Experimental Study of Single Bolted Connections of Woven Fabric GFRP Members

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1. Introduction

The number of applications of fiber reinforced polymer (FRP) composites in civil engineering field has been increased due to their excellent properties such as high strength and stiffness, low weight, outstanding corrosion and fatigue resisting capacity. Structural components need to be connected properly and adequately to build a reliable and safe structural system. In the civil engineering structure, mechanical connections such as bolted connection provide more advantages than the other connections and are often chosen to connect the members. However, a severe stress concentration occurs at bolt holes, which reduces the performance of the structure. Furthermore, the bolted connection of FRP members is much more complex than that of members of conventional structural materials such as steel, and the design guidelines of bolted connections are at a preliminary stage. Therefore, many issues need to be resolved before this advanced material can be fully utilized to provide confident connecting several parts of a structure.

This paper deals with an experimental investigation on strength and failure mode of single bolted connections made of woven fabric glass fiber laminates. Material tests are also performed to evaluate the mechanical properties. Strengths are calculated for those connections according to the existing design code and compared with the experimental results.

2. Experimental Study

2.1 Material test

Material tests are performed to determine the mechanical properties of laminate. The laminate is made of GFRP woven fabric with a thickness of 12 mm. Tension and compression tests according to the JIS standards are conducted in the loading and transverse to loading directions of the connection. Shear test is also conducted according to the JIS standard by applying the load in the 45° direction. Aluminum tab with a thickness of 2 mm is used in those tests to successfully introduce the force into the specimen and prevent the premature failure of the specimen. Short beam shear with three pin loads and short block compressive tests according to ASTM standards are conducted to obtain out-of-plane shear and compressive properties. All tests are performed by using MTS universal testing machine with displacement control system. Five specimens are tested in each test, and average properties from 5 specimens are listed in Table 1.

Table 1: Material properties of woven fabric laminate

E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
24,900	25,100	12,700	0.12	0.42	0.42	3,060	9,500	9,500
X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	Z_T (MPa)	Z_C (MPa)	S_{12} (MPa)	S_{13} (MPa)	S_{23} (MPa)
354	267	335	288	*46.3	484	46.3	33.3	34.8

2.2 Connection test

Six sets, three specimens each set, of single bolted connection tests are conducted with different geometric parameters. The connections are double-lap configuration where GFRP laminate is used as the main plate with a thickness, t_m, of 12 mm, and steel plates are used as the cover plate with a thickness, t_c, of 6 mm. The connection configuration is illustrated in Fig.1. The parameters of connections are width to bolt diameter ratio, w/d, and end distance to bolt diameter ratio, e/d, and torque, and six connection types from J1 to J6 are used in this study as shown in Table 2. The diameter of a steel bolt, d, is 16 mm, and the diameter of a bolt hole, d_h, is 17 mm, resulting in a clearance of 1 mm.

The tests are performed by using a universal testing machine. Two clip displacement transducers are used on both sides at the end of the cover plate to determine the relative displacement of the cover plate to the main plate.

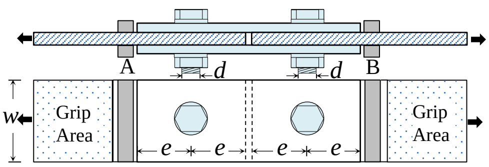

Fig. 1: Geometry of single bolted connection

Table 2: Parameters of the connections

ID	*w/d*	*e/d*	*Torque*
J1	3	4	3 N·m
J2	4	3	3 N·m
J3	4	4	3 N·m
J4	2	4	Pin bearing
J5	4	4	Pin bearing
J6	4	2	Pin bearing

3. Results and Discussions

In the experimental study, three basic failure modes are observed in the connections as shown in Fig. 2. Connections J1, J3 and J5 show bearing failure, connection J4 shows net-tension failure, and connections J2 and J6 show shear failure. The final failure mode of J1 and J3 seem to be a tension failure, but based on the observation on the main plate on the other side of connection, it is clear that the failure mode of J1 and J3 is bearing. Bearing damage propagates through the net section, and reduces the cross-section, and finally the connections fail by tension.

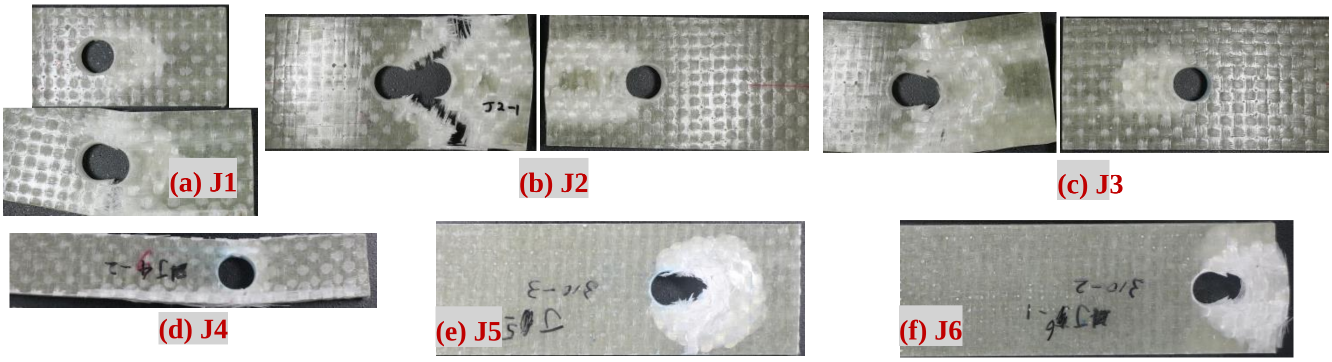

Fig. 2: Failure modes of single bolted connections

In the experiment, tensile load is applied in each connection up to rupture of the connection. Fig. 3 shows the load-relative displacement relationship of the connection obtained from the experiment. The relative displacement in the

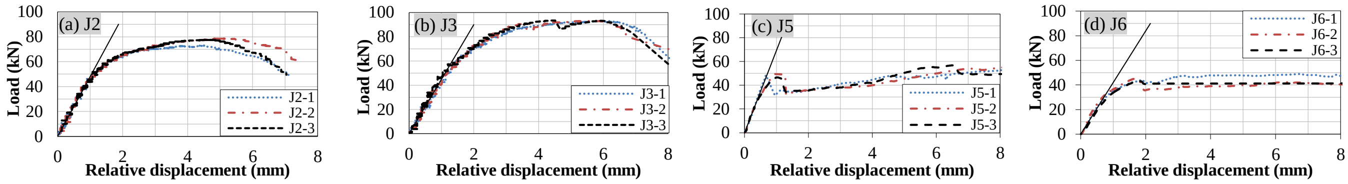

Fig. 3: Load-relative displacement relationship of single bolted connections

figure is the measured displacement minus the hole clearance. Therefore, curves are started from zero relative displacement. From Fig. 3(a) and (b), it is seen that the load is linearly increased up to about 50 kN, and then slope of curves is gradually decreased. It is because bearing damage occurs in the hole but the damage does not propagate at that load due to the confinement effect by the cover plates. Therefore, the connections with bolt axial load have larger ultimate strengths. The connection J2 is found to fail by shear failure although the load is higher than the load of bearing failure of the connection (J5) without bolt axial load. The load-displacement curve of the bearing failure connections with bolt axial load do not have a sudden drop of load, but the connections without bolt axial load have a load drop at the damage initiation. The connection J5 has a tendency of an increase in the load after the load drop. It may be due to confinement effect by the cover plates. Therefore, ultimate strength of J5 is considered at the first peak of the load-displacement curve. The connections with bearing and shear failure have large displacement until failure. It means that the shear failure mode is not a catastrophic bearing failure like tensile failure mode.

The average ultimate strength of connections from the experiment is shown in Table 3. The bearing strength is found to be higher by about 93% for the connection with axial load in bolts introduced by a bolt torque of 3 N·m when compared to the same geometry of the connection with pin bearing (no axial load in bolts). There is no effect of bolt axial load on the shear strength. The ratio of the connection strength of J2 to J6 is about 1.67 which is almost the same as a ratio of effective shear lengths of the connections. Strength of the connections with respect to the failure mode is calculated according to design code equations specified in the ASCE LRFD [1] and CNR-DT 205 [2] and compared with the experimental strengths. Resistance factor is not considered to calculate the strength. ASCE LRFD and CNR-DT 205 are used the same equation to calculate the bearing strength. The bearing and tensile failure strengths can be predicted well by the ASCE equation for the connection without bolt axial load (J4). The CNR-DT 205 prediction of tensile strength is higher than the strength of J4. Neither ASCE LRFD nor CNR-DT 205 can predict shear strength well, and the predictions are lower than the shear strength in experiment.

Table 3: Ultimate load and failure mode

ID	Experiment		HC Load (kN)	
	UL (kN)	FM	ASCE	CNR
J1	84.2	Bearing	51.3	51.3
J2	76.3	Shear	30.7	43.9
J3	93.1	Bearing	51.3	51.3
J4	45.7	Tension	39.7	63.5
J5	48.2	Bearing	51.3	51.3
J6	45.7	Shear	18.3	26.1

Note: UL=ultimate load, FM= Failure mode, HC=Hand calculation

4. Conclusions

Three basic failure modes, bearing, shear, tensile failure, are observed in the experiment. For the bearing failure mode, strength can be increased by about 93% due to a bolt torque of 3 N·m. Pin bearing and tensile strengths are predicted well by the ASCE codes, but the predicted shear strength is much lower than the experimental strength.

References

[1] ASCE, Pre-Standard for Load and Resistance Factor Design of Pultruded Fiber Reinforced Polymer Structures, 2010.

[2] National Research Council, Guide for the Design and Construction of Structures Made of FRP Pultruded Elements, CNR-DT 205, 2007.