EXPERIMENTAL STUDY ON DOUBLE LAP JOINTS COMPOSED OF HYBRID CFRP/GFRP LAMINATE

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ABSTRACT

This paper presents results from experimental studies on the behaviour of hybrid CFRP/GFRP laminates with double lap joints. A number of hybrid FRP coupon and full-scale beam specimens with bolted-only and bolted-and-bonded joints were tested. The results show that a combined use of steel bolts, adhesive bonding and V-notch splice plates in double lap joints was found to be an effective method for joining hybrid FRP laminates. The rough surface of V-notch splice plates and adhesive bonding contributes to improve the stiffness of joints.

KEYWORDS: CFRP/GFRP laminates, steel bolts, adhesive bonding, V-notch plates, beam, stiffness

1. INTRODUCTION

FRP composites have been increasingly used in civil infrastructure applications due to their advantageous properties such as high strength/stiffness, lightweight, and corrosion resistance. Recently, we have developed a hybrid FRP girder consisting of carbon and glass fibres in Japan and the idea is to use the superior strength of CFRP in the flanges while keeping the material costs low by using GFRP in the flanges and web. We have conducted a number of beam tests under four-point loading and failures were delamination of FRP laminates in the compressive flange at mid-span section, crushing of fibers in web and near the loading point due to load concentration (Mutsuyoshi et al., 2008). To prevent such types of failures, a stiff plate such as concrete deck is needed to provide on top of the beam to restrain the high interlaminar stress present in the compressive flange and a connection between hybrid FRP beam and concrete deck is an issue which should be investigated. Moreover, connections between beam-to-beam and beam-to-column are of other important issues since it is inevitable due to limitations of FRP beam size and the requirement of transportation and handling. Thus, the main purpose of this study is to develop effective joining methods for hybrid FRP. As the first step of the ongoing project, the behavior of beam-to-beam connections is investigated. To date, numerous experimental and analytical investigations of connections including mechanical fastening, adhesive bonding and the combination thereof have been conducted (Camanho and Matthews, 1997; Hart-Smith, 2002; etc.). However, the previous studies cover a wide range of FRP laminates with various fibre architect and matrix types, fibre lay-up and stacking sequences, etc., which result in different behaviour of joints. Thus, additional investigations are required to fully understand the characteristics of joints of hybrid CFRP/GFRP laminates. This study focuses on experimentally determined behaviour of joints in small scale (coupon) and large scale (beam) tests. A number of coupon and beam specimens with double lap bolted-only and bolted-and-bonded joints were tested to examine their strength and behaviour. The effect of V-notch splice plates and the contribution of adhesive bonding to the joint strength are discussed.

2. COUPON TESTS

2.1 Test specimen

A series of hybrid FRP laminate coupon specimens were tested with configuration of 6-bolt double lap joints as shown in Figs. 1 and 2. All specimens have the same width of 80mm, end distance of 30 mm, side distance of 20 mm, longitudinal and transverse hole spacing of 40 mm. The nominal thickness of the FRP laminates is 14 mm. The FRP laminates consist of CFRP and GFRP. The angle of CFRP was fixed to be zero degree while the angle of GFRP was zero, 90, ±45^{o} degree or Continuous Strand Mat (CSM). All specimens were manufactured using pultrusion process. Material properties of the FRP laminates are listed in Table 1.

All specimens were configured with the same ratios of end distance to bolt diameter (e/d_b = 3), laminate width to bolt diameter (w/d_b = 8), side distance to bolt diameter (s/d_b = 2), longitudinal spacing to bolt diameter (p/d_b = 4), transverse spacing to bolt diameter (g/d_b = 4), bolt diameter to plate thickness (d_b/t_{pl} = 1.1), washer diameter to bolt diameter (d_w/d_b = 2.5) and hole side clearance ($d_h - d_b = 0.05d_b$). Stainless steel bolts were used with a nominal diameter of 10 mm. The yield and ultimate strength of bolts are 600 MPa and 800 MPa, respectively. Holes were machined in the specimens using diamond tips. The specimens were lateral clamped with bolts through 9 mm thick steel plate in both sides. The torque was applied exactly at 20 Nm by controlling the presetting torque wrench. The same configuration was set for specimens with bolted-only and bolted-and-bonded joints. For the bolted-and-bonded joint specimens, the adhesive was pasted on both sides of the FRP laminates before applying the torque. The epoxy was cured in the temperature room one week before each test.

2.2 Test setup and measurement

All tests were conducted using a Universal Testing Machine (UTM) with a load capacity of 500 kN. The data logger was used to record load, displacement and strain data. The specimens were clamped by the grips of the testing machine at both ends and the tensile force was applied at the top and bottom end. Clip gages were attached on both sides of the specimen to measure the relative displacement between the FRP laminate and the steel plates. Each specimen was instrumented with back-to-back strain gages attached on the FRP laminate and the steel plates. The test setup is schematically illustrated in Fig. 2.

2.3 Test results and discussion

2.3.1 Effect of adhesive bonding

The comparison of load-relative displacement curves of specimens with bolted-only and bonded-and-bolted connection is shown in Fig. 3. For identification purpose, the specimen with bolted-only will be referred to as specimen A0 and the specimen with bonded-and-bolted will be referred to as specimen A1. The relative displacement in Fig. 3 indicates the difference in averaged displacement of clip gages attached on both sides of the specimen (one end of the clip gage is attached on the steel plate and the other end is attached on the specimen). As can be seen in Fig. 3, the load-relative displacement (load-displacement, in shortly) curve of the specimen A0 can be subdivided into four stages. For the first stage, there was no slipping between the steel plates and the FRP laminates when the load in the range of 0 to 15 kN. This is due to the effect of the tightening-torque applied to the bolts. For the second stage, the load-displacement curve behaves linearly when the load increases from 15 to 60 kN corresponding to the relative displacement of 0.0-1.0 mm. This indicates that the bolts gradually slipped into bearing region around the holes of FRP laminates. The third stage shows the nonlinear behavior of the load-displacement curve with the range of relative displacement from 1.0-5.5 mm. This might be due to the development of bearing failure in the FRP laminates combined with bending of the bolts. The final stage is the load reduction when the bolts start yielding. The load then suddenly dropped at approximately 330 kN after excessive failure strength of bolts.

Similarly, the load-displacement curve of the specimen A1 can be subdivided into four stages. The first stage shows the connection resist against slipping when the load is limited to 50 kN. This value is 3.3 times higher than that of the specimen A0 due to the contribution of adhesive bonding. The second stage indicates linear behavior of load-displacement curve when the load increases from 50-150 kN corresponding to the relative displacement of 0.05-0.3 mm. The third stage exhibits a gradual development of bearing failure in the FRP laminate together with local debonding of

Table 1 Mechanical properties of materials

Parameters	Notation	CF-0	GF-0/90	GF±45	GF-CSM
Young's Modulus	E_{11} (GPa)	128.1	25.9	11.1	11.1
	E_{22} (GPa)	14.9	25.9	11.1	11.1
Shear Modulus	G_{12} (GPa)	5.5	4.4	10.9	4.2
Poisson's Ratio	ν_{12} (-)	0.32	0.12	0.58	0.31

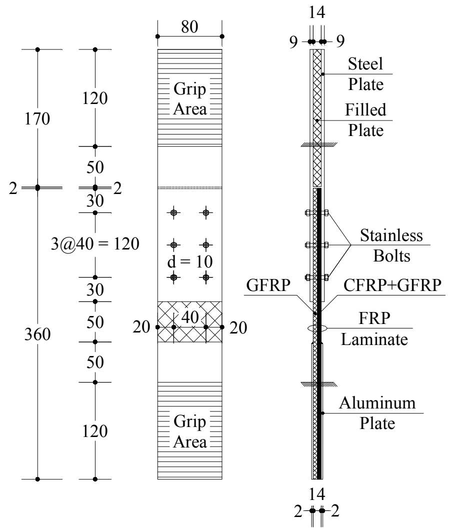


Fig. 1 Test configuration

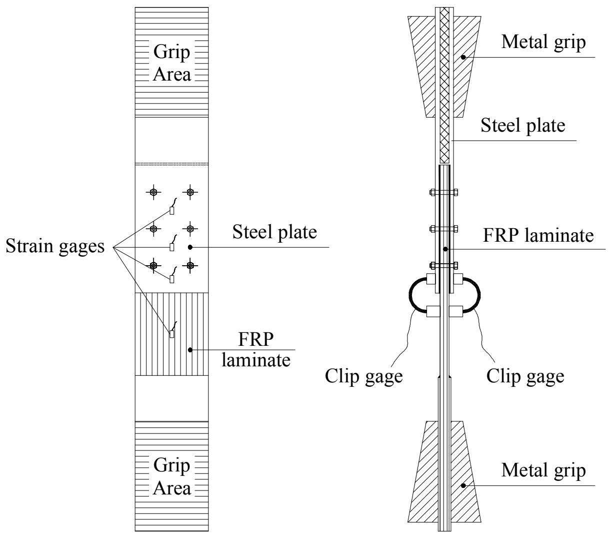


Fig. 2 Test setup

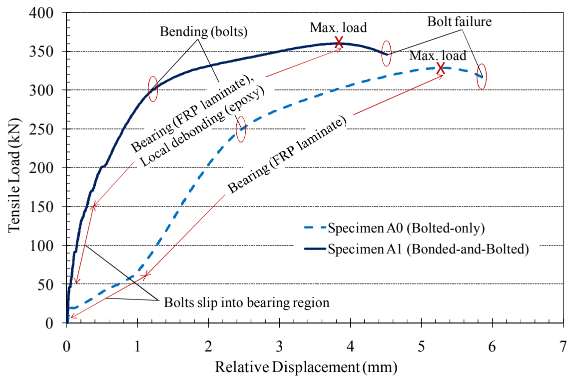


Fig. 3 Load-relative displacement curve

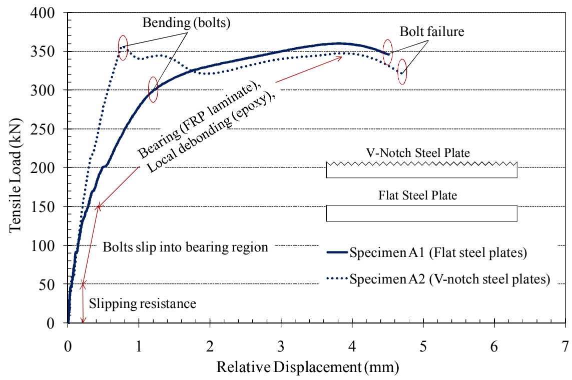


Fig. 4 Effect of splice plates

the epoxy layer and bending of bolts when the load increases from 150-360 kN corresponding to the relative displacement of 0.3-3.5 mm. The final stage shows the sudden failure of the specimen A1 at about 345 kN. It is clear from Fig. 3 that the stiffness of the load-displacement curve of the specimen A1 is much higher than that of the specimen A0. This suggests that adhesive bonding can improve considerably the slipping load and the stiffness of joints.

2.3.2 Effect of splice plates

To examine the effect of splice plates on the strength of joints, two specimens with the same configuration but different types of splice plates were tested. The specimen A1 using flat splice plates while specimen A2 using V-notch splice plates (height of V-notches = 0.5 mm). The original idea of using V-notch splice plate is to provide more clamping force between the splice plates and the hybrid FRP specimen (splice plates bite the specimen) with an appropriate amount of torque that will not lead to damages at the outermost surface of the specimen. Fig. 4 shows the comparison of the load-relative displacement relationship between specimens A1 and A2. The figure shows that the stiffness of load-displacement curve of these specimens is almost the same up to 140 kN. However, with the continuing increases of load, specimen A2 shows higher stiffness than that of specimen A1. The differences in stiffness tend to increase with the increases of load. This may be due to rough surface of the splice plate in specimen A2 contributed to improve bonding between the splice plates and the hybrid FRP specimen. Indeed, the load at which bolts start to bend of specimen A2 is approximately 14% higher than specimen A1. This indicates that adhesive layer may carry almost the load before debonding occurs. When the adhesive layer fails, the load is carried solely by bolts. Finally, both specimens A1 and A2 fail due to cutting of bolts.

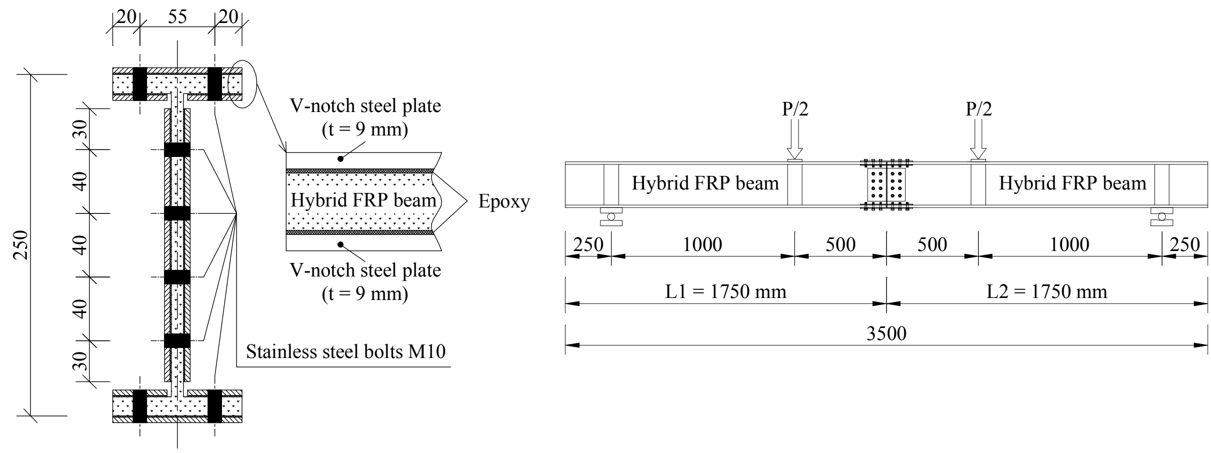
3. FULL-SCALE HYBRID FRP BEAM TESTS

3.1 Test specimen

Based on results from the coupon tests, the joint method of bonded-and-bolted with V-notch splice plates was selected for joining full-scale hybrid FRP beam. Tests were conducted on hybrid FRP I-beams of 95 mm wide, 250 mm high, 14 mm (flange) and 9 mm (web) thick. The hybrid FRP I-

Table 2 Beam test variables

Beam	Type of beams	Type of joints	Length of joined parts		Total length of beams	Number of bolts	
			L1 (mm)	L2 (mm)	L (mm)	Flange	Web
B0	Control beam (without joints)	n/a	n/a	n/a	3500	n/a	n/a
B1	Joined in flexural span	Bonded-and-Bolted	1750	1750	3500	8	8
B2	Joined in flexural span	Bonded-and-Bolted	1750	1750	3500	12	16



a. Cross section b. Elevation

Fig. 5 Details of specimen for full-scale test of bonded-and-bolted joints

beams were fabricated with a length of 3500 mm. A number of beams were cut into halves with each length of 1750 mm for joining in the flexural span. Butt joints of the cut beams at flanges and web using 9 mm thick V-notch steel plates, 10 mm stainless bolts and a very thin layer of epoxy were prepared. A torque of 20 Nm was applied to the bolts. The epoxy was cured in the temperature room for 7 days before the test. The hybrid FRP beam has same mechanical properties as that of the coupon specimens as listed in Table 1. Details of joints and specimens for full-scale tests are shown in Fig. 5.

3.2 Test setup and measurement

The beams were simply supported and tested in four-point bending at a span of 3000 mm with an interior loading span of 1000 mm. The test setup is shown schematically in Fig. 6. Linear Voltage Displacement Transducers (LVDT) and laser transducers were used to measure the deflection of the beams in mid-span section and under the loading points. 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. A high-speed camera was placed in front of the beams to record the sudden failure.

3.3 Test results and discussion

3.3.1 Load-deflection curve

The load-deflection curve at mid-span section of beams B0, B1, B2 under four-point bending test is shown in Fig. 7. The results show that both beams B0 and B2 behave linear up to failure. These two beams failed at almost the same load of approximately 190 kN. However beam B2 shows higher stiffness than that of beam B0 due to the contribution of the steel plates and bolts in the flanges and web. The failure modes of beams B0 and B2 were crushing of fiber near the loading point followed by the delamination of the top flange as shown in Fig. 8. In addition, web buckling in the flexural span was observed in the case of beam B2 due to the restraints of joints in the flanges and web. By a visual monitoring during the test of beam B2, it seems that failure did not happen in the joined part as expectation before the test. In contrast, beam B1 was expected to fail in the joined part. Indeed, beam B1 behaves linear up to only 130 kN. With the continuing increases of load, the behavior of beam B1 is nonlinear because of the local debonding of epoxy layers and the bending of bolts. The final failure mode of beam B1 were the cutting of bolts in the bottom flange leading to rotation of the splice plates in the web as can be seen in Fig. 9.

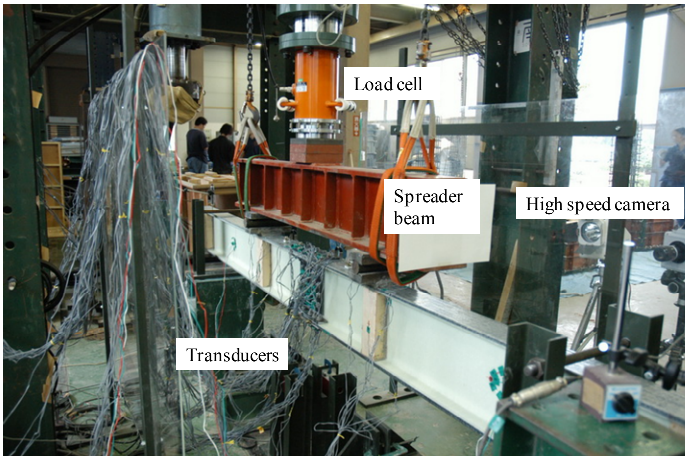


Fig. 6 Test setup and measurement

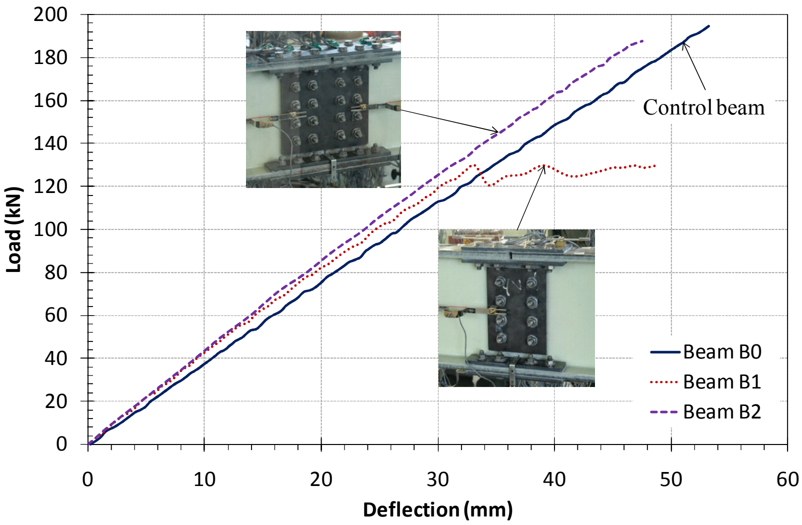


Fig. 7 Load-deflection curve

3.3.2 Load-strain curve of splice plates

Fig. 10 shows the relationship between the load and strain of the splice plates at the top and bottom flanges at mid-span section of beams B1 and B2. In the case of beam B1, the compressive strain behaves linear to the point that bolts are bent while the tensile strain behaves linear until local debonding of the epoxy layer is observed at around 90 kN. It is noted that at every initiation of debonding, a sudden decrease in the tensile strain is observed. Then, the strain increases again which indicates that the bolts start contributing to carry the load. Similarly, tensile strain of beam B2 behaves linear until the initiated debonding of approximately 160 kN while the compressive strain of beam B2 behaves linearly up to failure. This suggests that failure may not take place in the top flange of beam B2.

4. CONCLUSIONS

This paper presented the experimental studies on double lap joints composed of hybrid cfrp/gfrp laminate. Two types of connections were examined including bolted-only and bonded-and-bolted. The following main conclusions can be addressed:

1. The combined use of steel bolts, adhesive bonding and V-notch splice plates in double lap joints was found to be an effective method for joining hybrid FRP laminates. The rough surface of V-notch splice plates and adhesive bonding contributes to improve the stiffness and the slipping load of joints. Although adhesive bonding did not significantly increase the ultimate capacity of the connection, it improved the connection stiffness. Similar results were reported by Lopez-Anido et al. (1999).
2. The hybrid FRP beam with butt joints in flexural span using the effective joining method showed almost the same strength and stiffness as the beam without joints. The stiffness of joints was most likely depended upon the bonding surface and quality of epoxy layer while the ultimate load and failure mode of joints were governed by the number of bolts.

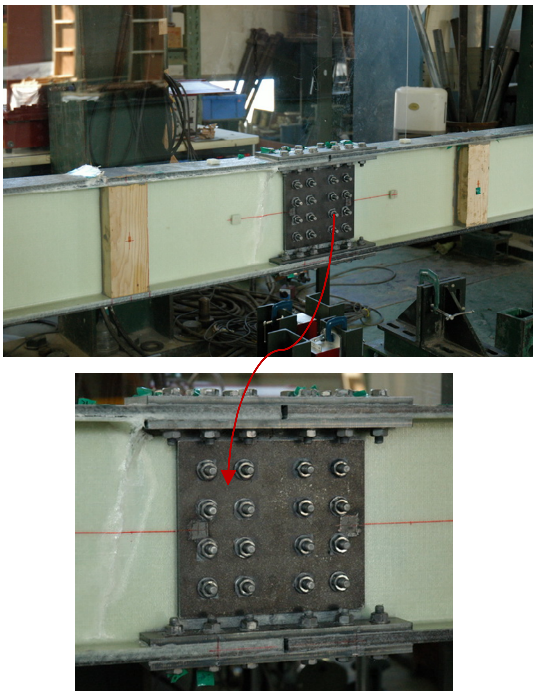


Fig. 8 Failure mode of beam B2

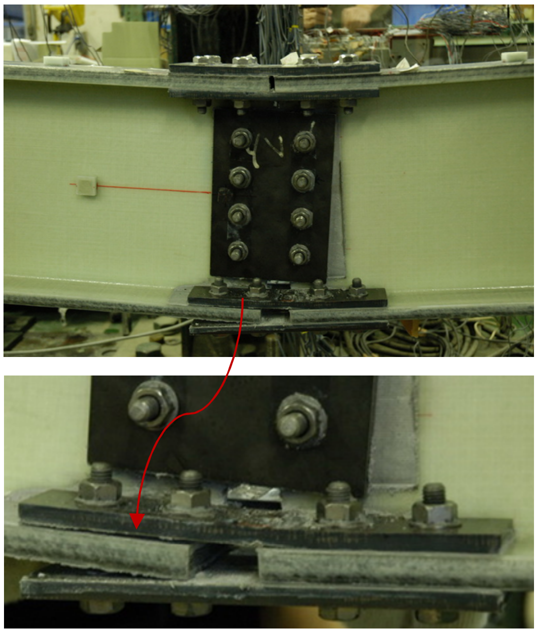


Fig. 9 Failure mode of beam B1

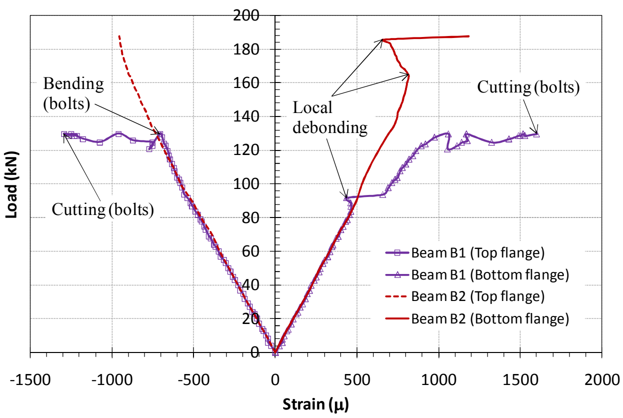


Fig. 10 Load-strain curve of splice plates

ACKNOWLEDGMENTS

This research was funded by a Ministry of Land, Infrastructure and Transport of Japan (MLIT) grant-in-aid for scientific research of construction technology, which is gratefully acknowledged.

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