- Technical Paper -

FLEXURAL BEHAVIOR OF GFRP AND ULTRA-HIGH STRENGTH CONCRETE COMPOSITE GIRDERS SUBJECTED TO ELEVATED TEMPERATURE

Isuru S. K. WIJAYAWARDANE*1, Hiroshi MUTSUYOSHI*2, Takaki ENDO*3 and Kuniaki MORIYA*4

ABSTRACT

Flexural behavior of glass fiber reinforced polymer (GFRP) I-beam, GFRP and ultra-high strength fiber reinforced concrete (UFC) composite girders subjected to elevated temperature are described here. UFC slab was connected to the I-beam using FRP bolts and epoxy resin. Tests were carried out to investigate the mechanical properties of materials subjected to high temperature. Four point bending tests were carried out and the experiment results revealed the glass transition temperature of the shear connectors determined the failure criteria of the GFRP and UFC composite beams.

Keywords: GFRP, ultra-high strength fiber reinforced concrete, composite beam, glass transition

1. INTRODUCTION

Corrosion is one of the severe problems in bridges exist in coastal environments and hence, high maintenance and renovation costs are incurred. Fiber reinforced polymer (FRP) is a cutting edge construction material due to its merits such as high tensile strength, light weight and high corrosion resistance. Experiments carried out at Saitama University revealed that the hybrid FRP (HFRP) I-beam was weak in bending and the beam was failed due to delamination of the compression flange [1]. HFRP I-beam consisted of carbon and glass fibers in the flange and only glass fibers in the web. Fig. 1 shows the delamination failure of HFRP beam.

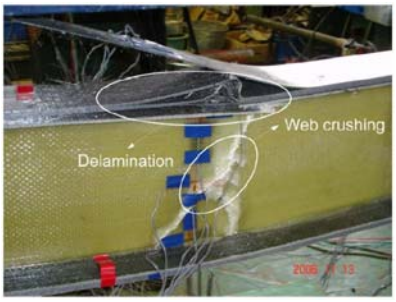


Fig. 1 Delamination of HFRP I-beam

The delamination failure of GFRP I-beam could be eliminated by strengthening the compression flange after installation of ultra-high strength fiber reinforced concrete (UFC) slab [2]. The UFC slab was consisted of 300mm long and 95mm wide segments, which were connected to the top flange of the GFRP I-beam using steel bolts and epoxy resin.

An investigation carried out on temperature effect on full scale FRP bridge showed the maximum temperature at the bridge deck during summer would be approximately 60ºC [3]. When the FRP material temperature approaches to glass transition temperature (T_g), the polymer resin changes from rigid to rubbery state [4]. On the other hand, mechanical properties of epoxy resin used to fix the UFC segments also can be changed at its T_g.

The objectives of this study are to investigate the flexural behavior of GFRP I-beam and GFRP-UFC composite beams with FRP bolts under elevated temperature.

2. TEST PROGRAM

2.1. Materials

(1) GFRP I-Beam

Pultruded GFRP I-beams consist of directional GFRP fibers (0º, 90º and ±45º), GFRP continuous strand mat (CSM) and vinylester epoxy resin. The layer composition of the GFRP composite beam is shown in Fig. 2. Overall length and height of the GFRP beam is 3500 mm and 250 mm, respectively. The flange is 14 mm in thickness and 95 mm in width and the web is 9 mm in thickness. Cross-sectional details of the beam are given in Fig. 3. The glass transition temperature of vinylester resin in GFRP I-beam was investigated by the method explained in Japanese industrial standards (JIS) [5]. According to that, vinylester resin had two T_g temperatures at 58°C and 80°C. Tensile coupon tests were carried out for temperatures 20ºC, 50ºC, 70ºC and 90ºC and the average tensile properties of GFRP flange and web are given in Table 1. Table 2 shows the average compression properties of GFRP flange and web. Compression coupon test were carried out for temperatures 20ºC, 60ºC, and 90ºC.

*1 PhD student, Graduate School of Science and Engineering, Saitama University, JCI Member
*2 Professor, Graduate School of Science and Engineering, Saitama University, JCI Member
*3 Master student, Graduate School of Science and Engineering, Saitama University, JCI Member
*4 Undergraduate student, Graduate School of Science and Engineering, Saitama University

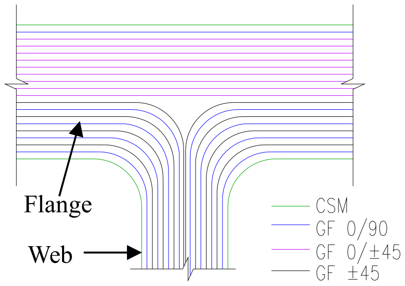


Fig. 2 Layer composition of GFRP I-beam

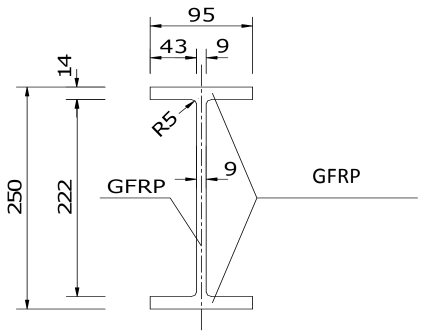


Fig. 3 Cross-sectional details of the GFRP I-Beam (unit: mm)

Table 1 Tensile properties of GFRP I-beam flange and web

Property	Temperature			
	20°C	50°C	70°C	90°C
Tensile strength of flange (N/mm^2)	448	367	369	293
Young's modulus of flange (kN/mm^2)	21.0	19.8	18.2	17.0
Tensile strength of web (N/mm^2)	270	266	207	174
Young's modulus of web (kN/mm^2)	17.8	15.5	12.5	12.0

Table 2 Compressive properties of GFRP I-beam flange and web

Property	Temperature		
	20°C	60°C	90°C
Compressive strength of flange (N/mm^2)	230	212	110
Compressive strength of web (N/mm^2)	223	191	157

(2) Ultra-high strength fiber reinforced concrete

UFC is a durable material because of the densely packed microstructure. UFC segments were precast and they consisted of steel fibers, premixed cementitious powder (ordinary Portland cement, Silica fume and Ettringite), water, sand and water reducing agent. The high strength steel fibers were of 0.2 mm in diameter and the lengths were 22 mm and 15 mm. Equal amounts of fibers from each length were used for UFC. The tensile strength of steel fibers was 2000 MPa and they were added at approximately 1.75% volume ratio. During the manufacturing time, 16mm diameter FRP bolts were embedded into the segments at 150 mm spacing (center to center). The size of UFC segments used for this study is 300x95x35 mm. The average mechanical properties of the UFC are listed in Table 3.

Table 3 Mechanical Properties of UFC

Property	Temperature			
	20°C	50°C	70°C	90°C
Compressive strength (N/mm^2)	178	173	173	171
Young's modulus (kN/mm^2)	44.8	42.0	42.0	42.0

(3) FRP bolts

FRP bolts were used in GFRP and UFC composite beams as a connecting material of UFC segments to the top flange of the I-beam. The reason for using FRP bolts is to improve the corrosion resistance of the composite girder in severe environments. T_g of FRP bolts was measured using JIS method [5] and there were two T_g values 53°C and 105°C. FRP bolt shear tests were carried out for 20°C, 60°C and 90°C. Test results are given in Table 4.

Table 4 Shear strength of FRP bolt

Property	Temperature		
	20°C	60°C	90°C
Shear strength (N/mm^2)	140	133	94

(4) Epoxy resin

As well as FRP bolts, in the GFRP and UFC composite girders, epoxy resin also used to connect the UFC segments to the GFRP flange. The objective of using epoxy resin was to increase the bonding between UFC and top flange of I-beam and obtain full interaction. Glass transition temperature of epoxy resin was 56°C. Shear tests were conducted for epoxy resin under 20°C, 60°C and 90°C and the results are shown in Table 5.

Table 5 Shear strength of epoxy resin

Property	Temperature		
	20°C	60°C	90°C
Shear strength with 0.9 safety factor (N/mm^2)	8.64	2.70	1.53

2.2. Test Variables and Experiment Procedure

Full scale beam flexural tests for six composite girder specimens were carried out and the test variables are listed in Table 6. All together 3 GFRP I-beams and 3 GFRP-UFC composite beams were tested. In all GFRP-UFC composite beams, 16mm diameter bolts were at 150 mm spacing (center to center). The gap between two consecutive UFC blocks were maintained at 10 mm in those composite beams. This gap was filled with cement mortar having compressive strength and Young's modulus of 90 N/mm^2 and 31 kN/mm^2, respectively.

Table 6 Test variables

Specimen name	I-beam material	Temperature °C	Availability of UFC
G-20	GFRP	20	No
G-60	GFRP	60	No
G-90	GFRP	90	No
GC-20	GFRP	20	Yes
GC-60	GFRP	60	Yes
GC-90	GFRP	90	Yes

Cross-section of GFRP I-beam is shown in Fig. 3. Fig. 4 shows the cross-sectional view of GFRP and UFC composite beam. The flexural and shear spans of the beams were 700 mm and 1250 mm, respectively. In order to prevent web buckling, GFRP stiffeners were installed at both sides of the web using epoxy resin. All the beams except G-20 and GC-20 (which were tested at room temperature), were heated up to the required temperature gradually and kept for one hour under the relevant temperature. Heating was done by 10 electric heaters and the beams were kept inside a heat insulated steel box (Fig. 5). Temperature of the beams were measures at three sections (at center of two shear spans and at the mid-span) using thermocouples.

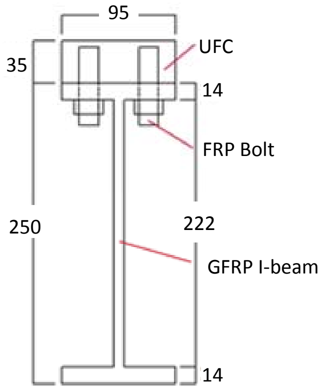


Fig. 4 Cross-section of GFRP and UFC composite beam (unit: mm)

All the specimens were tested under four point bending test and the experimental test setup is shown in Fig. 6. Load was applied at a constant rate by a manually controlled hydraulic jack, until the beam failure. Beam temperature was maintained at the relevant temperature until the beam failure. Average mid-span deflection was measured using two LVDT transducers connected to the both sides of the bottom flange. Strain of UFC slab, top flange, web and bottom flange at mid-span were measured using seven strain gauges.

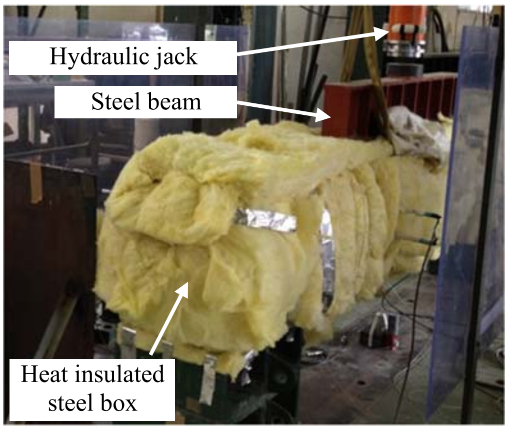


Fig. 5 Heating of GFRP I-beam and GFRP and UFC composite beams

3. TEST RESULTS AND DISCUSSION

Fig. 7 shows the failure patterns of the GFRP I-beams and Fig. 8 shows the failure patterns of GFRP and UFC composite beams. In both G-20 and G-60, the failure location was at the loading point but G-90 was failed at mid-span. In the case of GFRP and UFC composite beams, there were two types of failure patterns could observe. Both GC-20 and GC-60 were failed due to crushing of UFC segment in the flexural span. However, in the GC-60 beam, crushing of GFRP top flange and web and very small movement of all the UFC segments in the shear span (due to failure of epoxy resin) could be observed. Failure pattern of GC-90 beam was completely different from other beams and failure occurred by crushing of GFRP top flange and web in the shear span without damaging the UFC segments (Fig. 8c).

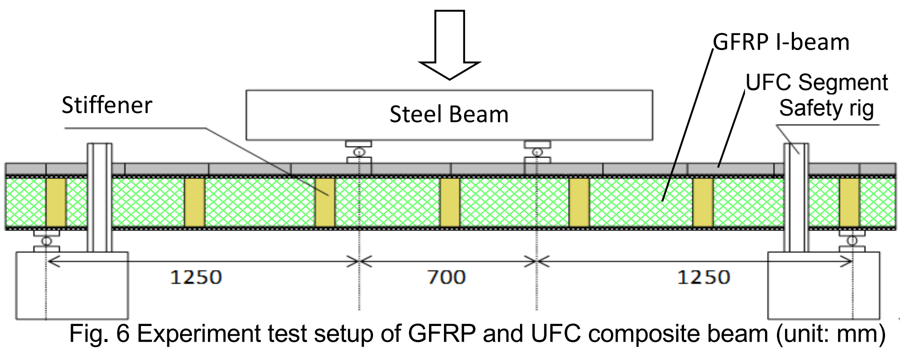
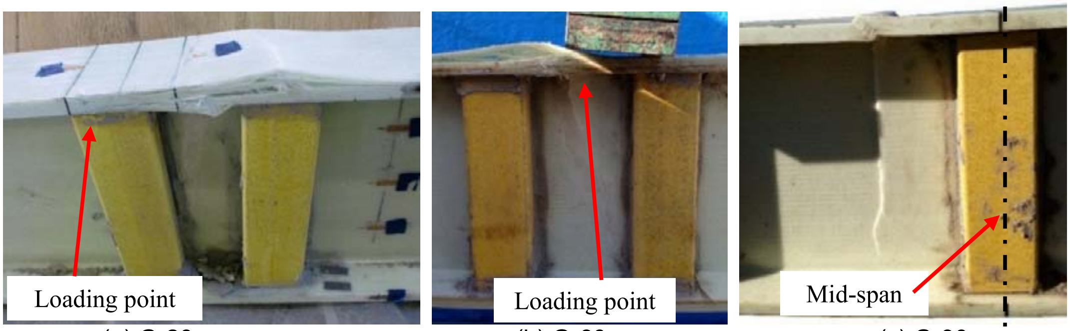


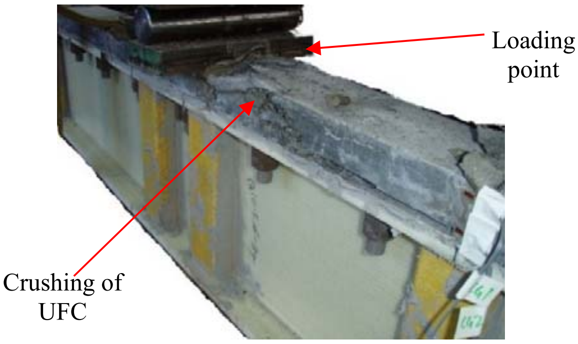
Fig. 6 Experiment test setup of GFRP and UFC composite beam (unit: mm)

Four UFC segments were completely detached from the GFRP top flange due to shear failure of both epoxy resin and FRP bolts in the shear span. Load vs. mid-span deflection relationship of GFRP I-beams and GFRP and UFC composite beams are shown in Fig. 9. According to the experiment results, the GFRP I-beams showed a significantly low flexural capacity and stiffness compared to that of GFRP and UFC composite beams, at all temperatures. Therefore, using of UFC is very important, in order to utilize the superior material properties of GFRP. With the installation of UFC segments, flexural capacity of composite beams could be increased by approximately 80%, 70% and 140% at temperatures 20°C, 60°C and 90°C, respectively. In all beams, flexural capacity and stiffness were reduced when temperature increases. However, there was a sudden reduction of the flexural capacity in G-90 and GC-90, compared to G-60 and GC-60. Reason for this sudden reduction was the losing of mechanical properties of

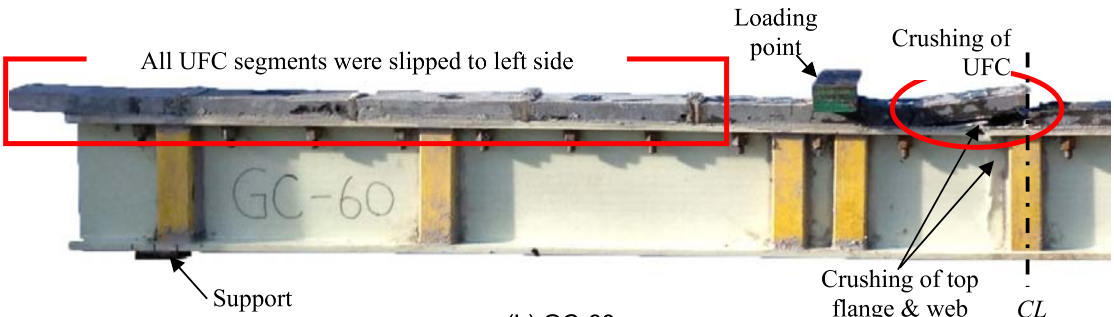


(a) G-20 (b) G-60 (c) G-90

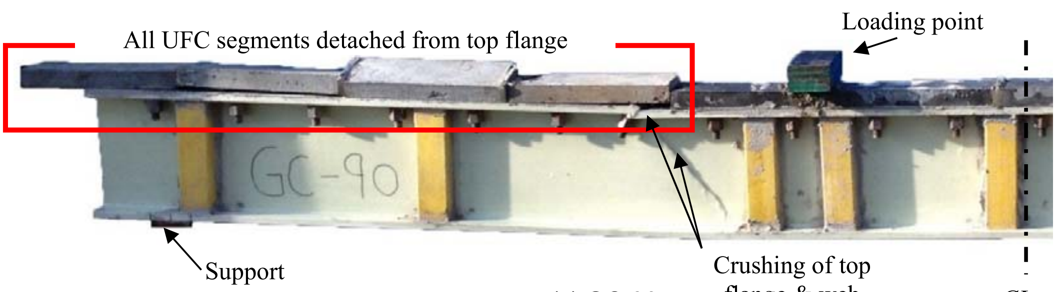
Fig. 7 Failure patterns of GFRP I-beams



(a) GC-20



(b) GC-60



(c) GC-90

Fig. 8 Failure patterns of GFRP and UFC composite beams

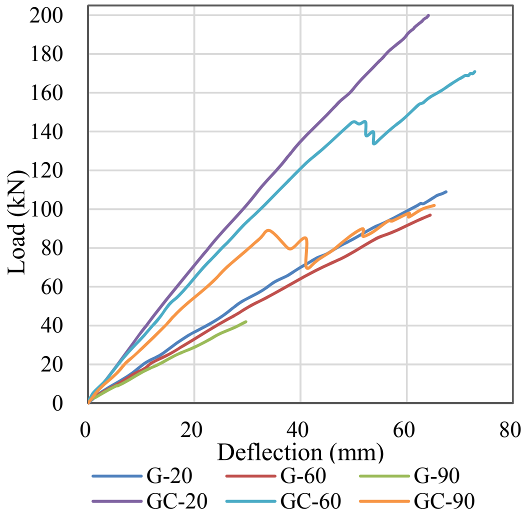


Fig. 9 Load – deflection relationship of GFRP I-beams and GFRP and UFC composite beams

materials (vinylester epoxy resin, FRP bolts and epoxy resin adhesive) due to glass transition. All the GFRP I-beams and GC-20 beam showed linear relationship between load and deflection, until failure. But in the beams GC-60 and GC-90, there was a sudden slip of UFC segments during loading (Fig. 9). The reason for this was failure of epoxy resin between the UFC and GFRP top flange. According to the material properties of epoxy resin T_g was 56°C, which was less than 60°C and hence, the shear capacity of epoxy might have been reduced.

Fig. 10 shows the strain distribution along the mid-span cross-section of GC-20, GC-60 and GC-90. Experiment results confirmed that the strain distribution at mid-span section was linear up to the failure in GC-20 and in the case of GC-60 and GC-90, a linear strain distribution along cross-section could be observed until the slipping of UFC segments.

3.1. Fiber Model Analysis

The behavior of GFRP and UFC composite beams was analyzed using Fiber Model and the results were compared with the experiment results. All girders were assumed to be behaved under Bernoulli-Euler theory. In fiber model, GFRP-UFC I-beam was divided into number of horizontal and longitudinal elements and each horizontal element was assigned with the appropriate material properties given in Section 2.1. It was assumed that the material properties of GFRP flange and GFRP web elements are homogeneous. In the analysis, full interaction between GFRP flange and UFC was considered and hence there was no slip. A bi-linear stress-strain relationship from the design code for UFC structures [6] was used to model UFC. The relationship between load and mid-span deflection obtained from the experiment and the analysis of GC-20, GC-60 and GC-90 is given in Fig. 11a, b and c, respectively.

Since the load vs. deflection relationship was linear in GC-20, both flexural capacity and stiffness could be well predicted in the fiber model analysis (Fig. 11a). In GC-60 and GC-90 beams, fiber model results were valid up to the failure of epoxy resin and at this point, the UFC segments were slipped (Fig. 11b and c). Total shear capacity of epoxy resin in the shear span was calculated for GC-60 and GC-90 using the material properties of epoxy resin. Using the fiber model, the vertical load which makes shear stress in the composite beam (at the UFC and top flange interface) equal to shear capacity of epoxy resin was calculated and marked in red color line in Fig. 11b and c. Similarly, FRP bolt shear capacity also calculated and the vertical load which makes shear stress in the composite beam equal to shear capacity of FRP bolts was calculated and marked in blue color line in Fig. 11b and c. According to the analysis, it is clear that the slipping occurs in both GC-60 and GC-90, when the vertical load is near to the load corresponds to the shear capacity of epoxy resin. After failure of epoxy resin, shear force in the UFC and top flange was taken by the FRP bolts.

Experiment and analysis results reviled that the failure criteria (flexural failure or shear failure) of the GFRP and UFC composite beams was determined by the shear capacity of FRP bolts. When the temperature of the GFRP and UFC composite beam increased over 53°C, (first glass transition temperature of FRP bolts), the shear capacity of FRP bolts tends to reduce. However, at 60°C, the shear stress developed in the shear span of the GFRP and UFC composite beam at failure was less than the FRP bolt shear capacity. Therefore, The GC-60 was failed due to crushing of UFC in the flexural span.

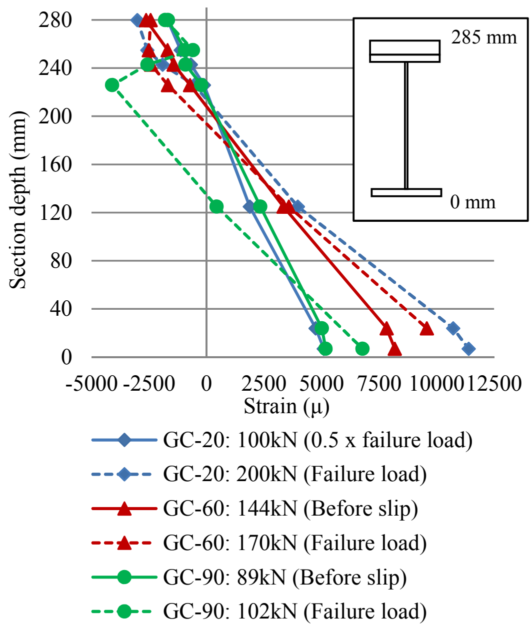
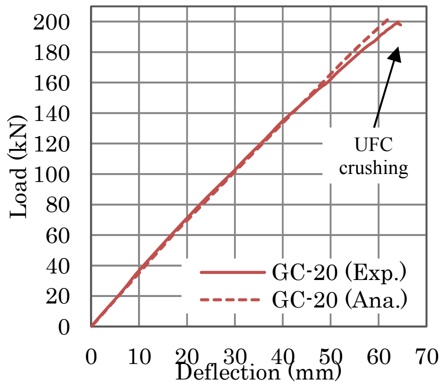


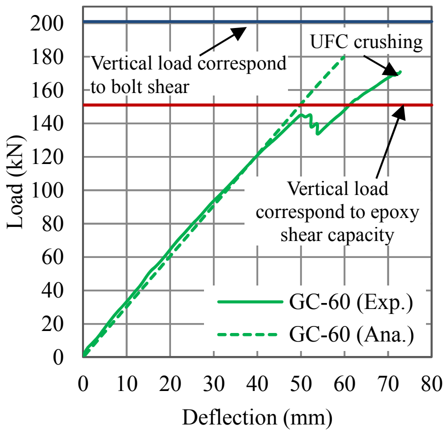
Fig. 10 Strain variation at mid-span section

At 90°C, the failure criterion was changed to shear failure. Reason for that was the shear stress developed in the shear span (at UFC and top flange interface) of the GFRP-UFC composite beam at failure was greater than the shear capacity of FRP bolts.

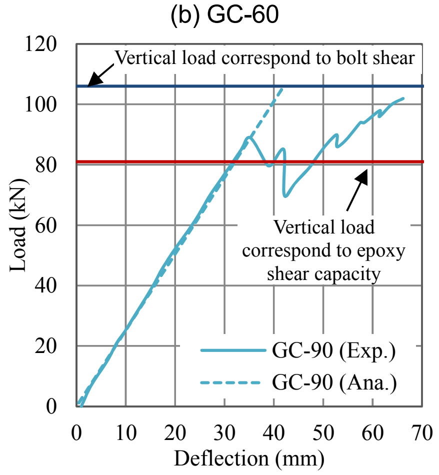
The experiments and analysis results were used in constructing GFRP-UFC short span pedestrian bridge at Onagawa, Japan in 2012 and the details of the bridge is described elsewhere [7].



(a) GC-20



(b) GC-60



(c) GC-90

Fig. 11 Load vs. Deflection relationship between experiment and analysis

4. CONCLUSIONS

(1) Flexural capacity and stiffness of GFRP I-beams are highly influenced by the glass transition temperature of vinylester epoxy resin.

(2) Final failure pattern (flexural failure or shear failure) of GFRP-UFC composite beams is determined by the shear capacity of the FRP bolts at the considered beam temperature. However, the maximum temperature of short span pedestrian bridges consisting of GFRP-UFC composite beams may not more than 65℃. Therefore, possibility of occurrence of FRP bolt shear failure would be minimum.

(3) In real situation, ultimate flexural capacity and stiffness of the GFRP-UFC composite beams can be significantly increased at any temperature, with the use of UFC segments.

(4) Fiber model can be used to analyze the flexural behavior of GFRP-UFC composite beams up to the slipping of UFC segments. In order to study the full behavior of the composite beam, authors will consider the deterioration of material properties by high temperature and also the partial interaction of GFRP I-beam and UFC. The results will be reported later.

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