THE SEISMIC VULNERABILITY OF ART OBJECTS

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ABSTRACT

Throughout history, objects of art have been damaged and sometimes destroyed in earthquakes. Even though the importance of providing seismically adequate design for nonstructural components has received attention over the past decade, art objects in museums, either on display or in storage, require further research. The research reported in this study was undertaken to investigate the seismic vulnerability of art objects. Data for this research was gathered from three museums in Montréal.

The seismic behaviour of three unrestrained display cases, storage shelves, and a 6m long dinosaur skeleton model structure was investigated according to the seismic hazard for Montréal and representative museum floor motions were simulated for that purpose. Particular attention was paid to the support conditions, the effects of modified floor surface conditions, the sliding and rocking response of unrestrained display cases, the location (floor elevation) of the display case and/or storage shelves, art object mass, and the dynamic properties of the display cases/storage shelves. The seismic vulnerability of art objects was evaluated based on the seismic response of the display cases/storage shelves at the level of art object display. The display cases were investigated experimentally using shake table testing. Computer analyses were used to simulate the seismic behaviour of storage shelves, and the seismic sensitivity of the dinosaur structure was determined via free vibration acceleration measurements. The floor contact conditions and floor elevation had a crucial effect on the unrestrained display cases, causing them to slide or rock vigorously. The distribution of content mass had a large impact on the response of the shelving system. As a result of experimental and analytical analyses, recommendations and/or simple mitigation techniques are provided to reduce the seismic vulnerability of objects of art.

RÉSUMÉ

Au cours de l'Histoire, les oeuvres d'art ont pu être endommagées et parfois détruites par les tremblements de terre. Bien que la conception parasismique de composants non structuraux ait reçu davantage d'attention cette dernière décennie, les objets d'art dans les musées, exposés ou en entreposage, exigent de plus amples recherches. L'auteure présente sa recherche sur l'étude de la vulnérabilité sismique des objets d'art. Les données pour cette recherche proviennent de trois musées à Montréal.

Le comportement sismique d'un modèle de squelette de dinosaure haut de six mètres, de trois présentoirs vitrés et d'étagères d'entreposage en tôle d'acier ont été examinés. Une attention particulière fut portée aux conditions d'appui, aux effets de l'état de la surface de contact entre les présentoirs et le plancher, au glissement et balancement des présentoirs, à l'emplacement et l'élévation des présentoirs et/ou des étagères, à la masse des objets d'art, et aux propriétés dynamiques des présentoirs et des étagères. La vulnérabilité sismique des objets d'art a été basée sur la réponse dynamique transitoire mesurée ou calculée sur les présentoirs et les étagères à la hauteur de la présentation des objets. Les présentoirs ont été soumis à des essais sismiques sur une table vibrante. Une analyse dynamique de modèles numériques a été effectuée pour déterminer le comportement sismique des étagères d'entreposage. La sensibilité sismique du modèle de squelette de dinosaure a été déterminée par une analyse des mesures d'accélérations transitoires suite à des faibles chocs. L'élévation ainsi que la nature du contact avec le plancher ont eu un effet crucial pour les présentoirs vitrés, les amenant à glisser ou balancer vigoureusement. La distribution du contenu de masse a eu un grand impact sur les contrecoups dans les étagères. A la suite du processus expérimental et de l'analyse des données, des recommandations et/ou des méthodes simples sont proposées pour réduire la vulnérabilité des objets d'art aux secousses sismiques.

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1 Introduction

1.1 BACKGROUND

According to CSA S832-05 (CSA 2005) building elements can be divided into two groups: structural components and operational and functional components (OFCs). Experience from past earthquakes has shown that damage from these components can be substantial and can pose significant life safety hazards, also in areas of low seismic risk. Earthquake damages in the past demonstrate that proper design for nonstructural components cannot be neglected. As a result, research on OFCs has increased over the past decade, but the need to research specific topics still exists. Examples of 20th century earthquakes give an indication of the extent of art objects damaged and sometimes destroyed. Review of research efforts on the protection of art in earthquakes indicates that the seismic mitigation for art objects is still a challenge. The challenge arises in the fact that certain physical characteristics and inherent damages make art objects (on display or in storage) particularly vulnerable to strong shaking. Furthermore conventional seismic mitigation techniques cannot always be utilized, as they might be of particular concern to the object surface and interfere with desired display characteristics. This research project was conducted in collaboration with three museums in Montréal, Canada: The Musée des Beaux-Arts de Montréal (MBAM), the McCord Museum, and McGill's Redpath Museum. Accompanying experimental testing via a shake table was performed at the structural testing facility of École Polytechnique de Montréal.

1.2 RESEARCH OBJECTIVES

It is the purpose of this research to investigate the seismic vulnerability of selected museum display cases, the dynamic behaviour of storage shelves loaded with glass negatives, and the seismic sensitivity of a dinosaur skeleton model structure. The scope and research objectives of this research project are as follows:

- Prepare a comprehensive literature review report to provide pertinent background knowledge to this study, critically analyze related research efforts, and identify research gaps.
- Inspect art objects on display and in storage and identify potential seismic vulnerabilities of three museums in Montréal.
- Identify the seismic hazard for Montréal and determine time-history curves which are representative of museum floors. A computer analysis of a comparable building model is performed for that purpose.
- Perform experimental shake table testing of three display cases to simulate seismic loading at the level of art object display.
- Conduct test series to investigate effects of display case geometry and stiffness, ground motion characteristics, location (floor elevation) of display cases, floor contact surface conditions, and art object mass. Ultimately, the dynamic behaviour of unrestrained display cases is determined and levels of acceleration developed at the level of art object display are evaluated.
- Investigate the dynamic behaviour of a storage shelving system, loaded with heavy, fragile contents, based on computer analyses.

- Conduct computer analyses to investigate effects of ground motion characteristics, location (floor elevation) of storage shelves, content mass distribution, and the stiffness of a link connecting shelves to form a shelving unit. Ultimately the acceleration and displacement response adequacy of the shelving system is determined and the response of contents located on the shelves is evaluated.
- Investigate the seismic sensitivity of a 6 m long dinosaur skeleton model structure based on its natural frequency properties.
- Compare the seismic design forces on the dinosaur skeleton to those recommended by the National Building Code of Canada (NBCC) 2005.
- Provide simple and economic recommendations based on result outcomes to safeguard art objects located on display cases and on shelving systems.
- Provide conclusions on the seismic analysis and experimental results and identify seismic vulnerabilities of art objects on display cases and in storage.

1.3 THESIS OVERVIEW

The work of accomplishing the aforementioned research objectives is presented in the remainder of this text.

Chapter 2 presents a summary of an accompanying comprehensive literature review report (Neurohr 2005), in which research efforts have been critically analyzed and gaps in research have been identified. The seismic hazard for Montréal is discussed in Chapter 3. Floor motion time history curves are presented for use in subsequent computer analyses and experimental works. The three subsequent chapters have each been assigned to the presentation of one case study, corresponding to the three museums of investigation. Chapter 4 presents the investigation of three display cases at the MBAM. This chapter describes the test specimens, experimental procedure, and presents and discusses shake table test results. The study of the storage shelving system of the McCord Museum is presented in Chapter 5, which includes the description of the computer model, a summary of results, which is accompanied by discussions and a prediction of art object response. Chapter 6 deals with the free vibration measurements used to analyze the seismic sensitivity of the dinosaur skeleton model structure at the Redpath Museum. Conclusions and recommendations based on results specific to each case study are summarized in Chapter 7. Chapter 7 concludes by identifying items which require further research. A detailed collection of data are provided in the Appendices.

2 Literature Review

A comprehensive literature review report has been prepared at the initial stage of this research project to investigate previous research efforts on the seismic vulnerability of art objects (Neurohr 2005). This report consisted of sections aimed to address the following issues:

- Evaluate physical characteristics which make OFCs, especially art objects, particularly vulnerable to earthquakes.
- Review the sections of the National Building Code of Canada (NBCC 2005), the National Earthquake Hazards Reduction Program Recommended Provisions (NEHRP 2003), and the CSA S832 standard (CSA 2005) containing provisions for the seismic design of nonstructural components.
- Evaluate available analysis methods and mitigation techniques specific to art objects.
- And, identify existing research needs to advance the protection of art objects in earthquakes.

This chapter provides a summary of that report to provide pertinent background knowledge to this text and demonstrate that research on the seismic mitigation techniques for art objects is of great relevance.

2.1 DAMAGE TO ARTIFACTS IN PAST EARTHQUAKES

Throughout history, objects of art have been damaged and sometimes destroyed during earthquakes. Examples of 20th century earthquakes give us an indication of the extent of art object losses. The 1924 Japan earthquake destroyed the Okura museum, and damaged the famous Hara collection (Visser 1924). A 1931 earthquake in Nicaragua caused considerable damage to the Biblioteca Nacional, and a 1972 earthquake destroyed it completely (UNESCO – WebWorld 1997). The National and University Library of the Former Yugoslav Republic of Macedonia sustained considerable damage from an earthquake in 1963. In the 1989 Loma Prieta earthquake in California, artifact damage of varying severity was observed at several museums in the Bay Area, as seen in Figure 2.1 (Metro and Podany 1990). At the San Francisco Museum of Modern Art it was observed that art exhibited on upper floors were damaged more severely than on lower building levels (Shank 1990). A large extent of pottery was destroyed due to severe damage to the museum structure in Agoo in the 1990 Philippine earthquake (Shiff 1991). Significant damage to traditional Japanese paintings occurred in the 1995 Kobe earthquake in Japan (Fitzgerald 1995). The earthquake which hit the Northern Sumatra region in Indonesia on March 28th, 2005 damaged a large extent of the collection of the Nias Heritage Museum, as seen in Figure 2.2 (ICOM – Disaster Relief for Museums 2006).

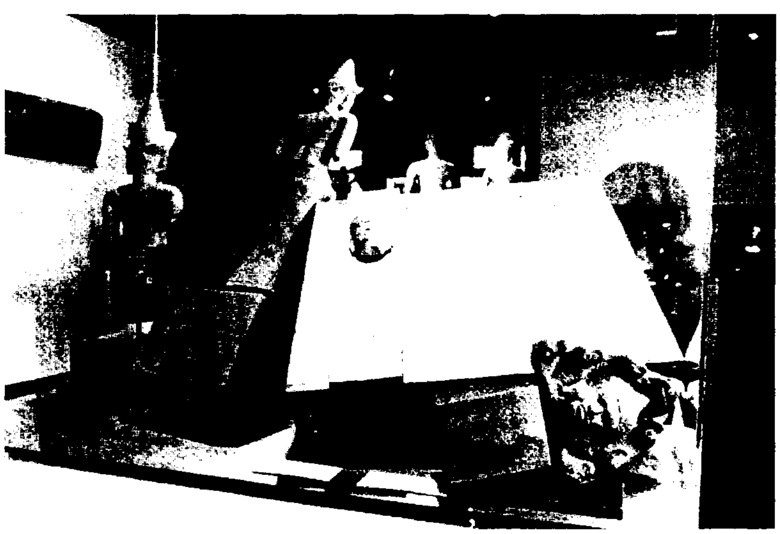


Figure 2.1: Stone sculptures in a freestanding showcase assembled as a wooden base with a plexiglas vitrine on top in the Asian Art Museum of San Francisco (Metro and Podany 1990)

Figure 2.2: Damage to valuable artifacts such as broken ceramics, pottery, old wood, megalithic stones, significant cracking to collections in storage in the Nias Heritage Museum (ICOM – Disaster Relief for Museums 2006)

While these are only some examples of earthquake damage to art in museums, it is important to mention that some museums have also implemented measures to reduce their collections' seismic vulnerability. While the 1994 earthquake in Northridge, California, caused damage estimated at $30 billion, art museums, which had protection measures in place, suffered relatively little (Anonymous 1994).

The history of earthquake damage to art objects underscores the significant losses already suffered in the past. However, it is now possible to implement measures which greatly reduce the seismic vulnerability of art objects, but the fact that even very recent earthquakes still result in considerable damage to art objects demonstrates that the problem of seismic protection for art objects persists and that the issue demands further exploration.

2.2 BEHAVIOUR OF ARTIFACTS UNDER EARTHQUAKE MOTION

2.2.1 Failure Modes

From extensive data collection of seismic damage to artifacts, the **factors contributing to damage** are summarized as follows (Metro and Podamy 1990):

- Impact of one object with another, with the ground, or with exhibit furniture; often increased through high density of exhibition space.
- Falling of nonstructural building components.
- Insufficient or lack of exhibition/storage restraints.

- Instability of the object or object-pedestal combination resulting in rocking, tipping, and overturning or sliding off exhibit pedestals, storage shelving, or interior shelves of showcases.
- Insufficient anchorage or attachment of object to pedestals, mounts or build-ups either in showcase or free-standing.
- Instability of exhibit mounts, pedestals, and build-ups or insufficient anchorage causing the entire object-mount-pedestal assembly to tip.
- Falling of objects from unrestrained open-storage shelving.
- Fixture through wax and monofilament proved insufficient when subjected to increased loads due to high accelerations.
- Wooden soles were unable to demonstrate sufficient flexibility to motion of supporting structure, causing the soles to split at their thinnest parts.

2.2.2 Vulnerabilities of Artifacts

Certain physical characteristics make OFCs especially vulnerable to earthquakes and lead to response characteristics different from structures (Villaverde 1997):

- OFCs attached at higher elevations are subjected to the amplified ground motion, and are therefore dependent on the structure's dynamic response characteristics. OFCs at different elevations are therefore subjected to different forces and motions.
- Because of their small weight and stiffness, their natural period of vibration may coincide with that of the structure, resulting in amplified dynamic response due to resonance. Closely-spaced natural periods of the combined structure-component system might lead to the response of the OFC being controlled by more than one mode of vibration.

- Small damping does not provide sufficient resistance against resonating motion and response of such a component is governed by the response of a system with complex valued natural frequencies and mode shapes.
- OFCs connected to the structure at multiple points are susceptible to distorting differential displacements and their connections are subject to out-of-phase motions.
- The inherent properties of OFCs are associated with functions other than those to resist seismic forces.
- The response is affected by the inelastic properties of the component as well as that of the structure.

Further it is recognized that the vulnerability of art objects is often increased because of unstable formats, irregular shapes, and their inherent weakness or brittleness.

2.3 REGULATIONS AND GUIDELINES FOR THE SEISMIC DESIGN OF NONSTRUCTURAL COMPONENTS

The literature review report that was prepared preceding this text (Neurohr 2005) presented existing regulations and guidelines available for the seismic design of nonstructural components. The sections of the National Building Code of Canada (NBCC 2005), the National Earthquake Hazards Reduction Program (NEHRP 2003) Recommended Provisions, and the CSA S832-05 standard (CSA 2005) containing provisions for the seismic design of nonstructural components were reviewed and presented. The performance and design and displacement requirements for OFCs accepted in these guidelines are briefly presented in this section.

2.3.1 Performance Requirements

The CSA S832 standard *Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings* (CSA 2005) was prepared to evaluate the seismic risk of nonstructural components in existing structures and to provide guidance on various seismic risk mitigation techniques. This standard sets the following performance objectives for OFCs:

1. **Life Safety:** The minimum performance level which ensures life-threatening movements or failure of OFCs are prevented.
2. **Immediate/Continued Occupancy:** Ensures that damage to the structure and OFCs is limited so that the building is safe for immediate occupancy but does not necessarily need to remain fully operational and functional.
3. **Functionality:** Referred to as a "post-disaster" building; a high level of seismic protection ensures that the building remains operational and functional during and after the earthquake.

The performance objectives further emphasize that the level of seismic performance reflects the **property protection** for specific OFCs, as in the case of art objects of particular value and/or cultural significance.

2.3.2 Design Force and Displacement Requirements

Provisions of current codes and guidelines ensure that OFCs are designed to withstand accelerations and deformations which are generated by the design earthquake. The provisions of the NBC outline the design force and displacement requirements for Canada. The design for lateral forces ensures that adequate anchorage for nonstructural components is provided, and displacement requirements have been developed to ensure that components have connections which provide adequate strength and flexibility to accommodate any differential displacements.

The basis to determine the seismic design force on OFCs, as outlined in provisions of codes and guidelines, always takes the form of the component weight times the floor acceleration as a ratio of gravity. Factors have been introduced with progress in research with the purpose of taking the dynamic interaction between the structure and its components into account. The current code provisions include factors to account for effects of ground acceleration and the distribution of acceleration along the height of the building, dynamic amplification to account for resonance between the building and its components, the energy-absorption capacity of the components and its connections, as well as a factor to account for the importance of the component.

2.4 ANALYTICAL RESEARCH ON ARTIFACTS IN THE PAST

Analytical and experimental research efforts on nonstructural components in the past have been reviewed in Neurohr (2005). Seismic mitigation techniques for nonstructural components are not always a viable option for many art objects, which are too fragile and valuable to be properly secured. Furthermore, adequate mitigation techniques need to comply with aesthetic requirements.

It appears that the first systematic scientific study on the earthquake behaviour of art objects was undertaken by the Getty Conservation Institute in collaboration with the University of Southern California in 1988 (Agbabian et al. 1988). A second study followed in 1990 (Agbabian et al. 1990). The purpose of these studies was to evaluate current seismic mitigation methods based on analytical as well as experimental analysis techniques for the development of museum guidelines. Other studies on this subject followed at the University of Rome, in Italy (Augusti et al. 1992; Augusti et al. 1995). These studies were conducted to evaluate display cases, which are restrained to the floor, and investigate the effect of ground motion parameters on unrestrained art objects exhibited in these display cases.

The seismic behaviour of art objects has mainly been investigated by analyzing the dynamic response of rigid bodies. Research has shown that most art objects can be considered rigid, since their large natural frequency will not resonate with the lower frequency structural response (Agbabian et al. 1988). The rigid body motions have been identified as: rest, slide, rock, slide and rock, translational jump, and rotational jump (Ishiyama 1984). Based on the conditions for rigid body motion (Zhu and Soong 1998), it can be observed that for a given object, a coefficient of surface friction can be specified, above which the body will not undergo any motion. In order for sliding to commence, the static friction coefficient has to be less than the geometric ratio b/h (width/height of object). The rock mode is initiated when the static friction coefficient is larger than b/h. A study which focused on the mitigation of seismic risk for museum contents emphasized that rocking and consequential overturning of objects should always be prevented, and sliding limited to acceptable values (Augusti et al. 1992).

Some research has been conducted to develop base-isolation devices to control the vibrations of art objects as a result of impulsive base excitations (Calio and Marletta 2003; Vestroni and Di Cintio 2000). Although base isolation is considered an effective means of reducing seismic forces, its application is usually limited to heavy statues and other objects of art of large size or particular cultural significance.

Under the National Earthquake Hazards Reduction Program (NEHRP), the Federal Emergency Management Agency (FEMA) has prepared a document on "Seismic considerations for steel storage racks located in areas accessible to the public". Storage rack seismic design practices are discussed and useful installation measures of pallet storage racks are presented. The scope of that report is, however, limited to single steel storage racks where contents have been elevated more than 8 ft above the ground.

2.5 RESEARCH NEEDS

The research needs that were identified by investigating efforts targeted at the seismic protection of art objects are as follows (Neurohr 2005):

- Current mitigation techniques for art objects seem to indicate that preferred mitigation practices involve isolating the object from ground motion, either by use of installing an isolation device, or reducing the surface coefficient of friction to allow sliding within limits. While base isolation is a very efficient mitigation technique, its application is usually limited to a small number of objects. Research has to be expanded to those objects accommodated by some type of display case which do not receive special isolation devices. Research was undertaken with display cases connected to the floor. The behaviour of unrestrained display cases needs investigation and has been studied in this research project.

- The acceleration demand along the height of the building has been subject to many studies. Disagreements still exist. As for display cases and storage cabinets in museums it is crucial to determine the acceleration at the height of art object display and the effect on resulting rigid-body motion of art objects.
- The sliding motion of rigid bodies in earthquakes was reviewed. Various effects, such as the bi-directional sliding motion, variation in the coefficient of friction, torsion, and the irregularity of the object are often neglected. Mitigation techniques which rely on the sliding motion of art objects need further research. Considering that the sliding of art objects might pose great risk in terms of life-safety and damage of the art objects, alternative mitigation techniques need to be evaluated as well. Significant research on connections specific for art objects, free-standing and hanging (pendulum as well as picture frames attached at multiple points) was not located. Many sources indicate that research in the area of component attachment needs to be continued.
- Art objects are often positioned on assembled blocks for aesthetics and improved visibility. The behaviour of these assemblages inside display cases and their effects on the art objects has not been studied.
- Typical museum storage systems, such as movable storage cabinets with fragile contents as well as roller-type systems for paintings have not been studied.

The research presented in this text was developed based on the research needs identified in the accompanying literature review and on identification of seismically vulnerable objects in museums which collaborated in this research.

3 Seismic Hazard

The seismic hazard for Montréal has been chosen to match the target uniform spectrum of the intraplate region of eastern Canada. Floor motions have been produced to simulate representative seismic motions at museum floors.

3.1 GROUND MOTION TIME HISTORIES

Time history records representing the seismic hazard of Montréal have been simulated for different levels of probability of exceedance (Atkinson and Beresnev 1998). The seismic hazard is represented in terms of most likely magnitude (M) – hypocentral distance (R) scenarios and has been modified with a fine-tuning scale factor to match the target uniform hazard spectrum (UHS) for Montréal for "firm soil" conditions (Filiatrault et al. 2004). Time histories were generated to match median levels over a specific period band (Atkinson and Beresnev 1998). The seismic hazard scenarios include small to moderate earthquakes at close distances (contributing to the short-period ground motion hazard) and larger events at greater distances (contributing to the long-period ground motion hazard). Table 3.1 summarizes the simulated ground motions. The assigned ground motion notation will be used hereafter.

Table 3.1: Simulated ground motion scenarios for Montréal

Ground Motion Notation	Magnitude M	Hypocentral Distance, R (km)	Fine-Tune Scale Factor	PHA (g)	PHV (m/s)	Ground Shaking Duration (s)
Probability of exceedance of 10% in 50 years						
10 M5.5R30	5.5	30	0.80	0.174	0.0525	4.9
10 M7R150	7.0	150	0.70	0.159	0.0819	19.1
10 M7R300	7.0	300	1.30	0.054	0.0448	25.1
Probability of exceedance of 2% in 50 years						
2 M6R30	6.0	30	0.85	0.430	0.170	6.3
2 M7R50	7.0	50	0.60	0.509	0.190	16.9
2 M7R70	7.0	70	0.90	0.301	0.149	20.1

3.2 FLOOR MOTION TIME HISTORIES

Display cases/shelving systems which are located on museum floors above ground level, are not directly subjected to the base ground motion but rather to the amplified floor motions generated by the dynamic response of the building. To account for the fact that the response of the display cases and shelving unit depends on their elevation of location, floor time histories were generated. A low-rise concrete building which has been modeled and validated with in situ measurements (Assi 2006) was considered to serve as a representation of the dynamic properties of the museum. Given that the focus is on the response of the display cases/shelving systems, rather than on the response of the museum building, this assumption was deemed generally appropriate considering the massive museum construction and the great effort associated with a detailed collection of data on the museum structure and subsequent dynamic modeling.

3.2.1 Building Model and Analysis Procedure

A dynamic analysis of a four-storey concrete building, located in Taiwan, was carried out using the commercial structural analysis program SAP2000 (Computers and Structures 2000) to determine the absolute acceleration response time histories of the building at various elevations representing the location of the display cases. Figures 3.1 and 3.2 depict the model. The periods for the first three modes of vibration were found to be 0.298s, 0.258s, and 0.174s respectively.

Floor seismic accelerations were derived from elastic analysis of the building model. It should be noted that an inelastic analysis would result in different floor accelerations, since inelastic damage leads to an elongation of the natural period of vibration of the building, changing the frequency content and intensity of the resulting floor accelerations.

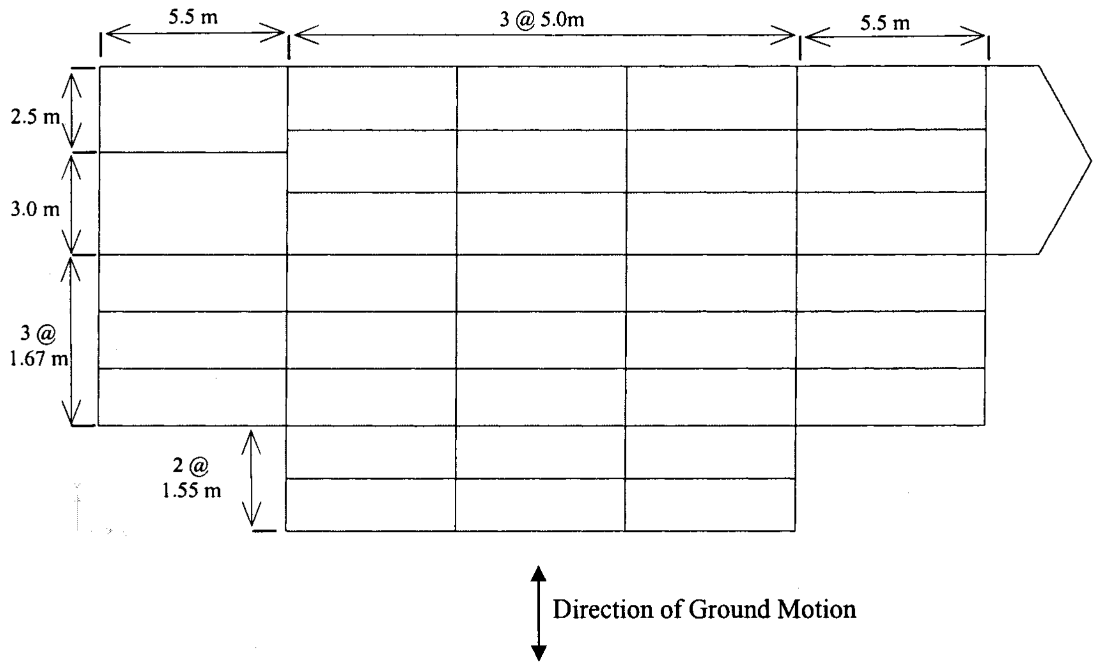


Figure 3.1: Plan view of the building model

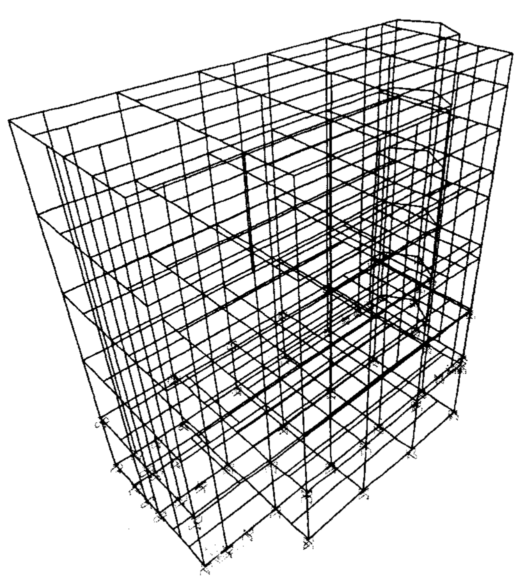


Figure 3.2: 3D elevation of the building model

3.2.2. Floor Acceleration Time Histories

Based on the ground motions listed in Table 3.1, floor motions were obtained for the building model. The floor (base) motion parameters can be obtained from Table 3.2.

Table 3.2: Simulated Floor Motions

Base Motion Notation	Elevation (m)	PHA (m/s2)	PHA (g)	Max. Displacement (m)	Base Shaking Duration (s)
Probability of exceedance of 10% in 50 years					
10 M5.5R30	0	1.500	0.153	0.0103	4.9
10 M5.5R30	5	1.237	0.126	0.0109	4.9
10 M5.5R30	10	1.578	0.161	0.0115	4.9
10 M7R150	0	1.106	0.113	0.0384	19.1
10 M7R150	5	1.083	0.110	0.0387	19.1
10 M7R150	10	1.391	0.142	0.0393	19.1
10 M7R300	0	0.699	0.0712	0.428	25.1
10 M7R300	5	0.867	0.0883	0.428	25.1
10 M7R300	10	1.509	0.154	0.428	25.1
Probability of exceedance of 2% in 50 years					
2 M6R30	0	3.883	0.396	0.0313	6.3
2 M6R30	5	3.643	0.371	0.0322	6.3
2 M6R30	10	3.961	0.404	0.0333	6.3
2 M7R50	0	3.010	0.307	0.0538	16.9
2 M7R50	5	3.452	0.352	0.0536	16.9
2 M7R50	10	4.737	0.483	0.0553	16.9
2 M7R70	0	2.806	0.286	0.140	20.1
2 M7R70	5	3.407	0.347	0.140	20.1
2 M7R70	10	4.066	0.414	0.140	20.1

The acceleration time history curves for base motion 2M6R30 and 2M7R70 at ground level, floor level 1 and 2 have been reproduced in Figure 3.3. A complete collection of all acceleration time history curves for the base motions in Table 3.2 can be found in Figure A1 in Appendix A.

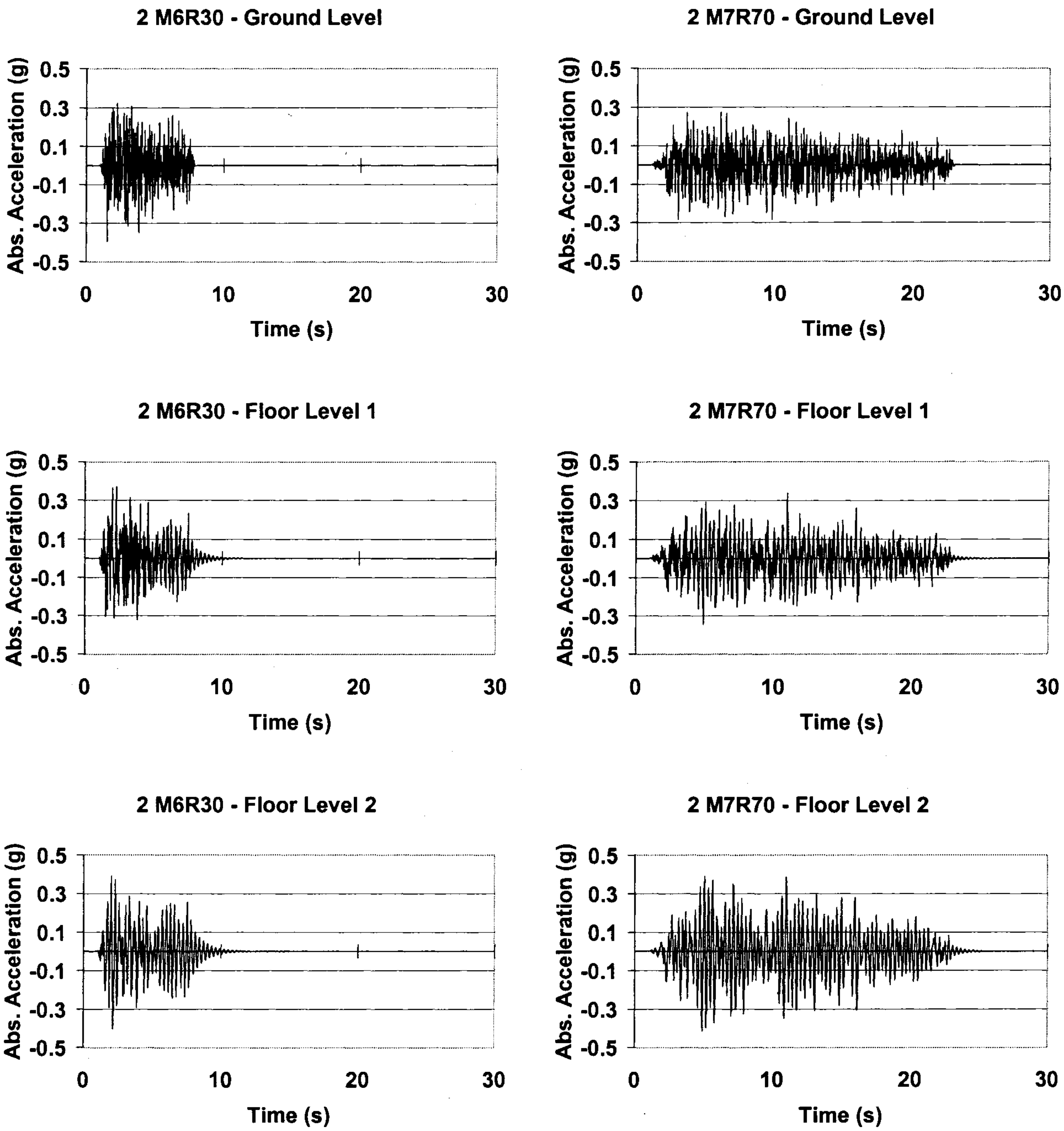


Figure 3.3: Absolute acceleration time history curves for base motions 2M6R30 and 2M7R70 at ground level, floor level 1, and floor level 2

The floor acceleration spectra (FAS) for base motions, as summarized in Table 3.3, were determined as seen in Figure 3.4. Note that base motions at a probability of exceedance of 10 % in 50 years and 2% in 50 years have been produced at different scales for clarity.

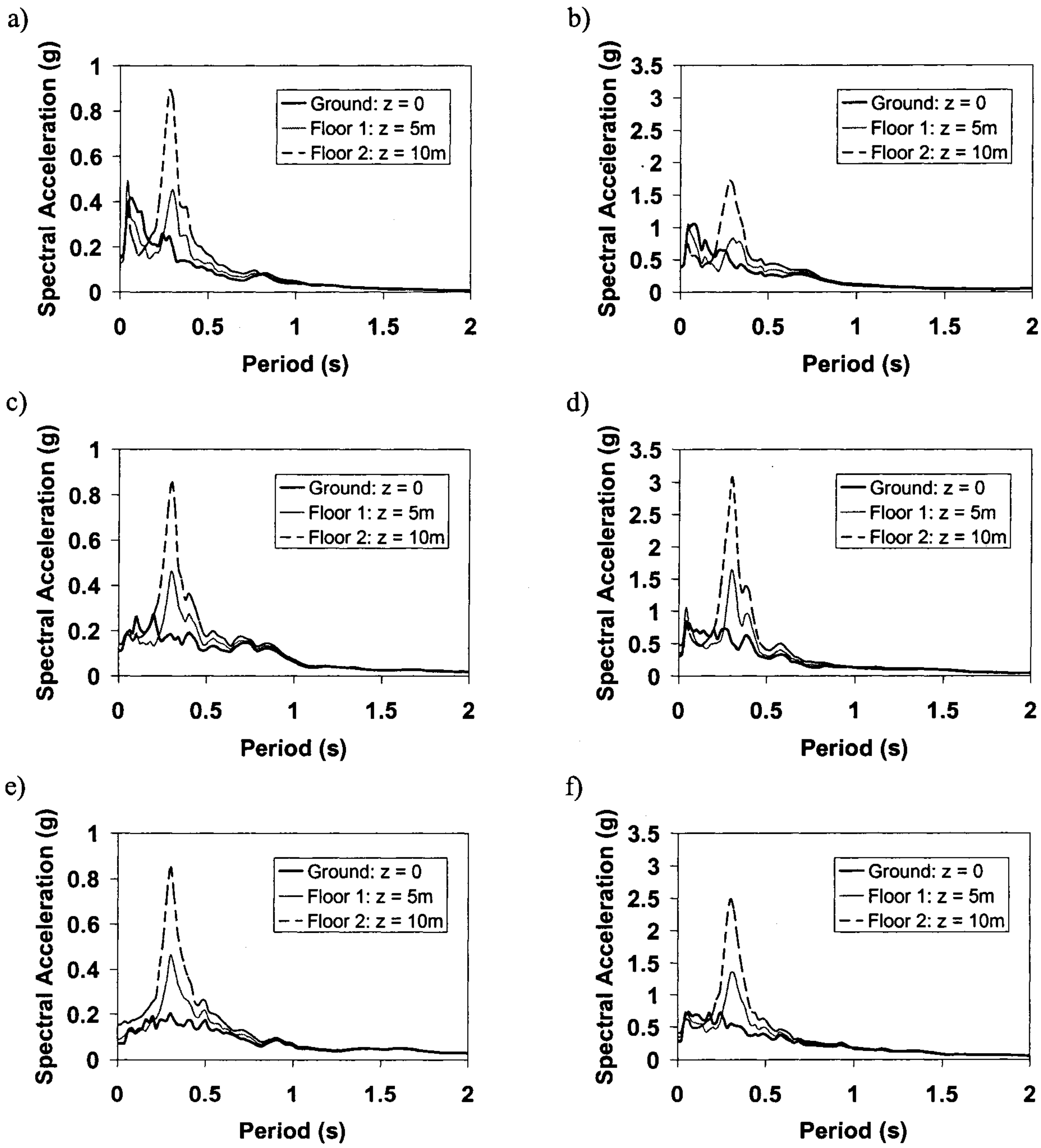


Figure 3.4: Floor acceleration spectra for base motions a) 10 M5.5R30, b) 2 M6R30, c) 10 M7R150, d) 2 M7R50, e) 10 M7R300, and f) 2 M7R70 at ground level, floor level 1, and floor level 2

As can be seen from the acceleration time history curves in Figure 3.3 and the Floor Acceleration Spectra (FAS) in Figure 3.4, the response at upper levels is significantly different from that at the building base ($z = 0$). In addition to changes in intensity, there are significant changes in the frequency content, as expected. Since the effect of the frequency content on unrestrained objects is not well known subsequent case studies will investigate display cases and a shelving unit acceleration time histories at ground level as well as elevations above ground level.

The above FAS provide an indication of the peak accelerations that objects located at a given floor would experience as a function of their fundamental period of vibration. It can be observed that each spectrum has significant peaks at periods corresponding approximately to the fundamental period of vibration of the building of 0.3s.

4 Case Study 1: MBAM Display Cases

The objective of this case study is to investigate the seismic vulnerability of three museum display cases provided by the Musée des Beaux-Arts de Montréal (MBAM). The effects of display case stiffness, earthquake motion characteristics, elevation of floor height, surface friction condition, and art object mass on display case behaviour were investigated to determine the seismic vulnerability of art objects exhibited on these supports. A series of shake table tests were conducted at the Structural Laboratory at École Polytechnique de Montréal for that purpose. Summaries of shake table test results and concurrent discussions are presented throughout this chapter and a detailed collection of the data is attached in Appendix B. Conclusions, recommendations and further research needs follow in Chapter 7.

4.1 DESCRIPTION OF SHAKE TABLE TESTS

4.1.1 Test Specimens

The three display cases tested are shown in Figures 4.1 to 4.3. They are made of high-density fibre board. Their geometries and mass are reported in Table 4.1. Display cases 2 and 3 are symmetric in geometry, whereas display case 1 is constructed so that its supports are asymmetric with respect to the table top. The support conditions are slightly different among the three display cases, as seen in Figure 4.4. While the base of display cases 1 and 3 have been modified with rubber supports, display case 2 consists of a smooth, wooden surface. The display cases are left unrestrained on museum floors. To simulate the surface friction conditions of the museum, hardwood and carpet floors were constructed and bolted on the shake table.

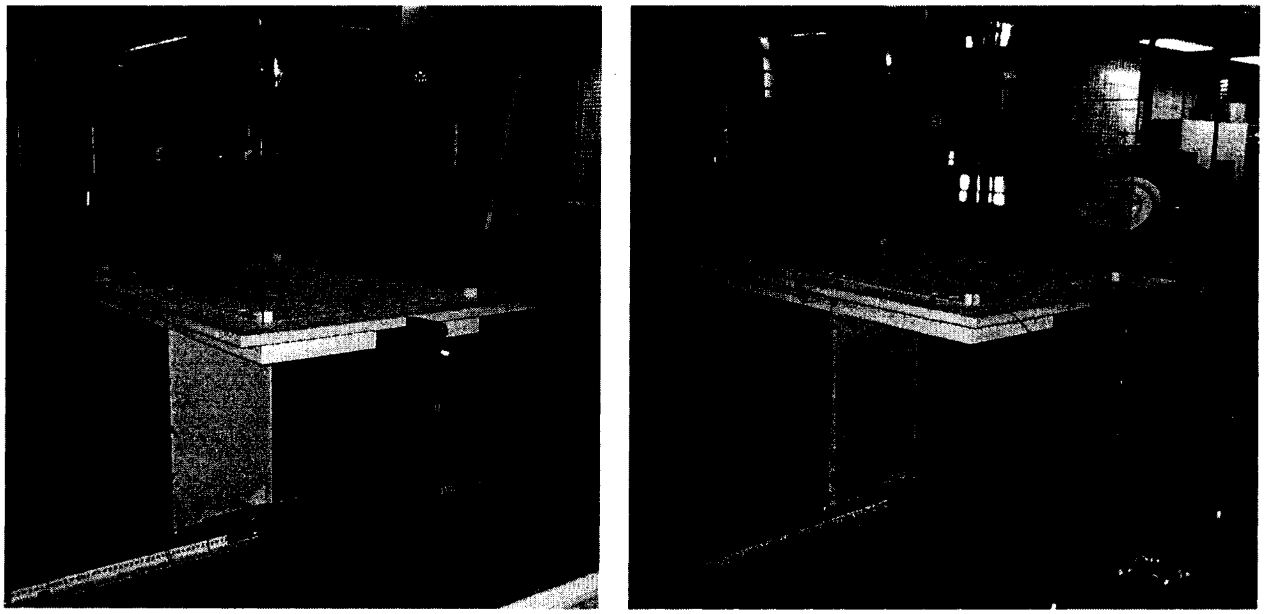


Figure 4.1: Display Case 1

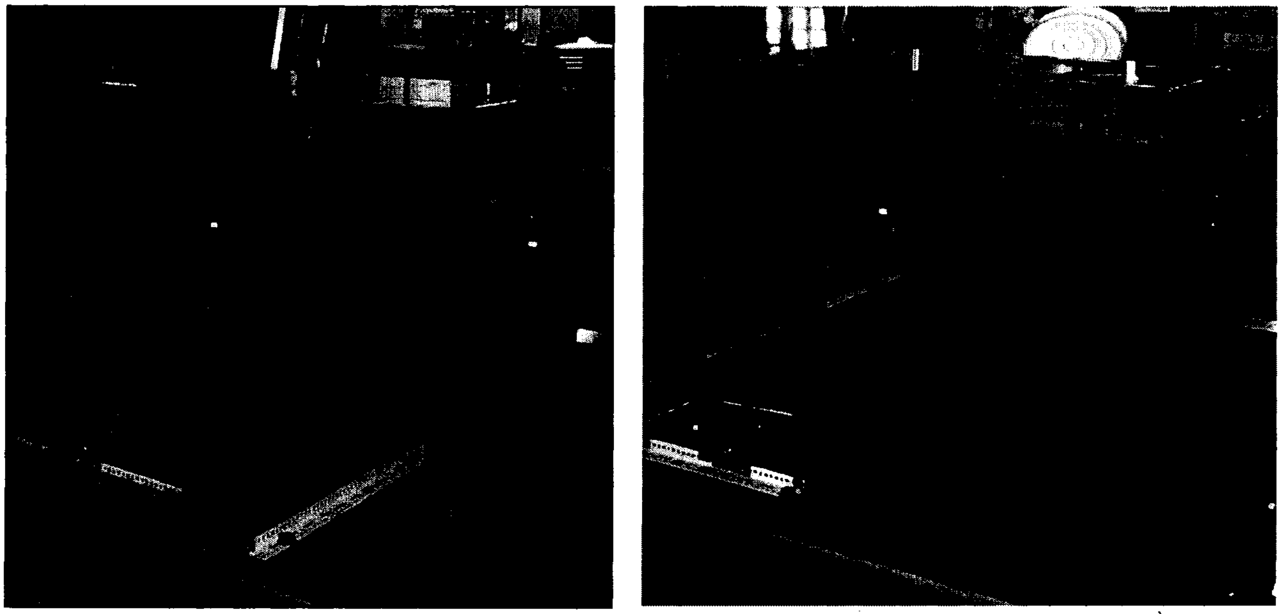


Figure 4.2: Display Case 2

Figure 4.3: Display Case 3

Table 4.1: Display Case Geometry and Mass

	Max. Dimension, Plan View (mm*mm)	Max. Height (mm)		Mass (kg)
Display Case 1	1850*1500	910		120
Plexiglas Cover 1	1390*885	880		27
			Total	**147**
Display Case 2	1590*770	910		55
Plexiglas Cover 2	1580*760	240		15
			Total	**70**
Display Case 3	675*675	1070		45
Plexiglas Cover 3	665*665	565		10
			Total	**55**

a) Display case 1 b) Display case 2 c) Display case 3

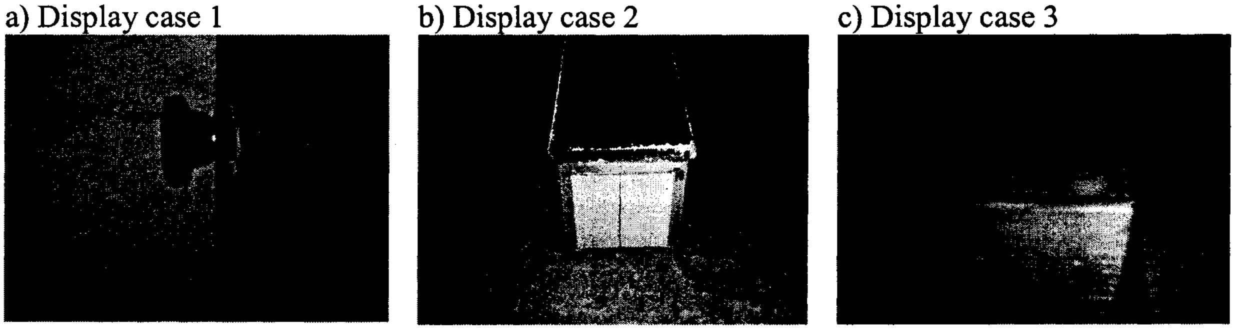


Figure 4.4: Support conditions of display cases 1, 2, and 3

4.1.2 Parametric Study

The following parameters were investigated to gain insight into their impact on the seismic response of the display cases:

Parameter 1: Display Case Geometry (Stiffness)

Three display cases of different geometry were tested to investigate their seismic response and allow for comparison of varying stiffness and dynamic properties.

Parameter 2: Ground Motion Characteristics

The effect of ground motions of different intensity-frequency content was investigated. The ground motions are as presented in Section 3. To reduce the number of test series, time histories shown in Table 3.2 at a probability of exceedance of 2% in 50 years were tested only. Further, this selection is consistent with the 2005 NBCC and results in higher acceleration demands, as seen in Figure 3.4.

Parameter 3: Location (floor elevation) of Display Case

Since many of the display cases are located on floors of the museum above ground level, they are not directly subjected to the base ground motion but rather to the amplified floor motions generated by the dynamic response of the building. To account for the fact that the response of the display cases depends on the floor elevation, floor motions have been simulated at building elevations of 5 m and 10 m. The floor motions were presented in Section 3 and were used as base motion input for display case 2 only.

Parameter 4: Floor Contact Surface Conditions

Two different floor surfaces were investigated to determine their effect on the seismic response of unrestrained display cases. Hardwood as well as carpet floors were constructed to simulate museum floor conditions.

Parameter 5: Art Object Mass

The seismic response of the display cases might be altered depending on the art object mass. Additional masses were therefore placed on the display surface of display case 2. Masses of 10 kg and 20 kg were investigated. This selection has been made because it was assumed that lighter masses will likely not have an effect on display case response and heavier masses are not representative of art objects on such supports. Hereafter, test series conducted with no additional mass, 10 kg masses, and 20 kg masses, are designated M0, M1, and M2 respectively.

4.1.3 Test Sequence

The test sequence was performed as outlined in Table 4.2. Each test series was performed to investigate the effect of the change of a single parameter. The experiments were repeated with the same set up at least three times. Additional test runs were performed, if initial analysis indicated that results did not appear to agree with those previously obtained. Testing emphasis was put on display case 2. Parameters to be tested can be interpreted more easily on display case 2 because of its simpler construction, as opposed to display case 1, which incorporates features that complicate the geometry. Initial free vibration tests determined that display case 2 possesses vibrational properties intermediate of display cases 1 and 3. Therefore, effects of floor elevation and art object mass were only studied on display case 2 to reduce the number of test series to be conducted. Random white noise excitations of increasing amplitude were performed prior to starting the test series to observe the overall behaviour of the display cases and to verify the test setup and instrumentation.

Table 4.2: Shake Table Test Series

Test Series	Display Case	Base Motion	Additional Mass Case
Hardwood Floor			
1	1	2 M6R30	M0
2	1	2 M7R50	M0
3	1	2 M7R70	M0
4	1 – Diagonal Placement	2 M6R30	M0
5	3	2 M6R30	M0
6	3	2 M7R50	M0
7	3	2 M7R70	M0
8	2	2 M6R30	M0
9	2	2 M7R50	M0
10	2	2 M7R70	M0
11	2	2 M6R30 – 1	M0
12	2	2 M6R30 – 2	M0
13	2	2 M7R50 – 1	M0
14	2	2 M7R50 – 2	M0
15	2	2 M7R70 – 1	M0
16	2	2 M7R70 – 2	M0
17	2	2 M6R30	M1
18	2	2 M7R50	M1
19	2	2 M7R70	M1
20	2	2 M6R30	M2
21	2	2 M7R50	M2
22	2	2 M7R70	M2
23	2	2 M7R50 – 1	M2
24	2	2 M7R70 – 2	M2
25	2	2 M7R50 – 1	M1
26	2	2 M7R70 – 2	M1
Carpet			
27	2	2 M6R30	M0
28	2	2 M7R50	M0
29	2	2 M7R70	M0
30	2	2 M6R30 – 1	M0
31	2	2 M6R30 – 2	M0

Table 4.2: Shake Table Test Series (Continued)

32	2	2 M7R50 – 1	M0
33	2	2 M7R50 – 2	M0
34	2	2 M7R70 - 1	M0
35	2	2 M7R70 – 2	M0
36	2	2 M6R30	M1
37	2	2 M7R50	M1
38	2	2 M7R70	M1
39	2	2 M6R30	M2
40	2	2 M7R50	M2
41	2	2 M7R70	M2
42	2	2 M7R50 – 1	M2
43	2	2 M7R70 – 2	M2
44	2	2 M7R50 – 1	M1
45	2	2 M7R70 – 2	M1
46	1	2 M6R30	M0
47	1	2 M7R50	M0
48	1	2 M7R70	M0
49	3	2 M6R30	M0
50	3	2 M7R50	M0
51	3	2 M7R70	M0

4.2 LABORATORY EQUIPMENT AND MATERIALS

4.2.1 Earthquake Simulation Facility

The seismic tests were conducted on the uniaxial shake table at the Structural Laboratory of École Polytechnique de Montréal. The main characteristics of the shake table can be obtained from Table 4.3.

Table 4.3: Shake Table Characteristics

Manufacturer	MTS Systems
Plan Dimensions	3353 mm x 3353 mm (128" x 128")
Bearing System	Four low-friction hydrostatic bearings
Frequency range	0-60 Hz
Maximum displacement	± 125 mm
Maximum speed	1.0 m/s (at full capacity); 1.3 m/s (empty)
Maximum acceleration	± 1.0 g (at full capacity); ± 3.0 g (empty)
Control System	MTS 469

4.2.2 Experimental Setup

Two floors, one having a hardwood and the other a carpet surface, were constructed to simulate museum conditions. These surfaces were mounted on ¾" thick plywood boards which were then bolted to the shake table. The floors covered an area of 8'* 8' (total of 64ft^2) to account for sliding of the unrestrained display cases. The specimens were placed on top of the shake table as indicated in Figure 4.5, where unsymmetrical display cases were positioned so that the short dimension was in the direction of shake table excitation.

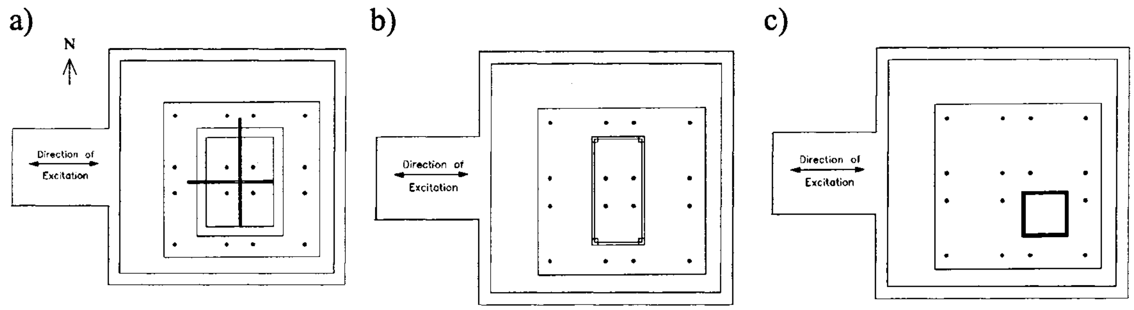


Figure 4.5: Plan view for setup of display cases a) 1, b) 2, and c) 3 on the shake table

4.2.3 Instrumentation

Instrumentation for each shake table test included accelerometers to determine acceleration responses and Linear Variable Displacement Transducers (LVDTs) to determine displacements. A film camera was set up to record each test series. The responses were recorded with a 10V DC data acquisition system. The location of the accelerometers and LVDTs is identified in Figures 4.6 to 4.8. Positive directions for accelerations and displacements in the horizontal plane were in the west and south directions for parallel and perpendicular displacements respectively, corresponding to the north arrow in Figure 4.5, and in the upward direction for the vertical plane.

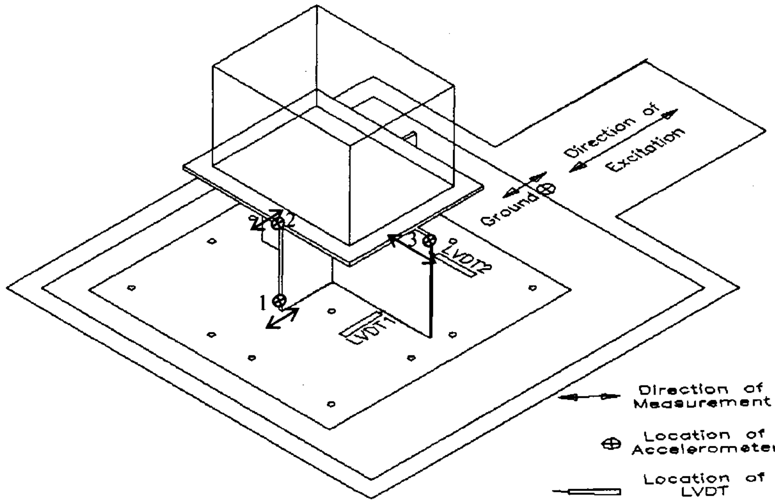


Figure 4.6: Instrumentation for display case 1

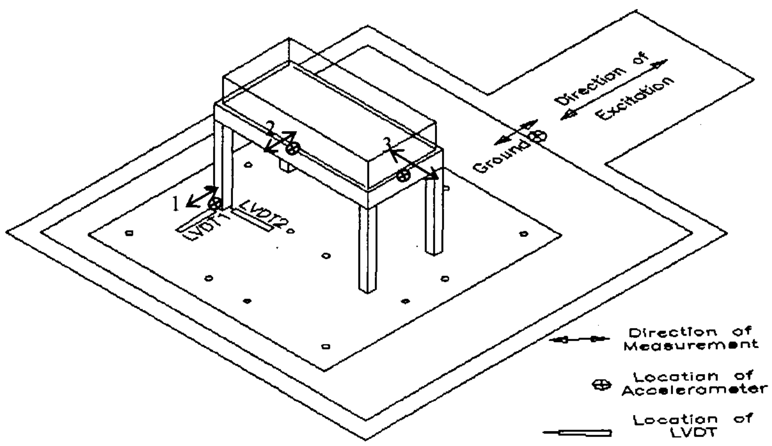


Figure 4.7: Instrumentation for display case 2

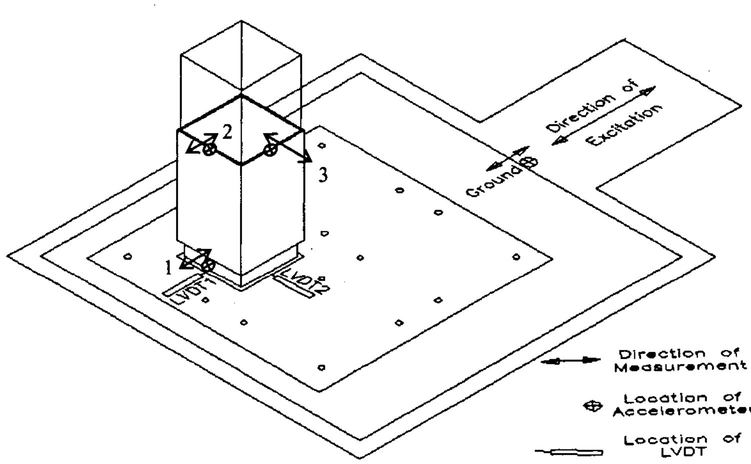


Figure 4.8: Instrumentation for display case 3

The accelerometers were installed to measure the absolute horizontal acceleration of the shake table and to monitor the acceleration response of the display cases at critical locations. Accelerometers of range +/- 2 g were installed on the shake table (labeled Ground Accel.) and at the base of the display case (labeled Accel.1), just above the floor surface. Accelerometers of range +/- 5 g were installed at the top of the display cases in the horizontal plane in the direction of excitation (labeled Accel.2) and perpendicular (labeled Accel.3) to it. For display cases tested on carpet, a third accelerometer of range +/- 5 g was installed at the top of the display cases (labeled Accel.4) to determine the vertical acceleration response to monitor the rocking response. The acceleration response of greatest interest is that measured at the top of the display case, at the location of the art object display, in the direction of shake table excitation. The results of the remaining accelerometers are important to monitor the overall behaviour of the display cases.

An LVDT is a device whose output signal represents the distance an object has displaced in one direction from a fixed reference point. Even though the shake table excitation is in one direction only, sliding and/or rocking of the display cases can occur in two horizontal directions. LVDTs were therefore installed parallel and perpendicular to the horizontal base motion. Small magnets were installed at the end of the LVDTs and steel plates were fastened to the display cases as target points, as seen in Figure 4.9. This ensured that LVDTs remain undamaged due to sideways motion of the display case in motion. The LVDTs were fixed to the floor surfaces of the shake table to determine the relative displacement between the display case and the shake table.

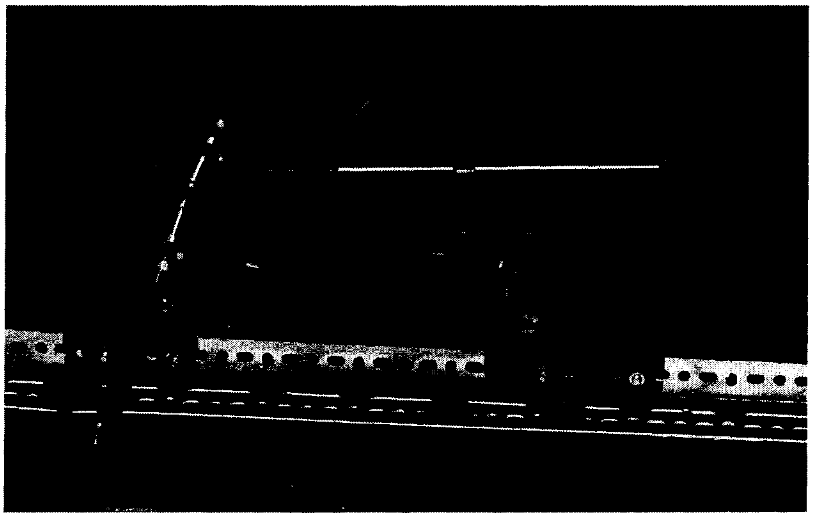


Figure 4.9: Installation of LVDTs, modified with magnets

4.3 FREE VIBRATION TESTS

Free vibration tests were conducted prior to shake table testing to obtain the fundamental frequency of vibration of the display cases. The tests were performed with display cases left unrestrained on each floor surface. An impact force was applied horizontally at the top of the display cases to monitor acceleration responses in directions parallel (Accel.2) and perpendicular (Accel.3) to the impact. Of interest is the acceleration response parallel to the weak axis of the display cases, corresponding to the direction of excitation of subsequent experimentation. Based on the acceleration response of the display case in free vibration, at an instant after the impact (Figure 4.10a), it was possible to obtain the fundamental frequency of vibration according to the peak of a Fast Fourier Transform (FFT) of the response signal. Figure 4.10b shows an example of a FFT performed on the response of display case 3. The FFT, obtained with the software SeismoSignal (Seismosoft 2004), shows how the amplitude of the ground motion is distributed with respect to the frequency. The parameter in the frequency domain is related to the amplitude of the ground motion by a single product, which was not defined in

SeismoSignal. The responses of display cases 1 and 2 did not result in one peak, but often in two or three peaks. Several runs were conducted for each display case on both floor surfaces and mean values were obtained for the fundamental frequencies as summarized in Table 4.4. The measured frequencies show that display case 1 is the most flexible, whereas display case 3 is the most rigid. The frequencies obtained for a range of 3.6 Hz to 13.7 Hz fall within a range that is excited by earthquakes, generally of a frequency content of up to 10 Hz. The sensitivity of the display cases was thus expected to vary. Differences between frequencies obtained for wood as well as carpet surfaces further predict varying display case responses.

Table 4.4: Summary of fundamental frequencies for display cases due to impact in weak direction

	Wood Surface	Carpet Surface
Display Case 1	3.6 Hz	4.5 Hz
Display Case 2	7.0 Hz	6.3 Hz
Display Case 3	13.7 Hz	10.7 Hz

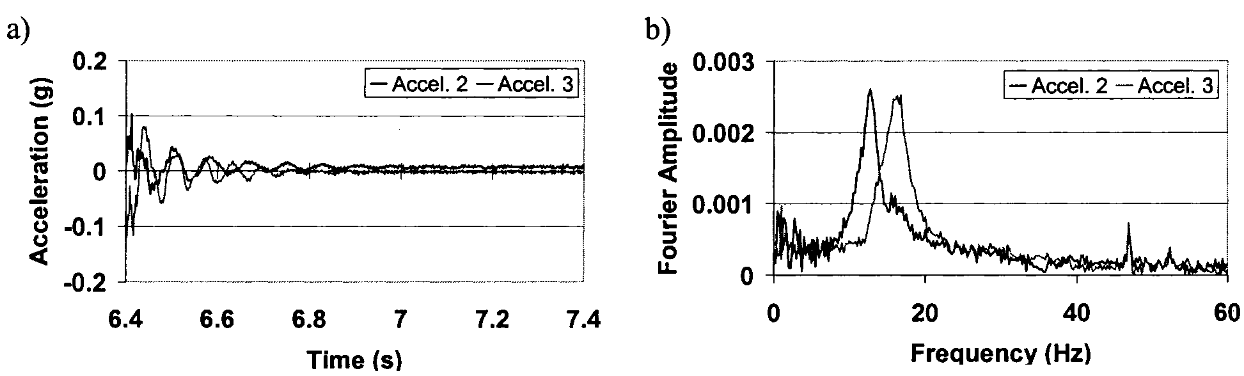


Figure 4.10: a) Acceleration response and b) corresponding FFT for display case 3 in free vibration on hardwood

4.4 TEST RESULTS

The accelerometer and LVDT measurements characterize the dynamic behaviour of each display case. The analysis and interpretation of such data are crucial for the validation of the experiments. To investigate the response of the display cases, accelerations were measured on the shake table (Ground Accel.), at the base of the display cases (Accel.1), and at the top of the display cases in directions parallel (Accel.2) and perpendicular (Accel.3) to the direction of excitation. The most critical acceleration for investigating the seismic vulnerability of art objects is at the top of the display, since art objects are exhibited at that location. The results which address effects of base motions, floor elevation, and art object mass on display cases will initially be investigated with hardwood floor conditions. The subsequent sections will investigate the effect of the same parameters with carpet conditions. Each of these sections will highlight pertinent points of discussion. Before proceeding with the presentation of data, comments will be made on the data processing of results and the effect of shake table tuning. Both issues directly affect the results and interpretation thereof.

Data Processing

At first, the software SeismoSignal (Seismosoft 2004) has been used to filter noise at frequencies of 30 Hz, 40 Hz, and 50 Hz. These lowpass filters had a strong impact on the resulting responses. The acceleration peaks were reduced by approximately 50%, and in some cases they were completely removed. It has then been decided to leave the signals unfiltered.

Effect of Shake Table Tuning

Comparing the peak accelerations obtained from the accelerometer installed directly on the shake table to those of the input signals, it was found that the output values were consistently higher. A FFT was performed on both the input and output signals of the base motions used in this experiment. Superimposing these curves in Figure 4.11 demonstrates that these signals diverge from each other in the frequency range of approximately 20 – 30 Hz. This discrepancy is due to the effect of tuning, causing amplification of the output signal. Although some divergence between the input and output signals can be expected, the accuracy of future experiments can likely be improved with improved shake table maintenance and installation procedures.

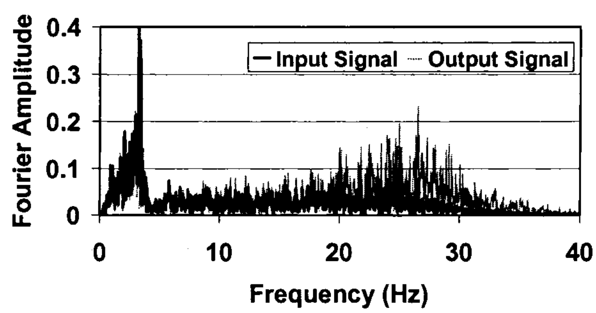


Figure 4.11: FFT for 2M7R70-1 for shake table input and output signals

4.4.1 Display Case Excitation based on Montréal Seismic Hazard

The frequency content of the excitation has a large impact on the display case response. Different intensity-frequency base motions, selected to match short-period, intermediate-period, and long-period seismic hazards for Montréal, as outlined in Chapter 3, were tested at three building levels. FFT analysis was performed on the output shake table accelerations to determine the frequency content of the display case excitation, as depicted in Figures 4.12 to 4.14 for base motions at different building elevations.

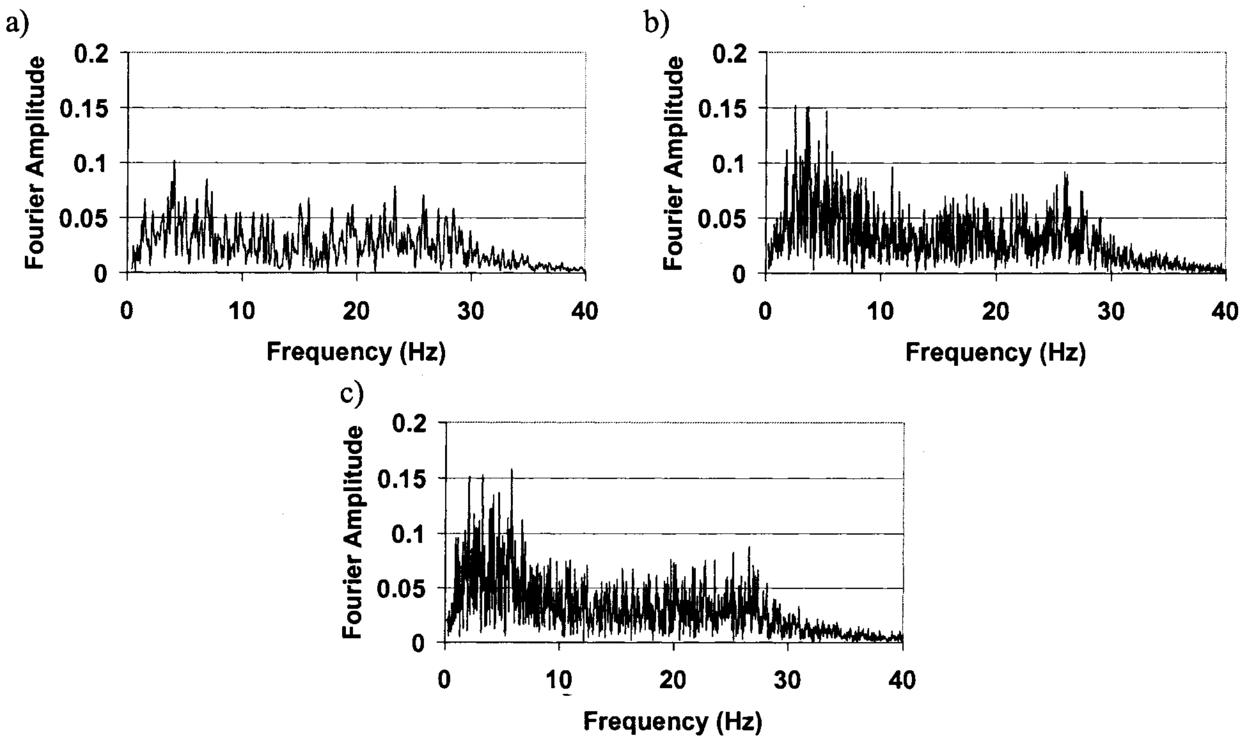


Figure 4.12: FFT of shake table accelerations at ground level for base motions a) 2M6R30, b) 2M7R50, and c) 2M7R70

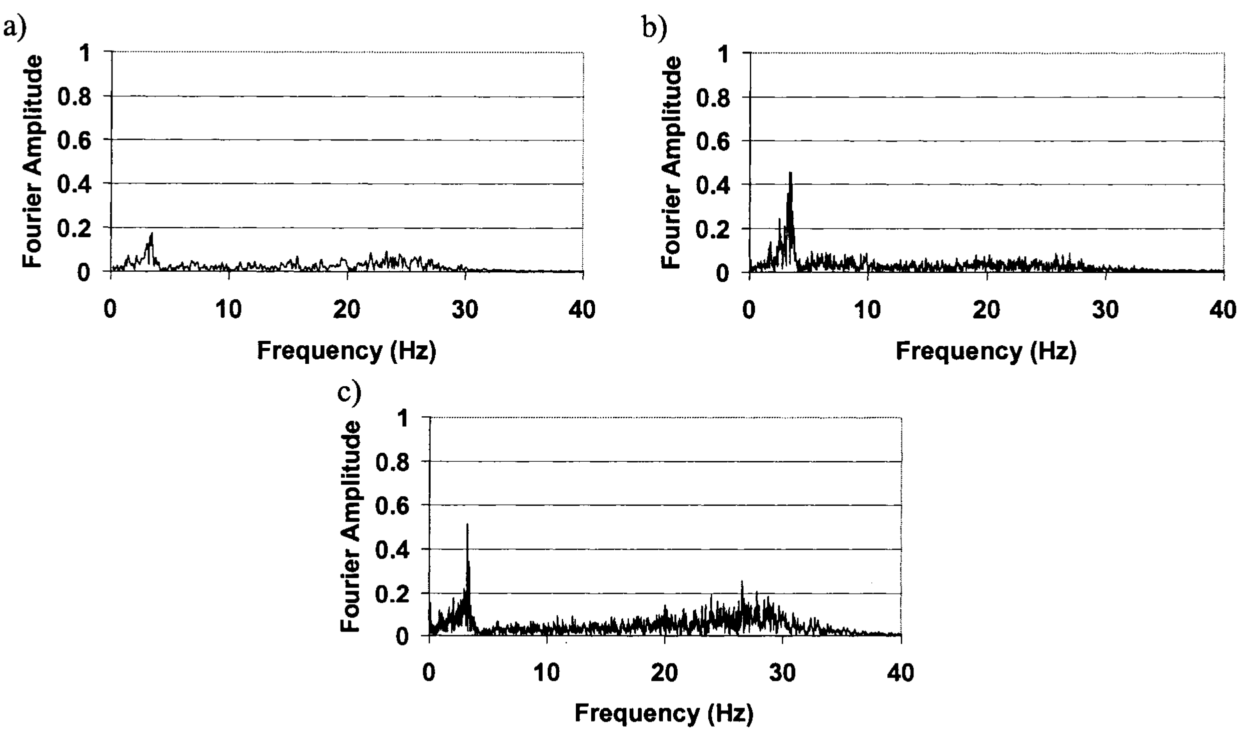


Figure 4.13: FFT of shake table accelerations at floor level 1 for base motions a) 2M6R30, b) 2M7R50, and c) 2M7R70

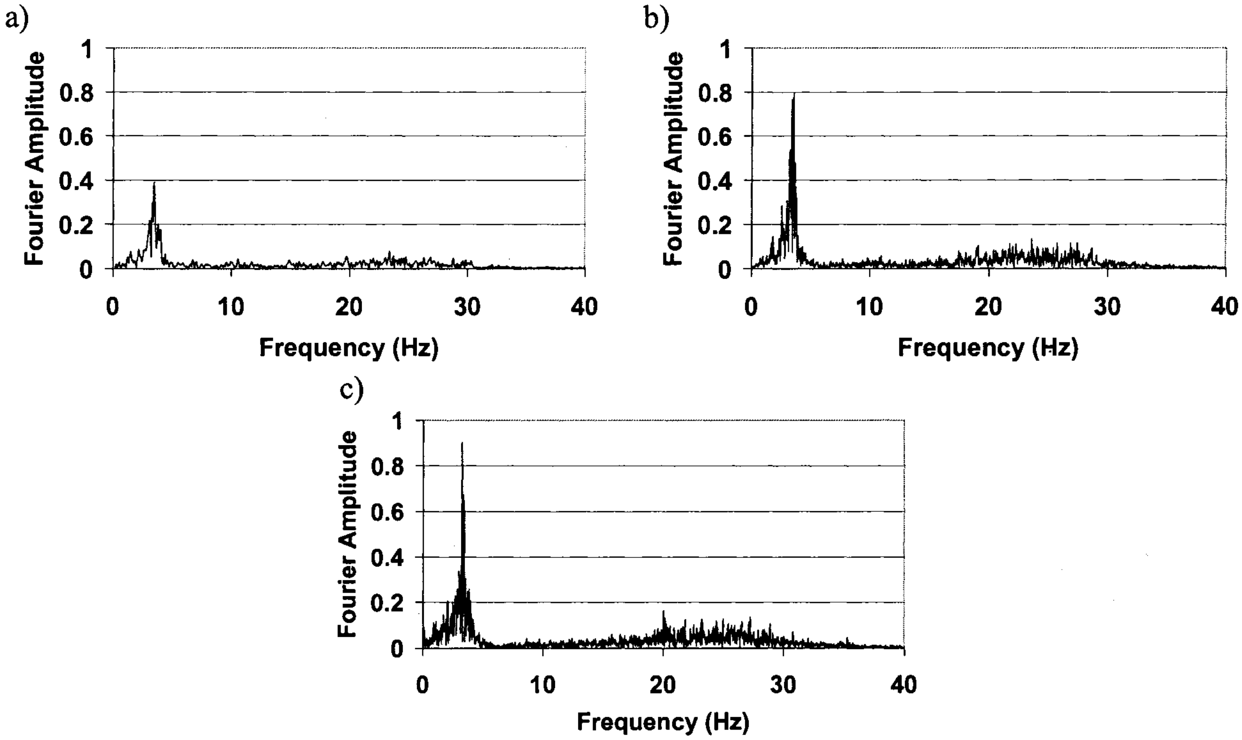


Figure 4.14: FFT of shake table accelerations at floor level 2 for base motions a) 2M6R30, b) 2M7R50, and c) 2M7R70

Figures 4.12 to 4.14 demonstrate the variation in acceleration frequency content at different floor elevations due to building filtering effects. For base signals at ground level, the frequency content extends over a broader frequency range, as seen in Figure 4.12. In comparison, Figures 4.13 and 4.14 demonstrate that frequencies have been filtered at floor elevations and that peaks emerge corresponding to the dynamic properties of the building. In general, it can be observed that base motions 2M7R50 and 2M7R70 are similar in frequency content. Note that Figure 4.12 depicts the FFT for ground level base motions at a different scale.

4.4.2 Base Motion Effects for Display Cases on Hardwood Floor

The results for display cases resting unrestrained on a hardwood floor are examined for different base motions, as summarized in Table 4.5. The values in brackets specify the ratio of each mean acceleration to the input acceleration (Ground Accel.). Display case 1 has a more complex asymmetric geometry that may cause torsional effects. These were examined by aligning the diagonal of the display case table top with the diagonal of the shake table. This additional test series is labeled 2M6R30-D in Table 4.5.

Table 4.5: Display case responses to different base motions on hardwood floor

Base Motion	Mean Ground Accel. (g)	Mean Accel. 1 (g)	Mean Accel. 2 (g)	Mean Accel. 3 (g)	Max. Displ. LVDT1 (mm)	Max. Displ. LVDT2 (mm)
Display Case 1						
2 M6R30	0.69	0.80(1.2)	0.36(0.5)	0.36(0.5)	2.0	0.2
2 M7R50	0.38	0.81(2.1)	0.37(1.0)	0.33(0.9)	2.8	0.3
2 M7R70	0.38	0.71(1.9)	0.32(0.8)	0.40(1.1)	1.9	0.2
2 M6R30-D	0.49	0.75(1.5)	0.95(1.9)	0.50(1.0)	5.7	4.9
Display Case 2						
2 M6R30	0.49	1.34(2.7)	0.77(1.6)	0.32(0.7)	1.6	0.6
2 M7R50	0.37	0.37(1.0)	0.86(2.3)	0.38(1.0)	0.9	0.3
2 M7R70	0.33	1.54(4.7)	0.98(3.0)	0.31(0.9)	1.9	1.0
Display Case 3						
2 M6R30	0.66	2.83(4.3)	0.63(1.0)	0.35(0.5)	1.4	0.4
2 M7R50	0.48	2.61(5.4)	0.61(1.3)	0.33(0.7)	2.4	0.2
2 M7R70	0.42	3.28(7.8)	0.61(1.5)	0.39(1.0)	1.0	0.5

The displacements recorded for the display cases were in the range of 0.2 to 2.8 mm. This range indicates that the displacements were not significant and that the display cases did not slide under different base motion input at ground level.

Table 4.5 indicates that peak accelerations occurred at the base of the display cases (Accel.1), just above the floor surface. These peak accelerations were the result of impacts between the unrestrained display case and the hardwood surface. The mean acceleration experienced at the base of display cases 1, 2, and 3 were 0.77 g, 1.08 g, and 2.91 g respectively. This corresponds to increases in accelerations with respect to the input by factors of 1.7, 2.8, and 5.8 respectively. Differences in display case dynamic and geometric properties as well as support conditions contribute to this variation in response. The energy dissipated during the impact between the display case and the floor surface is described by the restitution coefficient. Zhu and Soong (1998) conducted numerical analyses to quantify the possibility of toppling of rigid bodies due to base excitation. It was found that the toppling reliability is related to the restitution coefficient so that even under low level base excitations rigid bodies can overturn if the input energy is greater than the dissipated energy.

In general, results reveal that peak accelerations at the base of the display cases (Accel. 1) were higher than the corresponding peaks at the top of the display cases (Accel. 2). The highest reduction in peak acceleration was experienced for display case 3, at an average of 79%. Display case 2 experienced the least, at an average of 39%, while it was 55% for display case 1. The level of acceleration reduction is likely the result of damping effects inherent to each display case.

The greatest accelerations at the top (Accel. 2), at the level of art object display, were recorded for display case 2 at 0.98 g, while they were the least for display case 1 at 0.32 g, in the case of symmetric arrangement. The average acceleration-input ratios, shown in brackets, indicate that the response at the top of display case 1 had reduced to 0.8 of the input acceleration, while it was amplified at a ratio of 2.3 for display case 2 and at a lower ratio of 1.2 for display case 3. During shake table testing it was clearly observed that the connections between the legs and the table top of display case 2 were very flexible causing the table top to sway back and forth. The high accelerations induced at that location of mass concentration may thus be explained.

Even though display case 1 experienced the lowest accelerations at the critical location at the top of the display, the response was significantly increased when it was arranged diagonally to the direction of excitation. As opposed to acceleration reductions at the top with respect to the input, accelerations were amplified by a factor of 1.9. Further, the increased displacement of 5.7 mm recorded for this arrangement as opposed to the previously maximum displacement of 2.8 mm suggests that the display case started to slide. These results indicate that torsional effects dominate in the case of excitation at an angle to the principal axes, and exacerbate the response of a display case with asymmetric geometry.

With regard to the effect of varying seismic motions, it can be noted that the overall response of the display cases was similar under different base motions. Even though the peak shake table acceleration was recorded for base motion 2M6R30, the resulting responses were similar to those of the two remaining base motions. Referring to Figure 4.12, the difference in responses due to base motion 2M6R30 can be explained given that the frequency content of 2M6R30 is less than that of base motions 2M7R50 and 2M7R70, which are similar in shape and generally resulted in similar acceleration responses.

4.4.3 Effect of Floor Elevation for Display Case 2 on Hardwood Floor

The results of the test series conducted to investigate the effect of location of floor elevation for display case 2 on hardwood floor are summarized in Table 4.6. The values in brackets specify the ratio of each mean acceleration to the input acceleration.

Table 4.6: Effect of location (building elevation) on display case 2 response on hardwood floor

Base Motion	Mean Ground Accel. (g)	Mean Accel.1 (g)	Mean Accel.2 (g)	Mean Accel.3 (g)	Max. Displ. LVDT1 (mm)	Max. Displ. LVDT2 (mm)
Ground Level: z = 0 m						
2 M6R30	0.49	1.34(2.7)	0.77(1.6)	0.32(0.7)	1.6	0.6
2 M7R50	0.37	0.37(1.0)	0.86(2.3)	0.38(1.0)	0.9	0.3
2 M7R70	0.33	1.54(4.7)	0.98(3.0)	0.31(0.9)	1.9	1.0
Floor Level 1: z = 5 m						
2 M6R30 -1	0.42	1.20(2.9)	0.51(1.2)	0.18(0.4)	1.2	0.4
2 M7R50 -1	0.44	2.41(5.5)	1.18(2.7)	0.71(1.6)	7.7	2.1
2 M7R70- 1	0.51	1.29(2.5)	1.07(2.1)	0.43(0.8)	2.4	0.7
Floor Level 2: z = 10 m						
2 M6R30- 2	0.63	3.41(5.4)	1.90(3.0)	0.67(1.1)	16.5	3.6
2 M7R50- 2	0.63	4.08(6.5)	2.07(3.3)	1.18(1.9)	35.1	12.5
2 M7R70- 2	0.52	4.47(8.6)	1.74(3.4)	0.96(1.9)	15.3	8.0

The experiments demonstrated that the response of the display case on hardwood floor is governed by sliding. Whereas maximum displacements of 2 mm at ground level were assumed to be insignificant, maximum displacements of 7.7 mm and 35.1 mm for floor levels 1 and 2 indicate that sliding was initiated.

Maximum accelerations were recorded at the base of the display case. The average acceleration-input ratios, shown in brackets, indicate that the acceleration response at the top had increased by a factor of 2.3 with respect to the input when display case 2 was located at ground level, compared to an amplification factor of 3.2 when it was located on floor level 2. In addition, the acceleration and displacement responses in the direction perpendicular to the direction of excitation (Accel.3, LVDT2) had increased by 63% and 90% respectively at floor level 2 compared to ground level.

Figure 4.15 depicts time history curves for the acceleration and displacement responses of display case 2 at floor level 2. It can be observed that peak accelerations at the top of the display case (Accel.2 and Accel.3) and sliding correspond to locations of peak accelerations at the base of the display case (Accel.1). Further, peak accelerations at the top of the display case have been filtered significantly with respect to the base.

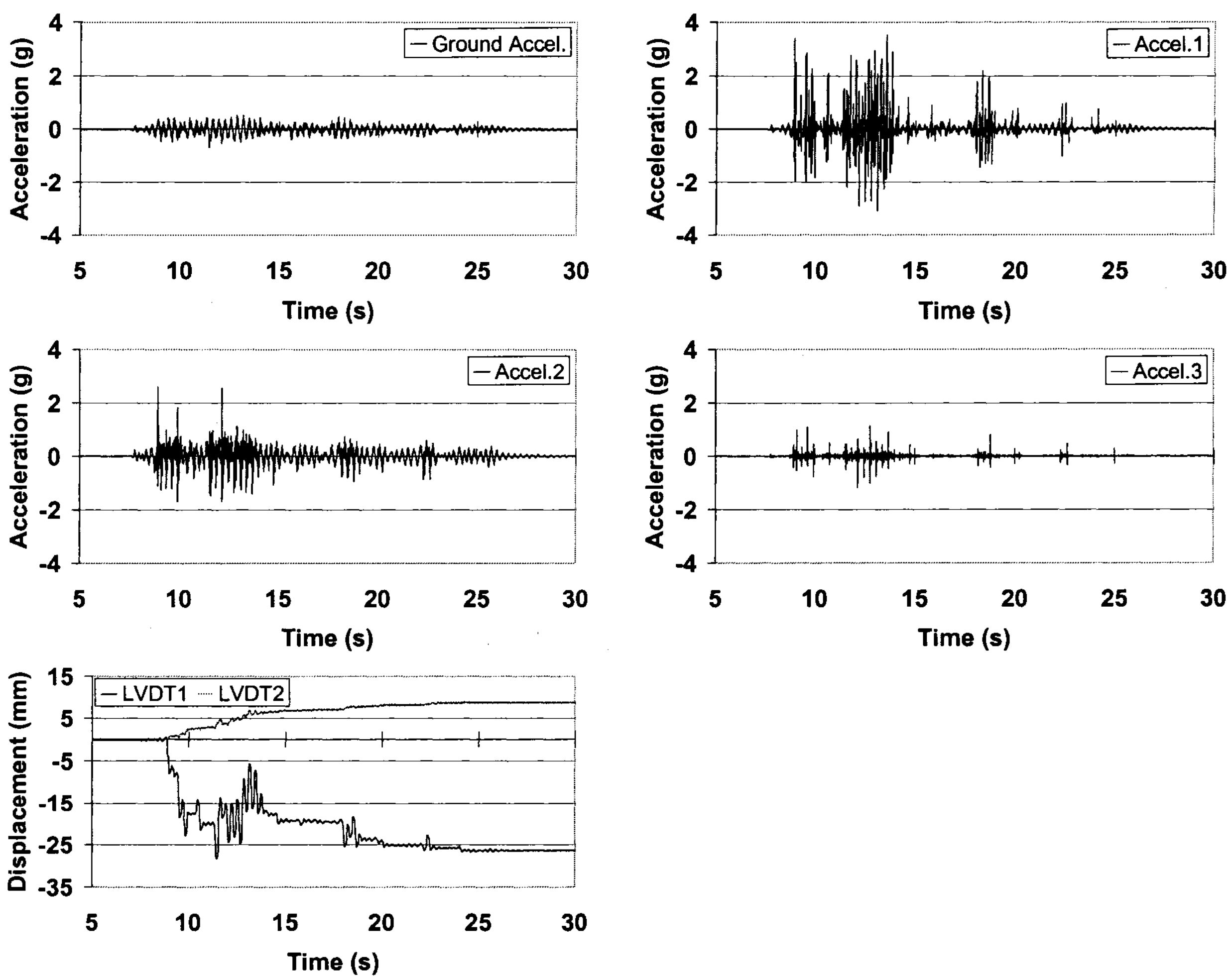


Figure 4.15: Time history response curves of display case 2 subjected to ground motion 2M7R50 at floor elevation 2

While the display case responses increased significantly for base motions at floor level 2, the same trend was not necessarily observed at floor level 1. Table 3.2 indicates that the peak acceleration for base motion 2M6R30 at floor elevation 1 has decreased. The FFT curves obtained for the base motions in Figure 4.12 further emphasize that the frequency content has changed at different floor elevations. As expected, both peak accelerations and the frequency content of excitation affect the display case response.

Research has indicated that the sliding motion is sensitive to the frequency content of its input excitation (Augusti and Ciampoli 1992, Lopez Garcia and Soong 2003). Results in Table 4.6 indicate that the intensity of input acceleration (Ground Accel.) had increased from level 1 to level 2 on average by 22%, while the sliding displacements had increased on average by 85%. This shows that the sliding response was amplified at floors of increased building elevation, corresponding to floor motions where the frequency content has been filtered due to the dynamic building response. Hence, sliding is particularly sensitive to the frequency content of excitation.

4.4.4 Effect of Art Object Mass for Display Case on Hardwood Floor

The results of the test series conducted to investigate the effect of art object mass on display case 2 with hardwood floor conditions are as indicated in Table 4.7. The values in brackets specify the ratio of each mean acceleration to the input acceleration (Ground Accel.).

Table 4.7: Effect of art object mass on display case response with hardwood floor

Ground Motion	Mean Ground Accel. (g)	Mean Accel. 1 (g)	Mean Accel. 2 (g)	Mean Accel. 3 (g)	Max. Displ. LVDT 1 (mm)	Max. Displ. LVDT 2 (mm)
No additional mass added (M0)						
2 M6R30	0.49	1.34(2.7)	0.77(1.6)	0.32(0.7)	1.6	0.6
2 M7R50	0.37	0.37(1.0)	0.86(2.3)	0.38(1.0)	0.9	0.3
2 M7R70	0.33	1.54(4.7)	0.98(3.0)	0.31(0.9)	1.9	1.0
Additional mass of 10 kg added (M1)						
2 M6R30	0.61	1.54(2.5)	0.57(0.9)	0.12(0.2)	3.0	0.7
2 M7R50	0.63	0.61(1.0)	0.56(0.9)	0.14(0.2)	0.7	0.2
2 M7R70	0.50	0.88(1.8)	0.57(1.1)	0.11(0.2)	1.1	0.4
Additional mass of 20 kg added (M2)						
2 M6R30	0.69	1.42(2.1)	0.97(1.4)	0.49(0.7)	2.0	0.3
2 M7R50	0.58	0.64(1.1)	1.12(1.9)	0.36(0.6)	0.9	0.3
2 M7R70	0.52	0.58(1.1)	0.90(1.7)	0.33(0.6)	0.8	0.5

When no mass was added, the acceleration at the top had increased on average by a factor of 2.3 with respect to the input acceleration. In comparison, the response was not modified when a mass of 10 kg was added and modified by a factor of 1.7 when a mass of 20 kg was added. Adding mass to a structure had the effect of reducing its frequency, if the stiffness was kept constant. The frequency content of accelerations at the location of art object display (Accel. 2) was compared for the different added masses. Amplifications were observed at slightly lower frequencies, which explain the changes in results.

4.4.5 Base Motion Effects for Display Cases on Carpet Floor

This section presents results obtained from investigating the same parameters as described in Section 4.4.2, however carpet floors were used summarized in Table 4.8. The values in brackets specify the ratio of each mean acceleration to the input acceleration (Ground Accel.). Comments on the variation of the frictional coefficient are thus made by comparing results of test series on carpet to those conducted on hardwood floor. Testing of display cases on a carpet surface revealed that display cases experience significant rocking. It was thus deemed necessary to install an additional accelerometer (Accel. 4) at the top of the display cases to measure the vertical acceleration response.

Table 4.8: Effect of carpet surface condition

Base Motion	Mean Ground Accel. (g)	Mean Accel. 1 (g)	Mean Accel. 2 (g)	Mean Accel. 3 (g)	Mean Accel.4 (g)	Max. Displ. LVDT1 (mm)	Max. Displ. LVDT2 (mm)
Display case 1							
2 M6R30	0.57	0.55(1.0)	0.45(0.8)	0.18(0.3)	0.78(1.4)	1.29	0.3
2 M7R50	0.49	0.61(1.2)	0.44(0.9)	0.14(0.3)	0.84(1.7)	1.58	0.2
2 M7R70	0.39	0.40(1.0)	0.49(1.3)	0.11(0.4)	0.49(1.3)	1.4	0.3
Display case 2							
2 M6R30	0.55	0.49(0.9)	0.64(1.2)	0.35(0.6)	0.30(0.6)	1.2	0.4
2 M7R50	0.45	0.93(2.1)	1.02(2.3)	0.22(0.5)	0.25(0.6)	2.0	0.82
2 M7R70	0.39	0.59(1.5)	0.57(1.5)	0.13(0.3)	0.11(0.3)	0.8	0.2
Display case 3							
2 M6R30	0.52	2.02(3.9)	0.77(1.5)	0.45(0.9)	2.73(5.3)	0.4	0.13
2 M7R50	0.41	2.10(5.1)	0.84(2.1)	0.40(1.0)	2.62(6.4)	0.4	0.1
2 M7R70	0.38	1.80(4.7)	0.72(1.9)	0.43(1.1)	2.69(7.1)	0.4	0.1

Changes in acceleration and displacement responses between display cases tested on carpet versus hardwood floor are due to surface contact conditions at the base. Figure 4.16 investigates the acceleration response and frequency content at that location.

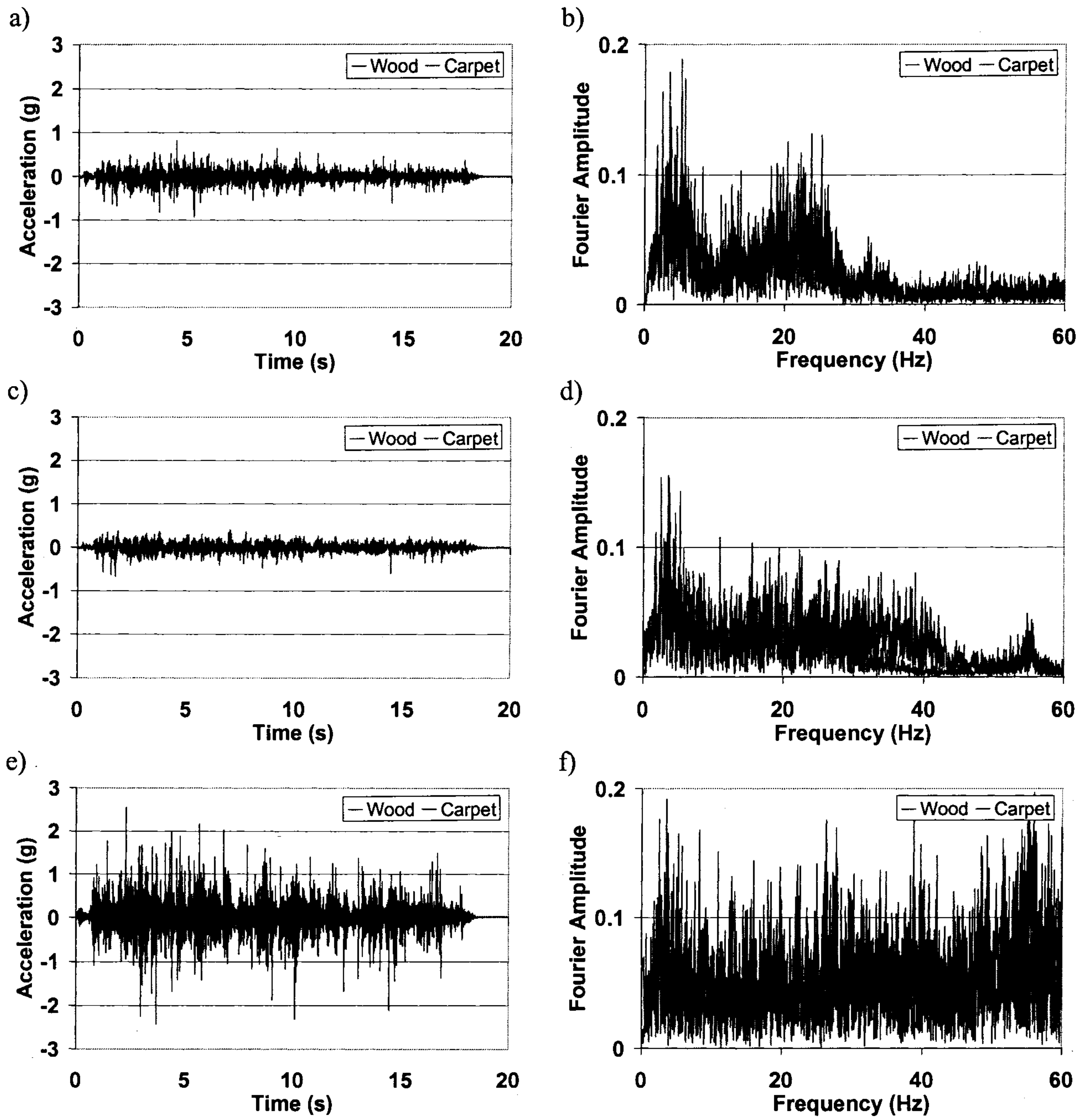


Figure 4.16: Acceleration response at the base (Accel. 1) of display case a) 1, c) 2, and e) 3 and corresponding FFT for display case b) 1, d) 2, and f) 3 for carpet and wood surface conditions due to base motion 2M7R50

By comparing Table 4.8 (carpet) to Table 4.5 (hardwood floor) and examining Figure 4.16, it can be observed that peak accelerations at the display case base (Accel.1) were less for display cases tested on carpet than on hardwood floor. The accelerations experienced at that location are partly the result of display case impact with the floor surface. The impact on hardwood surface is expected to be higher than on carpet, where damping effects of a softer surface lead to reduced acceleration responses at the base of the display cases. Carpet represents a floor condition of increased friction compared to hardwood. Hence increased friction forces develop at the contact between the support and the floor surface. It can thus be assumed that the different display case support conditions, as seen in Figure 4.4, and display case dynamic properties contribute largely to the variation in acceleration response and frequency content directly above the surface between display cases, as seen in Figure 4.16. Display case 3, which rocked vigorously during testing, not only experienced the maximum acceleration response at the base, but spikes of increased intensity were consistently present. A similar acceleration response of lower intensity can be observed for display case 1. Display case 2, on the other hand, demonstrates fewer spikes, resulting in an overall smoother response. This is possibly the result of display case 2 being more likely to slide than rock due to the absence of additional rubber supports at the base of the legs, as seen in Figure 4.4. Figure 4.16 further demonstrates that the frequency content at the base was modified the most for display case 2, when tested on carpet as opposed to hardwood floor.

Although display cases 1 and 3 experienced less acceleration at the top (Accel.2) compared to the base (Accel.1), the reductions were less for display cases on carpet than on hardwood floor. Compared to acceleration reductions of 55% and 79% for display cases 1 and 3 on hardwood floor, acceleration reductions were 23% and 61% on carpet. Ultimately, display cases 1 and 3 experienced higher accelerations at the art object display for carpet conditions than for hardwood floor. While carpet had an adverse effect in terms of levels of accelerations reached at the top of display cases 1 and 3, results indicate an improved response for display case 2 in this regard. Acceleration responses at the top of display case 2 with respect to the input acceleration were lower on carpet compared to hardwood floor on average by a factor of 0.7, while they were increased by factors of 1.3 and 1.5 for display cases 1 and 3 respectively. One possible explanation for this interesting observation is that the combination of supports and a surface of increased coefficient of friction resemble a fixed base condition for display case 1 and 3 more closely, whereas the same does not apply for display case 2 with a smooth support. Accelerations are therefore amplified as a result of more rigid base conditions which appear to be less efficient in reducing accelerations, whereas smoother support conditions have an isolating effect, thus reducing the accelerations. Given that accelerations at the display case base are less on carpet than on hardwood floor, as discussed following Figure 4.16, the resulting acceleration response at the top of display case 2 was ultimately less on carpet than on hardwood floor due to its support conditions.

Table 4.8 indicates that acceleration responses in the vertical direction (Accel.4) were on average 0.70g, 0.22g, and 2.68g for the three display cases respectively. This measurement provides an indication of the rocking response, therefore suggesting that display case 3 rocked the most, whereas display case 2 experienced the least acceleration response in the vertical direction.

4.4.6 Effect of Floor Elevation for Display Case 2 on Carpet

The results of the test series conducted to investigate the effect of floor elevation for display case 2 on hardwood floor were presented in Section 4.4.3. Table 4.9 presents the results for the same tests conducted on carpet. The values in brackets specify the ratio of each mean acceleration to the input acceleration (Ground Accel.).

Table 4.9: Effect of location (building elevation) on display case response on carpet

Base Motion	Mean Ground Accel. (g)	Mean Accel. 1 (g)	Mean Accel. 2 (g)	Mean Accel. 3 (g)	Mean Accel.4 (g)	Max. Displ. LVDT 1 (mm)	Max. Displ. LVDT 2 (mm)
Ground level: z = 0 m							
2 M6R30	0.55	0.49(0.9)	0.64(1.2)	0.35(0.6)	0.30(0.6)	1.2	0.4
2 M7R50	0.45	0.93(2.1)	1.02(2.3)	0.22(0.5)	0.25(0.6)	2.0	0.8
2 M7R70	0.39	0.59(1.5)	0.57(1.5)	0.13(0.3)	0.11(0.3)	0.8	0.2
Floor level 1: z = 5 m							
2 M6R30	0.45	0.60(1.3)	0.98(2.2)	0.28(0.6)	0.18(0.4)	1.1	0.3
2 M7R50	0.48	2.16(4.5)	5.76(12.0)	2.21(4.6)	3.91(8.2)	9.4	22.9
2 M7R70	0.42	2.26(5.4)	5.11(12.2)	2.01(4.8)	4.01(9.6)	11.0	43.4
Floor level 2: z = 10 m							
2 M6R30	0.56	2.65(4.7)	5.46(9.6)	3.30(5.9)	6.17(11.0)	8.9	31.9
2 M7R50	0.54	4.70(8.7)	5.94(11.0)	4.32(8.0)	10.4(19.3)	13.3	72.7
2 M7R70	0.51	4.71(9.2)	5.95(11.7)	4.47(8.8)	12.9(25.3)	30.5	85.0

Several observations can be made regarding the effect of increasing the coefficient of friction between contact surfaces, when testing display cases on carpet as opposed to hardwood floor. During testing it was clearly observed that the response of display cases on carpet was dominated by rocking, compared to sliding on hardwood floor. At ground level, the impact of modified surface conditions was discussed in the previous section and is not as pronounced as with base signals of increased building elevations. Results indicate that the display case did not experience significant displacements at ground level.

For base motions of increased elevations, acceleration responses were significantly amplified at higher elevations, with a peak response of 2.07g for hardwood floor versus 5.95g for carpet conditions. Accelerations of such magnitude are likely to damage fragile art objects, even if materials generally increase in strength and stiffness at very high strain rates, as is the case of high acceleration impacts occurring over a short time period. Future works with representative art objects would be useful to verify art object behaviour. These significant increases in acceleration response were the result of display cases tested with base motions 2M7R50 and 2M7R70. Although base motion 2M6R30, resulted in increased response on carpet compared to hardwood floor, the amplifications were smaller.

The effectiveness on reducing acceleration responses by reducing the coefficient of surface friction is shown in Figure 4.17, which has been produced for the acceleration response at the level of the display for carpet and hardwood floor surfaces for the first 8 seconds of 2M7R50 signals at floor elevation 1. This figure shows that for the first 4 seconds, the response of display cases on carpet and hardwood floor is similar. Once the display cases either start sliding or rocking at approximately 4.5 seconds, the response can be greatly reduced in the case of hardwood floor as opposed to carpet.

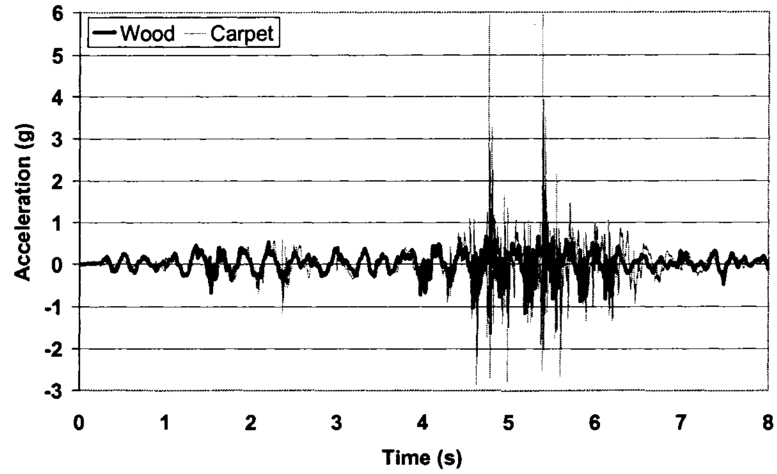


Figure 4.17: Comparison of acceleration response at the top of display case 2 (Accel. 2) for hardwood vs. carpet floors for the first 8 sec. of base motion 2M7R50 at floor elevation 1

Display case 2 rocked vigorously for test series of higher floor elevations, whereas the dominant response mode for hardwood floor was sliding. In addition to rocking, the display case also jumped so that the final displacement was larger for the display case on carpet than on hardwood floor. The displacement mode was further significantly different, in so far as the maximum peak displacement for carpet conditions was in the direction perpendicular to the direction of excitation, whereas the maximum displacement response was parallel to the direction of excitation for hardwood floor conditions. The displacement response of the display cases on carpet and wood for different floor elevations of base motion 2M7R50 are displayed in Figure 4.18.

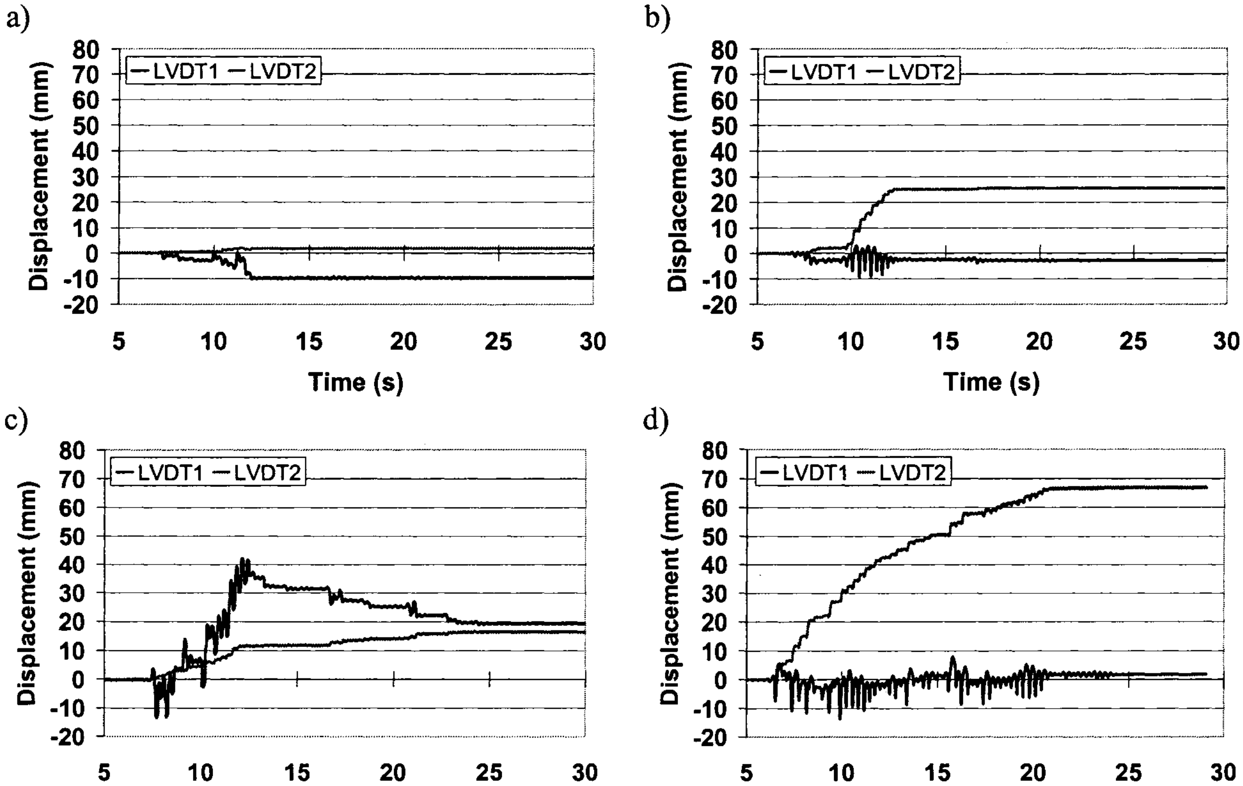


Figure 4.18: Displacement response for display 2 for base motion 2M7R50 for a) wood at floor elev. 1, b) carpet at floor elev. 1, c) wood at floor elev. 2, and d) carpet at floor elev. 2

Table 4.9 reveals that the peak acceleration response in the vertical direction (Accel.4) has increased by 93% at floor level 1 and by 98% at floor level 2 with respect to ground level, corresponding to values of 4.01g and 12.9g respectively. This indicates that art objects prone to rocking and/or overturning are at risk. Given that the shake table was limited to uniaxial excitation, the acceleration recorded was simply a response measure. A study demonstrated that the peak acceleration response of high-frequency sliding systems might be underestimated if the vertical component of earthquake excitation is not considered (Shakib and Fuladgar 2003), indicating that the response of unrestrained objects of art is further exacerbated in the case of a real earthquake. These measurements should be regarded with care, since they were recorded with accelerometers in the range

+/- 5g. It is possible that even though accelerometers are able to record outside of their range, these recordings are not accurate.

4.4.7 Effect of Art Object Mass for Display Case on Carpet

The results of the test series conducted to investigate the effect of art object mass on display case 2 with carpet floor conditions are as indicated in Table 4.10. The values in brackets specify the ratio of each mean acceleration to the input acceleration (Ground Accel.).

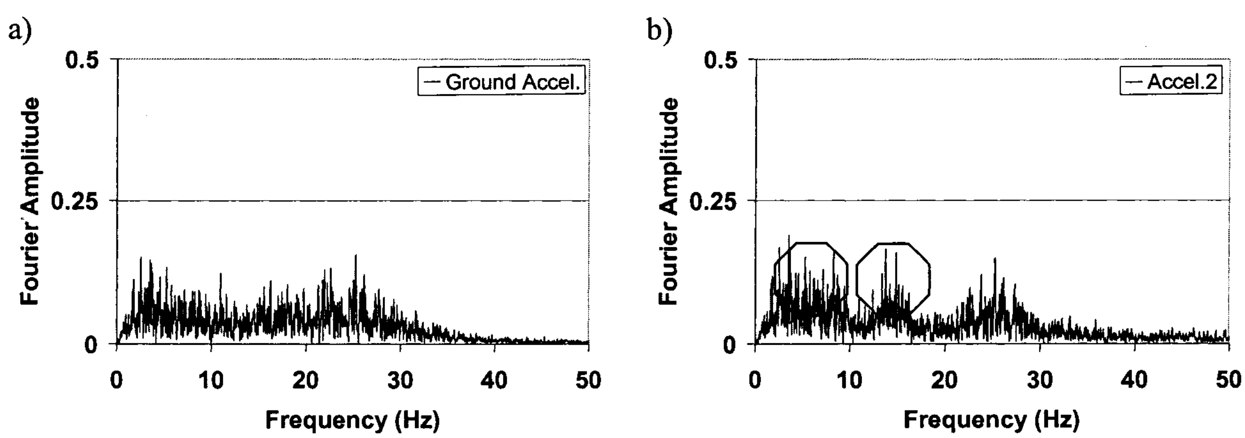
Table 4.10: Effect of art object mass on display case response with carpet floor

Base Motion	Mean Ground Accel. (g)	Mean Accel. 1 (g)	Mean Accel. 2 (g)	Mean Accel. 3 (g)	Mean Accel.4 (g)	Max. Displ. LVDT 1 (mm)	Max. Displ. LVDT 2 (mm)
No additional mass added: M0							
2 M6R30	0.55	0.49(0.9)	0.64(1.2)	0.35(0.6)	0.30(0.6)	1.2	0.4
2 M7R50	0.45	0.93(2.1)	1.02(2.3)	0.22(0.5)	0.25(0.6)	2.0	0.8
2 M7R70	0.39	0.59(1.5)	0.57(1.5)	0.13(0.3)	0.11(0.3)	0.8	0.2
Additional mass of 10 kg added: M1							
2 M6R30	0.56	0.53(1.0)	0.55(1.0)	0.14(0.3)	0.21(0.4)	1.1	0.3
2 M7R50	0.44	0.76(1.7)	1.30(3.0)	0.36(0.8)	0.30(0.7)	2.5	0.7
2 M7R70	0.37	0.60(1.6)	0.65(1.8)	0.22(0.6)	0.18(0.5)	1.1	0.2
Additional mass of 20 kg added: M2							
2 M6R30	0.55	0.53(1.0)	0.61(1.1)	0.17(0.3)	0.21(0.4)	1.0	0.2
2 M7R50	0.44	0.85(1.9)	0.83(1.9)	0.38(0.9)	0.61(1.4)	1.9	0.8
2 M7R70	0.37	0.69(1.9)	1.03(2.8)	0.30(0.8)	0.27(0.7)	1.0	0.2

While the accelerations at the top of the display case had, in general, decreased when masses were added to the display case on hardwood floor, they had increased on average by about 40% when masses of 10 kg and 20 kg were added to the display case on carpet. It appears that the changes are due to minor shifts in frequency content.

4.4.8 Display Case Frequency Content

Further investigation into the frequency content of the acceleration responses is useful to examine display case vibrational properties and compare them to results obtained from free vibration acceleration measurements after impact tests. In addition, observations can be made which reveal how accelerations are filtered due to the dynamic response of the display cases. Figure 4.19 compares the FFT of the acceleration recorded at the top of the display cases (Accel. 2) to the FFT of the acceleration recorded at the shake table (Ground Accel.) for the display cases on hardwood floor, where zones of amplification have been identified by circles. Figure 4.20 depicts the same curves for display cases on carpet. The zones of amplification are due to resonating effects near the display case natural frequencies of vibration. The differences observed in frequency content demonstrate the filtering effect for each display case.



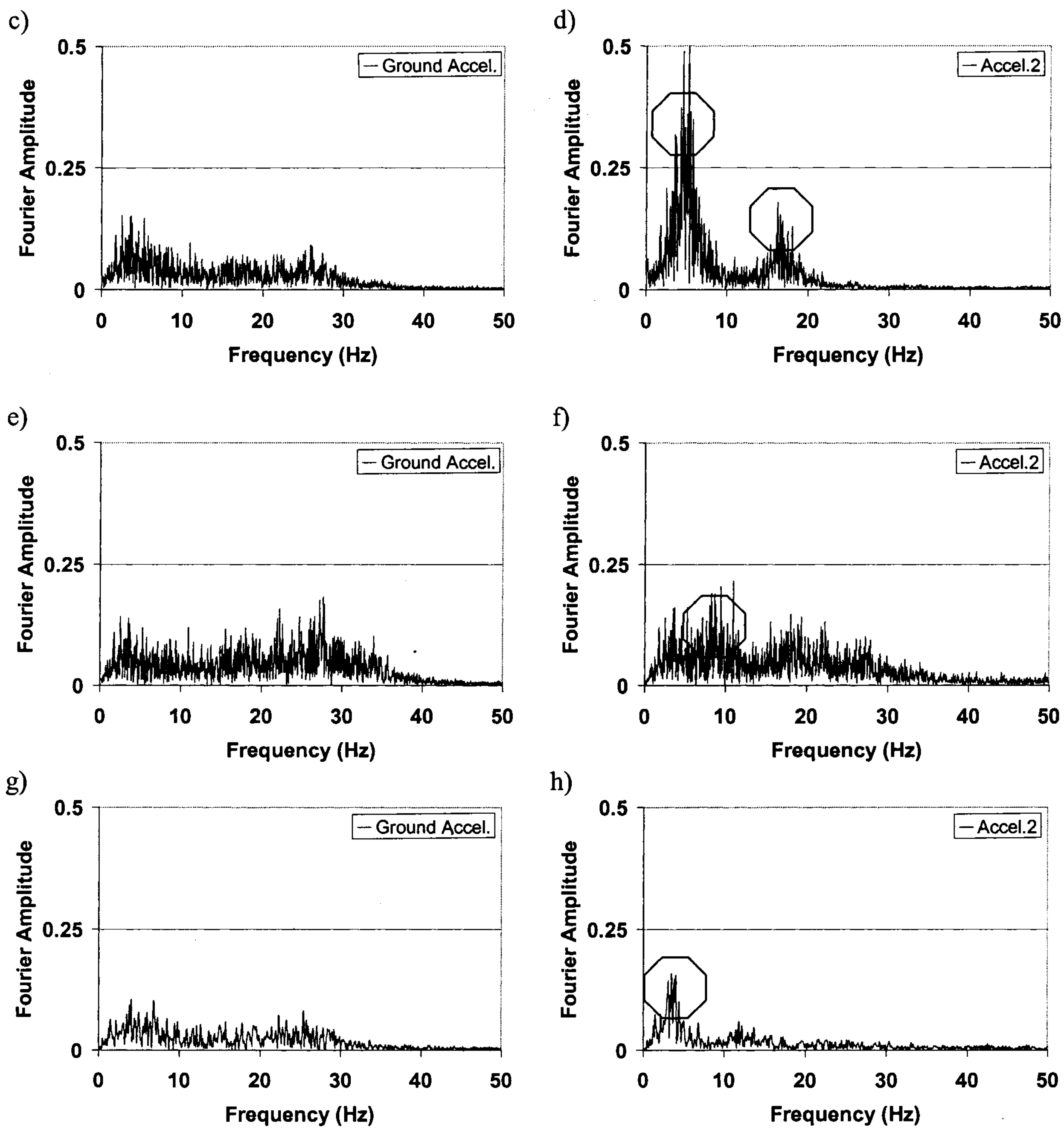


Figure 4.19: Comparison of FFT curves for shake table accelerations of display cases a) 1, c) 2, and e) 3 to accelerations at the top of display cases b) 1, d) 2, and e) 3 on hardwood floor due to base motion 2M7R50 and g) and h) for display case 1 at a diagonal arrangement

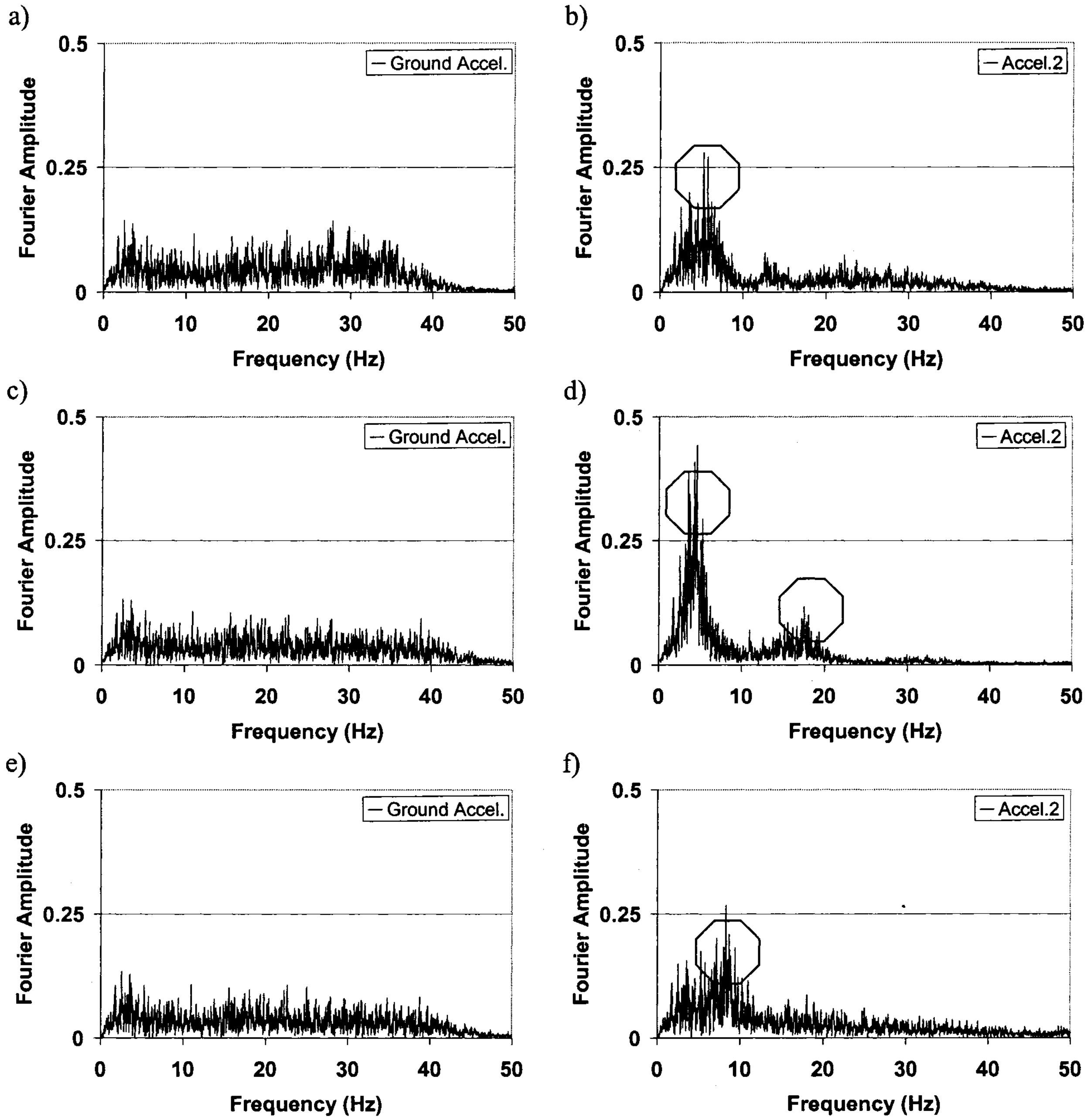


Figure 4.20: Comparison of FFT curves for shake table accelerations of display cases a) 1, c) 2, and e) 3 to accelerations at the top of display cases b) 1, d) 2, and e) 3 on carpet due to base motion 2M7R50

Figures 4.19 and 4.20 demonstrate that the frequency content at the display case top has been modified due to their dynamic response. While display case 2 has two clearly emerging peaks, changes in frequency content are characterized by amplification zones for display cases 1 and 3. These amplification zones are more defined for carpet conditions. In general, it appears that these peaks/zones of amplification agree with the display cases' natural frequencies of vibration identified from free vibration tests and shown in Table 4.4.

Figure 4.19 reveals that the frequency content has been significantly filtered by display case 2, while the filtering effect is the least pronounced for display case 3. Section 4.4.3 revealed that the frequency content of floor motions had a significant effect on the display case response. In the same manner, it can be expected that art objects will be affected by the frequency content of input excitation. The display case sliding response was significantly increased when excited by base motions of filtered frequency content. By analogy, it can be expected that art objects, which are subjected to base motions which have been filtered by the display case, will experience increased sliding. This would indicate that the sliding response of art objects would be increased if exhibited on display case 2, which filters the frequency content the most.

4.5 SUMMARY OF OBSERVATIONS

The seismic vulnerability of three museum display cases of different geometry, stiffness, and support conditions was investigated based on a parametric study, analyzing effects of base motion characteristics, floor height, surface coefficient of friction, and art object mass. This section will summarize observations and key points of discussion.

- **Overall Behaviour:** No display case damage, complete overturning, or the Plexiglas covers toppling off display cases occurred during experimentation. However, levels of accelerations reached at the level of art object display will likely damage fragile works of art.
- **Display Case Fundamental Frequency of Vibration:** From free vibration measurements following impact tests and frequency analyses, it was determined that display case 1 is the most flexible, while display case 3 is the most rigid. Their fundamental frequencies of vibrations span a range from approximately 3.6 Hz to 13.7 Hz for two different surface conditions, representing a frequency range which is usually excited by earthquake ground motions.
- **Base Motion Effects:** With regard to the effects of varying base motions at ground level, it was noted that the variability in responses was, for most cases, not great. The maximum difference in response at the top of display case 2 was 0.21 g. The ground motions were chosen to match the target uniform hazard spectrum for the Montréal region at a hazard level of 2% in years for scenarios of short-period and long-period ground motion hazard. Slight differences in amplitude and frequency content can be observed among these base motions, but effects were too small to draw definite conclusions for effects on display case response.

- **Support Conditions:** Peak accelerations were experienced at the base of the display cases. Variation in levels of accelerations between display cases are due to differences in support conditions, surface frictional coefficient, and display case dynamic properties. It appears that support conditions have a significant effect on display case response. Although it was observed that rubber supports and carpet have a beneficial role in damping floor vibrations, for seismic purposes, it appears that additional rubber supports for display cases on hardwood floor seem to have a disadvantage over a smoother surface. The latter will provide an isolating effect by allowing the display case to slide, resulting in lower accelerations at the level of display.
- **Acceleration Response at the Top of the Display Case:** With regard to display case behaviour under base motions of different frequency-amplitude content at ground level, the greatest accelerations at the top, the level where art objects are exhibited, were experienced for display case 2. During shake table testing, display case 2 strongly swayed back and forth due to flexible connections between the table top and its legs, therefore increasing accelerations at the top, where the mass of display case 2 is concentrated. Increasing the horizontal stiffness of display case 2 by strengthening the connection is expected to improve its seismic response.
- **Damping:** In general it was observed that peak accelerations at the top of the display cases were lower than at the base. The levels of reductions are most likely the result of structural damping and energy dissipated during the impact between the display case and the floor surface. Further investigation would be required to determine the exact nature of the physical mechanisms involved. Display cases 1, 2, and 3 experienced reductions in acceleration with respect to the base at 55%, 39%, and 79%. This

indicates that display case 3, the most rigid and light display case, had the most favourable damping effects. Acceleration reductions were less for carpet than for hardwood floor.

- **Torsional Effects of Display Case 1:** Although accelerations experienced at the top of display case 1 were lower than those of display cases 2 and 3, its acceleration response was exacerbated 2.6 times when arranged so that the direction of excitation is at an angle to the principal axes. This shows that torsional effects are induced by asymmetric features in the geometry of display case 1. It can thus be assumed that display case 1, due to its flexibility and torsional response is seismically vulnerable and that a symmetric geometry is preferred.

- **Floor Elevations:** The acceleration response at the top of the display case increased by 53% for hardwood floor conditions and by 83% for carpet conditions when the display case was located at floor level 2 compared to ground level. This corresponds to peak values of 2.07g for hardwood floor conditions and 5.95g for carpet. Accelerations of such magnitude will likely cause damage to fragile art objects. Displacement responses were also significantly increased for base motions at increased floor elevations with maximum displacements at floor level 2 of 35mm and 85mm for hardwood floor and carpet respectively. These results are consistent with findings at the San Francisco Museum of Modern Art where it was observed that art exhibited on upper floors were damaged more severely than on lower building levels (Shank 1990).

- **Surface Coefficient of Friction:** The display case response mode was completely changed between carpet and hardwood floors. For the display case on hardwood floor, the dominant mode of response was sliding, whereas it was characterized by rocking on carpet. The impact of modified surface conditions was more pronounced for base signals at increased building elevations, where the effectiveness on reducing acceleration responses by reducing the coefficient of surface friction was clearly observed once the display case started to slide. This is the result of a contact surface of reduced coefficient of friction having an isolating effect on the display case. The maximum accelerations at the top of the display case and the resulting display case displacements were approximately 65% higher on carpet than on hardwood floor.

- **Vertical Acceleration Response:** The acceleration response in the vertical direction was obtained for display cases on carpet. This measurement provides an indication of display case rocking and suggests that display case 3 rocked the most, whereas the response of display case 2 was least. The response was greatly exacerbated at increased floor elevations, where display case 2 reached a peak value of 12.9g. This indicates that especially light weight objects, typically displayed on these display cases, are particularly at risk.
- **Display Case Filtering Effect:** In terms of frequency content at the level of the art object display, a filtering effect of the display cases can be clearly observed. As a result, art objects are excited by filtered seismic motions. Sliding response is particularly sensitive to the frequency content of seismic motion so that sliding of unrestrained art objects is expected to increase with seismic motions of filtered frequency content. This would imply that the sliding response of art objects would be increased if exhibited on display case 2, which filters the frequency content the most, as opposed to display case 3, where filtering effects are the least pronounced.

- **Art Object Mass:** The effect of art object mass did not result in significant response modifications. It appears that changes are due to minor decreases in frequency content with an increase in mass. Overall, it is concluded that art objects are not heavy enough to significantly alter the dynamic properties of the display case.

5 Case Study 2: McCord Museum Storage Shelf System

The objective of this case study is to use dynamic analysis to investigate the seismic behaviour of a museum storage shelf system containing glass negatives, where every shelving unit weighing approximately 0.8kN is loaded with contents weighing a total of 113kN. SAP2000 (Computers and Structures 2000) was used for this study. A parametric study, investigating effects of ground motion characteristics, building elevation of storage shelf location, content mass distribution, and shelving system stiffness, was conducted to determine structural vulnerability. Structural improvements are recommended based on the simulation outcome. Art object response is predicted based on the acceleration response at the level of the shelves and the contact friction between the shelves and the contents. The dynamic analysis in SAP2000 first performs an eigenvalue analysis to extract natural frequencies of vibration and mode shapes of the shelf system with various mass configurations and subsequently determines the system response using modal analysis. The overall dynamic response of the shelving system is described by the maximum accelerations and displacements at the top.

5.1 MODEL DESCRIPTION

Figure 5.1 depicts the shelving system under consideration. The shelves are loaded with fragile glass negatives, individually stored in paper envelopes. On most shelves the envelopes are filed tight enough to avoid impact with adjacent glass negatives or the sides of the shelving system. The envelopes are filed so that the shorter side is along the depth of the shelf. No measures have been implemented to prevent contents from sliding off of shelves in the transverse direction.

Figure 5.1: Shelving System

The shelving system was modeled as linear elastic 2D steel frames (Hermitian elements) connected at the top of some columns to adjacent rows via small channel sections as indicated by dashed lines in Figures 5.2 and 5.3. These linking elements do not provide horizontal bracing for the shelving system. 2D and 3D views of the model can be seen in Figures 5.2 and 5.3 respectively. The shelf beams are cold formed steel members and the columns are perforated open sections to allow the aluminum hooks of the beam-end to form a beam-column connection. A close up of this typical connection is shown in Figure 5.4. Equivalent section properties were calculated and can be obtained from Table 5.1. Braces exist at intervals in the longitudinal direction of the shelving system, as seen in Figures 5.2 and 5.3.

Ideally the stiffness and performance of the connections would have been evaluated experimentally. Since this case study is strictly a numerical investigation, the model was initially analyzed with pin as well as fixed beam-column connections. The aluminum connection can be assumed to produce responses that lie in between those upper- and lower bound solutions. Significant differences in modal frequencies and mode shapes between the pin and fixed connections were not determined. Therefore, pin connections were used in subsequent analyses. These pin connections indicate that the rotational degree of freedom has been released and the resulting connection stiffness is 0 kN m/rad.

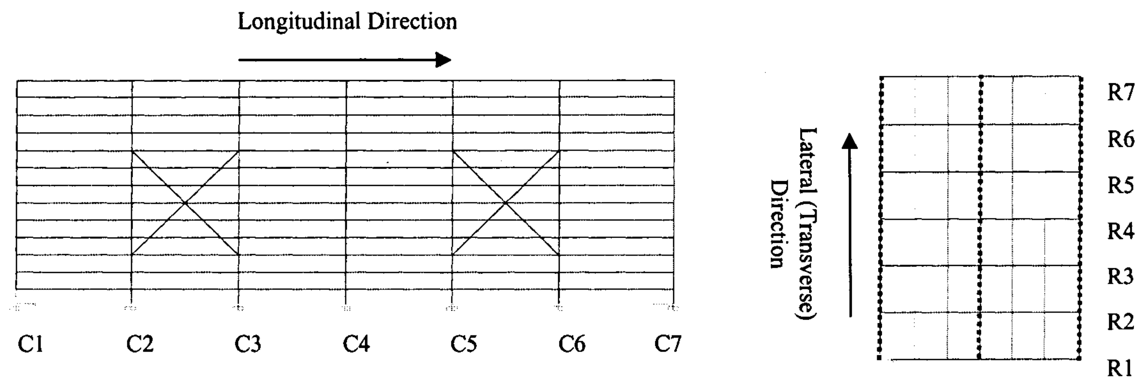


Figure 5.2: 2D Elevation and plan views of the model, column and row labels

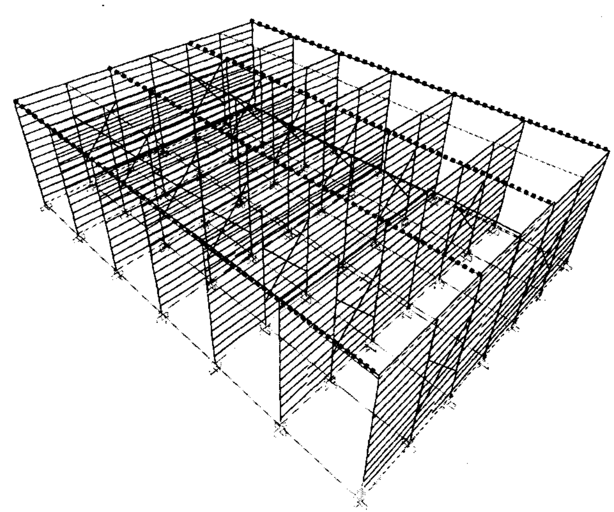


Figure 5.3: 3D view of the model

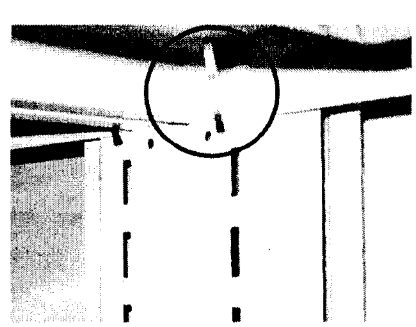


Figure 5.4: Detail of a typical aluminum connection

Table 5.1: Equivalent geometric properties

	Area (mm^2)	I_x (mm^4)	I_z (mm^4)
Columns: C1, C7	$1.48*10^3$	$7.932*10^7$	$2.156*10^6$
Columns: C2 – C6	$0.60*10^3$	$3.161*10^7$	$0.2917*10^6$
Shelves	$1.07*10^3$	$3.774*10^7$	$0.09143*10^6$
Braces	40	1333	13.33

The mass of the contents was added to the shelves. The masses were lumped at nodes at shelf beam mid span. The masses were determined according to the size and weight of the glass negatives located on the shelves and can be obtained from Table 5.2. This indicates that every shelving unit weighing approximately 0.8 kN is loaded with contents weighing a total of 113.0 kN, if the entire content weight is evenly distributed among shelving units. To simplify the model, the shelves were assumed to be of equal height.

Table 5.2: Equivalent content masses

	Weight/Shelf (kN)	Total Shelves (42 shelves/unit)	Total Weight (kN)
Mass 1	0.150	126 (= 3 rows)	19.0
Mass 2	0.720	126 (= 3 rows)	90.9
Mass 3	1.452	126 (= 3 rows)	182.9
Mass 4	1.648	126 (= 3 rows)	490.0
			782.8

5.2 COMPUTER ANALYSIS

This section presents necessary analysis considerations and the frequency analysis that preceded the investigation of the dynamic shelving behaviour under various parameters.

5.2.1 Analysis Considerations

Static stability of the model was initially verified. The dynamic analyses were performed with seismic base motions, as presented in Section 3, applied in the transverse direction (weak axis) of the shelving system.

5.2.2 Frequency Analysis

The lowest 30 natural frequencies and corresponding mode shapes of the shelf structure model, assumed on a rigid base, were calculated. The first few selected mode shapes in the weak direction (y-direction) of the shelves are shown in Figures 5.5 to 5.7.

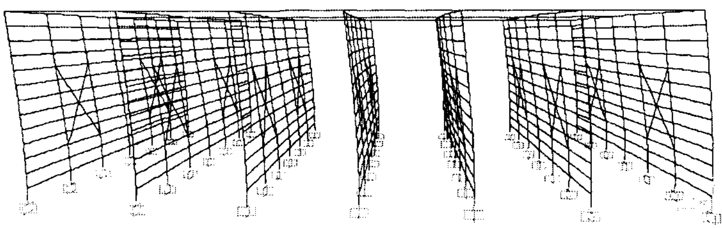


Figure 5.5: Mode 1 (T = 0.74s) – overall longitudinal sway

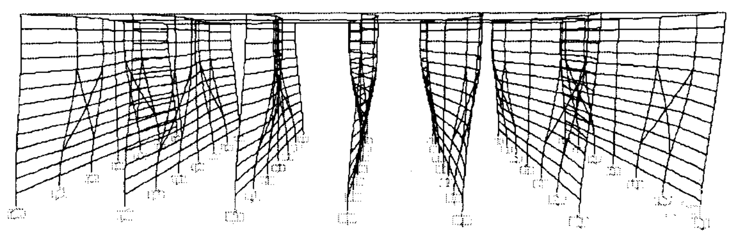


Figure 5.6: Mode 2 (T = 0.36s) – anti-symmetric longitudinal sway

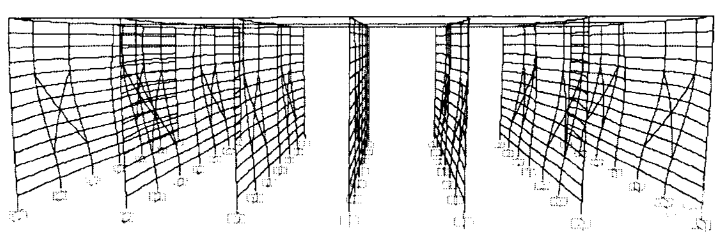


Figure 5.7: Mode 3 (T = 0.34s) – overall transverse sway

5.2.3 Parametric Study

The objective of this case study is to investigate the seismic behaviour of a shelving system. Several parameters were varied in the analysis to investigate their effect on the shelving system response. They are as follows:

Parameter 1: Ground motion characteristics

The effect of ground motions of different intensity-frequency content was investigated. The ground motions are as presented in Section 3.

Parameter 2: Shelving structure location (floor elevation) within the building

Since the shelving system is located on the third floor (referred to hereafter as level 2) of the museum, it is not only subjected to the base motion generated by the earthquake, but to the amplified motions generated by the dynamic response of the building. To account for the fact that the response of the shelving system depends on its elevation of location, floor motion histories at different levels ($z = 0$, 5 and 10 m) were used as base input. Parameters 3 and 4 were investigated with floor motion histories at an elevation of $z = 10$ m, where the shelving system is currently located.

Parameter 3: Content mass distribution

The shelving system was identified as being seismically vulnerable due to its brittleness and large content weight. Note that parameters 1, 2 and 4 were tested with the total mass uniformly distributed over the shelving system. In reality, the contents of varying size are stored systematically according to historical context. Therefore the mass is sometimes concentrated at some shelves which can possibly lead to torsional response due to eccentricities with respect to the centre of stiffness. The shelving system will be analyzed with contents of varying mass distributed in different configuration. The masses (Table 5.2) will be distributed as indicated in Table 5.3.

Table 5.3: Distribution of mass contents on shelving system

Case	Description
1	Even distribution: Mass of 158 kg has been evenly distributed among shelves.
2	Heavy mass at bottom: Contents have been distributed with decreasing weight as the height increases.
3	Heavy mass at top: Contents have been distributed with increasing weight as the height increases.
4	Torsional effect: Heavy masses have been concentrated at the bottom right and top left corners in plan view. The lighter masses have been concentrated at the remaining corners of the shelving system.
5	Mass at centre column: Heavy masses have been concentrated at the centre column of the shelving system

Parameter 4: Effect of Link Connection Stiffness

The shelving system consists of rows of shelves interconnected out-of-plane by a link (a small C-channel or an HSS as seen in Figure 5.8) to form a system. The axial stiffness of this link was varied to determine its effect on the overall system response. The actual links (HSS 25*25*2) were replaced, once with HSS 51*51*6.4 sections, and once with solid rectangular steel sections of size 100mm*100mm to represent a very stiff link.

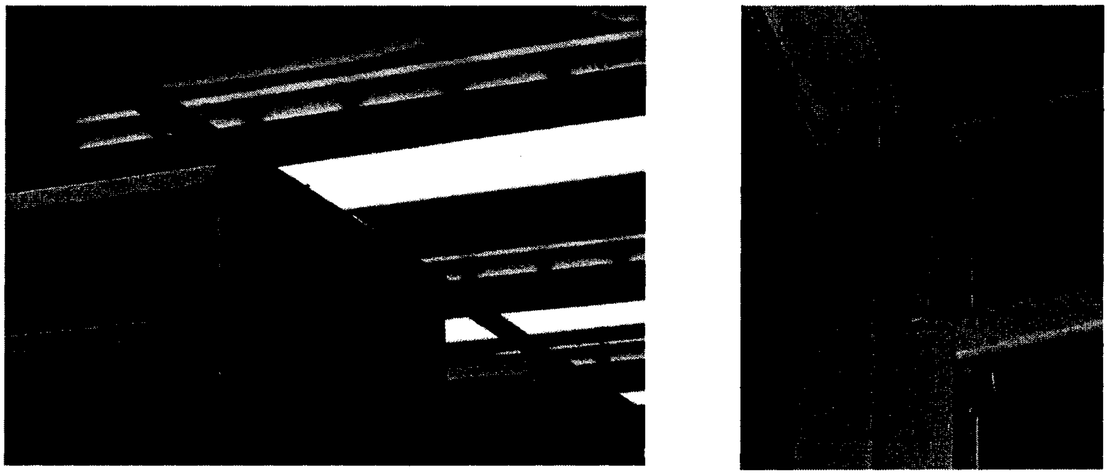


Figure 5.8: Link Connection (HSS and C-channel sections)

5.3 ANALYSIS RESULTS

The results for the maximum absolute acceleration, the maximum relative displacement, and the amplification of maximum acceleration (Maximum absolute acceleration/Maximum input base acceleration) with respect to the ground have been obtained for the analysis of each parameter and are presented in this section. With the exception of Parameter 3, in which the content mass has been redistributed among the shelving system, the maximum horizontal acceleration occurs at the top shelf of the centre of the shelving unit (C4, R4). The maximum horizontal displacement occurred at the top shelves of column C4, in most cases along all rows (R1 – R7). Note that amplification factors were not obtained from synchronous values, since the response at the top is delayed slightly with respect to the input at the base.

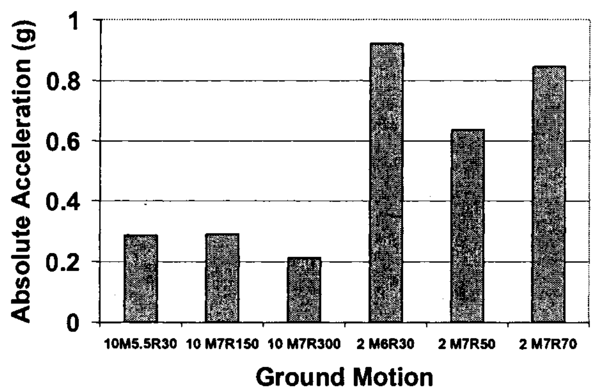
5.3.1 Effect of Ground Motion Characteristics

The results for the shelving system, analyzed with ground motions of different intensity-frequency content, are as summarized in Table 5.4 and Figure 5.9.

Table 5.4: Shelving System response under varying ground motion parameters

Ground Motion	Max. Absolute Acceleration (g)	Max. Relative Displacement (m)	Amplification of Acceleration
10 M5.5R30	0.29	0.0148	1.9
10 M7R150	0.29	0.0339	2.6
10 M7R300	0.21	0.0199	3.0
2 M6R30	0.92	0.0556	2.3
2 M7R50	0.64	0.0353	2.1
2 M7R70	0.85	0.0520	3.0

a)



b)

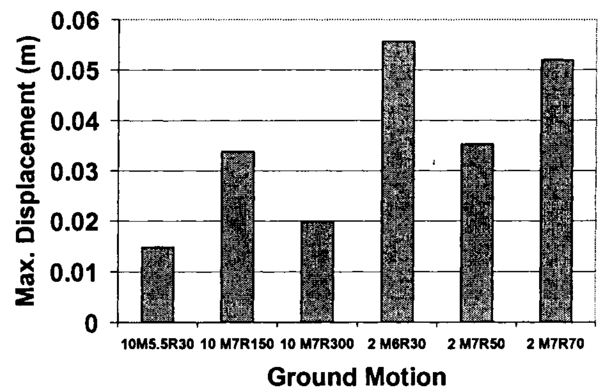


Figure 5.9: Ground motion effects on shelving system a) acceleration, and b) displacement response

The results obtained for the shelving system analyzed with ground motions of different intensity-frequency content indicate that acceleration responses varied between 0.21 g and 0.92 g, displacement responses varied between 0.0148 m and 0.0556 m, and the amplification of acceleration at the top level varied between 1.9 and 3.0. At a lower hazard level (10% in 50 years), the acceleration reduction between the maximum and the minimum response was equal to 28%, and at a higher hazard level (2% in 50 years) the acceleration reduction was equal to 30%. The maximum acceleration at both hazard levels occurred at a high-frequency content seismic scenario. Results indicate increased responses at higher intensity ground motions, corresponding to a probability of exceedance of 10% in 50 years, ranging from 55% for an intermediate-frequency content scenario to 75% for a low-frequency content event. Without modifying any parameters, the shelving system was also investigated with base motion applied in the strong (longitudinal) direction of the shelving system. Results indicated insignificant amplification of acceleration and small deflection responses.

5.3.2 Effect of Floor Elevation

The results of the analysis investigating the effect of location of floor elevation on the shelving system are as summarized in Table 5.5 and Figure 5.10.

Table 5.5: Response under varying base motions at different elevations

Base Motion	Elevation (m)	Max.Absolute Acceleration (g)	Max.Relative Displacement (m)	Amplification of Acceleration
10 M5.5R30	0	0.29	0.0148	1.9
10 M5.5R30	5	0.22	0.0184	1.9
10 M5.5R30	10	0.33	0.0230	2.0
10 M7R150	0	0.29	0.0339	2.6
10 M7R150	5	0.28	0.0356	2.6
10 M7R150	10	0.40	0.0375	2.8
10 M7R300	0	0.21	0.0199	3.0
10 M7R300	5	0.25	0.0246	2.8
10 M7R300	10	0.36	0.0296	2.4
2 M6R30	0	0.92	0.0556	2.3
2 M6R30	5	0.61	0.0663	1.6
2 M6R30	10	0.81	0.0773	2.0
2 M7R50	0	0.64	0.0353	2.1
2 M7R50	5	0.62	0.0444	1.8
2 M7R50	10	0.93	0.0579	1.9
2 M7R70	0	0.85	0.0520	3.0
2 M7R70	5	0.75	0.0583	2.2
2 M7R70	10	0.85	0.0655	2.1

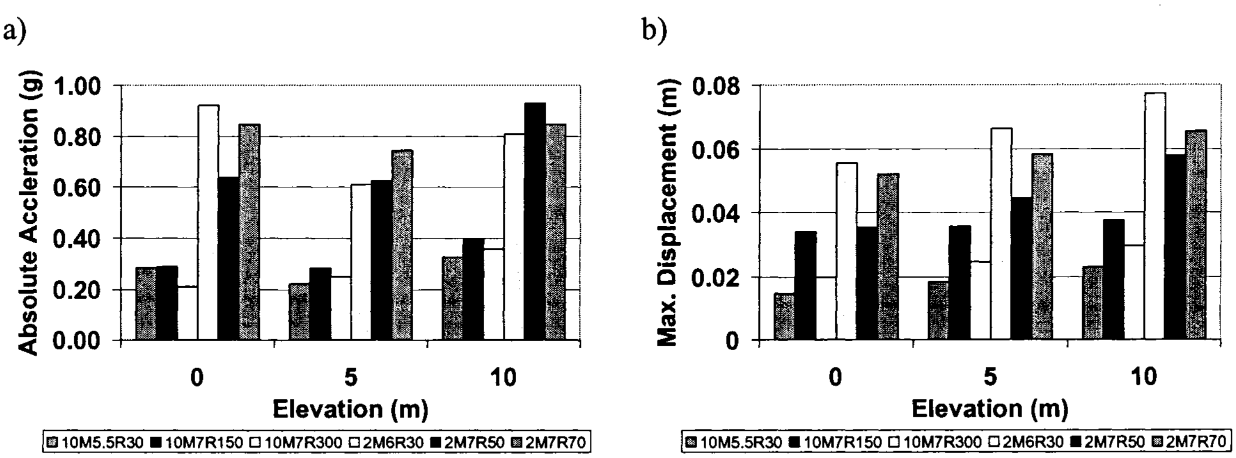


Figure 5.10: Floor motion effects on shelving system a) acceleration, and b) displacement response

The results obtained for the shelving system analyzed with floor motions at different building elevations indicate that acceleration responses varied between 0.21 g and 0.93 g, displacement responses varied between 0.0148 m and 0.0773 m, and the amplification of acceleration at the top level varied between 1.6 and 3.0. Comparing the minimum and maximum acceleration responses of 0.21 g and 0.92 g respectively at ground level (z = 0 m) to values of 0.33 g and 0.93 g at floor level 2 indicates slight modification in response due to base motions of filtered frequency content at upper floor elevations. Further, the response at floor level 1 was lower than at ground level. Figure 5.10a demonstrates more pronounced variations in acceleration response due to base motions of increased intensity at a higher seismic hazard level. The deflection responses consistently increased with increasing floor elevations with the lowest increase of 5% between floors for base motion 10M7R150 and the highest increase of 30% between floors of base motion 2M7R50. The maximum base shear of the shelving system was found to be equal to 209 kN. The maximum member compression forces at the base were found to be 4.9 kN.

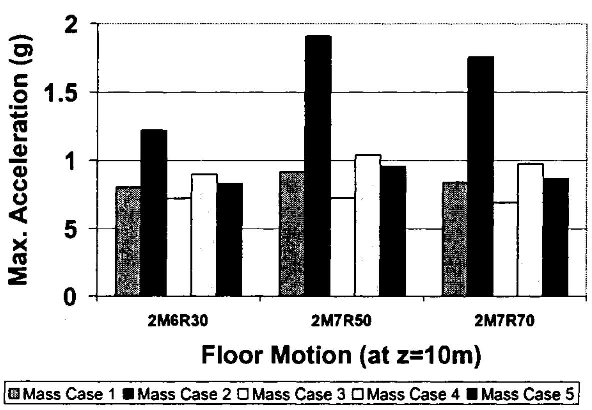
5.3.3 Effect of Content Mass Distribution

The results of the analysis, investigating the effect of art object mass distribution, are summarized in Table 5.6 and Figure 5.11. Results are for the shelving system located at a floor elevation of z = 10m. The resulting modification in the fundamental period of vibration was also recorded. When the shelving system was loaded eccentrically, the maximum acceleration and displacement responses occurred near the location of mass concentration, resulting in torsional effects. Otherwise, the maximum response remained near the top shelf of the most centre column.

Table 5.6: Shelving system response under varying mass configurations

Mass Case	Period (s)	Ground Motion	Max.Absolute Acceleration (g)	Max.Relative Displacement (m)	Amplification of Acceleration
1	0.74	2 M6R30	0.80	0.077	2.0
1	0.74	2 M7R50	0.92	0.058	1.9
1	0.74	2 M7R70	0.84	0.066	2.1
2	0.44	2 M6R30	1.22	0.052	3.1
2	0.44	2 M7R50	1.92	0.074	4.0
2	0.44	2 M7R70	1.76	0.076	4.3
3	0.73	2 M6R30	0.72	0.072	1.8
3	0.73	2 M7R50	0.72	0.051	1.5
3	0.73	2 M7R70	0.69	0.060	1.7
4	0.63	2 M6R30	0.90	0.059	2.3
4	0.63	2 M7R50	1.04	0.067	2.2
4	0.63	2 M7R70	0.98	0.072	2.4
5	0.63	2 M6R30	0.83	0.057	2.1
5	0.63	2 M7R50	0.96	0.063	2.0
5	0.63	2 M7R70	0.87	0.067	2.1

a)



b)

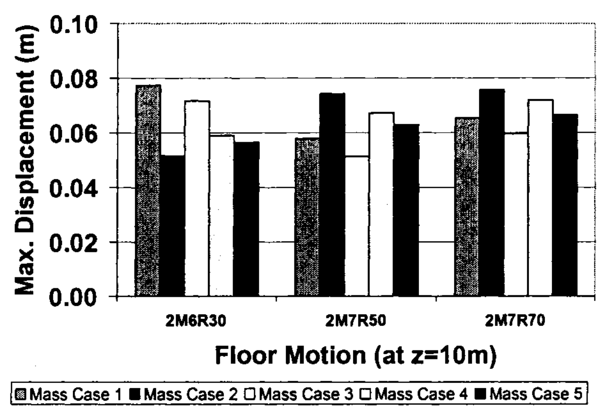


Figure 5.11: Effect of art object mass distribution on shelving system a) acceleration, and b) displacement response

The results obtained for content mass distributed on the shelving system in different configurations indicate that acceleration responses varied between 0.70 g and 1.92 g, displacement responses varied between 0.0514 m and 0.0773 m, and the amplification of acceleration at the top level varied between 1.5 and 4.3. These results indicate that the acceleration response was increased by 52% when heavy mass contents were located near the bottom (mass case 2) compared to the case of even mass distribution. Furthermore, this mass configuration reduced the fundamental period of vibration of the shelving system to 0.44s from 0.74s in the case of even mass distribution.

5.3.4 Effect of Link Connection Stiffness

The stiffness of the link, connecting rows of shelves, was modified to investigate its effect on the shelving system. The results are recorded in Table 5.7 and Figure 5.12 for the shelving system located at a floor elevation of z = 10m.

Table 5.7: Effect of Modified Link Properties

Base Motion	Link	Max.Absolute Acceleration (g)	Max.Relative Displacement (m)	Amplification of Acceleration
10 M5.5R30	Unchanged [1)]	0.33	0.023	2.0
10 M5.5R30	HSS 51*51*6.4	0.33	0.024	2.0
10 M5.5R30	Solid 100*100	0.27	0.024	1.7
10 M7R150	Unchanged	0.40	0.038	2.8
10 M7R150	HSS 51*51*6.4	0.40	0.038	2.8
10 M7R150	Solid 100*100	0.30	0.042	2.2
10 M7R300	Unchanged	0.36	0.030	2.4
10 M7R300	HSS 51*51*6.4	0.34	0.029	2.2
10 M7R300	Solid 100*100	0.25	0.025	1.6
2 M6R30	Unchanged	0.81	0.077	2.0
2 M6R30	HSS 51*51*6.4	0.77	0.075	1.9
2 M6R30	Solid 100*100	0.58	0.053	1.5
2 M7R50	Unchanged	0.93	0.058	1.9
2 M7R50	HSS 51*51*6.4	0.92	0.059	1.9
2 M7R50	Solid 100*100	0.58	0.056	1.3
2 M7R70	Unchanged	0.85	0.066	2.1
2 M7R70	HSS 51*51*6.4	0.82	0.066	2.0
2 M7R70	Solid 100*100	0.68	0.067	1.6

[1)] HSS 25*25*2

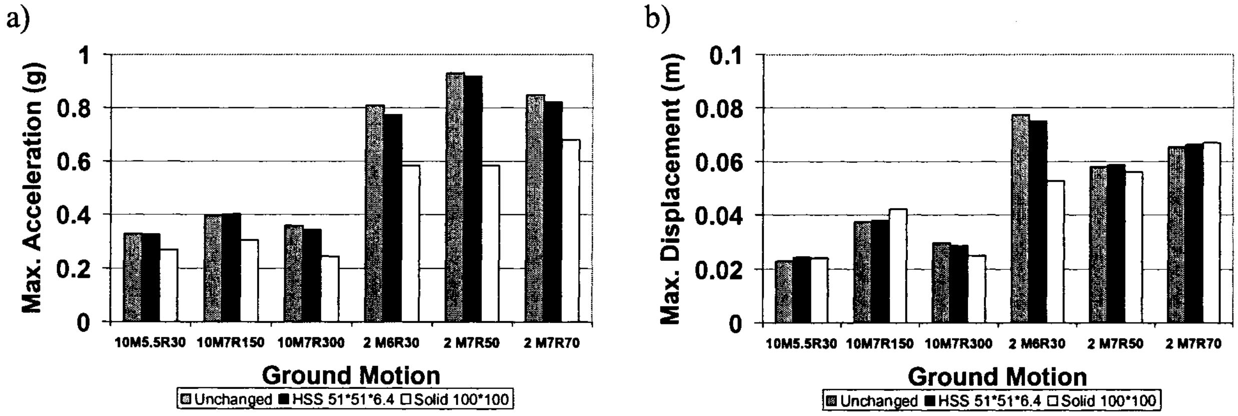


Figure 5.12: Effect of link connection stiffness on the a) acceleration, and b) displacement response of the shelving system

The results of the analysis which investigated the effect of modifying the stiffness of the link connecting rows of shelves to form a shelving system indicate that acceleration responses varied between 0.25 g for the case of a rigid link and 0.93 g for the section currently in place, displacement responses varied between 0.023 m and 0.077 m, and the amplification of acceleration at the top level varied between 1.3 and 2.8. Results indicate that the maximum acceleration response can be reduced on average by 3% by replacing the existing links by HSS 51*51*6.4 sections and by an average of 26% by replacing the existing links with solid rectangular steel sections of size 100mm*100mm. This latter section was chosen to investigate the axial stiffness, but does not represent a realistic size that would be used to improve the performance of the shelving system.

5.4 ART OBJECT RESPONSE

Based on analysis results, the predicted art object response will be discussed. Behaviour curves have been produced (Shenton 1996) to determine which type of motion (rocking, sliding) a rigid body will experience based on the peak base acceleration A_g, the coefficient of static friction μ_s at the interface, and the slenderness ratio H/B of the object, according to Figure 5.13. Two curves for rigid bodies of different slenderness ratios (H/B = 2 and 4) have been reproduced in Figure 5.14.

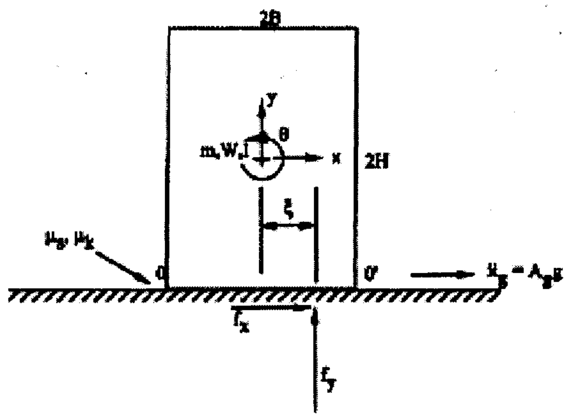


Figure 5.13: Rigid body, definition diagram (Shenton 1996)

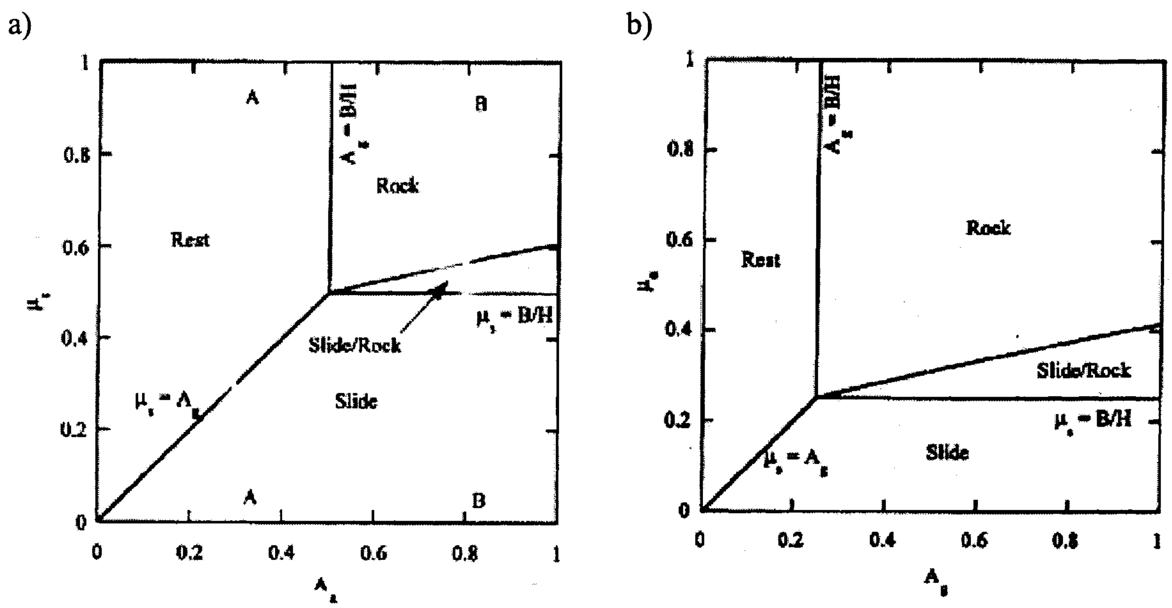


Figure 5.14: Behaviour curves indicating response modes for rigid bodies of slenderness ratio H/B equal to a) 2, and b) 4 (Shenton 1996)

Applying the behaviour curves to the contents of the shelving system, it can be determined that due to the low coefficient of friction between the paper envelopes and the steel shelves, the glass negatives will most likely start sliding transversely on the shelves and topple on the floor under, even small base motions.

5.5 DISCUSSION OF RESULTS

The following observations can be made about the results obtained from the analyses:

- The static stability of the loaded shelving system was verified and found acceptable.
- A frequency analysis of a loaded shelving system was performed on the lowest 30 modes of vibration. All 30 modes were found to have frequencies below 10 Hz; spanning the usual frequency range of earthquakes, indicating that these modes might be excited by an earthquake. Review of these modes indicated that the centre columns (C4) experience the greatest deflection.
- The shelving system experienced the greatest acceleration under ground motions corresponding to events of high-frequency content, where the minimum acceleration response is 28% lower than the maximum at a lower seismic hazard and 30% lower at a higher seismic hazard. As expected, the responses were significantly increased at ground motions of higher intensity, with an increase in 75% for short-frequency content events.
- The impact of floor motions, of varying intensity-frequency content, was not significant. This is most likely due to the fact that the shelving system contains several mode shapes at different frequencies that contribute significantly to the response. Therefore, floor motions whose frequency content has changed due to the filtering effect of the building will simply excite different modes of vibration. Deflection responses consistently increased with increasing floor elevations by up to 30% between floors of an intermediate-frequency content base motion.
- Placing the heaviest glass negatives at the bottom shelves has a negative impact on the shelving response, causing an increase in acceleration response of 52% compared to

the case of even mass distribution. This is due to the fact that the period of vibration of the shelving system has decreased. As a result, according to the response spectrum, the response of the system has shifted into a zone of increased acceleration response.

- The shelving system was loaded asymmetrically (Mass case 4) in an attempt to induce torsional eccentricities. Significant torsional response however was not observed. This is in accordance with the lack of a torsional mode identified in the frequency analysis. The distributed nature of the support points ensures good seismic behaviour in this respect.
- The acceleration response of the shelving system can be reduced by connecting the shelving rows with adjoining rows via links of increased stiffness. True diagonal bracing between the rows or groups of rows would likely be more efficient than stiffened links.
- The maximum horizontal acceleration and displacement occurred at the top shelf at the centre of the shelving unit, when the contents were equally distributed.
- The amplification of acceleration of the top shelf to the acceleration at the base ranges from approx. 1.5 to 3.0. Amplifications of up to 4 were obtained when the system was loaded such that the heaviest glass negatives are located at the bottom.
- A maximum deflection of 0.077 m at the top of the shelf was obtained. This corresponds to a drift of 3.4% of the total height. The lateral deflection limits for buildings are limited to 2.5% of the overall height, according to Cl.4.1.8.13 of the NBCC 2005. Since the shelving system is not located too close to the wall, pounding is not a problem and more stringent drift limitations are not necessary.
- Shelving contents can be expected to slide off shelves, even under small base motions.

6 Case Study 3: Redpath Museum Dinosaur Skeleton Display

The objective of this case study is to investigate the seismic sensitivity of the 6m long dinosaur skeleton model display located at the McGill Redpath Museum. The seismic vulnerability is determined based on acceleration measurements on the dinosaur structure left in free vibration after being excited by a small impact. The results of one free vibration test are presented in this chapter and a detailed collection of the data is attached in Appendix C. The seismic design force for the dinosaur model is determined according to the resulting frequency properties, and compared to the horizontal seismic design force as recommended by the 2005 NBC. This will give an indication of adequate support capacity.

6.1 SPECIMEN DESCRIPTION

The 6m long Albertosaurus Rex dinosaur skeleton model display, which is investigated in this case study, is currently located on the second floor of the McGill Redpath Museum. The composite skeleton structure is shown in Figure 6.1.

Figure 6.1: Albertosaurus Rex at the McGill Redpath Museum

The Albertosaurus libratus composite skeleton structure was manufactured in 1995 by Research Casting International (RCI). At that time records were not kept on how the skeleton was mounted. However, the following information was obtained from the manufacturer (personal communication with C. Mackie, Sept.9 2005). The vertebrae, ribs, skull, arms and possibly the pubis and ischium were made from water extended polyester (WEP) and the long bones were made of polyester gelcoat and fibreglass, which has been back filled in part with polyurethane expanding foam. The entire skeleton was painted with acrylic paint. A schedule 80 steel pipe runs through all the vertebrae and legs and serves as the connection to the base. The manufacturer estimated the weight of this structure at 600lbs (=2669N).

6.2 TESTING PROGRAM

The dinosaur structure was set into free vibration by small impacts such as touching the skeleton lightly, jumping nearby, or applying a small impact at the base. Acceleration measurements were taken while the structure was in free vibration. The acceleration response was recorded with a 10V DC data acquisition system.

6.2.1 Test Setup

The location and identification of four accelerometers, used to measure the response to small impacts, is shown in Figure 6.2.

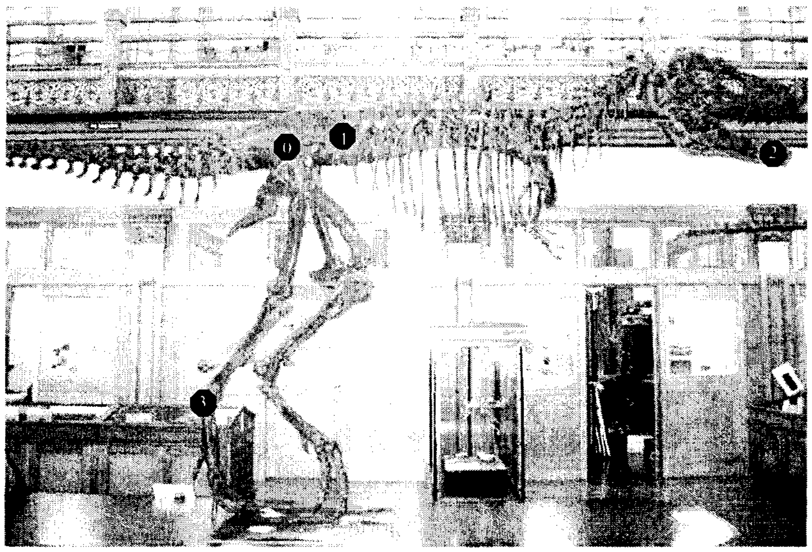


Figure 6.2: Location and identification of accelerometers

The placement of the accelerometers was chosen to capture a representation of the overall vibrational behaviour of the dinosaur structure. Accelerometer 0 was placed at the location where the legs join the body structure. Accelerometer 1 was installed to capture vibrations at a point on the structure which is approximately at half distance of the 6m long display, and assumed to be close to the location of the centre of mass. Accelerometer 2 was placed in the mouth of the skeleton structure at an outermost point of the display. Finally, accelerometer 3 was positioned to measure the response in the leg, close to the support. Accelerometer 3 was placed to measure the response in the vertical direction while the other accelerometers measure the horizontal accelerations in the longitudinal direction of the skeleton.

6.2.2 Test Runs

The dinosaur structure was set into free vibration by small impacts such as touching the skeleton lightly, jumping nearby, or applying a small impact at the base. A summary of the test runs can be obtained from Table 6.1.

Table 6.1: Test Runs

Run	Test Description
1	Ambient vibration, no impact imparted
2	Small impact imparted to lower leg in the horizontal direction along the length of the structure
3	Jumping nearby
4	Jumping nearby
5	Small impact imparted to lower leg in the horizontal direction
6	Small impact imparted to upper leg in the horizontal direction
7	Small impact imparted to the base in the horizontal direction

6.3 TEST RESULTS AND SEISMIC VULNERABILITY

Figure 6.3 presents the free vibration time history curves for the acceleration responses recorded for test runs 6 and 7. The results for the remaining test runs have been attached in Appendix C.

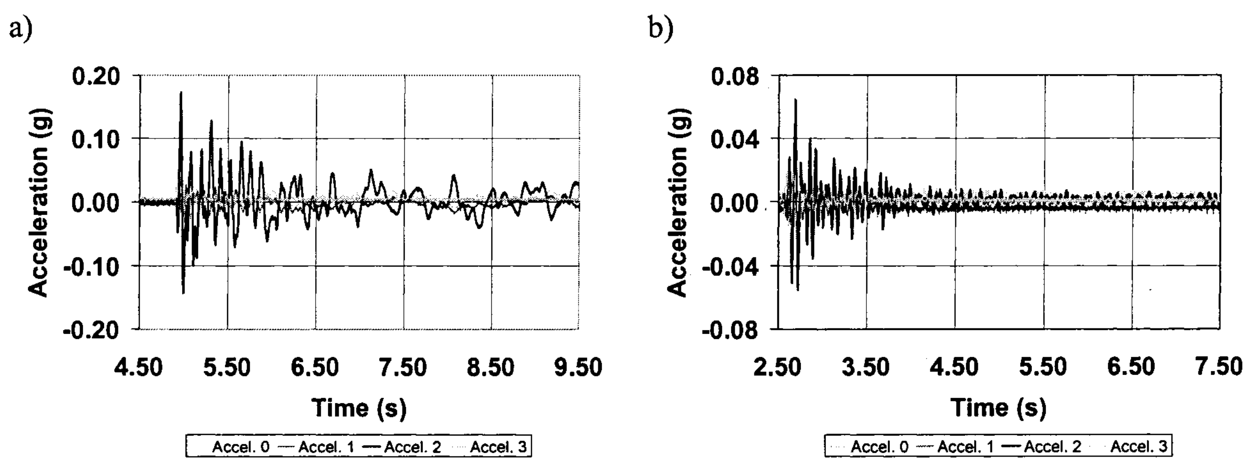


Figure 6.3: Free vibration response for a) test run 6, and b) test run 7

Results indicate the greatest acceleration response at the mouth of the dinosaur skeleton, the outermost point of the structure (Accelerometer 2). When the structure was set into vibration by an impact at the upper leg (test run 6), the acceleration response demonstrates that the response at the mouth is governed by local articulation effects, as seen by additional peaks in the time history response curve of Accelerometer 2 in Figure

6.3a. During the test run, the skeleton structure was seen to sway back and forth for a long time, which is a sign of light internal damping. Test run 7 consisted of a horizontal impact at the supporting base of the skeleton structure, and therefore simulates earthquake motions the closest.

A Fast Fourier Transform (FFT) analysis was carried out on the acceleration response records for each test run at a point after the impact to determine which frequencies were excited by impacts. Figure 6.4 shows the FFT for all accelerometers of test run 7. The results reveal that due to small impacts, the excited frequencies range from approximately 1 to 20 Hz, where accelerometer 2, located in the mouth, has a high-frequency content.

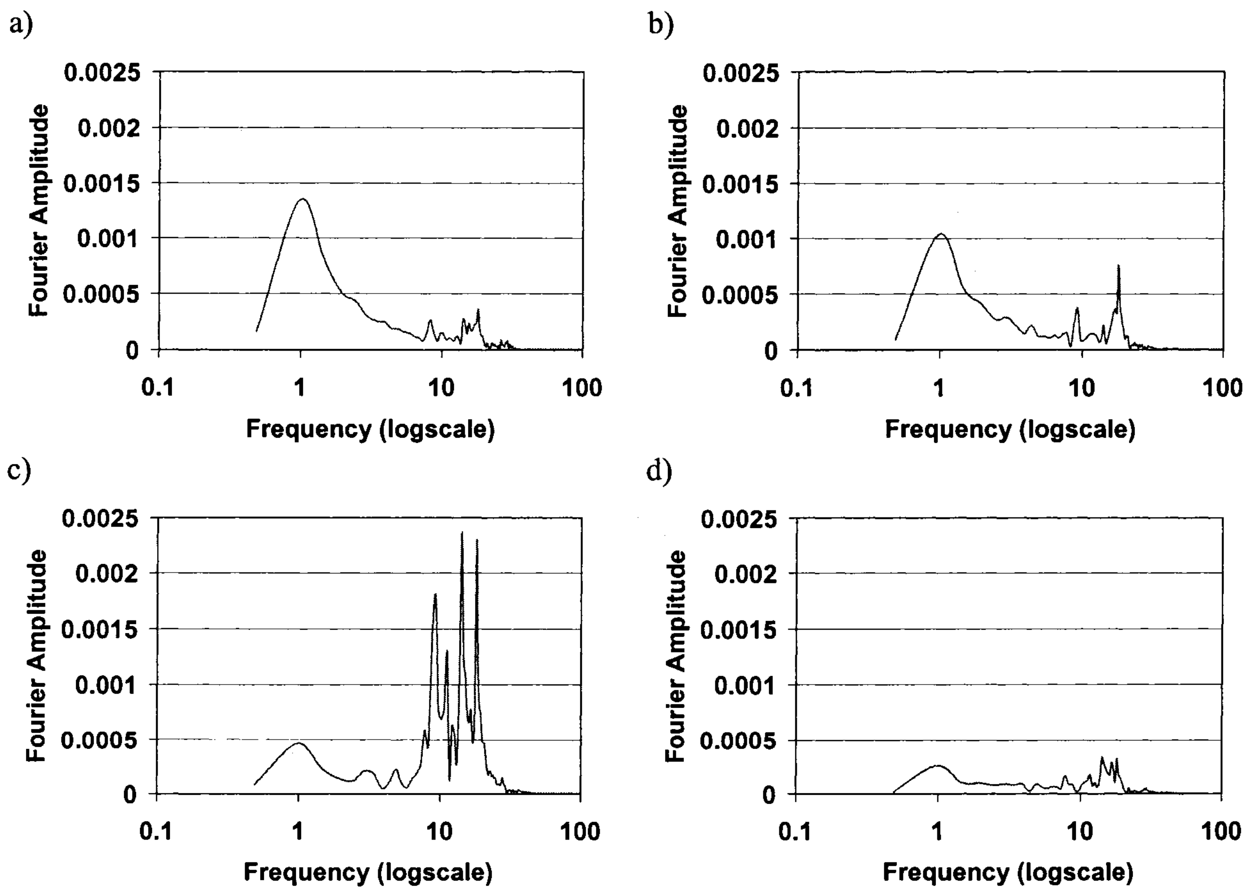


Figure 6.4: FFT for acceleration responses of accelerometer a) 0, b) 1, c)2, and d) 3 of test run 7

6.4 SEISMIC FORCE CALCULATION

This section will determine the seismic design force for the skeleton structure, based on the frequency properties previously obtained. As part of the seismic design requirements for nonstructural components, the 2005 NBC recommends a horizontal seismic design force, V_p that the component has to be designed to resist, as specified in Cl.4.1.8.17. The lateral force, V_p, is equal to:

[6.1] $V_P = 0.3F_aS_a(0.2)I_ES_PW_P$

Where:

F_a = Acceleration-based site coefficient. A soil report taken in 1993 to build the floor slab of the Macdonald Engineering Building (east of the Redpath Museum) revealed the presence of silty till at grade and limestone at depths of 11'-9" for bore hole 1 and 14'-7" for bore hole 2 (personal communication with Prof. Mitchell, 2006). This indicates that the Redpath Museum is most likely site class C. $F_a = F_v = 1.0$ for site class C.

$S_a(0.2)$ = The 5% damped spectral response acceleration for a period of 0.2 s = 0.69. This value was assumed, although it is likely that the dinosaur damping is less than 5%.

$S_a(1.0)$ = 0.14

I_e = Seismic importance factor for the museum. $I_e = 1.0$

S_p = Horizontal force factor for components and their connections.

$$= \frac{C_P A_r A_x}{R_P}$$

Where:

C_p = Factor to consider the increased risk associated with damage of components or elements dealing with toxic substances. $C_p = 1.0$

R_p = Element or component response modification factor. It represents the energy-absorption capacity of the element and its attachments. A schedule 80 steel pipe runs through all the vertebrae and legs and serves as the connection to the base. The skeleton would fall under Category 20 (Table 4.1.8.17) for flexible components with ductile material and connections. $R_p =$ 2.5

A_r = Element or component force amplification factor. It is a function of the ratio of fundamental period of the component and the fundamental period of the structure. The skeleton would fall under Category 20 (Table 4.1.8.17) for flexible components with ductile material and connections. $A_r = 2.5$

A_x = $(1 + 2h_x / h_n)$, Height Factor; The dinosaur is located on the 2nd floor, corresponding to approx. 2/3 of the building height.

$= 1+2(h_x/h_n) = 1+2(2/3) = 2.33$

W_p = The weight of the entire skeleton was estimated to be 600 lbs (= 2669 N)

According to Eq.6.1, the NBC 2005 recommends a seismic base shear design force for the dinosaur equal to:

$$V_P = 0.3F_aS_a(0.2)I_ES_PW_P =$$

$$V_p = 0.3*1.0*0.69*1.0*(\frac{1.0*2.5*2.33}{2.5})*2669 = 1287N$$

Results from the FFT analysis determined that the vibrational characteristics of concern are in the earthquake range from 1 to 20 Hz, corresponding to periods of vibration of 1 and 0.05s respectively. At a period of 0.05s, Sa(0.05) is equal to Sa(0.2), hence the design force remains unchanged. At a period of 1.0s, using Sa(1.0) equal to 0.14, the design force is equal to:

$$V_P = 0.3F_aS_a(1.0)I_ES_PW_P =$$

$$V_p = 0.3*1.0*0.14*1.0*(\frac{1.0*2.5*2.33}{2.5})*2669 = 267N$$

The dynamic amplification factor, A_r, is a function of the ratio of the natural period of the component to that of the structure. When this ratio is approximately equal to 1, A_r is 2.5. Otherwise it is 1.0. At a period of 1.0s, this factor has thus to be regarded with care.

This design force is equal to 10% of the total weight of the structure. It is verified that the base connection, consisting of a schedule 80 steel pipe, is able to resist this base shear force.

6.5 DISCUSSION OF RESULTS

The following observations can be made about obtained results:

- The Fourier Transform Amplitude curves that were obtained for each of the test runs from the free vibration analysis demonstrate that for a complex structure, like the skeleton, there are many significant modes of vibration. For example, accelerometer 2, which is located in the mouth of the dinosaur, has a frequency content which differs significantly from that at other locations due to local articulation effects. The results reveal that due to small impacts, the excited frequencies range from approximately 1 to 20 Hz. Since earthquakes are expected to excite frequencies up to 10 Hz, it can be concluded that the skeleton is potentially sensitive to seismic excitation.
- The seismic design force, recommended by the NBC 2005, is for the maximum anticipated forces and is therefore a conservative design requirement for this example.

7 Conclusions and Recommendations

The research presented in this text was conducted to investigate the seismic vulnerability of art objects. Art objects on display and in storage were inspected at three museums in Montréal for that purpose. Three areas were selected for further investigation and presented in the preceding chapters as case studies. The dynamic behaviour of three display cases from the MBAM was experimentally tested on a shake table. A computer analysis was performed on a storage shelf system at the McCord Museum, and the vibrational properties of a dinosaur skeleton model display at the Redpath Museum were investigated. This chapter presents conclusions of results obtained from these case studies, followed by practical recommendations for museums to address the seismic vulnerability of art objects. Several aspects concerning the seismic vulnerability of art objects require further study and this chapter concludes with a list, which identifies some of the major items.

7.1 CONCLUSIONS

This section presents conclusions for the case studies which were presented in the preceding chapters.

7.1.1 MBAM Display Cases

The following conclusions were drawn from the experimental works conducted to investigate the seismic behaviour of three display cases:

- No display case damage, complete overturning, or the Plexiglas covers toppling off display cases occurred during experimentation. However, levels of accelerations reached at the level of art object display will likely not be sustained by fragile works of art.

- The display case fundamental frequencies of vibrations span a frequency range from approximately 3.6 Hz to 13.7 Hz for two different surface conditions, representing a frequency range which is critical in earthquakes.
- Support conditions have a significant effect on display case response. Although it was observed that rubber supports and carpet have a beneficial role in damping floor vibrations, for seismic purposes, it appears that additional rubber supports for display cases on hardwood floor seem to have a disadvantage. A smoother surface on the other hand will provide an isolating effect by allowing the display case to slide, resulting in lower accelerations at the level of display.
- The greatest accelerations at the top, the level where art objects are exhibited, were experienced for display case 2. This is due to its flexible connections between the table top and legs.
- Damping was beneficial in reducing the accelerations at the top of the display cases with respect to the base and was most efficient in a rigid and light display case.
- Torsional effects are induced by asymmetric geometry features and increase the seismic vulnerability of art objects.
- The acceleration and displacement responses increased significantly at increased floor elevations. Resulting peak accelerations at the top of the display case will likely damage fragile art objects.
- The display case response mode was completely changed between carpet and hardwood floors. The response mode for hardwood floor was governed by sliding,

whereas it was characterized by rocking on carpet. The impact of modified surface conditions was more pronounced for base signals at increased building elevations, where the effectiveness on reducing acceleration responses by reducing the coefficient of surface friction was clearly observed once the display case started to slide. This is the result of a contact surface of reduced coefficient of friction having an isolating effect on the display case. The maximum accelerations at the top of the display case and the resulting display case displacements were on average 67% and 65% higher on carpet than on hardwood floor.

- The vertical acceleration response indicated that especially light weight objects, typically displayed on these display cases, are particularly at risk.
- A frequency filtering effect at the top of the display cases was clearly observed. As a result, art objects are excited by filtered seismic motions and sliding response can be expected to increase.
- Art objects are not heavy enough to significantly alter the dynamic properties of the display case.

7.1.2 McCord Museum Storage Shelves

The following conclusions were drawn from the computer analysis performed to investigate the seismic behaviour of a storage shelf system:

- The static stability of the loaded shelving system was found to be acceptable.
- The shelving system experienced the greatest acceleration under ground motions corresponding to events of high-frequency content. As expected, the responses were significantly increased at ground motions of higher intensity.

- The impact of floor motions of varying intensity-frequency content was not significant. This is most likely due to the fact that the shelving system contains several mode shapes at different frequencies that contribute significantly to the response. Therefore, floor motions whose frequency content has changed due to the filtering effect of the building will simply excite different modes of vibration.
- Placing the heaviest glass negatives at the bottom shelves has a negative impact on the shelving response as it lowers the fundamental period of vibration.
- Significant torsional response was not observed, most likely due to the distributed nature of the supports ensuring good seismic behaviour in this respect.
- The acceleration response of the shelving system can be reduced by increasing the stiffness of the system.
- The maximum horizontal acceleration and displacement occurred at the top shelf at the centre of the shelving unit, when the contents were equally distributed.
- The amplification of acceleration of the top shelf to the acceleration at the base ranges from approx. 1.5 to 3.0. Amplifications of up to 4 were obtained when the system was loaded such that the heaviest glass negatives are located at the bottom.
- A maximum deflection of 0.077 m at the top of the shelf was obtained. This corresponds to a drift of 3.4% of the total height. Since the shelving system under consideration is not located too close to the wall, pounding is not a problem and more stringent drift limitations are not necessary.
- Shelving contents can be expected to slide off shelves, even under small base motions.

7.1.3 Redpath Museum Dinosaur Skeleton Model Display

The following conclusions were drawn from the frequency analysis conducted to investigate the seismic behaviour of the dinosaur skeleton display:

- For a complex structure, like the skeleton, there are many significant modes of vibration. The frequency content differs significantly at different locations due to local articulation effects.
- Due to small impacts, the excited frequencies range from approximately 1 to 20 Hz. Since earthquakes are expected to excite frequencies up to 10 Hz, it can be concluded that the skeleton is vulnerable to seismic excitation.
- The seismic design force, recommended by the NBC 2005, is for the maximum anticipated forces and is therefore a conservative design requirement for this example.

7.2 RECOMMENDATIONS

Recommendations based on research outcomes are presented specific to each case study.

7.2.1 MBAM Display Cases

No display case damage, complete overturning, or the Plexiglas covers toppling off display cases occurred during experimentation. However, based on the Montréal seismic hazard specified in the NBC 2005, levels of horizontal accelerations reached at the level of art object display will likely not be sustained by fragile works of art. The motion of art objects exhibited on the display cases depends on the art object mass and geometric properties, on the friction conditions of the art object/display case interface, and on the characteristics of the seismic motion at the art object display. This section will provide recommendations by highlighting which display case geometric features and support conditions will reduce the seismic vulnerability of art objects and will discuss methods of art object display.

- The highest accelerations at the level of art object display were reached for display case 2. Display case 2 strongly swayed back and forth as a result of base motion excitation due to its flexible connections between the table top and its legs. It is recommended that this connection is stiffened with mechanical fasteners.
- The asymmetric geometry features of display case 1 exacerbated its seismic response. Display cases of symmetric geometry are more favourable in this regard.
- In general it was observed that peak accelerations at the top of the display cases were lower than at the base. The levels of reductions are the result of damping effects inherent to each display case. Display cases 1, 2, and 3 experienced reductions in acceleration with respect to the base at 55%, 39%, and 79%. This indicates that display case 3, the most rigid and light display case, had the most favorable damping effects. It is likely that display case 2 will experience less damping, if its connections are stiffened, as recommended. However, the overall result should be more beneficial as its lateral stiffness would increase.
- Support conditions have a significant effect on display case response. For seismic purposes, it appears that additional rubber supports for display cases on hardwood floor seem to have a disadvantage over a smoother surface which will provide an isolating effect by allowing the display case to slide, resulting in lower accelerations at the level of display. Consequentially, care has to be taken in leaving sufficient space between display cases and/or adjoining walls or partitions to avoid their impact.

- Carpet has an adverse effect on display case response mode in terms of peak accelerations and displacements reached. While the display cases slid on hardwood floor, they rocked on hardwood floor. In addition to rocking, the display case jumped so that the final displacement was larger for the display case on carpet than on hardwood floor. The maximum accelerations and displacements were on average by 67% and 65% higher on carpet than on hardwood floor.
- Both the acceleration and displacement responses were significantly increased for base motions at increased floor elevations. Particularly valuable objects of art, especially those made of brittle materials, are safer on ground level than floors of higher building elevations. This is consistent with damages observed in the San Francisco Museum of Modern Art in the 1990 earthquake (Shank 1990).
- A filtering effect, which is expected to particularly affect the sliding response of art objects, was clearly observed for the display cases. This would indicate that unrestrained art objects exhibited on display case 2 would slide the most, whereas they would slide the least on display case 3. It appears that a light, rigid display case will reduce the sliding response of art objects.
- The acceleration response of the display cases in the vertical direction further increases the seismic vulnerability of art objects, putting objects prone to rocking or overturning at risk. It is thus recommended that these art objects should be restrained at their base to prevent consequential rocking/jumping. Display case 2 has the most favourable response in this regard, whereas display case 3 rocked the most, increasing the response in the vertical direction as a result.

7.2.2 McCord Museum Storage Shelf System

The seismic performance of the shelving system under investigation is twofold. It consists of the seismic performance of the shelves as well as the response of the stored contents. The shelves have to be adequately designed, installed, and loaded to resist earthquakes. Hence, shelves have to be designed to prevent collapse and overturning and contents should be restrained.

Consistent with target performance levels, ground motions were chosen for the Montréal region to assess the seismic performance of the shelving system. The accelerations and deflections that the shelving system would experience under strong shaking were shown to be significant. Contents stored on the shelves with these levels of accelerations are expected to slide off and break. The current shelving system does not provide sufficient seismic resistance and is proven to be very vulnerable to ground shaking. Some recommendations are provided that can be implemented to improve the seismic performance system:

- Anchoring should be provided at the bases of the end and centre columns to avoid overturning of the shelving system.
- To increase the out-of-plane stability of the shelving system, the shelves should be connected at their top to adjacent shelving rows with steel members stiffer than presently used. True diagonal bracing between the rows or groups of rows would likely be more efficient than stiffened links.
- The shelving system is currently placed at a safe distance from the wall in the weak direction. The system experiences deflections up to approximately 8 cm at the top

under strong shaking. Sufficient space between the walls and the shelving system is needed to ensure that impact is avoided.

- To prevent contents from sliding off the shelf, the contents should be secured on the shelves. Contents can be restrained simply by installing cables, chains, or straps at the front of the shelves. Fasteners commonly used in earthquakes can be found at the following website: www.qsafety.com.
- To avoid contents from breaking due to impact with adjacent objects or the end of the shelf, they should be stored tightly or restrained sideways.
- Care has to be taken to avoid overloading of the shelves. Increased masses will induce increased seismic forces imposed on the system.
- Contents of varying mass are currently distributed over the shelving system according to historical context. This random mass configuration should be maintained and is consistent with nonstructural design requirements.
- Valuable seismic design practices as well as recommended seismic installation practices for steel storage racks are available on the Internet: www.bssconline.org/RackWkshp/RackFinalReport/RackGuide.html.

7.2.3 Redpath Museum Dinosaur Skeleton Model Display

The seismic vulnerability of a 6 m long dinosaur skeleton was investigated by determining the frequency properties of the skeleton from its free vibration response to small impacts. It was determined that the dinosaur is sensitive to earthquakes. According to the frequency properties extracted from acceleration measurements, the seismic design force for the dinosaur was determined and compared to that recommended by the 2005 NBC. It was determined that the NBC provides a conservative recommendation.

7.3 FUTURE WORK

To limit the scope of this research, three case studies were selected for detailed investigation. However, there are numerous storage shelving systems and display cases which possibly render art objects seismically vulnerable. Future work is recommended in the following areas:

- Three display cases of different geometric and dynamic properties were investigated. It would be useful to perform additional shake table tests on display cases to which structural improvements have been made. This would allow verification of recommended mitigation techniques and would provide an opportunity to systematize the effect of various mitigation parameters. Parameters of particular importance include support conditions, horizontal stiffness, as well as mass and geometric properties.
- This study was restricted to the investigation of three display cases. However, the diversity of display cases is great. Further research on displays which consist of assembled blocks would be of great interest.
- Movable storage cabinets as well as roller-type systems for paintings are typical of museum storage areas. These systems need to be analyzed.
- Further research should be conducted to look at restraints or support conditions of art objects, commonly used in museums.
- Structures should be investigated for a greater range of earthquakes, also investigating records of western locations, which are generally of a different duration and frequency content. Different ground motions might have an effect on the analytical results and recommendations obtained.

- Future work into the nonlinear inelastic behavior of the shelving system would be useful with special attention given to drift limitations.
- The art object mass was varied in the experimental work. However, the art object response also depends on its slenderness, and the location of the center of gravity. Further investigation into art objects of different physical characteristics are required to investigate art object behavior and the dynamic interactions with the display case.
- High acceleration peaks were recorded at the level of art object display. Although it is likely that these will damage fragile art objects, further experiments with representative art objects would indicate whether damages are significant or if materials have experienced an increase in strength and stiffness as a result of high strain rates during impact.
- Reductions in accelerations at the top of the display cases with respect to the base have been observed. Although structural damping and damping at the supports contribute largely to these reductions, further investigation is necessary to determine the exact nature of physical mechanisms involved.

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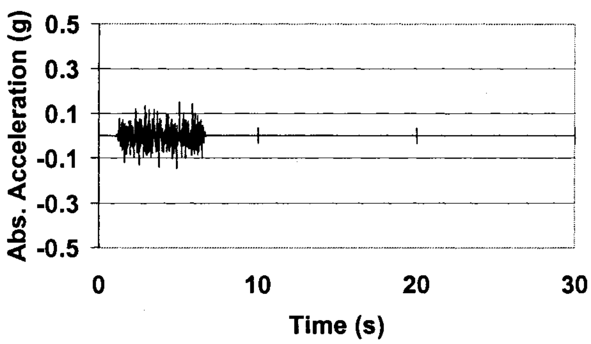
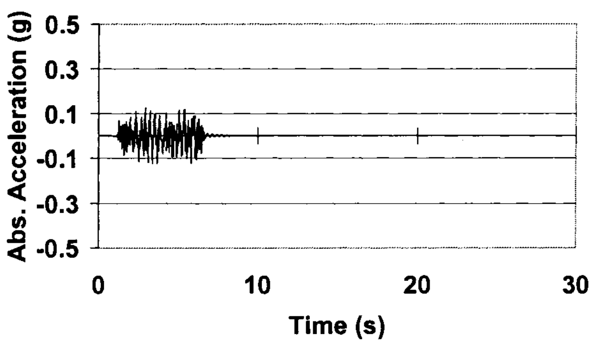
Appendix A

The data collected in this Appendix, corresponds to data on seismic hazard, presented in Chapter 3.

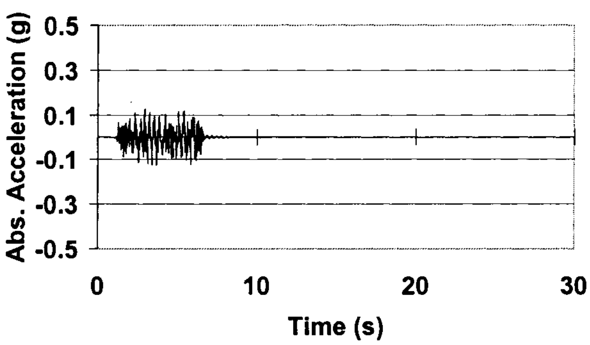
10 M5.5R30 - Ground Level



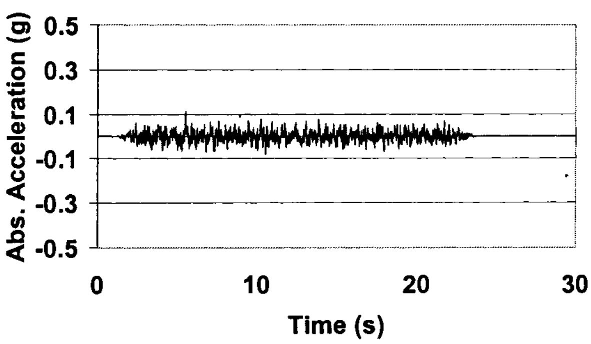
10 M5.5R30 - Floor Level 1



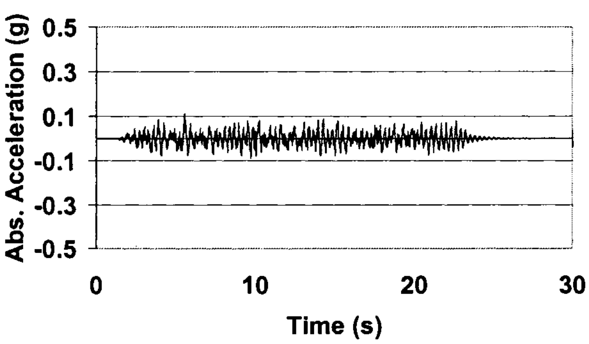
10 M5.5R30 - Floor Level 2



10 M7R150 - Ground Level



10 M7R150 - Floor Level 1



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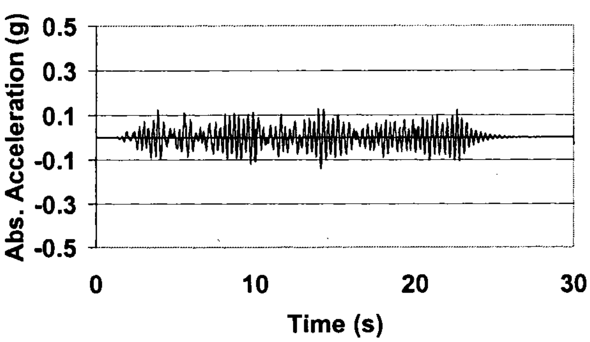
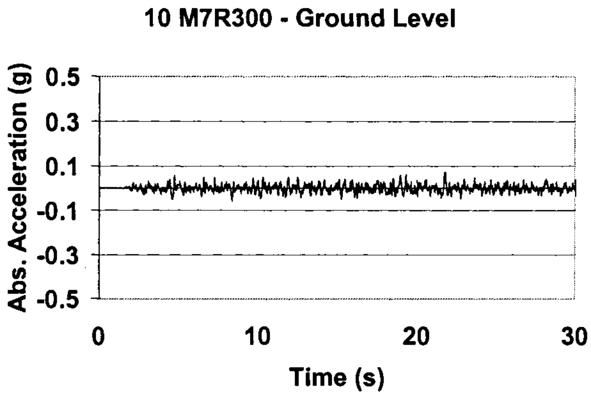
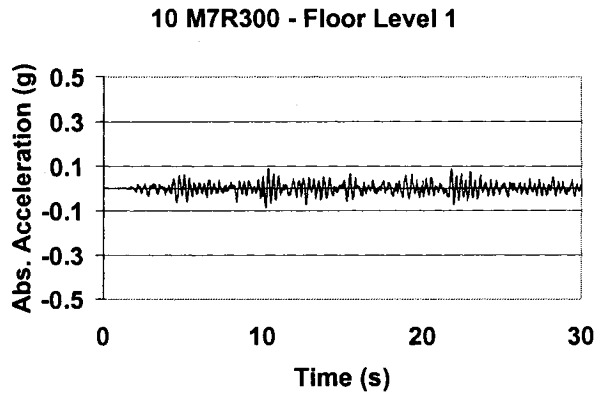
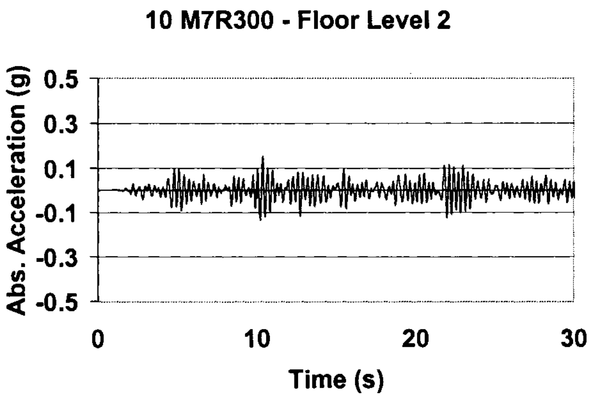
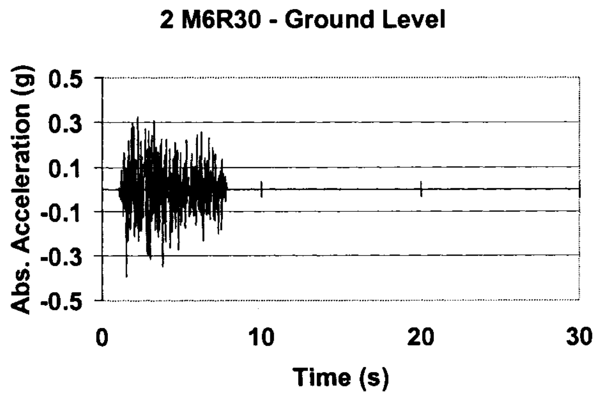
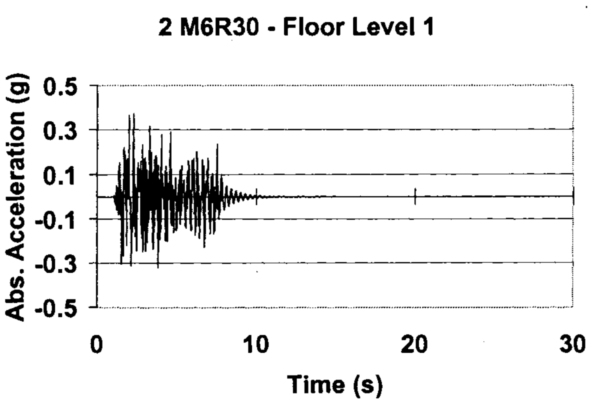


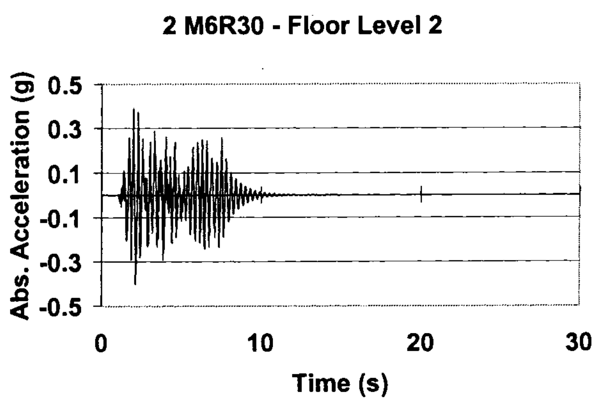

10 M7R300 - Ground Level
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)


10 M7R300 - Floor Level 1
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)


10 M7R300 - Floor Level 2
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)


2 M6R30 - Ground Level
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)


2 M6R30 - Floor Level 1
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)


2 M6R30 - Floor Level 2
Abs. Acceleration (g)
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
Time (s)

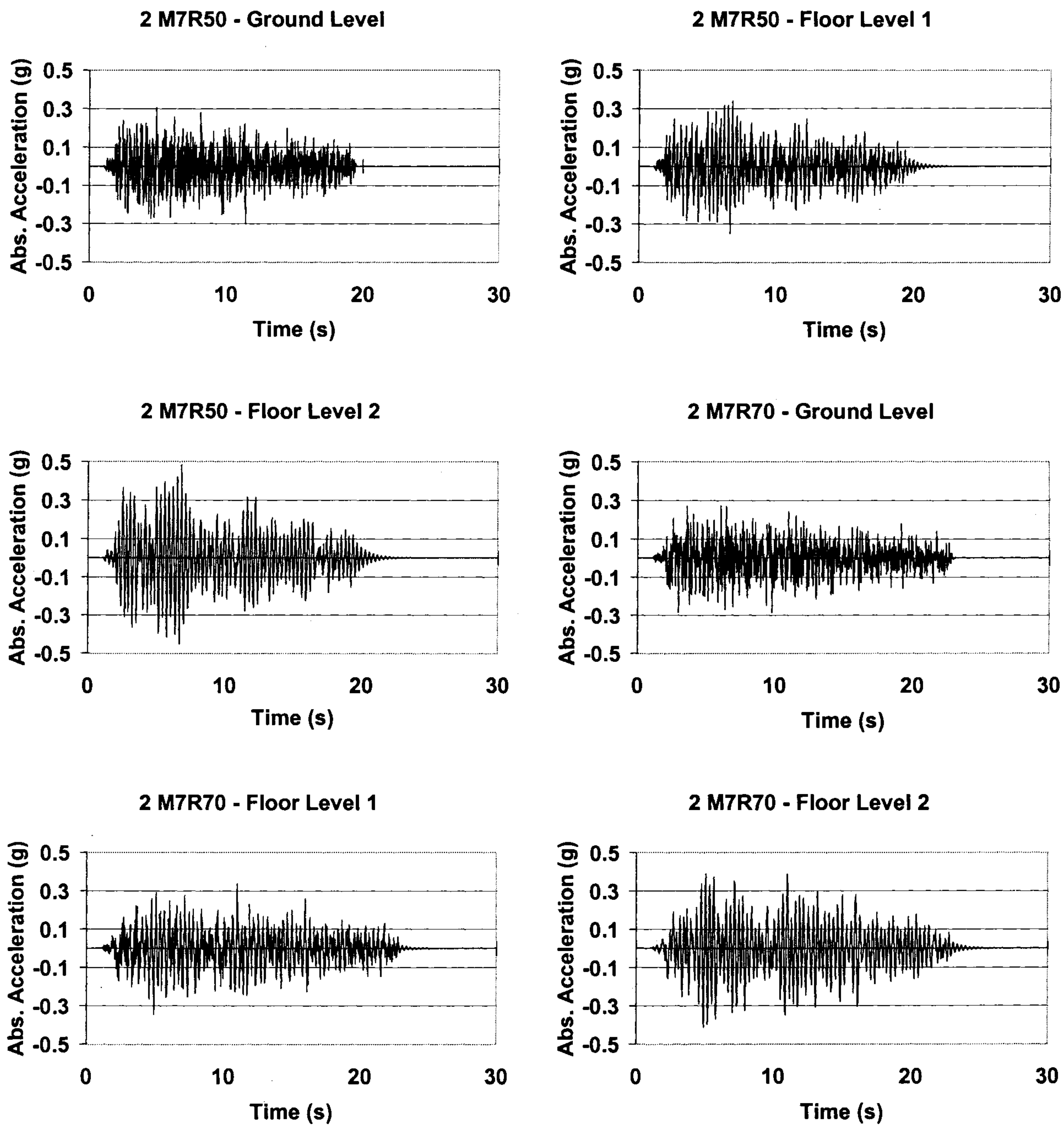


Figure A 1: Acceleration time history curves for base motions 10M5.5R30, 10M7R150, 10M7R300, 2M6R30, 2M7R50, and 2M7R70 at ground level, floor level 1 and floor level 2

Appendix B

The data collected in this Appendix, is from results of case study 1, on the MBAM display cases, presented in Chapter 4.

DISPLAY CASE 1

TEST SERIES	File Designation	Ground (g)	Mean Abs. Accel (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Accel. (g)	Standard Deviation
1	D1- V- 2M6R30- T1	-0.66982	0.691	0.035	-0.830204	0.796	0.030	-0.374012	0.362	0.012	-0.405538	0.360	0.066
	D1- V- 2M6R30- T2	-0.67203			-0.783262			0.3493176			-0.28401		
	D1- V- 2M6R30- T3	-0.73106			-0.773426			-0.363685			-0.391293		
2	D1- V- 2M7R50- T1	-0.37469	0.379	0.010	-0.83968	0.812	0.117	-0.352449	0.367	0.017	-0.28744	0.331	0.051
	D1- V- 2M7R50- T2	-0.37216			-0.912464			-0.384788			-0.318287		
	D1- V- 2M7R50- T3	-0.39141			-0.684013			-0.362338			-0.387731		
3	D1- V- 2M7R70- T1	-0.38826	0.382	0.006	-0.751073	0.708	0.039	-0.312051	0.316	0.008	-0.3401	0.405	0.064
	D1- V- 2M7R70- T2	-0.37595			-0.674624			-0.311602			-0.46875		
	D1- V- 2M7R70- T3	-0.38131			-0.699213			-0.325521			-0.405538		
4	D1- V- 2M6R30- T1	-0.42677	0.439	0.024	-0.711284	0.753	0.042	-0.753413	0.951	0.187	-0.659277	0.501	0.145
	D1- V- 2M6R30- T2	-0.42487			-0.753308			-0.973869			-0.375712		
	D1- V- 2M6R30- T3	-0.46686			-0.794885			-1.125629			-0.468305		

DISPLAY CASE 3

TEST SERIES	File Designation	Ground (g)	Mean Abs. Accel (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Accel. (g)	Standard Deviation
5	D3- V- 2M6R30- T1	-0.66383	0.655	0.009	2.4767522	2.828	0.396	0.639368	0.629	0.073	-0.315171	0.350	0.046
	D3- V- 2M6R30- T2	-0.6553			3.2568845			0.6963903			-0.402867		
	D3- V- 2M6R30- T3	-0.64615			2.7512514			0.5509161			-0.332532		
6	D3- V- 2M7R50- T1	-0.49085	0.480	0.014	-2.527718	2.607	0.149	-0.542385	0.608	0.059	-0.331196	0.334	0.014
	D3- V- 2M7R50- T2	-0.46402			-2.514306			-0.65643			-0.320958		
	D3- V- 2M7R50- T3	-0.48422			-2.778523			-0.624102			-0.349003		
7	D3- V- 2M7R70- T1	-0.41951	0.415	0.008	-3.972639	3.277	0.610	-0.609285	0.609	0.060	-0.399305	0.390	0.042
	D3- V- 2M7R70- T2	-0.42045			-2.831276			-0.54912			-0.344106		
	D3- V- 2M7R70- T3	-0.40562			-3.027986			-0.669451			-0.42557		

DISPLAY CASE 2

TEST SERIES	File Designation	Ground (g)	Mean Abs. Accel (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Accel. (g)	Standard Deviation
8	D2- V- 2M6R30- T1	-0.47601	0.495	0.046	-1.506169	1.340	0.210	-0.745331	0.769		-0.36859	0.321	0.062
	D2- V- 2M6R30- T2	-0.46086			-1.409603			-0.785291			-0.251513		
	D2- V- 2M6R30- T3	-0.54672			1.1033619			-0.77676		0.021	-0.343661		
9	D2- V- 2M7R50- T1	-0.35101	0.371	0.020	-0.360783	0.370	0.015	-0.802802	0.864		-0.405092	0.380	0.024
	D2- V- 2M7R50- T2	-0.39141			-0.36123			-0.981502			-0.376157		
	D2- V- 2M7R50- T3	-0.36963			-0.38716			-0.809088		0.101	-0.357461		
10	D2- V- 2M7R70- T1	-0.35164	0.328	0.020	-1.436874	1.541	0.166	-0.959501	0.979		-0.330306	0.314	0.029
	D2- V- 2M7R70- T2	0.315972			1.7323853			-0.998563			0.3316416		
	D2- V- 2M7R70- T3	-0.31723			-1.452521			-0.978808		0.020	-0.280449		

Figure B 1: Base motion effect on display cases acceleration response, wood floor

DISPLAY CASE 1

TEST SERIES	File Designation	LVDT 1 (Max) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (Max.) (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation
1	D1- V- 2M6R30- T1	-1.9889	**2.045**	**0.056**	0.15491	**0.170**	**0.030**	0.381044	**0.204**	**0.155**	-0.050119	**0.032**	**0.016**
	D1- V- 2M6R30- T2	-2.0446			0.20503			0.144053			0.027338		
	D1- V- 2M6R30- T3	-2.1004			0.15036			0.088291			-0.018225		
2	D1- V- 2M7R50- T1	2.749	**2.818**	**0.079**	0.223	**0.285**	**0.054**	0.27	**0.519**	**0.231**	0.018	**0.085**	**0.061**
	D1- V- 2M7R50- T2	2.9043			0.31438			0.724913			0.100238		
	D1- V- 2M7R50- T3	2.80207			0.31894			0.562272			0.136688		
3	D1- V- 2M7R70- T1	-1.9935	**1.888**	**0.093**	-0.17314	**0.155**	**0.018**	-0.204463	**0.091**	**0.100**	-0.013669	**0.035**	**0.019**
	D1- V- 2M7R70- T2	-1.8541			0.13669			-0.055763			0.041006		
	D1- V- 2M7R70- T3	1.81693			-0.15491			-0.013941			-0.050119		
4	D1- V- 2M6R30- T1	-0.6499	**5.695**	**4.463**	-12.514	**4.888**	**6.605**	5.232381	**5.840**	**1.330**	0.842906	**0.882**	**0.047**
	D1- V- 2M6R30- T2	7.30953			0.99782			4.921041			0.870244		
	D1- V- 2M6R30- T3	9.12646			1.15273			7.365297			0.934031		

DISPLAY CASE 3

TEST SERIES	File Designation	LVDT 1 (sliding (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (sliding (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation
5	D3- V- 2M6R30- T1	1.25001	**1.410**	**0.139**	-0.40095	**0.381**	**0.068**	1.0409	**1.121**	**0.079**	-0.236925	**0.257**	**0.042**
	D3- V- 2M6R30- T2	1.50094			-0.30527			1.198893			-0.227812		
	D3- V- 2M6R30- T3	1.47771			-0.4374			1.124544			-0.305269		
6	D3- V- 2M7R50- T1	2.18403	**2.351**	**0.147**	-0.19592	**0.246**	**0.075**	1.988863	**2.173**	**0.160**	-0.127575	**0.125**	**0.073**
	D3- V- 2M7R50- T2	2.41173			-0.20959			2.249088			-0.050119		
	D3- V- 2M7R50- T3	2.4582			-0.33261			2.281616			-0.195919		
7	D3- V- 2M7R70- T1	-1.0409	**1.036**	**0.216**	-0.42373	**0.453**	**0.039**	-0.260225	**0.246**	**0.064**	-0.318938	**0.358**	**0.039**
	D3- V- 2M7R70- T2	0.81785			-0.4374			-0.176582			-0.359944		
	D3- V- 2M7R70- T3	1.25001			-0.49663			0.302047			-0.396394		

DISPLAY CASE 2

TEST SERIES	File Designation	LVDT 1 (sliding (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (sliding (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ (mm)	Standard Deviation
8	D2- V- 2M6R30- T1	-1.4824	**1.552**	**0.060**	-0.64699	**0.645**	**0.385**	0.381044	**0.243**	**0.147**	-0.214144	**0.443**	**0.405**
	D2- V- 2M6R30- T2	-1.5846			0.25971			-0.088291			0.205031		
	D2- V- 2M6R30- T3	-1.5892			1.02971			0.260225			0.91125		
9	D2- V- 2M7R50- T1	1.12454	**0.866**	**0.224**	0.31438	**0.287**	**0.055**	0.645916	**0.392**	**0.222**	0.241481	**0.223**	**0.044**
	D2- V- 2M7R50- T2	0.73421			0.22326			0.292753			0.173138		
	D2- V- 2M7R50- T3	0.73885			0.32349			0.236991			0.25515		
10	D2- V- 2M7R70- T1	-1.7658	**1.919**	**0.454**	0.95681	**1.045**	**0.085**	-1.050194	**0.683**	**0.592**	0.906694	**0.966**	**0.054**
	D2- V- 2M7R70- T2	-2.4303			1.05249			-0.999078			1.011488		
	D2- V- 2M7R70- T3	-1.5614			1.12539			0			0.979594		

Figure B 2: Base motion effect on display case displacement response, Wood floor

DISPLAY CASE 1

TEST SERIES	File Designation	Ground (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. A (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 4 (g)	Mean Abs. Acc (g)	Standard Deviation
	D1- C- 2M6R30- T1	-0.58649	0.568		-0.52977	0.546		-0.41532	0.447		0.1420049	0.179		-0.723011	0.784	
46	D1- C- 2M6R30- T2	-0.56029			0.501609			0.4485454			-0.162037			-0.818182		
	D1- C- 2M6R30- T3	-0.558712		0.016	-0.60712		0.055	0.476832		0.031	0.2314814		0.047	-0.81179		0.053
	D1- C- 2M7R50- T1	0.4921086	0.494		-0.66747	0.612		-0.442259	0.441		0.1464565	0.144		-1.018466	0.845	
47	D1- C- 2M7R50- T2	0.4987374			-0.62142			0.4377695			-0.14245			-0.825284		
	D1- C- 2M7R50- T3	0.490846		0.004	-0.5481		0.060	0.4418105		0.002	0.1442307		0.002	-0.691051		0.165
	D1- C- 2M7R70- T1	0.3781566	0.385		0.41309	0.401		0.5051187	0.488		-0.131766	0.114		-0.526278	0.494	
48	D1- C- 2M7R70- T2	-0.37279			0.405043			0.4979348			-0.093038			-0.517045		
	D1- C- 2M7R70- T3	-0.404356		0.017	0.385819		0.014	0.4611172		0.024	-0.115741		0.019	0.4389204		0.048

DISPLAY CASE 3

TEST SERIES	File Designation	Ground (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. A (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 4 (g)	Mean Abs. Acc (g)	Standard Deviation
	D3- C- 2M6R30- T1	-0.504419	0.517		1.80481	2.016		0.5908766	0.770		-0.452724	0.445		3.3025564	2.725	
49	D3- C- 2M6R30- T2	-0.526199			2.141452			-0.730065			0.4433759			3.1051133		
	D3- C- 2M6R30- T3	-0.520202		0.011	2.101216		0.184	-0.988686		0.202	0.4402598		0.006	1.7684657		0.835
	D3- C- 2M7R50- T1	0.4182449	0.413		-2.45172	2.101		-0.796516	0.843		-0.384615	0.398		-3.288352	2.616	
50	D3- C- 2M7R50- T2	0.4078283			1.830293			-0.770025			-0.300926			-1.46804		
	D3- C- 2M7R50- T3	-0.411932		0.005	-2.02119		0.318	-0.961746		0.104	-0.508369		0.104	-3.090198		0.999
	D3- C- 2M7R70- T1	-0.389205	0.375		1.785139	1.803		0.7233299	0.715		-0.439815	0.430		-2.857954	2.688	
51	D3- C- 2M7R70- T2	0.3566919			-1.73015			-0.752066			-0.44204			2.4417611		
	D3- C- 2M7R70- T3	-0.379419		0.017	-1.89512		0.084	-0.670349		0.041	-0.407763		0.019	2.7656247		0.219

DISPLAY CASE 2

TEST SERIES	File Designation	Ground (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. A (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Acc (g)	Standard Deviation	Accel. 4 (g)	Mean Abs. Acc (g)	Standard Deviation
	D2- C- 2M6R30- T1	-0.532513	0.553		-0.50116	0.493		-0.539242	0.643		0.2550747	0.353		0.3025568	0.301	
27	D2- C- 2M6R30- T2	-0.548927			0.48015			-0.688757			0.4326922			0.3103693		
	D2- C- 2M6R30- T3	-0.577336		0.023	-0.49803		0.011	-0.699982		0.090	0.3721509		0.090	0.2904829		0.010
	D2- C- 2M7R50- T1	0.4444444	0.448		0.589682	0.928		-0.717044	1.017		-0.140224	0.225		-0.288352	0.247	
	D2- C- 2M7R50- T2	0.4116162			1.46191			-0.575162			-0.101051			-0.240057		
28	D2- C- 2M7R50- T3	0.4280303			1.011266			-1.45564			0.3307513			-0.279119		
	D2- C- 2M7R50- T4	0.4646465			0.943312			0.9864406			-0.222578			-0.171165		
	D2- C- 2M7R50- T5	0.489899		0.031	0.634835		0.351	-1.350126		0.384	0.3285255		0.105	-0.254972		0.046
	D2- C- 2M7R70- T1	0.3762626	0.393		-0.55526	0.590		-0.642062	0.571		-0.203437	0.125		0.1498579	0.113	
29	D2- C- 2M7R70- T2	-0.392045			-0.5253			-0.54912			0.0783476			0.0951704		
	D2- C- 2M7R70- T3	-0.410038		0.017	-0.68893		0.087	-0.520833		0.063	-0.093928		0.068	-0.09517		0.032

Figure B 3: Base motion effect on display case acceleration response, Carpet floor

DISPLAY CASE 1

TEST SERIE	File Designation	Ground (g)	LVDT 1 (Max) (mm)	Mean Rel.Disp (mm)	Standar Deviati	LVDT 2 (Max.) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 1 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 2 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio
	D1- C- 2M6R30- T1	-0.58649	-1.5056	1.287		-0.446513	0.273		-0.58086	0.263		-0.332606	0.128	
46	D1- C- 2M6R30- T2	-0.56029	-1.1478			-0.200475			-0.20911			-0.03645		
	D1- C- 2M6R30- T3	-0.558712	1.20819		0.192	0.173138		0.151	0		0.294	-0.013669		0.178
	D1- C- 2M7R50- T1	0.4921086	1.51953	1.580		-0.227813	0.226		0	0.029		-0.027337	0.015	
47	D1- C- 2M7R50- T2	0.4987374	1.57994			0.223256			-0.07435			0.009113		
	D1- C- 2M7R50- T3	0.490846	1.64035		0.060	0.227813		0.003	-0.01394		0.040	-0.009113		0.011
	D1- C- 2M7R70- T1	0.3781566	1.40336	1.434		0.273375	0.260		-0.02323	0.074		0.045563	0.035	
48	D1- C- 2M7R70- T2	-0.37279	-1.4545			0.236925			-0.11152			0.018225		
	D1- C- 2M7R70- T3	-0.404356	1.44518		0.027	0.268819		0.020	-0.08829		0.046	0.041006		0.015

DISPLAY CASE 3

TEST SERIE	File Designation	Ground (g)	LVDT 1 (sliding (mm)	Mean Rel.Disp (mm)	Standar Deviati	LVDT 2 (sliding) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 1 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 2 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio
	D3- C- 2M6R30- T1	-0.504419	-0.3485	0.353		0.1458	0.129		0.01394	0.025		0.063787	0.039	
49	D3- C- 2M6R30- T2	-0.526199	-0.316			-0.118463			0.04647			-0.022781		
	D3- C- 2M6R30- T3	-0.520202	0.39498		0.040	-0.123019		0.015	0.01394		0.019	-0.031894		0.022
	D3- C- 2M7R50- T1	0.4182449	0.34852	0.355		0.132131	0.134		0.05112	0.036		0.018225	0.020	
50	D3- C- 2M7R50- T2	0.4078283	0.3671			-0.113906			-0.01394			-0.004556		
	D3- C- 2M7R50- T3	-0.411932	-0.3485		0.011	-0.154913		0.021	-0.04182		0.019	-0.03645		0.016
	D3- C- 2M7R70- T1	-0.389205	-0.4368	0.435		0.141244	0.125		0.08829	0.043		0.022781	0.038	
51	D3- C- 2M7R70- T2	0.3566919	-0.4182			-0.118463			-0.02323			-0.022781		
	D3- C- 2M7R70- T3	-0.379419	-0.4507		0.016	-0.113906		0.015	0.01859		0.039	-0.068344		0.026

DISPLAY CASE 2

TEST SERIE	File Designation	Ground (g)	LVDT 1 (sliding (mm)	Mean Rel.Disp (mm)	Standar Deviati	LVDT 2 (sliding) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 1 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio	LVDT 2 (Final) (mm)	Mean Rel.Disp (mm)	Standard Deviatio
	D2- C- 2M6R30- T1	-0.532513	-1.2732	1.225		0.423732	0.413		-0.04182	0.082		0.209588	0.246	
27	D2- C- 2M6R30- T2	-0.548927	-1.2221			0.428287			-0.08829			0.250593		
	D2- C- 2M6R30- T3	-0.577336	-1.1803		0.047	0.387281		0.022	-0.11617		0.038	0.277931		0.034
	D2- C- 2M7R50- T1	0.4444444	-1.8727	1.999		0.774563	0.820		-0.35781	0.763		0.54675	0.705	
	D2- C- 2M7R50- T2	0.4116162	-2.9275			1.581019			-1.92845			1.508119		
28	D2- C- 2M7R50- T3	0.4280303	-2.2351			1.161844			-0.99908			1.120837		
	D2- C- 2M7R50- T4	0.4646465	-1.7333			0.282488			-0.46469			0.164025		
	D2- C- 2M7R50- T5	0.489899	-1.2268		0.633	0.300712		0.561	0.06506		0.734	0.186806		0.592
	D2- C- 2M7R70- T1	0.3762626	0.83644	0.764		0.18225	0.167		0.20446	0.121		0.091125	0.087	
29	D2- C- 2M7R70- T2	-0.392045	-0.7156			0.164025			0.08364			0.059231		
	D2- C- 2M7R70- T3	-0.410038	-0.7389		0.064	0.154913		0.014	0.07435		0.073	0.10935		0.025

Figure B 4: Base motion effect on display case deflection response, Carpet floor

DISPLAY CASE 2														
TEST SERIES	File Designation	Ground (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Acce (g)	Standard Deviation
8	D2- W- 2M6R30- T1	-0.47601	0.495		-1.50617	1.340		-0.74533	0.769		-0.36859	0.321	
	D2- W- 2M6R30- T2	-0.46086			-1.4096			-0.78529			-0.25151		
	D2- W- 2M6R30- T3	-0.54672		0.046	1.103362		0.210	-0.77676		0.021	-0.34366		0.062
9	D2- W- 2M7R50- T1	-0.35101	0.371		-0.36078	0.370		-0.8028	0.864		-0.40509	0.380	
	D2- W- 2M7R50- T2	-0.39141			-0.36123			-0.9815			-0.37616		
	D2- W- 2M7R50- T3	-0.36963		0.020	-0.38716		0.015	-0.80909		0.101	-0.35746		0.024
10	D2- W- 2M7R70- T1	-0.35164	0.328		-1.43687	1.541		-0.9595	0.979		-0.33031	0.314	
	D2- W- 2M7R70- T2	0.315972			1.732385			-0.99856			0.331642		
	D2- W- 2M7R70- T3	-0.31723		0.020	-1.45252		0.166	-0.97881		0.020	-0.28045		0.029
11	D2- W- 2M6R30- 1- T1	-0.41351	0.424		-1.34925	1.205		-0.42385	0.509		-0.16159	0.176	
	D2- W- 2M6R30- 1- T2	-0.4173			1.389485			-0.52532			-0.13488		
	D2- W- 2M6R30- 1- T3	-0.44066		0.015	0.87491		0.286	-0.57696		0.078	0.230591		0.049
12	D2- W- 2M6R30- 2- T1	-0.66761	0.630		-3.76744	3.412		-1.83369	1.903		-0.763	0.669	
	D2- W- 2M6R30- 2- T2	-0.67172			-2.71638			-1.75602			0.699341		
	D2- W- 2M6R30- 2- T3	-0.55019		0.069	-3.75179		0.602	-2.1197		0.192	0.543536		0.113
13	D2- W- 2M7R50- 1- T1	-0.40909	0.438		-2.47139	2.410		-1.21767	1.184		-0.91257	0.711	
	D2- W- 2M7R50- 1- T2	-0.50316			-2.25858			-1.18041			-0.68554		
	D2- W- 2M7R50- 1- T3	-0.40152		0.057	-2.5		0.132	-1.15302		0.032	-0.53508		0.190
14	D2- W- 2M7R50- 2- T1	#REF!	#REF!		#REF!	#REF!		#REF!	#REF!		#REF!	#REF!	
	D2- W- 2M7R50- 2- T2	-0.71275			-3.51663			-2.59474			-1.18323		
	D2- W- 2M7R50- 2- T3	-0.60227		#REF!	-4.71432		#REF!	-1.809		#REF!	-1.3377		#REF!
15	D2- W- 2M7R70- 1- T1	-0.52367	0.505		-1.41586	1.294		-1.07669	1.072		-0.34144	0.431	
	D2- W- 2M7R70- 1- T2	-0.50442			-0.81411			-1.26392			-0.55867		
	D2- W- 2M7R70- 1- T3	-0.48769		0.018	-1.65102		0.432	-0.87419		0.195	-0.39263		0.114
16	D2- W- 2M7R70- 2- T1	-0.50473	0.516		-3.97935	4.470		-1.60605	1.744		-1.00516	0.963	
	D2- W- 2M7R70- 2- T2	-0.52652			-4.71477			-1.37751			-1.00027		
	D2- W- 2M7R70- 2- T3	-0.51547		0.011	-4.71522		0.425	-2.24946		0.452	-0.88497		0.068

Figure B 5: Effect of floor elevation on acceleration response, Hardwood floor

DISPLAY CASE 2											
File Designation	LVDT 1 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ. (mm)
D2- W- 2M6R30- T1	-1.48235	1.552		-0.647	0.645		0.381044	0.243		-0.21414	0.443
D2- W- 2M6R30- T2	-1.58458			0.25971			-0.08829			0.205031	
D2- W- 2M6R30- T3	-1.58923		0.060	1.02971		0.385	0.260225		0.147	0.91125	
D2- W- 2M7R50- T1	1.124544	0.866		0.31438	0.287		0.645916	0.392		0.241481	0.223
D2- W- 2M7R50- T2	0.734206			0.22326			0.292753			0.173138	
D2- W- 2M7R50- T3	0.738853		0.224	0.32349		0.055	0.236991		0.222	0.25515	
D2- W- 2M7R70- T1	-1.76581	1.919		0.95681	1.045		-1.05019	0.683		0.906694	0.966
D2- W- 2M7R70- T2	-2.43032			1.05249			-0.99908			1.011488	
D2- W- 2M7R70- T3	-1.56135		0.454	1.12539		0.085	0		0.592	0.979594	
D2- W- 2M6R30- 1- T1	-1.43588	1.222		0.28249	0.374		-0.7435	0.520		0.209587	0.266
D2- W- 2M6R30- 1- T2	-1.34759			0.50574			-0.60874			0.410063	
D2- W- 2M6R30- 1- T3	-0.88291		0.297	0.33261		0.117	-0.20911		0.278	0.177694	
D2- W- 2M6R30- 2- T1	19.41464	16.524		3.08458	3.572		14.58654	9.023		2.95245	3.352
D2- W- 2M6R30- 2- T2	15.88302			4.1553			6.761203			3.804469	
D2- W- 2M6R30- 2- T3	-14.2752		2.629	3.47642		0.542	5.720303		4.846	3.298725	
D2- W- 2M7R50- 1- T1	-8.55954	7.722		1.36232	2.099		-7.6627	7.091		1.289419	1.988
D2- W- 2M7R50- 1- T2	-10.2417			2.15966			-9.63297			1.950075	
D2- W- 2M7R50- 1- T3	-4.36342		3.027	2.77476		0.708	-3.97773		2.871	2.724638	
D2- W- 2M7R50- 2- T1	#REF!	#REF!		#REF!	#REF!		#REF!	#REF!		#REF!	#REF!
D2- W- 2M7R50- 2- T2	-28.4621			8.94848			-26.3803			8.656875	
D2- W- 2M7R50- 2- T3	-34.6843		#REF!	11.8326		#REF!	-32.2679		#REF!	11.35873	
D2- W- 2M7R70- 1- T1	-3.33181	2.365		0.32349	0.659		-2.63478	1.814		0.177693	0.515
D2- W- 2M7R70- 1- T2	-1.46377			0.63332			-0.88291			0.523969	
D2- W- 2M7R70- 1- T3	-2.3002		0.936	1.0206		0.349	-1.92381		0.881	0.842906	
D2- W- 2M7R70- 2- T1	-15.33	15.344		6.54733	8.040		-11.5196	11.063		6.214725	7.694
D2- W- 2M7R70- 2- T2	-16.4499			3.86826			-10.3997			3.585769	
D2- W- 2M7R70- 2- T3	-14.252		1.099	13.7052		5.086	-11.2687		0.588	13.28147	

Figure B 6: Effect of floor elevation on displacement response, Hardwood floor

DISPLAY CASE 2														
File Designation	Ground	Mean Abs. Acce	Standard Deviation	Accel. 1	Mean Abs. Acce	Standard Deviation	Accel. 2	Mean Abs. Acce	Standard Deviation	Accel. 3	Mean Abs. Acce	Standard Deviation	Accel. 4	Mean Abs. Acce
	(g)	(g)		(g)	(g)		(g)	(g)		(g)	(g)		(g)	(g)
D2- C- 2M6R30- T1	-0.53251	0.553		-0.50116	0.493		-0.53924	0.643		0.255075	0.353		0.302557	0.301
D2- C- 2M6R30- T2	-0.54893			0.48015			-0.68876			0.432692			0.310369	
D2- C- 2M6R30- T3	-0.57734		0.023	-0.49803		0.011	-0.69998		0.090	0.372151		0.090	0.290483	
D2- C- 2M7R50- T1	0.444444	0.448		0.589682	0.928		-0.71704	1.017		-0.14022	0.225		-0.28835	0.247
D2- C- 2M7R50- T2	0.411616			1.46191			-0.57516			-0.10105			-0.24006	
D2- C- 2M7R50- T3	0.42803			1.011266			-1.45564			0.330751			-0.27912	
D2- C- 2M7R50- T4	0.464646			0.943312			0.986441			-0.22258			-0.17116	
D2- C- 2M7R50- T5	0.489899		0.031	0.634835		0.351	-1.35013		0.384	0.328526		0.105	-0.25497	
D2- C- 2M7R70- T1	0.376263	0.393		-0.55526	0.590		-0.64206	0.571		-0.20344	0.125		0.149858	0.113
D2- C- 2M7R70- T2	-0.39205			-0.5253			-0.54912			0.078348			0.09517	
D2- C- 2M7R70- T3	-0.41004		0.017	-0.68893		0.087	-0.52083		0.063	-0.09393		0.068	-0.09517	
D2- C- 2M6R30- 1- T1	0.461806	0.450		0.728272	0.602		-0.6928	0.984		-0.32541	0.281		-0.12429	0.179
D2- C- 2M6R30- 1- T2	0.45423			0.456903			-1.13236			0.189192			0.176136	
D2- C- 2M6R30- 1- T3	0.434028		0.014	0.620976		0.137	-1.12698		0.252	-0.32897		0.080	0.237926	
D2- C- 2M6R30- 2- T1	-0.54104	0.558		-3.57341	2.646		5.935257	5.455		3.591968	3.300		7.122158	6.175
D2- C- 2M6R30- 2- T2	-0.56944			1.946531			4.489944			2.705662			5.687499	
D2- C- 2M6R30- 2- T3	0.564394		0.015	-2.41953		0.837	5.940645		0.836	3.601762		0.515	5.714488	
D2- C- 2M7R50- 1- T1	0.475379	0.477		-2.15486	2.156		5.4023	5.756		-2.44079	2.210		3.775568	3.907
D2- C- 2M7R50- 1- T2	0.45423			1.8978			5.935257			-2.26318			3.31534	
D2- C- 2M7R50- 1- T3	0.502841		0.024	-2.41595		0.259	5.931216		0.307	1.927083		0.261	4.629971	
D2- C- 2M7R50- 2- T1	0.510732	0.542		4.710747	4.705		5.937502	5.941		-4.06205	4.322		9.948862	10.411
D2- C- 2M7R50- 2- T2	0.582071			4.698676			5.944686			-4.43777			10.49645	
D2- C- 2M7R50- 2- T3	0.53346		0.036	4.705382		0.006	5.940645		0.004	-4.46581		0.225	10.78764	
D2- C- 2M7R70- 1- T1	0.414773	0.417		-2.35113	2.263		4.284753	5.108		-1.98184	2.007		4.191761	4.005
D2- C- 2M7R70- 1- T2	0.424558			-2.12849			5.931665			1.594551			3.514914	
D2- C- 2M7R70- 1- T3	0.410669		0.007	2.309549		0.118	5.106413		0.823	-2.44435		0.425	4.308948	
D2- C- 2M7R70- 2- T1	-0.52999	0.508		4.705382	4.707		5.94289	5.946		-4.47204	4.468		12.72159	12.956
D2- C- 2M7R70- 2- T2	0.486742			4.709853			5.949176			-4.48362			13.07741	
D2- C- 2M7R70- 2- T3	0.507576		0.022	4.704935		0.003	5.946482		0.003	-4.44889		0.018	13.06818	

Figure B 7: Effect of floor elevation on acceleration response, Carpet

DISPLAY CASE 2												
File Designation	LVDT 1 (sliding)	Mean Rel.Displ.	Standard Deviation	LVDT 2 (sliding)	Mean Rel.Displ.	Standard Deviation	LVDT 1 (Final)	Mean Rel.Displ.	Standard Deviation	LVDT 2 (Final)	Mean Rel.Displ.	Standard Deviation
	(mm)	(mm)		(mm)	(mm)		(mm)	(mm)		(mm)	(mm)	
D2- C- 2M6R30- T1	-1.27324	1.225		0.423732	0.413		-0.04182	0.082		0.209588		
D2- C- 2M6R30- T2	-1.22213			0.428287			-0.08829			0.250593		
D2- C- 2M6R30- T3	-1.18031		0.047	0.387281		0.022	-0.11617		0.038	0.277931	0.246	0.034
D2- C- 2M7R50- T1	-1.87269	1.999		0.774563	0.820		-0.35781	0.763		0.54675		
D2- C- 2M7R50- T2	-2.92753			1.581019			-1.92845			1.508119		
D2- C- 2M7R50- T3	-2.23515			1.161844			-0.99908			1.120837		
D2- C- 2M7R50- T4	-1.73328			0.282488			-0.46469			0.164025		
D2- C- 2M7R50- T5	-1.22678		0.633	0.300712		0.561	0.065056		0.734	0.186806	0.705	0.592
D2- C- 2M7R70- T1	0.836438	0.764		0.18225	0.167		0.204463	0.121		0.091125		
D2- C- 2M7R70- T2	-0.71562			0.164025			0.083644			0.059231		
D2- C- 2M7R70- T3	-0.73885		0.064	0.154913		0.014	0.07435		0.073	0.10935	0.087	0.025
D2- C- 2M6R30- 1- T1	-1.29648	1.056		0.378169	0.287		-0.26952	0.133		0.350831		
D2- C- 2M6R30- 1- T2	-0.84573			0.241481			0.116172			0.195919		
D2- C- 2M6R30- 1- T3	-1.02696		0.227	0.241481		0.079	-0.01394		0.129	0.191363	0.246	0.091
D2- C- 2M6R30- 2- T1	6.389453	8.922		24.16179	31.889		4.962863	3.369		23.96132		
D2- C- 2M6R30- 2- T2	-8.60137			37.99001			0.934022			37.74853		
D2- C- 2M6R30- 2- T3	-11.7752		2.707	33.51578		7.056	-4.21007		2.142	33.34264	31.684	7.042
D2- C- 2M7R50- 1- T1	-11.1757	9.413		28.71349	22.944		-5.02792	2.852		28.52213		
D2- C- 2M7R50- 1- T2	-9.37739			25.62435			-2.87177			25.54234		
D2- C- 2M7R50- 1- T3	-7.68593		1.745	14.49343		7.479	-0.65521		2.186	14.32941	22.798	7.484
D2- C- 2M7R50- 2- T1	-13.9267	13.338		81.42019	72.733		2.2305	3.082		81.40196		
D2- C- 2M7R50- 2- T2	-13.62			67.04066			1.779753			66.82196		
D2- C- 2M7R50- 2- T3	-12.4676		0.769	69.73796		7.643	5.237028		1.880	69.30512	72.510	7.800
D2- C- 2M7R70- 1- T1	-9.84208	10.995		40.91968	43.351		5.083681	2.938		40.68731		
D2- C- 2M7R70- 1- T2	-10.5623			42.77408			2.109681			42.63739		
D2- C- 2M7R70- 1- T3	-12.5791		1.419	46.35984		2.766	1.621759		1.874	46.23227	43.186	2.813
D2- C- 2M7R70- 2- T1	32.01232	30.479		88.40036	85.011		29.33108	27.612		87.93563		
D2- C- 2M7R70- 2- T2	31.42682			77.41524			28.5504			76.8366		
D2- C- 2M7R70- 2- T3	27.99742		2.169	89.21593		6.590	24.95372		2.335	88.99268	84.588	6.734

Figure B 8: Effect of floor elevation on displacement response, Carpet

DISPLAY CASE 2												
File Designation	Groun (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Accel (g)	Standard Deviation
D2- W- 2M6R30- T1	-0.476	**0.495**		-1.50617	**1.340**		-0.74533	**0.769**		-0.36859	**0.321**	
D2- W- 2M6R30- T2	-0.461			-1.4096			-0.78529			-0.25151		
D2- W- 2M6R30- T3	-0.547		**0.046**	1.103362		**0.210**	-0.77676		**0.021**	-0.34366		**0.062**
D2- W- 2M7R50- T1	-0.351	**0.371**		-0.36078	**0.370**		-0.8028	**0.864**		-0.40509	**0.380**	
D2- W- 2M7R50- T2	-0.391			-0.36123			-0.9815			-0.37616		
D2- W- 2M7R50- T3	-0.37		**0.020**	-0.38716		**0.015**	-0.80909		**0.101**	-0.35746		**0.024**
D2- W- 2M7R70- T1	-0.352	**0.328**		-1.43687	**1.541**		-0.9595	**0.979**		-0.33031	**0.314**	
D2- W- 2M7R70- T2	0.316			1.732385			-0.99856			0.331642		
D2- W- 2M7R70- T3	-0.317		**0.020**	-1.45252		**0.166**	-0.97881		**0.020**	-0.28045		**0.029**
D2- W- 2M6R30- M1- T1	-0.375	**0.607**		-0.83968	**1.538**		-0.5599	**0.573**		-0.08992	**0.122**	
D2- W- 2M6R30- M1- T2	0.717			2.168723			0.582795			0.12776		
D2- W- 2M6R30- M1- T3	0.728		**0.201**	1.606759		**0.667**	0.576958		**0.012**	0.149127		**0.030**
D2- W- 2M7R50- M1- T1	-0.604	**0.631**		-0.63841	**0.607**		-0.52667	**0.559**		-0.16693	**0.144**	
D2- W- 2M7R50- M1- T2	-0.667			-0.59549			-0.56753			-0.12598		
D2- W- 2M7R50- M1- T3	-0.623		**0.032**	-0.58655		**0.028**	-0.58235		**0.029**	-0.13889		**0.021**
D2- W- 2M7R70- M1- T1	0.496	**0.503**		0.921853	**0.882**		0.625	**0.568**		0.107728	**0.106**	
D2- W- 2M7R70- M1- T2	-0.489			-0.78773			-0.56034			-0.11129		
D2- W- 2M7R70- M1- T3	-0.524		**0.019**	-0.93705		**0.082**	-0.51904		**0.053**	-0.09972		**0.006**
D2- W- 2M6R30- M2- T1	-0.675	**0.685**		1.693938	**1.423**		-1.16739	**0.970**		0.621439	**0.493**	
D2- W- 2M6R30- M2- T2	-0.68			1.229435			-1.03807			-0.54932		
D2- W- 2M6R30- M2- T3	-0.701		**0.014**	1.344331		**0.242**	-0.70582		**0.238**	-0.3076		**0.164**
D2- W- 2M7R50- M2- T1	-0.599	**0.579**		-0.66434	**0.645**		-0.92044	**1.121**		-0.43714	**0.356**	
D2- W- 2M7R50- M2- T2	-0.583			-0.57538			-1.23608			-0.36102		
D2- W- 2M7R50- M2- T3	-0.556		**0.022**	-0.6943		**0.062**	-1.20645		**0.174**	-0.26887		**0.084**
D2- W- 2M7R70- M2- T1	-0.533	**0.515**		-0.51323	**0.584**		-0.90203	**0.897**		-0.27822	**0.325**	
D2- W- 2M7R70- M2- T2	-0.471			-0.49401			-0.88227			-0.37037		
D2- W- 2M7R70- M2- T3	-0.543		**0.039**	-0.74481		**0.140**	-0.90697		**0.013**	-0.32674		**0.046**

Figure B 9: Effect of art object mass on acceleration response, Hardwood floor

DISPLAY CASE 2												
File Designation	LVDT 1 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ. (mm)	Standard Deviation
D2- W- 2M6R30- T1	-1.48235	**1.552**		-0.64699	**0.645**		0.381044	**0.243**		-0.21414	**0.443**	
D2- W- 2M6R30- T2	-1.58458			0.259706			-0.08829			0.205031		
D2- W- 2M6R30- T3	-1.58923		**0.060**	1.029713		**0.385**	0.260225		**0.147**	0.91125		**0.405**
D2- W- 2M7R50- T1	1.124544	**0.866**		0.314381	**0.287**		0.645916	**0.392**		0.241481	**0.223**	
D2- W- 2M7R50- T2	0.734206			0.223256			0.292753			0.173138		
D2- W- 2M7R50- T3	0.738853		**0.224**	0.323494		**0.055**	0.236991		**0.222**	0.25515		**0.044**
D2- W- 2M7R70- T1	-1.76581	**1.919**		0.956813	**1.045**		-1.05019	**0.683**		0.906694	**0.966**	
D2- W- 2M7R70- T2	-2.43032			1.052494			-0.99908			1.011488		
D2- W- 2M7R70- T3	-1.56135		**0.454**	1.125394		**0.085**	0		**0.592**	0.979594		**0.054**
D2- W- 2M6R30- M1- T1	-4.20078	**3.010**		1.3851	**0.686**		-3.72679	**2.450**		1.211963	**0.465**	
D2- W- 2M6R30- M1- T2	-2.94612			0.441956			-2.33273			0.18225		
D2- W- 2M6R30- M1- T3	-1.88198		**1.161**	0.232369		**0.614**	-1.29183		**1.222**	0		**0.654**
D2- W- 2M7R50- M1- T1	0.831791	**0.742**		0.195919	**0.190**		0.199816	**0.130**		0.022781	**0.061**	
D2- W- 2M7R50- M1- T2	0.724913			-0.16858			0.018588			-0.05923		
D2- W- 2M7R50- M1- T3	0.66915		**0.083**	0.205031		**0.019**	0.171934		**0.098**	0.100238		**0.039**
D2- W- 2M7R70- M1- T1	-1.23142	**1.058**		0.3645	**0.428**		-0.60409	**0.400**		0.236925	**0.263**	
D2- W- 2M7R70- M1- T2	-1.10131			0.460181			-0.43216			0.273375		
D2- W- 2M7R70- M1- T3	-0.84108		**0.199**	0.460181		**0.055**	-0.16264		**0.223**	0.277931		**0.022**
D2- W- 2M6R30- M2- T1	-2.68589	**2.012**		-0.46929	**0.301**		-1.84016	**1.211**		-0.26426	**0.153**	
D2- W- 2M6R30- M2- T2	-1.71934			0.18225			-0.98049			0.082013		
D2- W- 2M6R30- M2- T3	-1.63105		**0.585**	0.250594		**0.150**	-0.8132		**0.551**	0.113906		**0.097**
D2- W- 2M7R50- M2- T1	1.078075	**0.860**		0.32805	**0.305**		0.618034	**0.305**		0.227813	**0.245**	
D2- W- 2M7R50- M2- T2	0.785322			0.2916			0.2974			0.246038		
D2- W- 2M7R50- M2- T3	0.715619		**0.192**	0.296156		**0.020**	0		**0.309**	0.259706		**0.016**
D2- W- 2M7R70- M2- T1	0.799263	**0.771**		0.428288	**0.478**		0.343869	**0.226**		0.350831	**0.393**	
D2- W- 2M7R70- M2- T2	0.789969			0.478406			0.255578			0.428288		
D2- W- 2M7R70- M2- T3	-0.72491		**0.041**	0.528525		**0.050**	0.078997		**0.135**	0.40095		**0.039**

Figure B 10: Effect of art object mass on displacement response, Hardwood floor

DISPLAY CASE 2															
File Designation	Ground (g)	Mean Abs. Accel. (g)	Standard Deviation	Accel. 1 (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 2 (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 3 (g)	Mean Abs. Acce (g)	Standard Deviation	Accel. 4 (g)	Mean Abs. Acce (g)	Standard Deviation
D2- C- 2M6R30- T2	-0.548927			0.48015			-0.68876			0.432692			0.310369		
D2- C- 2M6R30- T3	-0.577336		0.023	-0.49803		0.011	-0.69998		0.090	0.372151		0.090	0.290483		0.010
D2- C- 2M7R50- T1	0.444444	0.448		0.589682	0.928		-0.71704	1.017		-0.14022	0.225		-0.28835	0.247	
D2- C- 2M7R50- T2	0.411616			1.46191			-0.57516			-0.10105			-0.24006		
D2- C- 2M7R50- T3	0.42803			1.011266			-1.45564			0.330751			-0.27912		
D2- C- 2M7R50- T4	0.464646			0.943312			0.986441			-0.22258			-0.17116		
D2- C- 2M7R50- T5	0.489899		0.031	0.634835		0.351	-1.35013		0.384	0.328526		0.105	-0.25497		0.046
D2- C- 2M7R70- T1	0.376263	0.393		-0.55526	0.590		-0.64206	0.571		-0.20344	0.125		0.149858	0.113	
D2- C- 2M7R70- T2	-0.392045			-0.5253			-0.54912			0.078348			0.09517		
D2- C- 2M7R70- T3	-0.410038		0.017	-0.68893		0.087	-0.52083		0.063	-0.09393		0.068	-0.09517		0.032
D2- C- 2M6R30- M1- T1	-0.592172	0.564		-0.54855	0.530		-0.50332	0.549		-0.08369	0.136		-0.1875	0.207	
D2- C- 2M6R30- M1- T2	-0.566919			0.523069			-0.6021			-0.16382			-0.18111		
D2- C- 2M6R30- M1- T3	-0.532197		0.030	-0.5186		0.016	-0.54194		0.050	-0.16026		0.045	0.25142		0.039
D2- C- 2M7R50- M1- T1	0.457071	0.440		0.876252	0.760		0.869702	1.298		0.232372	0.363		-0.21094	0.300	
D2- C- 2M7R50- M1- T2	0.435922			0.771191			-1.47495			-0.48923			0.345881		
D2- C- 2M7R50- M1- T3	0.427083		0.015	0.632153		0.122	-1.54993		0.373	-0.36592		0.128	0.34446		0.078
D2- C- 2M7R70- M1- T1	-0.363636	0.369		0.639753	0.599		-0.61243	0.647		0.347222	0.222		-0.27699	0.184	
D2- C- 2M7R70- M1- T2	-0.385732			-0.60622			-0.67619			-0.12642			-0.13281		
D2- C- 2M7R70- M1- T3	-0.356376		0.015	0.549893		0.045	-0.65329		0.032	0.190972		0.114	-0.14347		0.080
D2- C- 2M6R30- M2- T1	-0.572601	0.546		-0.55079	0.529		-0.5801	0.612		0.182514	0.175		0.201705	0.207	
D2- C- 2M6R30- M2- T2	-0.518308			-0.53425			-0.69819			-0.18875			0.18892		
D2- C- 2M6R30- M2- T3	-0.547348		0.027	-0.50206		0.025	-0.5572		0.076	-0.15358		0.019	0.230114		0.021
D2- C- 2M7R50- M2- T1	0.463699	0.440		0.987124	0.845		-0.6681	0.830		0.327635	0.385		0.395697	0.611	
D2- C- 2M7R50- M2- T2	0.427083			-0.701			-0.85893			0.435363			0.704545		
D2- C- 2M7R50- M2- T3	0.428346		0.021	-0.84809		0.143	0.961746		0.149	0.390847		0.054	0.732954		0.187
D2- C- 2M7R70- M2- T1	0.375316	0.368		0.612929	0.691		-0.95007	1.028		0.280894	0.303		-0.33381	0.268	
D2- C- 2M7R70- M2- T2	-0.365215			0.718437			-1.10587			0.332087			-0.27912		
D2- C- 2M7R70- M2- T3	-0.362058		0.007	0.741684		0.069	-1.02685		0.078	0.294694		0.026	0.189631		0.073

Figure B 11: Effect of art object mass on acceleration response, Carpet

DISPLAY CASE 2												
File Designation	LVDT 1 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (sliding) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 1 (Final) (mm)	Mean Rel.Displ. (mm)	Standard Deviation	LVDT 2 (Final) (mm)	Mean Rel.Displ. (mm)	Standard Deviation
D2- C- 2M6R30- T1	-1.273244	1.225		0.423732	0.413		-0.041822			0.209588		
D2- C- 2M6R30- T2	-1.222128			0.428287			-0.088291			0.250593		
D2- C- 2M6R30- T3	-1.180307		0.047	0.387281		0.022	-0.116172	0.082	0.038	0.277931	0.246	0.034
D2- C- 2M7R50- T1	-1.87269	1.999		0.774563	0.820		-0.357809			0.54675		
D2- C- 2M7R50- T2	-2.927531			1.581019			-1.928453			1.508119		
D2- C- 2M7R50- T3	-2.235147			1.161844			-0.999078			1.120837		
D2- C- 2M7R50- T4	-1.733284			0.282488			-0.464687			0.164025		
D2- C- 2M7R50- T5	-1.226775		0.633	0.300712		0.561	0.065056	0.763	0.734	0.186806	0.705	0.592
D2- C- 2M7R70- T1	0.836438	0.764		0.18225	0.167		0.204463			0.091125		
D2- C- 2M7R70- T2	-0.715619			0.164025			0.083644			0.059231		
D2- C- 2M7R70- T3	-0.738853		0.064	0.154913		0.014	0.07435	0.121	0.073	0.10935	0.087	0.025
D2- C- 2M6R30- M1- T1	1.0409	1.063		0.300712	0.322		0.116172			0.173137		
D2- C- 2M6R30- M1- T2	1.050194			0.337162			0.144053			0.191362		
D2- C- 2M6R30- M1- T3	-1.096663		0.030	0.32805		0.019	-0.023234	0.094	0.063	0.195919	0.187	0.012
D2- C- 2M7R50- M1- T1	-3.043703	2.497		0.824681	0.706		-1.742578			0.733556		
D2- C- 2M7R50- M1- T2	-2.286262			0.624206			-0.738853			0.54675		
D2- C- 2M7R50- M1- T3	-2.160797		0.478	0.669768		0.105	-0.274166	0.919	0.751	0.528525	0.603	0.113
D2- C- 2M7R70- M1- T1	1.064134	1.066		0.246038	0.225		0.22305			0.086569		
D2- C- 2M7R70- M1- T2	1.124543			0.250594			0.250931			0.159469		
D2- C- 2M7R70- M1- T3	1.008372		0.058	0.177694		0.041	0.092938	0.189	0.084	0.009112	0.085	0.075
D2- C- 2M6R30- M2- T1	1.059488	1.010		0.259706	0.228		0.255578			0.164025		
D2- C- 2M6R30- M2- T2	0.947963			0.186806			0.1487			0.068344		
D2- C- 2M6R30- M2- T3	1.022313		0.057	0.236925		0.037	0.199816	0.201	0.053	0.10935	0.114	0.048
D2- C- 2M7R50- M2- T1	-2.430316	1.882		0.806456	0.761		-1.068781			0.747225		
D2- C- 2M7R50- M2- T2	-1.398709			0.637875			-0.102231			0.5832		
D2- C- 2M7R50- M2- T3	-1.816928		0.519	0.83835		0.108	-0.339222	0.503	0.504	0.738113	0.690	0.092
D2- C- 2M7R70- M2- T1	1.045547	1.039		0.186806	0.222		0.288106			0.0729		
D2- C- 2M7R70- M2- T2	1.059488			0.273375			0.227697			0.164025		
D2- C- 2M7R70- M2- T3	1.013019		0.024	0.205031		0.046	0.213756	0.243	0.040	0.077456	0.105	0.051

Figure B 12: Effect of art object mass on displacement response, Carpet

Appendix C

The data collected in this Appendix, is from results of case study 3, on the Redpath Museum dinosaur skeleton display, presented in Chapter 6.

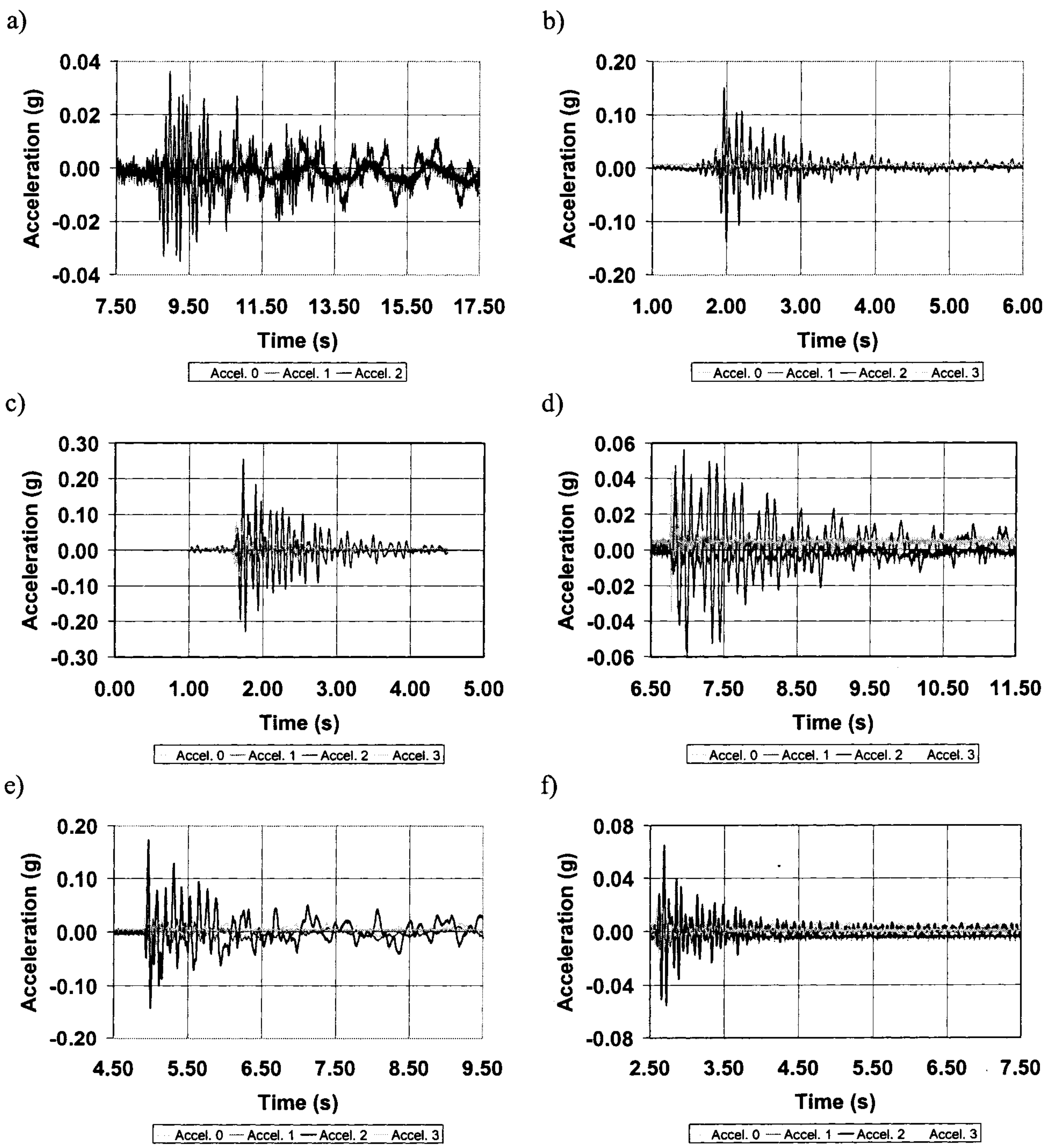


Figure C 1: Free vibration time history curves for the acceleration responses for test run a) 2, b) 3, c) 4, d) 5, e) 6, and 7

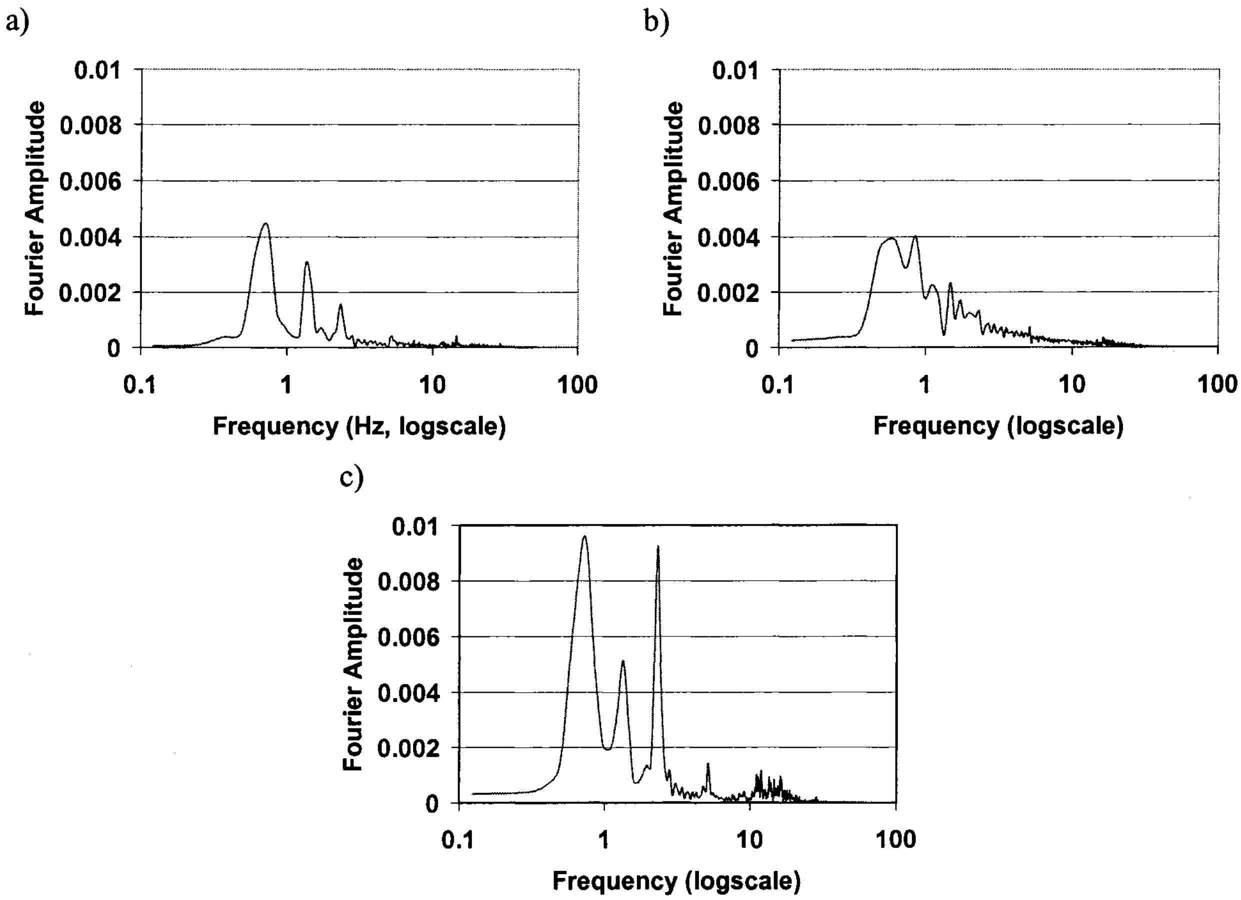


Figure C 2: FFT for acceleration responses of accelerometer a) 0, b) 1, and c) 2 of test run 2

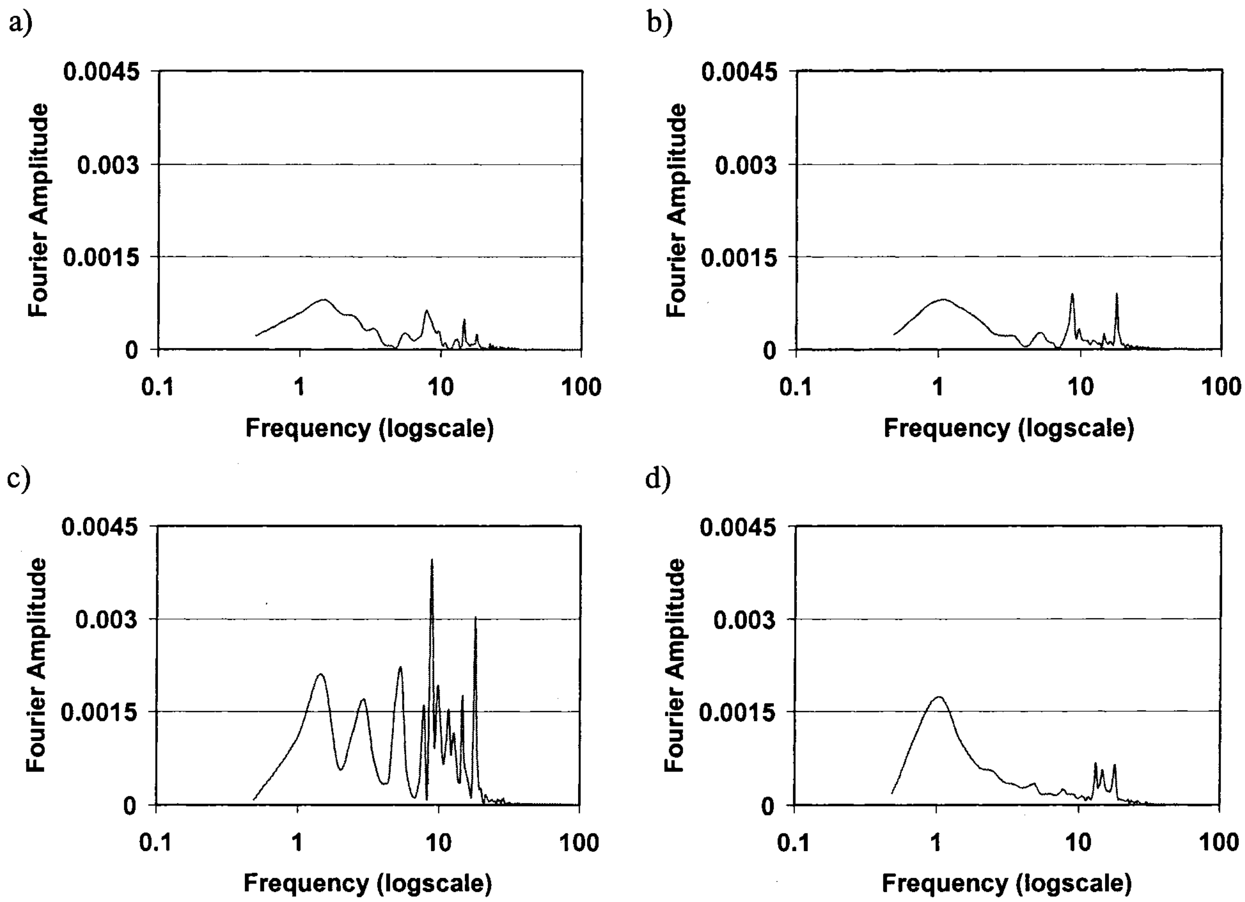


Figure C 3: FFT for acceleration responses of accelerometer a) 0, b) 1, c) 2, and d) 3 of test run 3

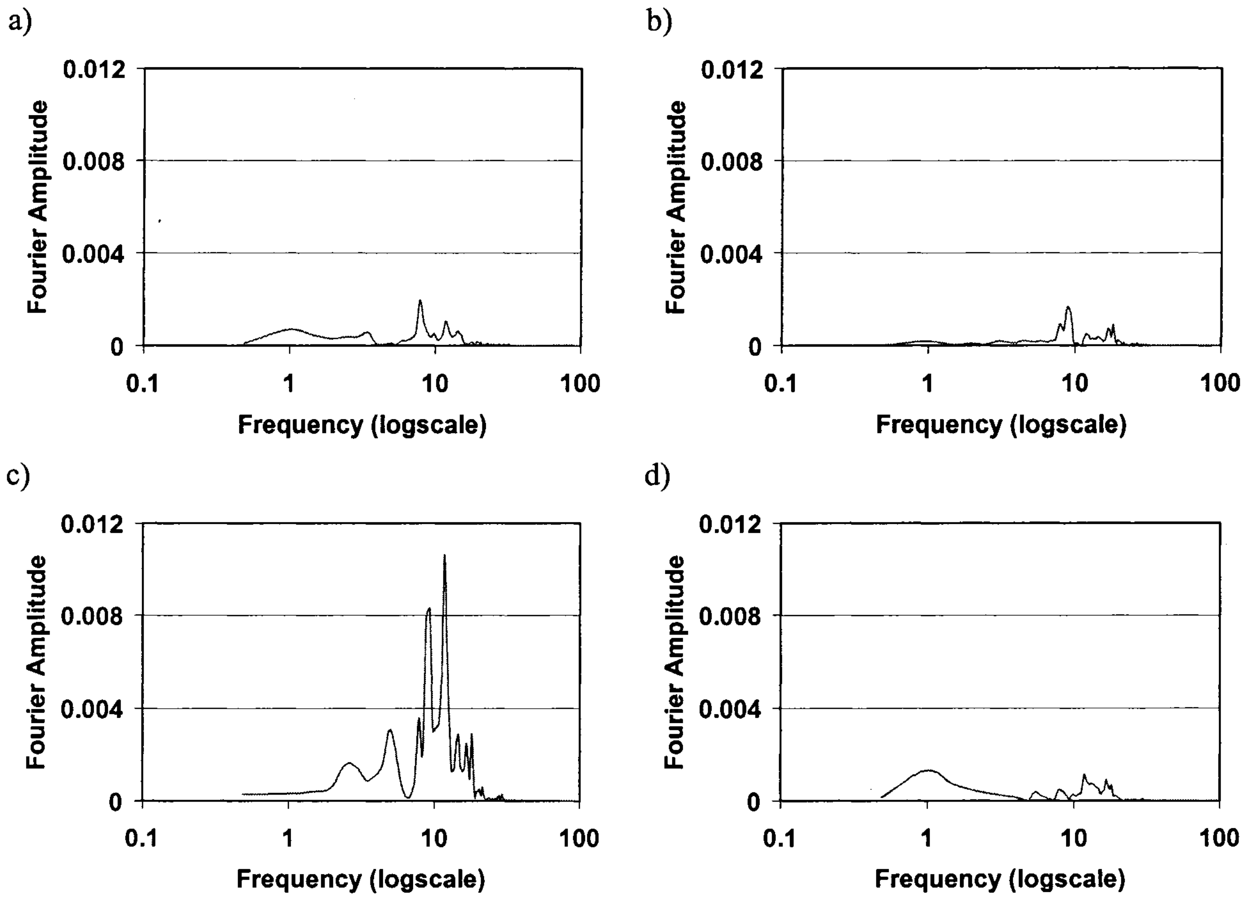


Figure C 4: FFT for acceleration responses of accelerometer a) 0, b) 1, c) 2, and d) 3 of test run 4

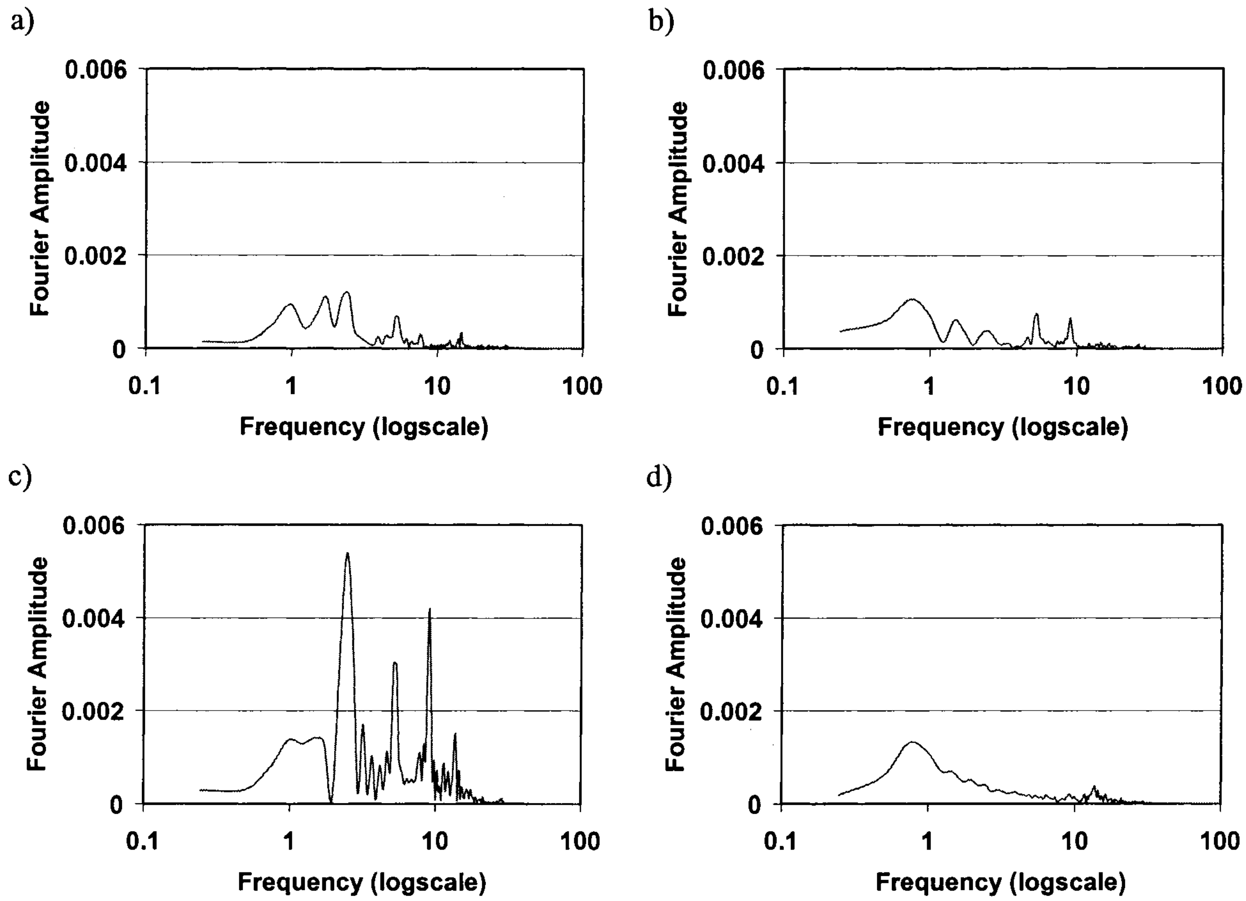


Figure C 5: FFT for acceleration responses of accelerometer a) 0, b) 1, c) 2, and d) 3 of test run 5

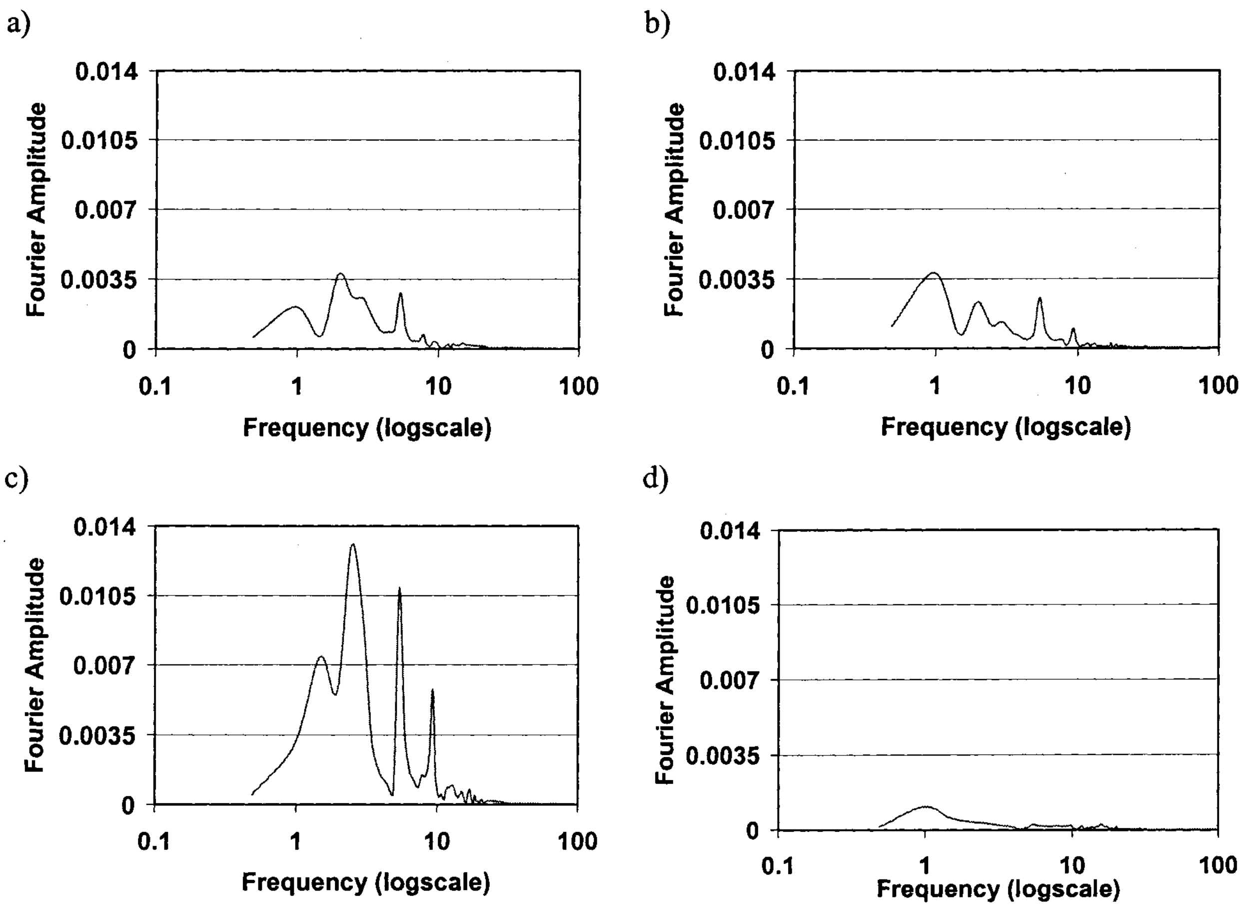


Figure C 6: FFT for acceleration responses of accelerometer a) 0, b) 1, c)2, and d) 3 of test run 6

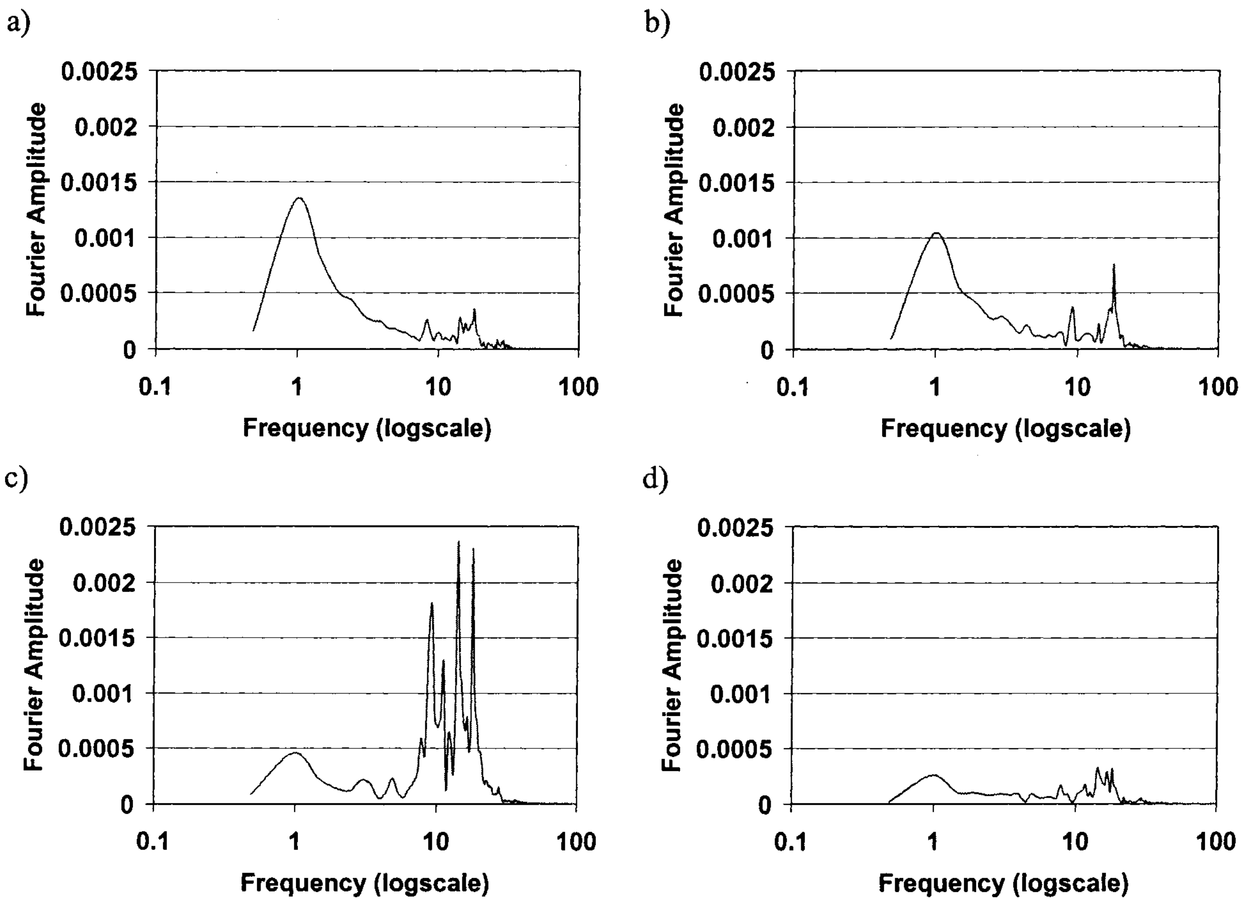


Figure C 7: FFT for acceleration responses of accelerometer a) 0, b) 1, c)2, and d) 3 of test run 7