International Journal of Sustainable Construction Engineering & Technology (ISSN: 2180-3242)
Vol 6, No 2, 2015

Case Study Evaluation of Steel Girder of Bridge Replacement by GFRP

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Received 18 December 2015; Revised 25 December 2015; Accepted 30 December 2015

Abstract

Nowadays, because of the steel desired tensile, compressive strength, and light weight especially in the large spans, it has been widely popular in the bridge construction. On the other hand, there are some disadvantages including corrosion, buckling and weaknesses in the higher temperatures, and unsuitable weld which would be resolved using Fibres Reinforced Polymer (FRP) profiles. The FRP is a remarkable class of composite polymers that can improve structural elements behaviours like as resistance against corrosion, fire, electricity, and magnetic fields. In this paper, composite GFRP & UHF beams along with the behaviour of I-shaped beam were studied and discussed under the point loads using numerical models, results were compared and verified with the experimental tests whereas two different beams were modelled and verified under static progressive loading performed with ABAQUS as an FEM base software. Finally, Moddares-Haqqani that is a steel girder bridge has been modeled by SAP software and maximum displacement has been determined. Then 4 GFRP beams modeled by ABAQUS software and best section has been determined. Beams are under dead and live loading. Purposes of this paper are evaluating of use of GFRP materials as a basic material in construction process and compare this operation with steel. Results shown that because of lower modulus of elasticity in GFRP compare with steel, displacement has increase in GFRP beams and hence beams dimension must be increase to limit displacement.

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

1.0 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 [1-4], only limited studies are available on GFRP beams bridges systems, which were mostly evaluated based on field- or lab-scale testing.

Fiber reinforced polymers discussed in many implemented researches as very few of them focus on GFRP polymers in "I" shaped sections but most of them cover composite polymers in fiber types only. These sections formed from fiber reinforced polymers in various layers while the direction of fibers affected the section behaviors.

Recently, an in-depth research with a special focus on the Fiber Reinforced Polymers (FRPs) and Ultra High Performance Concrete (UHPC) has been started to emphasize on the benefit of high performance materials in modern civil engineering. Prior to 1980s, the use of FRP materials was predominantly limited to the applications related to aerospace and marine industries. The highly interested FRP materials used in structural applications led to a dedicated research into their behavior under different loading conditions. Among the bridge structural elements, the study on the effect of cyclic loading is extremely important. Hence, in order to assess the fatigue behavior of FRP materials, early researches attempted to correlate the existing theories relating to the fracture mechanism with the continuum theory along with the experimental testing [5-10].

Further progress in research led to a shift towards strength and stiffness degradation methods to characterize the fatigue damage in FRP materials [11]. In conjunction with continued research into the behavior of FRP materials [8, 12-17], work towards the research and development of hybrid structural members also emerged near the beginning of the 21st century [18-24]. The research performed has shown a great promise for hybrid structural members with optimized cross-sections, which takes into the consideration of 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 the ultimate failure [25 and 26].

In this study, GFRP beams, the most economical among FRP materials, were considered. However, the carbon FRP (CFRP) has a very high tensile strength and stiffness over GFRP. In terms of the cost of the material and compared with CFRP and HFRP, GFRP has the higher priority. However, the self-weight of the composite girder has become comparatively low due to reduction of the cross-sectional area of the girder. [27]

Previously, a set of bending tests were carried out for UHF and GFRP composite girders with steel bolts but in reality, steel bolts can corrode and need maintenance which is not cost effective. In this research, the behavior of the UHF and GFRP composite girders carried out with FRP bolts has been analyzed and compared with the numerical analysis and a verified model.

In this study, a hybrid FRP beam that combines GFRP and UHF concrete was developed. The advantage of using this hybridization is to utilize the superior strength of UHF in the compressive flanges while keeping the material costs low by using GFRP in the flanges and web. By incorporating appropriate amount of GFRP/UHF in hybrid composite, a better performance be achieved [3,4].

This study focuses on the structural behavior of composite GFRP beams consisting of multi-layer carbon/glass. An I-shaped section of GFRP beam was developed as the first step of the ongoing research project since it is easily manufactured and commonly used in bridge structures. Then GFRP beam has been replaced to steel beam in bridge under same loading condition. For better evaluation of GFRP beam properties and compare with steel beam in bridges, four GFRP beam with different dimension has been modeled.

2.0 Experimental Test

2.1. GFRP Beam

In table 1 fiber arrangement in the GFRP beams is shown where GFRP I beams produced by Pultrusion[1] process have been used in an experimental test applying an FRP layer composition. Most of the GFRP fibers are oriented in the 0° direction with respect to their local axes but ±45° fibers provide the integrity in both flange and web while reducing the anisotropic behavior of the beam. Table 2 shows the mechanical properties of the GFRP

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

beam section materials. The overall height, length, and 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°	$0°/90°$	$\pm 45°\ to\ 90°$	$\pm 45°$	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 $\mathbf{0°/90°}$	GFRP MAT	GFRP $\mathbf{\pm 45°}$
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

2.2. UHF Blocks

In response to the increasing demand for a higher level and wider range of performances of concrete, in recent years, active research has been conducted to enhance the performance of concrete. One such example is ultra high strength fiber reinforced concrete(UHF) having excellent fluidity with a low waterbinder ratio, which achieves an ultra high compressive strength exceeding 180 N/mm^2. The UHF represents a concrete with improved durability and strength, which is significantly higher than inconventional normal strength concrete. This may result in reduced cross-sections and as a consequence smaller dead-load of structure.

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 [28]. The UHF blocks were made of a high strength concrete by embedding high strength steel fibers (2000 N/mm^2) which are 15mm and 22mm in length. The steel fiber content is almost 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 of 300mm, 95mm and 35mm respectively. Epoxy resin and FRP bolts were also used in fixing the UHF blocks within 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

2.3. 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 [27]. 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 on top flange, UHF blocks (having compressive strength and Young's modulus of 188MPa and 44GPa respectively) were fixed on the top flange using epoxy resin and FRP bolts (see Figure 2).

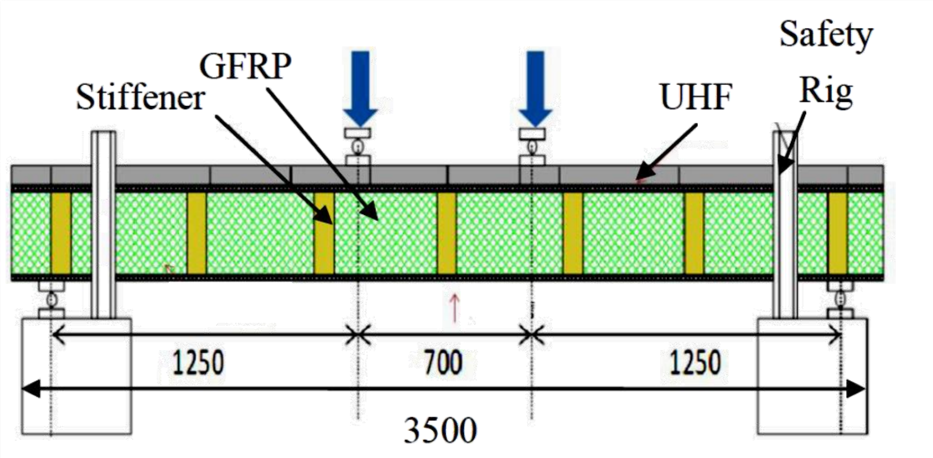


Figure1: Test setup (mm) [27]

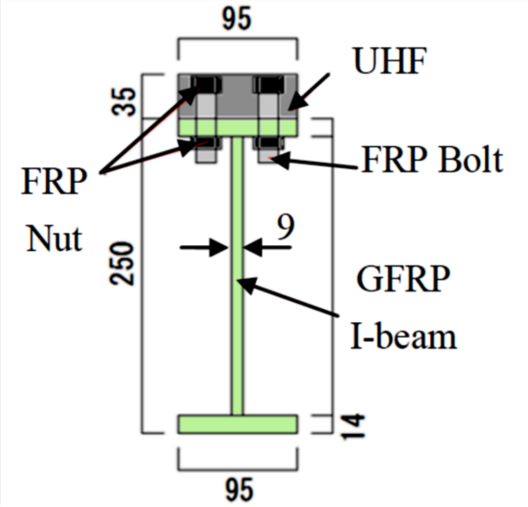


Figure 2: Cross-section of UHFGFRP I-beam (mm) [27]

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

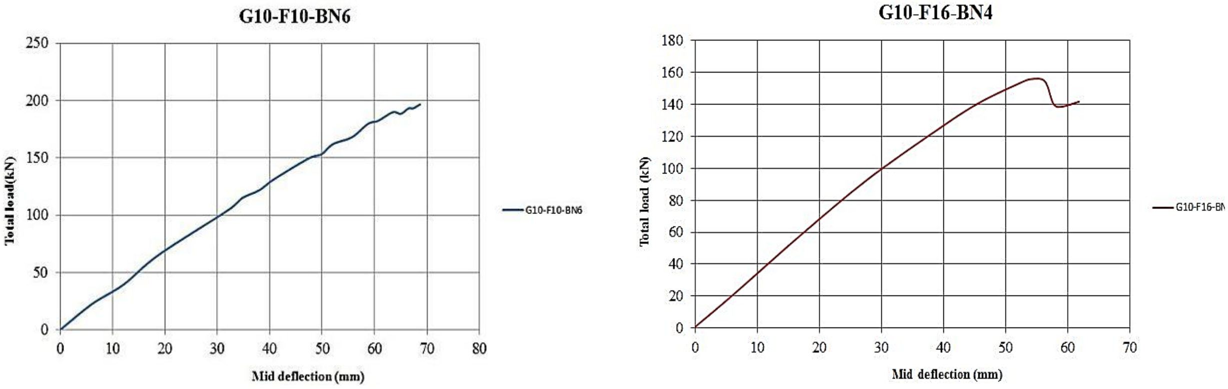
3.0 Experimental Test Results

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 because of low space between bolts while large bolts' space and bolts' diameter in specimen G10-F16-BN4 made failure in the UHF blocks and top flange along with shear failure of web in the bending span.

Figure 4 shows the load over the deflection of the experimental specimens with different test parameters considering the mid span deflection. In figure 4(a) even though crushing in the UHF blocks, GFRP beams did not experience any loss in load carrying capacity while in figure 4(b) shear failure made sudden decrease in load carrying capacity.

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

Figure 3: Failure Patterns of Specimens [27]



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

Figure 4: Load Deflection Curve [27]

4.0 Numerical Modeling

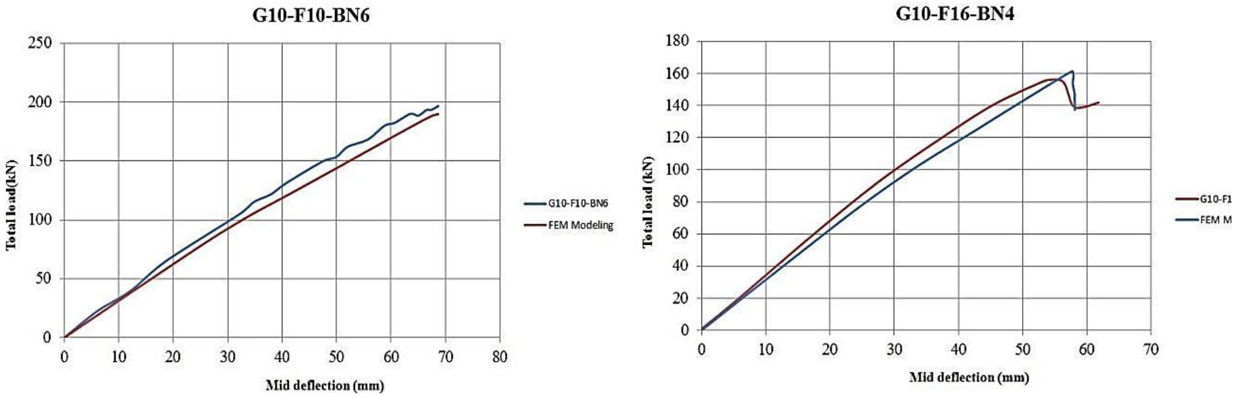
4.1. Verification

Abaqus FEA (formerly ABAQUS) due to the wide material modeling capability and the program's ability is used in the automotive, aerospace, and industrial products industries. Therefore, ABAQUS can meet all the requirements of the modeling including fiber structure of the GFRP composites and different mechanical properties in different directions.

G10-F16-BN4 and G10-F10-BN6 beams have been modeled with FEM ABAQUS software. The UHF and bolts are modeled with 3D elements. GFRP is non-isotropic material with a specific structure for the laminates hence, a numerical layered modeling with the shell elements have been used on. Loads are applied in a virtual 100mm by 100mm area and support condition is assumed completely symmetric and located in the two end of beam as a simple restrain. Analysis performed using the risk method and 1000N as an initial load. This load has been increased gradually until failure.

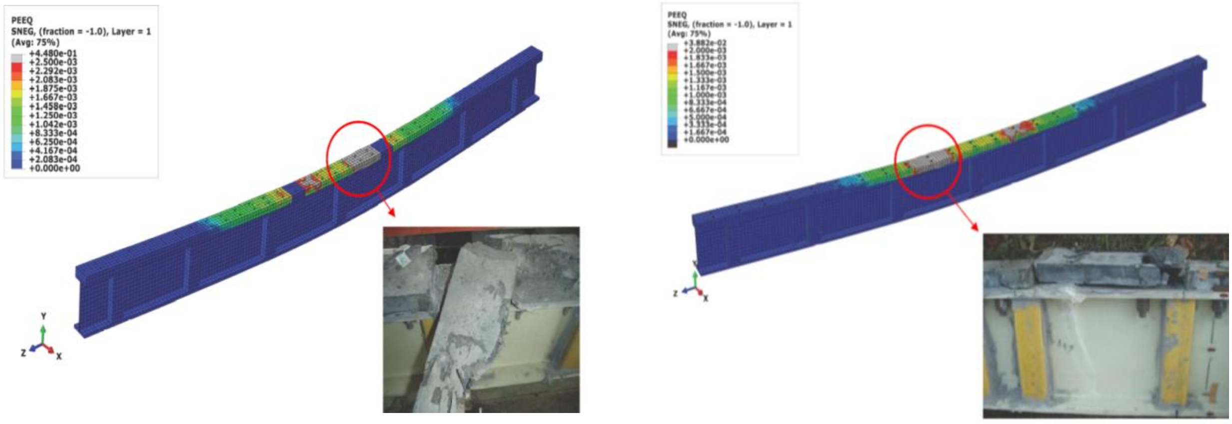
Three types of GFRP 0º, GFRP 45º and GFRP 0º to 90º, has been modeled where the name of each material shows the layers direction with using Hashin Damage method in order to define the nonlinear applications. Thickness of layers in Figure 5 illustrates load-deflection curves and compares FEM and experimental diagrams where initial slope and rapture mechanism are same.

We have reached the same results on the FEM modeling and experimental results with a slight variance. As illustrated in figure 6 where rapture mechanism for two modeled beams, in FEM modeling and full scale beam, has a same pattern with concrete yielding.



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

Figure 5: Load-Deflection Curve



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

Figure 6: Rapture Pattern in FEM Modeling

Comparing both the modeling and test results verify that FEM modeling could be effectively used to evaluate the performance of GFRP I-sections as a replacement for the "I" shaped steel beams. Modarres-Haqqani steel bridge in Tehran would be studied for possibility of replacing steel beams with the “I” shaped GFRP beams.

4.2. Numerical modeling using SAP

Modarres-Haqqani bridge has been modeled using SAP software in actual scale. However because of PC restrictions, Abaqus software could not be used for full scale structure modeling efficiently. This model is used to stress control and design of bridge sections. Loads are assigned according to dead and live loads. General scope of this paper is compare GFRP and steel sections in bridges. So only one load combination as dead plus live load are considered.

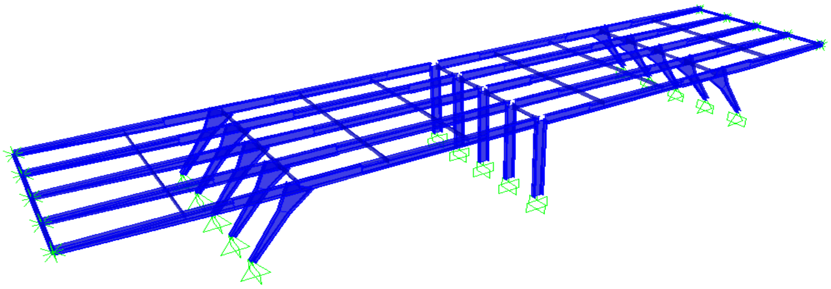


Figure 7: 3D view of Modarres-Haqqani bridge

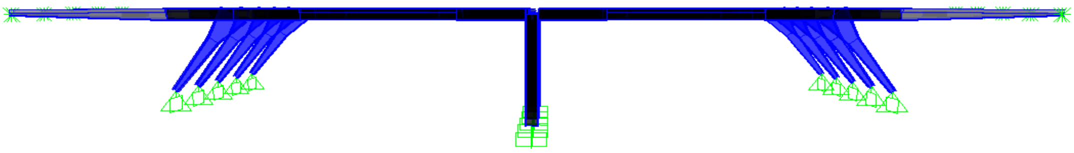


Figure 8: Side view of Modarres-Haqqani bridge

Table 5: Steel section properties

	Outside height (mm)	flange width (mm)	Top flange thickness(mm)	Bottom flange thickness (mm)	Web thickness (mm)
SECC-C	890	400	40	50	10
SECD-D	890	400	40	40	10
SECE-E	856	400	266	40	10
SECF-F	880	400	40	40	10

4.3. Loading conditions

The considered bridge has 10 cm and 25 cm thickness asphalt pavement and concrete deck respectively. asphalt density is 2200 kg/m³ and concrete density is 2500 kg/m³, so dead load could be calculated as asphalt $0.1 \times 22 = 2.2\, kN/m^2$ concrete $0.25 \times 25 = 6.25\ kN/m^2$.

Bridge live load assumed as 5 kN/m², hence total dead and live load on bridge is :

$$8.25 + 5 = 13.25\, kN/m^2$$

According to AASHTO Design Guide maximum allowable displacement for bridges is $^{1}/_{1000}$ bridge span so for mentioned bridge with maximum 20 meter span, maximum allowable displacement was calculated about 20 mm.

5. GFRP Beams replacement

As known modulus of elasticity of GFRP is smaller than steel so displacement under same loading condition will be increase by replacement of Steel with GFRP. Maximum bridge displacement must be restricted to 20mm. because of smaller modulus of elasticity in GFRP, displacement in same loading condition has been increased. Hence to limit displacement under 20mm, GFRP section dimensions and assigned load to each girder must be reduced so distance between girders must be reduced by added new giders in span (case 4)(see figure 9). As is clear case 4 has best condition and minimum displacement.

Table 6: GFRP section properties

	Wing dimensions	Web dimensions	UHF dimensions	MAX Displacement	Distance between girders
Case 1	25×400	15×1000	100×400	95mm	2m
Case 2	25×400	15×1200	100×400	34mm	2m
Case 3	25×400	15×1500	100×400	20mm	2m
Case 4	60×400	40×1000	250×400	16.7mm	1.8m

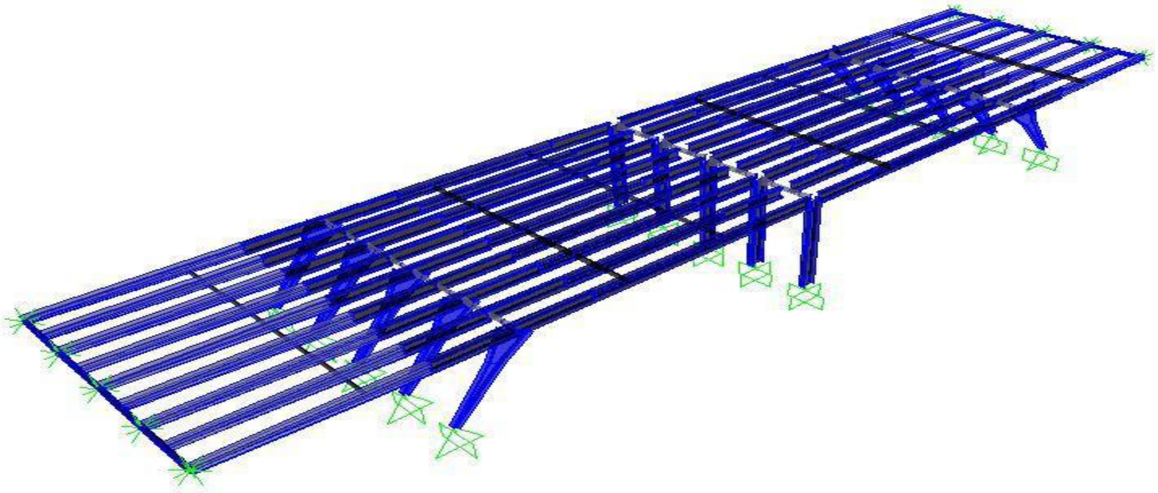


Figure 9: 3D View of Bridge with added Girders

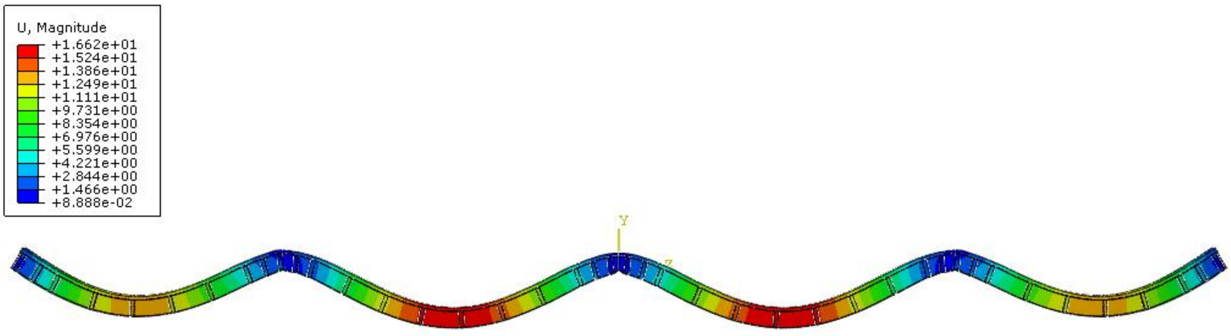


Figure 10: Case 4 Maximum Displacement

6. Results and Conclusions

In this paper Modarres-Haqqani bridge in Tehran has been evaluated. This steel bridge has four span and inclined restrains. It shows that GFRP could be as an alternative to traditional materials as steel. But GFRP materials has different properties from steel. GFRP modulus of elasticity and density is lower and has different properties in various directions. However results could be summarized as follow:

- Stiffness of GFRP materials are less than steel materials surprisingly and so in displacement limitations conditions, as mentioned bridge, dimensions of replaced GFRP section most be increased or assigned load to each GFRP girder most be decreased so steel beams heilght was 89 cm while new replacing GFRP beams height was 100 cm.
- Energy consuming and pollution gas development at initial parts of project increased by using of GFRP, but it could be compensated in long time because of easy use and suitable duration of GFRP.
- If GFRP modeling performed with FEM software, un-isotropic properties most be considered.
- Density of GFRP is less than steel and so GFRP sections has less weight than steel sections and easy for transportations. But in mentioned bridge, used materials has been increased in case of GFRP girders that steel girders, but because of GFRP density, total weight of structure could be same.
- GFRP materials has linear properties until failure and so has sudden fracture unlike steel materials.

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