Case study

Innovative and Sustainable Materials In Architectural Engineering

.

ABSTRACT

The advantages of fiber-reinforced polymer (FRP) composite material have attracted architectural engineers as alternative construction materials. FRP materials are noncorrosive, lightweight, exhibit high tensile strength, and stiffness, are easily fabricated and constructed. For architectural applications, FRP materials are fabricated using a polymer matrix, such as epoxy, vinyl ester, or polyester, and reinforced with various grades of carbon, glass, and/or aramid fibers. In this study, FRP coupons have been tested under axial tensile load to evaluate the strength of these materials for architectural application. Coupon specimens were cut from two different types of glass-FRP (GFRP) tubes namely: Type I and II, the two types had constant internal diameter equal to 152 mm. The GFRP tubes Type I consist of six layers with (±60°) fibers angles oriented mainly in the hoop direction with respect to the longitudinal axis of the tubes, the total thickness is 2.65 mm. While GFRP tubes I consist of fourteen layers with different fibers angles (±65, ±45, ±65) and the total thickness are 6.4 mm. The test results were presented and discussed. The strength of the coupon showed an acceptable level to be used for architectural application. Some of the FRP composites successful applications are briefly presented and discussed to provide the appropriate background for the application of FRP composites in architectural engineering. The promising results presented for the GFRP materials represent a further step toward architectural application.

Keywords: Fiber-reinforced polymer; Architectural; Application, Sustainable; Durable.

1. INTRODUCTION

Recently, the use of fiber-reinforced polymers (FRP) products in architectural engineering applications has come about as a result of the many desirable characteristics that are superior to those of conventional materials. With the world facing a crisis in terms of sustainable growth and environmental stability, the responsibility for change has fallen on to the entire engineering community. Green building movement, science in energy and environmental design, innovation for sustainability and many other programs are poised to steer the world toward greener direction. Although cost has traditionally been a major impediment to composites, advances in constituent material performance, manufacturing techniques, rehabilitation methods of in-service structures, structural optimization and rapid modular construction have recently lowered construction costs of composite-based infrastructure. FRP offers different advantages for buildings such as faster installation time, lightweight material, resistance to corrosion & less maintenance, cost savings, and more flexibility in the design.

However, there are interests to the overall durability of FRP composite materials, especially as related to their capacity for sustained load performance under harsh environmental conditions. In aggressive environments, FRP systems are subjected to moisture, salts, alkaline, ultraviolet radiations and freeze-thaw cycles, which it may cause degradation to the resin and fibers, hence limiting the strength. Among these factors, the influence of moisture absorption and exposure to freeze-thaw cycles are considered to be the most critical factors. Degradation due to moisture absorption may significantly reduce the life of FRP composites (Garcia, et al., 1998). Springer, et al., 1980 stated that the absorbed moisture can cause pronounced changes in modulus, strength, and strain to failure. Schulheisz, et al. 1997 recorded strength and stiffness reductions on the order of 20 percent and 5 percent, respectively, for E-glass/vinyl ester composites submerged in (77°F) water for a period of 200 days. Also, Phifer 2003 found tensile strength and stiffness reductions on the order of 60 percent and 10 percent, respectively, for Eglass/ vinyl ester composites submerged in fresh water for a period of about 2 years. The mechanical properties of the composites are also affected by cold temperatures and by the cycling process (Karbhari 2002). The implications of such strength and stiffness reductions on the design of concrete-filled FRP tube (CFFT) can be significant. The moisture content of submerged FRP composites increases through diffusion. The absorbed moisture can act as a plasticizer of the composite resin, and can cause matrix cracking, fiber-matrix deboning, and corrosion of glass fibers (stress corrosion) (Garcia, et al., 1998).

The advantageous properties of FRP composites are well understood and evidence exists that FRP composites can be a viable materials selection toward a sustainable built materials when considering direct and indirect benefits throughout a component or systems life cycle. In addition, there is evidence that FRP materials can offer several environmental advantages, (Halliwell 2010). As long as the FRP composites exists no fossil derived CO2 is admitted; Little water is needed during manufacturing. Lightweight of the material minimizes the need for heavy equipment and thus minimizing fuel consumption and emissions during construction. However, before composite materials can be used as an alternative to conventional materials as part of a sustainable environment a number of needs remain (Jain and Lee (2012), such as the development and availability of standardized energy consumption, integration of durability data and methods for service life prediction of structural members utilizing FRP composites.

The sustainability approach challenges architects to weigh environmental factors, energy/resource consumption, social factors, economic considerations, and performance criteria for building. The primary benefit of FRP composites will be its role in solutions that seek to extend the service life of existing structures and to develop new structures that achieve superior service life with minimal maintenance. Essentially, efficiently maximizing the benefit of potentially limited nonrenewable resources and avoiding the environmental, social, and economic impacts associated with replacement and new construction (Lee and Jain 2009).

2. METHEDOLGY

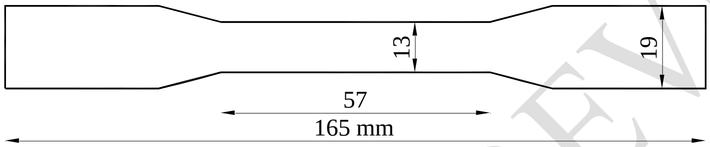
In this study, coupon specimens were cut from two different types of glass-fiber reinforced polymer (GFRP) tubes namely: Type I and II, the two types had constant internal diameter equal to 152 mm. The GFRP tubes Type I consist of six layers with (±60°) fibers angles oriented mainly in the hoop direction with respect to the longitudinal axis of the tubes, the total thickness is 2.65 mm. While GFRP tubes I consist of fourteen layers with different fibers angles (±65, ±45, ±65) and the total thickness are 6.4 mm. The FRP tubes were manufactured using continuous filament winding process adopted by FRE Composites. E-glass fiber and Epoxy resin were utilized for manufacturing these tubes. The glass fiber volume fraction as provided by the manufacture was 68%. The material properties for both the fiber and the resin are presented in Table 1. The winding angles of the tubes were optimized for below underground pipe applications. The coupon and ring specimens were conditioned to different exposure and then tested under axial tension, compression and hoop tension.

Table 1 Properties of fibers and resin

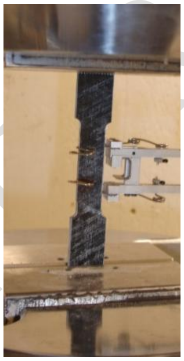
Glass fibers		Epoxy resin	
Linear mass (g / km)	2000	Density (kg / m3)	1200
Tensile modulus(MPa)	80 000	Tensile modulus(MPa)	3380
Poisson’s ratio	0.25	Poisson’s ratio	0.4

2.1 Results and Discussion

The experimental tests outlined in this paper are concerned with axial tension test to evaluate the strength of GFRP materials. Coupon specimens were cut from the FRP tubes according to ASTM D638-1, “Tensile properties of Plastics”. The tensile coupons dimensions were prepared according to the specification of the standard to provide an adequate gripping area at each end. The width of specimen at the grip length was more than that of the free length. Figure 1.a shows the typical dimensions of coupon specimens for different types of FRP tubes. Tests were performed using the MTS universal testing machine, direct tension was applied to the specimens under load control mode. The axial load was applied linearly, increasing from zero until specimen failure. The rate of loading was approximately equal to 3 to 4 kN/min. High pressure hydraulic wedge grips were used to hold the specimens in positions. The grip surfaces were deeply serrated with pattern similar to those of a coarse single-cut file, serrations about 2 mm apart and about 1.5 mm deep. The specimens were instrumented with extensometer at the middle of the specimens to measure deformations. Figure 1.b shows the test setup and instrumentation of the MTS universal testing machine.



(a) Specimen dimension



(b) Tests setup

Figure 1 Dimensions and test setup for coupon tension test

Failure of coupon specimens under axial tension load started with matrix cracking and was followed by fiber rupture in the longitudinal direction. Sound snapping could be heard with increasing the load, which attributed to cracking of the resin. Failure was always sudden, with a burst rupture of fibers almost always at the middle zone of the coupons. Figure 2 presents the dominant failure mechanisms observed for coupon tension test specimens. The average stress-strain relationships for five specimens are presented in Figure 3, at the first stage of loading the curve was linear up to 80% of the peak load. Beyond this level the curve was nonlinear up to failure. Small load drops accompanied by the change in the stiffness were observed. This resulted from the earlier rupture of fibers and matrix cracking. From the measured axial strains and stresses, the elastic modulus in the axial direction of the different specimens was determined. The average ultimate tensile stresses were 60.13 MPa and 60.16 MPa, while the average axial strains at the peak stress were 0.0069 to 0.0106 for tube I and II, respectively. The initial stiffness for the different types of the tube was affected by fibre orientation of each tube. From the measured axial strains and stresses, the elastic modulus in the axial direction of the different types of the tubes was determined. The values of the elastic modulus ranged from 14000 MPa to 18000 MPa.

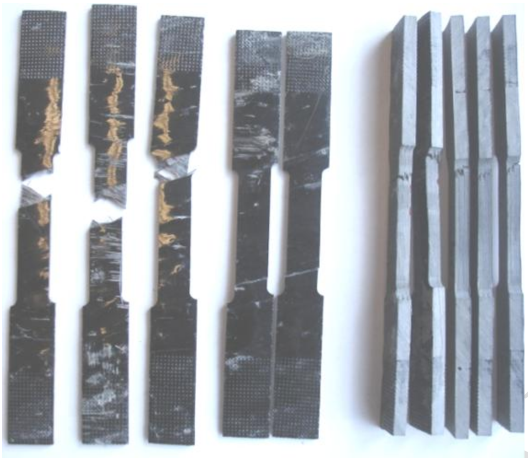


Figure 2 Dominant failure mechanisms for room temperature coupon tensile test

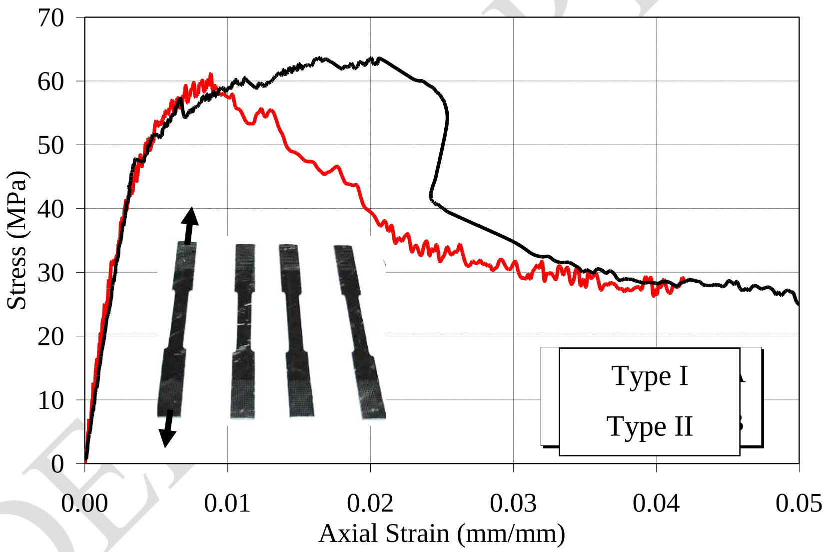


Figure 3 Stress-strain curve for room temperature coupon tensile test

3. APPLICATION OF FRP COMPOSITE MATERIALS IN ARCHITECTURE ENGINEERING

Some of the FRP composites successful application are briefly presented below to provide the appropriate background for the application of FRP composites both in civil and architectural engineering.

3.1 Pavilion

This travelling pavilion was designed, for Chanel, by Zaha Hadid and has been first exhibited in Hong Kong, Tokyo. From there it was packed up in 55 sea containers and shipped to Tokyo, closing there and heading to New York. Figure 4 shows it in New York's Central Park. Exhibiting Chanel's quilted bags designed by Karl Lagerfeld. The pavilion designed to display artworks that were inspired by Chanel's 2.55, a quilted chain-strap handbag, the pavilion certainly oozes glamour. Its mysterious nautilus like form, which can be easily dismantled and shipped to the next city on its global tour, reflects the keen architectural intelligence we have come to expect from its creator. FRP was selected for its formability (using hundreds of molded fiberglass panels mounted on a skeletal steel frame), lustrous finish and above all lightness as the pavilion needed to be transported between venues (Stacey 2013).

Figure 4 The Chanel Pavilion in Central Park (Stacey 2008)

3.2 Hongluo Club House

Hong Luo Villa district is a three-phased project. The sites for each phase are allocated along Hong Luo Lake, reflecting the grand view of the mountains sitting behind it. Hong Luo Club floats on the lake, creating an easily accessible public space at the center of the district (see Figure 5). The architects of Hongluo Clubhouse, Ma Yansong and Yosuke Hayano of MAD intend ‘the structure appear to ascend from the lake itself. A continuous, reflective surface rises up out of the water, becoming first the roof and then the walls of the clubhouse. This surface blurs the distinction between solid and liquid states, between building and environment.’ Framework of curved steel sections was used to build the roof of this house, which was clad on site with plywood. The plywood was coated on site with glass fibre reinforced epoxy resin, exploiting the inherent flexibility of GRP. The outer surface was painted silver. The design intent of this project is a tectonic, the role of the flowing folded roof surface is to define space and provide reflectance. The materials are not used in an expressive manner. Here we see FRP as a rival to the formability of concrete and this challenge has been extended by the invention of high performance concretes (Stacey 2003).

Figure 5. Honglu Clubhouse by MAD Architects (Stacey 2003)

3.3 Bexhill-on-Sea Band Stand

Bexhill-on-Sea Band Stand by Niall McLaughlin Architects from 2002 shown in Figure 6 is an example of a FRP skinned structure. The bandstand's design evolved from concepts developed by the children, in collaboration with the architects and architecture students, during a series of workshops held at the Pavilion. The Bandstand's shell-like canopy is engineered to provide near perfect acoustics and at the same time mirror its seafront location. The simple white finish and ultra modern steel, plywood & fibreglass construction of the bandstand, are a perfectly compliment to the modernist aesthetics and innovative construction techniques of the De La Warr Pavilion. The bandstand itself is movable, allowing it to be relocated to different areas of the terrace according to the season, or in order to accommodate the varying needs of performances. Producing a design for the bandstand, that was both elegant and ergonomic, had always been a major consideration. Therefore, throughout the project, a number of potential bandstand users including Battle Town Band, were consulted in order to ensure that the design could accommodate widest possible range of uses. The new De La Warr Pavilion Bandstand won awards from the Royal Institute of British Architecture (RIBA) and The Royal Institute of Australian Architects (RIAI). The jury said that: The form is exhilarating, recalling both the dynamics of early modernism and the organic aspirations of the present day. Architect and client have worked together with an admirable clarity of thought to achieve excellent results (De La Warr Pavilion 2013).

Figure 6. The Bexhill-on-Sea Band Stand (De La Warr Pavilion 2013)

3.4 Novartis Campus

The reception building for the Novartis Campus Located in Basel, Switzerland is a load-bearing construction consisting completely of glass. The design of the architect, Marco Serrain 2007, called for a high degree of transparency and what appears to be a floating roof. It has a wing-shaped roof made from glass fibre reinforced plastic (see Figure 7). The load-bearing façade, which consists solely of glass elements, makes it possible to do without any additional supporting structures between the floor and the roof. The roof is a 400 m², wing-like shape made from glass fibre reinforced plastic (GFRP). It unifies all functions, for example the supporting function, thermal insulation and waterproofing, in a single, seamless element. Keller, Hass and Vallée note that: “The roof must be lightweight due to the limited load-carrying capacity of the glass walls and, at the same time, it must provide thermal insulation and waterproofing for the building. Consideration of the complex double-curved geometry led to the use of a GFRP sandwich structure of variable depth” the static and constructive form of the roof and façade takes into account the manufacturing sequences, complex geometry and different behaviour of the materials used. The large, self-propelled swing doors fulfil numerous requirements for operation, safety, security and structural physics (Keller 2008, Ernst Basler 2013).

Figure 7. The reception building for the Novartis Campus Located in Basel, Switzerland (Ernst Basler 2013).

4. Conclusions

Based on the test result of this study, some important issues were better understood and quantified such as the tensile strength of the GFRP coupon specimens. The promising results presented for the coupon GFRP specimens represent a further step toward field application in architectural engineering. The successful architectural implantation demonstrates the effectiveness of FRP composites as new materials for architectural applications. This application opens the way for a major application of GFRP composite materials for green and sustainable buildings.

5.References

ASTM, (2008b), Standard test method for tensile properties of plastics, D638-08, West Conshohocken, Pa.

De La Warr Pavilion, (2013), Bandstand, http://www.dlwp.com/about-us/bandstand/.

Ernst Basler + Partner company, (2013).

Garcia, K., M.D., Hayes, Verghese, N., and Lesko, J.J., (1998), “The effects of cycling moisture aging on glass/vinyl ester composite system,” Proceedings, 3rd International Conference on Progress in Durability Analysis of Composite Systems, pp. 173–179.

Garcia, K., M.D., Hayes, Verghese, N., and Lesko, J.J., (1998), “The effects of cycling moisture aging on glass/vinyl ester composite system,” Proceedings, 3rd International Conference on Progress in Durability Analysis of Composite Systems, pp. 173–179.\

Halliwell S (2010) FRPs – the environmental agenda. Adv Struct Eng 13(5):783–791

http://www.archdaily.com/3310/hong-luo-club-house-mad/

http://www.compositesuk.co.uk/LinkClick.aspx?fileticket=51z23k8jRTU%3D&tabid=103&mid=526

http://www.ebp.ch/en/geschaeftsbereiche/ingenieurbau/aktuell/reception-building-novartis-campus-basel%20.html

http://www.nytimes.com/2008/10/21/arts/design/21zaha.html?scp=1&sq=chanel&st=cse

Jain R. and Lee L., (2012), Fiber Reinforced Polymer (FRP) Composites for Infrastructure Applications Focusing on Innovation, Technology Implementation and Sustainability, Springer Dordrecht Heidelberg London New York.

Karbhari, VM, Rivera, J and Dutta, PK.(2000), “Effect of short-term freeze-thaw cycling on composite confined concrete,” Journal of Composites for Construction, Vol. 4, 4:191-197.

Keller, T., (2008), Christoph Haas; and Till Vallée, “Structural Concept, Design, and Experimental Verification of a Glass Fiber-Reinforced Polymer Sandwich Roof Structure,” Journal of Composites in Construction July/August.

Lee L., and Jain R., (2009), “The role of FRP composites in a sustainable world,” Clean Techn Environ Policy. 11, PP 247–249.

Phifer, S.P., (2003), “Hygrothermal evaluation of pultruded polymer composite laminates—Experimentation, analysis, and prediction,” PhD dissertation, Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg,

Schultheisz, C.R., McDonough, W.G., Kondagunta, S., Schutte, C.L., Macturk, K.S., McAuliffe, M., and Hunston, D.L, (1997), “Effect of moisture on e-glass/epoxy interfacial and fiber strengths,” Composite Materials: Testing and Design, ASTM, STP 1242, pp. 257–286.

Stacey M., (2013), “Do we need to specify a high fibre diet?,” Materials of Invention Polymers and Architecture.

Stacey M.,(2003), “Renaissance or Revolution?,” Polymer Composites, International Conference, Proceedings: Façade Design And Procurement, CWCT,.