An Experimental and Numerical Study on the Pultruded GFRP I-Sections Beams

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Abstract

Using steel in bridges' construction because of their desired tensile and compressive strength and light weight especially in large spans was widely popular. Disadvantages of steel such as corrosion, buckling and weaknesses in high temperature and unsuitable weld could be solve with using Fibres Reinforced Polymer (FRP) profiles. The FRP is a remarkable class of composite polymers that can improve structural elements behaviour like corrosion resistance, fir resistance with good proofing and electricity and magnetic non-conductor. Nowadays except FRP reinforced bars and laminates, FRP I-beams are made and studied. The main reason for using FRP profiles is, prevent of corrosion and increase the load carrying capacity and durability, especially in large spans in bridges' deck. In this paper, behaviour of I-section glass fibres reinforced polymer (GFRP) beam is discussed under point loads with numerical models and results has been compared and verified with experimental tests.

Keywords: Glass Fibres Reinforced Polymer, Composite, I-section Beam, Durability, Finite Element Method, Numerical Model.

1 Introduction

Glass Fiber Reinforced Polymer (FRP) beams offer significant advantages for rapid replacement and new construction due to their favorable characteristics for durability, lightweight, high strength, rapid installation, lower or competitive life-cycle cost, and high quality manufacturing processes under controlled environments. The applications of FRP materials have been increasingly implemented in the world since mid-1990s. Although extensive research has been conducted on stiffness and strength evaluations of various types of FRP decks (Bakis et al 2002, Davalos et al 2005, Chen et al 2007 and 2010), only limited studies are available on GFRP beams bridges systems, which were mostly evaluated based on field or lab-scale testing.

2 Previous Application

In-depth research into the use of high performance materials for civil engineering structural applications has received an increasing amount of attention in recent years. More specifically, Fibre Reinforced Polymers (FRPs) as well as Ultra High Performance Concrete (UHPC) are two types of high performance materials that have been tested. Prior to the 1980s, the use of FRP materials was predominantly limited to applications related with the aerospace and marine industries. The emergence of interest in FRP materials for use in structural applications led to the beginning of dedicated research into their behavior under different loading types. In bridge structural members, the study on the effect of cyclic loading is extremely important. Early research attempted to correlate existing theories relating to fracture mechanism and the continuum theory along with experimental testing to assess the fatigue behavior of FRP materials (Dew Hughes et al 1973, Lang et al 1989, Reifsnider et al 1982, Schütz et al 1977, Talreja et al 1981 and 1985). Further progression in research led to a shift towards strength and stiffness degradation methods to characterize the fatigue damage in FRP materials (Demers et al 1998). In conjunction with continued research into the behavior of FRP materials (Schütz et al 1987, Bernasconi et al 2007, Lopez-Anido et al 1999, Rotem et al 1993, Sarkani et al 1999, Vassilopoulos et al 2010, and Yao et al 2000), work towards the research and development of hybrid structural members also emerged near the beginning of the 21st century (Cheng et al 2006, Dawood et al 2007, Deskovic et al 1995, Dutta et al 2007, Elmahdy et al 2010, Elmahdy et al 2010 and Moon et al 2009). The research performed has shown great promise for hybrid structural members with optimized cross-sections, which take into consideration the advantageous qualities and properties of each material component and can result in improved stiffness and strength while allowing for pseudo-ductile response prior to ultimate failure (Deskovic et al 1995 and Triantafillou et al 1992).

In this study, GFRP beams which are the most economical among FRP materials were considered. However, the carbon FRP (CFRP) and hybrid FRP (HFRP) have very high tensile strength and stiffness over GFRP. In terms of the cost of the material, GFRP has more importance compared to CFRP and HFRP. However, the self-weight of the composite girder has become comparatively low due to reduction of the cross-sectional area of the girder (I.S.K. et al 2013).

Previously, a set of bending tests were carried out for UHF and GFRP composite girders with steel bolts. But in real situation, steel bolts can corrode and maintenance need to be carried out which is not economical. In this research study, behavior of a number of full scale bending tests of UHF and GFRP composite girders which were carried out with FRP bolts was compared with numerical analysis and verified.

3 Experimental Test

3.1 GFRP Beam

GFRP I beams which were produced by Pultrusion[1] process using FRP layer composition were used in the experiment and the fibers arrangement in the beam is given in Table 1. Most of the GFRP fibers are oriented in the 0° direction with respect to their local axes and ±45° fibers provide the integrity in both flange and web and reduce the anisotropic behavior of the beam. Table 2 shows the mechanical properties of the GFRP beam section materials. The overall height, length and the flange width are 250mm, 3500mm and 95mm respectively, where the flange and web thicknesses are 14mm and 9mm respectively.

Table 1: Fiber Arrangement in GFRP Beam

Direction	0°	$0/90°$	$\pm 45/90°$	$\pm 45°$	Total GFRP %
Flange	0%	11%	45%	44%	100%
Web	26%	26%	0%	48%	100%

Table 2: Mechanical Properties of GFRP Materials

Mechanical Property	Unit	Notation	GFRP $0°/90°$	GFRP MAT	GFRP $\pm 45°$
Young Modulus	N/mm^2	E_{11}	24000	10000	11089
Poisson ratio	-	U_{12}	0.1	0.308	0.584
Shear Modulus	N/mm^2	G_{12}	3500	3800	10909

1 - Continuous Process for Manufacture of Composite Materials with Constant Cross Section.

3.2 UHF Blocks

Tensile strength cannot be well utilized in a GFRP "I" section beam subjected to bending stress due to delamination of the fibers at compression flange. By using the ultra-high strength fiber reinforced concrete or "UHF" blocks, the flexural capacity could be optimized significantly (Hai DN et al 2010). The UHF blocks were made of high strength concrete by embedding high strength steel fibers (2000 N/mm2) which have a 15mm and 22mm in length. The steel fiber content is around 1.75% of the volume of the block. Table 3 shows the mechanical properties of the UHF blocks. UHF blocks have length width and height 300mm, 95mm and 35mm respectively. Also, epoxy resin and FRP bolts were used to fix the UHF blocks to the GFRP beam.

Table 3: Mechanical Properties of UHF Blocks

Compressive strength (N/mm^2)	Young's Modulus (kN/mm^2)	Compressive Strain (μ)
188.8	44.0	4930

3.3 Test Set Up

Full scale four point bending tests were carried out for two numbers of GFRP and UHF composite I-beams having dimensions as illustrated in Figure 1 and Figure 2 (I.S.K. et al 2013). The test parameters (i.e. bolt diameter, bolt spacing and the availability of bolt head inside the UHF block) of each specimen are given in Table 4. In order to prevent delamination at top flange, UHF blocks have compressive strength and Young's modulus of 188MPa and 44GPa respectively were fixed to the top flange using epoxy resin and FRP bolts (see Figure 2).

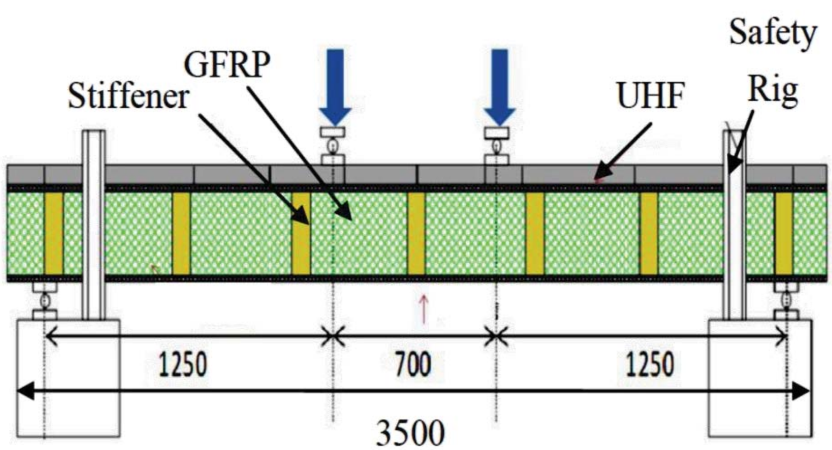


Figure1: Test setup (mm) (I.S.K. et al 2013)

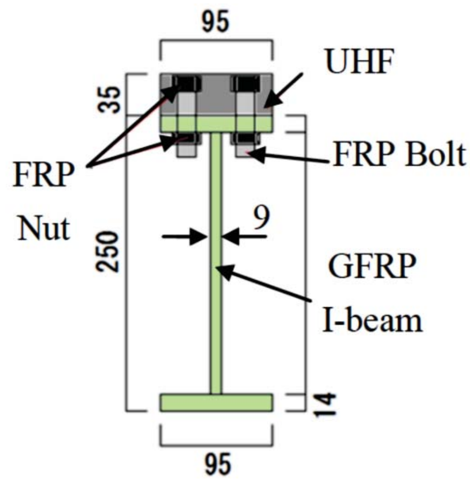


Figure 2: Cross-section of UHFGFRP I-beam (mm) (I.S.K. et al 2013)

Table 4: Parameters Test Specimens

Specimen	Bolt spacing (mm)	FRP bolt diameter (mm)	Bolt head in the UHF
G10-F10-BN6	100	10	Yes
G10-F16-BN4	150	16	Yes

4 Experimental Test Results

Failure patterns of each test specimen are illustrated in Figure 3. Specimen G10-F10-BN6 was failed due to crushing of UHF blocks in the bending span which as specimen G10-F16-BN4 and was failed by crushing of UHF blocks and top flange along with shear failure of web in the bending span.

Figure 4 shows the comparison of load vs. deflection relationships of experimental specimens with different test parameters. In this comparison mid span deflection was considered.

(a) G10-F10-BN6 (b) G10-F16-BN4

Figure 3: Failure Patterns of Specimens (I.S.K. et al 2013)

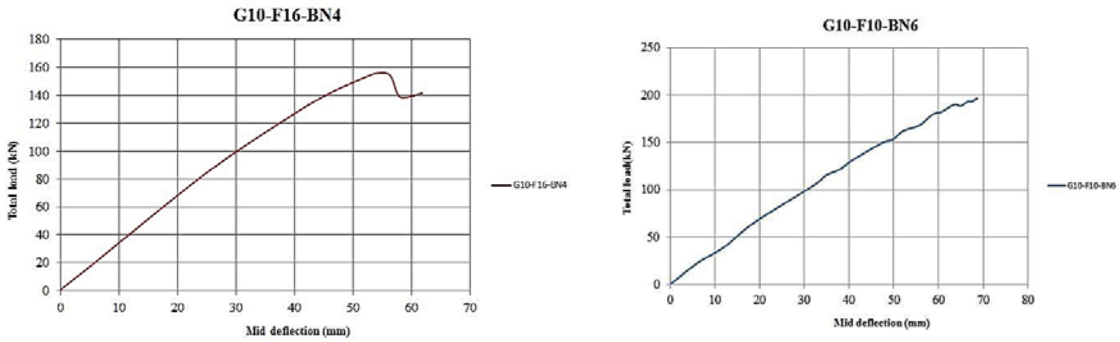


Figure 4: Load Deflection Curve (I.S.K. et al 2013)

5 Numerical Modeling

Abaqus FEA (formerly ABAQUS) is a software suite for finite element analysis and computer-aided engineering, originally released in 1978. The name and logo of this software are based on the Abaqus calculation tool. Abaqus is used in the automotive, aerospace, and industrial products industries. The product is popular with academic and research institutions due to the wide material modeling capability, and the program's ability to be customized. Abaqus also provides a good collection of multiphysics capabilities, such as coupled acoustic-structural, piezoelectric, and structural-pore capabilities, making it attractive for production-level simulations where multiple fields need to be coupled. According to fiber structure of GFRP composites and different mechanical properties in different directions, ABAQUS is suitable software that meets these requirements for exact modeling.

6 Numerical Modeling and Verification

G10-F16-BN4 and G10-F10-BN6 beams have been modeled with FEM ABAQUS software. The UHF and bolts are modeled with 3D elements, and because of GFRP layer structure, for beams modeling used of shell elements for beams modeling. GFRP is a non-isotropic material, and so for exact modeling, layered material in numerical modeling, has been used.

Loads are applied in virtual 100mm in 100mm area and support condition is assumed completely symmetric. Analysis performed by Risk method and 1000N as initial load.

Three types of GFRP0, GFRP45 and GFRP 0/90, has been modeled, which the name of each material, shows layers direction. Hashin Damage method used to define nonlinear applications. Thickness of layers is based on chapter III. Figure 5 illustrate load-deflection curves and compare FEM and experimental diagrams, too. Initial slope and rapture mechanism is same (figure 5).

As is clear, the difference between FEM modeling between software and experimental results are too small and can be acceptable. Rapture mechanism has great significant too. As illustrated in figure 6, rapture mechanism for two modeled beam, in FEM modeling and full scale beam, has same pattern, and in both of them, concrete yielding has been accrued.

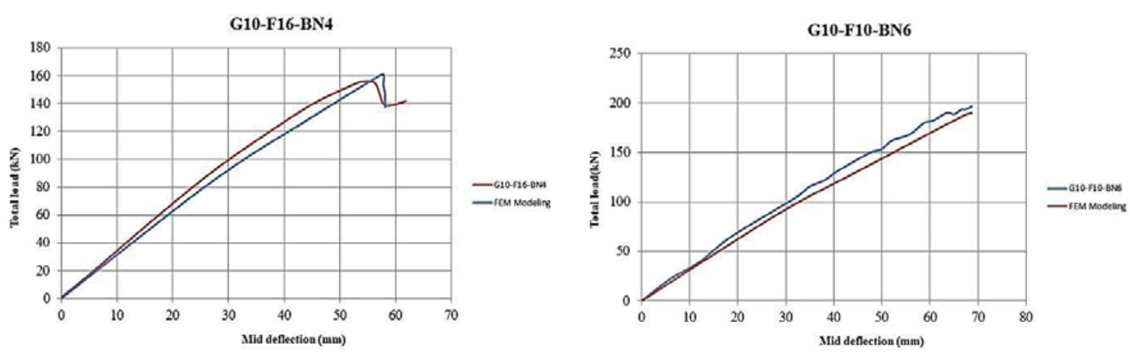
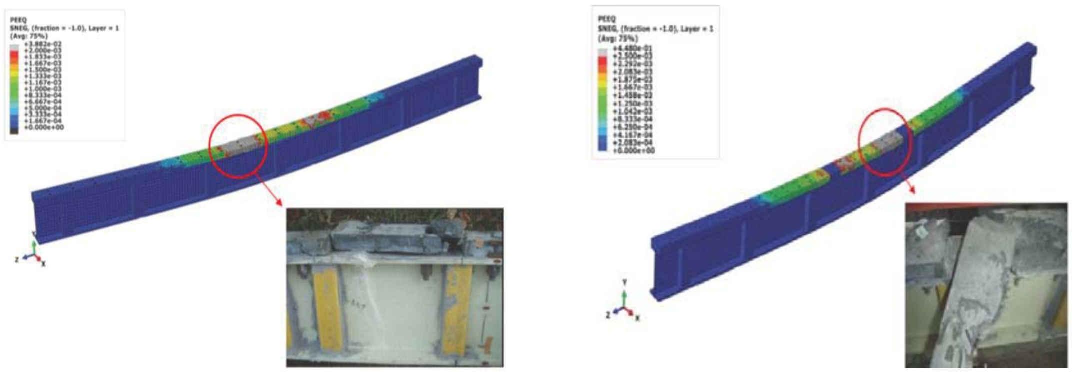


Figure 5: Load-Deflection Curve



(a) G10-F16-BN4 (b) G10-F10-BN6

Figure 6: Rapture Pattern in FEM Modeling

7 Conclusion

According to this paper, FEM software such as ABAQUS, can be used to modeling sophisticated structure applications. But this is required to exact modeling, in face of two different parts, such as steel and concrete, particularly. However because of PC restrictions, these software could not be used for full scale structure modeling efficiently, and this scope required developed in future.

Results certificates numerical modeling verification and so such modeling could be used to evaluate GFRP sections and replacement “I” shaped GFRP beam sections instead of other sections such as “I” shaped steel beams. Modarres-Haqqani steel bridge in Tehran has same condition and could be evaluating for “I” shaped GFRP beam replacement. This is clear that steel modulus of elasticity is greater than composite materials, so displacement of GFRP beams in same support and loading condition, is greater than steel beams. As shown in load-displacement curves, GFRP beam do not show yield point to rapture, so ductility is not considerable. However higher resistance against destructive environmental effects, such as corrosion, durability, in comparison other materials, turned it to appropriate alternative for new construction applications.

References

Bakis CE, Bank LC, Brown VL, Cosenza E, Davalos JF, Lesko JJ, et al. Fiber-reinforced polymer composites for construction-state-of-art review. J Compos Construct, ASCE 2002;6(2):73–87.

Bernasconi A, Davoli P, Basile A, Filippi A. Effect of fibre orientation on the fatigue behaviour of a short glass fibre reinforced polyamide-6. Int J Fatigue 2007;29(2):199–208.

Chen A, Davalos JF. Transverse shear with skin effect for composite honeycomb sinusoidal core sandwich. J EngMech, ASCE 2007;133(3):247–56.

Chen A, Davalos JF. Strength evaluations of sinusoidal core for FRP sandwich bridge deck panels. Compos Struct 2010;92(7):1561–73.

Cheng L, Karbhari VM. Fatigue behavior of a steel-free FRP-concrete modular bridge deck system. J Bridge Eng 2006;11(4):474–88.

Davalos JF, Chen A. Buckling behavior of honeycomb FRP core with partially restrained loaded edges under out-of-plane compression. J Compos Mater 2005;39(16):1465–85.

Dawood M, Rizkalla S, Sumner E. Fatigue and overloading behavior of steelconcrete composite flexural members strengthened with high modulus CRP materials. J Compos Constr 2007;11(6):659–69.

Deskovic N, Meier U, Triantaffilou TC. Innovative design of FRP combined with concrete: long-term behaviour. J StructEng 1995;121(7):1079–89.

Demers CE. Fatigue strength degradation of E-glass FRP composites and carbon FRP composites.Constr Build Mater 1998;12(5):311–8.

Deskovic N, Meier U, Triantaffilou TC. Innovative design of FRP combined with concrete: long-term behaviour. J StructEng 1995;121(7):1079–89.

Dew-Hughes D, Way JL. Fatigue of fibre-reinforced plastics: a review. Composites 1973;4(4):167–73.

Dutta PK, Lopez-Anido R, Kwon S-C. Fatigue durability of FRP composite bridge decks at extreme temperatures. Int J Mater Prod Technol 2007;28(1–2):198–216.

Elmahdy A. Experimental and analytical study of new hybrid beams constructed from high performance materials. Ph.D. Dissertation.University of Calgary, Department of Civil Engineering; 2010.p. 242.

Elmahdy A, El-Hacha R, Shrive N. Static and fatigue behaviour of hybrid high performance concrete beams. In: Proceeding of 13th ICSGE. Cairo (Egypt), December, 2010. p. 1102–11.

Hai DN, Mutsuyoshi H, Asamoto S and Matsui T (2010). Structural behavior of hybrid FRP composite I-beam. Elsevier,Construction and Building Materials, Volume 24, Issue 6, Pages 956–969.

I.S.K. Wijayawardane. Development of GFRP and UHF composite girders. The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13)Citation. September, 2013.

Lang RW, Manson JA, Hertzberg RW. Mechanisms of fatigue fracture in short glass fibre-reinforced polymers. J Mater Sci 1989;22(11):4015–30.

Lopez-Anido R, Dutta P, Bouzon J, Morton S, Shahrooz B, Harik I. Fatigue evaluation of FRP-concrete bridge deck on steel girders at high temperature. In: Proceedings of 44th international SAMPE symposium. Long Beach (California, USA), May, 1999. p. 1666–75.

Moon DY, Zi G, Lee DH, Kim B, Hwang YK. Fatigue behavior of the foam-filled GFRP bridge deck. Composites: Part B 2009;40(2):141–8.

Reifsnider KL, Jamison R. Fracture of fatigue-loaded composite laminates. Int J Fatigue 1982;4(4):187–97.

Schütz D, Gerharz JJ. Fatigue strength of a fibre-reinforced material. Composites 1977;8(4):245–50.

Talreja R. Fatigue of composite materials: damage mechanisms and fatigue-life diagrams. Philos Trans R Soc London Ser A 1981;378(1775):461–75.

Talreja R. A continuum mechanics characterization of damage in composite materials.Philos Trans R Soc London Ser A 1985;399(1817):195–216.

Triantafillou TC, Meier U. Innovative design of FRP combined with concrete. In: Proceeding of 1st ACMBS international conference. Sherbrooke (Québec, Canada), October, 1992. p. 491–500.

Rotem A. Load frequency effect on the fatigue strength of isotropic laminates. Compos SciTechnol 1993;46(2):129–38.

Sarkani S, Michaelov G, Kihl DP, Beach JE. Stochastic fatigue damage accumulation of FRP laminates and joints. J StructEng 1999;125(12): 1423–31.

Vassilopoulos A, Manshadi BD, Keller T. Influence of the constant life diagram formulation on the fatigue life prediction of composite materials. Int J Fatigue 2010;32(4):659–69.

Yao WX, Himmel N. A new cumulative fatigue damage model for fibrereinforced plastics. Compos SciTechnol 2000;60(1):59–64.