Behavior of bolted/bonded joints in pultruded hybrid CFRP/GFRP composites

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This paper presents results from experimental and analytical studies on the behavior of double lap joints in pultruded hybrid CFRP/GFRP composites. A number of hybrid FRP coupon and full-scale beam specimens with bolted-only and bonded-and-bolted 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 composites. The rough surface of V-notch splice plates and adhesive bonding contributes to improve the stiffness of joints. Theoretical analyis was carried out and the results showed a good correlation with the experiments.

Keywords: hybrid CFRP/GFRP composites, bolted-only, bonded-and-bolted, V-notch

1. INTRODUTION

FRP composites have been increasingly used in civil infrastructure applications due to their advantageous properties such as high specific strength, lightweight, and corrosion resistance. Recently, a hybrid FRP girder consisting of carbon and glass fibers have been developed. 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. A number of laboratory tests have been conducted to investigate the structural performance of hybrid FRP beam and the results showed a possibility of utilizing this beam as a bridge component¹⁾. However there are still two major issues needed to be further investigated before applying hybrid FRP beam for real bridge application. One is development of joining for hybrid FRP composites. The other is evaluation of environmental aspects such as amount of carbon dioxide emission (CO2) and life cycle cost of hybrid FRP bridges. As the second step of the ongoing FRP research project supported by Japanese government, this study focuses on the first issue with emphasis on developing an effective joining method for hybrid FRP composites.

Joining of FRP composite is commonly achieved by adhesive bonding, mechanical fastening or a combination of the two methods. The combination of adhesive bonding and mechanical fastening is often employed as a safeguard against defects within the adhesive layer which may lead to premature or catastrophic failure²⁾. Numerous experimental and analytical investigations on joining of FRP composites have been conducted which mainly focused on aerospace applications ³⁻⁸⁾. However, limited published works exist in the field of civil infrastructure applications. In addition, previous studies cover a wide range of FRP composites with various fiber architect and matrix types, fiber lay-up and stacking sequences, etc., which result in different behavior of joints. Thus, additional investigations are required to fully understand the characteristics of joints. This study focuses on experimentally and analytically determined behavior of joints of hybrid CFRP/GFRP composites in small scale (coupon) and large scale (beam) tests. A number of coupon and beam specimens with double lap bolted-only and bonded-and-bolted joints were tested to examine their strength and behavior. The effects of end distance, bolt-torque, V-notch splice plates and the contribution of adhesive bonding to the joint strength and failure modes are discussed.

2. COUPON TEST

2.1 Test Specimen

A series of hybrid FRP coupon specimens with bolted/bonded double lap joints were tested under tensile loading as shown in Fig. 1. All specimens were cut from the flanges of the large-scale hybrid FRP I-beams. Typical specimens have the same width of w = 80 mm, nominal

thickness of t = 14 mm, end distance of e = 30 mm, side distance of s = 20 mm, longitudinal and transverse hole spacing of p = g = 40 mm. The FRP laminates consist of CFRP and GFRP. The angle of CFRP was fixed to be zero degree to the longitudinal direction while the angle of GFRP was 0, 90, ±45 degree or Continuous Strand Mat (CSM). All specimens were manufactured using pultrusion process. Layer composition of hybrid FRP coupon specimens is shown in Fig. 2. Material properties of the FRP laminates are listed in Table 1.

Table 1 Material pr	operties of FF	P laminate
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Domonactore	Notation	CF	GF	GF	GF
Parameters	notation	0	0/90	±45	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	*v ₁₂ (-)	0.32	0.12	0.29	0.31

*Subscripts 11, 22 and 12 indicates properties of FRP materials in longitudinal direction (fiber direction), transverse direction (perpendicular to fiber direction) and shear direction, respectively.





Fig. 2 Layer composition of hybrid FRP composite

Typical specimens were configured with the same ratios of end distance to bolt diameter (e/d = 3), laminate width to bolt diameter (w/d = 8), side distance to bolt diameter (s/d = 2), longitudinal spacing (pitch) to bolt diameter (p/d = 4), transverse

spacing (gage) to bolt diameter (g/d = 4), bolt diameter to splice plate thickness ($d/t_{sp} = 1.1$), washer diameter to bolt diameter $(d_w/d = 2.5)$ and hole clearance $(d_h - d = 0.05d)$. Stainless steel bolts were used with a nominal diameter of 10 mm. The yield and ultimate strength of bolts are 450 MPa and 700 MPa, respectively. Holes were machined in the specimens using diamond tips. The specimens were lateral clamped with bolts through 9 mm thick splice plate in both sides. The torque was applied exactly at distinct values by controlling the presetting torque wrench. The same configuration was set for specimens with bolted-only and bonded-and-bolted joints. For the bonded-and-bolted joint specimens, a preset torque is applied to the bolts at the same time with the adhesive. The adhesive was then cured in the experimental room for 24 hours before each test. The mechanical properties of adhesive are shown in Table 2. A number of coupon specimens with double lap bolted-only and bonded-and-bolted joints were tested to examine their strength and behavior. The effects of end distance, bolt-torque, V-notch splice plates and the contribution of adhesive bonding to the joint strength and failure modes are discussed. Coupon test variables are listed in Table 3. It is necessary to emphasize that the results of coupon tests discussed in this paper are only applicable for a specific case in which the ratio of bolt diameter to laminate thickness is fixed to 0.7.

 Table 2 Mechanical properties of adhesive

Domonactore	Curing	Properties after curing		
Parameters	condition	(N/mm^2)		
Bending strength		50		
Compressive strength		70		
Compressive modulus	20±2°C	4000		
Tensile strength		20		
Tensile shear strength		10		

Table 3 Coupon test variables						
Specimen	Type of joint	Type of splice plate	No. of bolts	Torque (Nm)	¹ TAL (mm)	² ED
A0	†₿	Flat			n/a	
A1	††BB	Flat	6	20	0.1	3d
A2	††BB	V-notch			0.1	
TAL01					0.1	
TAL05	††BB	Flat	6	20	0.5	3d
TAL15					1.5	
E2d-B						2d
E3d-B	†₿	Flat	2	20	n/a	3d
E4d-B						4d
E2d-BB						2d
E3d-BB	††BB	Flat	2	20	0.1	3d
E4d-BB						4d
T5				5		
T20	††BB	Flat	2	20	0.1	3d
T30				30		

 $^{\dagger}B$ = Bolted-only; $^{\dagger}TB$ = Bonded-and-bolted; ^{1}TAL = Thickness of adhesive layer; ^{2}ED = End distance (distance from one end of the FRP laminate to the center of the nearest hole as shown in Fig. 1)

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 the both sides of the specimen to measure the relative displacement between the FRP laminate and the splice plates. Each specimen was instrumented with back-to-back strain gages attached on the FRP laminate and the splice plates. The test setup is schematically illustrated in Fig. 3.



Fig. 3 Test setup

2.3 Test Result and Discussion(1) Load and displacement curve

The comparison of load-relative displacement curves of specimens with configuration of 6-bolt double lap joints is shown in Fig. 4. 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 specimens A1 and A2 as shown in Table 3.





Note that the relative displacement in the figure indicates the difference in the averaged elongation of clip gages attached on both sides of the specimen (one end of the clip gage is attached on the splice plate and the other end is attached on the specimen). As can be seen, the load-displacement curve of the specimen A0 can be subdivided into four stages. For the first stage (1), there

was no slip between the splice plates and the FRP laminates when the load in the range of 0 to 15 kN. This is due to the effect of the bolt-torque applied to the bolts. For the second stage (2), 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 (3) 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/splice plates combined with shear/bending of the bolts. The final stage (4) is the load reduction 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 slip resistance of joints when the load is approximately 50 kN. This value is three times higher than that of the specimen A0 due to the contribution of adhesive bonding. It is noted that the bolt hole clearances are filled with the adhesive during the preparation of specimen A1. However, only a part of these are filled with the adhesive due to its high viscosity. Hence the second stage exists in the specimen A1 but the slip is significantly reduced compared to the specimen A0. Indeed, the second stage indicates linear behavior of load-displacement curve when the load increases from 50-130 kN corresponding to the relative displacement of 0.05-0.2 mm. The third stage (3) exhibits a gradual development of bearing failure in the FRP/splice plates together with local debonding of the adhesive layer and shear/bending of bolts when the load increases from 130-360 kN corresponding to the relative displacement of 0.2-3.5 mm. The final stage shows the sudden failure of the specimen A1 at about 345 kN. It is clear from Fig. 4 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 slip resistance and the stiffness of joints.

(2) Effect of Thickness of Adhesive Layer

The effect of thickness of adhesive layer was investigated using specimens with the same configuration as specimen A1. Three distinct specimens TAL01, TAL05 and TAL15 were prepared with the thickness of adhesive layer (TAL) of 0.1 mm, 0.5 mm and 1.5 mm, respectively. The load-displacement curve of all specimens is shown in Fig. 5.

The figure shows that all specimens have the same failure load and failure mode. The failure modes of these specimens were debonding of adhesive layer and shearing of bolts. From this figure, it reveals that the stiffness of the load-displacement curve is proportional to the thickness of adhesive layer. The specimen TAL15 had the highest stiffness while the specimen TAL01 had the lowest one. However, it is interesting to note that the specimen TAL15 had almost similar stiffness compared

to that of specimen TAL05 before major debonding takes place. This indicates that with the increase in thickness of adhesive layer from 0.5 to 1.5mm, the increase in joint stiffness is insignificant. The load at which major debonding occurs of specimen TAL05 is higher than that of specimen TAL15. From these results, it may suggest to use the thickness of adhesive layer of 0.5 mm for bonded-and-bolted connection of hybrid FRP composite. However, by looking at the load-displacement curve in a smaller scale of the initial loading stage, it is found that the specimen TAL01 shows a stable behavior while specimens TAL05 and TAL15 exhibit a zigzag behavior. The zigzag behavior may be caused by stress concentration in the area of the adhesive thickness holders leading to the local debonding of adhesive layer at these positions. In addition, it is not easy to control exactly the thickness of adhesive layer especially in the construction site. Hence the solution of no thickness control (thickness of adhesive layer is approximately 0.1-0.2 mm) is recommended to use for practical application.



Fig. 5 Effect of thickness of adhesive layer

(3) Effect of V-Notch Splice Plates

To examine the effect of splice plates on the strength of bonded-and-bolted 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 and spacing of V-notches are 0.5 mm and 1.0 mm, respectively). 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. 6 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 130 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 major debonding of adhesive layer and major shear/bending of bolts happen of specimen A2 is approximately 14% higher than specimen A1. This indicates that adhesive layer may carry almost the load before major debonding occurs. When the adhesive layer fails, the load is carried solely by bolts. Finally, both specimens A1 and A2 fail due to shearing of bolts.



(4) Effect of End Distance

To investigate the effect of end distance to the failure strength of joints, a number of specimens with 2-bolt configuration varying end distances (e) from 2d to 4d (where d is nominal diameter of bolt) were conducted. Two series of specimens with bolted-only and bonded-and-bolted joints were investigated. Fig. 7 shows the relationship between load and displacement of bolted-only joint specimens. It can be seen that the specimen E2d-B (with end distance of 2d) has lowest failure load and failed due to shear-out failure of the FRP laminate as shown in Fig. 8. The specimens E3d-B and E4d-B (with end distance of 3d and 4d, respectively) have almost the same failure load but different failure modes. The failure mode of specimen E3d-B was shear-out failure while the failure mode of specimen E4d-B was bearing failure. This indicates that specimen E4d-B is the most appropriate for the bolted-only joints. However, all specimens with bonded-and-bolted joints (E2d-BB, E3d-BB and E4d-BB) showed the same failure load and failure mode although the end distance was varied as same as bolted-only specimens. The load-displacement curve of bonded-and-bolted specimens is shown in Fig. 9. Since the load is mostly carried by the adhesive at the initial loading stage, the load reductions at around 40-70 kN seem to be caused by the local debonding of the adhesive. The failure mode of these specimens was bearing failure. The differences in failure mode of bolted-only and bonded-and-bolted specimens were due to the present of adhesive layer. As previous discussion, adhesive may carry almost the load before major debonding occurs. The load is then transmitted to the bolts but they could not cause the shear-out failure as bolted-only specimens. This suggests that shear-out failure was developed gradually but not suddenly. It is

concluded that the effect of end distance on the failure strength of bonded-and-bolted joints is not sensitive as that of bolted-only joint and the failure mode of bonded-and-bolted specimens is of desirable failure mode. The end distance of 3d is minimum requirement for designing of joints for hybrid FRP composites.



Fig. 7 Effect of end distance to bolted-only joint



Fig. 8 Failure mode of bolted-only specimens



Fig. 9 Effect of end distance to bonded-and-bolted joint

(5) Effect of Bolt Torque

The same configuration of bonded-and-bolted specimens using for the investigation of the effect of end distance was utilized to examine the effect bolt torque. Applied torques with values of 5 Nm (finger tight), 20 Nm and 30 Nm was investigated. Fig. 10 shows the load-displacement relationship of all specimens. The figure indicates that the load-displacement curve of specimen T5 and specimen T20 shows almost the same slope and failure load. However, specimen T30 exhibits slightly lower slope than the others. This implies that large amount of torque (30 Nm) may result in unequal spreading of adhesive layer and bonding strength could therefore reduce. From these results, it suggests that the effect of the applied torque is only to provide fixation between the splice plates and FRP specimen during adhesive cure. An appropriate amount of torque needs to be large enough to fix joint parts and to keep an equal spreading of adhesive layer. Based on the result of this study, it is recommended to use 20 Nm amount of torque for bonded-and-bolted connection of hybrid FRP composite.



2.4 Theoretical Derivation and Comparisons

Although the Serviceability Limit State (SLS) of joint may be defined as occurrence of slip but the Ultimate Limit State (ULS) must be cleared because of the brittle characteristics of hybrid FRP composite. Presently, no workable theoretical solution has been available to determine the behavior of double lap bonded-and-bolted joints of hybrid FRP composites. This section is concerned primarily with developing a solution for prediction of load-displacement relationship of bonded-and-bolted joints under the ULS. The behavior of load-displacement is obtained by modifying the theoretical work of Fisher 9-10). The theoretical solution is based on the following major assumptions: (1) bolts transmit the entire applied load by shear and bearing once major debonding/slip has occurred; (2) the stress-strain relationship of FRP laminate is linear-elastic. The displacements in bolts and plates are schematically shown in Fig. 11. The load-displacement relationship is defined by the following equation:

$$\delta = \delta_{elongation-FRP} + \delta_{elongation-splice} + \Delta_{bolt} \quad (2)$$

where δ = total displacement, $\delta_{elongation-FRP}$, $\delta_{elongation-splice}$ = elongation of FRP laminate and splice plate in the strip of hole pitch, Δ_{bolt} = displacement of bolts

$$\Delta_{bolt} = \delta_{shear/bending-bolt} + \delta_{bearing-FRP} + \delta_{bearing-splice} \quad (3)$$

In equation 3, $\delta_{shear/bending-bolt}$ = relative shear and bending

displacement of bolts, $\delta_{bearing-FRP}$ = bearing displacement in FRP laminate, $\delta_{bearing-splice}$ = bearing displacement in splice

plate

Displacement of bolts is determined using the modification of the empirical equation proposed by Fisher ⁹⁻¹⁰:

$$\Delta_{bolt} = -\frac{1}{\mu} \ln \left(1 - \left[\frac{P}{P_{bolt}^{u} N} \right]^{1/\lambda} \right) \quad (4)$$

with $P \le P_{bolt}^{u} N$

where μ , λ = regression coefficients, P = applied load, P_{bolt}^{μ} = ultimate shear load of one bolt, N = total number of bolts.





The elongations of FRP laminate and splice plates in the strip of hole pitch in equation 2 was approximated in the elastic range as

$$\delta_{elongation-FRP}^{elastic} = \frac{Pp}{A_{FRP}E_{FRP}} \quad (5)$$

$$\delta_{elongation-splice}^{elastic} = \frac{Pp}{2A_{S}E_{S}}; with \ P < P_{S}^{y} \quad (6)$$

In the inelastic range, the elongation of splice plates can be

obtained by the equation 7:

$$\delta_{elongation-splice}^{plastic} = \frac{P_{S}^{y} p}{2A_{S}^{n} E_{S}} + p\left[\frac{-1}{\left(\sigma_{S}^{u} - \sigma_{S}^{y}\right)\left(w/\left[w - d\right]\right)} \ln\left(1 - \left[\frac{P - P_{S}^{y}}{P_{S}^{u} - P_{S}^{y}}\right]^{2/3}\right)\right] \quad (7)$$
with $P_{S}^{y} < P \le P_{S}^{u}$

In equations 5, 6 and 7, P = applied load, p = pitch, A_{FRP} , E_{FRP} and A_S , E_S are respectively gross cross-sectional area and Young's modulus of FRP laminate and splice plates, A_s^n = net cross-sectional area of the splice plate, P_s^y , P_s^u and σ_s^y , σ_s^u are yield and ultimate load/stress of splice plates, w = width of the splice plate, d = nominal diameter of bolts.

The load-carrying capacity of bonded-and-bolted joints with 2, 4, 6 and 8-bolt configuration is shown in Fig. 12. The figure shows a good agreement between the experiments and analysis. The regression coefficients μ and λ in equation 4 were experimentally determined to be 1.2 and 0.4, respectively.



Since the regression coefficients are experimentally determined, it is possible to apply this theoretical solution for various test parameters such as bolt diameter, characteristics of splice plates and FRP laminate (material properties, geometry, and roughness of the surfaces). The theoretical solution is therefore applicable for double-lap bonded-and-bolted joints with V-notch splice plates which are found as the most effective joints in this study.

3. FULL-SCALE TEST OF HYBRID FRP BEAM WITH BUTT JOINTS

3.1 Test Specimen

The results of the tensile coupon tests were used for design of the large scale beams with butt joints. The double-lap bonded-and-bolted joint with V-notch splice plate were selected as the joining method for all beams. The end distance of 3d, the amount of torque of 20 Nm and the thickness of adhesive layer of approximately 0.1 mm were applied. The ultimate shear strength of bolts obtained from the coupon tests was utilized to predict the ultimate load of beams as presented in the appendix.

A number of laboratory 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-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 splice plates, 10 mm stainless bolts and a very thin layer of adhesive were prepared. A torque of 20 Nm was applied to the bolts. The adhesive was cured in the experimental room for 24 hours before the test. The hybrid FRP beam has the 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. 13. Beam test variables are listed in Table 4.

Table 4 Beam test variables							
		Length of		Total N	Numb	er of	
Beam	Type of joint	joined parts		length	bolts		
		L1	L2	L	Flange	Web	
		(mm)	(mm)	(mm)			
B0	†C	n/a	n/a	3500	n/a	n/a	
B1	†† P P	1750	1750	3500	8	8	
B2	DD	1750	1750	3500	12	16	

 $^{\dagger}C$ = Control beam (without joints); $^{\dagger\dagger}BB$ = Bonded-and-bolted joints



(b) Elevation Fig. 13 Details of specimen for full-scale test of joints

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. 14. 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.



Fig. 14 Test setup and measurement

3.3 Test Result and Discussion (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. 15. The results show that both beams B0 and B2 behave linear up to failure. Beam B2 failed at somewhat lower load than beam B0. However beam B2 shows higher stiffness than that of beam B0 due to the present of the splice plates and bolts in the flanges and web. Prediction of ultimate load of beam B1 and B2 was conducted and the results showed a good correlation with the experiments (Fig. 15). Details of computation are shown in the Appendix A. It should be noted that the flexural strength of beams will decrease about 10% when the effect of the web splice plates is not taken into account (as in this study). Hence the good agreement between the experiments and analysis may be due to the effect of V-notch splice plates.

The failure mode of beams B0 and B2 was crushing of fiber near the loading point followed by the delamination of the top flange. This type of failure mode is generally happened outside of the joint and located near the loading point due to the stress concentration ¹⁾. It is totally different with the "bearing" and "shear-out" failure which are taken place in the joint as presented in section 2.3. Bearing failure leads to an elongation of holes while shear-out failure is regarded as a special case of bearing failure.

Web buckling in the flexural span was observed in the case of beam B2 due to the constraints of joints in the flanges and web as shown in Fig. 16. By a visual monitoring during the test of beam B2, it seems that failure did not happen in the joined part as predicted. 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 major debonding of adhesive layers and the shear/bending of bolts. The final failure mode of beam B1 was the shearing of bolts in the bottom flange leading to rotation of the splice plates in the web (Fig. 16).



Bolt failure Web splice rotation Delamination Web crushing

Fig. 16 Failure mode of beams B1 and B2

(2) Load-Strain Curve of Splice Plates

Fig. 17 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, both the compressive and tensile strains behave linear to the points that major debonding of adhesive layer and major shear/bending of bolts occur. Then behavior of strains becomes nonlinear due to the bend/shearing of bolts. On the other hand, the compressive strain of beam B2 behaves linear up to failure while the tensile strain of beam B2 behaves nonlinear after the major debonding of adhesive layer takes place.

It is interesting to note that the load at which major debonding occur in the tension flange splice is always lower than that in the compression flange splice. Indeed, load is mostly carried by the adhesive before the occurrence of major debonding and the results from the coupon tests indicate that high peel stresses at the end of joint in the tension flange splice may cause the premature debonding. Conversely, peel stresses in the compression flange splice are typically not of concern for the separation of joints and the debonding in the compression flange splice may therefore happen at higher load than that in the tension flange splice.



Fig. 17 Load-strain curve of splice plates

4. CONCLUSIONS

This paper presented the experimental and analytical studies on the behavior of double lap joints in pultruded hybrid CFRP/GFRP composites. Two types of connections were examined including bolted-only and bonded-and-bolted. The following main conclusions can be addressed:

 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 composites. The rough surface of V-notch splice plates and adhesive bonding contributes to improve the stiffness of joints.

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 strength of adhesive layer while the ultimate load and failure mode of joints were governed by the number of bolts.

Theoretical analysis was carried out and the results showed a good correlation with the experiments.

ACKNOWLEDGEMENT:

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.

APPENDIX A

Prediction of Ultimate Load of Hybrid FRP Beam with Butt Joint in the Flexural Span

Assuming that the flanges are carried all of the bending moment and the shear force is resisted by the web alone. In this study, there is no shear force applied in the flexural span and the strength of joint is therefore governed by the magnitude of bending moment. The forces in the tension flange (T) and in the compression flange (C), shown in Fig. A1, are given by:

$$T = C = \frac{M}{H-t} = \frac{PL}{6(H-t)} \quad (A1)$$

where M = bending moment, H = height of hybrid FRP beam cross section, t = thickness of the flanges, P = applied load and L = span of beam.



Fig. A1 Calculation of flange forces

The ultimate load of joint is obtained when the tension and compression force reach the ultimate shear capacity of bolts:

$$T = C = P_{bolt}^{u} N = mA_b \tau_{bolt}^{u} N \quad (A2)$$

where P_{bolt}^{μ} = ultimate shear load of one bolt, N = total number of bolts in one flange, m = number of shear planes (m = 2), A_b = cross section area of one bolt, τ_{bolt}^{μ} = ultimate shear strength of one bolt.

From equations A1 and A2, the ultimate load of joint can be computed using the following equation:

$$P_{u} = \frac{6mA_{b}\tau_{bolt}^{u}N(H-t)}{L} \quad (A3)$$

Note that bearing load of the hybrid FRP composite and splice plate must satisfy the equation A4:

$$P_b^{pl} = Ndt_{pl}\sigma_b^u \ge P_u \quad (A4)$$

which d = nominal diameter of bolt, t_{pl} = thickness of FRP/splice

plate, σ_b^u = ultimate bearing strength of FRP/splice plate.

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(Received September 24, 2009)