BOLTED CONNECTIONS FOR FIBRE-REINFORCED COMPOSITE STRUCTURAL MEMBERS

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ABSTRACT

Bolted connections in orthotropic materials, such as fibre-reinforced composites, require much more attention to their design than standard isotropic materials. The use of these materials in civil structural applications is fairly new and there is a lack of sufficient information about the behaviour of bolted connections in fibre-reinforced composite members. The behaviour of connections in these materials is influenced by such factors as high stress concentrations, no yielding capability and reduced strength as the result of severed fibres caused by drilling bolt holes. Since the capacity of a structure is often limited by the capacity of its connections, the understanding of the behaviour of connections, in fibre reinforced composites, is extremely important.

This paper summarizes an experimental program undertaken at the University of Manitoba to examine the behaviour of bolted connections in fibre-reinforced composite structural members. A total of 102 single-bolt double-shear lap joints were tested. The effects of various parameters including the member thickness, the member width to hole diameter ratio, the edge distance to hole diameter ratio, and the fibre orientation with respect to the load are examined.
INTRODUCTION

Connections of structural members are extremely important as they could be the weak link in any structural system. In fibre-reinforced composite members this is especially important, due to the nature of the material. Bolted connections, which are the most practical connection for civil applications, not only sever the reinforcing fibres and thus reduce their overall strength of the composite but also introduce high stress concentrations which promote fracture. This is complicated by the fact that fibre reinforced composites are in general, a brittle material which exhibit no yielding capability.

Most of the current guidelines for the design of bolted connections for fibre-reinforced composite members are based on research conducted for aeronautical and automotive applications. Experimental and theoretical information can be found in many references including (Collings, 1977) and (Kretsis and Matthews, 1985). Very little work has been published related to bolted connections for civil engineering applications.

The experimental program, undertaken at the University of Manitoba, investigates the behaviour of bolted connections for glass fibre reinforced plastic (GFRP) structural materials. Test results and the effects of various parameters on the behaviour of bolted connections are discussed. Experimental results are compared to an analytical model developed at the Royal Military College of Canada.

EXPERIMENTAL PROGRAM

A total of 102 single-bolt double-shear lap joints made of glass fibre reinforced composite material (GFRP) were tested. The various parameters considered in the investigation were the member width to hole diameter ratio \((\text{w/d})\), the edge distance to hole diameter ratio \((\text{e/d})\), the thickness of the members \((\text{t})\) and the direction of the fibres with respect to the load.

The configuration of the single-bolt double-shear connection tested in this investigation is shown in Fig. 1. The two plate double-shear configuration was selected, to subject the composite GFRP members to concentrically applied loading and to eliminate bending effects. The test set-up simplified strain and displacement measurements and allowed direct observation of the various modes of failure. One LVDT device was used on each plate of the connection to measure the relative slip of the joint. In all the tested connections a 19 mm (3/4 in) high strength bolt was used. The hole diameter was 20.6 mm (13/16 in) providing a 1.6 mm (1/16 in) clearance for the bolt. The bolts were tightened by a torque wrench to a constant torque of 32.5 N-m (24 ft-lbs) for all connections.
The members tested were fabricated from EXTREN Flat Sheet/ Series 500, a pultruded glass fibre sheet produced by Morrison Molded Fiber Glass Company (MMFG). Three different thicknesses were used for this investigation, 9.525 mm (3/8 in), 12.7 mm (1/2 in) and 19.05 mm (3/4 in). The composite material is orthotropic, consisting of symmetrically stacked, alternating layers of identically oriented unidirectional E-glass roving and randomly-oriented E-glass continuous strand mat. The matrix consists of polyester plastic.

To determine the material properties, 80 tension tests, 75 compression tests, and 60 shear tests were done according to ASTM standards D638, D695, and D3846 respectively. The tests were done for all three thicknesses and at various angles of the fibres with respect to the loading direction.

**TEST RESULTS AND DISCUSSION**

The measured material properties for the two principal material directions are summarized in Table 1. The coefficients of variation for the tensile strengths at 0 and 90 degrees ranged from 6 to 16%, the tensile moduli from 10 to 20%, the compressive strengths from 4 to 10%, and the shear strengths from 7 to 26%. The results suggest large material variability.

The various modes of failure observed in this investigation are illustrated in Fig. 2. These include three basic modes consisting of net-tension failure shown in Fig. 2a, cleavage failure shown in Fig. 2b, and bearing failure shown in Fig. 2c, as well as two combined modes of failure consisting of bearing-net tension failure shown in Fig. 2d and bearing-cleavage failure shown in Fig. 2e. Net tension failure was characterized by typical fracture through the net section. Cleavage failure was characterized by a crack parallel to the applied load propagating from the end of the plate towards the bolt hole leading to the initiation of other cracks near the net section due to the formation of in plane bending stresses. Bearing failure was characterized by crushing of the material in the vicinity of the bolt-to-hole interface. The two combined modes were a combination of the various basic modes.

Typical load-displacement relationships for the three basic modes of failure are shown in Fig. 3. The displacement is the average of the two LVDT readings on each side of the connection and the load is the resistance of the two plates combined. The behaviour indicated that for the bolt torque used there was little friction resistance, since slipping of the connections occurred at the initial loading stage. Once the bolt slipped into bearing all the connections behaved linearly. Fig. 3 illustrates that for the connections that failed in a sudden manner such as in net-tension or cleavage, there was a considerable drop in load carrying capacity as each plate in the connection failed. Although this sudden drop in the load occurred in fractions of a second, it was confirmed by recording the load and displacement on a storage oscilloscope at a rate...
of 16,000 samples per second. For connections that failed in bearing, the load reduction occurred gradually as the bolt pulled through the composite plates and the overall behaviour was much more ductile than the other modes of failure.

The influence of fibre orientation on the modes of failure is shown in Fig. 4 for connections of the same dimensions. Due to the reinforcing nature of the member, in the transverse direction, with the unidirectional fibres at 45 and 90 degrees to the applied load, the typical cleavage failure which occurred in the "0 degree" connections, was suppressed for "45" and "90 degree" connections.

The effects of the member edge distance to hole diameter ratio (e/d) and the width to hole diameter ratio (w/d) for the three thicknesses used are given in Fig. 5 and 6 respectively. In these figures the bearing stress is computed as the measured ultimate load of the connection acting on the bearing area of the members. The bearing area is the product of the bolt diameter and the total thickness of the two GFRP members comprising the connection. Fig. 5 illustrates that by increasing the (e/d) ratio up to a value of 5, there is an increase in bearing stress and hence strength of the connection. Beyond an (e/d) ratio of 5 there is no increase in bearing stress and consequently no increase in connection strength. Fig. 6 indicates that there is no or little increase in strength past an (w/d) ratio of 5 as well.

For the three thicknesses considered in this study, Fig. 5 and 6 indicate that the thickness seemed to have little effect on the overall behaviour of the connection.

The net stress, based on the average applied stress across the net section, was examined as a function of the member width to edge distance ratio (w/e). Fig. 7 illustrates that the wider connections had lower net stresses than the narrow connections. These results indicate that wider sections are not as efficient as narrow ones. This could be attributed to the fact that most of the load is resisted by material within the vicinity of the hole as a result of the presence of high stress concentrations as shown in Fig. 8 for connections of three different widths. The stress concentration factor is equivalent to the ratio of the measured strain at the bolt hole to the strain of the member measured at the gross section away from the hole.

The effect of the angle of the unidirectional fibre layers with respect to the loading direction is shown in Fig. 9. The behaviour indicates that the strength of the connections is reduced as the angle of the fibres changes from 0 to 90 degrees.

ANALYTICAL MODEL

The load-displacement behaviour of the connections tested was predicted using a FEM model for bolted composite connections introduced by (Erki and Dutta, 1990). The two-part computer model combines the results of two-dimensional analyses, one
in the plane of the composite member and the second through the thickness of the joint. The model accounts for through-thickness effects and the fastener to plate contact problem. Using the Tsai-Wu quadratic polynomial failure criterion the model is able to predict the stiffness of the connections for the various failure modes quite well. The comparison of the model's results to the experimental load-displacement curves for connections that failed in net-tension, bearing-net tension, and cleavage are shown in the Fig. 10, 11 and 12 respectively.

SUMMARY AND CONCLUSION

Based on the results of this investigation the following conclusions were made:

1. Slipping resistance of the bolted connections was negligible at the level of bolt torque used.

2. Increasing the member thickness increased the load capacity of the connection, however the member thickness has insignificant effect on the bearing stresses and mode of failure of the connection.

3. Member width to hole diameter \((w/d)\) and edge distance to hole diameter \((e/d)\) ratios have a significant effect on the mode of failure. Increasing the values of \((w/d)\) and \((e/d)\) increases the connection strength up to a limiting value of 5.

4. In general the load capacity of the connection was increased by increasing width. However the efficiency of the connection was reduced as a result of the large stress concentrations at the bolt hole which could reach a value as high as 5 or 6.

5. Changing the angle of the fibres with respect to the applied load from 0 to 90 degrees reduces the strength of the connection.

6. The proposed analytical FEM model is capable of predicting the behaviour of connections with different modes of failure.

REFERENCES

Figure 1 Test Set-up

Table 1  Material Properties

<table>
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<tr>
<th>Thickness (mm)</th>
<th>Fibre Angle (deg.)</th>
<th>Tensile Modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Tensile Strength (MPa)</th>
<th>Comp. Strength (MPa)</th>
<th>Shear Strength (MPa)</th>
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Shear Modulus = 4.3 GPa
Major Poisson's Ratio = 0.29
Figure 2  Failure Modes
Figure 5 Bearing Stress vs. (e/d)

Figure 6 Bearing Stress vs. (w/d)

Figure 7 Net Stress vs. (w/e)

Figure 8 Strain Concentration Factors
Figure 3  Typical Load-Displacement Curves

Figure 4  Effect of Fibre Orientation on Failure Mode
Figure 9 Effect of Fibre Orientation

Figure 10 Analytical Model (NT-Failure)

Figure 11 Analytical Model (B-NT Failure)

Figure 12 Analytical Model (C-Failure)