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Effects of Compression-Compression Fatigue on Balanced Graphite/Epoxy Laminates with Holes

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Experimental investigations have been conducted to determine the effect of stacking sequence and ply orientation on the compression-compression fatigue behavior of graphite/epoxy composites. Static compression tests of $[\pm 45/0]_s$ and $[0/\pm 45]_s$ laminates were carried out prior to compression-compression fatigue tests. These laminates, which were the facings of sandwich beams, were of three different configurations: 1) unflawed, 2) a 0.25-in.-diam hole and 3) a 0.25-in.-diam hole clamped by washers held together by a loose fitting bolt. A much larger number of compression-compression fatigue tests on laminates containing 0.25-in-diam circular holes were carried out on the laminate systems denoted by $[0/\pm 30]_s$, $[\pm 30/0]_s$, $[0/\pm 45]_s$, and $[\pm 45/0]_s$. Damage initiation and growth was monitored during the tests. Comparison was made of failure modes between static and fatigue tests.

Background

IT has been demonstrated in previous investigations that for epoxy based graphite composite materials, compression-compression cyclic loading markedly reduces fatigue life. Ryder[1] tested two different unflawed graphite/epoxy laminates in constant amplitude compression fatigue at 10 Hz. Though no general method of predicting fatigue life is proposed, several important observations are noted. Both laminates were first tested statically in compression and tension. Ryder notes that the static compression strength data scatter is higher than for the same laminate in tension. In addition, the two different laminates exhibit different failure modes. Fatigue testing also showed a higher data scatter for compression. Failure modes in fatigue differ from static failure modes of the same laminate.

Rosenfeld and Huang[2] ran a series of fatigue tests on $[(0/\pm 45)_s]_3$ and $[(\pm 45/0)_s]_3$ graphite/epoxy laminates with and without holes. Tests were run at load ratios $R = 0$, -1, $-\infty$ with and without antibuckling guides. Their findings show that the introduction of compression loads in fatigue reduces life. Reversed loading, $R = -1$, is the most severe case. The laminate with a 0-deg ply on the surface had a significantly shorter life to first visible damage than did the laminate with ± 45-deg surface plies. The observed damage was delamination at the hole edge. For compression loading, the delamination became progressively more severe. Life to failure seems to be independent of stacking sequence. In addition, data from specimens of different widths correlates when plotted as a function of gross stress. From this observation, Rosenfeld and Huang conclude that the final failure mode is compressive buckling of delaminated sections.

Hahn[3] suggests that damage in composites can be any one or all of the following: fiber breaks, resin cracks, and delaminations between the plies of the laminate. All of these cracks are not separate but interconnected, making identification of crack paths highly complex.

These observations are obviously in contrast to the observed fatigue behavior in metals. Because of the heterogeneity inherent in composites, cracks no longer have the same implications as those in metals. Whereas fatigue in metals is understood in terms of nucleation and growth of a single dominant flaw, fatigue in composites is much more complex. From these findings it is clear that delamination plays an important role in compression fatigue. In order to understand this damage mechanism, it is necessary to examine three-dimensional elasticity solutions.

Pipes and Pagano,[4] Puppo and Evanson,[5] and Mandell[6] among others have demonstrated the importance of interlaminar stress states inherent in the three dimensionality of the composite materials. These stresses: τ_{xz}, τ_{yz} as well as σ_z, are confined to a region of width equal to the laminate thickness. Outside of this "free-edge effect" zone, laminate theory stresses are recovered. Of particular interest is the effect of stacking sequence on the magnitude and sign of these stresses. For example, a compressive σ_x will produce a distribution of σ_z which is predominantly tensile in a $[0/\pm 45]_s$ laminate while it is predominantly compressive in a $[\pm 45/0]_s$ laminate. It has been postulated that tensile interlaminar normal stresses aggravate observed delamination.

Tang[7] and Levy et al.[8] among others have shown that circular holes represent a free edge that induces severe interlaminar stresses. Delamination is observed to initiate at the hole. The delamination progresses to the point at which the delaminated section buckles, causing overall laminate failure.

The present investigation was concerned with the following three questions.

1) What are the failure modes of laminates in both static and fatigue loading?

2) How does the presence of a constraint (in the form of a washer clamped around a hole) affect the failure mode of a flawed laminate in both static and fatigue loading?

3) What is the effect of ply orientation on the fatigue life of flawed laminates?

The four different laminates used in this investigation were: $[0/\pm 45]_s$, $[\pm 45/0]_s$, $[0/\pm 30]_s$, and $[\pm 30/0]_s$.

To investigate the difference in failure modes between static and fatigue loading and how clamping affects laminate strength, the $[0/\pm 45]_s$ and $[\pm 45/0]_s$ laminates were used.

To investigate the effects of a change in ply orientation within the balanced laminate on the fatigue life, additional tests were conducted using $[0/\pm 45]_s$, $[\pm 45/0]_s$, $[0/\pm 30]_s$, and $[\pm 30/0]_s$. Data from this second series of tests consisted of damage accumulation sketches made after interrupting the tests periodically prior to catastrophic failure of the laminate.

Experimental Procedure

Hercules type AS1/3501-6 graphite/epoxy preimpregnated 12-in.-wide tape was used for all specimens. Laminates were hand layed-up then cured in a heated platen press using the

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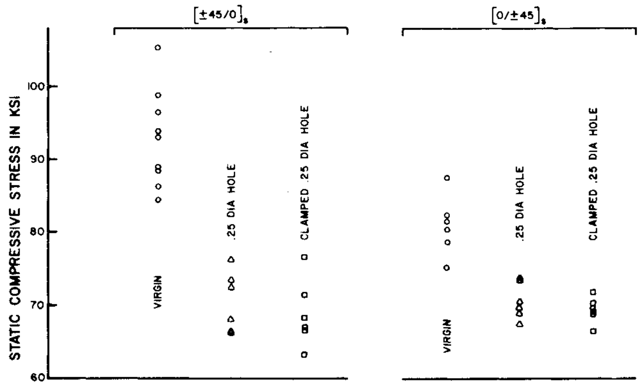

Fig. 1 Static compressive strength results.

following cure cycle: 18 min at 275°F and 15 psia followed by 30 min at 300°F and 100 psia, then another 35 min at 350°F and 100 psia. No postcuring was performed. Laminates were cut in 1.75-in. (44.45-mm) widths (nominal) from 12×14-in. (304.8×355.6-mm) panels using a water cooled diamond crusted wheel. With the protective peel-ply still attached the edges of each specimen were then sanded with 180 grit sandpaper to assure high-quality edges.

For the flawed laminates, 0.25-in.- (6.35-mm-) diam holes were hand drilled using first a diamond crusted drill then a diamond crusted reamer. The holes were positioned in the geometric center of each laminate and drilled with the peel-ply still attached.

Because the laminate is thin [0.00525 in. (1.34 mm) per ply], the buckling load is low. In order to induce compressive failure of the laminate prior to elastic instability, a means of stabilizing the laminate is required. The method chosen was to bond the laminate to an aluminum honeycomb core. American Cyanamid 12.5 pcf (25.4 mm thick) aluminum honeycomb was used as the core material. The bonding adhesive was American Cyanamid FM123-2, a high-strength film adhesive.

The static specimens were tested in a four-point bending fixture. They used a 3.5-in. (88.9-mm) moment arm and a 4-in. (101.6-mm) gage section. A Baldwin-Emery SR-4 testing machine was used for these tests. Small aluminum loading tabs were used to distribute point stresses and to protect the laminate from local crushing. A Baldwin SFU-1U universal fatigue machine was used for fatigue tests. The machine operates at a fixed frequency of 30 Hz. A double cantilever bending fixture was used. The fixture provides a constant bending moment throughout the gage section. The gage section used was 5.25 in. (133.35 mm) and the moment arm 3 in. (76.2 mm). The tension faces of these sandwich beams consisted of four unidirectional plies for the ±45 family and six unidirectional plies for the ±30 family.

The clamped holes were made by first drilling as described then inserting a 3/16-in. (4.7625-mm) bolt with washer and applying a torque of 25 in.-lb (2.82 N-m). It was postulated that if tensile interlaminar normal stress caused initial delamination, then a large compressive prestress would delay, if not eliminate, such tendency.

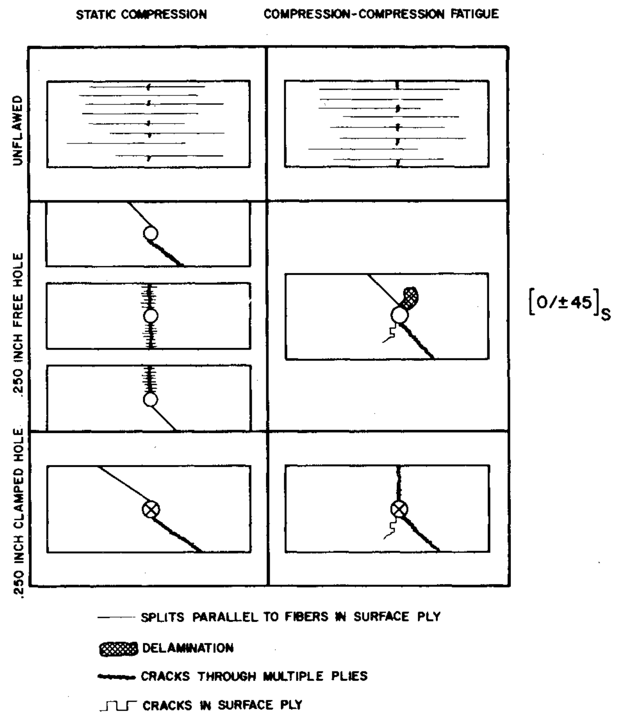

Fig. 2 Schematic representations of failure modes, $[0/\pm45]_s$ laminate.

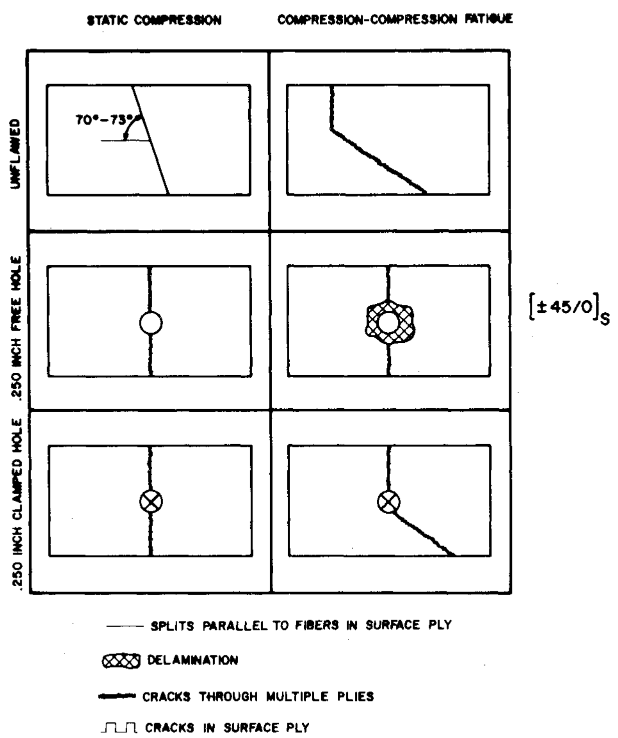

Fig. 3 Schematic representations of failure modes, $[\pm45/0]_s$ laminate.

Discussion of Results

Static Compression Tests

Static compression test results for the $[0/\pm45]_s$ and $[\pm45/0]_s$ laminates are shown in Fig. 1. A total of 39 specimens were tested. These laminates were of three different configurations: 1) unflawed, 2) a 0.25-in.-diam hole, and 3) a 0.25-in.-diam hole clamped by washers held together by a loose fitting bolt. The following observations can be made.

1) The mean strength of the $[\pm45/0]_s$ specimens is higher than for the $[0/\pm45]_s$ specimens. This agrees with the notion that the free edge interlaminar stresses normal to the plane of the laminate are compression for the $[\pm45/0]_s$ system and tension for the $[0/\pm45]_s$ system. The interlaminar tension at the free edge degrades the compression strength.

2) Once a hole is drilled, the mean strengths for the two systems are not appreciably different. This suggests that the strain concentrations caused by the holes dominate the free edge effect.

3) The clamped hole specimens of both the $[\pm45/0]_s$ and $[0/\pm45]_s$ systems exhibit about the same mean strengths.

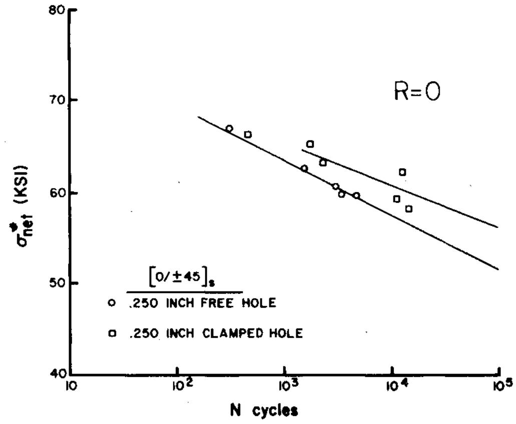

Fig. 4 Fatigue: free hole vs clamped hole.

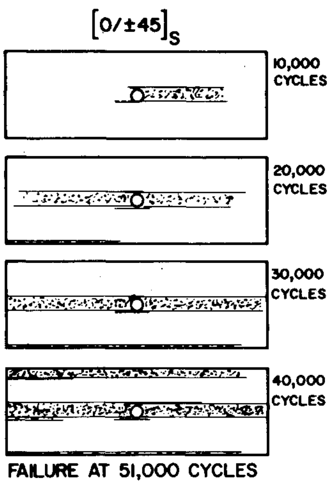

Fig. 5 Fatigue damage accumulation sketch $[0/\pm45]_s$; failure at 51,000 cycles.

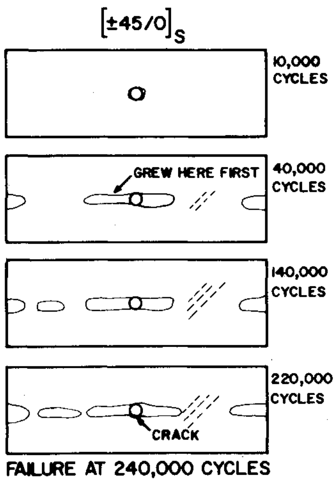

Fig. 6 Fatigue damage accumulation sketch $[\pm45/0]_s$; failure at 240,000 cycles.

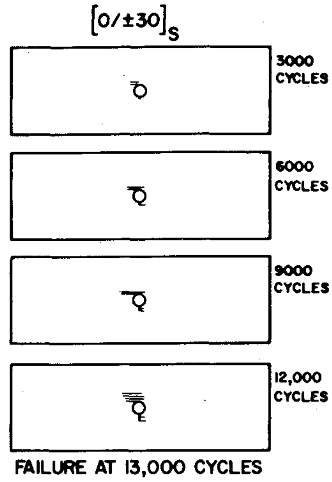

Fig. 7 Fatigue damage accumulation sketch $[0/\pm30]_s$; failure at 13,000 cycles.

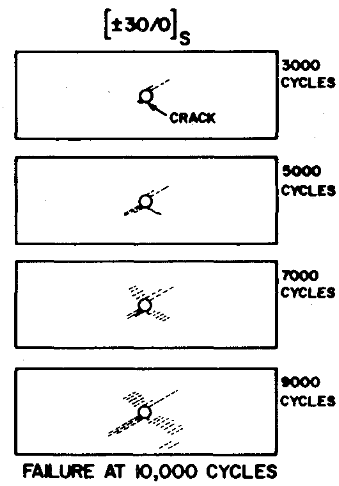

Fig. 8 Fatigue damage accumulation sketch $[\pm30/0]_s$; failure at 10,000 cycles.

4) The $[\pm45/0]_s$ specimens appear to exhibit a larger scatter than do the $[0/\pm45]_s$ specimens.

Failure Modes in Static and Fatigue

Schematic representations that compare the static and fatigue failure modes of the $[0/\pm45]_s$ and $[\pm45/0]_s$ laminates as observed in our fatigue tests are shown in Figs. 2 and 3, respectively. A total of 39 fatigue specimens which corresponds exactly with the static specimens reported earlier were tested. Observations are as follows.

1) There are significant differences in the failure modes between the two laminate systems.

2) The unflawed $[0/\pm45]_s$ specimens exhibit the same kinds of failure in both static amd fatigue loading. This is not true for the $[\pm45/0]_s$ system.

3) Generally, the fatigue modes of failure are different than the static modes (with the exceptions noted in 2). This points up the added complexities involved in damage tolerance and durability analyses for composites. In metals the final failures, whether due to cyclic or static applications of the loads, obey the same fracture mechanics formula. This fortuitous situation does not apply to the behavior of the advanced composites. The varieties of failure modes and the differences in failure modes between static and fatigue in the advanced composites points up the need for continued research.

4) There does appear to be some beneficial effect of the clamping action provided by the washers, as can be seen in Fig. 4. More data are required but if the trends exhibited in Fig. 4 are verified, then perhaps the beneficial effect of the clamping provided by mechanical fasteners can be used for design.

Fatigue and Ply Orientation

A much larger number of compression-compression fatigue tests ($R=0$) on laminates containing 0.25-in.-diam holes were carried out on the laminate systems denoted by $[0/\pm45]_s$, $[\pm45/0]_s$, $[0/\pm30]_s$, and $[\pm30/0]_s$. Damage initiation and damage growth was monitored during the tests. Figures 5-8 illustrate typical patterns for the four systems. These sketches were made from visual and tactile inspection only. Note that the dotted lines represent matrix cracking in the surface ply while solid straight lines represent through-cracks in the surface ply. Shaded areas represent surface plies that have buckled away from the subplies while closed curves represent delamination within the laminate. This damage was detectable due to the fact that when the machine was stopped, half the dynamic load was still being applied in the form of a

Table 1 Essential fatigue results

	No. of spec.	Cycles 10^3 Min N	Max N	Weibull parameters α	β	Max stress, ksi
$[0/\pm 30]_s$	12	1	24	1.4	9	49
$[\pm 30/0]_s$	12	3	37	1.4	13	53
$[0/\pm 45]_s$	11	6	121	1.6	50	49
$[\pm 45/0]_s$	12	10	331	1.6	190	49

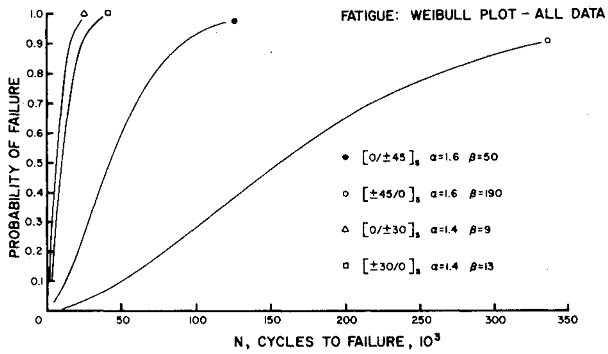

Fig. 9 Fatigue; Weibull plot, all data.

static load so that any internal delamination appeared as buckled ridges on the surface.

There was a large difference in the minimum and maximum number of cycles, N, to failure as shown in Table 1. The maximum likelihood estimates for the parameters α and β in the Weibull equation

$$P(N) = 1 - \exp[-(N/\beta)^{\alpha}]$$

are also shown in the table and the plots for the Weibull distributions are shown in Fig. 9. There is a large variation in N as graphically illustrated in the figure.

Damage at the hole was visually detected very early in the cyclic testing in all of the specimens. For example, there are 11 specimens in the $[0/\pm 45]_s$ group. Of these one failed at 6000 cycles. Nine of the remaining 10 showed visually discernible damage at 10,000 cycles. The remaining specimens which did not exhibit damage at 10,000 cycles exhibited damage at 20,000 cycles. The $[\pm 45/0]_s$ group of specimens exhibited similar behavior. For the other two groups, $[0/\pm 30]_s$ and $[\pm 30/0]_s$, most of the specimens exhibited damage at the hole by 3000 cycles. These results lead to the following comments.

1) Fiber breaks, matrix cracks, and delaminations characterize the damage accumulation associated with each of the four laminate systems. Considerable damage tolerance was demonstrated by the two groups which had ±45-deg plies in that the numbers of cycles from visual detection of damage at the hole to final failure were large. Why the two groups which had ±30-deg plies did not exhibit this same damage tolerance needs further investigation. Examples of failure modes are shown in Fig. 10 for the four systems.

2) It can be postulated that the initial damage at the hole immediately reduces the high strain concentration caused by the hole because the strain concentration exists only if the surface of the hole and the surrounding material remains continuous. Once the surface of the hole is damaged by splits or delaminations, then the "soundness" of the structure is breached and the continuous strain fields that lead to the high concentration cannot exist. In metals, the initiation of cracks at a hole means a transition from a stress concentration factor approach to a fracture mechanics approach in order to account for the theoretically infinite concentration at the crack tip. Thus, unlike metals and in direct contradistinction to metals, the initiation of damage at a hole leads to a reduction of the strain concentration and may in part explain the damage tolerance of these filamentary systems. This aspect of the behavior of composite materials, if exploited, would have great technological impact.

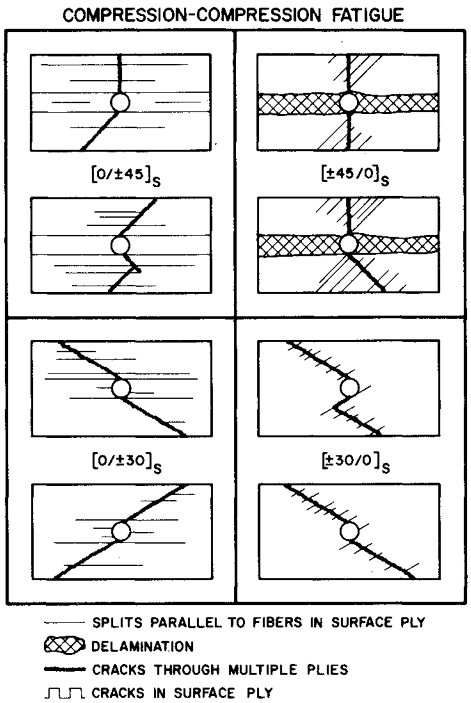

Fig. 10 Schematic representations of failure modes; $[0/\pm 45]_s$, $[\pm 45/0]_s$, $[0/\pm 30]_s$, $[\pm 30/0]_s$.

3) These results seem to indicate the range of cycles at which damage can be detected at the hole is appreciably less than the range of c'cles which encompasses failure. This may be due in part to tl.e fact that the observed damage mechanisms increases in complexity with the accumulation of loading cycles.

Acknowledgments

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