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BOLTED JOINTS IN LAMINATED COMPOSITES

Fu-Kuo Chang and George S. Springer
Department of Aeronautics and Astronautics
Stanford University, Stanford, California 94305

and

Richard A. Scott
Department of Mechanical Engineering and Applied Mechanics
The University of Michigan, Ann Arbor, Michigan 48109

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Abstract

Expressions were presented which can be used to estimate the strengths of continuous fiber reinforced composite laminates containing pin-loaded holes. The expressions apply to laminates containing either a single pin loaded hole, a single row of pin loaded holes, or two parallel rows of pin loaded holes.

Introduction

Considerable efforts have been made in recent years to develop analytical methods for calculating the strengths of mechanically fastened joints in laminated composites. Some of these efforts resulted in large computer codes which can be used to analyze the behavior of pin loaded holes in fiber reinforced organic matrix composites [1-10]. One of the latest codes (designed as "BOLT") provides the strength, the failure mode, and the stress and strain distribution in laminates containing either a single pin loaded hole, two pin loaded holes in parallel, or two pin loaded holes in series [1,2]. Thus, this code is a useful tool in the design of mechanically fastened composite joints.

BOLT, and similar computer codes, require the values of numerous material properties as well as access to a main frame computer. This, and the time required for numerical computations, often necessitates that the designer rely on approximate expressions for estimating the strengths of joints. To accommodate this design need, this paper presents simple expressions which can be used to estimate the strengths of composite laminates containing either a single pin loaded hole, a single row of pin loaded holes, or two parallel rows of pin loaded holes.

The expressions were developed on the basis of information generated by the BOLT computer code. Hence, the accuracies of the expressions are comparable to those of this code. The advantage of the expressions is that they do not require either computer calculations or knowledge of a wide range of material properties.

Problem Statement

Consider a plate of length L, width W, and thickness H made of undirectional fiber reinforced plies. The ply orientation must be symmetric with respect to the center plane ($x_3 = 0$, Figure 1) of the laminate. Furthermore, the ply orientations must be such that the laminate behaves in a linearly elastic manner. Laminate configurations which exhibit nonlinearly elastic behavior are not considered. Cross ply [0/90] and angle ply [±45] laminates generally fall in this latter category. Perfect bonding between each ply is assumed. Three types of problems are investigated (Figures 1 and 2):

a) a single hole of diameter D is located along the centerline of the plate.

b) one row of holes (of diameter D) is located in the plate,

c) two parallel rows of holes (of diameter D) are located in the plate.

A rigid pin, firmly supported, is placed inside each hole. There in no lateral force on the laminate such as would be provided by a tightened nut. Therefore, the expressions presented here are applicable to mechanically fastened joints in which lateral forces are negligible; they should be used only as guides in the design of tightened bolted joints.

A uniform tensile load P is applied to the lower edge of the plate. It is desired to find the maximum (failure) load (P_M) which can be applied before the laminate fails.

Failure Load

In this section, closed form, approximate expressions are presented for estimating the strength, defined as

$$S = \frac{P_M}{WH} \quad (1)$$

The expressions for strength presented below were developed by examining and analyzing numerical results generated by the BOLT program for a large number of laminates containing pin loaded holes with different geometries. The parametric studies (which form the basis of the expressions given in this paper) were performed for Fiberite T300/1034-C graphite-epoxy laminates. This material was used because all the numerical values of properties need for the computer calculations were available. Nevertheless, the resulting expressions may be of general validity and (with the use of the proper constants) may apply to composites made of other types of fiber resins.

a) Single Pin Loaded Hole

A careful examination of the results generated by the BOLT program shows that the strength of a laminate of width W, containing a single pin loaded hole of diameter D, located at a distance E from the edge (Figure 1) may be approximated by the expressions

$$S = g_E \left(\frac{D}{D_0}\right)^{-C} \frac{P_0}{(\frac{W}{D})D_0 H} \tag{2}$$

$$exp\left[\frac{(\frac{W}{D})^2}{(1-\frac{W}{D})} + 0.94\left(\frac{W}{D}\right) + 1.56\right] \left\{ \begin{array}{c} D \leq 1\ in \\ E > \frac{D}{2} \\ W > D \end{array} \right.$$

In Eq. (2), C is a dimensionless constant whose value depends only on the material. The parameter P_0 has the units of force and depends on the material, the laminate lay up, and the hole diameter. Procedures suitable for determining the values of C and P_0 are described in Section d. Values of P_0 and C are given in Table 1 for selected materials and selected laminate lay ups. D_0 is a reference hole diameter corresponding to the specified value of P_0. g_E is a parameter which depends only on the edge distance E. The values of g_E are

$$g_E = \left\{ \begin{array}{ll} 1 & E \geq 2.5D \\ (E/2.5D)^{\frac{1}{2}} & 0.5D < E < 2.5D \end{array} \right. \tag{3}$$

b) Single Row of Pin Loaded Holes

The strength of a laminate containing a single row of pin loaded holes is

$$S_p = \left[\,(N-2)g_H^2 + g_H g_S\,\right] S \left\{ \begin{array}{c} D \leq 1\ in \\ E > D/2 \\ G_H > D \\ Q > D/2 \end{array} \right. \tag{4}$$

where N is the number of holes (Figure 2). S is the strength of a laminate of width G_H containing a single pin loaded hole of diameter D (Figure 2). Hence, S is given by Eq.(2) with W being replaced by G_H. The parameters g_H and g_S depend only on G_H and Q, respectively, and are

$$g_H = \left\{ \begin{array}{ll} 1 & G_H \geq 2D \\ (G_H/2D)^{1/2} & D < G_H < 2D \end{array} \right.$$

$$g_S = \left\{ \begin{array}{ll} 1 & Q \geq 1.5D \\ (Q/1.5D)^{1/3} & 0.5D < Q < 1.5D \end{array} \right. \tag{5}$$

where there are only two holes in a row (Figure 1), Eq.(4) reduces to

$$(S_p)_{N=2} = g_H g_S S \left\{ \begin{array}{c} D \leq 1\ in \\ E > D/2 \\ G_H > D \\ Q > D/2 \end{array} \right. \tag{6}$$

The theoretical limits on E, G_H and Q given in Eq.(4) and (5) cannot, of course, be achieved in practice because the holes cannot contact each other or the sides of the laminate.

c) Two Rows of Pin Loaded Holes

The strength of a laminate of width W containing two parallel rows of pin loaded holes (Figure 2) is

$$S_S = [(N-2)g_H^2 + g_H g_S] S_{S2} \left\{ \begin{array}{c} D \leq 1\ in \\ E > D/2 \\ G_H > D \\ G_V > D \end{array} \right. \tag{7}$$

Where N is the number of holes in each row, S_{S2} is the strength of a laminate (of width G_H) containing only two pin loaded holes in a column (Figure 1). This strength may be approximated by the expression [11,12]

$$S_{S2} = \frac{1}{2} g_V (S + S_H) \left\{ \begin{array}{c} D \leq 1\ in \\ E > D/2 \\ G_H > D \\ G_V > D \end{array} \right. \tag{8}$$

S is the strength of a laminate containing only the "upper" pin loaded hole, i.e., the hole nearest to the upper edge. Consequently, S is given by Eq. (2) with the width W being replaced by G_H.

S_H is the strength of a laminate containing only a single open "unloaded" hole located at the position of the "lower" hole. S_H may be approximated by

$$S_H = \frac{P_1}{(\frac{G_H}{D})D_1 H}\left(\frac{D}{D_1}\right)^{-C}\left[B\left(\frac{G_H}{D}\right) - 1\right] \left\{ \begin{array}{c} D < 1\ in \\ 2D \leq G_H \leq 10D \end{array} \right. \tag{9}$$

P_1 and B are parameters whose values depend on the material, laminate lay up, and diameter. B is dimensionless and P_1 has the units of force. A procedure for determining P_1 and B is described in section d. Selected values of P_1 and B are included in Table 1. D_1 is a reference hole diameter corresponding to the specified values of P_1 and B. The parameter G_V depends only on the distance G_V (Figure 1). The values of g_V are

$$g_V = \begin{cases} 1 & g_V \geq 2D \\ (g_V/2D)^{1/2} & D < g_V < 2D \end{cases} \tag{10}$$

By combining Eqs.(2), (7), (8) and (9) we obtain

$$S_S = \frac{g_V}{2}\left[(N-2)g^2{}_H + g_H g_S\right]\left\{ g_E\left(\frac{D}{D_0}\right)^{-C} \frac{P_0}{\left(\frac{G_H}{D}\right)D_0 H} \right.$$
$$exp\left[\frac{(\frac{G_H}{D})^2}{1-(\frac{G_H}{D})} + 0.94\left(\frac{G_H}{D}\right) + 1.56\right] \tag{11}$$
$$\left. + \frac{P_1}{(\frac{G_H}{D})D_1 H}\left(\frac{D}{D_1}\right)^{-C}\left[B\left(\frac{G_H}{D}\right) - 1\right]\right\}$$

The restrictions which apply to this equation are the same as those of Eq.(7).

d) Determination of the Parameters P_0, C, P_1, B.

The use of the equations developed in the foregoing sections requires that the values of P_0, C, P_1 and B be known. The parameters P_0 and C can be evaluated either by measuring or by calculating (for example with the BOLT program) the strengths of laminates containing a single pin loaded hole. The values of P_0 and C are then determined from the expressions (see Eqs. 2)

$$P_0 = \frac{S_0 W_0 H}{exp\left(\frac{(\frac{W_0}{D_0})^2}{1-\frac{W_0}{D_0}} + 0.94\left(\frac{W_0}{D_0}\right) + 1.56\right)} \quad \begin{cases} D = D_0 = constant \\ W = W_0 = constant \end{cases} \tag{12}$$

$$C = -\frac{\ell_n\left(\frac{S_D}{S_0}\right)}{\ell_n\left(\frac{D}{D_0}\right)} \qquad \frac{W_0}{D_0} = \frac{W}{D} = constant \tag{13}$$

where S_0 and S_D are the known strengths of laminates with widths W_0 and W containing D_0 and D diameter pin loaded holes, respectively.

To determine P_1 and B, the strengths $(S_H)_{D1}$ of laminates containing an open hole of a given diameter $D1$ must be known for laminates of different width G_H. The strengths can be either measured or calculated. Once the strength $(S_H)_{D1}$ as function of width G_H is established the parameters P_1 and B can readily be obtained from the expression (see Eq.9)

$$(S_H)_{D1} = \frac{P_1}{G_H H}\left[B\left(\frac{G_H}{D_1}\right) + 1\right] \qquad D = D_1 = constant \tag{14}$$

Note that the plot $[(G_H)\,H(S_H)_{D1}]$ versus G_{H/D_1} results in a straight line. The foregoing procedure can be simplified if a width to diameter ratio of less than 2.5 is used in evaluating P_0 and B. For W/D < 2.5 laminates containing both pin loaded and open holes fail in tension mode and the strength of a laminate with an open hole is nearly identical to that of a laminate with a loaded hole of the same diameter

$$S \approx S_H \qquad \begin{cases} W/D < 2.5 \\ D_0 = D_1 \end{cases} \tag{15}$$

Thus, for W/D < 2.5 only, either the strengths of laminates with pin loaded holes or the strengths of laminates with open holes are needed for determining P_0 and C.

Discussion

The expressions presented in the foregoing may be used to estimate the strengths of laminates containing a single pin loaded hole (Eq.2), a single row of pin loaded holes containing two or more holes (Eq.4), and two rows of pin loaded holes containing two or more holes (Eq.11).

The use of these expressions requires the knowledge of four constants: P_0, C, P_1 and B. As described in the previous section, these constants can be determined readily either by numerical or experimental procedures.

In order to illustrate the accuracies of the expressions developed in the foregoing, strengths calculated by the expressions were compared to strengths generated by the BOLT code. The comparisons, presented in Figures 3 - 5, show that the expressions developed in this investigation approximate the strengths with reasonable accuracy. Under the conditions examined, the approximate and the numerical (BOLT code) results agree within about 20 percent. Thus, the expressions given in this paper should be useful to the designer. However, the restrictions and limitations should be borne in mind when applying these expressions. Whenever possible, the more accurate and less restricted computer codes should be employed in sizing mechanically fastened composite joints.

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TABLE 1. Values of the parameters C, P_0, P_1 and B

$T300/1034-C^a$	$D_0(in)$	C	$\frac{P_0}{H}\left(\frac{lbf}{in}\right)$	$\frac{P_1}{H}\left(\frac{lbf}{in}\right)$	B
$[(0/\pm45/90)_3]_s$	0.25	0.3	27624	7968	1.6
$[(90_2/\pm60/\pm30)_2]_s$	0.25	0.3	19472	4184	2.1
$T300/5208^b$					
$[(0/\pm45/90]_s$	0.25	0.3	29530	3174	3.5

a) from ref. [1.2].
b) deduced from the data given in refs. [9,11, 12].

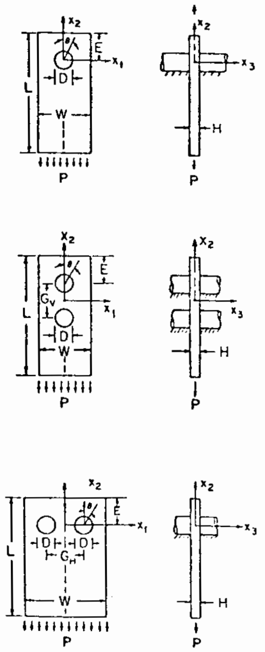

Figure 1. Description of the Problem. Top: Single Pin Loaded Hole; Middle: Two Pin Loaded Holes in a Column; Bottom: Two Pin Loaded Holes in a Row.

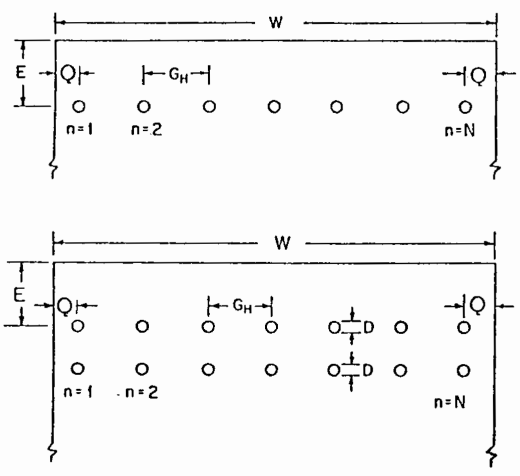

Figure 2. Description of the Geometry. Top: One Row of Holes; Bottom: Two Parallel Rows of Holes.

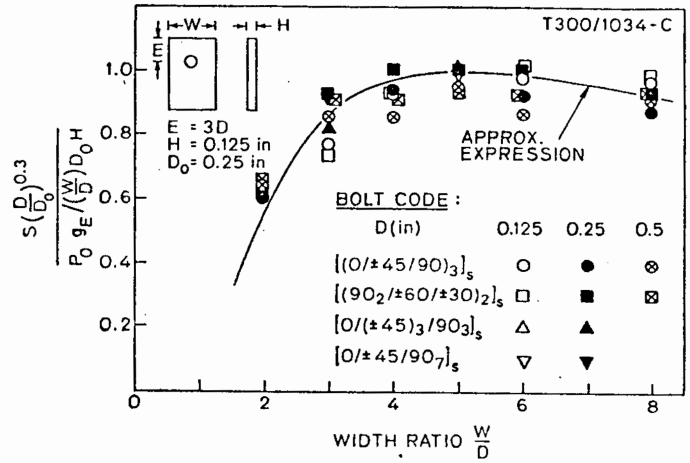

Figure 3. The Strengths Calculated by Equation (2) and by the BOLT Code. Comparisons of the Results for a Single Pin Loaded Hole.

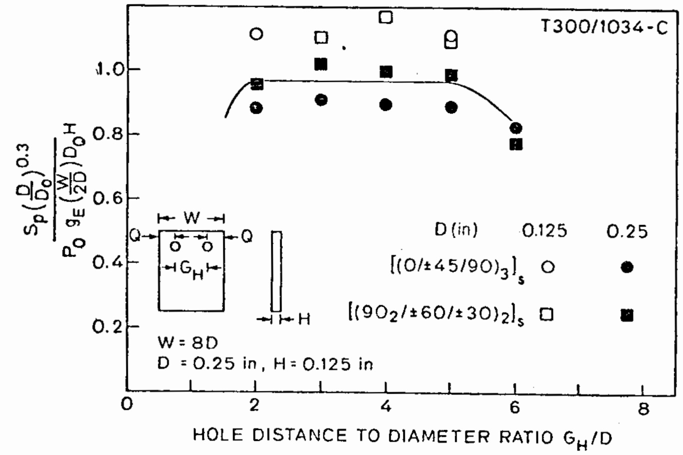

Figure 4. The Strengths Calculated by Equation (6) and by the BOLT Code. Comparisons of the Results for Two Pin Loaded Holes in a Row.

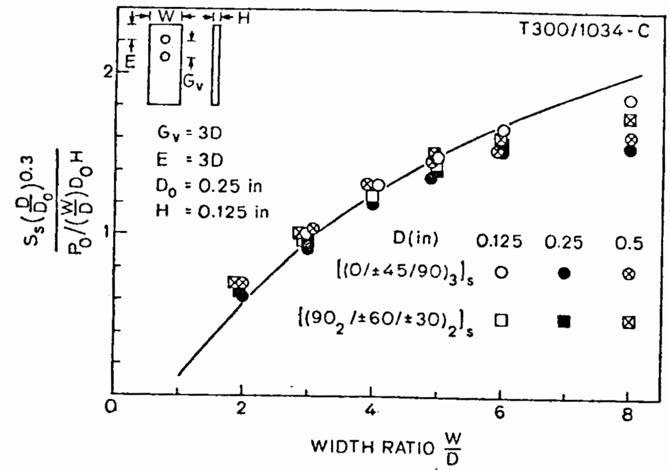

Figure 5. The Strength Calculated by Equation (11) and by the BOLT Code. Comparisons of the Results for Two Pin Loaded Holes in a Column.

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