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主 論 文 の 要 旨

論文題目　MECHANICAL BEHAVIOR OF MULTI-ROW BOLTED CONNECTIONS OF WOVEN FABRIC GFRP STRUCTURAL MEMBERS
（平織ガラスクロスを用いた FRP 部材の多列ボルト接合部の力学的挙動に関する研究）

氏　　名　KADER　Mohammad Abdul

論 文 内 容 の 要 旨

Although high strength-to-weight ratio, high stiffness-to-weight ratio, high durability, and corrosion resisting capacity make fiber reinforced polymer (FRP) composite materials extremely attractive to structural engineers, there are some factors that prevent the materials from being widely accepted as a structural material in civil engineering structures, which include a lack of standards and design guidelines, and a lack of experience of designing structures, especially connections, using these materials.

Bearing-type bolted connections are usually used to connect FRP structural members because friction-type bolted connections are difficult to design due to creep of FRP. In a bearing-type multi-row bolted connection, the load does not distribute uniformly among the bolt rows due to the relative displacement of the cover plates to the main plate; therefore, relative stiffness of the cover plates to the main plate is a vital factor of the load distribution. To understand mechanical behavior of a bearing-type multi-row bolted connection of FRP members, experimental and numerical investigations were conducted at Nagoya University. This study is focused on the effect of cover plate stiffness and connection geometry on the load distribution among the bolt rows as well as strength of connections made of woven fabric glass fiber reinforced composite material.

A series of 3D elastic finite element analyses of multi-row bolted connections were performed to determine the effect of cover plate stiffness on the load distribution among the bolt rows. Results showed that the load distribution in bearing-type multi-row bolted connections is significantly affected by the relative stiffness of the cover plate to the main plate. A connection with a higher cover plate stiffness tends to show lower efficiency. For a connection with steel cover plates, to increase the number of bolt rows more than three does not lead to a higher capacity of a connection. The results also indicate that the effect of geometric parameters of a connection on the load distribution is not significant.

In order to evaluate strength of a multi-row bolted connection accurately in a numerical simulation, a progressive damage model of FRP materials was implemented in a commercial finite element analysis software by using a user subroutine. A series of 3D non-linear finite element analyses based on the progressive damage material model were performed to evaluate behavior of multi-row bolted connections after the damage initiation. Based on the results, the effect of cover plate stiffness on the connection strength was examined. Results showed that a connection with FRP cover plates could resist a larger load than a connection with steel cover plates by about 6%, 19%, and 35%, for the two, three, and four-row bolted connections, respectively. In addition, it was found that a multi-row bolted connection with FRP cover plates needs a larger end distance than that with steel cover plates in order to avoid an end shear failure. Although current design codes specify different end distances for single and multi-row bolted connections with FRP cover plates, the same end distance may be required for both single and multi-row bolted connections to avoid the end shear failure.

An experimental program was conducted to understand the behavior of bolted connection. First, a series of material tests were performed to obtain material properties of GFRP laminates with thicknesses of 6, 9, and 12 mm which were used in the connection test. Then, single bolted connections were tested to failure. Three basic failure modes of net-tension, shear, and bearing failures were observed in the single bolted connections. Among the failure modes, only the net-tension failure mode was a catastrophic failure. The connection with bolt axial force that is equivalent to a finger-tight condition had 93% larger bearing strength and 30% larger shear strength than the connection without bolt axial force. The strength decreased by about 26% for the bearing failure and by about 8% for shear failure when the 6-mm steel cover plate was changed to 6-mm GFRP cover plate because cover plates would fail first; therefore, connections with a cover plate thickness half of the main plate may not be appropriate if the bearing failure is a desired mode, and a thicker cover plate may be required. For a single bolted connection with a *w/d* ratio of 4 and *e/d* ratio of 4 showed a bearing failure. Therefore, $w/d = 4$ and $e/d = 4$ are recommended as minimum requirements for the bearing failure.

A series of multi-row bolted connections were tested to failure. Three basic failure modes of net-tension, shear, and bearing failures were also observed in the multi-row bolted connections. The effect of *w/d*, *p/d*, and *e/d* on the ultimate strength of the connection is significant. The strength is linearly increased with *w/d* ratio for the case of net-tension failure, and *p/d* and *e/d* ratios for the case of shear failure. The net-tension failure switches to the bearing failure when the *w/d* ratio is changed from 3 to 6 for the two-row bolted connection and from 5 to 9 for three-row bolted connection. The shear failure switches to the bearing failure when the *p/d* ratio is changed from 3 to 5. The strength is linearly increased with number of bolt rows for the case of bearing failure. The results also showed that ultimate strength is not affected by cover plate stiffness for any failure modes, although the load distribution among the bolt rows is different in the elastic range. A connection with GFRP cover plates having a half of the main plate thickness showed lower ultimate strength than that with a higher stiffness of cover plate, although numerical results showed that the connection with FRP cover plates having a half of the main plate thickness has a more uniform load distribution and can have a larger strength than those with the other cover plates. The difference between the experiment and numerical analysis indicates limitations of the numerical model tha is proposed in this study. One of the limitations is a lack of consideration of the confinement effect in the thickness direction of FRP plates.

The connections that satisfy the minimum requirements of ASCE LRFD Pre-standard failed in either net-tension or shear failure rather than bearing failure. Therefore, the minimum requirement of multi-row bolted connection would be $e/d = 4$, $p/d = 5$, and $w/d = 6$ for two-row and 9 for three-row bolted connection. The ultimate bearing strength is proportional to the number of bolt rows regardless of connection geometries and cover plate types. Therefore, the ultimate bearing strength of a multi-row bolted connection can be evaluated by multiplying the strength of a single bolted connection by the number of bolt rows.

Simple design equations to evaluate strength of a connection for different failure modes were proposed based on the experimental results. It was proved that the proposed formulae could predict the ultimate strength and failure mode of multi-row bolted connections examined in the experimental program with high accuracy.