（28） DEVELOPMENT OF INNOVATIVE HYBRID FRP COMPOSITE BEAMS COMPOSED OF CF/GFRP

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In this study, a hybrid Fiber Reinforced Polymers (FRP) composite I-Beam consisting of Carbon Fiber Reinforced Polymers (CFRP) and Glass Fiber Reinforced Polymers (GFRP) has been developed and its behavior has been investigated. The innovative feature of this beam is the use of hybrid composition of CFRP and GFRP in flanges to obtain the optimum structural performance while only GFRP is utilized in the web to reduce the overall cost. Two series of beams with the same height and different flange widths varying the volume content of CFRP in flanges were tested under four points loading. The experimental investigations revealed that the beams with a small flange width failed due to crushing of fibers near the loading point and the delamination of the compressive flange between the interface of CFRP and GFRP layers. The delamination might be caused by the large difference in the stiffnesses of CFRP and GFRP leading to high stress concentration at the interface. The failure mode of these beams depends upon the volume content of CFRP in the flanges. In the case of wide flange width beams, the failure in compression zone was observed due to local buckling. The buckling was caused by the concentration of high stresses on the flange free-edges and due to high width-to-thickness ratio. Thus, a further investigation is needed to avoid such abovementioned failures so as to utilize FRP material more effectively.

Key Words: *Hybrid FRP, Beam, Volume Content, Delamination, Buckling*

1. INTRODUCTION

Fiber Reinforced Polymers (FRP) materials are progressively used in civil infrastructure applications due to their advantageous properties such as high specific strength, light-weight and corrosion resistance. In bridge engineering field in Japan, FRP materials are mainly used for strengthening of concrete bridges and columns. The first entire FRP pedestrian bridge in Japan with a two span continuous beam was built in 2001 (Fig. 1). All the structural members of this bridge were made of GFRP.

Fig. 1 Okinawa Road Park Bridge (2001)

Over the last decade there has been significant growth in the research and development of all-FRP bridge structures in the world. Numerous theoretical and experimental investigations have been reported worldwide regarding the behavior of all-FRP beam. Bank (1989) [1] presented an experimental methodology for the simultaneous determination of the section flexural modulus and the section shear modulus of thin-walled fiber reinforced polyester and vinylester E-glass pultruded beams. Davalos et al. (1996) [2] carried out the analysis and design of E-glass pultruded FRP beams in bending. Khalid et al. (2005) [3] performed an experimental and finite-element analysis for glass/epoxy composite I-beams under axial compression and bending load modes.

In abovementioned studies, the materials used were mainly GFRP. However, the combination use of GFRP and CFRP in a beam is still limited so far. CFRP has high tensile strength and high stiffness but relatively expensive while GFRP has lower strength and stiffness but is less expensive than CFRP. The combination use of these two materials in a beam may benefit from the strength-to-cost aspect when they are utilized in an effective way. Thus, this study focuses on an experimental investigation of the behavior of hybrid FRP beams consisting of carbon/vinylester and glass/vinylester. An I-shaped section of FRP beams is proposed as a first step of the ongoing research project since it is easily manufactured and commonly used in bridge structures. Two series of I-beams with the same height and different flange widths were tested varying the volume content of CFRP and GFRP in flanges and preliminary experimental results were described.

2. EXPERIMENTAL PROGRAM

2.1. Experimental variables and material properties

The cross section employed in this study was I-shaped FRP beams. All beams were manufactured by the Resin Transfer Molding process consisting of carbon and E-glass/epoxy. Two series of beams, A-series and B-series, with the same height of 250 mm and different flange widths were tested under four points loading at a span of 3000 mm. The flange width of A-series and B-series are 95 mm and 250 mm, respectively. The dimensions of the beams are shown in Figs. 2a and 2b. All beams were made of CFRP and GFRP in the flanges and only GFRP in the web. Some GFRP layers in the web were extended to the flanges in each beam. To utilize carbon and glass fibers more effectively, the angle of fibers was varied through the thickness of FRP laminate. The angle of CFRP was fixed to be zero degree to longitudinal direction while the angle of GFRP was zero or ±45 degree to avoid the anisotropic characteristic of FRP materials. To investigate an appropriate beam design from a viewpoint of cost and strength, three different compositions of carbon fiber with the volume content of 52%, 33% and 14% were used in the flanges as shown in Table 1. The mechanical properties of carbon and E-glass fibers used in this experiment are shown in Table 2. Web stiffeners were installed under the loading points and supports to prevent buckling of the beam (Fig. 2b). The steel box stiffeners were bonded with FRP beam by epoxy adhesion.

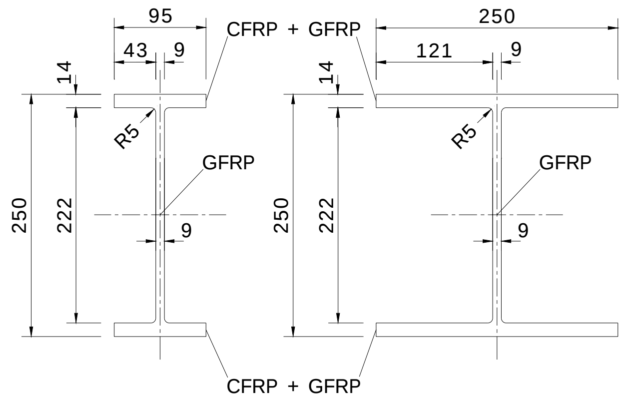

Fig. 2a Beam cross-section

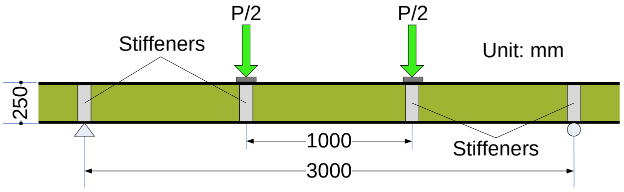

Fig. 2b Beam elevation

Table 1 Experimental variables

Beam		CFRP (%) 0*	GFRP Roving[1] (%) 0/90*	GFRP Roving[1] (%) ±45*	GFRP MAT[2] (%) -
Flange	[3]A-0, [4]B-0	52	10	13	25
	[3]A-1, [4]B-1	33	29	13	25
	[3]A-2	14	48	13	25
Web	All beams	-	32	42	26

*[1]Continuous fibers; [2]Chopped fibers; [3]A-series; [4]B-series; *Angles of fibers*

Table 2 Mechanical properties of materials

Notation	CFRP	GFRP Roving	GFRP MAT
Volume fraction (%)	50	50	20
Longitudinal young modulus (GPa)	113	24	10
Transverse young modulus (GPa)	7.4	24	10
In-plane shear modulus (GPa)	3.2	3.5	3.7
Poison's ratio (-)	0.32	0.1	0.3

2.2. Experimental setup

To investigate the behavior and failure modes of the beams, four points loading tests were conducted on all types of beams. The test setup is shown schematically in Figs. 3a and 3b. The load was measured with load cells between the jack and steel plates. For all beams, Linear Voltage Displacement Transducers (LVDT) was used to measure the deflection of the beams in mid-span section and under the loading points (Fig. 4). A number of strain gages were attached in flexural span, shear span and near the loading points to measure the strain distributions of the beams. The data logger and switch boxes were used to record the data during the test. Safety rigs were installed near the supports to prevent beams from sudden falling in the case of any lateral buckling (Fig. 3a). Teflon sheets were used in the gap between the safety rig and the beam to restrict the frictional effects in the case of any touch during the test.

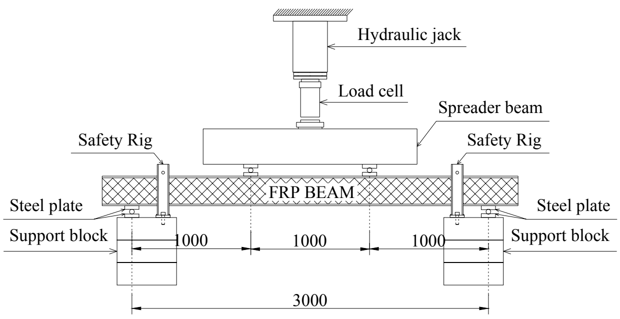

Fig. 3a Test setup

Fig. 3b Schematic view of test setup

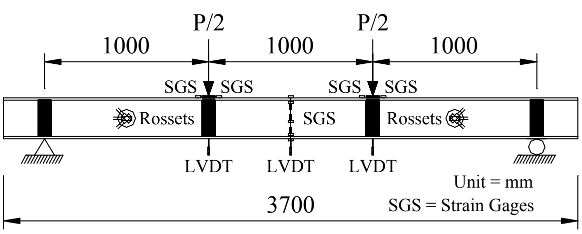

Fig. 4 Positions of measurement devices

3. EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained from the experimental investigation are presented including the load-deflection response, failure modes and strain distributions of A-series and B-series beams.

3.1. Load-deflection response and failure modes of A-series beams

Fig. 5 shows the relationship between the load and mid-span deflection of A-series beams. It can be seen that the behavior of all beams was almost linear-elastic up to the failure. The slope of load-deflection curves at mid-span section is proportional to the volume content of CFRP in the flanges. The experimental data demonstrate that an increment of 20% CFRP in the flanges can give approximately 10% increment in overall beam stiffness. The failure modes of A-series beams are shown in Figs. 6, 7 and 8. It was the crushing of fibers in the web and near the loading point and the delamination of the compressive flange between the interface of carbon and glass fibers. The buckling of the top flange seems to appear after the delamination.

Unlike the stiffness, the load carrying capacity of the beam is not proportional to the volume content of CFRP in the flanges. The ultimate load of beam A-1 is the largest while the ultimate load of beam A-0 and A-2 are almost the same. The ultimate loads of all tested beams and corresponding mid-span deflections and strains are listed in Table 3. A close observation during the test suggests that the failure at the loading point of beam A-0 may be due to the stress concentration. In addition, in the case of beam A-2, since the flange stiffness is comparatively smaller due to smaller volume content of CFRP, web crushing at the loading span seems to occur before the delamination failure. Therefore, it is concluded that the load carrying capacity of the beam is not related with the volume content of CFRP but governed by the failure mode.

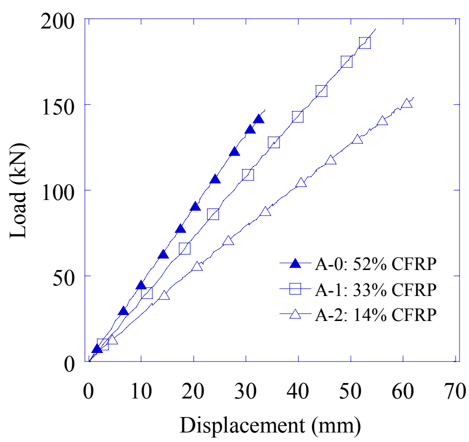

Fig. 5 Load-Deflection of A-series beams at mid-span

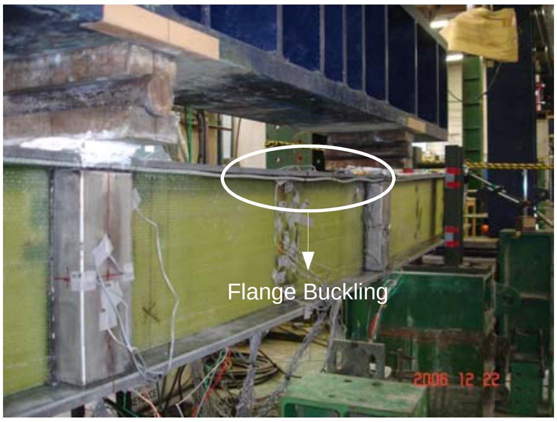

Fig. 6 Buckling of the top flange (Beam A-0)

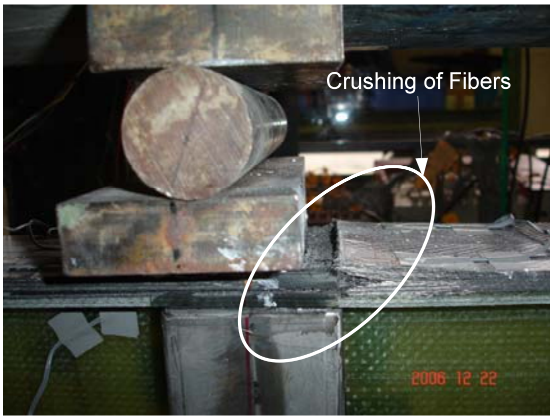

Fig. 7 Crushing of fibers near the loading point (Beam A-0)

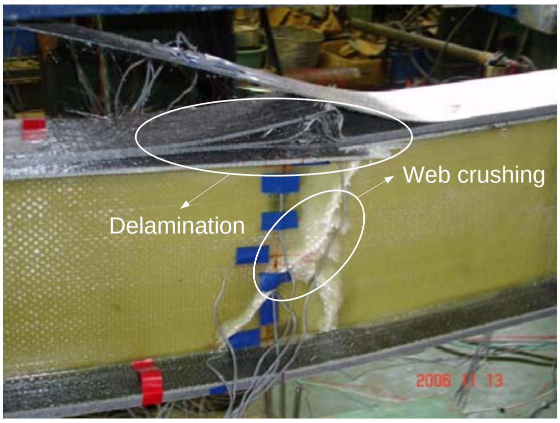

Fig. 8 Delamination and web crushing of beams A-1 and A-2

Table 3 Experimental results at ultimate load
(Negative strain values indicate compression)

Beam	Ultimate Load (kN)	Mid-span deflection (mm)	Top flange strain (μ)	Bottom flange strain (μ)
A-0	146.90	33.50	-3671	3598
A-1	194.86	56.62	-6132	6245
A-2	153.89	62.00	-7119	7352
B-0	239.83	30.30	-3428	2334
B-1	234.84	36.98	-4614	3177

3.2. Load-deflection response and failure mode of B-series beams

The load-deflection curves at mid-span, measured for the wide flange width beams (B-series), are shown in Fig. 9. The two beams, B-0 and B-1, varying the volume content of CFRP in flanges showed almost linear-elastic behavior up to 190-220 kN before the initial local buckling can be observed in the compressive zone. Fig. 10 shows the local buckling observed during the test. The local buckling is mainly caused by the concentration of high stresses on the flange free-edges and due to high width-to-thickness ratio. Indeed, the experimental data show that the maximum strains on the flange free-edges at the ultimate load of beam B-0 and B-1 are 7348 μ and 8466 μ respectively while the center strains at the mid-span of these beams are only 3428 μ (beam B-0) and 4614 μ (beam B-1). The local buckling also caused a significant increment of the deformation and a slight decrease of the stiffness of the beams. Consequently, the response of the beam changed from linearity to nonlinearity in this state. The ultimate loads of these two beams are almost the same at around 235 kN. The final failure mode of B-series beams is the local buckling of the top flange leading to separations of laminates and crushing in the web as represented in Fig. 11. Although the stiffness of beam B-0 and B-1 is about 50% higher than that of beam A-0 and A-1 respectively, but their ultimate load carrying capacity increases only 38.7% for beam B-0 and 17% for beam B-1.

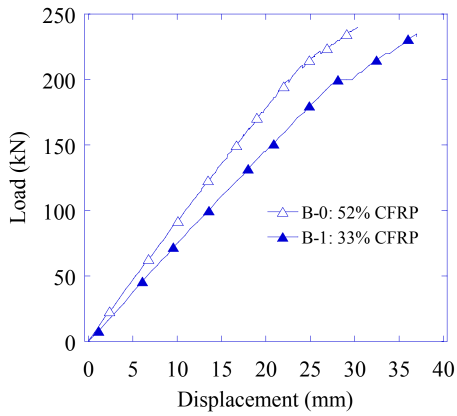

Fig. 9 Load-Deflection of B-series beams at mid-span

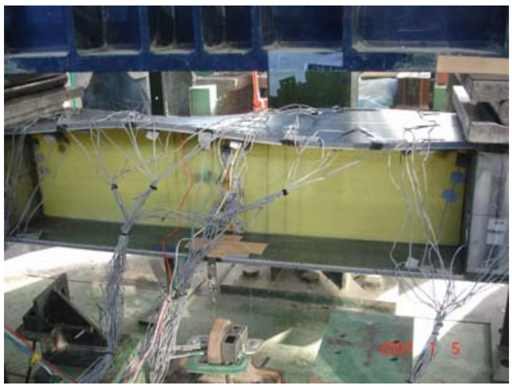

Fig. 10 Local buckling of beam B-0 and B-1

Fig. 11 Failure mode of beam B-0 and B-1

3.3. Strain distributions of A-series beams

Fig. 12 shows the relationship between load and longitudinal strain at the top and bottom flange at the mid-span section. The results indicate that both compressive and tensile strain behave linearly up to the failure. Fig. 13 represents the vertical strains at the top and bottom web at the mid-span section. It is interesting to note that the vertical tensile strain was observed in the top of web while the vertical compressive strain was observed in the bottom of web. This phenomenon can be found only in the case of anisotropic materials. Fig. 14 illustrates the mechanism of delamination. It is likely that the difference in the stiffnesses of stiff composition of CFRP and GFRP of the flange and relatively soft GFRP from the web caused the delamination and the appearance of vertical tensile strain in the web produced the separation of the interface of CFRP and GFRP layers. Similar failure mode was reported by other researchers (Bank et al. 1999) [4]. It is concluded that the load carrying capacity of the beam is dominated by the difference in the stiffnesses of fibers at the interface. It is likely that the larger difference in stiffnesses results in the higher separation appearance at the interface.

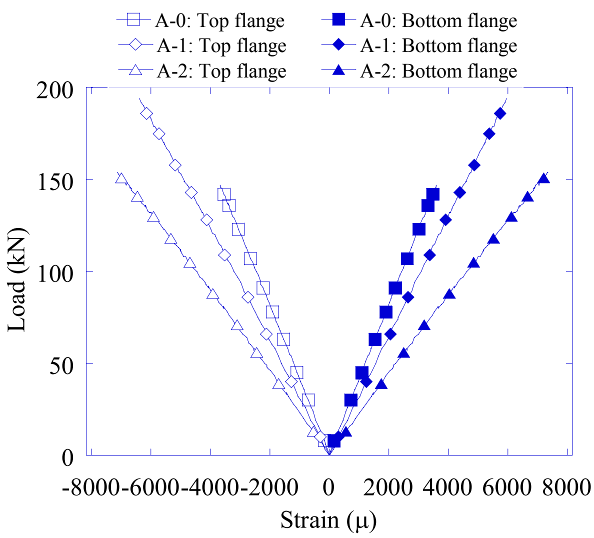

Fig. 12 Load-Longitudinal strain of A-series beams

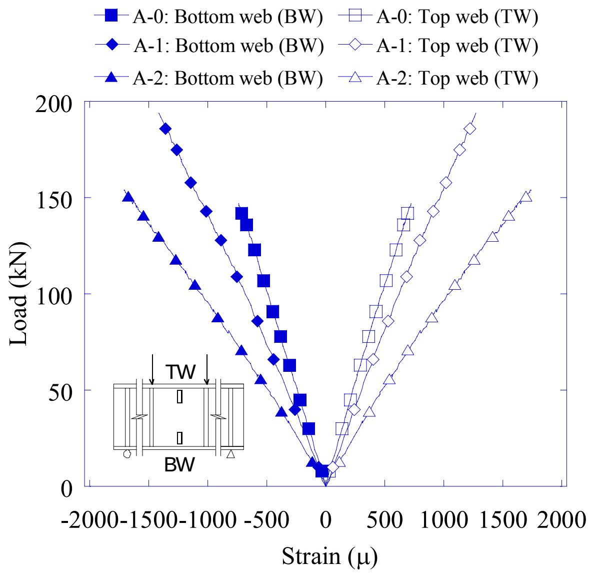

Fig. 13 Load-Vertical strain of A-series beams

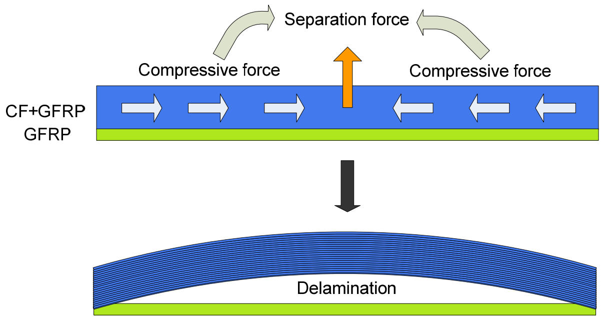

Fig. 14 Mechanism of delamination

3.4. Strain distributions of B-series beams

Fig. 15 represents the relationship between the load and longitudinal strain at the top and bottom flange at the mid-span section of B-series beams. It can be seen that the compressive strains in top flange behave nonlinearly when the load is over 190-200kN while the tensile strains in bottom flange response linearly up to the failure. In addition, both the ultimate compressive and tensile strains of the beams do not reach the maximum strain of FRP materials. The distribution of vertical strains at the top and bottom web at the mid-span section of beams B-0 and B-1 are shown in Fig. 16. The tensile vertical strains increased significantly from the initial buckling load while this increment of compressive strains in the bottom web is comparatively small (the ultimate tensile strain at the failure is approximately 5000 μ while the ultimate compressive strain at the failure is only 1300 μ). When the beam is buckled, the out-of-plane stresses at the flange free-edges are rapidly grown producing high tensile stress in compressive zone. Thus, it can conclude that local buckling is the main cause leading to the premature failure of B-series beams.

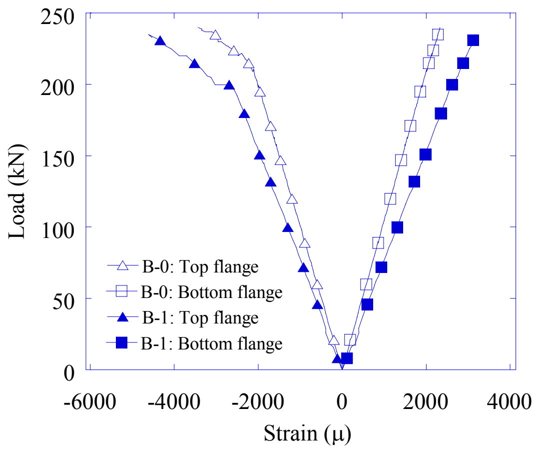

Fig. 15 Load-Longitudinal strain of B-series beams

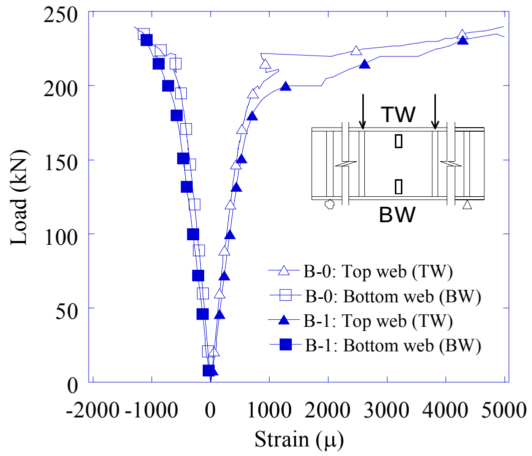

Fig. 16 Load-Vertical strain of B-series beams

4. CONCLUDING REMARKS

In this paper, behavior of hybrid FRP I-beams under four points loading is described. The following conclusions can be drawn:

(1) The beams with a small flange width behave linearly under load and failed suddenly due to the crushing of fibers near the loading point and the delamination of the compressive flange between the interface of carbon and glass fibers. The failure mode of beams depends upon the volume content of CFRP in flanges. It is likely that the difference in the stiffnesses of CFRP and GFRP caused the separation of laminates and the load carrying capacity of the beams is not related to strength and stiffness of the fibers but the failure mode.

(2) The beams with a wide flange width failed in the local buckling in the top flange leading to the separations of laminates at the interface and crushing in the web. The buckling was caused by the concentration of high stresses on the flange free-edges and due to high width-to-thickness ratio.

(3) A further investigation is needed to avoid such abovementioned failures so as to utilize FRP material more effectively.

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