Strength of Bearing-type Multi-row Bolted Connections of FRP Composite Members with Varying Cover Plate Stiffness

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FRP composite materials have been used in civil engineering field. In civil engineering construction, to connect several components, bolted connections are often selected due to their several advantages. However, a severe stress concentration occurs at holes, which reduces strength of the connection of FRP composite structure. Therefore, the study is concentrated on bolted connection of FRP composite structure.

In this study, experimental studies are performed to determine the mechanical properties of FRP woven fabric laminate with a thickness of 12 mm. The tests are performed according to the JIS and ASTM standard and obtained mechanical properties 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

A number of single bolted connection tests are also conducted under tensile loading with different geometric parameters: width to bolt diameter ratio, *w/d*, and end distance to bolt diameter ratio, *e/d,* shown in Table 2. GFRP laminate is used as the main plate with a thickness, t_m, of 12 mm. The cover plate is made of steel with a thickness of 6 mm. 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.

Table 2: Geometric parameters

No	*w/d*	*e/d*
J1	3	4
J2	4	3
J3	4	4

Finite element (FE) analysis is performed two to four rows bolted connections with a double-lap configuration. Different thicknesses of cover plates are used to change the cover plate stiffness: 6, 9 and 12 mm for FRP cover plates, and 6 mm for steel cover plates. Different geometric parameters of bolted connections are also examined with the change of cover plate stiffness shown in Table 3. FE models are created using the software, ABAQUS, with solid composite elements. Due to symmetry conditions, a quarter of a connection is modelled and symmetry boundary conditions are applied in the planes. Contact pairs are defined where different parts may contact each other.

Table 3: Geometric parameters of connections

Type	M	N	O	P	Q	R	S
w/d	3.0	4.0	5.0	5.0	5.0	5.0	5.0
p/d	5.0	5.0	5.0	3.0	4.0	5.0	5.0
e/d	3.5	3.5	3.5	3.5	3.5	2.5	3.0

In this study a stress-strain relationship is considered for the material as $\varepsilon = MC_0\sigma$, where $\sigma^T = [\sigma_{11}, \sigma_{22}, \sigma_{33}, \tau_{12}, \tau_{13}, \tau_{23}]$, $\varepsilon^T = [\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \gamma_{12}, \gamma_{13}, \gamma_{23}]$, C_0 is the compliance matrix without damage, and M is the damage operator proposed by Matzenmiller et al. [1] to consider degraded coefficients, $1/(1-d_{ij})$, of the compliance matrix. The coefficients are depended on the damage indices (d_L, d_T) which are determined according to the reference [2]. Here, components of the damage indices, d_{ij}, are $d_{11}=d_L$, $d_{22}=d_T$, $d_{33}=d_T$, $d_{12}=\max(d_L, d_T)$, $d_{13}=\max(d_L, d_T)$ for $d_{13} \leq 0.8$ otherwise 0.8, $d_{23}= d_L$ for $d_{23} \leq 0.8$ otherwise 0.8.The material constitutive model is implemented in Abaqus, through a user subroutine UMAT.

In the experiment, load-relative displacement curves from the experiment are plotted in Fig. 1. It is seen that the load is linearly increased up to about 50 kN, and then slope of curves is gradually decreased. The connections J2 and J3 have large displacement at the ultimate strength. It means that the connection J2 that shows shear failure is not a catastrophic failure. The FE analysis results also include in Fig. 1. The results are in good agreement with experimental results until the load of 50 kN, but ultimate strengths are much lower than those from the experiment. It may cause of confinement effect in plate due to the bolt clamping in the connection.

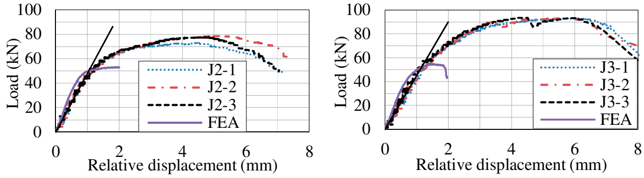

Fig. 1 Load-relative displacement relationship of single bolted connections

In the experiment, two basic failure modes are observed as shown in Fig. 2. Connection type J1 and J3 show bearing failure and connection type J2 shows shear failure. Connections J1 and J3 also have the shear propagation in the plate. Damage index contours from FEA are also shown in Fig. 2. They indicate failure modes from FEA, which are in good agreement with the experimental failure modes.

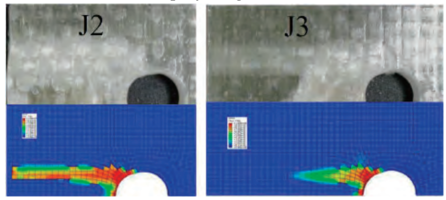

Fig. 2 Damage of single bolted connection

In multi-row bolted connection, failure modes obtained from the numerical analysis are shown in Table 4. It can be observed that the failure mode changes with the geometric parameters. It can be seen that failure mode also depends on the stiffness of cover plate. For Type M connections with three and four rows, failure mode changes from bearing to tensile failure when cover plate is changed from 6 mm steel plate to 6 mm FRP plate. This is because the higher stiffness ratio of the cover plate to the main plate leads to a more uneven distribution of load among bolt rows. Type R and Type S connections have a small end distance and they show shear failure at the ends of all the connections except three and four-row bolted connections with steel cover plates. It is caused of lower load transfer by the last row of bolt compared with the other rows for a multi-row bolted connection with higher stiffness ratio.

Table 4 Failure mode of the connections

Connection Type			M	N	O	P	Q	R	S
Connection	2-row	FRP 6 mm	BF	BF	BF	SF	BF	BF, ESF	BF, ESF
		Steel 6 mm	BF	BF	BF	SF	BF	BF, ESF	BF, ESF
	3-row	FRP 6 mm	TF	BF	BF	SF	BF	BF, ESF	BF, ESF
		Steel 6 mm	BF	BF	BF	SF	BF	BF	BF
	4-row	FRP 6 mm	TF	BF	BF	SF	BF	BF, ESF	BF, ESF
		Steel 6 mm	BF	BF	BF	SF	BF	BF	BF

Note: BF = bearing failure; TF = net-tension failure; SF = shear failure; ESF = end shear failure.

To determine the effect of cover plate stiffness on the ultimate strength of connections, the strength ratio (r_s=$F/F_{F6.0}$) of Type O connections the varying stiffness ratio of cover plates to the main plate shown in Fig. 3. The stiffness ratio is the ratio of stiffness of two cover plates to that of the main plate in the loading direction. It can be observed that the strength ratio of the connections decreases with an increase of the stiffness ratio. For the two, three and four-row bolted connections with steel cover plates having a half thickness of the main plate, the strength is lower than that the strength of bolted connections with FRP cover plates having a half thickness of the main plate by 4%, 9% and 16%, respectively. Therefore, in terms of the strength, it is better to make the stiffness of two cover plates be the same as that of the main plate.

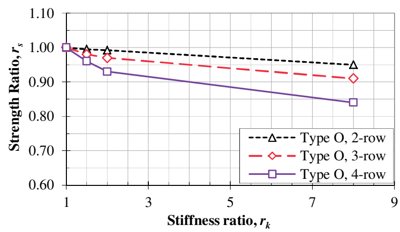

Fig. 3 Effect of stiffness ratio on ultimate strength

Reference

[1] Matzenmiller A, Lubliner J, and Taylor R.L., "A constitutive model for anisotropic damage in fiber-composites", *Mechanics of Materials*, 1995, 20: 125-152.

[2] Kader, M.A., Kitane, Y., and Itoh, Y., "Effects of cover plate stiffness on ultimate strength of bearing-type multi-row bolted connections for FRP composite structures", *Proc. of JSCE 69th Annual Conference*, 2014, Osaka University, CS2-002, pp.3-4.