DESIGN OF BOLTED CONNECTIONS FOR ORTHOTROPIC FIBRE-REINFORCED COMPOSITE STRUCTURAL MEMBERS

Charles N. Rosner and Sami H. Rizkalla
Structural Engineering and Construction Research and Development Centre, University of Manitoba
Winnipeg, Manitoba R3T 2N2 CANADA

ABSTRACT

The use of orthotropic materials such as fibre-reinforced composites in civil structural applications is fairly new and there is a serious lack of information about the behaviour and design of the bolted connections normally used for structural members. In light of this, a comprehensive experimental and analytical investigation was conducted at the University of Manitoba to study and to determine the behaviour of bolted connections in composite materials used for civil engineering applications. Based on the research findings a design procedure is introduced which accounts for material orthotropy, pseudo-yielding capability, and other factors that influence bolted connection behaviour. The proposed model is capable of predicting the ultimate capacity and the mode of failure of the connections. Because of the generic nature of the model, the design guidelines can be applied to a multitude of composite material systems. Due to the model’s simplicity, the proposed design procedure is ideal for implementation in design codes.
INTRODUCTION

The high strength-to-weight ratio of fibre-reinforced composite materials makes them extremely attractive as a building material to the civil engineer. Although much research has been conducted on the behaviour of this material for the aeronautical and automotive industries, there has been very little research conducted for the civil engineering field, especially in the area of bolted connections. Bolted connections, which are the most practical connection for civil applications, not only sever the reinforcing fibres and thus reduce the overall strength of the composite, but also introduce high stress concentrations which promote fracture. This is complicated by the fact that the behaviour of fibre-reinforced composites lies somewhere between that of perfectly elastic behaviour and fully plastic behaviour and therefore cannot be characterized by either.

A comprehensive experimental and analytical investigation was conducted at the University of Manitoba to study and to determine the behaviour of bolted connections in composite materials for civil engineering applications. Based on the research findings, a design procedure was developed. The proposed methodology is capable of predicting the ultimate capacity and failure mode of single-bolt double-shear connections.

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 (w/d), the edge distance to hole diameter ratio (e/d), the thickness of the members (t) and the direction of the fibres with respect to the applied load as given in Table 1.

The configuration of the single-bolt double-shear connection tested in this investigation is shown in Fig. 1 with the basic geometric parameters given in Fig. 2. 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. A 19 mm (3/4 in) high strength bolt was used in all the tested connections. A hole diameter of 20.6 mm (13/16 in) provided a 1.6 mm (1/16 in) clearance for the bolt in all connections. 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 in a polyester matrix.

To determine the material properties, 80 tension tests, 75 compression tests, and 60 shear tests were tested according to ASTM standards D638, D695, and D3846 respectively. The tests were conducted 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 principal material directions are summarized in Table 2. The given coefficients of variation reflect the large material variability.

The various modes of failure observed in this investigation are illustrated in Fig. 3. These consisted of three basic modes including net-tension failure as shown in Fig. 3a, cleavage failure as shown in Fig. 3b, and bearing failure as shown in Fig. 3c. Two
combined modes of failure were also observed: bearing-net tension failure as shown in Fig. 3d and bearing-cleavage failure as shown in Fig. 3e. 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. 4. The displacement is the average of two LVDT readings, one on each side of the connection, and the load is the resistance of the two plates combined. The behaviour indicated that there was little friction resistance for the specified applied torque, since slipping of the connections occurred at the initial loading stage. Once the bolt slipped into bearing all the connections behaved linearly. Fig. 4 illustrates that for the connections that failed in a sudden manner such as in the case of net-tension or cleavage, there was a considerable drop in load carrying capacity as each plate in the connection failed. The sudden drop in the load occurred in fractions of a second as was confirmed by the load and displacement response recorded by 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. 5 for connections of the same dimensions. Due to the presence of the unidirectional fibres at 45 and 90 degrees to the applied load, the typical cleavage failure that had occurred in the connections with the fibres at 0 degrees to the applied load, was suppressed for the corresponding connections that had the fibres at 45 and 90 degrees to the applied load.

PROPOSED DESIGN PROCEDURE

The proposed design procedure is semi-empirical and semi-analytical, using a modified version of the theory presented by (Hart-Smith, 1978) which accounts for the elastic stress concentrations at a loaded bolt hole in brittle isotropic materials. The correlation factors for the three fibre directions used in this investigation were evaluated based on the experimental results. The correlation factors account for the composite’s orthotropy, pseudo-yielding capability, and other factors which influence bolted connection behaviour. Since the basis of the theory is for elastic isotropic materials, the theory could be applied to many material systems using limited test data to determine the corresponding correlation factor for the specific composite material.

The proposed design procedure provides an overall failure envelope. The envelope includes criteria for net tension failure and bearing/cleavage failure. For a given geometrical configuration of a connection, the envelope is capable of predicting the ultimate strength and the mode of failure.

Net Tension Failure

The maximum stress adjacent to a bolt hole along a net section of a plate, \( \sigma_{\text{max}} \), for a given applied load, \( P \), perpendicular to the net section can be determined as follows:

\[
\sigma_{\text{max}} = k_2 \frac{P}{t(w-d)}
\]  (1)
where $t$, $w$, and $d$ are the thickness, width, and hole diameter of the connection respectively, as shown in Fig. 2. The elastic tensile stress concentration factor $k_e$ could be estimated using the expression proposed by Hart-Smith for an isotropic, perfectly elastic material as follows:

$$k_e = 2 + (w/d - 1) - 1.5 \left( \frac{(w/d - 1)}{(w/d + 1)} \right)$$  \hspace{1cm} (2)

where, $\theta$ is a non-dimensional factor and is a function of the edge distance to width ratio $(e/w)$ and is given by:

$$\theta = 1.5 - \frac{0.5}{e/w}$$  \hspace{1cm} (3)

It should be noted that the $\theta$ expression is a modified version of the one presented by Hart-Smith to include practical values of the $(e/w)$ range.

It should be reiterated that the stress concentration factor given in Eq.(2) is for isotropic elastic materials and not fibre-reinforced composites which exhibit different behaviour. To correlate the two materials, it has been reasonably shown that the stress concentrations in isotropic elastic materials $k_e$ and those in fibre composites $k_c$ could be linearly related and could be expressed by the following equation (Hart-Smith, 1978):

$$(k_c - 1) = C(k_e - 1)$$  \hspace{1cm} (4)

where:

$$k_c = \frac{F_u}{P_{ult}} \left( \frac{w-d}{P_{ult}} \right)$$  \hspace{1cm} (5)

The correlation factor $C$ can be determined via a regression analysis of a limited number of experimental observations and thus can be easily determined for any given composite material system with a certain fibre direction. The correlation factor accounts for the composite's orthotropy, pseudo-yielding capability, clearance effects, and other factors which affect bolted connection behaviour. This linear relationship is valid only for the net tension mode of failure and therefore experimental results for connections that failed in net tension should be used only. In Eq.(5) $F_u$ is the ultimate tensile strength of the composite material in the loaded direction and $P_{ult}$ is the ultimate load.

Through algebraic manipulation of Eq.(1), (2), and (4), the expression for the ultimate load of a single bolted composite material connection that fails in net tension is:

$$P_{ult} = \frac{t w F_u}{C(k_e - 1) + 1} \left( 1 - \frac{d}{w} \right)$$  \hspace{1cm} (6)

Given the correlation factor "C" and the properties of a composite material, the design engineer can predict the ultimate "net tension failure" load of a single bolt connection, of any geometry, using Eq.(6). The above equation can be used to produce a family of failure envelopes and is shown in Fig. 6 in terms of the connection efficiency $(P_{ult}/(t w F_u))$ and the ratio $(d/w)$. Each envelope given in Fig. 6 is given for a constant $(e/d)$ value. Included in Fig. 6 is the experimental data for the 0-degree-fibre-angle connections that failed in net tension with $C=0.33$. As can be seen, the failure envelopes predict the test results extremely well. Reported data (Rosner, et al., 1992) indicated that connection strengths increased with increasing edge-distance up to a maximum value of $(e/d)=5$. Therefore, the failure envelope corresponding to $(e/d)=5$ is set as the outermost failure envelope.
Bearing/Cleavage Failure

As the (d/w) ratio becomes small, net tension failure is normally preceded by bearing failure for connections with large edge distances and by cleavage or shearout failure for connections with small edge distances. It was found in this investigation that cleavage failure is related to pure bearing failure by a simple quadratic expression in terms of the ratio (d/2e), (Rosner, 1992). This finding was used to introduce an expression for the ultimate load of a connection that fails in bearing or cleavage as follows:

\[
P_{br} = \frac{F_{br}}{F_{tu}} \frac{d_{bol}}{d} \left( \frac{10}{9} - \frac{5}{9} \frac{d}{e} \right)^2 \frac{d}{w}
\]

where \(F_{br}\) is the ultimate bearing strength of the fibre composite material and \(d_{bol}\) is the diameter of the bolt. Eq.(7) was used to produce a family of non-dimensional failure envelopes in terms of the ratio (d/w) and the structural efficiency \((P_{tu}/(t \cdot F_{tu}))\), as shown in Fig. 7. The various envelopes are given for a constant (e/d) ratio.

The average bearing strength of the material was determined to be 1.9 times the ultimate tensile strength for the material used in the experimental program. Using a value of \(F_{br}=1.9 \cdot F_{tu}\), Eq.(7) was used to predict the behaviour of all the 0-degree-fibre-angle connections that failed in bearing or cleavage as given in Fig. 7. The experimental data including the cases of cleavage failure are in excellent agreement with the proposed model.

In this investigation it was found that connections with (e/d)~5 failed predominantly in bearing. Therefore as a limiting case when (e/d) approaches 5, the squared term in Eq.(7) becomes unity and the expression reduces to one characterizing pure bearing failure. Therefore the expression for pure bearing, accounting for the difference in bolt and hole diameters, is simply the product of the ratio of the material's bearing strength to tensile strength and the ratio (d/w). Test results also indicated that for (e/d)<5 the mode of failure was predominantly cleavage.

The shearout mode of failure was not observed in this experimental investigation due to the presence of a high volume of random fibres in the material used. However, since shearout and cleavage can be considered types of bearing failures with inadequate edge distances, it is reasonable to assume that the behaviour for cleavage failure discussed here could be applicable to shearout failure which would occur in other composite materials.

Design Procedure

Using the failure envelopes of the two failure criteria described above, one family of design envelopes were developed as shown in Fig. 8. For a given geometrical configuration, material properties, and correlation coefficient, the proposed overall failure envelope can be used to determine the ultimate load and the mode of failure of a connection.

Using the proposed design procedure, the predicted and experimental ultimate loads for all the 0-degree-fibre-angle connections tested in this investigation are given in Fig. 9. The comparison indicates that most of the data fall close to the 1:1 correspondence line or are on the conservative side.

It should be noted that the correlation coefficient is not only dependent on the material system used but also on the angle of the principal material directions. Obviously connections that were tested with the principal fibre direction at 45 and 90 degrees to the applied load had lower ultimate loads than their "0 degree" counterparts. However, due to even lower values of \(F_{tu}\) in these directions their efficiencies were actually higher than their "0 degree" counterparts. This means that the failure envelopes for the "0 degree" case can be used to predict conservatively the loads of angled-fibre cases.

Practical Application

Given a connection with the dimensions \(w=130\) mm, \(e=40\) mm, \(t=12\) mm, \(d=21\) mm, \(d_{bol}=19\) mm and the material property \(F_{tu}=166\) MPa, the structural efficiency can be determined from the envelopes in Fig. 8 for (d/w)=0.16 and (e/d)=2 and is equal to 0.185.
Consequently the ultimate load $P_{ue}=\text{Efficiency} \cdot w \cdot F'_{u}$ is equal to 47.9 kN. Since the failure is located within the straight line portion of the envelope, the failure is a bearing or cleavage failure. In this case the failure is cleavage, since $(e/d)<5$. If a similar connection is used except with $w=40$ mm and thus $(d/w)=0.53$, the efficiency is found to be 0.32 and hence the ultimate load is 25.5 kN with the governing mode of failure being net tension. These results can also be achieved mathematically using Eq.(6) and Eq.(7) with a correlation factor of $C=0.33$ and $F_{b}^{'}=1.9 F_{b}$ as determined experimentally for this type of material.

CONCLUSIONS

The proposed design procedure predicts the ultimate load and failure mode of the tested connections with an adequate degree of accuracy. Because the procedure is based on isotropic theory and uses empirical data to correlate the failure criteria it could be used for a variety of different composite material systems.

The correlation coefficient which relates the isotropic theory to composite materials accounts for material orthotropy, pseudo-yielding capability, hole size and clearance effects. In some respects the coefficient can be thought of as a "catch all" factor accounting for all those effects which complicate the stress analysis of a loaded bolt-hole. It is therefore reasonable to expect that as the material systems and connection configurations used by civil engineers become more standardized, a data base of test results could be developed to allow the design engineer to "pick and choose" the appropriate "C" value from a design code without ever doing a single test.

Considering the versatility and simplicity of this design procedure it is ideal for implementation in future design codes.

REFERENCES


Table 1 Experimental Parameters

<table>
<thead>
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<th>Parameter</th>
<th>Dimensions:</th>
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<tr>
<td>Thickness &quot;t&quot; (mm)</td>
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<td>Width &quot;w&quot; (mm)</td>
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<td>Edge Distance &quot;e&quot; (mm)</td>
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<tr>
<td>Fibre Angle (deg.)</td>
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Table 2  Material Properties

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Fibre Angle (deg.)</th>
<th>Tensile Modulus (GPa)</th>
<th>Elongation (%)</th>
<th>Tensile Strength (MPa)</th>
<th>Compressive Strength (MPa)</th>
<th>Shear Strength (MPa)</th>
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<td></td>
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</tr>
</tbody>
</table>

Coefficient of Variation: 5.3 to 3.8 to 5.3 to 4.0 to 7.4 to
for each Property: 16.4% 14.0% 16.4% 9.7% 26.1%

Shear Modulus = 4.3 GPa
Major Poisson's Ratio = 0.29

Figure 1 Test Set-up
Figure 2  Connection Parameters

Figure 3  Failure Modes
Figure 4  Typical Load-Displacement Curves

Figure 5  Effect of Fibre Orientation on Failure