

# Effects of Cover Plate Stiffness on Load Distribution of Bearing-Type Multi-Row Bolted Connections for FRP Composite Structures<sup>†</sup>

by

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The present study investigates the effect of different thicknesses of steel and fiber reinforced polymer (FRP) cover plates on the mechanical behavior of bearing-type multi-row bolted connections for FRP composite structures. Connections with a double-lap configuration up to four rows of bolts subjected to tensile loads have been studied numerically. These numerical data are examined in detail to understand the effects of cover plate stiffness on load distributions among rows of bolts. The study also considers the influence of geometric parameters on the load distributions. For validation of the connection model, numerical results are compared with experimental results available in literature. The results showed that the load distribution in bearing-type multi-row bolted connections is significantly affected by the cover plate stiffness. A connection with higher cover plate stiffness tends to show lower efficiency. For a connection with steel cover plates, to increase number of bolt rows more than three does not lead to a higher capacity of a connection. The results also indicate that effect of geometric parameters on the load distribution is not significant with change of cover plate stiffness.

## Key words:

*FRP composites, Bearing type bolted connection, Load distribution, Cover plate stiffness, Finite element analysis*

## 1 Introduction

Since 1960s fiber reinforced polymer (FRP) composites have been used primarily in the fields of mechanical engineering, aeronautics and aerospace, defense industries to achieve lighter structures and better performance. In civil engineering structures, for the last two decades, FRP composite members have increased their acceptance as structural members and connections which are required to carry loads for long periods of time, often in harsh environmental conditions. However, the connections represent potential weak points in the structure. Therefore, the structural integrity and load-carrying capacity of the overall structure largely depend on the design of the connections.

In FRP composite structures, three types of connections are commonly used, namely, mechanically fastened connections, adhesively bonded connections, and combined connections. Mechanically fastened or combined connections are the dominant connection types in connecting engineering structural members made of FRP in civil structures. Mechanical connections offer several advantages: they are not sensitive to surface preparation, service temperature, or humidity; their strength does not scatter as much as bonded connections; they can be easily inspected; and they can be disassembled without destroying the structure for repair and inspection. However, a severe stress concentration occurs at holes of the connection, which reduces the total efficiency of the connection. The efficiency depends on failure mode of the connection<sup>1)</sup>.

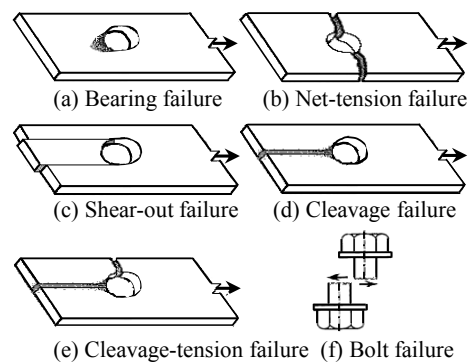


Fig. 1 Failure modes of bolted connection in tension.

Failure modes of the bearing-type bolted connection depend on connection geometry<sup>2)-3)</sup>, fiber orientation<sup>2)</sup>, stacking sequence<sup>4)</sup>, friction and bolt torque, and so on. There are following principal failure modes in the bolted connection<sup>5)</sup>: (a) bearing failure as in the elongated bolt hole, (b) net-tension failure in the reduced cross section through the bolt hole, (c) shear out failure, (d) cleavage failure (actually transverse tension failure), (e) cleavage-tension failure, and (f) bolt failure. These modes are shown in Fig. 1. In addition, failure may consist of their combination. The bearing failure mode is less catastrophic than other failure modes<sup>6)</sup> and usually offers the highest capacity.

This paper focuses on the bearing-type multi-bolted connections with a double-lap configuration of FRP members. In the bearing-type bolted connections, load is not distributed equally among rows of bolts due to relative displacement

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between cover plates and the main plate. This load distribution depends on the relative stiffness of cover plates to the main plate<sup>7)</sup>, bolt position, bolt-hole clearance, bolt-torque or tightening of the bolt, friction between member plates and at washer-plate interface. Feo, Marra, and Mosallam<sup>8)</sup> investigated the load distribution among rows of bolts up to four rows in pultruded FRP structural members. The connections were double-lap configuration with FRP cover plates each having a half of the stiffness of the main plate. In the Pre-Standard for load and resistance factor design hereafter referred to as LRFD Pre-Standard<sup>9)</sup> proposed the load distribution coefficients up to three rows for FRP and steel cover plates and Structural design of polymer composites-EUROCOMP design code and hand book<sup>10)</sup> (hereafter referred to as EUROCOMP) and Guide for the design and construction of structures hereafter referred to as CNR DT 205/2007<sup>11)</sup> proposed the load distribution among the rows of bolts up to four rows for FRP and steel cover plates where each cover plate have a half of the main plate thickness. However, the effect of different cover plate stiffness on the load distribution has not yet been studied for multi-row bolted connections.

The aim of this paper is to examine the effects of cover plate stiffness on the load distribution among rows of bolts in multi-row bolted connections of FRP structural members. The study also includes the influence of connection geometry on the load distribution. Based on the load distribution, efficiency and capacity of connections are evaluated with respect to a single bolt connection.

## 2 Material Properties and Connections

### 2.1 Connection Geometry

The bolted connections with double-lap configuration of one line by two, three or four rows of bolts are examined by finite element analysis, which are shown in Fig. 2. The main plate is an FRP plate with a thickness,  $t_m$ , of 12 mm. Steel bolts with a diameter,  $d$ , of 16 mm and the bolt hole diameter,  $d_h$ , of 17.6 mm are used, resulting in a clearance of 1.6 mm. Two types of cover plate material are considered: FRP and steel. To change the cover plate stiffness, different thicknesses of cover plates are used: 6, 9 and 12 mm for FRP cover plates, and 3, 4.5, and 6 mm for steel cover plates, which corresponds to stiffness ratios of two cover plates to the main plate of 1.0, 1.5, and 2.0 for FRP cover plates and 7.35, 11.0, and 14.7 for steel cover plates, respectively. A thickness of cover plate larger than 12 mm for FRP or smaller than 3 mm for steel is not realistic from either design or practical aspect. Therefore, a stiffness ratio between 2.0 and 7.35 is not considered. The stiffness ratio can be defined as the ratio of the stiffness of two cover plates to the main plate. The stiffness ratio,  $r_k$ , can be expressed using the following equation:

$$r_k = \frac{2t_c w E_c}{t_m w E_m} = \frac{2k_c}{k_m} \quad (1)$$

where,  $t_c$  = thickness of cover plate,  $t_m$  = thickness of main plate,  $w$  = width of plates,  $E_c$  = modulus of elasticity of cover plate in the loading direction,  $E_m$  = modulus of elasticity of main plate in the loading direction,  $k_c$  = stiffness of each cover plate in the loading direction, and  $k_m$  = stiffness of the main plate in the loading direction.

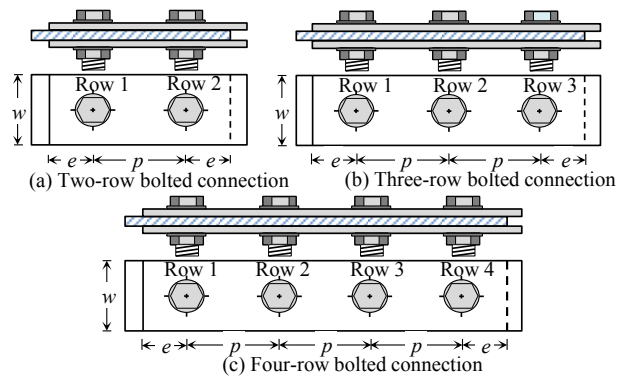


Fig. 2 Geometry of connections.

As geometric parameters of bolted connections, plate width to bolt diameter ratio,  $w/d$ , pitch distance to bolt diameter ratio,  $p/d$ , edge distance to bolt diameter ratio,  $e/d$ , are also examined with the stiffness ratio,  $r_k$ . The geometric parameters are shown in Table 1. Connection type represents a set of geometric parameters, and seven types from Type A to Type G are considered in this study. To designate each connection geometry, a connection ID is used in this study. A connection ID consists of a number of bolt rows, connection type, cover plate material, and cover plate thickness as shown in Fig. 3.

Table 1 Geometric parameters of connections.

| Type  | A   | B   | C   | D   | E   | F   | G   |
|-------|-----|-----|-----|-----|-----|-----|-----|
| $w/d$ | 4.0 | 4.0 | 4.0 | 3.0 | 5.0 | 4.0 | 4.0 |
| $p/d$ | 3.0 | 4.0 | 5.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| $e/d$ | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 1.5 | 2.5 |

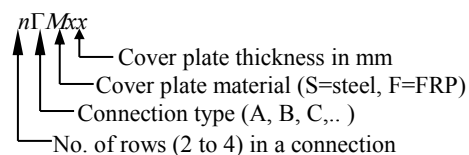


Fig. 3 Definition of connection ID.

### 2.2 Material Properties

For FRP plates, quasi-isotropic glass-fiber laminates are assumed. A thickness of each ply is 0.375 mm, and a stacking sequence is symmetric in each laminate. Material properties

of unidirectional lamina are given in Table 2.

Table 2 Material properties of unidirectional lamina<sup>4)</sup>.

| $E_{11}$ (GPa) | $E_{22}$ (GPa) | $\nu_{12}$ | $G_{12}$ (GPa) |
|----------------|----------------|------------|----------------|
| 32.1           | 5.74           | 0.33       | 1.24           |

To obtain a complete set of material properties, other material properties are determined according to the relations of transverse isotropic materials, i.e.,  $E_{33} = E_{22}$ ,  $G_{13} = G_{12}$ ,  $\nu_{13} = \nu_{12}$ . The following approximations are also considered<sup>12)</sup>:  $G_{23} \approx G_{12} \approx G_{13}$  and  $\nu_{23} \approx \nu_{12} \approx \nu_{13}$ . Material properties of steel for bolt and cover plate are as follows: Young's modulus  $E = 200$  GPa and Poisson's ratio  $\nu = 0.3$ .

### 3 Finite Element Model

In this study, finite element analysis is performed to examine the effect of cover stiffness on load distribution among rows of bolts of multi-row bolted connections. Finite element models of the connections are created using the general purpose finite element software, ABAQUS<sup>13)</sup>.

Due to symmetry conditions, only a quarter of a connection is model. The finite element model and boundary conditions are shown in Fig. 4. At the end of main and cover plates are considered free, whereas at the center of cover plate x-symmetric boundary conditions are defined and a displacement is applied at the continuous edge of the main plate. Three dimensional solid elements are used to model FRP composite plates, steel plates, and steel bolts and washers. Washer and bolt are modelled as a single part. Surface based contact definition is employed where different parts may contact each other. In the contact definition, Coulomb friction model with a frictional coefficient of 0.2 is used. The penalty method is utilized. Finger-tighten torque, that is equivalent to an axial pre-tension force of 500 N is assumed and applied to bolts. In ABAQUS, this force is applied to a cross-section of bolt shank as a prescribed assembly load<sup>13)</sup>. Elastic analysis is performed.

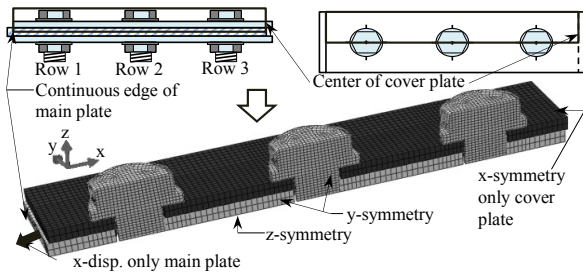


Fig. 4 Finite element model.

### 4 Results and discussion

Load distribution coefficients among the rows of bolts in the connections are evaluated from the analysis results. The

load distribution coefficient for a bolt is defined as the ratio of load transferred by the bolt to the total load transferred by the connection. The load distribution coefficients can be determined by the following equation:

$$C_i = \frac{P_i}{\sum_{i=1}^n P_i}, \text{ for } i = 1, 2, \dots, n \quad (2)$$

where,  $C_i$  = load distribution coefficient of the  $i$ th of row,  $n$  = number of rows in the connection,  $P_i$  = load transferred by the bolt in the  $i$ th row. In Eq. (2), a summation of load transferred by bolts is used as the total load because the load transferred by the friction between the main plate and cover plates are found to be only 1 to 2% of the total load in this study, and the amount of the load transferred by the friction depends on the assumed coefficient of friction, the assumed axial force in bolts, and the total applied load.

Based on the load distribution, efficiency and capacity of the connection are also evaluated.

#### 4.1 Model Validation

The load distribution coefficients for a connection with an FRP cover plate having half the stiffness of an FRP main plate are given in Table 3 for Type B connection, which is set to satisfy the minimum requirements specified by LRFD Pre-Standard. Load distribution coefficients from the present finite element analysis are in very good agreement with previously reported studies<sup>8)-11)</sup>, which validates the finite element model of the present study. The load distribution coefficients are the same as those of EUROCOMP<sup>8)</sup> and close to the others.

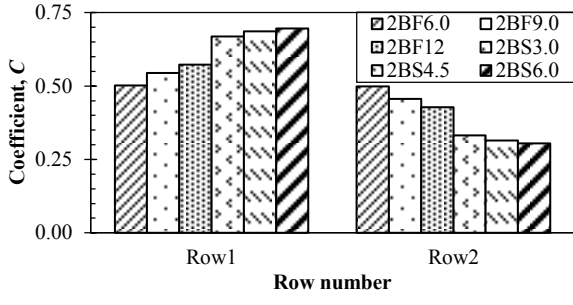
Table 3 Load distribution coefficients of FRP/FRP bolted connection.

| Materials                       | Three rows of connection |       |       |
|---------------------------------|--------------------------|-------|-------|
|                                 | Row 1                    | Row 2 | Row 3 |
| FEA of this study               | 0.37                     | 0.26  | 0.37  |
| Feo et al. <sup>8)</sup>        | 0.36                     | 0.28  | 0.36  |
| LRFD Pre-Standard <sup>9)</sup> | 0.40                     | 0.20  | 0.40  |
| EUROCOMP <sup>10)</sup>         | 0.37                     | 0.26  | 0.37  |
| CNR DT 205/2007 <sup>11)</sup>  | 0.41                     | 0.17  | 0.41  |

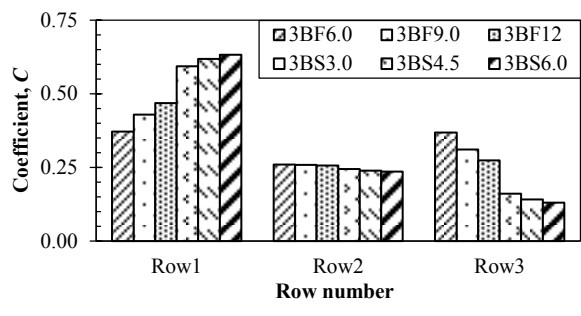
#### 4.2 Load Distribution

The load distribution coefficients among rows of bolts are presented in Fig. 5 for steel and FRP cover plates with different thicknesses for the connection Type B.

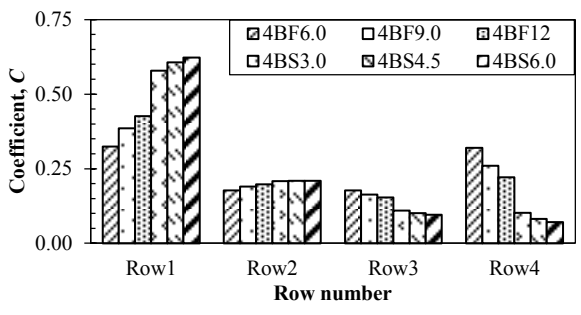
From Fig. 5, it is observed that the load distribution among the rows of bolts depends on the material and thickness of cover plate. Loads distribution coefficients in connections with steel cover plates are very different from those in connections with FRP cover plates, which is caused by the difference in the stiffness of cover plates. When connections with 6 mm cover plates are compared, the load distribution coefficients in the first row (Row 1) of two, three,



(a) Two-row bolted connections



(b) Three-row bolted connections



(c) Four-row bolted connections

Fig. 5 Effect of cover plate on load distribution.

and four-row bolted are 0.50, 0.37, 0.32 for FRP cover plates and 0.69, 0.63, 0.62 for steel cover plates. Therefore, just by changing FRP cover plates to steel cover plates of the same thickness, the load distribution coefficients will be increased by as much as 93% in the four-row bolted connection. It should be noted that capacity of a connection depends on the load distribution coefficient in first row<sup>9</sup>. For steel cover plate, changing thickness of cover plates from 3 mm to 6 mm dot not result in a significant change of load distribution coefficients. On the other hand, a significant change is observed in the load distribution when the thickness of FRP cover plate is changed from 6 mm to 12 mm. The load distribution coefficient in the first row of the two, three, and four-row bolted connections is increased from 0.50 to 0.57, from 0.37 to 0.47, and from 0.32 to 0.43, respectively, by changing the thickness of FRP cover plates from 6 mm to 12 mm for the 12 mm main plate.

Figure 6 shows the trend of the effect of stiffness ratio on load distribution among bolt rows in bolted connections with three rows. It can be observed that the load distribution

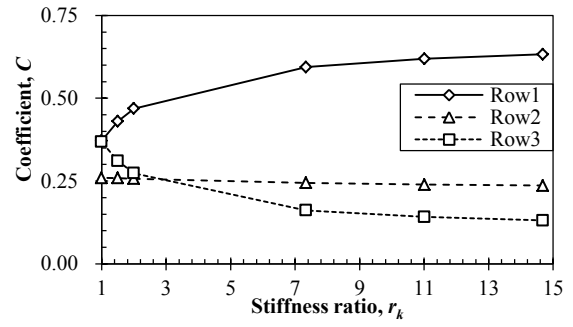


Fig. 6 Effect of stiffness ratio on load distribution for the three-row bolted connections.

coefficients increase in the first row and decrease in the last row (Row 3) with an increase in the cover plate stiffness. For the intermediate row, the load distribution coefficient is not much affected by the stiffness ratio. The rate of change of the load distribution decreases with an increase in the stiffness ratio. Therefore, for the connections with steel cover plates, the load distribution does not change significantly due to different cover plate thicknesses. The same trend is also found in two and four rows cases.

### 4.3 Efficiency and Capacity

Efficiency of a bearing-type multi-row bolted connection for FRP composite structures depends on the load distribution among the rows of bolts. It is partly because FRP composite materials are brittle in nature. The efficiency is defined as the ratio of the sum of load distribution coefficients among bolt rows to the maximum load distribution coefficient in the connection multiplied by the number of rows as expressed in Eq. (3):

$$\eta = \frac{\sum_{i=1}^n C_i}{nC_{\max}}, \text{ for } i = 1, 2, \dots, n \quad (3)$$

where  $\eta$  = efficiency of a connection,  $C_i$  = load distribution coefficient of the  $i$ th row,  $C_{\max}$  = the maximum load distribution coefficient among the rows of bolts, and  $n$  = the number of bolt rows in the connection. Note that the sum of load distribution is equal to unity. Therefore, Eq. (3) can be reduced to

$$\eta = \frac{1}{nC_{\max}} \quad (4)$$

From Eq. (4), it is exhibited that the efficiency of a connection depends on the maximum load distribution coefficient in a connection.

Figure 7 shows the efficiency of Type B connections for varying stiffness ratio of cover plates to the main plate. It is observed that the efficiency of the connections decreases with an increase of the stiffness ratio and also with the number of rows. For the two, three and four-row bolted connections with steel cover plates having a thickness of 6 mm are found to be the lowest efficiency as 0.72, 0.53 and 0.40, respectively. On the other hand, the efficiency of the two, three and four-row

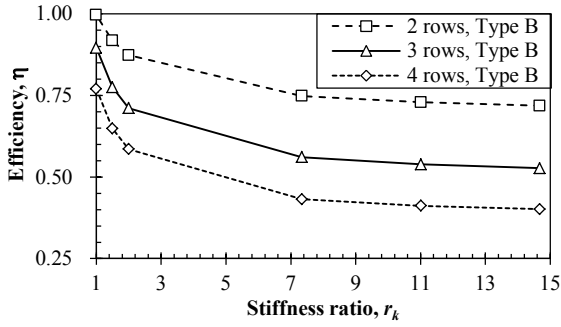
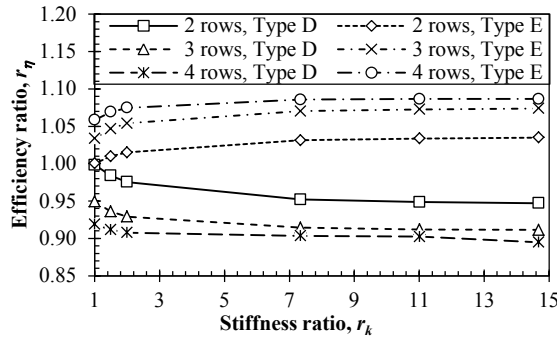
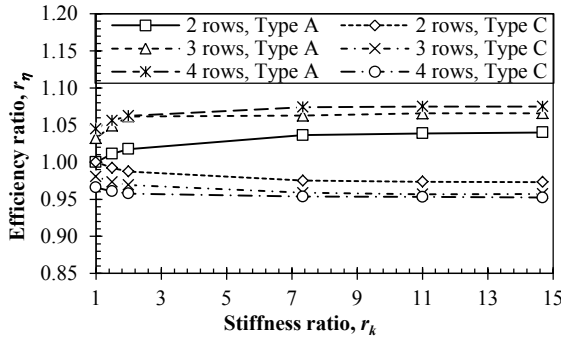


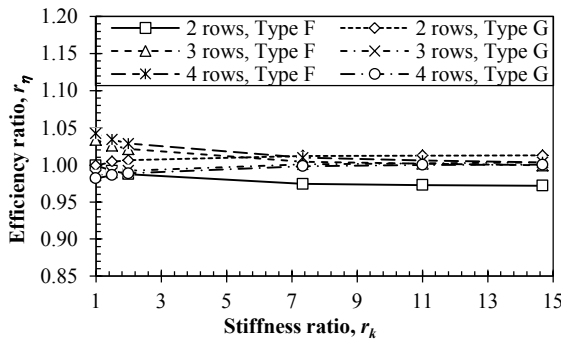
Fig. 7 Effect of stiffness ratio on efficiency.



(a)  $w/d$  ratio



(b)  $p/d$  ratio



(c)  $e/d$  ratio

Fig. 8 Effect of geometric parameters on efficiency.

bolted connections with FRP cover plate that have a half of the main plate thickness are equal to 1.00, 0.90 and 0.77, respectively. Therefore, in terms of efficiency, it is better to make the stiffness of cover plate be the same as that of the main plate.

To examine the effect of different geometry, efficiency is

Table 4 Change of efficiency  $\Delta\eta$  (%) due to the change of geometric parameters.

| Number of rows | $n=2$ |       | $n=3$ |       | $n=4$ |       |     |
|----------------|-------|-------|-------|-------|-------|-------|-----|
|                | FRP   | Steel | FRP   | Steel | FRP   | Steel |     |
| Cover plate    | +1    | 0~2   | 3     | 3~5   | 7     | 6     | 9   |
|                | -1    | 0~-1  | -5    | -5~-7 | -9    | -9    | -11 |
| $\Delta(p/d)$  | +1    | 0~-1  | -3    | -3    | -4    | -4    | -5  |
|                | -1    | 0~2   | 4     | 3~6   | 7     | 4~6   | 7   |

compared among connections with different geometry. Figure 8 shows the relationship between the efficiency ratio and the stiffness ratio for connections with different geometric parameters. The efficiency ratio,  $r_\eta$ , is defined by the following equation:

$$r_\eta = \eta / \eta_{nBMxx} \quad (5)$$

where  $\eta$  = efficiency of a connection,  $\eta_{nBMxx}$  = efficiency of Type B connection with the same number of rows and the same cover plate.

From Fig. 8, it is seen that the efficiency also depends on the geometric parameter of a connection. The efficiency increases with the increasing  $w/d$  ratio or the decreasing  $p/d$  ratio. It means that the efficiency increases with an increase in the connection stiffness, where the connection stiffness can be defined as the ratio of connection load to connection displacement within elastic range. However, the efficiency is not sensitive to changing  $e/d$  ratio. It is also observed that the efficiency does not change significantly with the change of stiffness ratio. The change of efficiency in percentage for increasing a  $w/d$  ratio or a  $p/d$  ratio is given in Table 4.

In this study, the capacity of a connection is defined relative to that of a single bolt connection. It is assumed that the capacity of a multi-row bolted connection is reached when a load on the bolt row that has the maximum load distribution coefficient among rows reaches the capacity of a single bolt connection. Furthermore, a linearly elastic behavior of the connection is assumed. In this case, capacity can be evaluated as the efficiency of a connection multiplied by the number of bolt rows in the connection as shown in Eq. (6):

$$Q = n\eta \quad (6)$$

where  $Q$  = capacity of a connection with respect to a single bolt connection. Therefore, the capacity can be directly evaluated from the efficiency, and they have the same physical meaning. Substituting Eq. (4) into Eq. (6) and with some arrangements, Eq. (6) can be rewritten as:

$$Q = \frac{1}{C_{max}} \quad (7)$$

Figure 9 shows the capacity in relation to the stiffness ratio for Type B connections. It is observed that the capacity of the connections in the range of the low stiffness ratio, i.e., connections with FRP cover plates decreases sharply with the

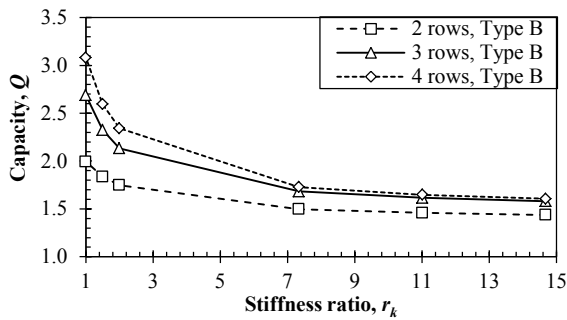


Fig. 9 Effect of stiffness ratio on capacity.

increase of stiffness ratio, whereas the capacity of the connections for the higher stiffness ratio, i.e., those with steel cover plates, does not change with the change of the stiffness ratio. It is also observed that increasing the number of rows, more than three, in a connection with the steel cover plate does not increase its capacity. On the other hand, the number of rows can be increased to increase the capacity of connection with FRP cover plate. The capacity of two, three and four-row bolted connections with FRP cover plates having a thickness of 6 mm are equal to 2.0, 2.69, and 3.08, respectively.

### 5 Conclusions

The following salient conclusions can be drawn based on the findings of the present study.

- (1) In bearing-type multi-row bolted connections of FRP structural members, load distribution coefficients vary with a change of cover plate stiffness. Coefficients of the first and the last rows are affected significantly with the change of cover plate stiffness, while those of intermediate rows are insensitive. However, when the stiffness ratio of cover plates to the main plate becomes greater than 7, load distribution coefficients do not change any more. Therefore, for a connection with steel cover plates, load distribution is insensitive to the cover plate thickness.
- (2) Efficiency of a connection is significantly affected by the cover plate stiffness. The efficiency of two, three and four-row bolted connections with the steel cover plate having a half of main plate thickness are equal to 0.72, 0.53 and 0.40, respectively, whereas the efficiency of two, three and four rows of bolted connections with the same thickness of FRP cover plate are equal to 1.00, 0.90 and 0.77, respectively.
- (3) Capacity of a connection largely depends on the cover plate stiffness. An increase in the number of rows more than three in a connection with steel cover plate does not result in a significant capacity increase.
- (4) Effect of geometric parameters on load distribution is not significant with the change of cover plate stiffness. A change of efficiency is within 10% by increasing or decreasing  $w/d$  or  $p/d$  ratio.

These conclusions were obtained by the numerical analysis of multi-row bolted connections with two to four bolt rows having a main plate thickness 12 mm. How the thickness of the main plate affects these conclusions should be examined by an experimental study.

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