(7) Effect of Washers on Mechanical Behavior of Single-lapped Connections in GFRP Plates using Tapping Screws

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In recent years, mechanical characteristics of FRP connections using bolts/rivet have been researched in detail, and they are used in many FRP structures. However, the connection lack bearing strength compared with material strength and they need the prepared holes. In this paper, we surveyed the tapping screw connection strength and effects of washers on connection strength of single-lapped FRP plates using tapping screw under tensile-shear loading by experimental data and finite element method (FEM). The connection strength 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 tapping screws connection in GFRP plates. Moreover, FEM was proposed to investigate the bearing strength of connections and there were good agreements between FEM and experimental results.

Key Words: *GFRP, Tapping crews, Connection strength, Single-lapped connection*

1. INTRODUCTION

Fiber reinforced Plastics (FRP) has currently been widely used in the fields of vehicles, medical and nursing care equipment, aircraft and aerospace, boat and ship, energy, etc because they have many good characteristics compared with other materials[1)]. The first good characteristics are light weight and high strength. Almost Carbon Fiber Reinforced Plastics (CFRP) has a smaller specific gravity and greater tensile strength than carbon steel. Pultruded Glass Fiber Reinforced Plastics (GFRP) has the same tensile strength as carbon steel and smaller specific gravity than aluminum. The second good characteristics is a material could be freely designed. FRP is a composite material of resin and fibers, the strength is mostly determined by the fibers. Metal is an isotropic material with similar strength in all directions, but FRP has an anisotropic material property which can freely determine directional strength by arrangement method of fibers. Hence, FRP is a material could give appropriate strength depending on the application and shape used. The third good characteristics are high corrosion resistance, decay in wood and rust in metal do not occur. Therefore, FRP material can be used for a long time, requires less maintenance, reducing the life cycle cost.

Because of these characteristics, FRP has also been used in architecture and civil engineering field. For example, in the architecture sector, it has been used in the large space of the roof frames, indoor swimming pools, etc[2)]. In the civil engineering sector, it has been used in pedestrian bridge, floodgate, etc[3)]. At present, because the connection behavior of FRP connection is relatively complex, it is impossible to construct freely like wood, concrete, steel.

If that problem is solved, FRP will be a material which can change significantly the construction of structure. Unlike steel, the connection of FRP cannot weld, so mechanical connection, an adhesive connection, or both have been used. However, the mechanical properties of the 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 has been much research about the mechanical connection for FRP by metallic bolts/rivet[4]. 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, using tapping screw to solve this problem, improve initial stiffness and bearing strength of the connection is a great solution. Furthermore, the screw has a drill at the tip, there don't need hole-processing, increasing construction speed; the diameter of tapping screw is about 3 to 5 mm, so the cutting of fibers inside FRP material by connection section can be reduced, increasing connection performance. However, because of tapping screw's rotation in single-lapped connection, it can't 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 tapping screw was decreased when comparing with double-lapped GFRP plates connection[5]. Reducing the rotation of tapping screw while bearing load by increasing the diameter of the washer, thereby increasing the connection strength of single-lapped GFRP plates using tapping screw should be considered carefully. In this paper, we surveyed the screw connection strength and effects of washers on connection strength of single-lapped FRP plates using tapping screw under tensile-shear loading by experimental data and finite element method (FEM).

2. EXPERIMENT

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

Table-1 Mechanical properties of specimen

FRP materials	Value
Tensile strength(MPa)	408
Longitudinal elastic modulus (GPa)	28
Glass content rate (weight %)	54

FRP plates used in the experimental test were cut from original C-shape FRP materials with the dimensions length=150mm, width=500m, and thickness=6.5mm. 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. Tapping screws were made of stainless steel. Tapping screws were tightened by an electric screwdriver, tightening torque of the screw was controlled as 15 N.m in order to prevent the damage to the specimen material.

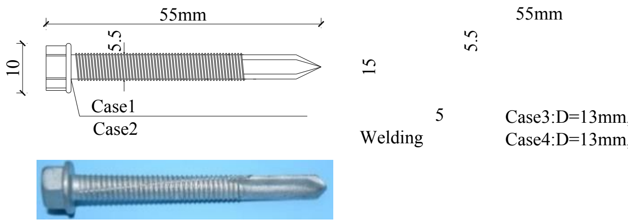

Figure-1 Tapping screws without added washer

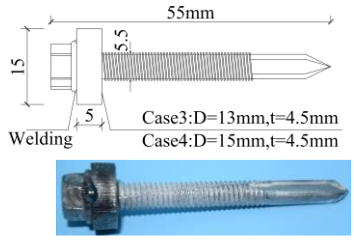

Figure-2 Tapping screws with added washer

(1) Experimental methods

(a) Pull-out tests

Figure-3 shows experimental method and setup. Because the shaft neared tapping screw-head does not have threats, we put 5mm thickness-washer between tapping screw-head and FRP plate 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 6.47mm.

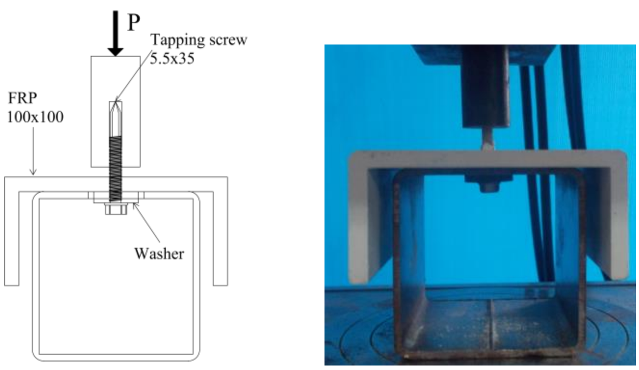

Figure-3 Experimental method and setup

(b) Single-lapped tensile-shear test

The experiment was conducted with 4 different cases to survey the influence of the washer on the connection strength. Case 1 is tapping screws without the washer. Cases 2, 3, 4 include washer diameter with 10mm, 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 are clamped onto the machine, the load was applied on the top, data recording includes load and crosshead displacement. In case 1, in order to release the effect of the washer on FRP plate, the distance between the washer and FRP plate is 5mm. The connection strength of FRP plate was investigated through single-lapped tensile-shear loading test.

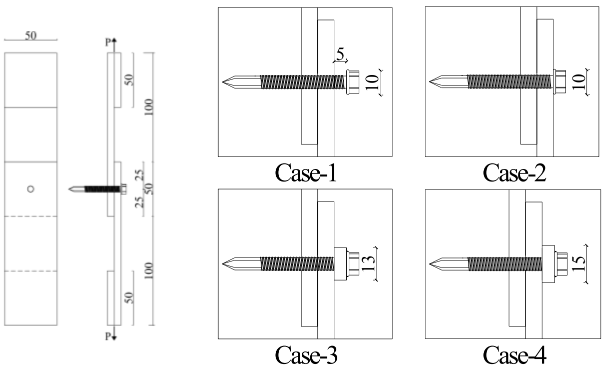

Figure-4 Experimental method

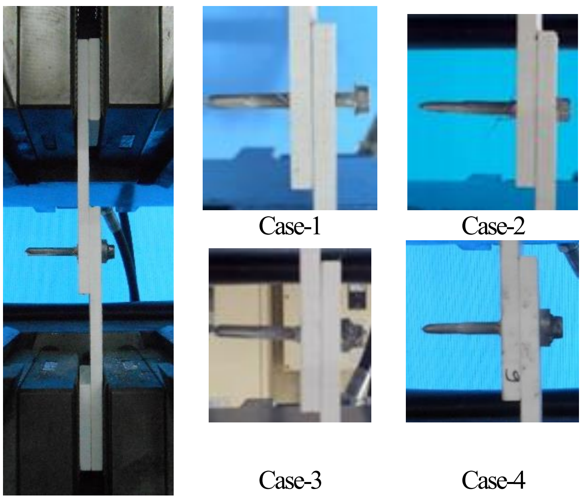

Figure-5 Experimental setup

(2) Experimental results and discussions

(a) Pull-out tests

Figure-6 shows the load-displacement relations. Table-2 summarizes results obtained by the pull-out tests. The loading was gradually decreased after reaching the maximum load in all specimens. Figure-7 shows Load-K/ΔK curves. 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 $\Delta K/K$ reaches 0.5, then the loading of elastic limit is calculated to be $0.93P_{max}$(specimen 1).

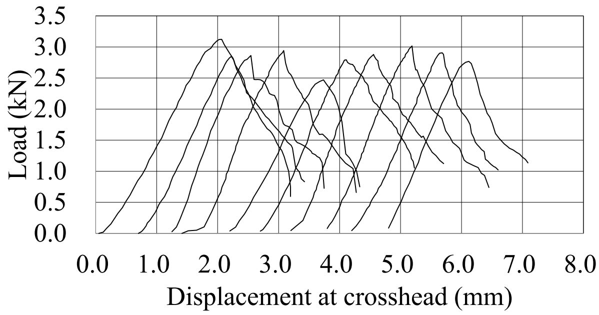

Figure-6 Load-displacement relations

Table-2 Summarization of pull-out tests results

N_o	Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8	Sp9	Sp10
Thickness (mm)	6.50	6.53	6.43	6.43	6.50	6.47	6.47	6.40	6.53	6.43
Average thickness (mm	6.47									
CV of Thickness %	0.67									
P_{max} (kN)	3.12	2.85	2.86	2.94	2.47	2.79	2.88	3.02	2.91	2.77
Average P_{max} (kN)	2.86									
CV of P_{max} %	5.72									
P_{max}/t (kN/mm)	0.44									
K (kN/mm)	1.77	2.18	2.83	2.84	1.77	2.18	2.76	2.46	2.07	2.32
Average K (kN/mm)	2.32									
CV of K%	16.38									

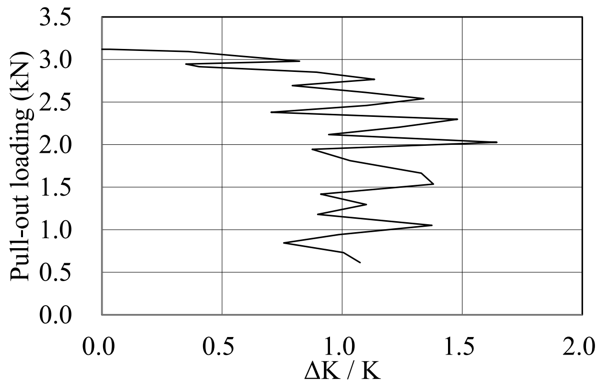

Figure-7 Load- $\Delta K/K$ relation (specimen 1)

(b) Single-lapped tensile-shear test

Figure-8 shows load-displacement relations, Figure-9 shows the maximum load, an average of maximum load, and a variation coefficient of maximum load, Table-3 shows the load capacity per unit thickness and average bearing strength of the experiment results for case 1, 2, 3, 4. The impact modes of the washer on FRP plate are shown in Figure-10, the typical failure modes of the hole and FRP plates are shown in Figure-11, the deformation modes are shown in Figure-12, the rotation restriction by washer is shown in Figure-13.

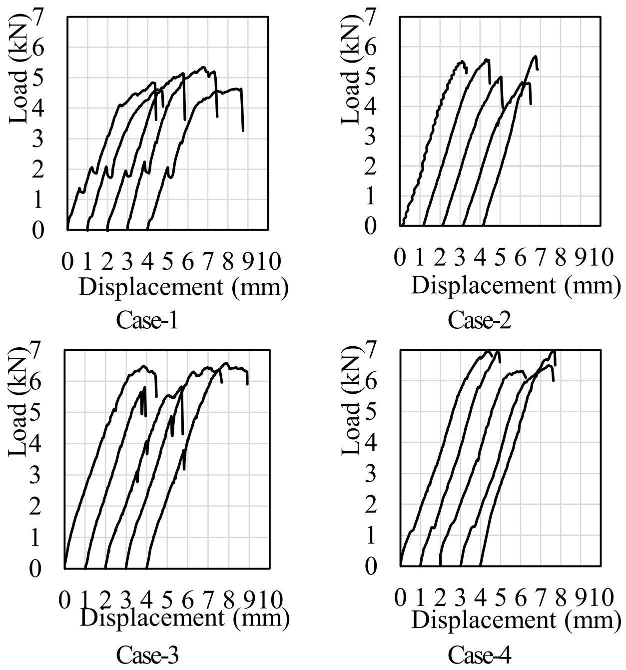

Figure-10 Load-displacement relations

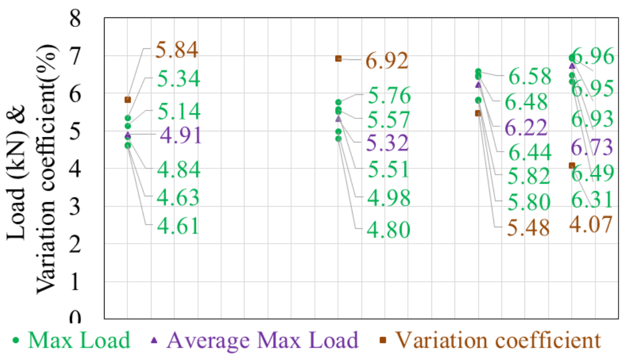

Figure-11 Experimental results

Table-3 Load capacity per unit thickness, average bearing strength

	Case 1	Case 2	Case 3	Case 4
Average thickness (mm)	6.58	6.46	6.53	6.53
Load capacity per unit thickness (kN/mm)	0.75	0.82	0.95	1.03
Average bearing strength (MPa)	135.84	149.77	173.41	187.33

Because tapping screw is rotated by shear loading as shown in Figure-12, the occurrence of partial shear failure leads to hole-failure occurred early, resulting in the load rapidly decreased after reaching the maximum load in all specimens as shown in Figure-10. The max load increased when increasing the diameter of the washer because the rotation was restrained by washer as shown in Figure-13. This rotation restriction helps to reduce partial shear-out failure in connection. The stiffness of steel washer is higher than FRP plate, rotation restriction by washer lead to the deformation of FRP plate at the contact position between FRP plate and washer as shown in Figure-10. In case of specimens having a washer, load linearly increased and a variation coefficient of maximum load decreased depending on washer's diameter as shown in Figure-9.

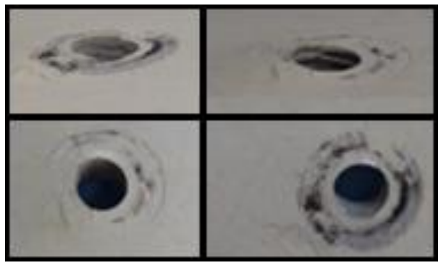

Figure-10 Impact modes of washer on FRP plate (case 3)

Figure-11 Typical failure modes of the hole and FRP plate

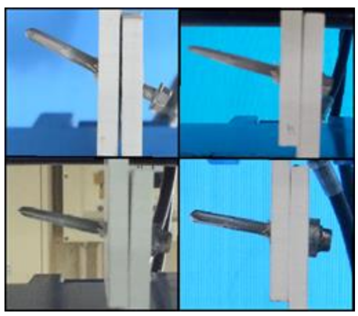

Figure-12 Deformation modes

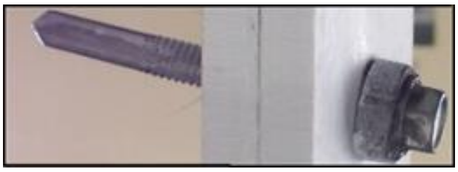

Figure-13 Rotation restriction by washer (case 3)

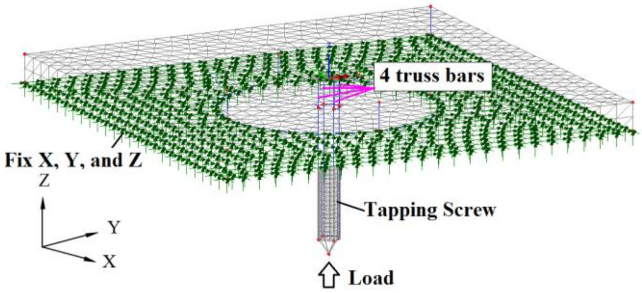

Figure-14 Model pull-out tests in FEM

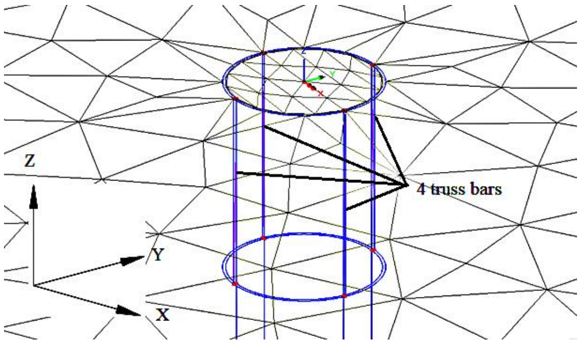

Figure-15 Model truss bars in pull-out tests

3. FINITE ELEMENT METHODS

(1) Finite element method model

In FEM, important FEM features in the connections were the initial contacts between component parts. The contacts of FRP connection using tapping screw include initial contact between washer with FRP plate and contact between tapping screw with FRP plates. The simulation of this contact is very important to an analysis by FEM.

(a) Pull-out tests

In experiments, the tapping screw and FRP plates were held by the screw thread. In this research, we modified the contact between tapping screw with FRP plates by 4 truss bars for every FRP plate with the approximate stiffness with screw threads. We determined when these truss bars were failed, it means the connections were failed.

The materials of these truss bars are steel with the elastic modulus E=205 (GPA). In order to define the stiffness as well as other properties of the truss bars, we conducted the pull-out tests. From the pull-out tests, the average stiffness and sectional area for the truss bars were calculated following to the equations (1) and (2).

$$k_{ave} = \frac{K_{ave}}{t_{FRP}} \tag{1}$$

$$A = \frac{k_{ave} \times t^2_{FRP}}{4E} \tag{2}$$

Here, k_{ave} is the average stiffness for truss bars that was applied into FEM. K_{ave} =2.3 (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 bars. A is the sectional area of the truss bars. From equations (1) and (2), the sectional area that was calculated for every truss bar was 18.3×10^{-3} (mm^2).

Also, the initial uniaxial yield stress for every truss bar was 39079 (MPa), which was calculated from equation (3)

$$\sigma = \frac{P_{\max}}{4A} \tag{3}$$

These values will be assigned into FEM to check the accuracy of the results of pull-out tests. The model of pull-out tests in FEM is shown in Figure-14. The model of truss bars in the pull-out test is shown in Figure-15.

(b) Single-lapped tensile-shear test

Single-lapped tensile-shear test was carried out using nonlinear 3-D analysis in FEM 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 model of single-lapped tensile-shear test modeling are shown in Figure-16, Figure-17. The positions of truss bars are shown in Figure-18.

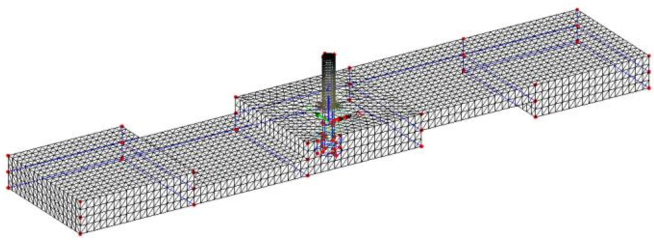

Figure-16 Overview of single-lapped tensile-shear test modeling

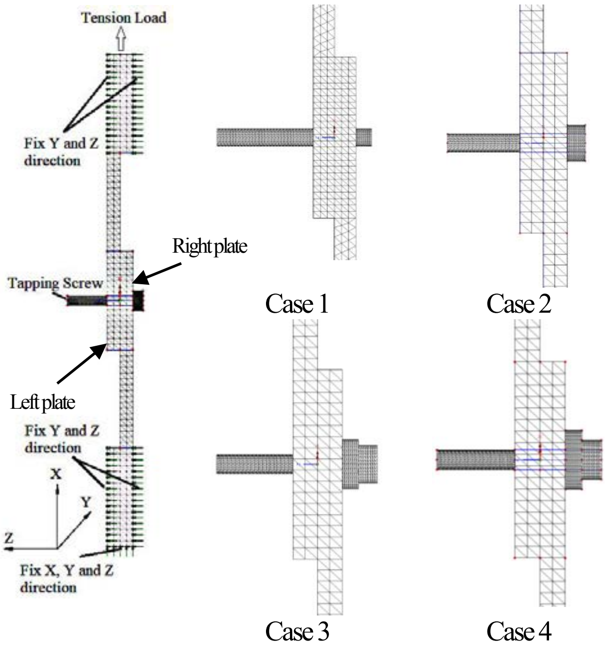

Figure-17 Modelling of single-lapped tensile-shear test in FEM

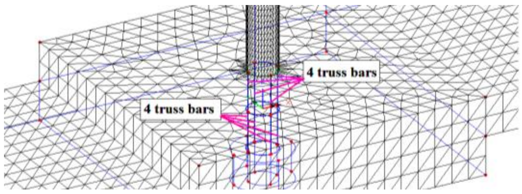

Figure-18 Truss bars of single-lapped tensile-shear test in FEM

(2) Finite element analysis results

(a) Pull-out tests

Figure-19 shows the relationships between the loading and crosshead displacements that obtained from both experiments and FEM. The red line shows the result in FEM. There was good agreement between experimental data and FEM results. Therefore, the truss bar could be used for the simulation of contacts between FRP plates and tapping screw replace for tapping screw thread.

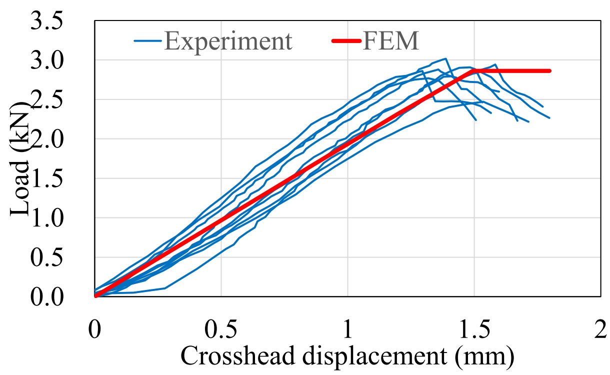

Figure-19 Experimental data and FEM results of Pull-out test

2.1 Single-lapped tensile-shear test

Figure-20 shows the relationships between the loading and cross-head displacements obtained from both experiments and FEM. The maximum load in FEM is the load corresponding to the time in which the bar reaches the initial uniaxial yield stress. Figure-21 shows the comparison average maximum load between experiments and FEM. There were good agreements between experimental data and FEM results. We simulated the distance between tapping screw and hole in FRP plate is 0.1mm in order to simulate four truss bars. Because of the effect of this clearance, the bearing strength of connection was decreased, so the results of FEM analysis in all case are smaller than experimental data. According to FEM results, in case of specimens having a washer, load still linearly increased when increasing washer's diameter as experimental data. Figure-22 shows the deformation of tapping screw and FRP plates. Figure-23 shows the stress distribution in tapping screw with the load level 4.6 (kN). In finite element methods, the compressive stress appeared in the tangential positions between FRP 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.

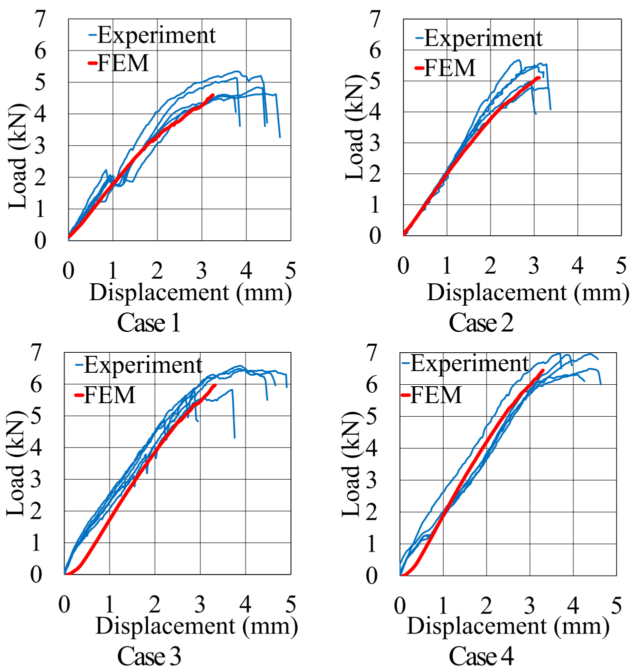

Figure-20 Load-displacement relations in experiments and FEM

Figure-24 shows the longitudinal stress distribution in FRP plates with the load level 4.6 (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 shear-out 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-24.

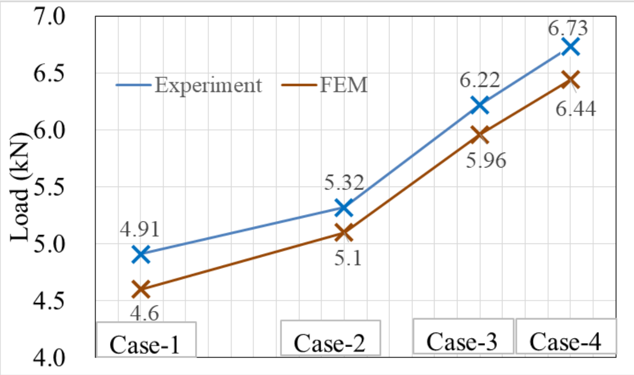

Figure-21 Maximum load of experiments and FEM in all cases

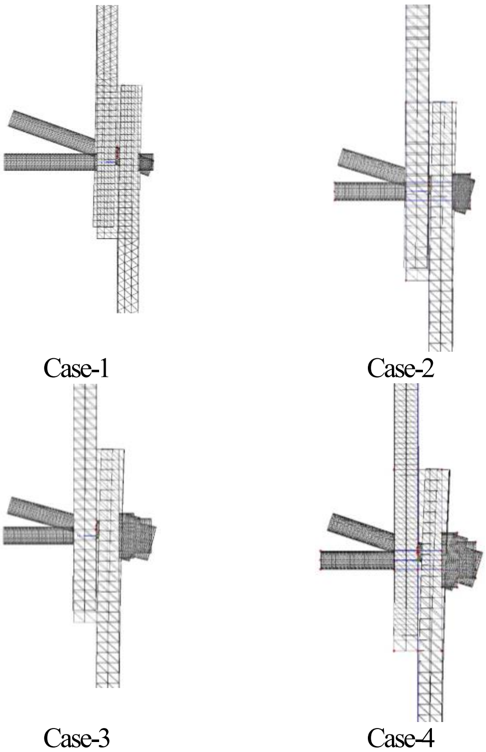

Figure-22 Deformation modes in FEM

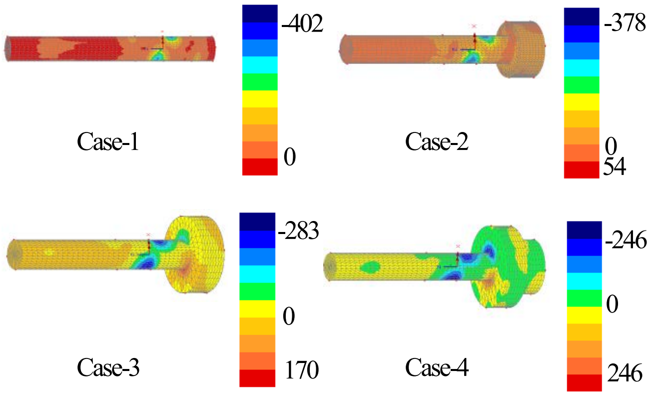

Figure-23 The stress distribution in tapping screw with the load level 4.6 (kN) (Unit: MPa)

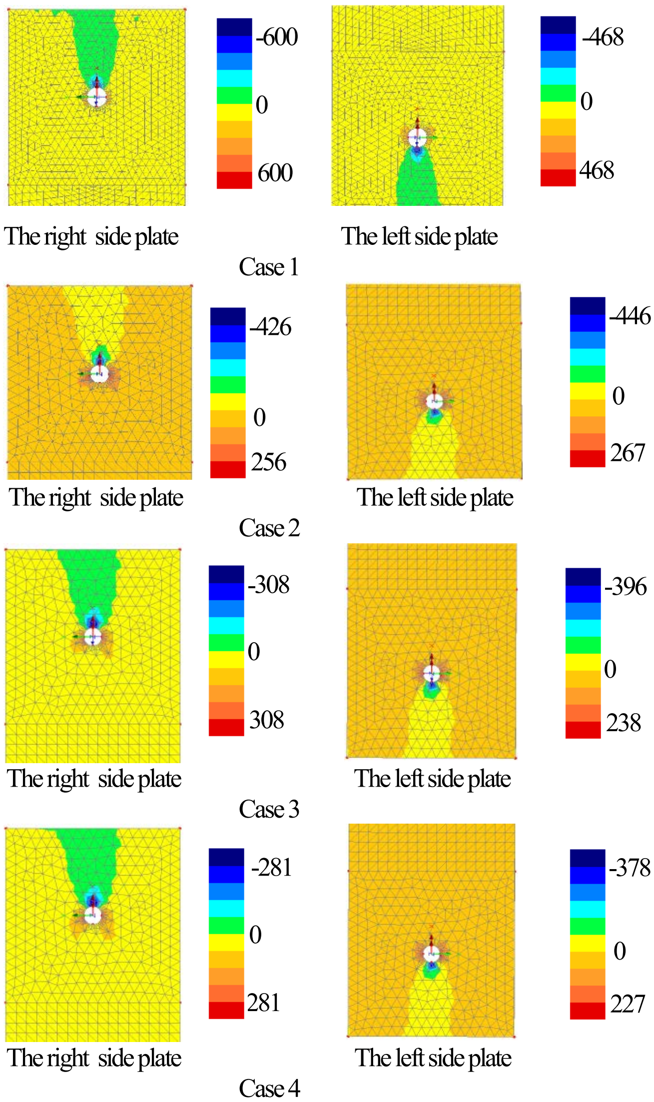

Figure-24 The longitudinal stress distribution in FRP plates with the load level 4.6 (kN) (unit: MPa)

4. CONCLUSION

In this study, we surveyed the screw connection strength and effects of washers on connection strength of single-lapped FRP plates using tapping screw under tensile-shear loading by experimental data and finite element method (FEM). Then, the following conclusive remarks are obtained.

1) The connection bearing strength in GFRP plates depends on washer's diameter; when increasing washer's diameter, the connection bearing strength linearly increased. Hence increasing washer's diameter to a reasonable level is an effective method to increase the load carrying capability for tapping screws connection in GFRP plate.
2) We proposed the truss bars model to simulate the pull-out behavior of connection in FEM and there were good agreements between FEM results and experimental data. Hence, the pull-out behavior of connection can be simulated by truss bar and failure of connection is determined by yielding of truss bars.

ACKNOWLEDGMENT

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ドリルビスを用いた GFRP 板材のシングルラップ接合部におけるワッシャーの影響

グエン　ゴック　ユン・ファン　ヴィエットニュット・佐竹　ちとう・松本　幸大

近年，ボルトやリベットを用いた FRP 材料の接合部の特性が詳細に研究されており，多くの FRP 構造で使用されている．しかし，クリアランスの影響で接合部の耐力は材料の強度より低下しおり，接合部には穴の加工が必要である．ドリルビスは先端にドリルを備えているため，下穴の加工が不要である．そのため，接合部のクリアランスを無くすことで，初期剛性および耐力が改善でき，施工速度の向上も期待される．本論文では，実験データと有限要素法（FEM）によるドリルビスを用いた GFRP 板材のシングルラップ接合部の力学特性や座金の影響について分析を行う．FRP 板材の接合部の強度は座金の直径に依存し，座金の直径を大きくすると，接合部の強度が増加した．したがって，座金の直径を適切な範囲で増加させることは，FRP 板材の接合部の強度を高める有効な方法である．さらに，FEM を用いて接合部の強度を分析するための提案し，実験結果と一致することを示した．