NOTCH SENSITIVITY OF CFRP PLATES UNDER COMPRESSION

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This paper describes the static compressive response of carbon fibre reinforced plastic (CFRP) laminates with a single or two open holes. Failure is due to 0° fibre microbuckling surrounded by delamination. This is an instability failure mode which initiates at the hole boundary at approximately 80% of the ultimate strength.

A two-dimensional finite element analysis is performed to study the interaction effect between a pair of 5 mm diameter holes as a function of hole spacing; for no interaction the hole centres should be placed at least four hole diameters apart. The strength of plates with a single hole is also predicted using a recently developed cohesive zone fracture model.

INTRODUCTION

The notched compressive strength is a significant limiting property when designing composite structures on the basis of strength. The compressive strength of modern CFRP plates is typically 60%-70% of their tensile strength and is further reduced by the presence of fastener holes and cut-outs. Previous work by Soutis *et al.* [1-3] has shown that failure of T800/924C CFRP notched laminates is due to microbuckling of the load-bearing fibres aligned with the loading direction (0° fibres). Strength reductions of more than 40% were observed.

In the present paper the effect of hole spacing upon the compressive strength of carbon fibre-epoxy plates is discussed. This is important for the positioning of bolt holes and for the assessment of in-service damage which may comprise a number of closely spaced defects. The compressive strengths for laminates with a single and two holes are presented. A 2-D finite element analysis is performed to calculate the stress distribution near the holes and to find the minimum hole-hole separation for no hole interaction. The notched compressive strength is predicted by using a new fracture model [3].

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EXPERIMENTAL PROCEDURE

Multi-directional laminates were autoclaved from Toray T800 carbon fibres pre-impregnated with Ciba Composites BSL 924C epoxy resin. The proportion of 0° layers was varied from 100% to 17%, Table 1. All multi-directional laminates were symmetric about the mid-plane, consisted of 24 plies and were ≈3 mm thick

Compression tests were performed on unidirectional specimens of gauge section 10 mm x 10 mm (laminate designation L0) using a modified Celanese test rig [4]. The multi-directional specimens (laminates L1 - L6, Table 1) were of gauge section 116 mm x 50 mm, and were tested using an anti-buckling device to prevent Euler buckling during the test. Aluminum end tabs were bonded to all specimens.

In the notched coupons, circular holes of diameter 4 mm - 25 mm were drilled symmetrically about the specimen mid-point. Four different hole configurations were tested: **a)** single hole; **b)** a pair of holes transverse to the loading axis; **c)** two holes in the longitudinal direction and **d)** two holes at 45° to the loading axis. For the two hole configuration, the hole diameter was d=5 mm and the hole centre-centre spacing ranged from a=1.5d to a=3.5d. Tests were conducted at a displacement rate of 0.017 mm s^{-1}; strain gauges were employed on both faces of test pieces to measure axial strain, and to monitor the degree of bending [1,2]. Five tests were performed for each lay-up and hole configuration.

TEST RESULTS

Unnotched specimens

In the unidirectional $[0_8]s$ laminate failure occurs at an average failure stress $\sigma_f = 1600$ MPa , and an average failure strain $\varepsilon_f = 1.1\%$. In comparison, the average tensile strength for this material equals 2400 MPa. Post failure examination of the fracture surfaces revealed that failure is by fibre microbuckling or kinking [2]. The fibres break at two points, and create a kink band inclined at an angle 5-15° to the transverse direction. The fibres within the band rotate by ≈30° from the initial fibre direction and the kink width is ≈60 μm.

In the multi-directional materials, laminates L1-L6, failure is always by microbuckling of the 0° plies, and is accompanied by delamination between the off-axis and 0° plies, and by plastic deformation in the off-axis plies. The scatter in strength is less than 10% and the failure strain is almost independent of lay-up and comparable to the failure strain of the unidirectional laminate, see Table 1.

TABLE 1- Compressive strength properties of T800/924C composite.

Lay-up	% 0-plies	σ_{un}/MPa	E^{+}_{yy}/GPa	ε_f/%	$(K_c/\sigma_{un})^2$/mm
L0	100	1615	160	1.1	-
L1	67	1010	109	1.04	2.50
L2	50	810	88	1.1	3.29
L3	50	670	78	0.96	2.3
L4	50	820	84	1.05	2.38
L5	25	568	58	1.07	5.6
L6	17	428	41	1.35	6.68

+ Laminate stiffness in the loading direction
L1: $[(\pm45/0_4)_2]_s$, L2: $[(\pm45/0_2)_3]_s$, L3: $[(0/90_2/0)_3]_s$, L4: $[\pm45/0_2/90_2/0_2/90_2/0_2]_s$,
L5: $[(\pm45/0/90)_3]_s$, L6: $[(\pm45)_2/0/(\pm45)_2/0/\pm45]_s$

Notched specimens

All specimens failed from the hole in a direction transverse to the loading axis. The remote failure stress of the single hole specimen σ_n normalised by the unnotched failure stress σ_{un} is shown in Fig. 1 as a function of hole radius R normalised by semi-width w of the specimen. The notch strengths are bounded by the simple failure criteria of ideally brittle response and the ideally notch insensitive response, Peterson [5]. For small holes the data lie above the ideally brittle curve due to the development of sub-critical damage in the form of microbuckling, delamination, matrix plasticity and matrix cracking. This damage reduces the stress concentration at the edge of the hole and delays final failure to higher applied stresses. It should be noted from Fig. 1 that the angle-ply dominated laminate L6 is less notch sensitive than the lay-ups L1-L5 which is dominated by 0° layers.

This is consistent with the value of the damage parameter $(K_c / \sigma_{un})^2$ for each lay-up, shown in Table 1. The damage parameter $(K_c / \sigma_{un})^2$ has the dimensions of length, and gives an approximate measure of the flaw size which the material can tolerate before the failure load becomes dependent upon flaw size [3].

The failure loads for L2 laminate containing two 5mm holes are presented in Fig.2. Hole-hole interaction ceases and the failure load, P_{oo}, equals that for a specimen containing a single hole, P_o, when the hole-hole centre spacing exceeds four times the hole diameter. The failure load for the specimens with two holes parallel to the loading axis exceeded that for a specimen containing a single hole by up to 20%. This is consistent with the reduction in stress concentration factor (K_o/K_{oo}) at the edge of the hole when a single hole is replaced by two holes with their axis parallel to load direction, Fig.3. Note that for this two hole geometry the net sectional area is equal to that of the specimen with one hole. The stress concentration factor (SCF) is determined by a 2-D finite element analysis [6].

Strength predictions

A novel engineering model has been developed by Soutis and co-workers [3] to predict the compressive kinking failure of laminated carbon fibre epoxy panels containing a single hole. The crack model is of the large-scale bridging type and assumes that a kink band emanating from the hole behaves like an *overlapping mode I crack,* with normal crack bridging compressive stresses that drop linearly with crack overlap from a maximum value of the unnotched compressive strength. The area under the curve of crack bridging stress versus overlap displacement is derived from a separate compressive kink propagation experiment, wherein the "toughness" (K_c) of a specimen containing a sharpened long slit is measured, Table 1. This simple crack bridging model gives an accurate prediction of failure load for a range of hole sizes and laminates, Fig.4. The model is accurate to within 10% for the L1 (0° dominated laminate) but is less accurate for laminate L6 which is composed mainly of ±45° plies. For laminate L6 the damage is diffuse in nature, and a cohesive zone presentation for damage becomes less appropriate.

CONCLUDING REMARKS

The compressive failure of unidirectional and multidirectional unnotched carbon/epoxy composites is controlled by fibre microbuckling. The off-axis plies have only a small influence on the compressive failure strain.

The notched strength of the six lay-ups studied lay above the ideally brittle response, due to development of subcritical damage in the form of 0° microbuckling, delamination and matrix cracking. The damage reduces the stress concentration at the edge of the hole and delays final failure to higher applied stresses than those predicted by the maximum stress criterion.

The effect of hole-hole spacing upon the compressive strength is similar qualitatively to the effect upon the SCF at the edge of each hole. For holes transverse and at ±45° to the loading axis a decrease in hole-hole spacing gives rise to an increase in SCF and a decrease in compressive strength. For holes aligned with the loading axis, a decrease in hole-hole spacing causes the SCF to decrease and the compressive strength to increase. For $a/d \geq 4$ the holes stop to interact.

The cohesive zone model [3] is able to predict the effects of hole size and lay-up upon the compressive strength. However, this engineering model at present applies only to plates with a single hole and takes as its input the in-plane compressive fracture toughness of the laminate. Further work is required to understand the microstructural origins of the compressive fracture toughness, and to predict it for a multi-directional laminate from lamina or material data.

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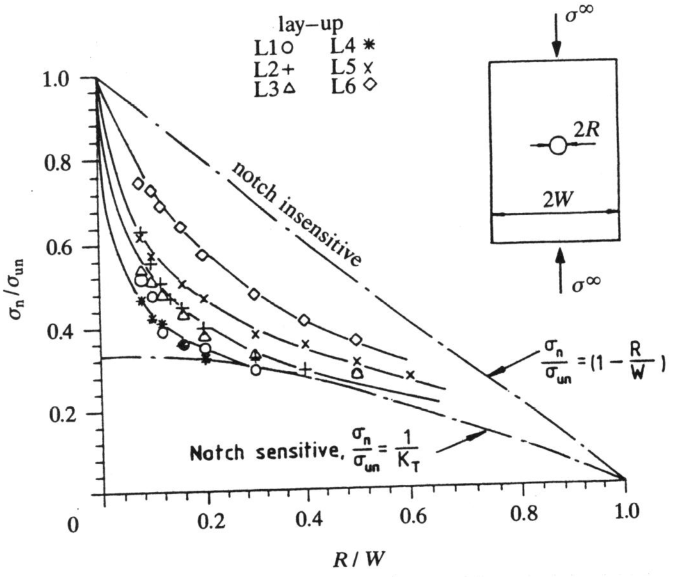

Figure1 Effect of hole diameter on the compressive strength of T800/924C plates. The notch sensitive curve shown is for the quasi-isotropic laminate L5.

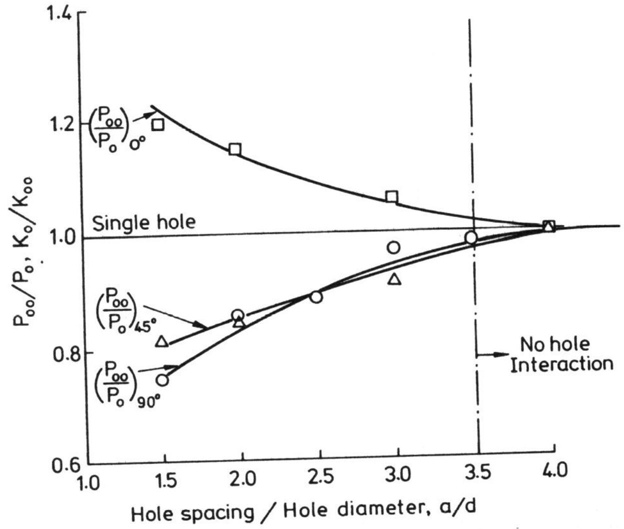

Figure 2 Failure load of specimen with two holes normalised by the strength of plate with a single hole (L2 laminate).

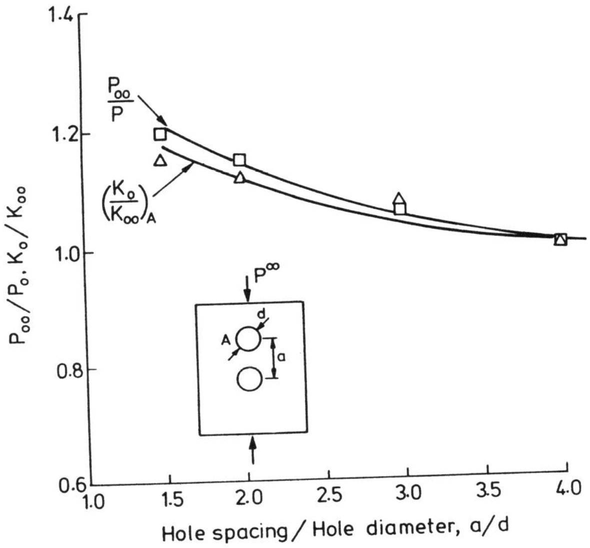

Figure 3 Hole-hole interaction in specimens with two holes parallel to the loading axis (L2 laminate).

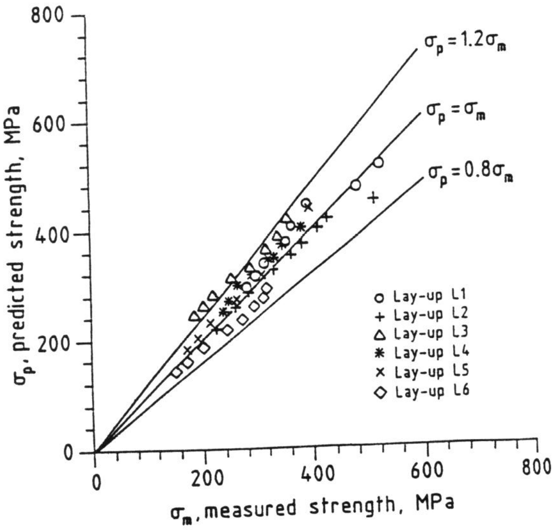

Figure 4 Predicted notched compressive strength plotted versus measured values for various T800/924C laminates.