IOP Conf. Series: Materials Science and Engineering **371** (2018) 012027 doi:10.1088/1757-899X/371/1/012027

Study on Mechanical Behavior of Self-tapping Screws Connection Using Washers in Single-Lapped Glass Fiber Reinforced Plastic Plates by Experiment and Finite Element Analysis

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Abstract. In recent years, mechanical characteristics of Glass Fiber Reinforced Plastic (GFRP) connections using bolts/rivet have been researched in detail, and they are used in many GFRP structures. However, the connection lack bearing strength compared with material strength and they need the prepared holes. In this paper, we surveyed the self-tapping screws connection strength and effects of washers on connection strength of single-lapped GFRP plates using self-tapping screws under tensile-shear loading by experiment and finite element analysis (FEA). The strength of self-tapping screws connection in GFRP plates depends on the washer's diameters. When increasing washer's diameter, the bearing strength of connections increased. Hence, increasing washer's diameter at reasonable levels is an effective method to increase the load carrying capability for self-tapping screws connection in GFRP plates. Moreover, FEA was proposed to investigate the bearing strength of connections and there were good agreements between FEA and experimental results.

1. Introduction

Fiber Reinforced Plastic (FRP) has currently been widely used in the fields of vehicles, aircraft, because of their have many good characteristics when comparison with other materials such as light weight, high strength, high corrosion resistance, good freedom of molding, etc[1]. These characteristics lead to high seismic resistance, long life, and ease in construction; therefore, FRPs have also been used in architecture and civil engineering field[2]. At present, because the connection behavior of FRP connection is relatively complex, it is impossible to construct freely like concrete and steel. If that problem is solved, FRP will be a material which can change significantly the construction structure. Unlike steel, the connection of FRP is difficult to welding, so mechanical connection, adhesive connection, or both of them have been used. However, the mechanical properties of connection, which are indispensable for constructing structures by FRP material, are not clarified sufficiently. Therefore, accumulation of research results to improve design method are necessary. There have been many researches about mechanical connection for FRP by steel bolts/rivet[3]. This connection requires drilling to create the holes in FRP material first and bearing strength is lower than the material strength due to the influence of connection clearance. Hence, solving this problem to improve initial stiffness of connection and bearing strength by tapping screw should be considered carefully. Furthermore, the screw has a drill at the tip, so there don't need hole processing, increasing

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construction speed. However, because of self-tapping screw's rotation in single-lapped connection, it cannot mobilize all the material strengths inside connection together, lead to the partial damage occurred. Therefore, the bearing strength of single-lapped GFRP plates connection using self-tapping screw was decreased when comparing with double-lapped GFRP plates connection [4]. Reducing the rotation of self-tapping screws while bearing load by increasing the diameter of the washer, thereby increasing the connection strength of single-lapped GFRP plates using self-tapping screws should be considered carefully. In previous study, we investigated the self-tapping screws connection strength and effects of washers on connection strength of single-lapped GFRP plates using self-tapping screws with the end distance was 25mm. The load early reached the maximum load and rapidly decreased in all specimens due to the occurrence of shear-out failure. This problem leads to the sudden collapse of the construction structure, danger for the users because we cannot recognize the symptoms of failures. Increasing end distance in order to increase connection strength, structure stability, and investigate other self-tapping screws connection's failure modes should be researched in detail. In this study, we surveyed the self-tapping screws connection strength and effects of washers on connection strength of single-lapped GFRP plates using self-tapping screws with end distance was 50mm, under tensile-shear loading by experiment and finite element analysis (FEA).

2. Experiment

In this study, GFRP which was used in the experiment is pultruded GFRP (AGC Matex manufactured "Plalloy" C100B), fiber is mainly roving, resin uses unsaturated polyester. The mechanical properties of the GFRP materials are shown in Table 1.

Table 1. Mechanical properties of GFRP materials

GFRP materials	Value
Tensile strength (MPa)	446
Longitudinal elastic modulus (GPa)	30
Glass content rate (weight %)	55

GFRP plates used in the experimental test were cut from original C-shape GFRP materials with the 175mm length, 50mm with and 6.5mm thickness. Self-tapping screws (Japan Power Fastening manufactured "MB TEKS" HEX#5), which were used in the experimental tests, are shown in Figure 1 and Figure 2. Self-tapping screws were made of stainless steel. Self-tapping screws were tightened by an electric screwdriver, tightening torque of the self-tapping screws was controlled as 15 Nm in order to prevent the damage to the specimen material.

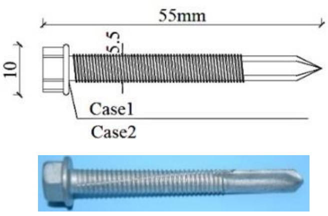

Figure 1. Self-tapping screws without alternative washer (Unit: mm).

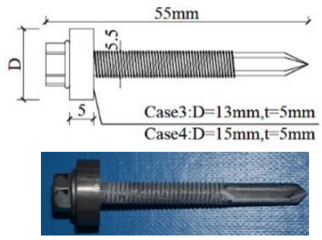

Figure 2. Self-tapping screws with alternative washer (Unit: mm).

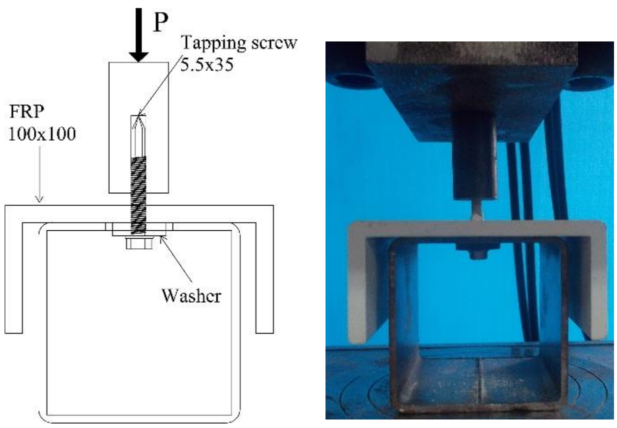

Figure 3. Experimental method and setup of Pull-out test (Unit: mm).

2.1. Experimental methods

2.1.1. Pull-out tests. Figure *3* shows experimental method and setup. Because the shaft neared tapping screw-head does not have threads, we put 5mm thickness-washer between self-tapping screws-head and FRP plates in order to accurately survey bearing strength in the pull-out test. Specimens were cut from the long C-shaped material into 100mm segments with an average thickness of 6.53mm.

2.1.2. Single-lapped tensile-shear tests. The experiment was conducted with 4 different cases to survey the influence of the washer on the connection strength. Case 1 is self-tapping screws without the washer's effect. Case 2 is original self-tapping screws with washer's diameter 10mm. Cases 3, 4 include self-tapping screws with alternative washer with the diameters 13mm and 15mm, respectively. Figure 4 shows the experimental methods with specimen's dimension, we have five specimens for each case, each specimen includes two FRP plates and two added plates for fixing in the testing machine. Figure 5 shows the experimental setup. All the tests were conducted by a universal testing machine, the top and bottom of the specimens were clamped onto the machine, data recording includes load and crosshead displacement. In case 1, in order to release the effect of the washers on GFRP plates, the distance between the washers and GFRPs plate is 5mm. The connection strength of single-lapped GFRP plates was investigated through single-lapped tensile-shear loading test.

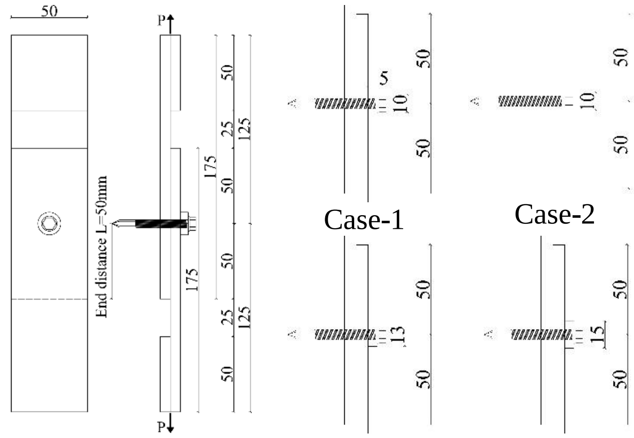

Figure 4. Experimental method (Unit: mm).

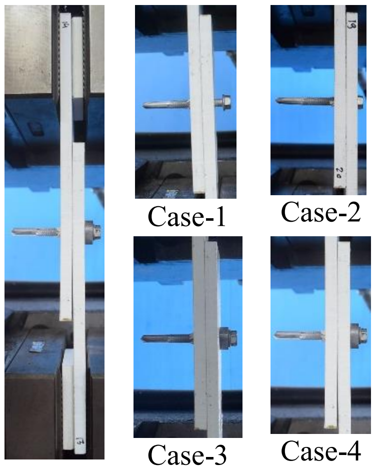

Figure 5. Experimental setup.

2.2. Experimental results and discussion

2.2.1. Pull-out tests

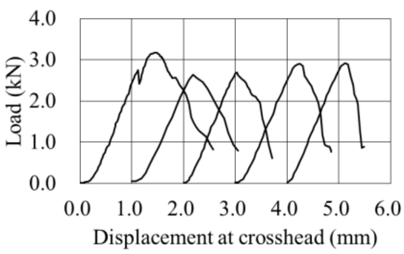

Figure 6. Load-displacement relations.

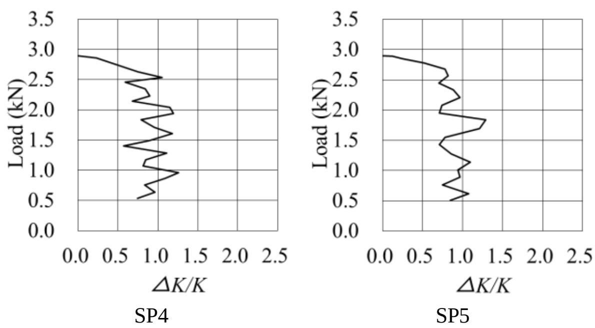

Figure 7. Load-ΔK/K relation (specimen 4, 5).

Figure 6 shows the load-displacement relations, the loading was gradually decreased after reaching the maximum load in all specimens. Figure 7 shows Load-*ΔK/K* curves (specimen 4, 5). From this Figure, we can know the levels of the load which load-displacement curves is still linear. *K* is the stiffness (inclination until linear completed), *K* was calculated from $0.2P_{max}$ to $0.5P_{max}$ of the load-displacement curves. *ΔK* is the inclination of previous plot in each experimental plot. The elastic limit is defined as the loading when *ΔK/K* reaches 0.5[5] then the loading level of elastic limit is calculated to be $0.96P_{max}$. Table 2 summarizes results obtained by the pull-out tests.

Table 2. Summarization of pull-out test results.

N_o	SP1	SP2	SP3	SP4	SP5
Thickness (mm)	6.54	6.53	6.52	6.55	6.52
P_{max} (kN)	3.18	2.64	2.70	2.91	2.92
Stiffness K (kN/mm)	3.04	2.75	3.33	2.97	2.94
Average thicness (mm)			6.53		
CV of thickness (%)			0.18		
Average P_{max} (kN)			2.87		
CV of P_{max} (%)			6.65		
Average Stiffness K (kN/mm)			3.00		
CV of K (%)			6.28		

2.2.2. Single-lapped tensile-shear test. Figure 8 shows load-displacement relations. Figure 9 shows the comparison of maximum loads between case-end distance 25mm[6] and case-end distance 50mm. The deformation of GFRP plates at the contact position between GFRP plates and washers are shown in Figure 11, the deformation modes of specimens and the rotation restriction of self-tapping screws by washers are shown in Figure 12. Self-tapping screws in single-lapped connection is rotated by shear loading as shown in Figure 12, lead to the occurrence of partial bearing-failure. Shear-out failure didn't occur as case-end distance 25mm, so maximum load of case-end distance 50mm higher than case-end distance 25mm in all specimens as shown in Figure 9.

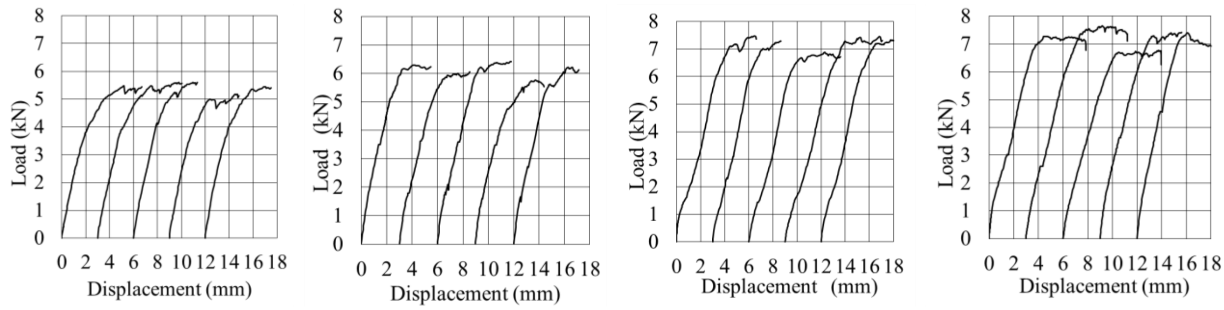

Figure 8. Load-displacement relations.

The max load increased when increasing the diameter of the washer because the rotation was restrained by washer as shown in Figure 12. This rotation restriction helps to reduce partial bearing-failure in the connections. The coefficient of variations (CV) are around 5% in all experimental cases as shown in Figure 9. It can be said that the experimental results are quite stable. With specimens having washer in case of end distance 25mm, the load linearly increased when increasing washer diameter from 10mm to 15mm. However, specimens having washer in case of end distance 50mm, when increasing washer's diameter from 10mm to 13mm, load increased significantly, and increasing washer's diameter from 13mm to 15mm, load slightly increased as shown in Figure 9. In case end distance 50mm, comparing with bearing strength in double-lapped connection (240MPa) [7], bearing strength in single-lapped connection is still lower; however, the bearing strength has increased significantly in case washers diameter 15mm (201MPa) compared with case no washers influence (150MPa), approximately 35% as shown in Figure 10. Increasing end distance lead to bearing-failure occurred, shear-out failure didn't occur. After reaching maximum load, the load remained approximate maximum load level for long periods while displacement still increased as shown in Figure 8. This helps the user can see the signs of damage before the collapse of the structure, increasing the structure safety. Because the stiffness of steel washers is higher than GFRP plates, rotation restriction of self-tapping screws by washers lead to the deformation of GFRP plates at the contact position between GFRP plates and washer as shown in Figure 11.

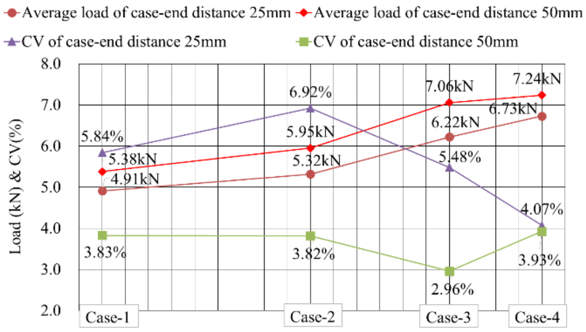

Figure 9. Comparison max load between case end distance 25mm and case end distance 50mm.

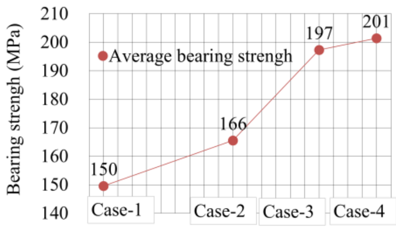

Figure 10. Average bearing strength.

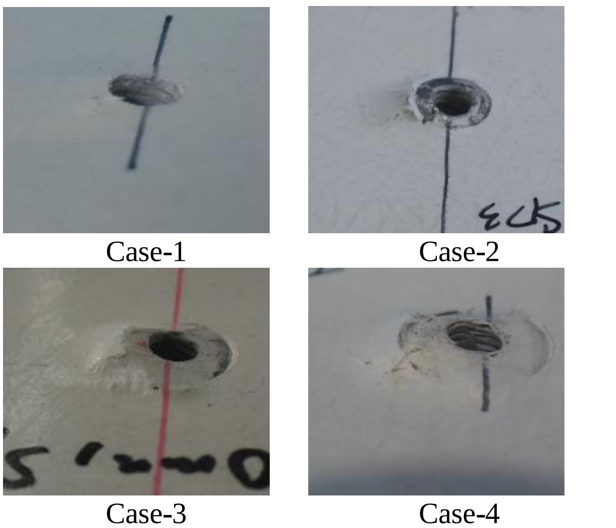

Figure 11. The deformation of GFRP plates at the contact position between GFRP plates and washers.

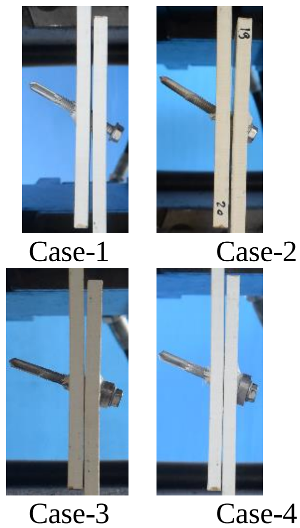

Figure 12. Deformation modes of specimens

3. Finite element analysis

3.1. Finite element analysis

In FEA, important FEA features were the initial contacts between component parts. The contacts of self-tapping screws connection in GFRP plates include initial contact between washer with GFRP plates and contact between self-tapping screws with GFRP plates. The contact between the washer and GFRP plates was taken easily by available frictional contact properties. Because the contact was only the frictional contact. However, the simulation of contact between self-tapping screws and GFRP plates were not only frictional contact but also pull-out contact. The simulation of pull-out contact through self-tapping screw's threads is necessary to analysis by FEA, but it is very complicated. Hence, we used truss elements instead of this pull-out contact properties in simulation.

3.1.1. *Pull-out test.* In experiments, the self-tapping screws and GFRP plates were held by the screw thread. In this research, we modified the contact between self-tapping screws with GFRP plates by four truss elements for every GFRP plates with the approximate stiffness with self-tapping screw threads. We determined when these truss elements were yielding, it means the connections were failed. The materials of these truss elements are assumption with the elastic modulus E=205 (GPa). In order to define the stiffness as well as other properties of the truss elements, we conducted the experimental pull-out tests. From the experimental pull-out tests, the sectional area for the truss elements were calculated following to (1).

$$A = \frac{K_{ave} \times t_{FRP}}{4E} \quad (1)$$

Here, K_{ave}=3 (kN/mm) is the average stiffness obtained from pull-out tests. t_{FRP} is the average thickness of FRP plates, this is also the length of the truss elements. A is the sectional area of the truss elements. From (1), the sectional area that was calculated for every truss element was 23.9x10-3 (mm^2). Also, the initial uniaxial yield stress for every truss element was 30 (GPa), which was calculated from (2)

$$\sigma = \frac{P_{\max}}{4A} \quad (2)$$

These values will be assigned into FEA to check the accuracy of the results of pull-out tests. The model of pull-out tests in FEA is shown in Figure 13. The model of truss elements in the pull-out test is shown in Figure 14.

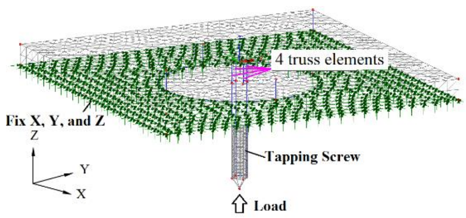

Figure 13. Model pull-out tests in FEA.

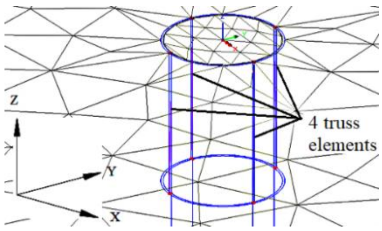

Figure 14. Model truss elements in pull-out tests.

3.1.2. Single-lapped tensile-shear test. Single-lapped tensile-shear test was carried out using nonlinear 3-D analysis in FEA to analysis the strength of the connections with 4 different cases. Case 1 is tapping screws without the washer. Cases 2, 3, 4 include washer diameter with 10mm, 13mm, and 15mm respectively. The overview and truss element's positions of single-lapped tensile-shear test model are shown in Figure 15, Figure 16. The model of single-lapped tensile-shear test in all case are shown in Figure 17.

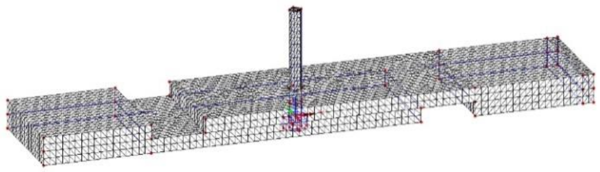

Figure 15. Overview of Single-lapped tensile-shear test model

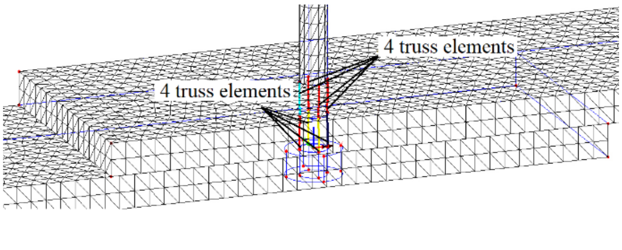

Figure 16. Truss elements of single-lapped tensile-shear test model.

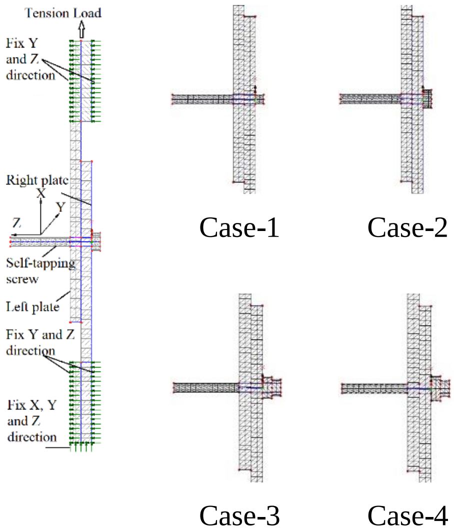

Figure 17. Single-lapped tensile-shear test model in case 1, 2, 3, and 4.

3.2. Finite element analysis results

3.2.1. Pull-out test. Figure 18 shows the relationships between the loading and crosshead displacements that obtained from both experiments and FEA. The red line shows the result in FEA. There was good agreement between experimental data and FEA results. Therefore, the present analysis model using truss elements could be used for the simulation of contacts between GFRP plates and tapping screws replace for tapping screw's threads.

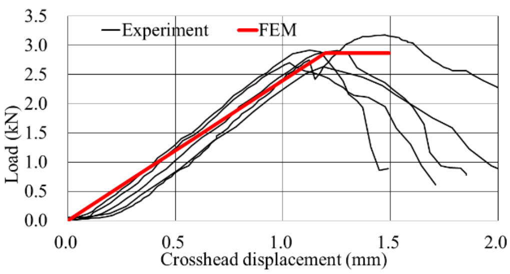

Figure 18. Experimental data and FEA results of Pull-out test.

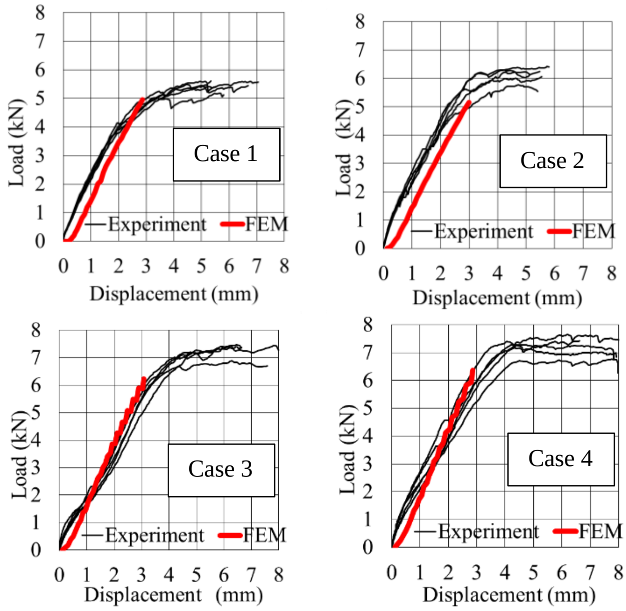

Figure 19. Load-displacement relations in experiments and FEA.

3.2.2. Single-lapped tensile-shear test. Figure 19 shows the relationships between the load and cross-head displacement obtained from both experiments and FEA. The red line shows the result in FEA. The maximum load in FEA is the load at the time in which the truss elements reaches the initial uniaxial yield stress.

The slope of load and cross-head displacement curve in FEA results corresponding with experimental results as shown in Figure 19. Figure 20 shows the comparison between average maximum load of experiments and FEA. There were good agreements between experimental data and FEA results. We simulated the distance between self-tapping screws and holes in GFRP plates is 0.1mm in order to simulate four truss elements. Because of the effect of this clearance and the limitation of the number of truss elements, the bearing strength of connection in FEA analysis was decreased, so the results of FEA analysis in all case are lower than experimental data as shown in Figure 20. According to FEA results shown in Figure 20, in case of specimens having a washer, increasing washer diameter from 10mm to 13mm, load increased significantly, but increasing washer diameter from 13mm to 15mm, load slightly increased, so it can be said that FEA results closely relate with experimental results. Figure 21 shows the stress distribution in self-tapping screws with the load level 4.9 (kN). In finite element analysis, the compressive stress appeared in the tangential positions between GFRP plates and tapping screw. When the diameter of the washer increased, the compressive stress decreased in the tapping screw and the tensile stress increased in the intersection positions between tapping screw and washer with the same load level. This is because when the washer's diameter increased, the constrained rotation of tapping screw was increased and this leads to the decrease of compressive stress concentration. Figure 22 shows the longitudinal stress distribution in FRP plates with the load level 4.9 (kN). In the areas between two FRP plates, the concentration of compressive stress occurred higher than other areas; therefore, the damage also occurred first in these areas. This damage was good correspondence with the bearing-failures that occurred in the same areas in the experiments. Moreover, the concentration of compressive stress decreased corresponding to the decrease of compressive stress in the tapping screw when the washer's diameters increased in the same load level as shown in Figure 22. Figure 23 shows the load and self-tapping screw's rotation relation, θ is the rotation angle of self-tapping crews under tensile-shear load testing. Figure 24 shows the deformation of self-tapping screws and GFRP plates at the load level 4.9 (kN). The rotation of the self-tapping screws were constrained by the washers, so the self-tapping screws using larger washer's diameter have smaller rotational angle at the same level of load as shown in Figure 23 and Figure 24. The difference of slopes of load and self-tapping screw's rotation relation curve between all cases corresponding to the difference of maximum load in experiment and FEA results.

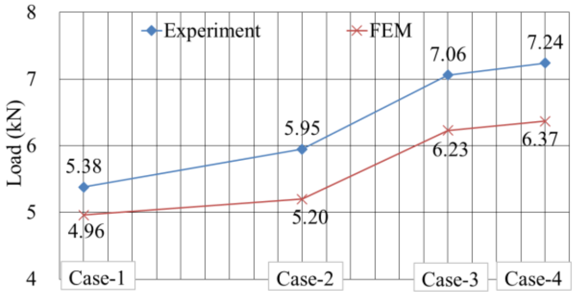

Figure 20. Comparison between average maximum load of experiments and FEA.

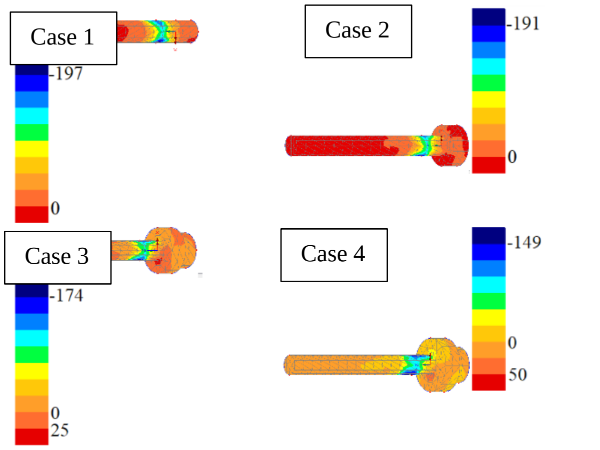

Figure 21. The stress distribution in tapping screw with the load level 4.9 (kN) (Unit: MPa).

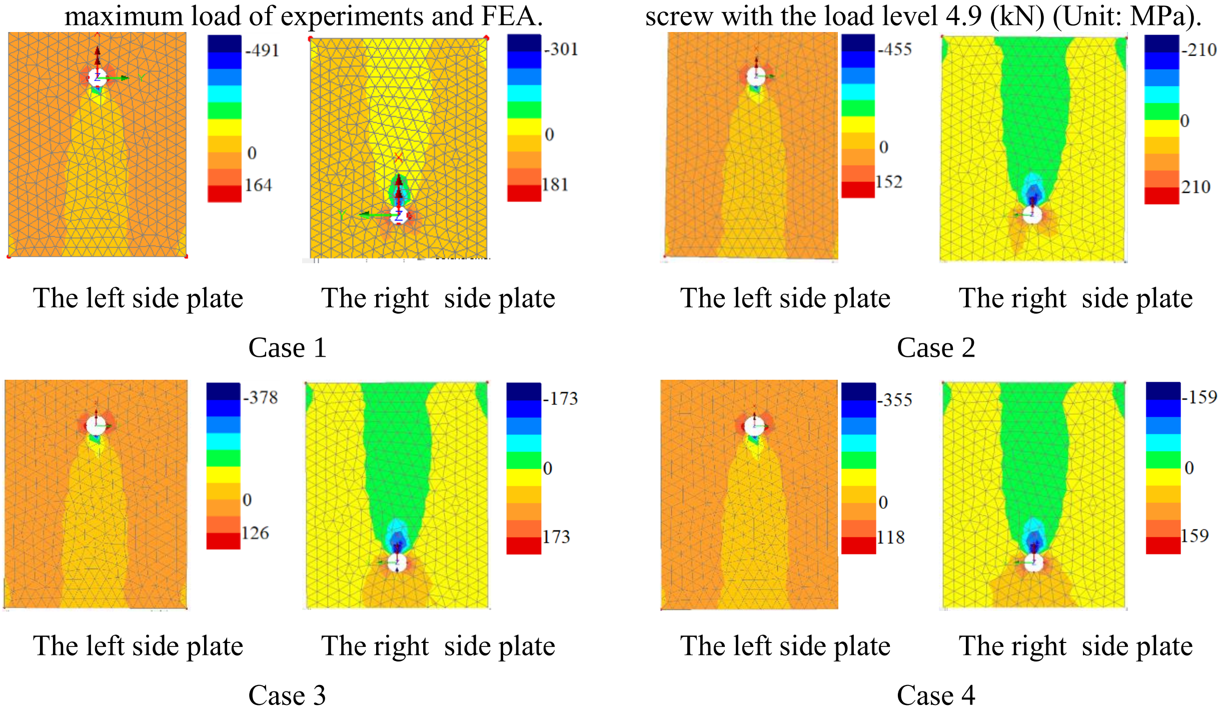

Figure 22. The longitudinal stress distribution in FRP plates with the load level 4.9 (kN) (unit: MPa)

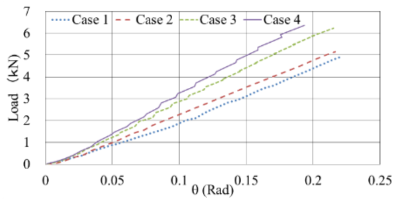

Figure 23. Load and Self-tapping screw's rotation relation.

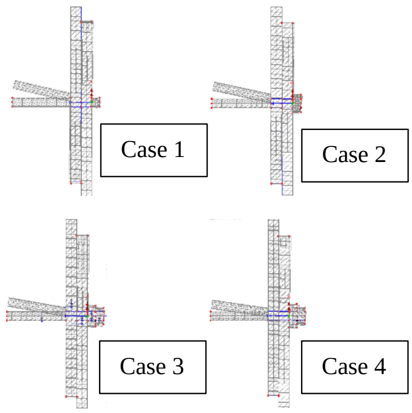

Figure 24. Deformation modes in FEA with the load level 4.9 (kN).

4. Conclusion

In this study, we surveyed the self-tapping screws connection strength and effects of washers on connection strength of single-lapped GFRP plates using self-tapping screws with end distance was 50mm, under tensile-shear loading by experiment and finite element analysis (FEA).

- Then, the following conclusive remarks are obtained:
- The connection strength in GFRP plates using self-tapping screws depends on washer’s diameter; when increasing washer’s diameter, the connection strength increased. Hence increasing washer’s diameter to a reasonable level is an effective method to increase the load carrying capability for self-tapping screws connection in GFRP plates.
- The occurrence of shear-out failure is the reason load early reached the maximum load and rapidly decreased then. Hence, increasing the length of end distance to a reasonable level to avoid the shear-out failure is a good method to increase connection strength and connection stability, avoid the sudden damage.
- We proposed the truss elements model to simulate the pull-out behavior of connection in FEA. We conducted experimental pull-out test in order to determine truss element properties in finite element analysis model. There were good agreements between FEA results and experimental results in pull-out test and single-lapped tensile-shear test. Hence, the pull-out behavior of connection can be simulated by truss elements and failure of connection is determined by yielding of truss elements. This simulation method can be used to investigate mechanical behavior of single-lapped and double-lapped GFRP plates connection using single or multiple self-tapping screws in the future research.

5. References

[1] JEC Group：THE CHALLENGING WORLD OF COMPOSITES，2013.6

[2] Alfred Kofi GAND, Tak-Ming CHAN, James Toby MOTTRAM, "Civil and structural engineering applications, recent trends, research and developments on pultruded fiber reinforced polymer closed sections: a review," Front. Struct. Civ. Eng. 2013, 7(3): 227–244. DOI 10.1007/s11709-013-0216-8.

[3] Yukihiro Matsumoto, Seishi Yamada and Iwao Komiya: Nonlinear Failure Behavior and Bearing Strength of Bolted Joints in Fiber Reinforced Polymer Plates, Proceeding of The SAMPE Tech 2012 (SAMPE Tech 2012) (North Charleston, USA), 2012.10

[4] Nguyen Ngoc Duong, Phan Viet Nhut, Chito SATAKE, Yukihiro MATSUMOTO: Effect of Washers on Mechanical Behavior of Single-lapped Connections in GFRP Plates using Tapping Screws, The 12th Symposium on Research and Application of Hybrid and Composite Structures- Architectural Institute of Japan (7), 2017.11.

[5] Yukihiro MATSUMOTO, Yuya INOUE and Kazunari MATSUNO: Fundamental Study on Joint Strength using Tapping Screw for GFRP, Proceeding of the 12th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-12) & the 5th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures.
[6] Nguyen Ngoc Duong, Phan Viet Nhut, Chito SATAKE, Yuya INOUE, Yukihiro MATSUMOTO: Influence of Washers on Mechanical Behavior of Single Lap Connection in GFRP Plates using Tapping Screws, Summaries of Technical Papers of The 72nd Annual Meeting-Japan Society of Civil Engineers (CS5-020), 2017.9.
[7] Yuya Inoue, Nguyen Ngoc Duong, Chito Satake and Yukihiro Matsumoto: Mechanical Characteristics of Connection for GRFP Plates using Tapping Screws, International Conference of Global Network for Innovative Technology & AWAN International Conference in Civil Engineering (AICCE) 2017.

Acknowledgment
In this study, GFRP materials were supplied by AGC MATEX CO., LTD and Self-tapping screws were supplied by Japan Power Fastening Co Ltd.