The Feasibility of Fibre Reinforced Polymers as an Alternative to Steel in Reinforced Concrete

Christian Barker
McGill University
April 2016

Abstract

The corrosiveness of steel compromises the structural integrity of reinforced concrete (RC) structures and costs the infrastructure industry billions of dollars every year. In response to this, engineers have developed fibre reinforced polymers (FRPs) - non-metallic composite materials of superior strength to be used in place of steel. The three most commonly used FRPs in construction are carbon, glass, and aramid. This paper discusses the feasibility of each FRP as an alternative to steel in RC structures by comparing their mechanical properties, sustainable merits, and costs. Research reveals that while glass FRP is most sustainable, its poor strength and durability render it unusable for most RC applications. Aramid FRP's strength and durability fell short of carbon's and it is most expensive. Carbon FRP demonstrates the highest strength, greatest durability, and lowest final costs making it the most feasible FRP to replace steel in RC. Recommendations for future implementation include establishing building codes, improving recyclability and lowering initial costs.

Introduction

Concrete is one of the world's oldest and most influential construction materials. Composed simply of fine and coarse aggregates bound by a hard paste, concrete has formed some of the world's most famous structures including the Hoover Dam, the Burj Khalifa and the Roman Coliseum. Today, concrete is the single most used man-made material in the world [1] due to its incredible and unmatchable compressive strength. However, there exists a fundamental problem with concrete, its severe lack of tensile strength.

Concrete is one tenth as strong in tension as in compression, which causes concrete structures subjected to bending forces to fail easily [1]. This issue has been overcome since the late 19th century when civil engineers began combining concrete with steel in reinforced concrete [2], illustrated by Figure 1.

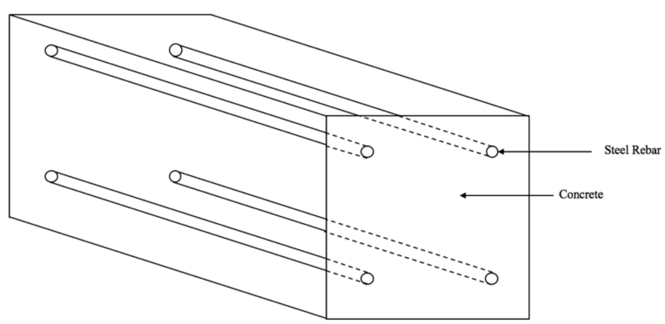

Figure 1. Schematic Representation of Reinforced Concrete.

Steel is strong and ductile, allowing it to resist high tensile forces while yielding plastically before failing. However, there exists a major problem with steel which continues to affect the construction industry. Steel, like most metals, is corrosive. Reinforced concrete subjected to corrosion loses structural integrity and costs the infrastructure industry billions of dollars every year [3]. In 2005, “direct annual corrosion costs were about $276 billion… out of that amount, 16.4% is the estimated direct costs of corrosion of infrastructure” [4]. That amounts to $45.3 billion dollars (in 2005) being spent on the repair or replacement of RC structures damaged by corrosion. In response to this problem, engineers and scientists have begun developing advanced materials to replace steel in RC structures.

Technological advancements within the past 25 years have led to the development of fiber reinforced polymers as an innovative alternative to steel in reinforced concrete [5]. Not only are they non-corrosive, but “FRPs have a much better strength-to-weight ratio than steel and this makes them an ideal material for applications in repair, rehabilitations, and strengthening works” [5]. The three most widely used FRPs in the concrete industry include carbon, glass, and aramid fiber reinforced polymers (CFRP, GFRP, and AFRP). While each provides a solution to the destructive and expensive problems associated with steel, the question of which FRP is most feasible still exists. This research paper will compare and contrast these three FRPs as alternative materials to steel for applications in RC structures based on their mechanical properties, sustainable merits, and economic costs. It will then provide recommendations for its future implementation. It will conclude that carbon fiber reinforced polymer is the most ideal FRP alternative to steel in reinforced concrete.

Background

Over the past 25 years, scientists have discovered that, “continuous long fibers can be used as a replacement of the steel as a reinforcing material for reinforced and pre-stressed concrete construction” [5]. FRPs are a composite of extremely fine fibers embedded in a matrix, as illustrated by Figure 2.

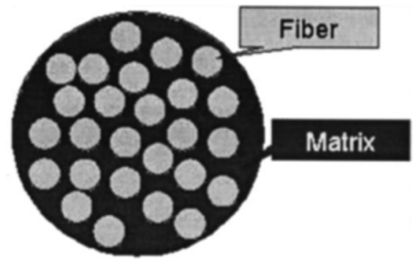

Figure 2: FRP Cross Section [5].

The fibers, from which FRPs get their tensile strength, make up 50 to 65% of the composite's total volume, with diameters ranging from 6 to 15 microns [5]. Carbon fibers are classified as pitch carbon or PAN carbon fibers, the former of which is made from petroleum or coal pitch and the latter from polyacrilic nytril (PAN). Glass fiber is made of silica and similarly classified into two groups. E-glass fibers are made of boric acid and aluminate, while the AR-glass fibers contain zirconia to prevent corrosion [5]. Aramid fiber, known commercially as Kevlar, is an organic fiber [5].

The matrix is made of resins including epoxies, vinylesters and polyesters whose purpose is to bind fibers, transfer loads from the concrete to the fibers and protect the fibers from damage [5]. Since the 1970's, FRPs have been manufactured by a process called "pultrusion" which consists of, "pulling a fiber material through a resin bath and then through a heated shaping die, where the resin is cured" [5], as illustrated by Figure 3 [6].

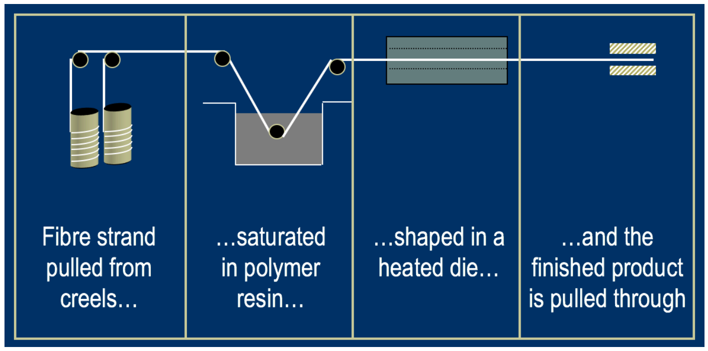

Figure 3. Simplified representation of the modern pultrusion method [6].

To assess the feasibility of carbon, glass, and aramid FRPs as alternatives to steel in RC applications, they must be compared to each other and to steel based on relevant variables. There are three criteria that this paper will use to discuss and compare the previously noted FRPs to steel: mechanical properties, sustainability, and costs. Each criterion contains sub-variables in order to analyze the materials on a more detailed level. When comparing the materials based on mechanical properties, the sub-variables used are tensile strength, stress-strain relationship and durability. To discuss the materials based on sustainability, FRPs will be compared based on their energy requirement and Green House Gas (GHG) emissions at the production stage and sustainable merits during their service life. The individual FRPs will then be compared to each other and to steel based on their recyclability. Finally, the sub-variables used to compare the materials based on cost include production costs, commercial costs and material cost per unit-force per unit-length.

Discussion

Mechanical Properties

The most suitable FRP to replace steel in RC should have mechanical properties comparable to or better than steel. The most important mechanical property of FRPs is tensile strength. Steel's ultimate tensile strength ranges from 483 to 690 MPa [6]. In comparison, FRP tensile strength is much higher. CFRP's ultimate tensile strength is the highest of the FRPs, ranging from 1200 to 2410 MPa. AFRP's tensile strength ranges from 1200 to 2068 MPA and GFRP's from 517 to 1207 MPa [6]. It is clear that CFRP is the strongest material while GFRP is the weakest. However, the elastic properties of the materials must also be considered.

The elastic modulus and the stress-strain relationship for each material is imperative for civil engineers to consider because it represents the behavior of the material up to failure. Figure 4 illustrates this relationship for each material superimposed on one diagram, and Table 1 summarizes their elastic properties. The data demonstrates that CFRP's elastic modulus most closely resembles that of steels while being up to four times stronger, making it the most mechanically attractive FRP. However, the data also demonstrates that, "though all the fibers exhibit a higher tensile strength than steel, the elongation before the material finally fails is very small for the fibers" [5], inferring FRPs are more feasible materials when structures are expected to experience small deflections. For real-world applications, the durability of these materials is of equal importance to strength and stiffness.

Table 1: Mechanical Properties of CFRP, GFRP, AFRP, steel [6].

Material	Ultimate Strength (MPa)	Elastic Modulus (GPa)	Failure Strain (%)
GFRP	517-1207	30-55	2-4.5
CFRP	1200-2410	147-165	1-1.5
AFRP	1200-2068	50-74	2-2.6
Steel	483-690	200	>10

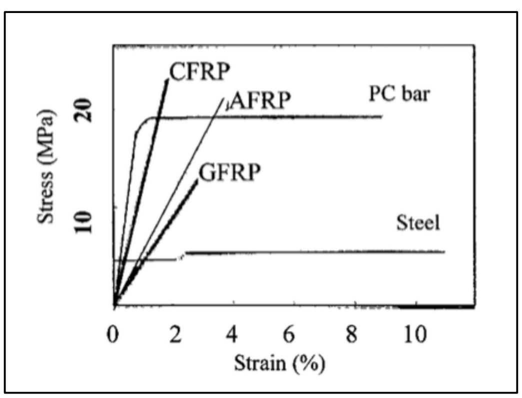

Figure 4. Stress-strain relationship between CFRP, GFRP, AFRP, steel [5]. Note Stresses are x10^3.

There are many factors that need to be considered when discussing and comparing the durability of FRPs. This paper is specifically concerned with FRP rods used in concrete structures as an alternative to steel rebar. Therefore, the FRPs should be highly resistant to the alkalinity of concrete, extremely durable in freeze-thaw conditions and show great resistance to static and cyclic loading. The durability characteristic of carbon, glass, and aramid FRPs is summarized in Table 2 [5].

Table 2. Durability Characteristics of CFRP, AFRP and GFRP [8]. 100% indicates a full resistance [5].

	Fiber			
Particulars	Carbon	Aramid	Glass	Notes
Alkali resistance	95%	92%	15%	NaOH, 40°C, 1,000 h
Acidic resistance	100%	60–85%	100%	HCl, 40°C, 120 days
Ultraviolet ray resistance	100%	45%	81%	0.2 MJ/m^2/h, 1,000 h
	FRP rods			
Particulars	CFRP	AFRP	GFRP	Notes
Static fatigue	91%	46%	30%	20°C, 100 years (calculated)
Cyclic fatigue	85%	70%	23%	100 MPa Amp., 2 million cycles
Alkali resistance	100%	98%	29%	NaOH, 40°C, 120 days
Ultra-violet ray resistance	77%	69%	90%	3 years exposure
Freeze-thaw resistance	100%	100%	100%	−20 to +15°C, 300 cycles
High temperature resistance	80%	75%	80%	−10 to 60°
Fire resistance	75%	65%	75%	350°C

It is without question that CFRP has the best durability characteristics. In contrast, GFRP has the worst with the exception of UV, high temperature and fire resistance, which is irrelevant because FRPs are embedded deep within concrete which is highly resistant to all of these particulars.

Sustainability

Before discussing the sustainability of FRPs, it should be noted that a lack of academic studies on the environmental impact of AFRPs prevents a complete comparison. The ideal material to replace steel would be produced at a lower temperature to minimize the energy requirement and yield less CO_2 to limit GHG emissions in the interest of minimizing its contribution to the greenhouse effect. In this regard, GFRP would be the superior material as illustrated by Table 3. However, this does not make up for its substantially lower strength and durability which ultimately renders GFRP an infeasible option for most RC structures.

Table 3. CO_2 emissions and production temperature.

Materials	CO_2 Emissions (kg-CO_2/kg)	Production Temperature (°C)
Steel	5.15 - 7.40 [7]	1400 [8]
CFRP	22.4 – 31 [9]	1200-2400 [10]
GFRP	2.6 [9]	1400 [10]
Aramid Fiber	19.7 [11]	Not found

While CFRP requires more energy to produce than steel and emits almost 4 times as much CO_2 in the process, there is still a sustainable advantage of using this in RC structures [8]. For example, "the lightweight [CFRP] rebars and a higher tensile capacity allows for lighter weight structures. This in turn provides for less concrete and less cover is necessary to protect the rebars from aggressive environments" [8]. Concrete emits up to 800 kg-CO_2 per kg produced [7]. Therefore, although CFRPs emit more CO_2 in their manufacturing process, implementing this technology in RC structures would drastically reduce the amount of concrete needed and thus ultimately lower CO_2 emissions from the concrete production industry. Another sustainable advantage of CFRP is that due to its superior strength and durable qualities over other FRPs and steel, CFRP will have the longest lifespan in RC structures and thus preventing the environmental costs associated with replacement or repair.

To conclusively determine which FRP is the most sustainable option to replace steel in RC, their individual potentials for recycling must be assessed. In this regard steel is advantageous over FRP materials because it is extremely reusable and recyclable [8]. GFRP and CFRP are recyclable as well; however, re-processing both materials significantly decreases their strengths. GFRP loses 50-90% of its tensile strength from reprocessing, whereas CFRP only loses 20-30% [9]. The diminished strength of GFRP from recycling is far too low for it to be reused feasibly. Carbon Fibers, on the other hand, "have a higher return value than glass fiber reinforcement" [10] which makes them the feasible option. To conclude, while the production of GFRP emits the least amount of CO_2, the longer life span and reclaimed value of re-processed CFRP make it a more recyclable and ultimately more sustainable material.

Cost

The high costs of FRPs compared to steel have been a major reason for their unpopularity in RC construction today [12]. However, research on the FRP industry has concluded that, "we should not disregard FRPs because the cost of manufacture is greater than that of steel, as the life cycle costing and other 'hidden' costs, (such as for repairs) are not included" [12]. In fact, many researchers believe that although initial costs are high, FRPs are a better choice than steel when a structure requires a longer lifespan [12].

Table 4 summarizes the initial commercial costs, the initial cost ratio to steel and costs per unit-force per unit length of the materials being discussed [12].

Table 4. Comparison of costs of steel, GFRP, AFRP and CFRP [12].

Material	Initial Costs (£/kg)	Cost/Steel Cost	Cost per unit-force per unit-length (£/MN*m)
Steel	0.38	1	8.6478
GFRP	3.75	9.87	10.4
AFRP	12.5	32.89	12.94
CFRP	10.625	27.96	8.2102

The presented data demonstrates that while the initial cost of CFRP is significantly higher than steel, it costs the least to supply the equivalent tensile strength to a structure. Therefore, one would save money using CFRP to reinforce their concrete because they would need the least amount of material to supply the desired strength. This result was further concluded by Ioannis Balafas and Chris Burgoyne, who created a method to calculate and compare the cost of using aramid, carbon, and glass FRPs to steel in equivalent RC structures [12]. The results are summarized below in Table 5.

Table 5. Results of study conducted by Ioannis Balafas and Chris Burgoyne [12].

Case	Parameter value	Glass				aramid				carbon				steel		
		Ap (mm^2)	depth (m)	Cost (£/m)	Cost glass/steel	Ap (mm^2)	depth (m)	Cost (£/m)	Cost aramid/steel	Ap (mm^2)	depth (m)	Cost (£/m)	Cost carbon/steel	Ap (mm^2)	depth (m)	Cost (£/m)
span	3.50	1113	0,41	19,2	2,11	621	0,41	20,1	2,21	632	0,34	19,3	2,13	710	0,29	9,09
	4.50	1426	0,52	23,8	2,20	795	0,53	24,9	2,31	774	0,44	23,3	2,16	912	0,37	10,79
	5.50	1739	0,64	28,3	2,27	969	0,65	29,7	2,38	943	0,54	27,8	2,22	1110	0,45	12,49
	7.00	2229	0,81	35,4	2,34	1242	0,82	37,2	2,46	1209	0,69	34,6	2,30	1383	0,58	15,09
flange width	rectangular	975	1,08	24,3	1,83	533	1,10	25,1	1,88	541	0,94	23,0	1,73	723	0,80	13,33
	0.40	1446	0,77	25,9	2,04	805	0,78	27,1	2,13	811	0,67	25,8	2,02	974	0,60	12,74
	0.80	2360	0,65	35,7	2,45	1317	0,66	37,6	2,58	1272	0,54	35,2	2,41	1242	0,47	14,59
	1.20	3262	0,58	46,1	2,68	1821	0,59	48, 7	2,83	1745	0,48	45, 8	2,66	1285	0,46	17,19

The study found that regardless of the structure's dimensions, CFRP was consistently the least expensive FRP to use. Therefore, regardless of the high initial costs of CFRP, it is the most economical to use as an alternative to steel in reinforced concrete.

Conclusion

Fiber reinforced polymers offer an innovative solution to the structural and financial problems plaguing the infrastructure industry due to steel's corrosiveness. They are stronger and more durable than steel and therefore offer a longer service life to structures. This minimizes the need for repair and replacement which currently costs the infrastructure industry billions of dollars a year. However, they are not easily recycled and initially cost much more than steel. As a result, FRPs are not widely accepted in today's construction industry. The three most commonly used in concrete construction are carbon, glass, and aramid FRPs. GFRP produces the lowest GHG emissions during the production phase but has the lowest strength and worst durability of the FRPs. AFRP, which showed durability properties similar to CFRP, is more expensive and weaker. Therefore, while CFRP showed the highest GHG emissions and initial costs, its superior mechanical properties, long service life, recycling capabilities, and low final costs make it the most feasible FRP to use as an alternative to steel in RC structures.

Recommendations

For CFRP to establish itself as a feasible reinforcement in the concrete industry, there must be substantial changes to building codes, its recyclability, and its upfront costs. Researchers at the Kingston University London believe that, "the single greatest disadvantage for FRP has been the lack of design codes" [8]. Taketo Uomoto, a world leader in FRP research, agreed that, "efforts needed to be made for design codes for FRP and this would mean greater ease and use of FRP in buildings and not just as an alternative material" [8]. While there are official design codes for CFRP in countries such as the USA and Europe, more countries must follow suit for CFRPs to become a feasible alternative to steel.

In a world that is now conscious of its impact on the environment and highly values sustainable technology, engineers must design CFRPs to be more reusable to earn global acceptance. As stated by the research of Conroy, Halliwell and Reynolds, “FRP suppliers could lose their market share to metal and other industries if they cannot ensure that their FRP components can be reused or recycled at the end of their life” [13]. Finally, the construction industry will not accept FRPs as a feasible alternative to steel unless their commercial prices drop. The reason for CFRPs high initial cost is because, “carbon fibre manufacturers have decided to concentrate on the small-volume, high-price, high-technology markets such as aerospace, rather than go for the high-volume, low-price, basic-technology civil engineering market” [14]. If CFRP manufacturers begin to see the potential in the construction market, eventually costs can drop and their popularity will rise.

Works Cited

[1] A.J. Boyd, Topic: “Concrete”, Montreal, McGill University, 2014.

[2] Engineer’s Outlook, “History of Reinforced Concrete and Structural Design,” 11 October 2011. [online]. Available: https://engineersoutlook.wordpress.com/2011/10/11/structural-concrete-design/. [Accessed 22 02 2016].

[3] J. G. Cabrera, “Deterioration of Concrete Due to Reinforcement Steel Corrosion,” *Cement & Concrete Composites*, vol. 18, no. 1, pp. 47-59, 1996.

[4] M. Yunovich, N. G. Thompson and P.Y. Virmani, “Corrosion protection system for construction and rehabilitation of reinforced concrete bridges,” *International Journal of Materials and Product Technology (IJMPT)*, vol. 23, no. 3, pp. 269-285, 2005.

[5] T. Uomoto, H. Mutsuyoshi, F. Katsuki and S. Misra, “use of Fibre Reinforced Polymer Composites as Reinforceing Material for Concrete,” *Journal of Materials in Civil Engineering*, vol. 14, no. 3, pp. 191-209, 2002.

[6] Y. Shao, Topic: “FRP”, Montreal, McGill University, 2014.

[7] H.S. Park, B. Kwon, Y. Shin and Y. Kim, “Cost and CO_2 Emission Optimization of Steel Reinforced Concrete Columns in High-Rise Buildings,” *Energies*, vol. 6, no. 11, pp. 5609-5624, 2013.

[8] M. Pearson, T. Donchev and M. Limbachiya, "An Investigation into the Sustainability of FRP Reinforcement Bars," in *Durability and Sustainability of Fibre Reinforced Polymer (FRP) Composites for Construction and Rehabilitation*, London, 2011.

[9] J.R. Duflou, Y. Deng, K. Van Acker and W. Dewulf, "Do fibre-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessement-bases study," *Materials Research Society Bulliten*, vol. 37, no. 4, pp. 374-382, April 2012.

[10] A.U. Zaman, S.A. Gutub, M.F. Soliman and M.A. Wafa, "Sustainability and human health issues pertinent to fibre reinforced polymer composites usage: A review," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 11, pp. 1069-1084, 2014.

[11] Dyneema, "DSM Dyneema protects people and the environment," January 1, 2013. [Online]. Available: https://www.dsm.com/content/dam/dsm/dyneema/en_GB/Downloads/Case%20Studies%202013/DSM_Dyneema_LP_Customer%20information%20sheet_180113.pdf. [Accessed February 23, 2016]

[12] I. Balafas and C. Burgoyne, "Initial Cost Considerations on the Use of Fibre Reinforced Plastics in Reinforced Concrete Structures," in *2nd ConFibreCrete Young Researchers' Seminar, Corfu, 2002.*

[13] A. Conray, S. Halliwell and T. Reynolds, "Composite recycling in the construction industry," in *The 2nd International Conference: Advanced Polymer Composites for Structural Applications in Construction*, Watford, 2006.

[14] C. Burgoyne and I. Balafas, "Why is FRP Not a Financial Success?," in *The 8th International Symposium on Fiber Reinforced Polymer Polymer Reinforcement for Concrete Structures*, Patras, 2007.