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Failure modes of single and multi-bolted joint in the pultruded fiber reinforced polymer composite members

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Abstract. In this paper, we discussed the structural behavior of bolted lap-joint connections in pultruded FRP structural members. Especially, bolted connections in pultruded FRP members are investigated for their failure modes and strength. Specimens with single and multiple boltholes are tested in tension under bolt-loading conditions. All of the specimens are instrumented with strain gages and the load-strain responses are monitored. The failed specimens are examined for the cracks and failure patterns. The purpose of this paper is to predict the failure strength by using the ratio of the results obtained by the experiment and the finite element analysis. In the study, several tests are conducted to determine the mechanical properties of pultruded FRP materials before the main experiment. The results are used in the finite element analysis for single and multiple bolted lap-joint specimens. The results obtained by the experiment are compared with the results obtained by the finite element analysis.

1. Introduction

Fiber reinforced polymer (FRP) composites have high specific strength and stiffness compared with those of conventional structural materials such as concrete and steel. FRP composites have several advantages such as non-magnetic and non-conductive properties, high resistance to corrosion and chemical attack. Due to the excellent physical, chemical, and mechanical properties of FRP composites, it is beginning to be widely used in the aerospace, shipbuilding, automotive, and leisure industries, as well as civil engineering and construction. However, although FRP is recognized as an alternative of steel structural member, it is very difficult to predict the structural behavior due to complex failure mode depending on the kind of composite material and connection method. In addition, most of the composite material suitable for use as construction materials have a disadvantage in that the reinforcing fibers are arranged in the axial direction of the members, hence the strength of the bolted connections is considerably low. The pultrusion process shown in figure 1 is a cost effective composite manufacturing technique in which continuous reinforcing fibers with other additional fabric layers are pulled from creels and are passed through a resin tank where fibers are impregnated with polymer resin. The saturated fibers are drawn through a preforming and heating die in which polymerization into a hardened form takes place. The pultruded FRP (PFRP) is considered as an orthotropic (transversely isotropic) material because fibers are placed to the longitudinal direction of the member [1]. In order to use the PFRP as the structural material, basic research on the structural behavior of the bolted joint should be preceded.

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Figure 1. Pultrusion process [2].

A study on the bolted connection of PFRP is conducted by Abd-El-Naby on the effect of FRP shear strength and bolt-hole shape, which varies with the fiber volume ratio in the loading direction [3]. In addition, Prabhakaran studied using the design equation of the load and resistance factor design method (AISC-LRFD) of the American Institute of Steel Construction for FRP connections connected by bolts [4]. However, since failure modes are limited to net-tension failure and block shear failure, there are limitations in using the failure modes as basic data for various failure modes of composites. In addition, Choi considers various effects of stress distribution, surface friction coefficient, and torque on the circular hole, through the finite element analysis [5]. However, additional experiment is necessary. In Lee's study, it is confirmed through the lap-joint test of the PFRP that a number of bolts and the arrangement of bolts cause the change of strength [6]. In the experimental program E-glass fiber and polyester resin composite with 55% fiber volume ratio produced by the pultrusion process with structural profiled cross-section are used.

In this study, it is attempted to find the design method and guideline for connection of the most effective FRP connection method. The FRP plate width, the number of bolts, the spacing between the bolts, and the size of the bolt holes are arbitrarily determined, and the finite element analysis for the joints is conducted. The load - displacement behavior is investigated by performing the tensile test. The fracture mode of the member is confirmed, and the stress distribution is investigated through the strain gages attached to the surface of test specimen.

2. Failure mode of bolted connection

As discussed by Bank, the pultruded parts used in the connection are made of orthotropic materials, and therefore the orientation of the individual parts in the connection is critical, unlike in steel-bolted connections, where the base material is isotropic and not orientation dependent. Failure modes of bolted lap joints are mainly net-tension failure, shear-out failure, cleavage failure, block-shear failure, and bearing failure. Each failure mode is shown in figure 2. First, net-tension failure is caused by the cross-sectional area reduced by the bolt hole. Therefore, the tensile strength is reduced due to the reduction, so the plate is broken along the bolt line. Second, shear-out failure is a phenomenon that the fracture of the member touching the neck part of the bolt progresses further and then it becomes weak to the shear resistance and is broken along the shear section. Third, the cleavage failure is a phenomenon that the bolt-hole section of the member that receives the load from the neck part of the bolt does not resist the load and is broken as if it is cracked. Fourth, block shear failure is a phenomenon in which shear fracture and net section tensile fracture occur at the same time. Finally, bearing failure is that the cross-section of the bolt hole of the member that comes into contact with the neck part of the bolt is gradually broken when the member is subjected to a load and a loss occurs in the cross-section. According to Bank, bearing failure may be need to induce for the safety of the



Figure 2. Failure modes of single-bolt lap-joint in-plane connection [7]..

3. Mechanical properties of PFRP materials

The purpose of this study is to provide basic data for the design of bolted joints of PFRP. Before performing the tensile test of the PFRP specimen with bolted connection, it is necessary to investigate the material properties of the PFRP. Therefore, the axial tensile test, the compression test in the direction perpendicular to the member axis, and the shear strength test were performed.

Because of the specimen length limitation in the structural shape, it is difficult to make the test specimen suggested in ASTM D 3916. Therefore, prismatic bar shape specimen with rectangular cross-section is made with reference to existing research results [8]. The test results are given in table 1.

Specimen	Thickness	Width	Length	Tensile strength	Tensile modulus	of Poisson's
number	(mm)	(mm)	(mm)	(MPa)	elasticity (GPa)	ratio
No. 1	6	25.4	254	584.3	38.6	0.24
No. 2	6	25.4	254	553.8	37.1	0.16
No. 3	6	25.4	254	664.5	34.5	0.09
No. 4	6	25.4	254	592.9	35.4	0.24
No. 5	6	25.4	254	571.9	32.3	0.25
Average	6	25.4	254	583.0	35.7	0.24

Table 1.	The	axial	tensile	test resi	ilt.
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Table 2. The compression test result in the direction perpendicular to the member axis.

Specimen	Thickness	Width	Length	Compressive	Compressive modulus	Poisson`s
_	(mm)	(mm)	(mm)	strength (MPa)	of elasticity (GPa)	ratio
No. 1	6	20	80	109.7	12.3	0.07
No. 2	6	20	80	123.6	11.0	0.08
No. 3	6	20	80	137.4	14.2	0.10
No. 4	6	20	80	135.5	9.8	0.10
No. 5	6	20	80	152.2	16.0	0.06
Average	б	20	80	141.7	13.3	0.09

Compression tests are in principle conducted to ASTM D 3410 M-08 [9]. However, it is difficult to apply to the material to be used, because of dimension of the member. Therefore, compressive strength and compressive elastic modulus were determined from the experimental results using the compression test proposed by Yoon [10]. The results are given in table 2. Among the five specimens,

No. 1 and No. 2 specimens were not failed by fracture, so they were excluded from the average calculation.

The shear test is conducted according to ASTM D 5379 M-05 [11] and the test results are given in table 3.

Specimen		Width	Length	Maximum	Shear strength	Shear modulus of
		(mm)	(mm)	displacement	(MPa)	elasticity (MPa)
				(mm)		
Longitudinal	No. 1	10.99	6.51	1.05	44.6	45.5
Direction	No. 2	10.97	6.49	1.02	55.0	40.7
	No. 3	10.92	6.50	0.80	46.6	45.8
	No. 4	11.02	6.48	0.93	46.9	39.2
	No. 5	11.00	6.61	1.09	51.5	45.5
	Average	10.98	6.52	0.98	48.9	43.3
Transverse	No. 1	10.99	6.51	3.06	67.3	51.4
Direction	No. 2	10.97	6.49	1.47	75.4	54.8
	No. 3	10.92	6.50	1.38	74.9	55.5
	No. 4	11.02	6.48	1.32	70.6	55.6
	No. 5	11.00	6.61	1.34	69.1	53.9
	Average	10.98	6.52	1.71	71.4	54.2

Table 3. The shear test result in the longitudinal direction.



Figure 3. Experimental types.

4. Experiments on the behavior of PFRP bolted connection

The experimental types are shown in figure 3. Each type has a different number and arrangement of bolts. A-Type has a square arrangement of four bolts, and B-Type has double bolts arrangement vertically. C-Type has double bolts arranged horizontally, and D-Type has single bolt. The variable is the end distance to bolt diameter ratio (e/d_b) . In this case, e/d_b is set to 3, 4, and 5, since the effect on the ultimate load of the joint is negligible even if the e/d_b value increases to 5 or more at the joint of single bolt [12]. The experiment results are given in table 4, and the failure modes are indicated by letters as bearing failure (B), shear-out failure (S), and cleavage failure (C).

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Specimen	e/d_b	Failure	Failure mode			
		load (kN)	B ₁₁	B ₁₂	B ₂₁	B ₂₂
A-Type	3	43.6	В	S	S	S
	4	66.6	S	S	С	S
	5	66.2	С	В	В	В
B-Type	3	19.8	В	-	S	-
	4	36.2	S	-	None	-
	5	42.5	В	-	В	-
C-Type	3	17.4	S	S	-	-
	4	24.9	В	В	-	-
	5	26.3	S	S	-	-
D-Type	3	8.3	S	-	-	-
	4	11.7	С	-	-	-
	5	13.7	S	-	-	-

Table 4. Experimental result on the behavior of PFRP bolted connection.

The experimental results show that the failure loads increase with increasing e/d_b 3 to 4 (about 55%). However, the failure loads are small enough to be ignored, in case of e/d_b 4 to 5. In addition, although the recommended geometric dimension is satisfied when e/d_b value is 3 [7], the fracture strength is very small compared with the case of 4 and 5, so it is considered that it is difficult to use in the practical design.

As e/d_b value increased, failure modes are changed from shear-out failure to bearing failure at A and B-Types. However, at C and D-Types, the obvious change is not observed. Therefore, additional experiments are needed to confirm whether the location of bolts affects to the change of failure mode.

5. Comparison of results obtained by FEA (finite element analysis) and experiment

To evaluate the stress distribution of the PFRP specimens with bolts and to predict the structural behavior of bolted connection, general purpose finite element analysis (FEA) program, ANSYS Ver. 11 [13] is used. With reference to the experiment mentioned above, the material assumed to be linear elastic and orthotropic. The tensile stress distribution in the axial direction is shown in figure 4.

Based on the test results, the tensile strength of the net section of the material was calculated using equations (1) and (2), when the specimen was broken.

$$\sigma_{net} = \frac{P_t}{A_{net}} \tag{1}$$

$$A_{net} = t_{pl}(w - nd_h) \tag{2}$$

In equations (1) and (2), σ_{net} is the stress in the net section of the specimen, P_t is the tensile load acting on the specimen, and A_{net} is the net cross section of the member excluding the bolt holes. t_{pl} is the thickness of the specimen, w is the width of the specimen, n is the number of bolts on the same horizontal line, and d_h is the diameter of bolt hole.

Comparison between experimental and FEA results for the strength at the net section is given in table 5. The reliability of A, B, C-Type is about 77%. However, D-Type has a different tendency (about 174%) from the previous experiment. It is necessary to increase reliability at the single bolt case through the additional experiment.



Figure 4. FEA result.

Specimen		In-plane stress (MPa)		1/2
type	e/d_b	Experimental result (1)	FEA result ②	
A-Type	3	134.6	202.83	0.66
	4	205.6	254.62	0.81
	5	204.3	256.09	0.80
B-Type	3	89.2	137.70	0.65
	4	163.1	195.46	0.83
	5	191.4	232.32	0.82
C-Type	3	53.7	64.31	0.84
	4	76.9	101.63	0.76
	5	81.2	105.30	0.77
D-Type	3	37.4	20.51	1.82
	4	52.7	32.79	1.61
	5	61.7	34.36	1.80

Table 5. Comparison of experiment results and FEA.

6. Conclusion

In this paper, the mechanical properties and structural behavior of bolted connections are investigated by experiment. The finite element analysis is also conducted on the bolt connected PFRP composite members. Following conclusions are made:

- Failure mode from the tensile test of bolted lap-joint in the PFRP were classified into shearout, cleavage, and bearing failure with respect to e/d_b values.
- When e/d_b value of the joint decreases, shear-out failure mode tends to occur. As e/d_b value increases, cleavage and bearing failure modes tend to occur.
- The tensile strengths obtained by the experiments of the lap-joints are similar to those obtained by the finite element analysis at A, B, and C-Type specimens. However, D-Type, single bolt case, needs to increase reliability through the additional experiments. Although A, B, and C-Type specimens show similar trends, D-Type specimen shows no trend. Therefore, it is necessary to study further to establish the design criteria, in addition to these results.

From these results, we confirmed that the relation between the end distance to bolt diameter ratio

 (e/d_b) and failure mode. In addition, the fracture strength in the net section fracture can be predictable using the finite element analysis. If the failure mode and strength can be predicted in advance, the net section tensile strength, shear-out failure strength, cleavage failure strength, and bearing failure strength of the bolted PFRP members can be determined and reflected in the structural design.

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