STUDY ON FRICTIONAL BEHAVIOR AND MAXIMUM STRENGTH OF GFRP MEMBERS CONNECTED BY HIGH STRENGTH FRICTIONAL BOLTS

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ABSTRACT
In this research, in order to investigate frictional behavior, maximum strength and relaxation behavior of the frictional joints made of GFRP members connected by high strength bolts and splice plates, the slip test and the bolt relaxation test were conducted. The test specimens were prepared, which consisted of high strength bolts, connected plates made of GFRP and splice plates made of GFRP or stainless. The FE analysis was also executed to study mechanism of the stress concentration around the holes of the frictional joints and to estimate its maximum strength. The slip test showed that the slip coefficient of the specimens using the stainless splice plates was larger than 0.4. And it was found that the slip coefficient could estimate by tribology theory which was the science and technology of interacting surface in relative motion and of related subjects and particles. The bolt relaxation test for a year provided that the reduction of the bolt axial force of the specimen with the stainless splice plates was less than 5 % and lower than that of the specimen using the GFRP splice plates. From the FE analysis results, the maximum strength of the GFRP frictional bolted joint could calculate based on considering the stress concentration.

KEYWORDS
GFRP, frictional bolted joint, high strength bolts, slip coefficient, maximum strength

INTRODUCTION
Adhesive joints and mechanical joints connected by rivets or bearing bolts already have been used for the connected parts of FRP structures (Clarke, J.L. (ed), 1996); for example the FRP pedestrian bridges or the FRP hydraulic gates. And there are many researches for these joints used for FRP materials. On the other hand, frictional bolted joints used by high strength bolts have been frequently used for the connections of steel structures as the connecting method on site in Japan. For large size infrastructures like road bridges which are subjected to large loads, adhesive / rivet joints have to need larger adhesive area / larger size rivets or bolts than those of the joints of FRP pedestrian bridges to obtain the shear resistance force against these loads. The frictional high strength bolted joints may have the high performance against shear resistance force because the higher the fastening torque or the slip coefficient become, the larger the shear resistance (slip resistance) of the joint become. Although the shear resistance force of the frictional joints are defined by the slip coefficient, the number of bolts, the number of contact surface and the bolt axial force (torque), the slip coefficient of the joints made of FRP is little known. On the other hand, the slip coefficient of steel material is well known as about 0.2 to 0.5 and can be changed by the treatment of the contact surfaces. The creep of polymer constituting of FRP plates occurs due to the high axial bolted force, and then the axial force will be decreasing due to the creep. The amount of the axial force loss is larger than that of the joints made of steel (Kishima, T. et al, 2010).

Therefore, in this research, experimental and analytical studies are conducted to investigate the frictional behavior which are contained of the slip coefficient and the mechanism of the slippage, the maximum strength and the relaxation behavior of the frictional bolted joints which are made of GFRP plates and high strength bolts.

SLIP AND RELAXATION TEST
Specimen
The specimens were mainly divided into two classes which were for the slip test and for the relaxation test. Furthermore three different types of specimens for each test were prepared as listed in Table 1. The GG specimens were made of GFRP splice and connected plates. The GS specimens consisted of stainless splice plates and GFRP connected plates to improve the slip coefficient and the creep of the GFRP plates. The SS specimen made of stainless plates was also prepared to obtain the slip coefficient between stainless plates. Three same specimens were prepared in each type of specimens for the slip test. Figure 1 shows the configurations and the dimension of the specimens for the slip test and the relaxation test. The specimens were a double lapped joint and fastened by F10T (Standard value of tensile strength: 1,000MPa and yielding point : 900MPa) high strength bolts. The thickness of the connected plate (28 mm) was decided by the ratio of the design slip strength by the design GFRP tensile strength as 0.6. Table 2 shows the laminated constitution of the GFRP plates used in this research. The GFRP plates were manufactured by hand lay-up method. The holes for the bolts on the plates were opened by a drill and the diameter of the holes was opened larger (22.5mm) than the diameter of the bolts (20.0mm). Therefore, external force which acted on the joints is only transferred to frictional force as shear resistance of the joints without the bearing force of the bolts and plates.

The contact surfaces of the GFRP plates were treated by sandpapers, and the contact surfaces of the stainless plates were treated by blast finishing. Table 3 shows the measurement results of arithmetic mean roughness $R_a$ as the roughness parameter of the plates. Since each treatment of the surface was different way, the roughness parameter $R_a$ of the GFRP plates was about 10 times smaller than that of the stainless plates. The GFRP plates were difficult to treat the surface by the blast because of breaking the surface laminate.

### Table 1. Types of specimens

<table>
<thead>
<tr>
<th>Experiment Type</th>
<th>Specimen Name</th>
<th>Connected plate</th>
<th>Splice plate</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>F-GG</td>
<td>GFRP</td>
<td>GFRP</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>F-GS</td>
<td>GFRP</td>
<td>SUS</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>F-SS</td>
<td>SUS</td>
<td>SUS</td>
<td>3</td>
</tr>
<tr>
<td>Relaxation</td>
<td>R-GG</td>
<td>GFRP</td>
<td>GFRP</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>R-GS</td>
<td>GFRP</td>
<td>SUS</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>R-SS</td>
<td>SUS</td>
<td>SUS</td>
<td>1</td>
</tr>
</tbody>
</table>

(a) Slip test specimen  
(b) Relaxation test specimen  

Table 2. Laminated constitution of GFRP plates

<table>
<thead>
<tr>
<th>GFRP Member</th>
<th>Thickness(mm)</th>
<th>Connected Plate</th>
<th>Splice Plate</th>
<th>Fiber Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFM</td>
<td>28</td>
<td>1</td>
<td>1</td>
<td>0°, 90°</td>
</tr>
<tr>
<td>CSM</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>0°, 90°</td>
</tr>
<tr>
<td>#580</td>
<td>40</td>
<td>1</td>
<td>1</td>
<td>0°, 90°</td>
</tr>
<tr>
<td>#800</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>0°, 90°</td>
</tr>
<tr>
<td>Fiber Content Rate</td>
<td>0.49</td>
<td>0.45</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Roughness of contact surface of each plate (Average value)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Roughness Parameter Ra (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Connected plate</td>
</tr>
<tr>
<td>F-GG</td>
<td>0.49</td>
</tr>
<tr>
<td>F-GS</td>
<td>0.47</td>
</tr>
<tr>
<td>F-SS</td>
<td>5.12</td>
</tr>
</tbody>
</table>

**Slip Test Method**

The bolt calibration tests were carried out to estimate the relationship between the bolt axial force and the strain at the bolt shank or head before the slip test so that the bolt axial force can be calculated by the value of the strain. Each high strength bolt was fastened controlling by the strain value until 182kN which was a standard value of a M20 high strength bolt for the joints of steel members.

The slip test was conducted by using the 1000kN universal loading tester as shown in Figure 2. The connected plates of the specimens were gripped by the chuck of the machine and the specimens was subjected to tensile load. After the bolts fastened, about 24 hours later, the slip test started to observe the relaxation behavior of the GFRP plates.

In the slip test, load, relative displacement between the connected plate and the splice plate, displacement of the joint and strains of the high strength bolts and the connected plates were measured.

![Figure 2. Overview of slip test](image)

**Relaxation Test Method**

The relaxations of the bolt axial force were measured for R-GG, R-GS and R-SS specimens as shown in Table 1 and Figure 1 (b). The bolt axial forces were indirectly measured by the strain gauges using the result of the bolt calibration test. The strains of the bolts had been continued to hourly measure for 365 days after fastening the bolts.

**Material Property**

Before the slip and the relaxation tests were carried out, the material tensile test were executed to obtain the mechanical properties of GFRP plates used as the connected plates and the splice plates. Five material test pieces were prepared for each plate. Because the plate used for the connected plate was thick and had 28 mm thickness, the material test pieces were broken at grip end due to shearing force from the grip before obtaining the maximum strength of this material. Therefore the mechanical property of the GFRP plate was only obtained from the splice plate which had 16mm thickness. And the mechanical property of the stainless plate was obtained from the mill sheet of the steel company.

Table 4 shows the mechanical properties of the GFRP plates and the stainless (SUS316L) plates used in this research. It is found that the elastic modulus of the GFRP plates is about 10 times as low as that of steel material. As the 28 mm plates cannot be obtained the mechanical properties, the predicted value of tensile strength of the 28 mm plate was estimated by using the tensile strength of the 16mm plate and the ratio of the number of the laminate / thickness of each plate. The estimated tensile strength of the 28mm plate is 357MPa (=313 x (40/28) / (20/16))
RESULTS AND DISCUSSIONS

Slip Test Results

Figure 3 (a) and (b) show the relationship between the load and the total displacement of the specimens, and between the load and the relative displacement respectively. Representative example data from three specimens in each type of specimens are shown in Figure 3. And the results of the slip test are summarized in Table 5. The slip coefficient and the design slip coefficients were calculated by Equation (1) in Table 5. The design coefficients were estimated by using a design bolt axial force 165 kN which were a standard value of a M20 high strength bolt. The slip coefficient were calculated by using the measured real bolt axial force before loading of the slip test. The values in Table 5 are average values of the results of three same specimens.

\[ \mu = \frac{P_{sl}}{m \cdot n \cdot N_B} \]  

where, \( \mu \); slip coefficient, \( P_{sl} \); slip load, \( m \); number of contact surfaces, \( n \); number of bolts and \( N_B \); Axial bolt force.

From Figure 3 (a), the loads of the F-GG and the F-GS specimens were suddenly decreased several times in loading because slippage occurred between the splice plate and the connected plate in this time as shown in Figure 3 (b) (U or L in Figure 3 (b) means upper or lower side of the specimen). The F-GG specimen firstly slipped at upper side of the joint about 150 kN and then second slippage occurred at lower side of the joint about 180 kN. The first slippage of F-GS specimen occurred at both sides at about 310 kN. In the F-SS specimen, slippage occurred about 150 kN, and the amount of the load decrement after the slippage was lower than that of other specimens. From Table 5, it is found that the slip coefficient of the GS specimen is the largest value of all specimens and that is more than 0.4, which is the lowest standard value of frictional joints in Japanese steel bridge standard. It is also found that the slip coefficient of the F-GG and the F-SS specimens are about 0.3 or lower than 0.3. The reason why the slip coefficient of the F-GS specimen is the largest in the test is that the projections of hard stainless splice plate bite the soft surface of the GFRP connected plate. This phenomena will be explained in exact detail in the next section. The design slip coefficients calculated by the design bolt axial force are lower than the real slip coefficients calculated by the real bolt axial force because the bolt axial force is decreased due to the creep of the GFRP plates or the relaxation of metal material. The bolt axial force of the F-GG specimen was decreasing by about 25% from the initial fastening force after 24 hours.

Figure 3. Load-displacement curve
Table 5. Slip test results (Average value)

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Slip Strength (kN)</th>
<th>Design slip Coefficient</th>
<th>Bolt force (Before test) (kN)</th>
<th>Slip Coefficient</th>
<th>Maximum Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-GG-AV</td>
<td>187.5</td>
<td>0.284</td>
<td>136.6</td>
<td>0.343</td>
<td>329.6</td>
</tr>
<tr>
<td>F-GS-AV</td>
<td>308.5</td>
<td>0.467</td>
<td>171.7</td>
<td>0.449</td>
<td>357.5</td>
</tr>
<tr>
<td>F-SS-AV</td>
<td>152.2</td>
<td>0.230</td>
<td>177.0</td>
<td>0.215</td>
<td>-</td>
</tr>
</tbody>
</table>

Discussion on the Slip Coefficient by Triborogy Theory

The tribology is the one of the field of mechanical engineering, which deals with the friction and lubrication problem between solids (Bowden, P. F. and Tabor, D., 2001). In the field, there are several theories concerning real frictional mechanism and frictional coefficient, which are 1) convexo-concave theory, 2) adhesion theory, 3) adhesion part growing theory and 4) ploughing theory and so on. Recently it is thought that the theory 2) to 4) are reliable theories. Equation (2), (3) and (4) can calculate a theoretical frictional coefficient of solids made of metal material considered by theory 2), 3) and 4). The frictional coefficient calculated by Equation (2) is expressed by ratio of material shear strength / material hardness in the theory 2). Equation (3) is improved and developed from the theory 2) and also defined the frictional coefficient by parameters related to material shear strength and hardness. In the theory 4) ploughing is occurred at contact surfaces between a hard material solid and a soft material solid as shown in Figure 4. Therefore the frictional coefficient shown in Equation (4) is defined by the apex angle of the projections of the hard material on the contact surface. Recently, it was confirmed the frictional coefficient between the soft solid and the hard solid can calculate adding the frictional coefficients estimated by Equation 2) and 4) or 3) and 4).

\[ \mu_1 = \frac{F}{W} = \cdots = \frac{s_o}{p_o} = \frac{s_o}{H} \quad (2) \]
\[ \mu_3 = \frac{F}{W} = \cdots = \frac{k}{\sqrt{\alpha(1-k^2)}} \quad (3) \]
\[ \mu_s = \frac{F}{W} = \cdots = \frac{2}{\pi} \cot \theta \quad (4) \]

where, \( \mu_1 \); frictional coefficient defined by adhesion theory, \( \mu_2 \); frictional coefficient defined by adhesion part growing theory, \( \mu_3 \); frictional coefficient defined by ploughing theory, \( F \); shear force, \( W \); vertical force, \( s_o \); maximum shear strength, \( p_o \); plastic flow pressure, \( H \); indentation hardness, \( k = s/s_o (0 < k < 1) \), \( s \); shear strength, \( \alpha = p_o/s_o^2 \) and \( \theta \); half of apex angle of circle cone (see Figure 4).

From the slip test, difference between the slip coefficient of the F-GG specimen (0.343) from that of the F-GG specimen (0.449) is 0.106. It is thought that the difference value between the F-GS specimen and the F-GG specimen is affected due to the ploughing action. Figure 5 shows the surface shape of the stainless splice plate. The value of average apex angle of the stainless splice plate from the measurement is 80.4 degree and the value of \( \mu_3 \) is 0.108 which is calculated by Eq. (4). The GFRP plate also has the frictional coefficient calculated by the adhesion theory, and this value would be near the result of the F-GG specimen (0.343). As above mention the frictional coefficient between solids would be expressed by \( \mu_1 + \mu_3 \) or \( \mu_2 + \mu_3 \). Therefore the frictional coefficient of the GFRP-Stainless joint is calculated by adding the value of 0.343 which is the frictional coefficient by the adhesive action to the value of 0.108 which is the frictional coefficient due to the ploughing action by the roughness data. It is found that this calculated value is very near the slip coefficient of the F-GS specimen obtained from the slip test.
From this consideration of frictional behavior it is shown that if the hard solid such as steel or stainless
is used for the splice plate, the slip coefficient of the double lapped joint made of GFRP has a possibility to
increase due to the ploughing action.

Discussion on the Maximum Strength
The mean value of the maximum load of the F-GG and F-GS specimens are shown in Table 5. In all F-GG and
F-GS specimens, the connected plates were broken due to tensile stress in the cross sectional area of the hole at
the outer side bolt as shown in Figure 6. From Table 5, it is found that the maximum load of the F-GS specimens
is larger than that of the F-GG specimens. The shear resistance force of the GS specimen are larger than that of
the F-GG specimen because the GS specimen has larger slip resistance due to the slip coefficient. And the
maximum load of the F-GG or the F-GS specimens cannot estimate by the simple calculation way that the net
section area multiplies the tensile strength of GFRP (t=28mm×bn=(90-22.5) mm×313 N/mm²/1000=592 kN ≠
330 or 358 kN). The reason why the GFRP material has a brittle property and it is affected to the stress
concentration due to containing many voids in the adhesion in comparison with metal material. In this study, FE
analysis was carried out to confirm the mechanisms of these phenomena on the maximum strength such as the
slip coefficient and the stress concentration.

In FE analysis, all parts (bolts, washers and plates) of the test specimen were modelled as 1/8 model
considering symmetry by solid elements as shown in Figure 7. Load and constraint conditions were positioned as
shown in Figure 7. In first step of the analysis, the bolts were fastened by displacement and then the connected
plate was subjected to tensile load at the edge of the model in second step. Contact surfaces between the plates
and between the washers and the bolts were introduced as contact conditions that are defined by the Penalty
method based on the Amontons/Coulomb's frictional law. For the horizontal direction condition, the frictional
coefficients were set as 0.385 and 0.500 for the F-GG and F-GS specimens. The rigid contact condition taking
account of contact and separation were defined for the vertical direction condition. Material properties of GFRP
and stainless used the result of the material test. Although GFRP is the anisotropic material, the specimen was
modelled as isotropic material only because of considering the qualitative effect of the stress concentration. As
analytical cases, three cases were prepared, which were the real F-GS and F-GG models to investigate the effect
of the stress concentration, and the little fastened F-GS model ( bolt axial force is 10kN, model name; F-GS-0) to
consider the effect of the frictional strength.
Figure 8 shows the axial stress counter of connected plates of the F-GG and F-GS models reached to maximum strength respectively. It is seen that the axial tensile stresses of both the F-GG and F-GS become the largest at the side of the hole near the loading position. The maximum stress at maximum load of the F-GG and F-GS model was 377.3MPa and 369.4MPa respectively. These values are a little larger than the result of the predicted value of the 32mm GFRP plate (357MPa). The maximum load of the GFRP plate with the hole becomes lower than the calculation value because FRP material has brittle property and plates with holes are affected to the stress concentration.

FE analysis of F-GS-0 model was carried out to investigate the frictional effect for the maximum strength of the GFRP plate. Figure 9 shows the result of the analysis. The maximum load of the F-GS-0 model is lower about 30% than the result of the F-GS real model because the frictional resistance of the F-GS specimen was continuing after the slippage.

From these analytical results, it is found that the maximum strength of the frictional joint made of GFRP plates is affected to the stress concentration and the frictional resistance.

**Relaxation Test Result and Discussion**

Figure 10 shows the result of the relaxation test for a year and for three days. From Figure 10, it is seen that the bolt axial force of each specimen rapidly decreases for 24 hours and loosely decreases after a day. Table 6 summarizes the results of the relaxation test. From the figure and the table, R-GG specimen showed the largest decrement of bolt axial force of all specimens for a year. And R-GS specimen has a good performance for
relaxation behavior (about 13 % decrement) for a year in comparison with R-GG specimen because total GFRP plate thickness of the R-GS is lower than that of the R-GG specimen and the compressive stress due to the bolt axial force is dispersed in the splice plate made of stainless. The ratio of bolt axial force / total GFRP thickness of the R-GG and the R-GS specimens after a year are shown in Table 6. The ratio of the R-GS specimen is lower than that of R-GG specimen because of the effect of the compressive stress dispersing.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>1 day</th>
<th>7 days</th>
<th>365 days</th>
<th>Residual bolt force/GFRP thickness (%/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-GG</td>
<td>15.1</td>
<td>20.0</td>
<td>32.1</td>
<td>0.535</td>
</tr>
<tr>
<td>R-GS</td>
<td>6.1</td>
<td>8.3</td>
<td>13.2</td>
<td>0.471</td>
</tr>
<tr>
<td>R-SS</td>
<td>5.0</td>
<td>6.7</td>
<td>6.9</td>
<td>-</td>
</tr>
</tbody>
</table>

CONCLUSIONS

To investigate frictional behavior, maximum strength and relaxation behavior of frictional joints made of GFRP members connected by high strength bolts and splice plates, a slip test, a relaxation test and a FE analysis were conducted. The mainly results of this research are summarized as follows.

1) The slip test showed that the F-GS specimen consisted of GFRP connected plate and stainless splice plate has the largest slip coefficient more than 0.4. This might be because that the projections of the splice plate made of hard material bite into the GFRP connected plate made of soft material.
2) The slip test and the FE analysis indicated that the maximum strength of specimens using the GFRP plate material for the connected plate cannot estimate by the simple calculation way which only multiplies the net section area by the tensile stress, because of the stress concentration and brittle property of GFRP.
3) The FE analysis indicated that the maximum strength of the GFRP bolted joint might increase by 30% compared with the little fastened model.
4) The relaxation test for a year showed that although the bolt axial force of the R-GG specimen decreased by about 32%, the bolt axial force of the R-GS specimen decreased by about 13% because of the total GFRP thickness and the effect of the stress distribution.

REFERENCES