BOLED CONNECTIONS FOR FIBER-REINFORCED COMPOSITE STRUCTURAL MEMBERS: ANALYTICAL MODEL AND DESIGN RECOMMENDATIONS

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\textbf{ABSTRACT:} The use of fiber-reinforced composite materials in civil structural applications is relatively new and there is a serious lack of information on the behavior and design of the bolted connections normally used for structural members. As a result, a comprehensive experimental and analytical investigation was conducted at the University of Manitoba to study the behavior of bolted connections in composite materials used for civil engineering applications. Based on the research findings and observed behavior, a design procedure is introduced, which accounts for material orthotropy, pseudoyielding capability, and other factors that influence bolted-connection behavior. 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.

\textbf{INTRODUCTION}

The high strength-to-weight ratio of fiber-reinforced composites makes them extremely attractive structural materials to the civil engineer. Although much research has been conducted on the behavior of advanced composite materials for the aeronautical and automotive industries, there is very little research in the civil engineering field, especially in the area of bolted connections.

The design of bolted connections with fiber-reinforced composites is much more complex than with standard structural materials such as steel. Bolted connections, which are the most practical connection for civil applications, not only sever the reinforcing fibers and reduce the overall strength of the composite, but also introduce high stress concentrations, which promote fracture. This is complicated by the behavior of fiber-reinforced composites lying somewhere between perfectly elastic and fully plastic behavior and, therefore, not being characterized by either.

A comprehensive experimental and analytical investigation was conducted at the University of Manitoba to study and determine the behavior of bolted connections with 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 fabricated from fiber-reinforced composite materials.

\textbf{EXPERIMENTAL OBSERVATIONS AND ANALYSIS}

The behavior of bolted joints is highly dependent on the geometric dimensions of the connection. The experimental investigation to study the behavior of single-bolted connections including test results, modes of failure, and failure mechanisms is included in a companion paper (Rosner and Rizkalla 1995). In this investigation three basic failure modes consisting of net-tension, cleavage, and bearing failure were observed for the different geometric dimensions considered in the experimental program (Rosner 1992). Test results indicated that the net-tension and cleavage-failure modes were characterized by sudden crack propagation and, thus, the failure was catastrophic in nature. The bearing-failure mode, on the other hand, had a much more ductile behavior. Some of the important observations and conclusions derived from the experimental program are summarized as follows:

1. The ultimate load capacity of a single-bolt connection increased by increasing the geometric dimensions of the member. However, increasing the width-to-hole-diameter ratio (w/d) beyond five or the edge-distance-to-hole-diameter ratio (e/d) beyond five had an insignificant effect on the ultimate load capacity of the connection.

2. The mode of failure was determined by the geometric dimensions of the connection. Connections that had a small width tended to fail in tension, regardless of the size of the edge distance. Wider connections tended to fail in bearing when the edge distances were relatively large. Cleavage failure occurred for wide connections with relatively small edge distances.

3. The material is relatively brittle under static loading, as is evident by the catastrophic cracking during a net-tension or cleavage-type failure. However, due to local bearing stresses some noncatastrophic cracking and stress redistribution were observed around the bolt hole prior to complete failure. This suggests the material has the ability to redistribute stresses and is not perfectly elastic.

4. The measured stress concentrations at the bolt hole were found to be as high as five to six times the nominal stress. The predominate geometric parameter that affected the stress concentrations and efficiency of the joint was the width of the connection.

5. The ultimate load of a connection tended to decrease as the orientation of the unidirectional fibers was varied from 0° to 90° with respect to the applied load. The measured material strength also decreased as the fiber orientation was varied from 0° to 90°. However, the decrease in the material strength was more significant than the decrease in the ultimate load of a connection with a corresponding fiber orientation. This suggests that there are certain mechanisms that allow redistribution of the stresses to produce a higher ultimate load than would be predicted using only the ratios of the tensile strengths in the appropriate fiber orientations.

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ANALYTICAL MODEL

Background

The proposed analytical model describes the behavior of double-shear single-bolted connections in a fiber-reinforced composite material in terms of the ultimate load capacity and mode of failure. The model is semiempirical and consists of two basic failure criteria, which account for the various modes of failure.

The first criterion predicts the ultimate load capacity of a connection that fails by the net-tension-failure mode. Prediction of the ultimate tensile strength is based on a modified version of the theory presented by Hart-Smith (1978). The theory accounts for the elastic stress concentrations at a loaded hole in an isotropic elastic material. For a fiber-reinforced composite material, Hart-Smith (1978) introduced a correlation coefficient that can be derived from experimental tests. This correlation coefficient relates the elastic stress concentration, which occurs in an isotropic elastic material, to the stress concentration that occurs in a fiber-reinforced composite material for a connection of the same geometry. The correlation coefficient accounts for the composite's orthotropy, pseudoyielding capability, heterogeneity, and other factors that influence the behavior of a bolted connection. Since the theory is generally based on elastic isotropic materials, it can be applied to many composite-material systems using only limited test data. Once the correlation coefficient for a specific material system is established, the ultimate net-tension load can be predicted for any geometry.

The second criterion used in the model describes the bearing-failure mode of a bolted connection. Prediction of the ultimate bearing capacity of a connection is based on the bearing strength of the material, which can be determined from experimental results. In the proposed model, cleavage failure is treated as a special type of bearing failure with an inadequate edge distance.

Structural Efficiency of Connection

The structural efficiency, $\Phi$, of a bolted connection can be defined as

$$\Phi = \frac{P_{ul}}{t \cdot w \cdot F_{ut}}$$

where $P_{ul}$ = ultimate load of the connection; $t$ = member thickness; $w$ = member width, as shown in Fig. 1; and $F_{ut}$ is the unnotched tensile strength of the material. Because of the hole, the ultimate strength of a member in a bolted connection will obviously be less than that of a similar member without a hole and, therefore, the range of the efficiency will always be between 0 and 1.

Net-Tension-Failure Criterion

The maximum stress, $\sigma_{max}$, adjacent to a bolt hole along a net section of a member subjected to an applied load, $P$, perpendicular to the net section, can be determined as follows:

$$\sigma_{max} = k_u \frac{P}{t(w - d)}$$

where $d$ = hole diameter of the connection as shown in Fig. 1. The elastic stress concentration factor $k_u$ corresponds to the maximum stress adjacent to the hole.

The elastic stress concentration factor $k_u$ for an isotropic, perfectly elastic material can be determined as follows (Hart-Smith 1978):

$$k_u = 2 + \frac{w(d - 1)}{w(d + 1)} \left( \frac{w(d - 1)}{w(d + 1)} \right)^{\theta}$$

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

$$\theta = 1.5 - \frac{0.5}{e/w}$$

for $e/w \leq 1$; $\theta = 1$, for $e/w \geq 1$ \((4a,b)\)

Eqs. (3) and (4) were developed based on experimental data and theoretical deductions from several sources, as described in detail by Hart-Smith (1978). Eqs. (3) and (4) were derived so as to produce a monotonic function in terms of the hole-diameter-to-width ratio ($d/w$) and edge-distance-to-width ratio ($e/w$).

The connection test results suggest that the limiting value of $\theta = 1$ when $e/w \geq 1$ may not be valid for the material used in this investigation. This is evident from the observation that the ultimate average net stress of the connections tended to increase with an increasing $e/w$ ratio, even past the value of $e/w = 1$ as shown in Fig. 2. Therefore, (4) as originally proposed by Hart-Smith (1978), was modified for the proposed model to a single function of $e/w$, as follows:

$$\theta = 1.5 - \frac{0.5}{e/w}$$

for $0 \leq e/w$ \(5\)

For a perfectly elastic material, when the maximum induced stress $\sigma_{max}$ reaches the tensile strength of the material $F_{ut}$, net-tension failure occurs as the crack catastrophically propagates through the net section. The failure mode in this case is brittle and sudden. Therefore, by rearranging (2) and replacing the maximum stress $\sigma_{max}$ by the ultimate tensile strength of the elastic material $F_{ut}$, the ultimate load of the connection can be determined as follows:

$$P = \frac{F_{ut}}{k_u} \cdot t \cdot (w - d)$$

From (1) and (6), the efficiency of the connection can be shown to be

FIG. 1. Connection Parameters

FIG. 2. Effect of $e/w$ on Net Stress

JOURNAL OF MATERIALS IN CIVIL ENGINEERING / NOVEMBER 1995 / 233
\[ \Phi = \frac{1}{k_w} (1 - d/w) \]  
(7)

For a perfectly plastic material, where the material can yield extensively before failure, the stress concentration factor \( k_w \) could eventually reach unity and (7) will be reduced to

\[ \Phi = (1 - d/w) \]  
(8)

Eq. (7) (perfectly elastic material) and (8) (perfectly plastic material) are presented in Fig. 3 in terms of the ratio \( d/w \) and for a constant value of \( e/w = 1 \).

In Fig. 3 as \( d/w \) approaches 1, the member width approaches the size of the hole diameter and, therefore, the efficiency of the connections will certainly approach zero for both elastic and plastic materials. By increasing the member width with respect to the hole diameter, which means decreasing the \( d/w \) ratio, the efficiencies increase for both types of materials. For a perfectly plastic material, which can yield extensively before failure, the stresses will be uniform at the net section as shown in Fig. 4(a). In this case the stress concentration factor \( k_w \) is unity and the efficiency will approach one as the \( d/w \) ratio approaches zero, as shown in Fig. 3. For a perfectly elastic material, the stress concentration factor at the bolt hole \( k_w \), as described by (7), will approach infinity, as shown in Fig. 4(b). Therefore, for a perfectly elastic material, the efficiency will reach a maximum and then approach zero as the \( d/w \) ratio approaches zero. The maximum efficiency that could be achieved for a perfectly elastic material connection is 0.21 at \( d/w = 0.4 \), as reported by Hart-Smith (1978).

Fiber-reinforced composite does not have the yielding capability of a ductile metal and, therefore, does not behave like a perfectly plastic material. However, since composite materials still exhibit some stress concentration relief in the form of matrix cracking, fiber-matrix debonding, fiber breakage, and fiber pullout, they do not behave like a perfectly elastic material either. Therefore, the behavior of bolted connections in fiber-reinforced composite materials is neither fully plastic nor fully elastic but somewhere in between, as shown in Fig. 3.

Since bolted connections in fiber-reinforced composites exhibit some stress redistribution before ultimate failure the stress concentration factor \( k_w \), for isotropic perfectly elastic materials, is too high for fiber-reinforced composites and, therefore, it predicts an efficiency that is too low. To correlate the two materials, it is reasonably shown that the stress concentration factors in isotropic elastic materials, \( k_w \), and in fiber-reinforced composites, \( k_w \), are linearly related. The relationship can be expressed in terms of a correlation coefficient \( C \), in the following equation by Hart-Smith (1978):

\[ (k_w - 1) = C(k_w - 1) \]  
(9)

where \( k_w = \frac{F_{w}}{P_{ult}} \).

The term \( k_w \) = average stress concentration factor observed at failure of a bolted connection using composite material members; and \( k_w \) = corresponding elastic stress concentration factor of a connection with the same geometry using a perfectly elastic isotropic material. Based on (9) and (10), the correlation coefficient \( C \) can be determined for any fiber-reinforced composite material using a limited number of experimental tests. The correlation coefficient accounts for the composite's orthotropy, pseudo-yielding capability, and other factors that affect the behavior of bolted connections. The linear relationship in (9) is valid only for the net-tension mode of failure, and only experimental results for connections that failed in net tension were used to determine the correlation coefficient.

The correlation coefficient will vary from one composite material to the next, and is also a function of the fiber orientation with respect to the applied load. In this investigation, connections were tested with the applied load at 0°, 45°, and 90° to the unidirectional fiber layers (Rosner 1992). A least-squares regression analysis was used to determine the correlation coefficient from the measured results as shown for the connections with a 0° fiber orientation in Fig. 5. For this analysis, values of the composite stress concentration factor \( k_w \) were determined using (10) and the values of \( k_w \) were based on (3) for the same connection geometry. In Fig. 5, the correlation coefficient \( C \) represents the slope of the best-fit straight line. Due to the nature of (9), the best-fit curve is constrained by the point (1,1). The correlation coefficients for the fiber orientations of 0°, 45°, and 90° were found to be 0.33, 0.21, and 0.25, respectively, for EXTREN Flat Sheet/Series 500 [the material used in this investigation (Rosner]
The standard errors of the correlation coefficients as determined from the regression analysis were 0.0153, 0.096, and 0.0307, respectively.

Using the stress concentration factor $k_w$ and (7), the efficiency of a single-bolted connection in a fiber-reinforced composite can be expressed as

$$\Phi = \frac{1}{k_w} (1 - d/w)$$

Eq. (11) can be expressed in terms of $C$ and $k_w$ as

$$\Phi = \frac{1}{C(k_w - 1) + 1} (1 - d/w)$$

Consequently, the ultimate load of a single-bolted connection in a composite material can be determined using (1) as follows:

$$P_{ub} = \Phi(t \cdot w \cdot F_{ub})$$

Therefore, for a given correlation coefficient and tensile strength of the material, the design engineer can predict the ultimate net-tension-failure load of a single-bolt connection of any geometry, using (13).

Eq. (12) was used to produce a family of failure envelopes in terms of the connection’s efficiency and the ratio $(d/w)$, as shown in Fig. 6, for connections with a fiber orientation of $0^\circ$. Each envelope in Fig. 6 is given for a constant $e/d$ ratio. The failure envelopes follow the trend of the test results extremely well. The experimental results indicated that connection strengths tended to increase with increasing edge distances 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 Criterion**

As $d/w$ approaches zero, the connection becomes infinitely wide with respect to the hole diameter, and net-tension failure is preceded by bearing failure for connections with large edge distances and by cleavage or shearout failure for connections with small edge distances. The ultimate bearing capacity of a connection is obviously dependent on the bearing strength of the material. Using the results of full-size connections, the bearing strength of a material $F_{ub}$, can be determined as

$$F_{ub} = \frac{P_{ub}}{t \cdot d_{bol}}$$

where $d_{bol}$ = diameter of the bolt.

The efficiency of a connection that fails in bearing can be expressed in terms of the ratios $d/w$ as

$$\Phi = \frac{F_{ub} \cdot d_{bol}}{F_{ub} \cdot d \cdot w}$$

Eq. (15) is presented in Fig. 7 for various $F_{ub}/F_{ub}$ ratios with $d = d_{bol}$. The term $(F_{ub}/F_{ub})/(d_{bol}/d)$ is equivalent to the slope of the lines shown in Fig. 7.

In this investigation it was found that edge-distance-to-hole-diameter ratios, $e/d \geq 5$, did not increase the bearing stresses appreciably. The failure for these connections was predominantly bearing failure; therefore, all connections that had $e/d \geq 5$ were used to determine the material bearing strength, $F_{ub}$. Using (15), Fig. 8 illustrates the best-fit line using a least-squares regression analysis. From the test results of the single-bolted connections, the bearing strength to tensile strength ratios, $F_{ub}/F_{tu}$, were found to be 1.84, 2.20, and 2.13 for the $0^\circ$, $45^\circ$, and $90^\circ$ fiber orientations, respectively (Rosner 1992). This translates into bearing strengths of 306 MPa (44.4 ksi), 258 MPa (37.4 ksi), and 235 MPa (34.1 ksi). The corresponding standard errors of the regression analysis were 0.095, 0.170, and 0.129.

For a given $d/w$ ratio and for adequate edge distances, the predominant mode of failure is bearing. With a decreasing $e/d$ ratio, the mode of failure tends to change from bearing failure to cleavage failure. In this investigation it was found that cleavage failure is related to bearing failure by a simple quadratic expression in terms of the ratio $(d/2e)$. This expression is a reduction factor, which relates the efficiency of a connection that would tend to fail in bearing to the efficiency of a similar connection, with a smaller edge distance, that would tend to fail in cleavage. The cleavage reduction factor $\Psi$ is expressed in terms of $(d/2e)$ as follows (Rosner 1992):
\[ \Psi = \left(1 - \frac{d}{2e}\right)^2 \]  

(16)

The quadratic expression for the reduction factor was found to be the simplest and fitted extremely well with the measured data. By introducing this reduction factor into (15), an expression that characterizes both bearing and cleavage failure can be defined as follows:

\[ \Phi = \frac{F_{rb}}{F_m} \frac{d_{hub}}{d} \frac{d}{w} = \frac{F_{rb}}{F_m} \frac{d_{hub}}{d} \left(1 - \frac{d}{2e}\right)^2 \frac{d}{w} \]  

(17)

Eq. (17) satisfies the limiting case as \( e/d \) approaches \( \infty \), as the quadratic term in (17) becomes unity and the efficiency reduces to the expression for bearing failure as given in (15). Eq. (17) also satisfies the other limiting case, which occurs when \( e/d \) approaches 0.5, and the expression predicts a zero capacity for the connection. This is due to the fact that \( e \), which is measured to the center of the bolt hole, cannot be less than half the hole diameter.

The results of this investigation showed that for connections with \( e/d \geq 5 \) the failure mode is predominantly bearing. Therefore, to satisfy this observed limit, the cleavage reduction factor should reduce to 1 when \( e/d = 5 \). To accomplish this, the constants in the cleavage reduction factor must be computed based on the observed boundary conditions. Eq. (17) can be rewritten in terms of constant coefficients \( a \) and \( b \) as follows:

\[ \Phi = \frac{F_{rb}}{F_m} \frac{d_{hub}}{d} \left(a - b \frac{d}{e}\right)^2 \frac{d}{w} \]  

(18)

Therefore, to satisfy the upper limit when \( e/d = 5 \):

\[ \left(a - \frac{b}{5}\right) = 1 \]  

(19)

and to satisfy the lower limit when \( e/d = 0.5 \):

\[ (a - 2b) = 0 \]  

(20)

Solving (19) and (20) simultaneously, the two constant coefficients were found to be \( a = 10/9 \) and \( b = 5/9 \).

Therefore, for \( e/d \leq 5 \), (18) becomes the following for cleavage failure:

\[ \Phi = \frac{F_{rb}}{F_m} \frac{d_{hub}}{d} \left(\frac{10}{9} - \frac{5}{9} \frac{d}{e}\right)^2 \frac{d}{w} \text{ for } e/d \leq 5 \text{ (cleavage)} \]  

(21)

For \( e/d \geq 5 \), (18) reduces to (15) for bearing failure

\[ \Phi = \frac{F_{rb}}{F_m} \frac{d_{hub}}{d} \frac{d}{w} \text{ for } e/d \geq 5 \text{ (bearing)} \]  

(22)

Using (21) or (22), the ultimate load of a connection can be determined as

\[ P_{ub} = \Phi(t \cdot w \cdot F_m) \]  

(23)

Eqs. (21) and (22) were used to produce a family of failure envelopes in terms of the efficiency and the ratio \( d/w \) as shown in Fig. 9 for connections with a 0° fiber orientation. The various envelopes are given for constant \( e/d \) ratios. The curves are in excellent agreement with the measured experimental values for both bearing and cleavage modes of failure, as shown in Fig. 9.

The shearout mode of failure was not observed in this experimental investigation because of a high volume of random fibers 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 behavior for cleavage failure discussed here could be applied to shearout failure, which could occur in other types of composite materials.

**Failure Envelopes**

Superimposing the failure envelopes of the two aforementioned failure criteria, one set of design envelopes was developed for each fiber orientation as shown in Figs. 10–12 for the 0°, 45°, and 90° fiber orientations, respectively. Given a particular connection geometry \( t, w, e, d, \) and \( d_{hub} \), the efficiency and mode of failure of the connection can be predicted using the proposed failure envelopes for the corresponding \( d/w \) and \( e/d \) ratios and the given fiber orientation. The efficiency can also be determined using (12) for net-tension failure and (21) or (22) for cleavage/bearing failure.
FIG. 12. Design Envelopes for 90° Connections

FIG. 13. Experimental versus Model Results for 0° Connections

FIG. 14. Experimental versus Model Results for 45° Connections

The measured ultimate loads of the connections tested in this program are compared to the predicted values from the proposed design procedure for the 0°, 45°, and 90° connections in Figs. 13–15, respectively. The comparison indicates that most of the data fall close to the 1:1 correspondence line or are on the conservative side. On average, the predicted loads were within 10% of the experimental values. For the 0° connections the correspondence between the predicted and experimental failure modes was excellent, with only a few discrepancies occurring for connections that had failed in a combined failure mode.

Obviously connections that were tested with the principal fiber direction at 45° and 90° to the applied load had lower ultimate loads than their 0° counterparts. However, due to the lower values of $E_s$ in these directions, their efficiencies were actually higher than their 0° counterparts as shown in Figs. 10–12. This means that the failure envelopes for the 0° case can also be used to conservatively predict the loads of connections of all fiber orientations considered in this investigation.

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. Therefore, it is reasonable to expect that as the material systems and connection configurations used by civil engineers become more standardized, a database of test results could be developed to allow the design engineer to pick and choose the appropriate $C$ value from a design code without performing a single test. Considering the versatility and simplicity of this design procedure it is ideal for implementation in future design codes.

**DESIGN PROCEDURE**

Based on the preceding discussion, the design engineer could use one set of failure envelopes, as given in Fig. 10, and the ultimate tensile strength and bearing strength of the material in the direction of the applied load to predict the ultimate load capacity for a given connection. For a given $d/w$ and $e/d$ ratio, the efficiency of a connection may be read directly from the graph. Once the efficiency is known, the ultimate load of a connection can be evaluated using (23). The mode of failure is determined by the relative magnitude of the $d/w$ and $e/d$ ratios. For those connections with $d/w$ and $e/d$ ratios falling on the curved part of the failure envelope, the mode of failure will be bearing. For those connections that lie on the straight portion of the failure envelope, the mode of failure will either be bearing, if $e/d < 5$, or cleavage, if $e/d > 5$.

Alternatively, the expressions for the connection efficiency may be used to determine the ultimate load of a connection.
For a given connection geometry, the efficiency corresponding to a net-tension failure given by (12) and the efficiency corresponding to a bearing/cleavage failure given by (21) and (22) can be determined. The lowest efficiency and corresponding mode of failure will govern. As before, once the connection efficiency has been determined, the ultimate load capacity of a connection can be evaluated by (23).

NUMERICAL EXAMPLES

Example 1

Given a connection made from EXTRAN Flat Sheet/Series 500 with the dimensions $w = 130$ mm, $e = 40$ mm, $t = 12$ mm, $d = 21$ mm, $d_{bh} = 19$ mm, and the material property $F_{tu} = 166$ MPa, the structural efficiency can be determined from the envelopes in Fig. 10 for $d/w = 0.16$ and $e/d = 2$ and is found to be 0.185. Consequently, the ultimate load $P_{ub} = \Phi \cdot t \cdot w \cdot F_{tu}$ is equal to 48 kN. Because the failure point is located within the straight line portion of the envelope, the failure is of the bearing or cleavage type. In this case the failure is cleavage, since $e/d < 5$.

The same results can be obtained using (12) and (21) with a correlation factor of $C = 0.33$ and $F_{tu} = 1.84 F_{tn}$, determined experimentally for this type of material. The expression for net-tension failure (12) gives an efficiency of 0.27 and a $P_{ub}$ (net tension) = 70 kN, while (21) gives an efficiency of 0.18 and a $P_{ub}$ (cleavage) = 47 kN. Since (21) is critical, the failure mode is cleavage.

Example 2

By increasing the edge distance in the previous example, the mode of failure can be changed from cleavage failure to a more desirable bearing failure. Setting $e = 110$ mm so that $e/d = 5.2$, the efficiency can be determined from Fig. 10 to be 0.28 and $P_{ub} = 72$ kN. Since $e/d \geq 5$ the mode of failure will be of the bearing type.

Using (12), the net-tension efficiency can be determined to be 0.31 and $P_{ub}$ (net tension) = 80 kN. Using (22), the bearing efficiency is found to be 0.27 and $P_{ub}$ (bearing) = 70 kN, similar to that obtained from Fig. 10. Because the bearing-failure criterion predicts the lower ultimate load, it is critical.

Example 3

If a connection similar to the foregoing examples is used, except with $w = 40$ mm and $e = 40$ mm, the reduced width can produce a net-tension mode of failure. With $d/w = 0.53$ and $e/d = 2$, the efficiency is found (from Fig. 10) to be 0.32. The ultimate load is 25.5 kN with the governing mode of failure being net-tension, since the failure point lies on the curved part of the failure envelope.

Similarly, by using (12), the net-tension efficiency is determined to be 0.32 and $P_{ub}$ (net tension) = 25.7 kN. Using (21), the bearing/cleavage criterion predicts an efficiency of 0.59 and a $P_{ub}$ (cleavage) = 47 kN. The net-tension criterion is critical and, therefore, the mode of failure will be of the net-tension type.

SUMMARY AND CONCLUSIONS

Based on the experimental results and the established theory on bolted joint behavior, a mathematical model and design procedure are proposed to predict the ultimate load and failure mode of single-bolted connections in fiber-reinforced composite materials. The model provides an overall failure envelope, which includes criteria for net-tension failure and bearing/cleavage failure. The major conclusions drawn from the analytical part of this investigation are as follows.

The proposed design procedure predicts the ultimate load and failure mode of the connections with an adequate degree of accuracy. On an average, the predicted loads were within 10% of the experimental values. For connections with a 0° fiber orientation with respect to the applied load, the correspondence between the predicted and experimental modes of failure is excellent.

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.

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

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APPENDIX I. REFERENCES


APPENDIX II. NOTATION

The following symbols are used in this paper:

- $a, b$ = constant coefficients;
- $C$ = correlation coefficient;
- $d$ = diameter of bolt hole;
- $d_{bol}$ = diameter of bolt;
- $d_{bd}$ = bolt-diameter-to-hole-diameter ratio;
- $d/w$ = hole-diameter-to-width ratio;
- $e$ = edge distance (measured from center of bolt hole);
- $e/d$ = edge-distance-to-hole-diameter ratio;
- $e/w$ = edge-distance-to-width ratio;
- $F_{tu}$ = bearing strength of composite material in the direction of the applied load;
- $F_{un}$ = unnotched tensile strength of an isotropic elastic material or a composite material in the direction of the applied load;
- $F_{ul}/F_{nu}$ = ratio of bearing strength to unnotched tensile strength;
- $k_{cv}$ = average stress concentration factor observed at failure of a bolted connection using composite material;
- $k_{se}$ = elastic stress concentration factor corresponding to the maximum stress adjacent to the hole for a connection using perfectly elastic isotropic material;
- $P_{ab}$ = ultimate load capacity of connection;
- $t$ = thickness of composite plate;
- $w$ = width of composite plate;
- $w/d$ = width-to-hole-diameter ratio;
- $\theta$ = nondimensional factor that is a function of the edge-distance-to-width ratio $e/w$;
- $\sigma_{max}$ = maximum stress adjacent to bolt hole along the net section of the connection plate;
- $\Phi$ = structural efficiency; and
- $\Psi$ = cleavage reduction factor.