Damage and Fracture of Composite Materials under Cyclic Loads

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ABSTRACT

The response of composite laminates to long-term, cyclic loading conditions is dependent on mode and level of loading, material system, geometry, and laminate stacking sequence. An overview of basic damage mechanisms in notched laminates is presented. The relationships between damage and long-term response, specifically changes in residual tensile and compressive strength and life, are discussed for several composite systems with different matrix materials subjected to reversed cyclic loading.

KEY WORDS

Composite materials, damage, fatigue, fracture, strength, stiffness, life, long-term behavior.

Composite materials offer many opportunities to incorporate innovative concepts into the design of structures to improve their efficiency and performance. Weight savings, ease of manufacturing, lifetime cost effectiveness, and the ability to design materials with specified properties make composites very attractive to materials users. Composite materials have given new meaning to the concept "design for performance." Many performance statements for machines, components, and structures require that damage tolerance and/or durability specifications be satisfied. This means that factors which govern the ability of a material to maintain certain performance critical properties, such as strength and stiffness, during the expected lifetime must be understood and incorporated into the material before optimized damage tolerance and durability can be designed into the structure.

Until recently, damage tolerance of composite materials has been evaluated to measure resistance to fracture under primarily monotonic loading conditions. Interlaminar fracture toughness, open hole compressive strength, and compressive strength after impact serve as common measures of the ability of thermoset and thermoplastic matrix composites to resist damage and maintain properties under monotonic, short-term loading conditions. However, the properties which measure damage tolerance under short-term conditions are not good indicators of damage tolerance and performance under long-term loading conditions (O'Brien, 1986; Curtis, 1987; Baron and Schulte, 1987; Bakis et al., 1988b).

BASIC DAMAGE MECHANISMS

Damage modes, such as matrix cracking, delamination, and fiber fracture are present under both short- and long-term loading conditions. However, the number, intensity, distribution, and interactions of the damage mechanisms are much different under the two loading conditions. For example, matrix cracks which initiate and increase in density early in life under long-term, cyclic loading conditions reduce the critical value of strain energy release rate necessary to initiate delamination (Wang, et al., 1985). Also, delamination growth under cyclic loading is greatly influenced by the mode II component of strain energy release rate, whereas initiation under monotonic conditions is largely mode I controlled. Furthermore, threshold values of critical strain enrgy release rate for edge delamination driven response under cyclic loading are much lower than those under monotonic loading (O'Brien and Murri, 1987). The intensity and distribution of fiber fractures are also different for monotonic and cyclic loading. Under cyclic loading, fibers fracture in widely dispersed arrays throughout life and localize in regions of high stress concentration associated with matrix damage before fracture (Jamison, 1986; Razvan et al., 1987).

Although descriptions of damage mechanisms can be generalized, a more complete understanding of damage and its influence on performance, especially long-term performance, must consider the modes and levels of loading, material systems, geometry, and stacking sequence of plies. This paper presents an overview of damage in notched composite laminates and discusses the consequences of damage during long-term cyclic loading. Specific attention is given to those factors which change strength and limit life, as defined by fracture.

DAMAGE IN NOTCHED LAMINATES

The different responses of notched composite laminates to modes of loading can be illustrated with the aid of Fig. 1, showing three nominally identical, notched laminates which failed due to different forms of tensile loading. Each specimen is an 8 ply, T300/5208 graphite epoxy laminate with a $[45,90,-45,0]_s$ stacking sequence. The specimens are 1.5 in. wide and have a 0.375 in. diameter center hole which was drilled using a diamond core drill.

Figure 1a is a fractured specimen which was subjected to monotonic tensile loading. The mean tensile strength of specimens loaded monotonically to fracture was 48.6 ksi, based on net section area. The fracture surface in each ply is regular and well defined and passes through the hole. Figure 1b shows a specimen which was cyclically loaded with a maximum stress of 85% of the notched tensile strength at R=0.1 for 200,000 cycles or approximately 91% of expected fatigue life. The damaged specimen was then loaded in monotonic tension to failure. The mean residual tensile strength of damaged specimens for this loading condition was 63.2 ksi, or 130% of the initial strength of undamaged specimens. A specimen which failed due to cyclic loading at a maximum stress of 85% of the notched tensile strength at R=0.1 is shown in Fig. 1c. The presence of fatigue damage prior to fracture is clearly indicated by the irregular fracture surfaces in Figs. 1b and 1c, although the specimen which failed in fatigue at 85% of initial strength has much more damage and a different fracture surface in each ply.

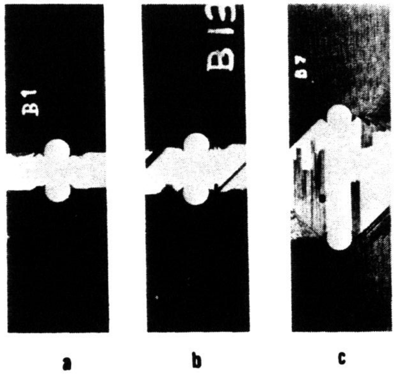

Fig. 1. Fracture surfaces of notched, quasi-isotropic graphite epoxy laminates:
(a) monotonic tension, no prior damage;
(b) monotonic tension after 200,000 cycles at $\sigma_{max} = 0.85\sigma_{ult}$; and
(c) fatigue failure after 220,000 cycles at $\sigma_{max} = 0.85\sigma_{ult}$.

The distributed nature of fatigue damage and the effect of different cyclic load levels on fracture can be seen in Fig. 2. Fatigue damage in woven graphite polyimide notched laminates is more dispersed for low cyclic stress, long life situations that it is for high cyclic stress, short life situations. The fracture surfaces change from localized at high stress levels to irregular and widely distributed at low stress levels.

Damage due to cyclic loading produces changes in the response of composite laminates, as indicated by the strength and stiffness change data shown in Fig. 3. The data correspond to graphite epoxy specimens, such as those shown in Fig. 1b, cyclically loaded to selected numbers of cycles and monotonically loaded to fracture. Stiffness measurements were made using strain data from an axial extensometer located across the center hole (Kress and Stinchcomb, 1985). The three stages of stiffness change are due to initiation, progression, and interaction of damage events throughout the lifetime and are representative of the fatigue response of notched and unnotched composite laminates. The increase in residual tensile strength realtive to the initial notched strength is due to a change in the effective geometry of the hole produced by damage and will be described later. Strength increase corresponds to the first and second stages of stiffness change during the first 80 to 85% of fatigue life. During the final stage of life, damage weakens the ligaments of supporting material on each side of the hole, stiffness decreases rapidly, tensile strength decreases to the level of the maximum cyclic stress, and the specimen fractures.

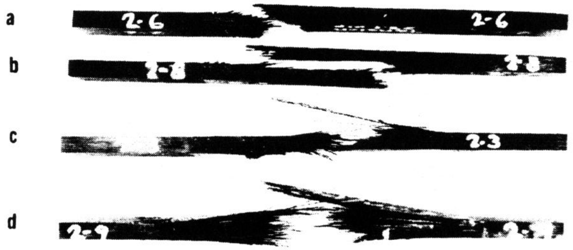

Fig. 2. Failure modes (edge-view) of a C3000/PMR-15 woven laminate after (a) monotonic tension; (b) 410 cycles; (c) 150,000 cycles; and (d) 940,000 cycles.

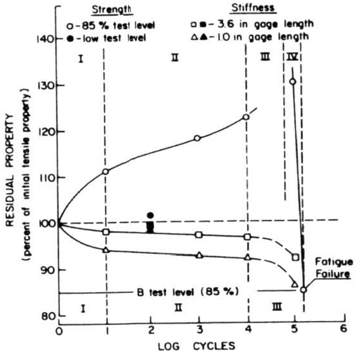

Fig. 3. Stiffness change and residual tensile strength of notched, quasi-isotropic graphite epoxy laminates.

An understanding of the fatigue response of composites can be developed from an understanding of the complex damage state which evolves during cyclic loading. Early in the fatigue life of the notched, graphite epoxy laminates shown in Fig. 1, matrix damage (cracks and delaminations) develop in the off-axis plies and in the zero degree plies tangent to the hole as indicated by the penetrant enhanced radiograph in Fig. 4. The large dark areas above and below the hole are aluminum tabs used to position the extensometer. Delaminations occur between cracked plies and their borders are defined by large matrix cracks in the adjacent plies. Further evidence of the constraint imposed on the extent of delamination growth by the properties of adjacent plies is shown in Fig. 5. This schematic of the delamination patterns at the interfaces of the $[45,90,-45,0]_s$ laminate was

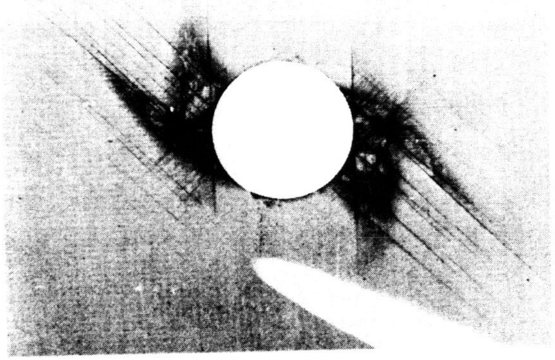

Fig. 4. Fatigue damage in a notched, quasi-isotropic graphite epoxy laminate after 10^5 cycles.

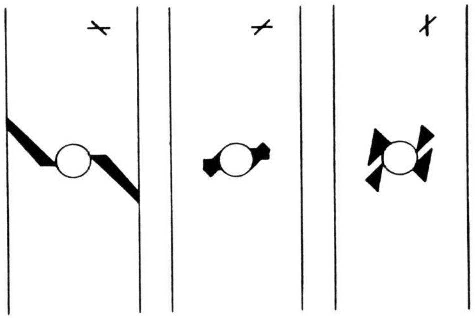

Fig. 5. Delamination patterns on interfaces of a notched, quasi-isotropic graphite epoxy laminate.

made by deplying damaged specimens (Freeman, 1982) and viewing the deplied surfaces through a light microscope. The orientation of the plies adjacent to each interface is shown in the upper right corner of each frame. The information contained in the radiograph and the schematic is complementary. The radiograph presents an overlay of the damage field through the thickness of the laminate; whereas the deply schematic gives detailed information on each interface.

Unlike matrix cracks and delaminations, graphite fiber fractures are difficult to detect nondestructively, although some correlations have been made between acoustic emission and broken fibers (Jamison, 1986). Figure 6 is a scanning electron micrograph of a deplied zero degree ply from the center of a 32 ply $[0,45,90,-45]_{S4}$ T300/5208 graphite epoxy notched laminate subjected to completely reversed (R=-1) cyclic loading. At low stress amplitudes, fiber fractures are dispersed as shown, but are more localized at high stress amplitudes. Detailed studies of fiber fracture during low stress amplitude loading of quasi-isotropic T300/5208 and AS4/1808 graphite epoxy notched laminates revealed that fiber fractures occur in regions adjacent to delaminations after the delaminations form. However, fiber fracture in 45 degree plies occurr early in life and precede delamination at 0/45 interfaces in $[0,45,0,-45]_{S4}$ AS4/1808 laminates (Razvan et al., 1987). There is a strong interaction between matrix damage modes, material system, load levels, and fiber fracture. These interactions and their effect on long-term performance are not well understood.

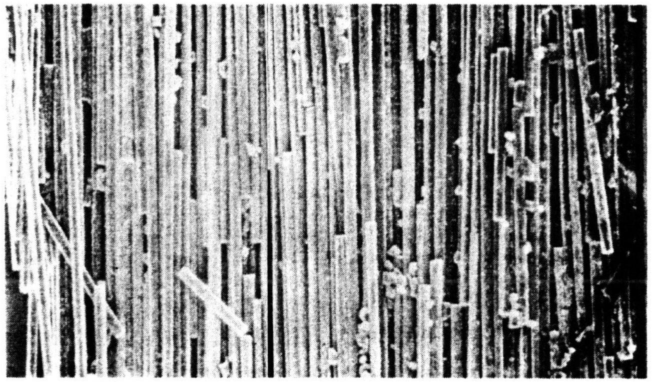

Fig. 6. Graphite fiber fractures on an interior zero degree ply, low cyclic stress level, R=-1, late life.

To summarize, damage development during long-term cyclic loading is a complex, interactive process. Multiple damage events initiate, grow, and interact at different periods and rates during the life of a notched laminate. The nature, intensity, and distribution of damage controls response of the laminate, as measured by stiffness change, strength, and life. The damage evolution process and associated response of composite laminates is highly dependent on mode and level of loading, material system, geometry, and arrangement of plies.

Damage produces local changes in geometry which, in turn, alter the path of the load through the material. Loads are distributed away from the damage site into adjacent plies and undamaged regions of material. In the case of notched laminates, matrix damage reduces the high concentration of stress at the notch through an effective change in geometry and redistributes stresses through the ligaments of material adjacent to the notch to satisfy equilibrium principles. The net effect is a reduction in the local stress concentration factor at the notch and an increase in the average stress in the ligaments. The process of damage and stress redistribution continues during each cycle of loading until the local stress state matches a critical component of the local strength state, at which time failure takes place. When laminates are subjected to more complex loading, such as reversed cyclic loading, several components of the strength state are changing during the lifetime, and several failure modes must be anticipated. Some examples are described later in this paper. A schematic of the damage process during fatigue lifetime and the attendant change in compressive strength of a composite laminate is given in Fig. 7, where the left ordinate axis is residual compressive strength normalized with respect to initial compressive strength.

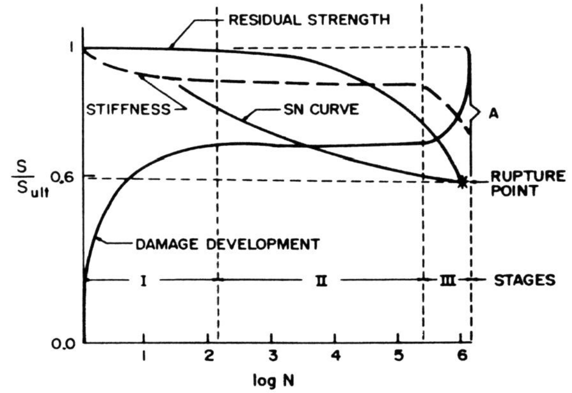

Fig. 7. Schematic of damage development, strength change, and stiffness reduction during fatigue life.

RESPONSE UNDER REVERSED CYCLIC LOADS

The consequences of damage in composite materials are changes in their response to applied loads. A brief description of the experimental procedure used in the Materials Response Group Laboratories to measure changes in response due to reversed cyclic loading is provided here. A more complete description is given in the paper by Bakis et al. (1988a). The test method approximates the long-term response of a component by permitting the composite coupon to freely respond to the imposed loads and to fail in a "natural" mode rather than in a "constrained" mode due to some test fixture usually designed to restrict or prevent compressive instability failures. The method has been successfully used to measure the long-term response of graphite fiber reinforced composite material systems including T300/5208 and AS4/3501-6 (epoxy matrix materials), AS4/1808 (a toughened epoxy matrix material) with and without interlayers, and AS4/PEEK (a tough thermoplastic matrix material). The specimen shown in Fig. 8 is 1.5 in. wide, has a 0.375 in. diameter center hole, and is 32 plies thick. The stacking sequence of specimens discussed in this paper is $[0,45,90,-45]_{S4}$, although other ply arrangements and thicknesses have been tested in the lab. The selection of width and notch size and geometry is arbitrary and can be based entirely on design or service requirements.

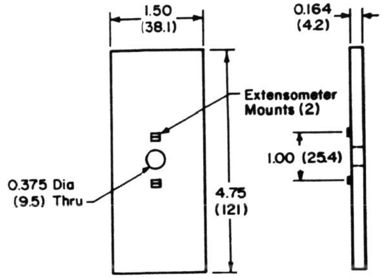

Fig. 8. Specimen used to study response of notched laminates to tension-compression cyclic loads. Dimension in inches and (mm).

Test specimen unsupported length is of paramount importance when evaluating material response to loading spectra with compressive components. A systematic method of determining the unsupported length is described in the reference paper. The present graphite epoxy and graphite PEEK specimens were designed using the largest value of unsupported length which produces a nearly pure compression failure mode under a monotonic load greater than the largest cyclic compressive load imposed during long-term loading. Mechanical tests were conducted with servo-controlled, hydraulically-actuated testing machines equipped with hydraulic grips capable of reversed loading. Figure 9 is a cutaway view of a specimen fixed in a grip using alignment plates to assure accurate and repeatable positioning of the specimen.

Specimens were tested in load control under completely reversed load conditions (R=-1) at a frequency of 10 Hz. Stress-life (S-N) data are plotted in Fig. 10. Life is defined as the failure of the material to support the applied tensile or compressive load. At high cyclic stresses, those which resulted in fatigue lives less than 10^4 cycles, the PEEK laminates have the shortest fatigue lives. At low cyclic stress levels, resulting in fatigue lives greater than 10^6 cycles, PEEK, 1808, and 3501-6 laminates have longer fatigue lives than do 5208 laminates. Differences in damage development with different load levels produce different response in the material systems. In general the more brittle matrix composites perform better at high stress levels and the tougher matrix composites perform better at low stress levels, as indicated in Fig. 11 where the stresses have been normalized with respect to the compressive strength of notched laminates. The straight lines are least square fits to the data and are included to indicate trends in the fatigue response.

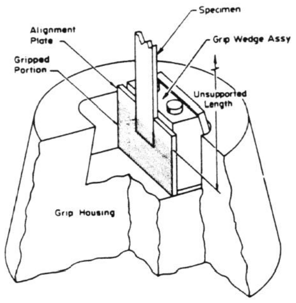

Fig. 9. Alignment fixture and gripping arrangement.

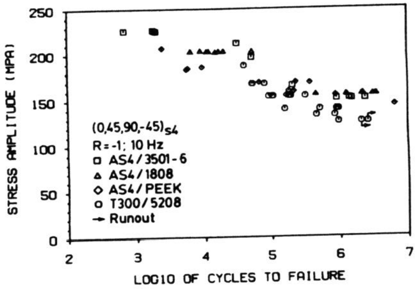

Fig. 10. Stress life data for four composite materials subjected to completely reversed cyclic loading.

The effects of load level and material system on damage development and response can be understood more clearly by examining the X-ray radiographs in Figs. 12-14. Damage at early, intermediate, and late stages of life is

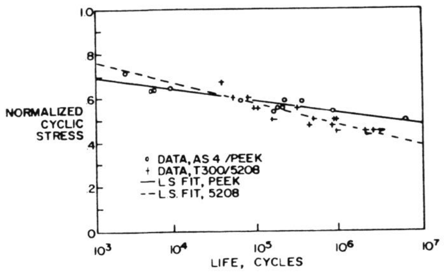

Fig. 11. Stress life data for brittle matrix and thermoplastic matrix composite materials subjected to completely reversed cyclic loading.

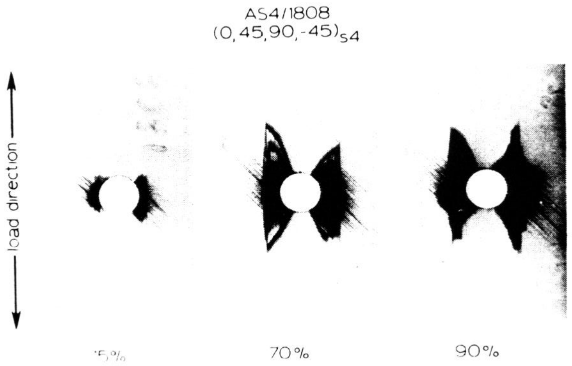

Fig. 12. Damage in a toughened epoxy matrix composite at early, intermediate, and late stages of life; low stress level.

shown in Fig. 12 for a toughened epoxy matrix laminate having a fatigue life of 11,400 cycles. The damage patterns (modes and distributions) are also typical of those in the untoughened epoxy matrix systems. Matrix cracks, delaminations, and fractured fibers are present in each material; but there are fewer matrix cracks and more fractured zero degree fibers in the 1808 system than in the brittle epoxy matrix systems at comparable stages of life.

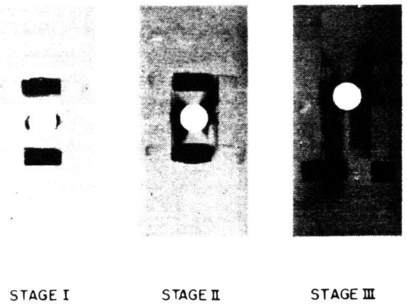

Fig. 13. Damage in a thermoplastic matrix composite at early, intermediate, and late stages of life; low stress level.

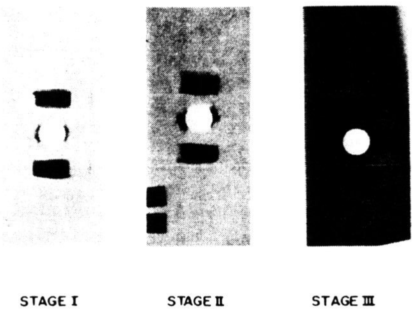

Fig. 14. Damage in a thermoplastic matrix composite at early, intermediate, and late stages of life; high stress level.

The sequence of X-rays at selected percentages of fatigue life give a clear picture of the progression of damage during life. Damage begins at the hole as matrix crcks in all plies early in life, followed by delaminations which appear to fill in the regions of high matrix crack density at later stages of life. Zero degree fibers fracture incrementally between matrix cracks in the zero degree plies. The major direction of matrix damage growth at intermediate and late stages of life is parallel to the zero degree fibers. All toughened and untoughened epoxy laminates fail in compression.

Figure 13 shows damage in an AS4/PEEK laminate tested under low stress, long life conditions. The damage patterns are similar to those for the toughened epoxy system. The dark spots above and below the hole are tabs used to position the extensometer and identification labels. Figure 15 shows the incremental nature of fractured zero degree fibers at an intermediate stage of life. At low stress levels, matrix damage grows parallel to the zero degree fibers in the PEEK laminates as it does at all stress levels in the epoxy matrix laminates. The failure mode of PEEK laminates tested at low stress levels is compression.

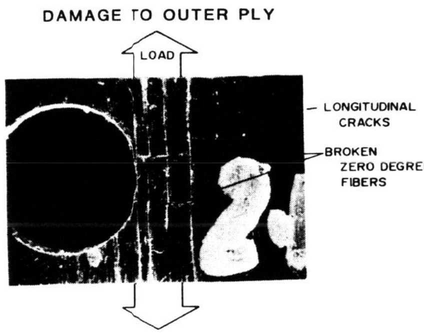

Fig. 15. Broken zero degree fibers on the surface of a quasi-isotropic, thermoplastic matrix composite.

Damage modes in PEEK laminates subjected to high cyclic stress levels, Fig. 14, are the same as those in laminates tested at low cyclic stress levels. However, the distributions and growth directions are notably different. At intermediate and late stages of life, the matrix damage grows perpendicular to the zero degree fibers and the laminates fail in tension, not compression.

Differences between the long life and short life performances of the thermoplastic and the epoxy systems are due to a change in the fatigue failure mode. Under low cyclic stress levels, all of the notched materials tested failed in compression with the PEEK material having the longest life. Under high cyclic stress levels, the PEEK material failed in tension and had generally shorter life than the toughened and untoughened epoxy materials which failed in compression.

LOAD LEVELS, MATERIAL SYSTEMS, AND RESIDUAL STRENGTH

Transition in failure mode from compression at low stress levels to tension at high stress levels is due to the way in which residual tensile and compressive strength change with damage during cyclic loading. Figure 16 illustrates the changes in residual tensile strength (normalized with respect to initial tensile strength) and residual compressive strength (normalized with respect to initial compressive strength) of the two composite material systems with contrasting matrix materials: T300/5208 and AS4/PEEK. Residual strength is measured by cycling a specimen to a selected number of cycles or to a specified damage condition and stopping the test. The specimen is then loaded monotonically in either tension or compression to fracture. The data shown in Fig. 16 are for specified damage conditions. The portion of the fatigue life expended prior to halting the cyclic loading is estimated by comparing stiffness degradation with the stiffness degradation of similar specimens that had been cycled to failure at the same stress level.

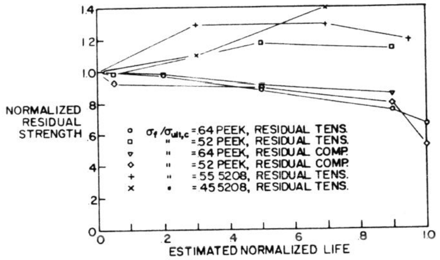

Fig. 16. Change in residual strength of brittle and tough matrix composites during fatigue life.

All T300/5208 specimens show an increase in residual tensile strength at the three cyclic stress levels through a normalized life of 0.95. Similarly, AS4/PEEK specimens cycled at a normalized stress of 0.523 (low stress) show an increase in residual tensile strength through 95 percent of life. However, the AS4/PEEK specimens cycled at a high normalized stress (0.642) show decreases in residual tensile strength throughout life. The AS4/PEEK specimens tested for residual compressive strength show loss of strength as a result of completely reversed cyclic loading. Normalized residual tensile strength data for 1808 toughened epoxy matrix composite laminates tested at high stress levels fall between the data for the epoxy and thermoplastic matrix materials. At low levels, normalized residual tensile strength of 1808 matrix material increases during the first half of life and decreases to about that of PEEK matrix material during the second half of life (Bakis <u>et al.</u>, 1988b).

Residual tensile strength increase is due to matrix damage (cracks in off-axis plies and delaminations) near the hole. The damage increases the effective radius of the hole, thereby reducing the local stresses at the hole and redistributing the load in the ligaments of material on each side of the hole. As an illustration, Fig. 17 shows data for two T300/5208

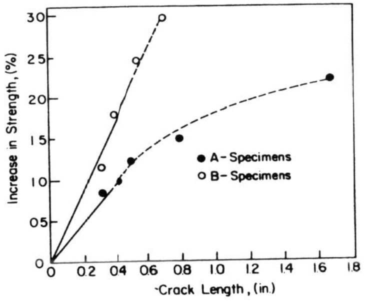

Fig. 17. Increase in residual tensile strength with length of zero degree ply matrix cracks for two notched, quasi-isotropic graphite epoxy laminates.

quasi-isotropic, notched laminates subjected to tension-tension (R=0.1) cyclic loads. The A specimens are eight ply $[0,90,\pm45]_s$ laminates, and the B specimens are the eight ply $[45,90,-45,0]_s$ laminates discussed previously and described in Figs. 1,3-5. Residual tensile strength of both laminates increases as the length of the zero degree ply cracks tangent to the hole increases during cyclic loading. Measurements using moiré interferometry show a reduction in the stress concentration factor in the damaged region around the hole. The relationship between stress concentration and length of the tangent cracks is shown in Fig. 18 (Kress and Stinchcomb, 1985). The result is an increase in the residual tensile strength of the laminates containing matrix damage around the hole.

Under reversed cyclic loading, all T300/5208 laminates and AS4/PEEK laminates subjected to low cyclic stresses suffer matrix damage which increases tensile strength. The laminates fail in compression due to stiffness loss caused by matrix damage and fiber fracture. At high cyclic stresses, damage in the tough matrix laminate develops transversely from the hole and reduces the load carrying capability of the ligaments. During the relatively short fatigue lives, the cycle dependent development of matrix damage in the tough, thermoplastic material is not sufficient to reduce the stress concentration at the hole and redistribute the load away from the hole. High local stresses at the hole produce fiber fractures which progress sequentially across the ligaments, reducing their tensile strength and causing a fatigue fracture of the laminate during the tensile portion of the loading cycle. The suppression of matrix damage due to high values of interlaminar fracture toughness does not permit the beneficial

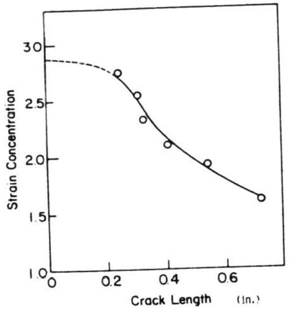

Fig. 18. Decrease in stress concentration in zero degree ply with increase in crack length for a type A laminate.

effects of damage to occur in notched laminates under high cyclic stresses. Consequently, the tough laminates fail in tension at high stress levels at fatigue lives less than those of the less tough systems which fail in compression.

CLOSURE

The response of notched composite laminates to long-term, cyclic loading is a complex process. The process is dependent on a number of interacting factors including material properties, magnitude and mode of loading, and mode and distribution of damage. Matrix cracks, delaminations, and fractured fibers are present in epoxy matrix, toughened epoxy matrix, and thermoplastic matrix composites. Under comparable loading conditions, there are fewer matrix cracks in the tougher matrix materials. Delaminations are also less extensive. Fractured fibers are localized and occur through the thickness of tough matrix materials, whereas failed fibers are isolated and dispersed in brittle matrix systems. The significance and consequences of each individual damage mode are dependent on the mode of loading (tension-tension, tension-compression, and/or compression-compression) and the magnitude of loading. The governing relationships between material properties and long-term cyclic behavior are intricate and subtle, even more so than those describing short-term monotonic behavior. The long-term relationships are not well understood.

There are two classifications of competing damage modes that affect fatigue response and two competing failure modes that limit long-term performance. First, matrix damage (cracks and delaminations) around notches increases tensile strength by notch blunting. However, matrix damage also reduces stiffness and decreases support of the load bearing fibers which collectively reduce compressive strength. The second major damage mode classification is the failure of load bearing fibers which appear as incremental ply fractures in the tougher matrix materials. Both tensile and compressive strength decrease due to transverse damage development and loss of stiffness, respectively. The degree of competition is a function of matrix material and load levels.

Throughout the life of a composite laminate or structural component, multiple, subcritical "failures" occur at the micro level (constituent failures) and at the element level (ply failures). Subcritical failures increase in number and density and interact to produce failure at the laminate level--fracture, a single event which defines life. At this time, capabilities to predict long-term performance, including residual strength and life, are limited by an incomplete knowledge of the factors which govern damage development and an incomplete understanding of the mechanics of long-term performance. It is clear that present understanding of short-term behavior of composite materials does not provide a sufficient foundation for extrapolation to long-term behavior. Progress toward understanding the relationships between damage and its effects on residual strength and life is essential to the development of damage tolerance methodologies for certification of composite structures. Establishment of such relationships is also important to the development and qualification of new material systems which will satisfy long-term damage tolerance requirements at high design strain levels. Truly, interdisciplinary materials, mechanics, and structural reliability programs must be undertaken to achieve these challenging but exciting goals.

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