(13) STUDY ON USING GLASS FIBER SHEET FOR IMPROVEMENT PULTRUDED GFRP MULTI-BOLTED CONNECTIONS

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Pultruded glass fiber reinforced polymers (PGFRPs) were known as an advanced material for constructions: high strength, stiffness-to-weight ratios, ease of installation, high corrosion resistance, high durability, and high tailorable. Among many existing issues in design criteria for PGFRP, the design of connection is considered as one of the most important aspects. Glass fiber sheets (GFSs) can be used for strengthening bolt connections in PGFRP. In this study, major aspects of connection were considered to design specimens: Number of bolts, end distance, and type of GFSs to investigate strengthening effect. All types of GFSs provide significant improvements in the ultimate loads of the PGFRP bolted connections. From those results, the number of the bolt and the connection area, which was represented by end distance, can be reduced as an effective method. The relationship between failure modes and strengthening parameters of the specimen was investigated and explained.

Key Words: *Pultruded GFRP, multi-bolts, strengthening, glass fiber sheets, GFS, failure modes*

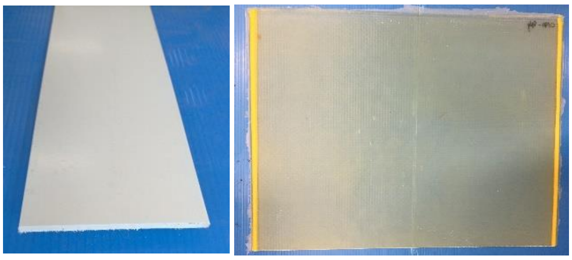
1. Introduction

Nowadays, as the most popular class of the mutual FRP composite, pultruded glass fiber reinforced polymers (PGFRP) have been more frequently used in industry and construction. The advantage properties that counterpart to changing from conventional material by use PGFPR, consist of lightweight, high strength, stiffness, etc. [1] Furthermore, PGFRP can be alternate for traditional construction materials because of its advanced properties: resistance to chemicals, nonmagnetic, isothermal, and electrical conductivity, fatigue resistance, and easy installation [2]. One of the largest markets of PGFRPs in the construction field is the pedestrian bridge. The other typical applications of PGFRP included in building: structure and their element [3]; marine construction/wastewater treatment plant with overcoming the corrosion problem under the severe sea or chemical environment [4]. There are some standards, guidelines, and instructions in application in PGFRP design [5].

Since there are convenience and economy in the application, the bolted connection is the most common type for PGFRP as well as the wide application in steel structure. Along with the development of PGFRP applications, more issues must be solved in structural connection design. Several studies have been conducted to investigate connection problems and their results were highlighted [6-7]. Ascione et al. [8] investigated the effect of fiber direction on bearing failure strength of GFRPs pin bearing bolted. The result has shown a linear decrease in ultimate load depending on the bolt's diameter. The authors have proposed a design formula for predicting ultimate bearing load for the various directional angle of fiber and bolt diameter. Persson and Eriksson [9] investigated static and fatigue performance on steel bolt and blind bolts. Cooper and Turvey [10] researched in PGFRP bolted connection with the clamping force.

The structural criteria for bolted connection in PGFRP normally prefer to be estimated by the strength of the connection rather than the strength of the profile member. In this study, the strengthening effect of bonded glass fiber sheets (GFSs) on the strength of PGFRP's connections was investigated. The strength connections testing was conducted with several conditions include: changing the end-distance and number of the bolt. Some researchers have developed the material properties by using a strengthening layer and pasted it to PGFRP, some implemented with an increased number of the bolt or end-distance. Nhut et al (2021) [11] implemented a strengthening experiment in a single bolted connection by using GFSs. The result showed noticeably development of connection strength. GFSs were calculated as a cost-effective material for upgrade the strength of PGFRP by Uddin, N. (2004) [12].

In summary of the research literature review, PGFRP is advanced and highly applicable material. Many studies have tried to improve the performance of this kind of material. Since some researchers concluded that the bearing load of connection is larger when the angle of load direction and fiber direction was reduced [7], this study is focused on the connection test with the fiber direction in was the same direction of loading. Moreover, many authors demonstrated that failure modes could be changed by varying the geometric parameters, such as the edge distance to bolt diameter ratio and side distance to bolt diameter ratio [13]. The multi-bolt is the most common connection applied in construction. Nevertheless, there is rarely research implemented to study the strengthening of this kind of connection. In this study, we tried to apply GFS with integrated conditions, including in the number of the bolt and the end distance of the connection area. Based on observation and testing results, effectiveness in strengthening for multi bolted connection in the PGFRP was demonstrated.



a) PGFRP original plate

b) GFS after molding

Fig-1. Material for experiment

2. Specimen's specification

(1) PGFRP

A commercial product of Fukui Fibertech Co., Ltd (Toyohashi, Aichi, Japan), with named is FS1005, which comprises from 3 phases of constituent: continuous direction fiber (CD), glass fiber mat (GFM), and unsaturated polyester resins were to make the specimens. There is a special bond that the manufacture used for combining those parts to become a PGFRP profile sheet.

The original plate was shown in Fig-1 has an average thickness is 5mm. The 3D model in Fig-2. also described detail of PGFRP, which included 0.5mm thickness of the outside GFM parts and 4mm thickness of the inside CD part. Dimension of the specimens was designed to meet the minimum criteria of ACSE Pre-standard [5]. The specimens were made by cutting from the central parts of the PGFRP plate with the width w=84mm. Then, the GFSs were bonded onto both sides of the PGFRP plate using E250 adhesive (product of Konishi, Osaka, Japan) to become designated specimens.

(2) Glass fiber sheet

The study used 3 types of GFS, which are shown in Fig-1.b and illustrated by the green color area in Fig-2. Two original materials 0°/90° woven roving (ERW580-554A) and chop strand mat CSM (ECM450-501) (products of Central Glass Co., Ltd., Tokyo, Japan with weights were 580 (g/m^2) and 450 (g/m^2), respectively were used. In the first type, 3 layers of 0°/90° were stacked, then cut to made [0/90] lamination or rotated ±45° to made [±45] lamination. The third type of GFS was [CSM], which was made from 3 layers of CSM laminae. These layers were stacked by VaRTM molded method. The VaRTM method can decrease the thickness of various layers and increase the fiber content. In a past study, Nhut (2021) [11] has proposed the detail of GFSs molding process.

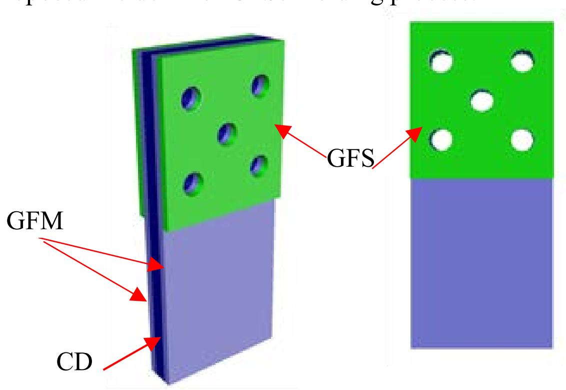


Fig-2. Material for experiment

(3) Specimens

Two faces of PGFRP were pasted by 2 GFSs for strengthening. Bond material, E250 adhesive has the elastic modulus and Poisson's ratio of 3.5 GPa and 0.35, respectively (from the manufacturer). After bonded, specimens were drilled to make bolt holes with the number of bolts as described in Table 1.

The 12mm diameter (M12) steel bolt with a 14mm bolt hole was used.

3. Test setup

In this study, a tensile test was conducted to investigate the strength of bolted connections. Table 1 shows the test program for the PGFRP connection with a list of 24 specimen types, these specimens were combined from 3 input conditions: including the number of the bolt, type of GFS, and the end-distance. There are 3 samples for each type of combination specimen, this means a total of 84 samples were implemented in the testing. The thicknesses of the GFSs were measured after molding and before sticking them on the PGFRP surfaces. In the table, NS_{T-N} denotes the non-strengthened specimen; $[0/90]_{T-N}$, $[\pm45]_{T-N}$, and $[CSM]_{T-N}$ denotes the specimens strengthened by 0°/90°GFS, ±45° GFS, and CSM on both sides, respectively. Whereas *T* represents the ratio of end-distance (*e*) and bold diameter (*d*) (*e*=2*d* and *e*=3*d*), *N* is the number of bolts (*N*=2;4 and 5). The experiment used a 1000KN Maekawa tensile testing machine as shown in Fig-3.

Table 1. Test program for PGFRP connections

Specimen	End distance *e* (mm)	No. of Bolts	t_{GF} (mm) avg
NS$_{2-2}$	24	2	-
NS$_{2-4}$	24	4	-
NS$_{2-5}$	24	5	-
NS$_{3-2}$	36	2	-
NS$_{3-4}$	36	4	-
NS$_{3-5}$	36	5	-
[0/90]$_{2-2}$	24	2	1.259
[0/90]$_{2-4}$	24	4	1.260
[0/90]$_{2-5}$	24	5	1.260
[0/90]$_{3-2}$	36	2	1.285
[0/90]$_{3-4}$	36	4	1.246
[0/90]$_{3-5}$	36	5	1.246
[CSM]$_{2-2}$	24	2	1.650
[CSM]$_{2-4}$	24	4	1.608
[CSM]$_{2-5}$	24	5	1.570
[CSM]$_{3-2}$	36	2	1.610
[CSM]$_{3-4}$	36	4	1.590
[CSM]$_{3-5}$	36	5	1.590
[±45]$_{2-2}$	24	2	1.210
[±45]$_{2-4}$	24	4	1.230
[±45]$_{2-5}$	24	5	1.230
[±45]$_{3-2}$	36	2	1.200
[±45]$_{3-4}$	36	4	1.244
[±45]$_{3-5}$	36	5	1.244

4. Experiment result

(1) Failure modes of the specimens in the PGFRP connections

There are 5 main types of failure modes that occurred in PGFRP specimens in the experiment. The typical failure modes are illustrated as the 3D view in Fig-4. which were observed for each typical specimen. The real failure specimen's pictures in different failure modes were described in Table 2 and Table 3.

MODE 1 was a shear out failure in all PGFRP sections and obtained in 2 bolts and 4 bolts with non-strengthened specimens (NS). MODE 2 occurred in 5 bolts NS specimens, and include two failure elements: shear-out inside (CD layer) and block shear failure outside (GFM layer). MODE 3 is a combined failure mode with shear-out in the CD layer, and debonding failure between CD and GFM. This failure mode occurred in 4 and 5 bolts with [0/90] and [±45] GFS specimens. The case when GFM-GFS slipped and fall out a part of the CD layer is called de-bonding. MODE 4 was obtained in all of CMS strengthened specimens (2,4 and 5 bolts). It consists of net-tension for combination GFS-GFM part and shear-out in CD part. MODE 5 failure is a bearing in GFS/GFM part and shear-out in the CD part. This mode was taken in [0/90] and [±45] GFS specimens with 2 bolts. The detail of failure modes was shown in Table 2.

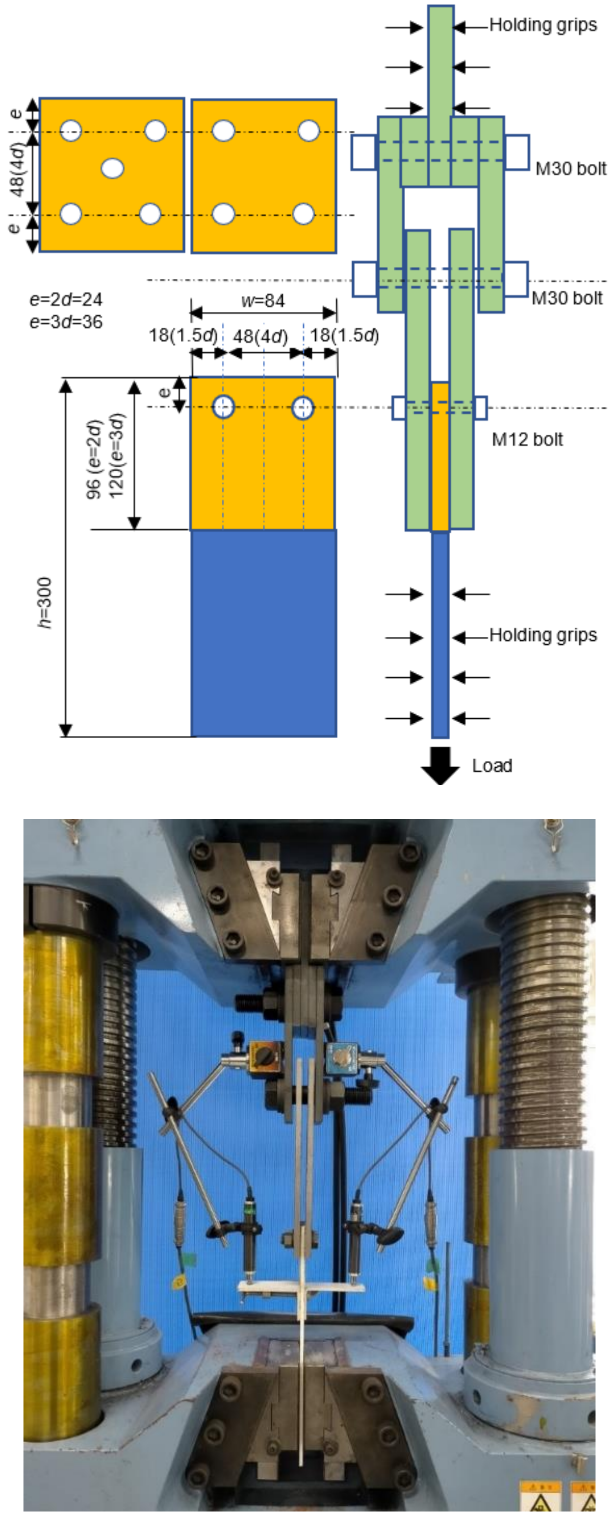


Fig- 3. Test setup diagram

Table 2. Detail of failure mode in specimens
("x" indicates the type of failure mode that occurred in each component)

MODE	CD	GFM					GFS	
	Shear-out	Net-tension	Block-shear	Shear-out	De-bonding	Bearing	Net-tension	Bearing
1	x			x				
2	x		x					
3	x				x			
4	x	x					x	
5	x					x		x

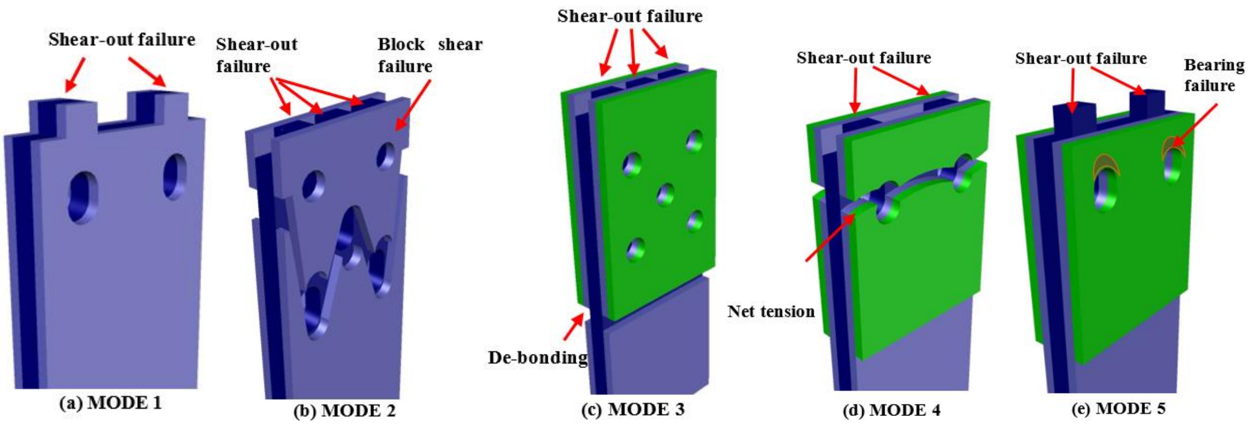
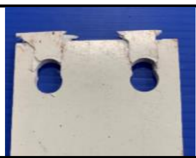
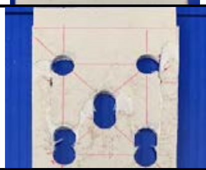
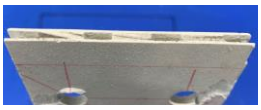
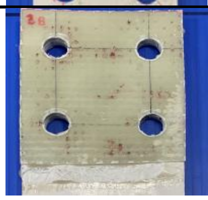
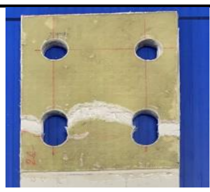
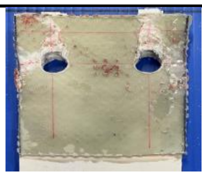
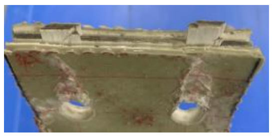


Fig-4. Failure modes of the PGFRP connections

Table 3. List of failure modes type occurred in specimens

Specimens	Failure mode	Front side view	Topside view
NS$_{2-2}$ NS$_{2-4}$ NS$_{3-2}$ NS$_{3-4}$	MODE1		
NS$_{2-5}$ NS$_{3-5}$	MODE2		
[0/90]$_{2-4}$; [0/90]$_{2-5}$ [0/90]$_{3-4}$; [0/90]$_{3-5}$ [±45]$_{2-4}$; [±45]$_{2-5}$ [±45]$_{3-4}$; [±45]$_{3-5}$	MODE 3		
[CSM]$_{2-2}$; [CSM]$_{2-4}$; [CSM]$_{2-5}$ [CSM]$_{3-2}$;[CSM]$_{3-4}$; [CSM]$_{3-5}$	MODE 4		
[0/90]$_{2-2}$ [0/90]$_{3-2}$ [±45]$_{2-2}$ [±45]$_{3-2}$	MODE 5		

Based on the observation of failure modes and result of load-displacement as shown in Fig-5, the tendency of failure modes is explained as follows:

- MODE 1 occurred in all thicknesses of NS 2 and 4 bolts. The result met with other previous studies result investigated the failure mode in the base plate PGFRP. The other mode in NS is MODE 2: block shear with three-bolt rows in five bolts specimens. The location of the center bolt made GFS layer in outside tend to failure along the shortest line instead of failure line same in NS specimens with 4 bolts. The inside layer was an observed failure as shear-out mode.
- While bearing failure occurred in [0/90] and [±45] GFS with 2 bolts specimens, the debonding between GFM and CD part was witnessed in these GFSs with 4 and 5 bolts specimens. The MODE 3 represented for this failure mode. This means that bonding strength is less than bearing/shear strength in those specimens. (The bond is manufactural adhesives material to bonded GFM and CD).
- The bond strength is higher than bearing/shear strength in 0/90]; [±45] GFS with 2 bolts specimens, corresponded with bearing failure modes in GFS in MODE 5.

(2) Strengthening effects of GFSs on the PGFRP connections

(a) Load-displacement relations

Fig-5 shows the crosshead loads- displacements diagram of all specimens in the PGFRP connections. All types of GFS or non-strengthening specimens are divided into groups that specimens have the same parameter of end-distance/bolt diameter ratio (e/d) and the number of bolts. There are six group:

- 2bolts and e=2d; 2bolts and e=3d;
- 4bolts and e=3d; 4bolts and e=3d;
- 5bolts and e=2d; 5bolts and e=3d;

The average values of displacements were obtained from the cross-head as shown in Fig. 5. The numbers 1,2 and 3 at end of the name code are represented for 3 samples in each type of specimen. The initial increases in the displacements were moved and adjusted in the graph to provide a better overall view of all the load-relative displacement relationships.

Fig- 5a,b shows the load-displacement relations of 2 bolts specimens. After reaching the maximum load, loading in [0/90] and [±45] GFS specimen with 2 bolts was kept in a period before dropping. This is because bearing failure occurred in GFSs (MODE 5). In the other failure modes, loading rapidly decreases after reaching the ultimate load. The maximum load corresponding to the point of stiffness reduction was called damage load [10]. In the case of 4 bolts and 5 bolts specimens, which are illustrated by Fig.5 c, d, e, and f, the bearing failure did not occur in the GFSs of [0/90] and [±45]. Since the de-bonding has occurred in the GFSs of [0/90] and [±45], it can conclude that the bonding strength is smaller than the bearing strength in 4 or 5 bolts specimens. The quantitative investigation to clarify bond strength will be conducted in the next study.

Table 4. The ultimate loads of PGFRP connections and strengthening effects of GFSs.

(a) Ultimate load of non-strengthening specimens

Types	NS_{2-2}	NS_{2-4}	NS_{2-5}	NS_{3-2}	NS_{3-4}	NS_{3-5}
1	20.56	44.73	48.28	24.45	40.82	54.06
2	18.89	42.29	56.39	23.03	48.37	52.70
3	19.62	39.25	52.42	21.90	48.06	58.15
Avg	**19.69**	**42.09**	**52.36**	**23.13**	**45.75**	**54.97**

(b) Ultimate load of [0/90] GFS strengthening specimens

Types	$[0/90]_{2-2}$	$[0/90]_{2-4}$	$[0/90]_{2-5}$	$[0/90]_{3-2}$	$[0/90]_{3-4}$	$[0/90]_{3-5}$
1	44.70	72.33	78.10	51.78	79.66	83.42
2	38.19	84.82	71.68	49.21	75.41	76.98
3	42.14	80.64	76.96	48.48	83.46	75.32
Avg	**41.68**	**79.26**	**75.58**	**49.82**	**79.51**	**78.57**
P_{st}/P_{NS}	2.12	1.88	1.44	2.15	1.74	1.43

(c) Ultimate load of [±45] GFS strengthening specimens

Types	$[\pm45]_{2-2}$	$[\pm45]_{2-4}$	$[\pm45]_{2-5}$	$[\pm45]_{3-2}$	$[\pm45]_{3-4}$	$[\pm45]_{3-4}$
1	40.31	74.39	89.31	43.87	89.8	87.08
2	40.51	75.30	74.83	46.21	90.23	91.02
3	41.79	84.53	76.71	45.94	83.64	80.93
Avg	**40.87**	**78.07**	**80.28**	**45.34**	**87.89**	**86.34**
P_{st}/P_{NS}	2.08	1.85	1.53	1.96	1.92	1.57

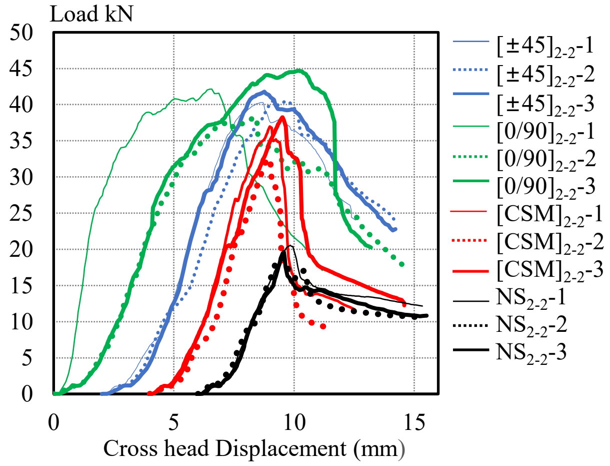
(d) Ultimate load of [CSM] GFS strengthening specimens

Types	$[CSM]_{2-2}$	$[CSM]_{2-4}$	$[CSM]_{2-5}$	$[CSM]_{3-2}$	$[CSM]_{3-4}$	$[CSM]_{3-5}$
1	36.97	70.18	72.92	45.50	79.06	74.82
2	32.58	72.57	77.04	47.01	77.88	78.29
3	38.25	77.08	72.07	48.6	70.08	76.04
Avg	**35.93**	**73.27**	**74.01**	**47.04**	**75.67**	**76.38**
P_{st}/P_{NS}	1.83	1.74	1.41	2.03	1.65	1.39

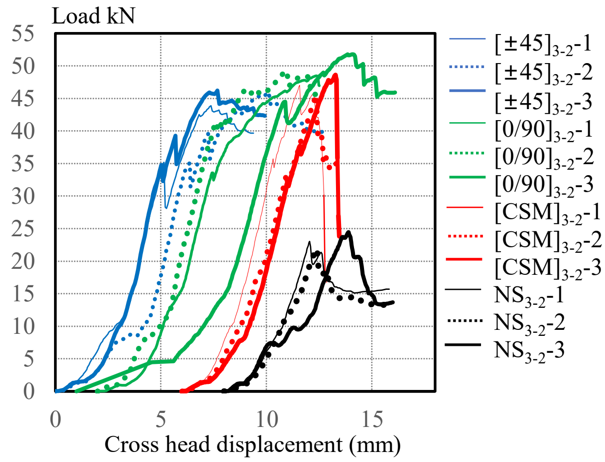
P_{st}: The ultimate loads of strengthened specimens.
P_{NS}: The ultimate loads of NS specimens.

(b) Strengthening effect related to types of GFSs.

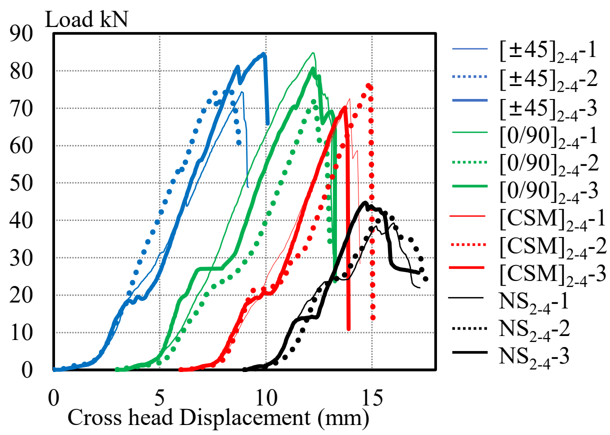
Table 4. shows obtained ultimate loads in the connection strength test. The average results of three samples for each designed specimen was illustrated by line graphs in Fig-6. The maximum load of GFSs was higher than the load in NS specimens in all types of GFSs (the other parameters: number of the bolt and end-distance were fixed). The effectiveness of the specimens after strengthening is also demonstrated by P_{st}/P_{NS} ratio, varying from 1.4 to 2.1. Although some [0/90] GFS specimens showed better results, generally [±45] specimens were slightly higher in maximum load. In Table 5. a, b [CSM] effective ratio is lower than in any of other GFSs, at 40% with 5 bolts specimens.



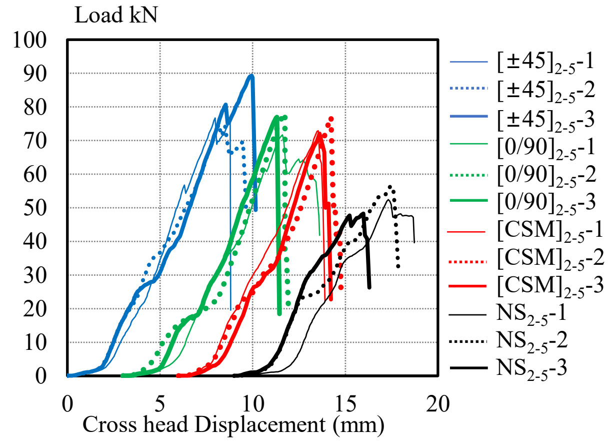
(a) 2bolts and *e*=2*d*



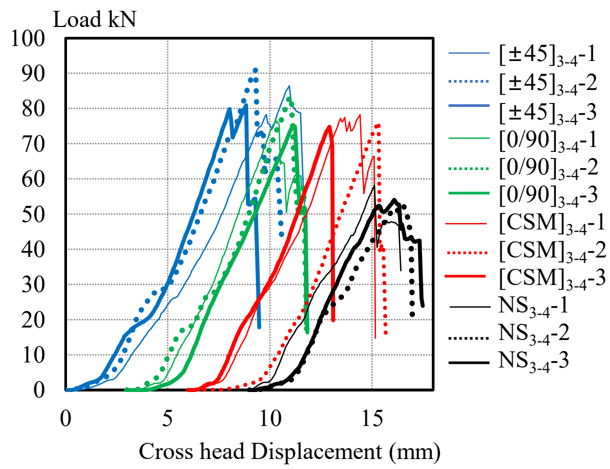
(b) 2bolts and *e*=3*d*



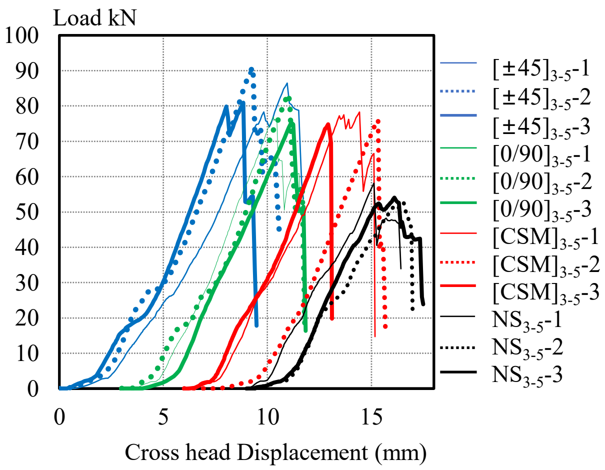
(c) 4bolts and *e*=2*d*



(d) 5bolts and *e*=2*d*



(e) 4bolts and *e*=3*d*



(f) 5bolts and *e*=3*d*

Fig-5. Investigation ultimate load in the PGFRP connections of all specimens.

(c) Strengthening effect related to the number of bolts.

It is a significant increase in connection strength when changing bolt quantity from 2 bolts to 4 bolts. The effectiveness was also noticeable in NS in the case of changing 4 bolts to 5 bolts. However, the strengthening effect was trivial in GFSs specimens when changing from 4 to 5 bolts. In [0/90], [±45] GFS, the ultimate load in 4 bolts-specimens even was higher than in 5 bolts-specimens because the area of bonding was decreased by one more bolt hole area. In [CMS] specimens, the tensile strength of GFS was not change clearly when adding 1 more bolt from 4 bolts to 5 bolts. This is due to the length of failure section, the main factor that makes net-tension failure, was not change in these cases. On the other hand, the NS specimens were obtained the failure mode change from MODE 1 (2 and 4 bolts) to MODE 2: 5 bolts (block shear). The length of the along shear area was increased in case 5 bolts. Consequently, it made better strength in comparison with 2 or 4 bolts.

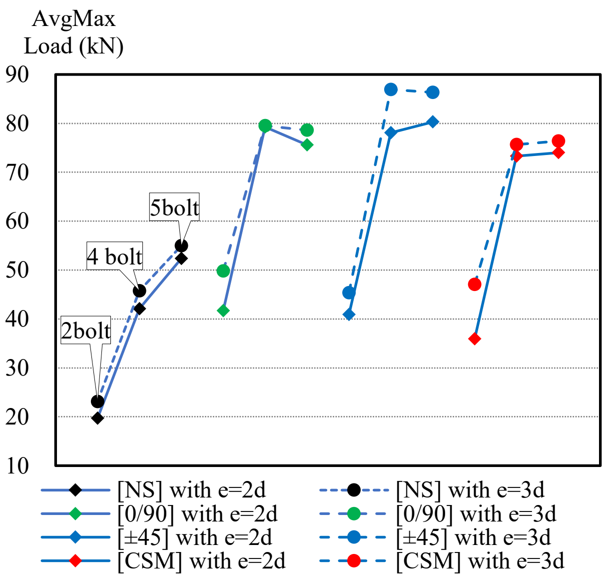


Fig-6. Average Ultimate Load of specimens

Table 5. strengthening effective of GFS

(a) *e=2d* specimens

No. bolt	[±45]	[0/90]	[CSM]
2	108%	112%	83%
4	85%	88%	74%
5	53%	44%	41%

(b) *e=3d* specimens

No. bolt	[±45]	[0/90]	[CSM]
2	96%	115%	103%
4	92%	74%	65%
5	57%	43%	39%

Table 6. Comparison of the strengthening effect of *3d* end -distance specimens to *2d* end-distance specimens

No. bolt	[±45]	[0/90]	[CSM]	NS
2	10.9%	19.5%	30.9%	17.5%
4	12.6%	0.3%	3.3%	8.7%
5	7.6%	4.0%	3.2%	5.0%

(d) Strengthening effect related to end-distance.

Besides the effect of the number of bolts and the type of GFS, the end distance *e* was also investigated in this study. Table 6. provides the percentage of increasing strength when changing from end-distance *e=2d* to *e=3d*.

In the case of 2 bolts, all specimens were shown a sharp effect with an increasing ratio ranging from 10.9% to 30.9%. The adding end-distance made the failure-out section of CD layer was longer. The reason above made maximum load stronger in *e=3d* specimens.

In the type of 4 or 5 bolts specimens, only [±45] with 4 bolts specimens shows an increase in connection strength (around 12% increase).

The bonding strength of CD and GFS layer was a major element when evaluation MODE 2 and MODE 5. These represent a failure mode occurred in 4 or 5 bolts specimens (except [CSM] specimens). The distribution and area of effective bonding will be continuously investigated as a supplement for more understanding of this issue.

5. Conclusion

This study implemented the test to investigate the effectiveness of strengthening in multi bolted PGFRP connection by three kinds of GFSs. In the experiment, specimens were also divided into groups which were combined by the number of bolts, end distance (*e/d* ratio), and type of GFSs. Based on the result and observed failure modes, there are some major conclusions as following:

- There are 5 types of failure modes that occurred in a total of 84 samples of 24 type specimens in the testing. In 2 and 4 bolts NS specimens, shear-out occurred in the whole cross-section. The block-shear failure occurred at GFM and shear out at CD in 5 bolts NS specimens. The failure modes in GFSs specimens were all combined from two-component failures. All the [CSM] specimens were the net-tension failure in GFSs parts, while the failure modes in [0/90] and [±45] specimens were dependent on the number of the bolt. The combination between bearing failure in GFS/GFM and shear-out failures in CD parts can be seen in 2 bolt specimens. On the other hand, the combination of shear-out failure in CD parts and debonding between CD -GFM parts was found in [0/90] and [±45] with 4 and 5 bolts specimens.
- The effectiveness of strengthening by GFSs was demonstrated significantly through the result of the test. The maximum loads in all the GFS specimens were higher than the NS specimens from 1.4 to 2.1 times. Therefore, the number of bolts in NS specimens can be reduced by GFS strengthening (from 4, 5 bolts to 2 bolts) as an application. Furthermore, the end-distance (connection area) in NS specimens can be reduced by GFS strengthening (from *e*=3*d* to *e*=2*d*).
- In comparison between GFSs, the type of [0/90] specimens were the highest effect in the case of 2 bolts with both *2d* and *3d* end-distance. Among the 4 and 5 bolt GFSs specimens, the [±45] specimens were the highest effect, the second was the [0/90]. The types of [CSM] have the lowest effectiveness in all GFSs specimens. This result is necessary for the selection GFSs types in strengthening the PGFRP connection.
- The effectiveness of the increasing number of the bolt was also investigated. There is an effectiveness in the NS specimens and GFSs in case increasing from 2 to 4 bolts. However, it was an unremarkable result in GFSs specimens with an addition from 4 to 5 bolts. It means that the increase in the number of the bolt could be considered as a strengthening method for NS specimens.
- Increasing end-distance was shown as an effective method in the case of 2 bolts for all NS and GFSs specimens.

The occurred failure modes in multi-bolt were shown quite complicate with five types of failure. It is necessary to conduct more further investigation to analyze and sufficiency explanation in failure tendency.

6. Reference

[1] Frigione, M., & Lettieri, M.: Durability Issues and Challenges for Material Advancements in FRP Employed in the Construction Industry, (2018)

[2] Bank, L. C.: Composites for construction: structural design with FRP materials. John Wiley & Sons (2006)

[3] Liu, T., et al.: A comprehensive review on mechanical properties of pultruded FRP composites subjected to long-term environmental effects. Composites Part B: Engineering, 191, 107958. (2020)

[4] Bazli, M., et al.: Mechanical properties of pultruded GFRP profiles under seawater sea sand concrete environment coupled with UV radiation and moisture. Construction and Building Materials, 258, 120369. (2020)

[5] ASCE 2010 Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures Submitted to American Composites Manufacturers Association (ACMA)

[6] Bank, L. C., et al.: Design and performance of connections for pultruded frame structures. Journal of reinforced plastics and composites, 13(3), 199-212. (1994)

[7] Prabhakaran, R., & Robertson, J.: An experimental investigation of load-sharing in a multi-bolt pultruded composite joint. In Second International Conference on Composites in Infrastructure National Science Foundation (Vol. 2). (1998)

[8] Ascione, F., et al.: On the pin-bearing failure load of GFRP bolted laminates: an experimental analysis on the influence of bolt diameter. Composites Part B: Engineering, 41(6), 482-490. (2010)

[9] Persson, E., & Eriksson, I.: Fatigue of multiple rows bolted joints in carbon/epoxy laminates: ranking of factors affecting strength and fatigue life. International journal of fatigue, 21(4), 337-353. (1999)

[10] Cooper, C., & Turvey, G. J.: Effects of joint geometry and bolt torque on the structural performance of single bolt tension joints in pultruded GRP sheet material. Composite structures, 32(1-4), 217-226. (1995).

[11] Viet, N. P., et al.: Improving the shear strength of bolted connections in pultruded GFRP using glass fiber sheets. Composite Structures, 255, 112896. (2021)

[12] Uddin, N., et al.: Cost-effective bridge girder strengthening using vacuum-assisted resin transfer molding (VARTM). Advanced Composite Materials, 13(3-4), 255-281. (2004)

[13] Turvey, G. J.: Bolted connections in PFRP structures. Progress in Structural Engineering and Materials, , 146-156. (2000)

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