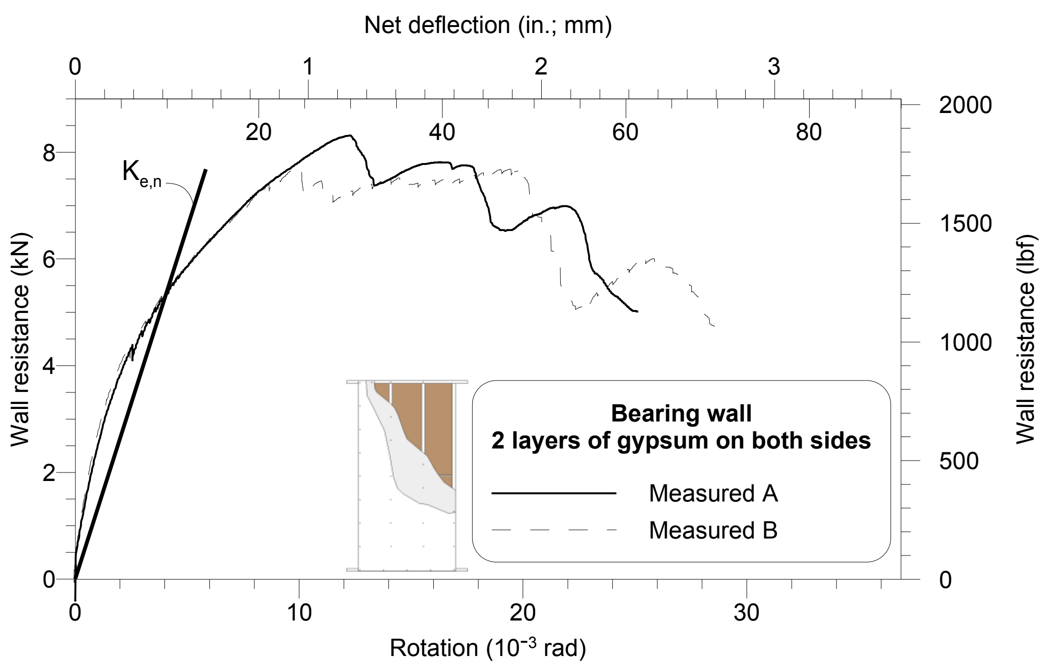
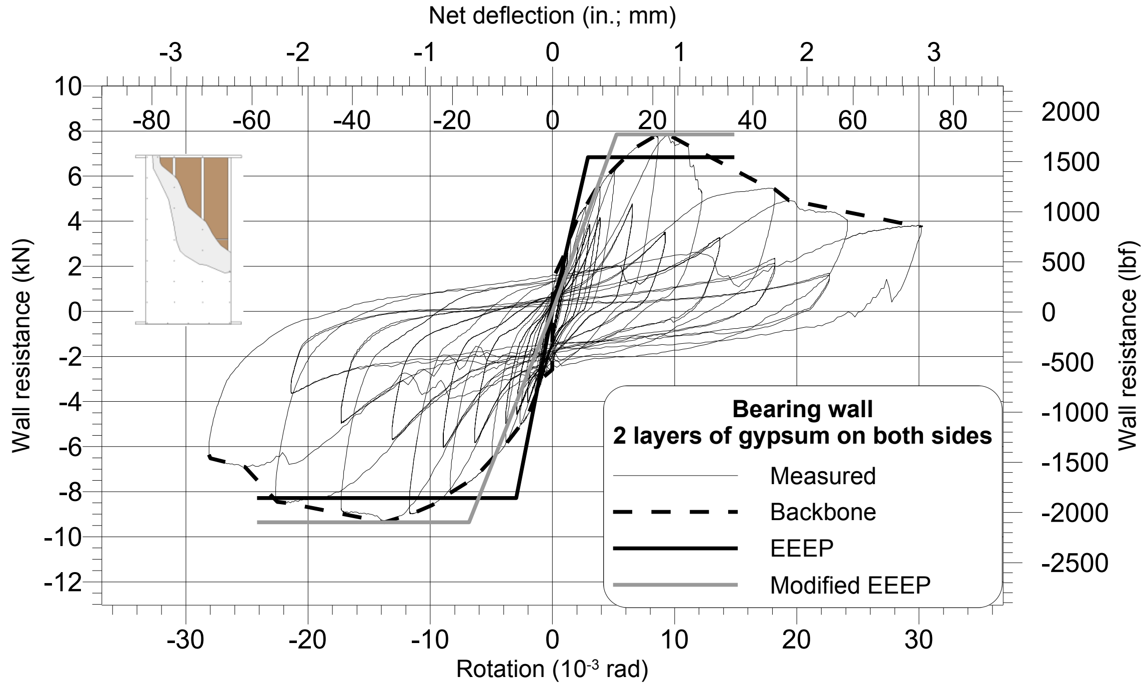



**Figure C-88 Comparison of the recommended stiffness and the test results for tests 80A-M and 80B-M**

**Table 19 Monotonic test results for tests 80A-M and 80B-M**

| | Parameters | Specimens 80A-M | Specimens 80B-M | Units |
|---|---|---|---|---|
| Test Results | $F_u$ | 8.31 | 7.68 | kN |
| | $\Delta_{net,u}$ | 29.80 | 47.28 | mm |
| | $F_{0.4u}$ | 3.32 | 3.07 | kN |
| | $\Delta_{net,0.4u}$ | 3.82 | 2.92 | mm |
| | $K_e$ | 0.87 | 1.05 | kN/mm |
| | $F_{0.8u}$ | 6.65 | 6.15 | kN |
| | $\Delta_{net,0.8u}$ | 45.47 | 52.02 | mm |
| | $\Delta_{net,max}$ | 45.47 | 52.02 | mm |
| | Normalized energy (1) | 6.51 | 6.48 | J/mm |
| EEEP Analysis | $F_y$ | 7.16 | 6.91 | kN |
| | $\Delta_{net,y}$ | 8.23 | 6.56 | mm |
| | Ductility ($\mu$) | 5.52 | 7.93 | - |
| | $R_d$ | 3.17 | 3.85 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 17.23 | 15.63 | mm |
| | $K_{e,mod.EEEP}$ | 0.48 | 0.49 | kN/mm |

(1) Energy dissipated under the EEEP curve



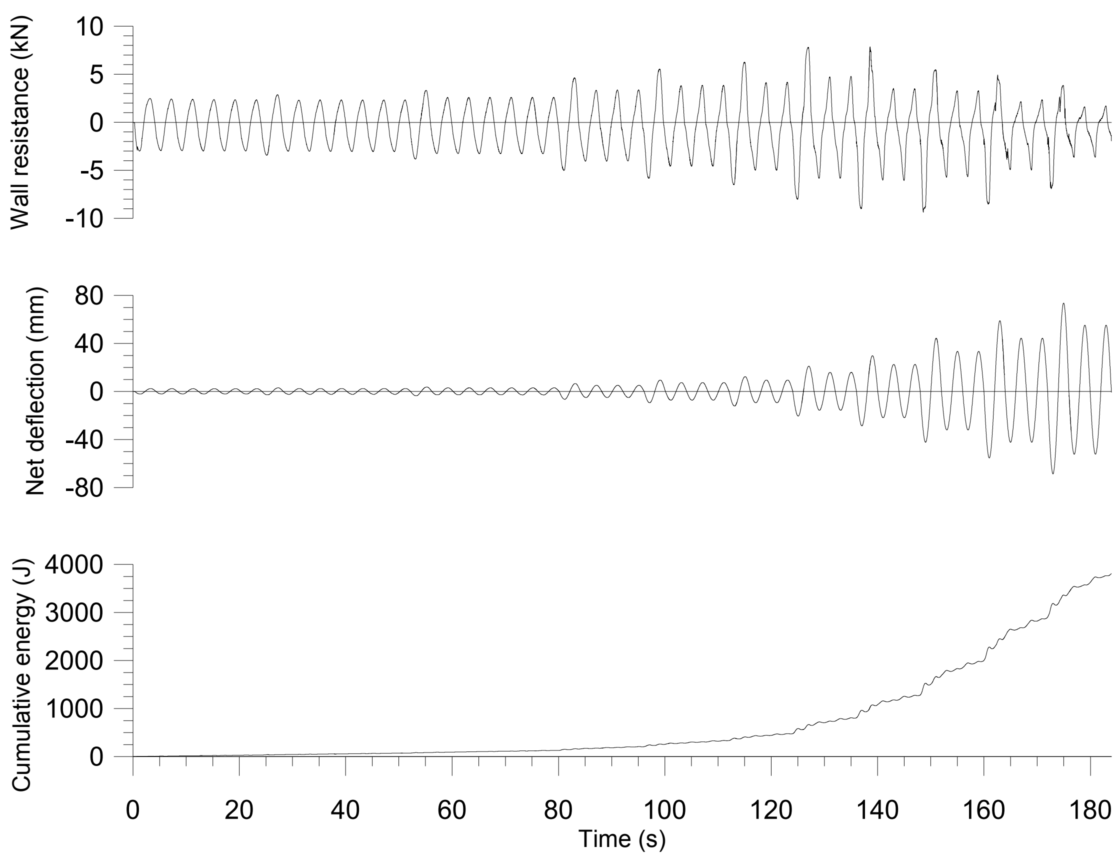




**Figure C-89 Measured and EEEP curves and time history for test 81A-C**

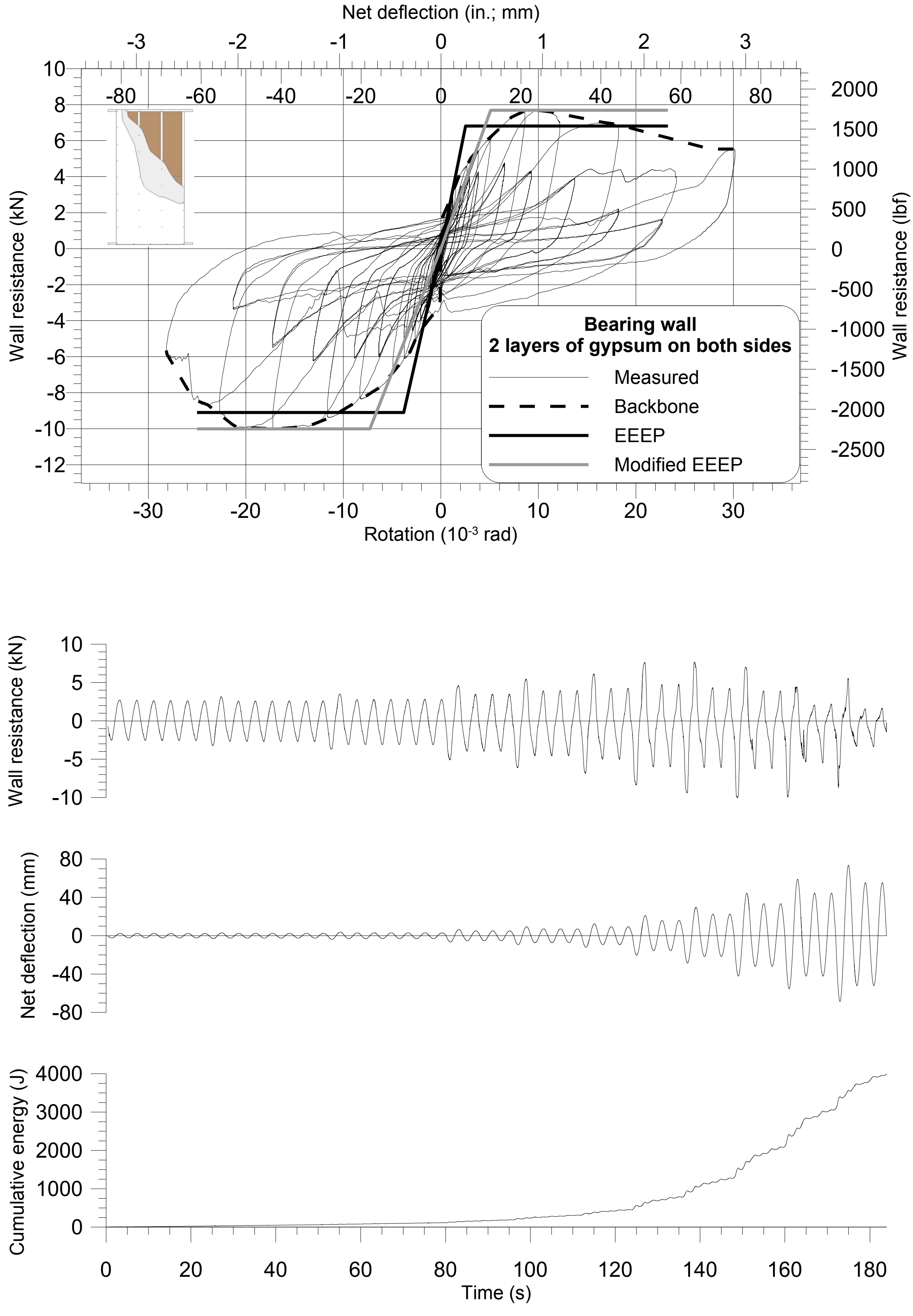



**Figure C-90 Measured and EEEP curves and time history for test 81 B-C**

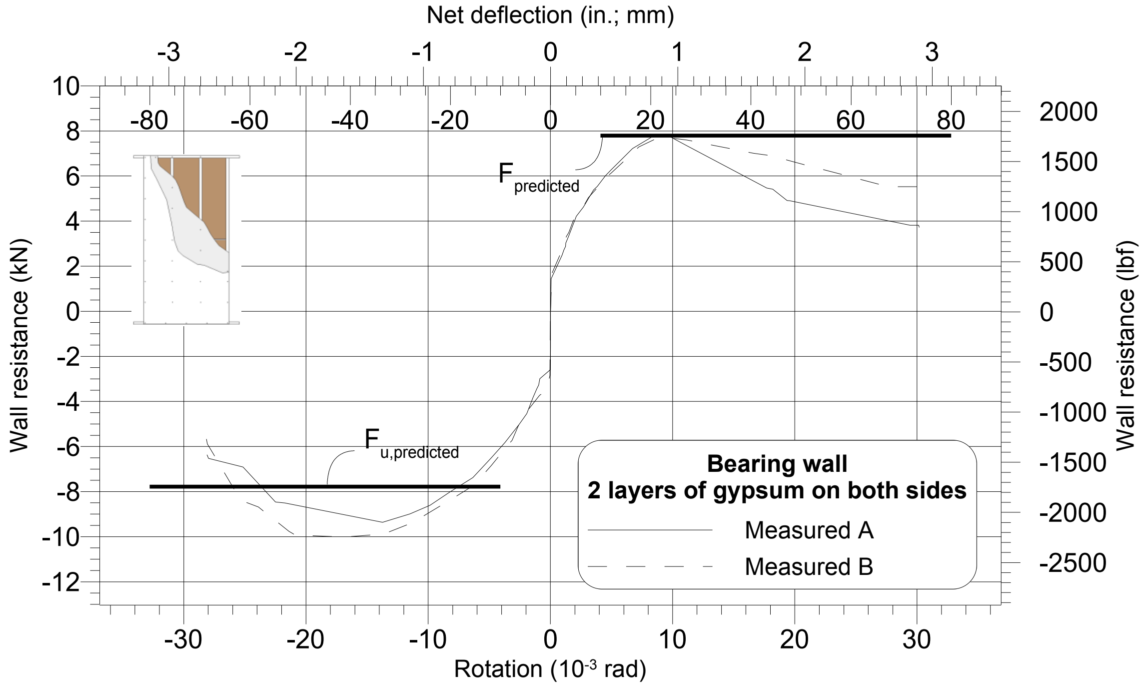



**Figure C-91 Comparison of the predicted strength and the test results for bearing wall tests 81 A-C and 81B-C**

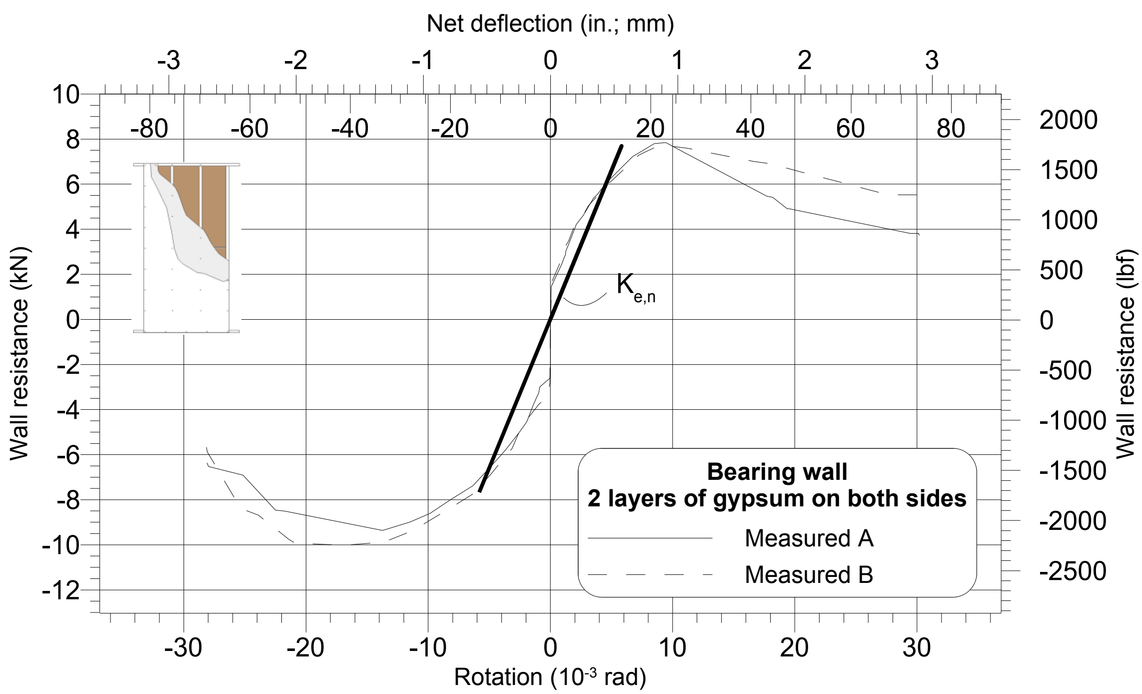



**Figure C-92 Comparison of the recommended stiffness and the test results for tests 81 A-C and 81B-C**

**Table 20 Cyclic test results for tests 81A-C and 81B-C**

| | Parameters | Specimens | | | | Units |
|---|---|---|---|---|---|---|
| | | 81A-C | | 81B-C | | |
| | | Positive | Negative | Positive | Negative | |
| Test Results | $F_u$ | 7.84 | -9.36 | 7.68 | -10.02 | kN |
| | $\Delta_{net,u}$ | 23.03 | -33.57 | 24.01 | -41.17 | mm |
| | $F_{0.4u}$ | 3.14 | -3.74 | 3.07 | -4.01 | kN |
| | $\Delta_{net,0.4u}$ | 3.25 | -3.27 | 2.78 | -4.09 | mm |
| | $K_e$ | 0.96 | 1.14 | 1.11 | 0.98 | kN/mm |
| | $F_{0.8u}$ | 6.28 | -7.49 | 6.15 | -8.02 | kN |
| | $\Delta_{net,0.8u}$ | 36.30 | -58.99 | 56.79 | -62.84 | mm |
| | $\Delta_{net,max}$ | 36.30 | -58.99 | 56.79 | -61.00 | mm |
| | Normalized energy (1) | 6.17 | -7.78 | 6.44 | -8.41 | J/mm |
| EEEP Analysis | $F_y$ | 6.83 | -8.29 | 6.81 | -9.11 | kN |
| | $\Delta_{net,y}$ | 7.08 | -7.24 | 6.16 | -9.30 | mm |
| | Ductility (μ) | 5.1 | 8.1 | 9.2 | 6.6 | - |
| | $R_d$ | 3.04 | 3.91 | 4.18 | 3.48 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 12.79 | -16.66 | 12.44 | -17.76 | mm |
| | $K_{e,mod.EEEP}$ | 0.61 | 0.56 | 0.62 | 0.56 | kN/mm |

(1) Energy dissipated under the EEEP curve

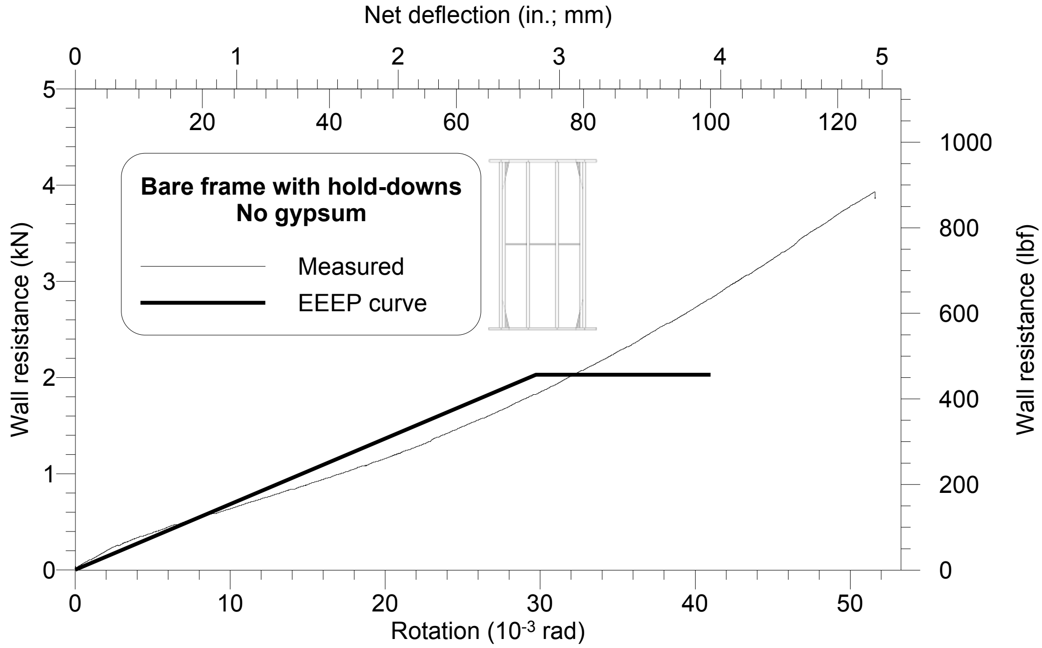



**Figure C-93 Measured and EEEP curves for test 82AM**

**Table 21 Monotonic test results for test 82A-M**

| | Parameters | Specimen 82A-M | Units |
|---|---|---|---|
| Test Results | $F_u$ | 3.93 | kN |
| | $\Delta_{net,u}$ | 125.72 | mm |
| | $F_{0.8u}$ | 3.14 | kN |
| | $\Delta_{net,0.8u}$ | - | mm |
| | $K_e$ (2) | 0.0280 | kN/mm |
| | $\Delta_{net,max}$ | 100.00 | mm |
| | Normalized energy (1) | 1.29 | J/mm |
| EEEP Analysis | $F_y$ | 2.03 | kN |
| | $S_y$ | 1.66 | kN/m |
| | $\Delta_{net,y}$ | 72.52 | mm |
| | Ductility ($\mu$) | 1.4 | - |
| | $R_d$ | 1.33 | - |

(1) Energy dissipated under the EEEP curve

(2) Obtained with a linear regression fitted with the least square method

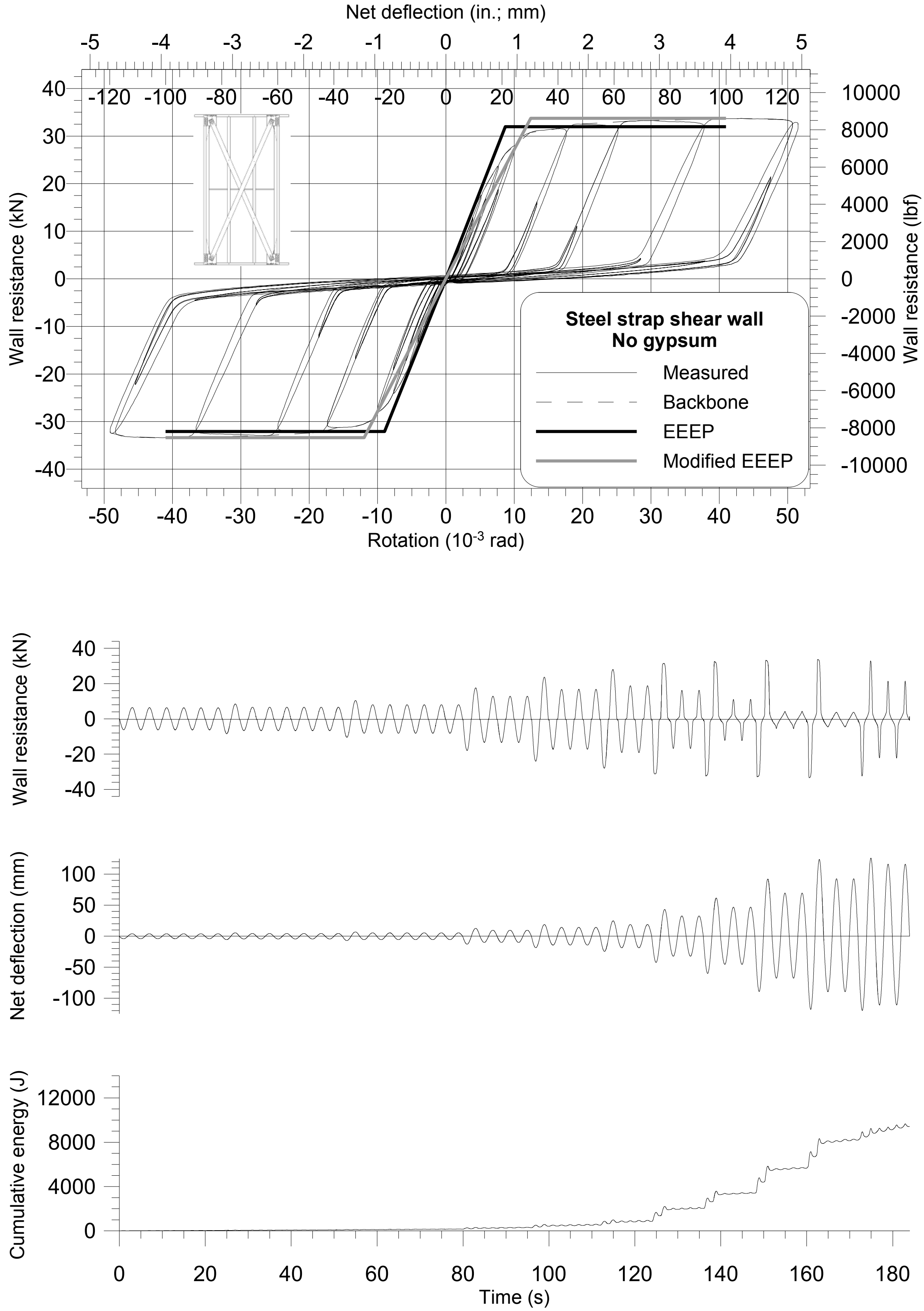



**Figure C-94 : Measured and EEEP curves and time history for test 83A-C**

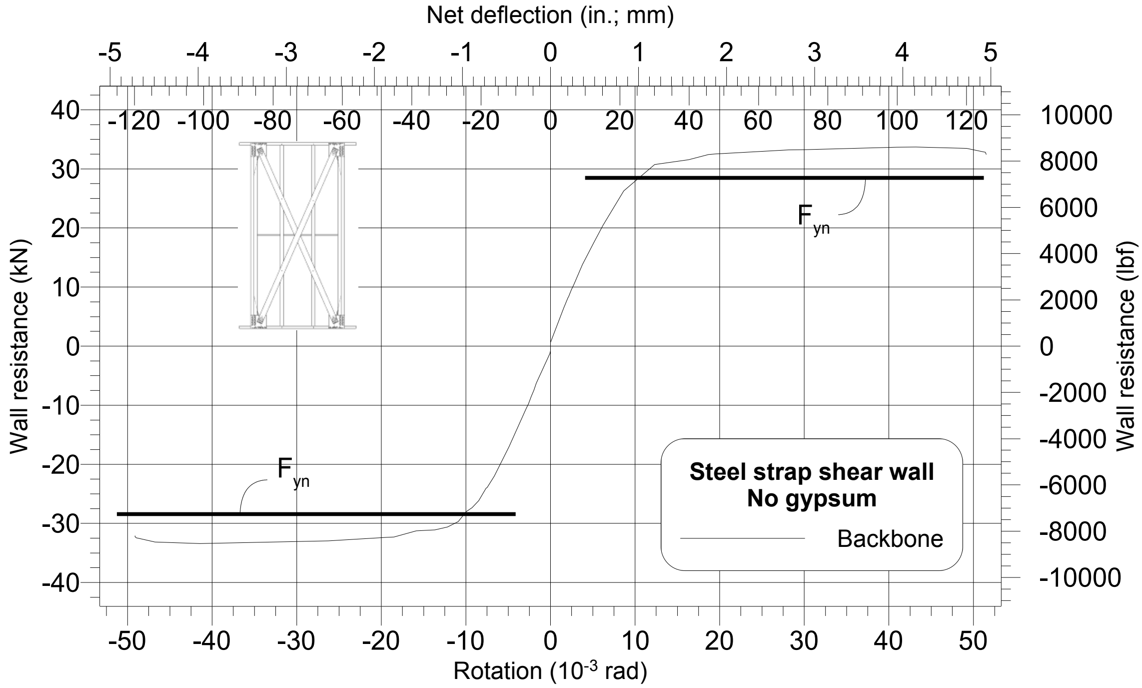



**Figure C-95 Comparison of the predicted probable yielding strength (calculated according AISI S213 and AISI S400) and the test measurements for test 83A-C**

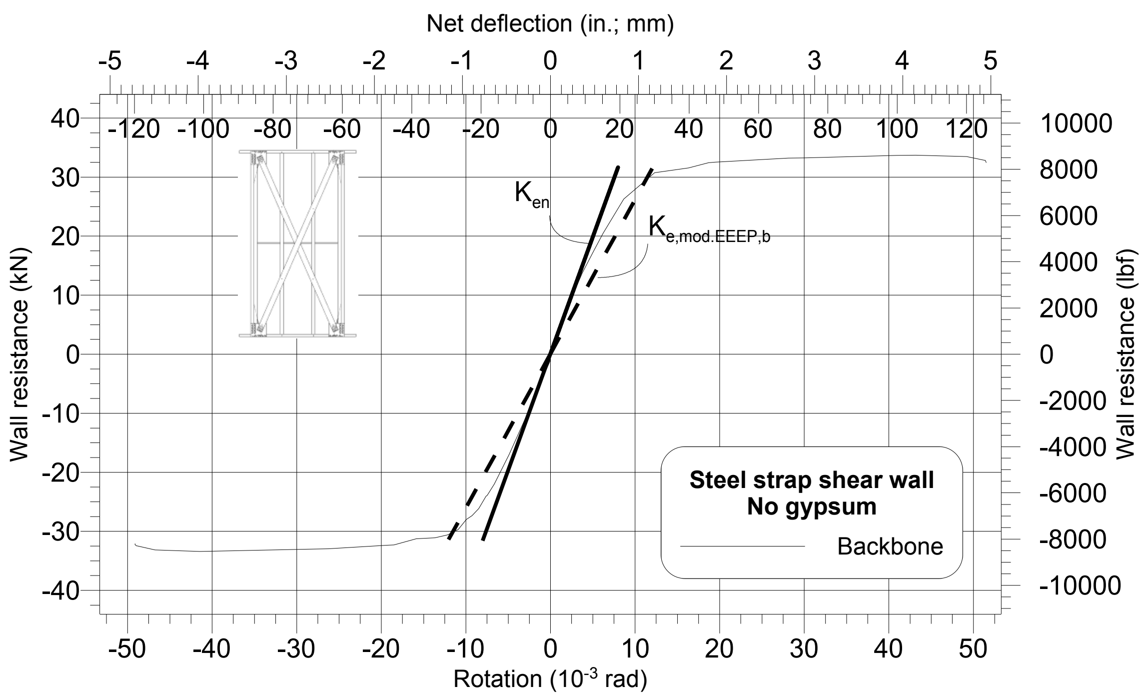



**Figure C-96 83A-C**

**Table 22 Cyclic test results for test 83A-C**

| | Parameters | Specimens 83A-C Positive | Specimens 83A-C Negative | Units |
|---|---|---|---|---|
| Test Results | $F_u$ | 33.69 | -33.40 | kN |
| | $\Delta_{net,u}$ | 105.36 | -101.15 | mm |
| | $F_{0.4u}$ | 13.42 | -13.42 | kN |
| | $\Delta_{net,0.4u}$ | 8.93 | -9.14 | mm |
| | $K_e$ | 1.50 | 1.47 | kN/mm |
| | $F_{0.8u}$ | 26.83 | -26.83 | kN |
| | $\Delta_{net,0.8u}$ | - | - | mm |
| | $\Delta_{net,max}$ | 100 | -100 | mm |
| | Normalized energy [(1)] | 28.55 | -28.59 | J/mm |
| EEEP analysis | $F_y$ | 31.95 | -32.10 | kN |
| | $\Delta_{net,y}$ | 21.25 | -21.86 | mm |
| | Ductility (μ) | 4.71 | 4.57 | - |
| | $R_d$ | 2.90 | 2.85 | - |
| Modified EEEP analysis | $\Delta_{y,mod.EEEP}$ | 30.31 | -29.16 | mm |
| | $K_{e,mod.EEEP}$ | 1.11 | 1.15 | kN/mm |
| Prediction (Actual dimensions) | $F_{yp}$ | 29.30 | -29.13 | kN |
| | $K_p$ | 1.68 | 1.68 | kN/mm |
| Prediction (Nominal dimensions) | $F_{yn}$ | 28.44 | -28.44 | kN |
| | $K_n$ | 1.62 | 1.62 | kN/mm |
| Strain gauge results | Max strain | 5954 | 6598 | - |
| | Yielding strain | 1617 | 1617 | - |
| | Yielding status | OK | OK | |

[(1)] Ratio of energy dissipated under the backbone curve by maximum displacement

# Appendix D. Comparison of the predicted behavior to the tested specimens

**Table D.1 Nominal strength: Detailed comparison of the nominal and test values of the yielding in-plane shear resistance for gypsum-sheathed strap-braced walls**

| Gypsum-sheathed strap-braced wall tests | | $S_y$ (kN/m) | $S_y/(S_{ya}+A_gS_y')$ |
|---|---|---|---|
| **70A-M** | | 28.35 | 0.921 |
| **70B-M** | | 29.30 | 0.952 |
| **71A-C** | *Positive* | *28.82* | *0.937* |
| | *Negative* | *-29.36* | *0.954* |
| | **Average** | 29.09 | 0.945 |
| **71B-C** | *Positive* | *28.33* | *0.921* |
| | *Negative* | *-28.90* | *0.939* |
| | **Average** | 28.61 | 0.930 |
| **Configuration average** | | **28.84** | **0.937** |
| **72A-M** | | 37.20 | 0.933 |
| **72B-M** | | 38.33 | 0.961 |
| **73A-C** | *Positive* | *37.36* | *0.937* |
| | *Negative* | *-39.34* | *0.987* |
| | **Average** | 38.35 | 0.962 |
| **73B-C** | *Positive* | *36.60* | *0.918* |
| | *Negative* | *-39.21* | *0.983* |
| | **Average** | 37.91 | 0.951 |
| **Configuration average** | | **37.95** | **0.952** |
| **74A-M** | | 29.67 | 0.931 |
| **74B-M** | | 29.92 | 0.939 |
| **75A-C** | *Positive* | *31.10* | *0.976* |
| | *Negative* | *-33.23* | *1.043* |
| | **Average** | 32.16 | 1.009 |
| **75B-C** | *Positive* | *31.16* | *0.978* |
| | *Negative* | *-32.61* | *1.023* |
| | **Average** | 31.88 | 1.000 |
| **Configuration average** | | **30.91** | **0.970** |
| **76A-M** | | 31.03 | 0.973 |
| **76B-M** | | 31.81 | 0.998 |
| **77A-C** | *Positive* | *31.37* | *0.984* |
| | *Negative* | *-32.77* | *1.028* |
| | **Average** | 32.07 | 1.006 |
| **77B-C** | *Positive* | *32.41* | *1.017* |
| | *Negative* | *-33.85* | *1.062* |
| | **Average** | 33.13 | 1.039 |
| **Configuration average** | | **32.01** | **1.004** |
| | **Average of the test / predicted ratios** | | 0.966 |
| | **Standard deviation** | | 0.0339 |
| | **Coefficient of variation** | | 0.0351 |

**Table D.2 Probable strength: Detailed comparison of the different methods to predict the probable in-plane shear resistance for gypsum-sheathed strap-braced walls**

| Gypsum-sheathed strap-braced wall tests | | $S_u$ (kN/m) | $S_{u,n1/p1} = S_{yn/yp} + 1.1\,S_{ya}$ | | $S_{u,n2/p2} = S_{yn/yp} + 1.2\,S_{ya}$ | | $S_{u,n3/p3} = S_{yn/yp} + 1.3\,S_{ya}$ | | $S_{u,p4} = S_{sbf} + n(S_g - S_{bf})$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | $S_u / S_{u,n1}$ | $S_u / S_{u,p1}$ | $S_u / S_{u,n2}$ | $S_u / S_{u,p2}$ | $S_u / S_{u,n3}$ | $S_u / S_{u,p3}$ | $S_u / S_{u,p4}$ |
| **70A-M** | | 30.24 | 0.979 | 0.982 | 0.957 | 0.961 | 0.937 | 0.940 | 0.942 |
| **70B-M** | | 31.57 | 1.021 | 1.019 | 0.999 | 0.996 | 0.978 | 0.975 | 0.984 |
| **71A-C** | *Positive* | *30.82* | *0.997* | *0.994* | *0.976* | *0.973* | *0.955* | *0.952* | *0.961* |
| | *Negative* | *-31.02* | *1.004* | *1.004* | *0.982* | *0.982* | *0.961* | *0.961* | *0.967* |
| | **Average** | 30.92 | 1.001 | 0.999 | 0.979 | 0.978 | 0.958 | 0.957 | 0.964 |
| **71B-C** | *Positive* | *30.20* | *0.977* | *0.982* | *0.956* | *0.960* | *0.936* | *0.939* | *0.941* |
| | *Negative* | *-30.75* | *0.995* | *0.999* | *0.973* | *0.977* | *0.952* | *0.956* | *0.958* |
| | **Average** | 30.48 | 0.986 | 0.990 | 0.965 | 0.969 | 0.944 | 0.948 | 0.950 |
| **Configuration average** | | **30.80** | **0.997** | **0.998** | **0.975** | **0.976** | **0.954** | **0.955** | **0.960** |
| **72A-M** | | 40.69 | 0.995 | 0.994 | 0.957 | 0.957 | 0.922 | 0.922 | 0.952 |
| **72B-M** | | 41.34 | 1.010 | 1.010 | 0.972 | 0.972 | 0.937 | 0.937 | 0.967 |
| **73A-C** | *Positive* | *39.76* | *0.972* | *0.968* | *0.935* | *0.932* | *0.901* | *0.898* | *0.930* |
| | *Negative* | *-41.74* | *1.020* | *1.017* | *0.982* | *0.979* | *0.946* | *0.944* | *0.977* |
| | **Average** | 40.75 | 0.996 | 0.993 | 0.959 | 0.955 | 0.924 | 0.921 | 0.953 |
| **73B-C** | *Positive* | *39.19* | *0.958* | *0.958* | *0.922* | *0.922* | *0.888* | *0.889* | *0.917* |
| | *Negative* | *-41.14* | *1.006* | *1.002* | *0.968* | *0.964* | *0.933* | *0.929* | *0.963* |
| | **Average** | 40.16 | 0.982 | 0.980 | 0.945 | 0.943 | 0.911 | 0.909 | 0.940 |
| **Configuration average** | | **40.73** | **0.996** | **0.994** | **0.958** | **0.957** | **0.923** | **0.922** | **0.953** |
| **74A-M** | | 31.87 | 0.992 | 0.993 | 0.968 | 0.969 | 0.945 | 0.946 | 0.934 |
| **74B-M** | | 31.92 | 0.994 | 0.994 | 0.970 | 0.970 | 0.947 | 0.947 | 0.936 |
| **75A-C** | *Positive* | *32.77* | *1.021* | *1.018* | *0.996* | *0.993* | *0.972* | *0.970* | *0.961* |
| | *Negative* | *-34.75* | *1.082* | *1.080* | *1.056* | *1.054* | *1.031* | *1.029* | *1.019* |
| | **Average** | 33.76 | 1.051 | 1.049 | 1.026 | 1.024 | 1.002 | 0.999 | 0.990 |
| **75B-C** | *Positive* | *32.92* | *1.025* | *1.021* | *1.000* | *0.996* | *0.976* | *0.973* | *0.965* |
| | *Negative* | *-34.11* | *1.062* | *1.062* | *1.037* | *1.036* | *1.012* | *1.011* | *1.000* |
| | **Average** | 33.52 | 1.044 | 1.041 | 1.018 | 1.016 | 0.994 | 0.992 | 0.983 |
| **Configuration average** | | **32.77** | **1.020** | **1.019** | **0.996** | **0.995** | **0.972** | **0.971** | **0.961** |
| **76A-M** | | 33.31 | 1.037 | 1.034 | 1.012 | 1.009 | 0.988 | 0.985 | 0.977 |
| **76B-M** | | 33.77 | 1.052 | 1.047 | 1.026 | 1.021 | 1.002 | 0.997 | 0.990 |
| **77A-C** | *Positive* | *33.77* | *1.052* | *1.048* | *1.026* | *1.023* | *1.002* | *0.999* | *0.990* |
| | *Negative* | *-33.98* | *1.058* | *1.061* | *1.033* | *1.035* | *1.008* | *1.011* | *0.996* |
| | **Average** | 33.88 | 1.055 | 1.055 | 1.029 | 1.029 | 1.005 | 1.005 | 0.993 |
| **77B-C** | *Positive* | *34.45* | *1.073* | *1.069* | *1.047* | *1.043* | *1.022* | *1.018* | *1.010* |
| | *Negative* | *-35.02* | *1.090* | *1.086* | *1.064* | *1.060* | *1.039* | *1.035* | *1.026* |
| | **Average** | 34.73 | 1.082 | 1.078 | 1.055 | 1.051 | 1.030 | 1.027 | 1.018 |
| **Configuration average** | | **33.92** | **1.056** | **1.053** | **1.031** | **1.028** | **1.006** | **1.003** | **0.994** |
| | **Average of the test / predicted ratios** | | 1.017 | 1.016 | 0.990 | 0.989 | 0.964 | 0.963 | 0.967 |
| | **Standard deviation** | | 0.0308 | 0.0293 | 0.0325 | 0.0312 | 0.0348 | 0.0337 | 0.0238 |
| | **Coefficient of variation** | | 0.0303 | 0.0288 | 0.0329 | 0.0316 | 0.0361 | 0.0350 | 0.0246 |

**Table D.3 In-plane shear stiffness: Detailed comparison of the different methods to predict the in-plane shear stiffness of gypsum-sheathed strap-braced walls**

| Gypsum-sheathed strap-braced wall tests | | $K_{e,mod.EEEP}$ (kN/mm) | $K_{e,mod.EEEP}/K_{e,n1}$ with $K_{e,n1} = K_{e,mod.EEEP,g} + K_n$ | $K_{e,mod.EEEP}/K_{e,p1}$ with $K_{e,p1} = K_{e,mod.EEEP,g} + K_p$ | $K_{e,mod.EEEP}/K_{e,p3}$ with $K_{e,p2} = K_{e,mod.EEEP,g} + K_{e,mod.EEEP,b}$ |
|---|---|---|---|---|---|
| **70A-M** | | 1.62 | 0.672 | 0.664 | 0.871 |
| **70B-M** | | 1.74 | 0.722 | 0.710 | 0.935 |
| **71A-C** | *Positive* | *1.64* | *0.680* | *0.669* | *0.882* |
| **71A-C** | *Negative* | *1.53* | *0.635* | *0.627* | *0.823* |
| **71A-C** | **Average** | 1.59 | 0.658 | 0.648 | 0.852 |
| **71B-C** | *Positive* | *1.50* | *0.622* | *0.615* | *0.806* |
| **71B-C** | *Negative* | *1.47* | *0.610* | *0.602* | *0.790* |
| **71B-C** | **Average** | 1.49 | 0.616 | 0.609 | 0.798 |
| **Configuration average** | | **1.61** | **0.667** | **0.658** | **0.864** |
| **72A-M** | | 1.89 | 0.721 | 0.711 | 0.913 |
| **72B-M** | | 2.08 | 0.794 | 0.782 | 1.005 |
| **73A-C** | *Positive* | *1.92* | *0.733* | *0.722* | *0.928* |
| **73A-C** | *Negative* | *1.89* | *0.721* | *0.711* | *0.913* |
| **73A-C** | **Average** | 1.91 | 0.727 | 0.716 | 0.920 |
| **73B-C** | *Positive* | *2.00* | *0.763* | *0.755* | *0.966* |
| **73B-C** | *Negative* | *1.78* | *0.679* | *0.672* | *0.860* |
| **73B-C** | **Average** | 1.89 | 0.721 | 0.713 | 0.913 |
| **Configuration average** | | **1.94** | **0.741** | **0.730** | **0.938** |
| **74A-M** | | 1.68 | 0.792 | 0.781 | 1.070 |
| **74B-M** | | 1.70 | 0.802 | 0.791 | 1.083 |
| **75A-C** | *Positive* | *1.62* | *0.764* | *0.750* | *1.032* |
| **75A-C** | *Negative* | *1.62* | *0.764* | *0.750* | *1.032* |
| **75A-C** | **Average** | 1.62 | 0.764 | 0.750 | 1.032 |
| **75B-C** | *Positive* | *1.74* | *0.821* | *0.806* | *1.108* |
| **75B-C** | *Negative* | *1.61* | *0.759* | *0.745* | *1.025* |
| **75B-C** | **Average** | 1.68 | 0.790 | 0.775 | 1.067 |
| **Configuration average** | | **1.67** | **0.787** | **0.774** | **1.063** |
| **76A-M** | | 1.69 | 0.797 | 0.782 | 1.076 |
| **76B-M** | | 1.61 | 0.759 | 0.745 | 1.025 |
| **77A-C** | *Positive* | *1.71* | *0.807* | *0.792* | *1.089* |
| **77A-C** | *Negative* | *1.44* | *0.679* | *0.670* | *0.917* |
| **77A-C** | **Average** | 1.58 | 0.743 | 0.731 | 1.003 |
| **77B-C** | *Positive* | *1.72* | *0.811* | *0.796* | *1.096* |
| **77B-C** | *Negative* | *1.59* | *0.750* | *0.736* | *1.013* |
| **77B-C** | **Average** | 1.66 | 0.781 | 0.766 | 1.054 |
| **Configuration average** | | **1.63** | **0.770** | **0.756** | **1.040** |
| | | **Average of the test / predicted ratios** | 0.741 | 0.730 | 0.976 |
| | | **Standard deviation** | 0.0535 | 0.0517 | 0.0875 |
| | | **Coefficient of variation** | 0.0721 | 0.0709 | 0.0896 |

# Appendix E. Parameters of the Pinching4 material in the numerical models

## Table E.1 Backbone and pinching parameters of the numerical models

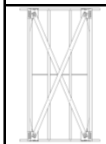
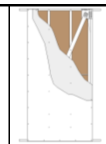
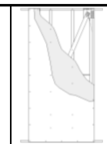
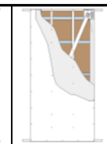
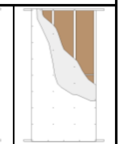
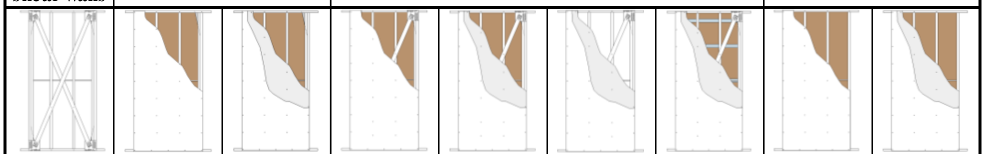
| | | Test specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Strap-braced shear walls | Gypsum-sheathed shear walls | | Gypsum-sheathed strap-braced shear walls | | | | Gypsum-sheathed bearing wall | |
| | |  |  |  |  |  |  |  |  |  |
| **Name of the specimen** | | 65 A-M<br>83 A-C | 66 A-M<br>66 B-M<br>67 A-C<br>67 B-C | 68 A-M<br>68 B-M<br>69 A-C<br>69 B-C | 70 A-M<br>70 B-M<br>71 A-C<br>71 B-C | 72 A-M<br>72 B-M<br>73 A-C<br>73 B-C | 74 A-M<br>74 B-M<br>75 A-C<br>75 B-C | 76 A-M<br>76 B-M<br>77 A-C<br>77 B-C | 78 B-M<br>78 C-M<br>79 A-C<br>79 B-C | 80 A-M<br>80 B-M<br>81 A-C<br>81 B-C |
| Gypsum panels: Pinching4 Backbone curve parameters | **$ePd_1$** | NA | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00001 | 0.00017672 | 0.00019672 |
| | **$ePd_2$** | | 0.0007 | 0.0005 | 0.0007 | 0.0005 | 0.0005 | 0.0005 | 0.00334143 | 0.002419 |
| | **$ePd_3$** | | 0.00580463 | 0.00868768 | 0.00580463 | 0.00868768 | 0.00868768 | 0.00868768 | 0.00863623 | 0.00565465 |
| | **$ePd_4$** | | 0.0204918 | 0.02585631 | 0.0204918 | 0.02585631 | 0.02585631 | 0.02585631 | 0.02295082 | 0.01639344 |
| | **$ePf_1$** | | 2186.97 | 12000 | 2186.97 | 12000 | 6000 | 6000 | 2792.841 | 3353.44208 |
| | **$ePf_2$** | | 8628 | 19380.79 | 8628 | 19380.79 | 9690.395 | 9690.395 | 7472.69235 | 8074.59165 |
| | **$ePf_3$** | | 9349.19 | 22060.7 | 9349.19 | 22060.7 | 11030.35 | 11030.35 | 8647 | 9370 |
| | **$ePf_4$** | | 1646.02 | 3186.94 | 1646.02 | 3186.94 | 1593.47 | 1593.47 | 2184.14555 | 2199.10563 |
| | **rDisp** | NA | 0.5 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.4 |
| | **rForce** | | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| | **uForce** | | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.1 | 0.1 |
| Strap-braces: Pinching4 Backbone curve parameters | **$ePd_1$** | 0.000001 | NA | NA | 0.000001 | 0.000001 | 0.000001 | 0.000001 | NA | NA |
| | **$ePd_2$** | 0.00178545 | | | 0.00178545 | 0.00178545 | 0.00178545 | 0.00178545 | | |
| | **$ePd_3$** | 0.2 | | | 0.2 | 0.2 | 0.2 | 0.2 | | |
| | **$ePd_4$** | 0.3 | | | 0.3 | 0.3 | 0.3 | 0.3 | | |
| | **$ePf_1$** | 5221223.23 | | | 5221223.23 | 5221223.23 | 5221223.23 | 5221223.23 | | |
| | **$ePf_2$** | 724892970 | | | 724892970 | 724892970 | 724892970 | 724892970 | | |
| | **$ePf_3$** | 906786346 | | | 906786346 | 906786346 | 906786346 | 906786346 | | |
| | **$ePf_4$** | 0 | | | 0 | 0 | 0 | 0 | | |
| | **rDisp** | 0.9 | NA | NA | 0.9 | 0.9 | 0.9 | 0.9 | NA | NA |
| | **rForce** | 0.04 | | | 0.04 | 0.04 | 0.04 | 0.04 | | |
| | **uForce** | -0.03 | | | -0.03 | -0.03 | -0.03 | -0.03 | | |
| | **$eNd_1$** | -0.000001 | NA | NA | -0.000001 | -0.000001 | -0.000001 | -0.000001 | NA | NA |
| | **$eNd_2$** | -0.001 | | | -0.001 | -0.001 | -0.001 | -0.001 | | |
| | **$eNd_3$** | -0.01 | | | -0.01 | -0.01 | -0.01 | -0.01 | | |
| | **$eNd_4$** | -0.1 | | | -0.1 | -0.1 | -0.1 | -0.1 | | |
| | **$eNf_1$** | -0.001 | | | -0.001 | -0.001 | -0.001 | -0.001 | | |
| | **$eNf_2$** | -0.001 | | | -0.001 | -0.001 | -0.001 | -0.001 | | |
| | **$eNf_3$** | -0.001 | | | -0.001 | -0.001 | -0.001 | -0.001 | | |
| | **$eNf_4$** | -0.001 | | | -0.001 | -0.001 | -0.001 | -0.001 | | |
| | **nrDisp** | 0.33 | NA | NA | 0.33 | 0.33 | 0.33 | 0.33 | NA | NA |
| | **nrForce** | 0.0001 | | | 0.0001 | 0.0001 | 0.0001 | 0.0001 | | |
| | **nuForce** | 0 | | | 0 | 0 | 0 | 0 | | |

**Table E.2 Degradation parameters and maximum energy dissipation of the numerical models**

| | | Test specimens | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Strap-braced shear walls | Gypsum-sheathed shear walls | | Gypsum-sheathed strap-braced shear walls | | | | Gypsum-sheathed bearing wall | |
| | |  | | | | | | | | |
| Name of the specimen | | 65 A-M<br>83 A-C | 66 A-M<br>66 B-M<br>67 A-C<br>67 B-C | 68 A-M<br>68 B-M<br>69 A-C<br>69 B-C | 70 A-M<br>70 B-M<br>71 A-C<br>71 B-C | 72 A-M<br>72 B-M<br>73 A-C<br>73 B-C | 74 A-M<br>74 B-M<br>75 A-C<br>75 B-C | 76 A-M<br>76 B-M<br>77 A-C<br>77 B-C | 78 B-M<br>78 C-M<br>79 A-C<br>79 B-C | 80 A-M<br>80 B-M<br>81 A-C<br>81 B-C |
| Gypsum panels: Pinching4 Backbone curve parameters | $gK_1$ | NA | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| | $gK_2$ | | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 |
| | $gK_3$ | | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 1.2 | 1.2 |
| | $gK_4$ | | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 1.2 | 1.2 |
| | $gK_{lim}$ | | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 |
| | $gD_1$ | NA | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| | $gD_2$ | | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 |
| | $gD_3$ | | 1.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 2 | 2 |
| | $gD_4$ | | 1.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 2 | 2 |
| | $gD_{lim}$ | | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.5 | 0.5 |
| | $gF_1$ | NA | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $gF_2$ | | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| | $gF_3$ | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | $gF_4$ | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | $gF_{lim}$ | | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 |
| | $gE$ | NA | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4 | 8 |
| Strap-braces: Pinching4 Backbone curve parameters | $gK_1$ | 1 | NA | NA | 1 | 1 | 1 | 1 | NA | NA |
| | $gK_2$ | 1 | | | 1 | 1 | 1 | 1 | | |
| | $gK_3$ | 0.23 | | | 0.23 | 0.23 | 0.23 | 0.23 | | |
| | $gK_4$ | 0.23 | | | 0.23 | 0.23 | 0.23 | 0.23 | | |
| | $gK_{lim}$ | 0.9 | | | 0.9 | 0.9 | 0.9 | 0.9 | | |
| | $gD_1$ | 0.05 | NA | NA | 0.05 | 0.05 | 0.05 | 0.05 | NA | NA |
| | $gD_2$ | 0.05 | | | 0.05 | 0.05 | 0.05 | 0.05 | | |
| | $gD_3$ | 1.5 | | | 1.5 | 1.5 | 1.5 | 1.5 | | |
| | $gD_4$ | 1.5 | | | 1.5 | 1.5 | 1.5 | 1.5 | | |
| | $gD_{lim}$ | 0 | | | 0 | 0 | 0 | 0 | | |
| | $gF_1$ | 0.1 | NA | NA | 0.1 | 0.1 | 0.1 | 0.1 | NA | NA |
| | $gF_2$ | 0.1 | | | 0.1 | 0.1 | 0.1 | 0.1 | | |
| | $gF_3$ | 2 | | | 2 | 2 | 2 | 2 | | |
| | $gF_4$ | 2 | | | 2 | 2 | 2 | 2 | | |
| | $gF_{lim}$ | 0 | | | 0 | 0 | 0 | 0 | | |
| | $gE$ | 6 | NA | NA | 6 | 6 | 6 | 6 | NA | NA |