EFFECT OF BOLT TIGHTENING TORQUE ON THE STRENGTH OF BOLTED CONNECTION BETWEEN HYBRID FRP ANGLE SECTION AND STEEL GUSSET PLATE

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1. Introduction

Hybrid FRP composites for construction structure applications are now being developed. The innovative feature of hybrid FRP optimizes the combined use of carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) for maximum structural performance while minimizing production cost[1]. The capacity of a structure is often limited by the capacity of its connection, thus a reliable jointing system should be determined in order to use the hybrid FRP members for practical applications[1]. In a bolted connection, the strength is influenced by several factors such as connection geometry, fiber orientation, stacking sequence, friction, bolt tightening torque, clearance of hole, cover plate stiffness, and so on. Therefore, the evaluation of hybrid FRP bolted joints is necessary to determine the behavior of the joints.

This evaluation aimed to investigate the effect of bolt tightening torque on the strength of bolted hybrid FRP with a galvanized steel plate in the specific context of power transmission steel tower design. The effects of clamping force and friction force due to the tightening torque are also considered to determine the behavior of the joint.

2. Experimental Design

The specimens consisted of two hybrid FRP equal-leg angle sections with dimensions of 50 mm x 5 mm and 100 mm x 14 mm. Essentially this hybrid FRP laminate layer consists of carbon fiber in the 0° (longitudinal) direction and glass fiber in the directions of ±45° and 90°. The hybrid FRP members were joined to the galvanized gusset plate (GPL) bolted with galvanized full thread bolts. Standard washers in accordance with the steel transmission tower design rules were used as the lateral restrain of the hybrid FRP members. All specimens were prepared based on the JSCE-recommended geometric connection configurations[2] for bolted lap joints, which were designed to fail into a bearing failure mode. The bearing failure mode is normally desirable in FRP bolted joints because it develops slowly, giving plenty of warning before ultimate failure. JIS B 1083 was used as the reference to define the maximum value of bolt tightening torque. Three different values of tightening torque were used: maximum value, half value, and hand tightening (zero torque). Single and multiple bolt joints consisting of 2 and 3 bolts were used as the parameter of the experiment. The details of the specimens are shown in Table 1.

The slip coefficient test was carried out prior to this experiment to obtain the clamping force and slip coefficient between hybrid FRP and galvanized GPL. The clamping force is assumed as the value of the axial bolt force. The slip coefficient values for hybrid FRP of 50 mm x 5 mm with M-16 bolt and 100 mm x 14 mm with M-20 bolt are 0.52 and 0.47, respectively. According to JIS standards and Mottram bearing stress test, relevant material properties were obtained as shown in Table 2. The mechanical properties and slip coefficient were used to predict the bolted joint load capacity for hybrid FRP composites.

The specimens were tested in tension using the tension machine shown in Fig. 1. The slip displacement between the specimen and GPL was measured relative to a fixed point on the specimens using a Pi-shape displacement transducer which was mounted onto a hybrid FRP and GPL side. The load and displacement of the specimens were recorded with a data logger.

Table 1. Details of specimens

ID	Total Case	Member size	b	t	a	L	Bolt Size	Bolt Number	d_h	Torque	Clamp. Force	e_1	e_2	s
			mm	mm	mm^2	mm	mm		mm	N・m	kN	mm	mm	mm
A1	2					442		1	17.5			64	25	-
A2	2	L50X5	50	5	475.0	586	M-16	2	17.5	73.8	22.36	48	25	80
A3	2					746		3	17.5			48	25	80
A1-M	2					442		1	17.5			64	25	-
A2-M	2	L50X5	50	5	475.0	586	M-16	2	17.5	36.9	11.18	48	25	80
A3-M	2					746		3	17.5			48	25	80
A1-T	2					442		1	17.5			64	25	-
A2-T	2	L50X5	50	5	475.0	586	M-16	2	17.5	-	-	48	25	80
A3-T	2					746		3	17.5			48	25	80
B1	2					540		1	21.5			80	40	-
B2	2	L100X14	100	14	2531.9	720	M-20	2	21.5	164.6	40.15	60	40	100
B3	2					920		3	21.5			60	40	100
B1-M	2					540		1	21.5			80	40	-
B2-M	2	L100X14	100	14	2531.9	720	M-20	2	21.5	82.3	20.08	60	40	100
B3-M	2					920		3	21.5			60	40	100
B1-T	2					540		1	21.5			80	40	-
B2-T	2	L100X14	100	14	2531.9	720	M-20	2	21.5	-	-	60	40	100
B3-T	2					920		3	21.5			60	40	100

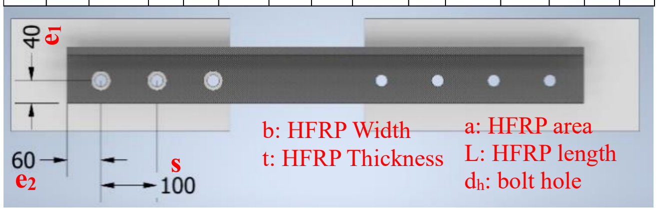

Table 2. Mechanical properties of hybrid FRP

Properties	Unit	L50×5			L100×14		
		Tension	Compression	Bearing	Tension	Compression	Bearing
Modulus	GPa	87.7	82.1	-	76.8	73.2	-
Max. Stress	MPa	1261.0	347.0	126.0	1225.0	462.0	256.0

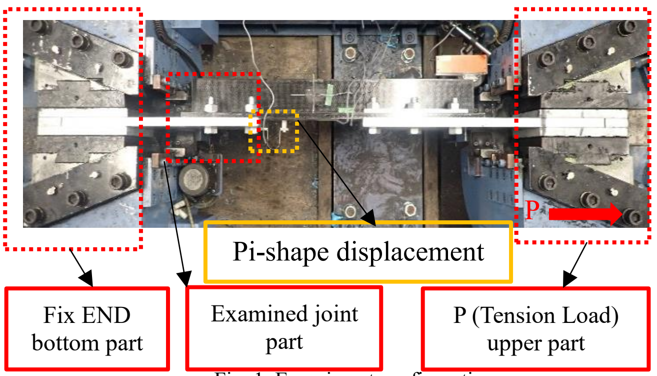

Fig. 1. Experiment configuration

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3. Experiment results

A total of 32 specimens failed in the bearing failure mode as shown in Fig. 2, resulting from the JSCE connection parameters that have a high e_1/d_h ratio. These results are in line with existing research theories. According to the results, the joint behavior under tension load can be divided into five stages as shown in Fig. 3. Generally, the specimen with maximum or half torque has a friction force effect that comes from clamping force, whereas hand tightening specimens do not. The friction force effect gives specimens a no-slip effect (slip resistance), which lasts until the applied load reaches the value of slip resistance. When the applied load exceeds the slip resistance, the hybrid FRP member will move toward the applied load direction until the bolt is in full contact with hybrid FRP and GPL bolt-hole edge. This is called the initial settlement of the bolt (bolt slip stage). The load vs displacement was reasonably linear after the bolt fully contacted the edge of the bolt hole. This linear region was interrupted by either the joint specimen starting to fail or the joint stiffness reducing significantly. The stiffness of the joint, characterized by the slope of the load vs displacement curve. The load at which the joint stiffness starts to reduce is referred to as the bearing damage load. Fig. 4 shows the influence of bolt tightening torque on the behavior of the load-displacement curve graph of the bolted joint on B1 specimens. As a result of decreasing the clamping force, the slope of the load-displacement curve decreases with decreasing the tightening torque. Joint with hand tightening torque has the lowest slope of the load-displacement curve than other joints where the bolt tightens with torque. Moreover, it is clear that the maximum loads decreased with the applied torque. Similar behavior was observed for other specimens as shown in the maximum load ratio graph in Fig.5. Maximum load ratio is defined as the maximum bearing load value of the half and hand tightening torque specimens relative to the maximum bearing load value of the maximum tightening torque specimen. However, only on the B2-M specimens (half torque of 100 mm x 14 mm specimen with a multi-bolt joint of 2 bolts), the bearing load slightly higher around 1.5% than the maximum torque specimens (B2).

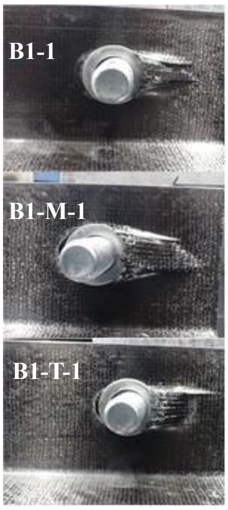

Fig. 2. Bearing failure

The load capacity due to bearing, P_b was calculated using Eq. 1. According to Bank[3)], the material compressive strength can be used for approximate calculation of bearing strength.

$$P_b = \sigma_b d_b t n \tag{1}$$

In the above equations, σ_b, d_b, t, n denote compressive strength of hybrid FRP, diameter of bolts, thickness of the hybrid FRP, and number of bolts, respectively. Considering the effect of the friction force, the slip resistance can be calculated using Eq. 2. Eq. 3 was proposed as the equivalent bearing load for the specimen with a friction force effect.

$$F_f = F_c \mu \tag{2}$$

$$P_{eb} = P_b + F_f \tag{3}$$

where F_f= Slip resistance; F_c= Clamping force; μ = slip coefficient; and P_{eb}= Equivalent bearing capacity. A good agreement between equivalent bearing capacity obtained by Eq. 3 and ultimate bearing strength from the experiment can be found in Table 3.

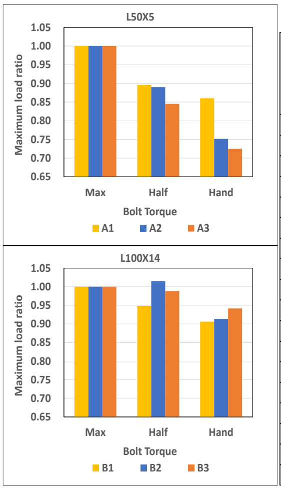

Fig. 5. Maximum load ratio

Table 3. Comparison results

ID	Expt. P_{be}(Ave)	Cal. P_{bt}	Slip Resistance	Equiv. P_{eb}	P_{be}/P_{eb}	FL. Mode
	kN	kN	kN	kN		
A1	42.93	27.76	11.63	39.39	1.09	B
A2	84.47	55.52	23.25	78.77	1.07	B
A3	133.10	83.28	34.88	118.16	1.13	B
A1-M	38.44	27.76	5.81	33.57	1.15	B
A2-M	75.18	55.52	11.63	67.15	1.12	B
A3-M	112.51	83.28	17.44	100.72	1.12	B
A1-T	36.93	27.76	0.00	27.76	1.33	B
A2-T	63.51	55.52	0.00	55.52	1.14	B
A3-T	96.55	83.28	0.00	83.28	1.16	B
B1	145.50	129.36	19.07	148.43	0.98	B
B2	281.03	258.72	38.14	296.86	0.95	B
B3	432.95	388.08	57.21	445.29	0.97	B
B1-M	138.01	129.36	9.54	138.90	0.99	B
B2-M	285.27	258.72	19.07	277.79	1.03	B
B3-M	427.82	388.08	28.61	416.69	1.03	B
B1-T	131.86	129.36	0.00	129.36	1.02	B
B2-T	256.78	258.72	0.00	258.72	0.99	B
B3-T	407.63	388.08	0.00	388.08	1.05	B

B: Bearing Failure

4. Conclusions

Based on the results of the experiment, the following conclusions are made:

- Due to the high e_1/d_h ratio, all of the tested specimens failed into bearing failure mode.
- The clamping force is generated when a bolt tightening torque is applied to the specimen, resulting a friction force effect in the connection.
- The bearing strength of a bolted joint can be evaluated by using bearing strength and slip resistance.
- It is clear that the maximum loads decreased with a reduction in the applied torque.
- The clamping force has affected the displacement behavior of the joint. Joint with hand tightening torque has the lowest slope of the load-displacement curve than other joints where the bolt tightens with torque.

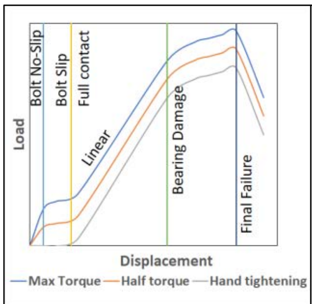

Fig. 3. Joint behavior

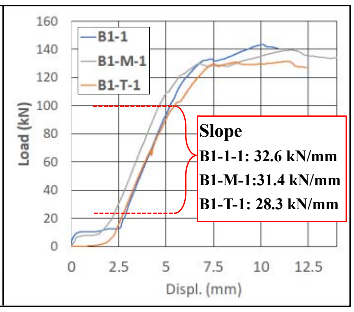

Fig. 4. Load-displacement curve graph

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