Film Reinforced Multifastened Mechanical Joints in Fibrous Composites

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[±45] graphite fiber/epoxy resin composites were fabricated to form double lap bolted joints, each containing three bolts abreast at constant pitch distance. The specimens were tested to measure the joint strenghtening effectiveness of colaminated boron/polyimide film, introduced locally at 6 or 12 volume percent levels. Such film additions increased the load transfer capacity of the joint systems to nearly double that of the corresponding fiber-only specimens. This behavior, in qualitative and quantitative agreement with the earlier experiments on single-bolted lug configurations, indicated that boron film can contribute significant tensile, bearing, and shear strength to this type of multi-fastened joint design. The resulting stiffness increase did not prevent the uniform distribution of the load among the several fasteners in these experiments.

Introduction

FOR a practical application of high strength, low weight composites in structural designs, the development of mechanical fastening and joining methods is desirable, particularly where disassembly for inspection or maintenance is important. However, many of the problems of mechanical joint failures by so-called shear-out, by delamination, or in bearing have not been solved. Various attempts at strengthening the joint area with added material have tended to increase the total weight without commensurate strength increase.[1,2]

A possible solution to this problem is provided by boron in the form of thin structural film. This material exhibits high stiffness, high bearing strength, and low weight properties which are transversely isotropic in the laminar plane. Its effectiveness as a local reinforcement for singly bolted joints in [±45] and [O_2, ±45] types of fibrous composites has been reported in a recently completed investigation.[3] The salient results of that research are summarized in Fig. 1 which shows the measured tensile load capacities of single bolt, double lap connections in [±45] and [O_2, ±45] graphite/epoxy composites. Load transfer by means of bolted connections caused immediate reductions of the coupon tensile strength, owing to the area reduction and additionally to stress concentration effects of the drilled bolt hole. Reinforcing the bolted connections with 6 or 12 volume percent of laminar boron, however, restored the load capacity to 70% of the original strength in the [O_2, ±45] laminate, and up to 150% in the case of the [±45] laminate, where as a result the fracture occurred away from the bolted connection. The extra film added about 10×10^{-3} in. to the thickness and about 4×10^{-4} lb/linear inch of edge to the weight.

The strength/weight effectiveness of boron film edge reinforcement was estimated by comparing the results for [O_2, ±45] fiber configurations with data published for other reinforcing materials,[1,2] such as self-reinforcement (i.e., extra plies of boron fiber) or stainless steel shims, added to boron fiber panels; also titanium doublers used to reinforce graphite fiber panels. The basis of comparison was the strength/weight index SWI defined as

$$\mathrm{SWI} = (\Delta P/P)/(\Delta W/W) \tag{1}$$

where $\Delta P/P$ was the percent increase in the load carrying capacity resulting from the addition of doubler material; and $\Delta W/W$ was the corresponding percent increase in areal density. (Theoretically SWI = 1 for isotropic, homogeneous materials). The comparison is shown graphically in Fig. 2. In ascending order, the strength/weight indexes were

Titanium	0.41
Stainless Steel	0.73
Boron fiber	1.30
Boron film	2.18

An additional effect of boron film in the joint was the reduction in the observed relative displacements δ/D (where δ was the displacement, measured at bearing failure, between the lap plates and the specimen; and D was the bolt diameter). For illustration, experimental results of earlier work[7] are shown in the bar graphs of Fig. 3. For the [±45] case, the mean relative displacement at maximum load, δ/D = 7.2%, was reduced to 6.1 or 5.6%, respectively, by additions of 6 or 12 volume percent film. In the case of [O_2, ±45] fiber laminates, the relative displacements were 13.7, 10.6 and 5.7%, in the same respective order. These results indicated clearly the trend toward monotonic decrease of the joint compliance with

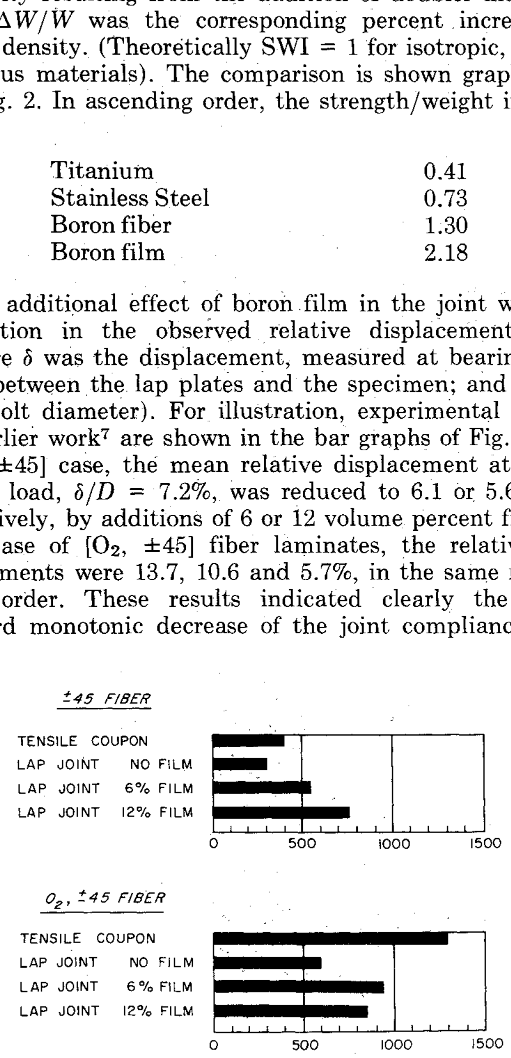

Fig. 1 Tensile strength of single bolt joints in [±45] and [O_2, ±45] graphite fiber composites.

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Index categories: Materials, Properties of; Structural Composite Materials (Including Coatings).

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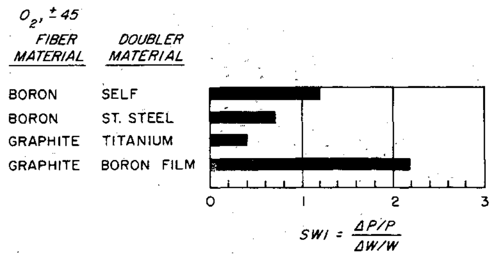

Fig. 2 The strength/weight index SWI for various doubler materials.

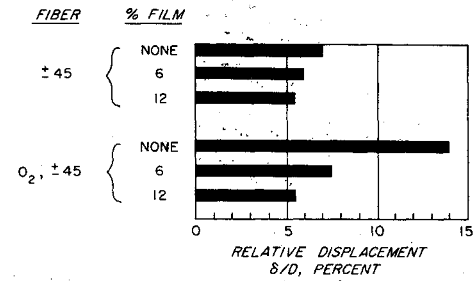

Fig. 3 Relative joint displacements at bearing failure in single bolt, double lap joints.

increasing film fractions. Whether such increased material stiffness might not be detrimental for joints containing multiple fasteners was the subject of the present investigation.

Specimen Preparation

Laminate Fabrication

Hercules type HT-S graphite fiber was drum-wound and impregnated with a resin system comprising CIBA EPN 1138-A85 epoxy resin and BF_3/MEA hardener in the ratio 60:1 by weight. B-staging and cutting from the drum gave a uniaxial prepreg warp sheet which was cut to laminate size with due regard for fiber direction. The film reinforcement was fabricated by the vapor deposition of boron on polyimide resin film (DuPont Kapton), as described in detail elsewhere.[4-6] The product was a flat ribbon, overall width 10 in., up to 50 ft continuous lengths. Plies of the required size were sheared out of the middle 8 in. of the ribbon. The physical properties were as follows:

Substrate material	Polyimide resin film
Substrate thickness (10^{-3} in.)	0.27 to 0.28
Coating material	Boron
Coating purity (%)	99.8+
Coating thickness (10^{-3} in.)	0.14 to 0.32
Total ply thickness (10^{-3} in.)	0.41 to 0.60
Boron volume fraction (%)	34 to 53
Density (lbs./in.^{3})	0.060 to 0.067

Plies of the fiber and film were coated with fresh resin mixture and cured between heated pressure platens. Further details including the time/temperature/pressure schedule have been shown in Table 1 of Ref. 7.

Three laminates with dimensions 7 × 8 in. were fabricated. One of these was comprised of fiber only, whereas the other two included additions of film in a central band across the laminate. This geometry allowed sectioning into 6 specimens, each having a film reinforced edge to a depth of approximately 1.5 in. A typical specimen is shown schematically in Fig. 4, where the several dimensional parameters are also defined. The panel sections comprised 4 plies of graphite fiber with thickness t_o, while the edge sections were selectively augmented with interleaved boron film to form a stiffened margin of thickness t_e. The various reinforcement contents, lay up sequences, and densities are shown in Table 1.

Bolted Joint Geometry

Failure Modes

Three independent, easily distinguishable modes of failure in a bolted joint are tensile (fracture across the hole), bearing (crushing under the bolt and elongation of the hole beyond given limits), and end rupture (confined to the region between the hole and the specimen boundary). In Ref. 7, rudimentary design criteria had been developed which were moderately successful in producing at will one of these three failure modes by a suitable balance of the dimensions w (specimen width), D (bolt diameter), and e (edge distance). For the present investigation, the design for bolt size followed this established philosophy, whereas the design for edge distance was based on a newer analysis.

Specimen Design—Bolt Size

It was assumed, as before, that the tensile and bearing strengths measured by coupon tests were not strongly notch sensitive. This supposition was supported for the case of [±45] laminates by the results of earlier work (see Table XII, p. 51, of Ref. 7). The basic mechanical properties of [±45] fiber laminates (test coupons) with zero, 6, or 12 volume percent additions of boron film have been measured,[3] and are shown here in Table 1. Using these values in the zeroeth-order approximation

$$(\sigma_t{}^L)(w - 3D_b) = (\sigma_{pb}{}^L)(3D_b) \tag{2}$$

where $\sigma_t{}^L$ and $\sigma_{pb}{}^L$ are the longitudinal tensile and pin bearing strengths, respectively, the balanced bolt diameter D_b was computed. Design-D values larger or smaller than D_b favor the tensile or bearing failure mode, respectively. With this consideration, bolt diameters D = 0.188 in. were designed for all specimens biased toward the ten-

Table 1 The physical and mechanical properties of bidirectional fiber and film/fiber laminates

Geometry[a]	Reinforcement volume fraction: Graphite fiber, %	Reinforcement volume fraction: Boron film, %	Total %	Thickness in.	Density lb/in.^{3}	Tensile strength[b] $\sigma_t{}^L$ 10^3 psi	Bearing strength[b] $\sigma_{pb}{}^L$ 10^3 psi	Tensile modulus[b] $E_t{}^L$ 10^6 psi	Torsional modulus[b] $G_{LT}{}^L$ 10^6 psi
$(\pm45)_s$	53.1	none	53.1	0.044	0.053	12.2	49.6	3.0	2.3
$(+45, I_5, -45, \bar{I}_5)_s$	42.6	6.0	48.6	0.055	0.054	18.3	83.6	6.6	2.7
$(I_6, +45, I_6, -45, \bar{I}_6)_s$	36.7	12.7	49.4	0.064	0.053	23.4	73.1	10.1	3.7

[a] I stands for one film element, +45 or −45 stands for one graphite fiber layer having the corresponding off-axis orientation. A number subscript indicates repeats, the subscript ( )$_s$ indicates the location of a mirror plane of symmetry.

[b] In ±45 laminates, the longitudinal and transverse properties (parallel to the L and T directions, respectively), are identical. Thus, $\sigma_t{}^L = \sigma_t{}^T$, $E_t{}^L = E_t{}^T$, and so on.

Table 2 The strength of multi-bolted lap joints in fibrous composites edge reinforced with boron film

Panel thickness t_o in.	Edge thickness t_e in.	Volume fraction of boron % in edge	Specimen number	Maximum load P_{max} lb	Net[a] tensile stress in edge 10^3 psi	Gross[b] tensile stress in panel 10^3 psi	Bearing stress under bolt[c] 10^3 psi	Relative hole elongation %	Failure mode and location[d]
			D = 1.25 in., e = 0.312 in., e/D = 2.5 Bearing failure predicted						
0.043	0.043	none	B – B.1	1060	13.8	11.2	66.5	9.6	B(E)/R(E)
			B – B.2	890	11.3	9.4	54.7	4.5	B(E)/R(E)
0.043	0.053	6.0	B/BI – B.1	1230	12.8	13.2	61.8	4.4	B(E)/T(E)
			B/BI – B.2	1560	16.4	16.9	79.2	11.4	B(E)/T(E)
0.044	0.064	12.7	B/IBI – B.1	1710	14.9	18.2	71.9	5.3	B(E)/T(N)
			B/IBI – B.2	1520	12.9	15.6	62.6	3.3	T(N)
			D = 0.188 in., e = 0.375 in., e/D = 2.0 Tensile failure predicted						
0.044	0.044	none	B – T.1	980	13.6	10.2	39.9	2.2	T(E)
			B – T.2	1110	15.3	11.3	44.0	2.7	T(E)
0.043	0.053	6.0	B/BI – T.1	1720	19.9	17.9	57.3	1.3	T(E)
			B/BI – T.2	1690	19.7	18.2	56.6	1.1	T(E)
0.044	0.064	12.7	B/IBI – T.1	2050	19.9	21.5	57.3	1.4	T(P)
			B/IBI – T.2	2020	19.3	20.7	55.7	0.7	T(P)
			D = 0.188 in., e = 0.250 in., e/D = 1.33 End rupture predicted						
0.044	0.044	none	B – R.1	840	11.9	8.7	34.3	2.1	R(E)
			B – R.2	880	12.5	9.2	35.9	2.9	R(E)/T(E)
0.043	0.053	6.0	B/BI – R.1	1250	14.5	13.3	41.7	2.8	R(E)/T(E)
			B/BI – R.2	1180	13.6	12.2	39.2	2.4	R(E)/T(E)
0.044	0.064	12.7	B/IBI – R.1	1420	13.4	14.6	38.9	1.0	R(E)/T(E)
			B/IBI – R.2	1600	15.3	16.5	44.1	1.8	R(E)/T(E)

[a] Net tensile stress = $P_{max}/(w\text{-}3D)(t_e)$.
[b] Gross tensile stress = P_{max}/wt_o.
[c] Bolt bearing stress = $P_{max}/3Dt_e$.
[d] B—bearing failure, T—tensile failure, R—end rupture. The fracture zone was located at (E)—edge, (N)—neck, or (P)—panel. Symbols following a slash/indicate secondary failures.

sile failure mode, and alternatively D = 0.125 in. for specimens for which incipient bearing failure was predicted.

Specimen Design—Edge Distance

The edge distance e should be designed so as to control the breaking or tearing of the bolt out of the specimen edge. End rupture can always be prevented, in principle, by simply making e large enough, but this is not weight-effective. The optimal value of e below which end-rupture would occur first was derived in previous work by a very simple analysis where various possible modes of bolt break-out were considered.[7] It was shown there that, in most cases, fracture due to transverse tension would be the critical mode, and failures by radial splitting (from the bolt hole out to the edge) were predicted. The failure modes which were actually observed[7] agreed with the predictions in the majority of the cases.

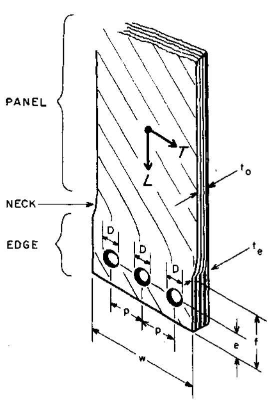

Fig. 4 Schematic diagram of edge reinforced fiber composite. The dimensional parameters D, e, f, p, t_o, t_e, w are defined.

An improved analysis of the stresses and moments in the region between bolt hole and edge has been developed which accounts for possible variations of the distribution of the contact forces between bolt and hole, arbitrary degrees of rotational constraints at the boundaries of this region, and arbitrary variations of the lateral splitting forces introduced by the bolt. A full derivation of this limit analysis is beyond the scope of this paper and has been shown elsewhere.[8] The results expressed a critical lower

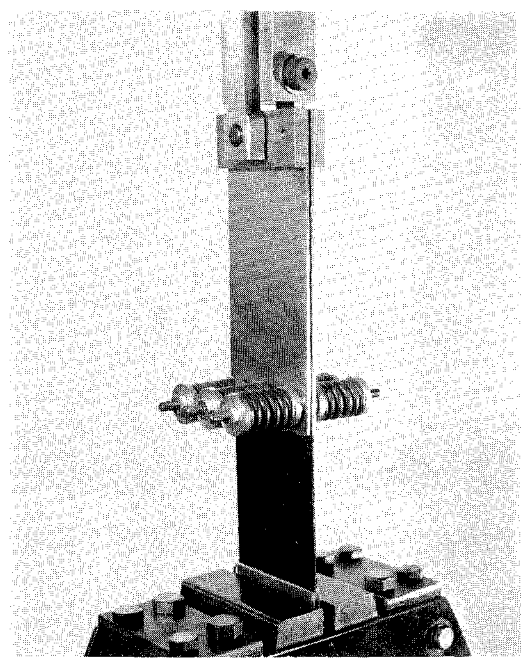

Fig. 5 Photograph of triple-bolted joint tension test setup.

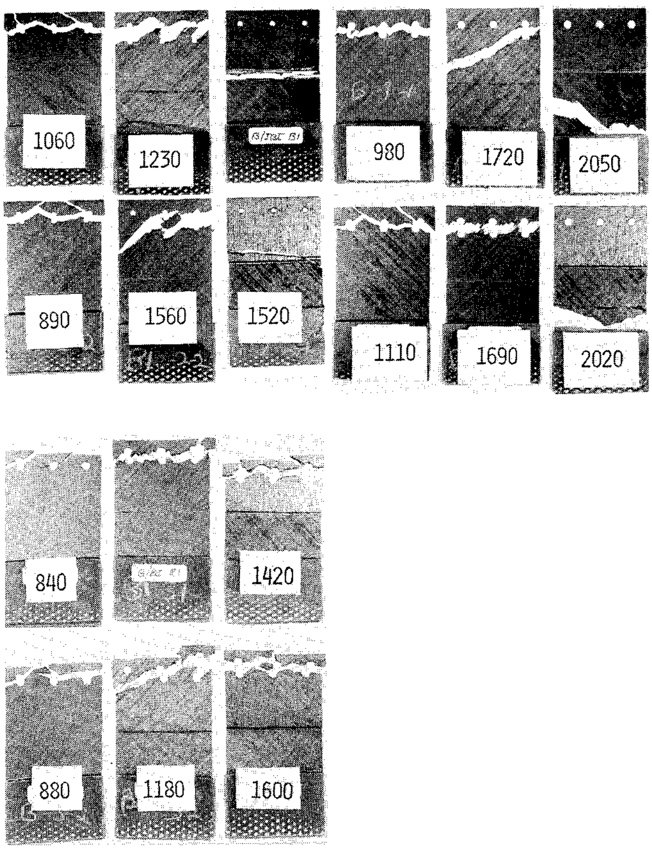

Fig. 6 Fractured triple-bolted joint specimens, designed to promote a) bearing, b) tensile or c) end rupture failures. Specimen width is 2.25 in.

bound for the edge distance ratio e/D as a function of the material strength properties σ_t^T (the transverse tensile strength) and σ_{pb}^L (the longitudinal pin bearing strength). Making e/D smaller than this bound implied with great certainty joint failure by the lateral splitting mode of end rupture, no matter what the actual stress field around the hole may be. Furthermore, reasonable estimates for the appropriate design—e/D tending to suppress premature end rupture were derivable.

The material properties σ_t^T, σ_{pb}^L of [±45] graphite fiber laminates, with and without film additions, were known from previous work,[3] and have been shown here in Table 1. These values, together with the critical lower bound design procedures discussed in full in Ref. 8, allowed us to specify two design values for the end distance ratio. For suppression of the end rupture mode, e/D = 2.5 was

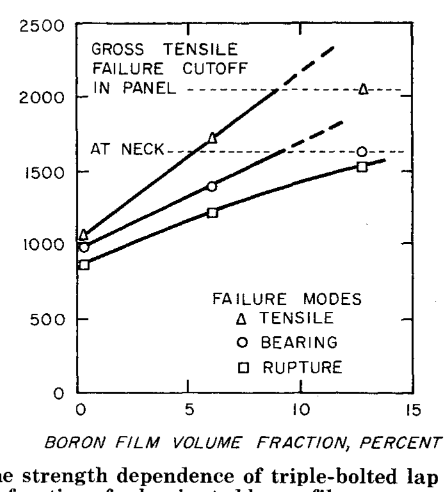

Fig. 7 The strength dependence of triple-bolted lap joints on the volume fraction of colaminated boron film.

Table 3 A comparison of joint strengths in single- and multi—fastened film/fiber composites

Volume fraction of boron film in edge, %	None		6.0		12.7	
number of bolts	1	3	1	3	1	3
Net tensile stress in edge 10^3 psi	9.6	14.5	17.7	19.8	19.3	19.6
Gross tensile stress in panel 10^3 psi	7.2	10.7	15.3	18.0	16.9	21.1
Maximum total load, lb	248	1045	521	1705	641	2035
Load per bolt, lb	248	348	521	568	641	678
Hole elongation at failure, %	2.6	2.5	3.5	1.2	1.0	1.0

called for; to promote premature failure by end rupture, e/D was held to 1.3.

Specimen Design—Pitch Distance

The design of the multi-bolted connections was fixed as a single row of three bolts, spaced at equal pitch p = 0.75 in. Thus the middle bolt had bolt neighbors on both sides, providing a reasonable model for a continuous bolted seam. The over-all specimen width w was made nominally 2.25 in., that is, 3 times the width of the single-bolted lug connections tested in previous work,[3] to allow direct comparisons.

Three bolts in parallel in this fashion require a certain strain capacity in the joint. For example, a 0.005 in. fabrication tolerance in the edge distance of one of three 0.125-in.-diam bolt holes will cause the bolt to seat and transfer load only after the other two bolts have been subject to a 4% relative displacement. Uniform load distribution among three bolts under these condition would therefore require a local strain capacity greater than 4%.

A more severe condition exists in laminates of greater over-all thickness where a single row of parallel bolts is no longer sufficient to carry the normal in-plane load, and joint failure by bolt-shear must be considered. In that case it is necessary to design for multiple bolts arranged in series, that is, in line along the load direction. Series arrangements of bolts are in fact quite common in actual design practice. In the present investigation, however, the laminates were thin enough to need only a single row of bolts (parallel arrangement). This design also permitted us to investigate bolted joints in the order of their complexity.

Specimen Fabrication

The sectioned specimen plates, shown schematically in Fig. 4, were prepared as described for the single-bolted types in Section 4.3 of Ref. 7, except that the number of holes per specimen here was 3. Two drilling jigs, one each for the sizes D = 3/16, 1/8 in. facilitated machining of the bolt holes with good alignment. Holes were drilled with solid tungsten carbide twist drills and a spray mist coolant on a machine shop drill press.

The test specimens numbered 18 and were grouped as follows:

a) Three materials types:
1) ±45 graphite fiber with no edge reinforcement (B)
2) ±45 graphite fiber with 6 vol. % boron film edge reinforcement (B/BI)

3) ±45 graphite fiber with 12 vol. % boron film edge reinforcement (*B/IBI*)

b) Three specimen configurations:
 1) D = 0.188 in., e/D = 2, to promote tensile failure ($-T$)
 2) D = 0.125 in., e/D = 2.5, to promote bearing failure ($-B$)
 3) D = 0.188 in., e/D = 1.3, to promote end rupture ($-R$)

c) Two specimens of each type to indicate degree of repeatability (0.1, 0.2)

Even though the ±45 fiber orientation is not common in actual component design, except perhaps for certain shear web applications, it was chosen as the base-line material for the present work in order to allow a direct comparison of the results with the antecedent research on single-bolted lug configurations.[7] This is discussed further below.

Method and Results of Mechanical Testing

Mechanical Testing

Specimens were protected at their passive ends with fiber glass pads for holding in the Instron wedge grips. The bolted ends were assembled with the lap plates by means of threaded rods, tensioning springs and clamping nuts, as described in Ref. 7. Three pairs of springs preloaded to 200 lb each, provided invariant bolt head clamping pressure. The Instron cross head was operated at 0.02 in./min while load and displacements were continuously recorded. The test was continued to specimen fracture. A photograph of the test apparatus is shown in Fig. 5.

Test Results

The results of the multi-bolted joint tests are summarized in Table 2. The data have been divided into three groups according to design geometry and the associated predicted failure modes. The column headings indicate the observed data (maximum load $P_{\max}$, relative hole elongation at failure δ/D, and the location and modes of the failures as well as the calculated stresses (net and gross tensile stress, bolt bearing stress). These are engineering stresses averaged over the appropriate cross-sectional area, as indicated in the footnotes to Table 2.

In the last column, the observed failure modes are described by type and location, as follows: *B*, *T*, or *R* indicate the bearing, tensile, or end-rupture modes, respectively. This type-code is followed by the location code (in parenthesis): (*E*), (*N*), or (*P*), standing for fracture in the edge, neck, or panel zones, respectively, as defined schematically in Fig. 4.

The cases of bearing failure were identified by visible elongation of the bolt hole, or alternatively when the relative displacement δ/D exceeded 4%. In either event, continued loading of the specimen was possible and tensile or end rupture failures terminated the test, after the specimen could be considered to have failed by the 4% hole deformation criterion. Such secondary failures have been indicated following a slash (/).

The end rupture mode (transverse tension mechanism) was identified by fracture surfaces parallel to the loading direction, connecting at least one of the bolt holes with the edge. Such initial failures were usually followed by secondary tensile fractures running diagnonally or laterally and this has also been indicated by a slash (/) in the last column of Table 2.

The fractured specimens are shown in Figures 6a–c. Some details of these photographs are discussed further below.

Discussion of Results

Failure Mode Prediction

Of the six specimens designed for bearing failure (Fig. 6a), five exhibited relative hole deformations in excess of 4%, as predicted. Five of the six tensile-mode specimens (Fig. 6b) clearly showed tensile fracture, while the sixth (B-T.2) failed by a diagonal, rather than the longitudinal, mode. Finally, the set of specimens designed for end-rupture by transverse tension (Fig. 6c), did fail by that predicted mode in four cases out of six. The other two (B-R.1 and B/BI-R.2) failed by diagonal tension in the end region. This is not quite the same as the transverse tension mode, nevertheless it was a kind of end-rupture. The three sets of specimens thus in general behaved as predicted, indicating that rational design criteria for the fiber/film combination may be realized with relatively little additional development.

Effectiveness of Film Reinforcement

In a bolted joint, the three defined failure modes may be considered as independent mechanisms, analogous to three separate links in a chain. To strengthen the chain, it is necessary to augment the strength of each link equally and simultaneously, since the weakest "link" will always govern the over-all strength.

Boron/polyimide film exhibited this power of reinforcing all three failure mechanisms (links) of bolted joints in fibrous composites (the chain), as shown in Fig. 7 where the experimentally observed tensile load capacities of triple-bolted joint specimens have been plotted as a function of the boron film volume fraction. The incremental addition of film to the [±45] fiber composites raised the load capacities approximately in proportion to the level of the added film, and it did so with comparable magnitude in all three groups of specimens where tensile, compressive, or the end-rupture mode occurred. This indicated clearly that in these tests the film was close to uniformly effective as a tensile, compressive, and shear reinforcement, owing, it is believed, to its properties of continuity and isotropy in the film plane.

In two cases, the joints were over-reinforced by the film additions, and ordinarily tensile fractures in the gross section of the panel (for B/IBI − B, see Fig. 6a) or of the neck (for B/IBI − T, see Fig. 6b) terminated the tests. In the duplicate samples B/IBI − T.1 and −T.2, particularly, the physical appearance of the failed specimens suggested that the 12% film-reinforced bolted ends represent a better load-transfer design than the conventional fiberglass pad and wedge-grip arrangement at the passive ends, since the fracture zones extended into the passive grip area, whereas the bolted ends of the specimens appeared to be undamaged.

Multi-Bolt vs Single Bolt Behavior

The main purpose of this investigation was to show experimentally whether the reinforcing properties of boron film could be applied usefully in multi-bolted joints. The actual breaking loads of the triple-bolted specimens were in fact higher than three times the single bolt joint loads recorded in the antecedent work,[3] while the observed load/displacement behavior (that is, the joint stiffness) was much the same in both investigations.

Table 3 makes this comparison explicit. Multi-bolt results were averaged from Table 2 of this report, while the comparable single bolt data have appeared in Tables X, XII, and XIII of Ref. 7. There seems to be good evidence here that excessive material stiffness was not a problem. Quite to the contrary, these results seemed to identify boron film as a joint strengthening material for multi-bolted joint configuration in [±45] fibrous composites.

Conclusions

These experiments gave consistent empirical evidence for the joint strengthening potential of colaminated B/PI film, in the special case of thin (~0.044 in.) [±45] carbon fiber composites. We do not, at this stage, have an explanation for this phenomenon in terms of analytical mechanics. It may be supposed, however, that the major contribution of B/PI reinforcing film is its shear stiffness and its effectiveness as an interlaminar shear coupling element between skewed fiber plies, since the normal tensile strength of the film material (about 40–50,000 psi) is less than the longitudinal tensile strength of reinforcing fibers.

Work[9] is presently in progress to investigate the more general cases of thicker laminates (16 ply of carbon fiber with O_2, ±45 geometry), in which single bolt and three-bolts-in-line (series) arrangements will be tested in static and fatigue loading. This work is expected to corroborate with greater generality the experimental results that have been reported here.

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