MECHANISMS OF FRACTURES IN FIBER-REINFORCED LAMINATES

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ABSTRACT

Structures composed of fiber-reinforced materials may exhibit various kinds of defects incurred in the manufacturing process or during service. The ability to forecast the effects of such damages on the safe operation of aerospace structures presupposes the development of principles of damage mechanics, analogous to fracture mechanics of metals but considerably more complex. The identification of potential failure modes and the judgment of their contribution to the progression of observed damages require extended empirical and analytical investigations. Until the various mechanisms of damage progression are understood and predictable, the disposition of an afflicted structure must be supported by costly and time-consuming tests. The ultimate goal of all such efforts ought to be the establishment of reliable and relatively simple accept/reject/repair criteria for the support of series productions and for maintenance requirements. The related activities of the DFVLR Institute for Structural Mechanics are guided by this goal. The present paper does not purport to offer simple solutions; rather, it aims to convey the complexity of the issue of damage mechanics and to describe several of the more important mechanisms of fracture.

KEY WORDS

Fiber-reinforced laminates, damage mechanics, fracture mechanisms, failure modes, failure analysis, matrix cracks, delaminations, environmental effects.

INTRODUCTION

The concept of fiber-reinforced materials is not new and certainly not an invention of this century. However, only in recent years has the development of special fibers, in combination with appropriate matrix materials, led to promising applications in the aerospace industry. Of dominant interest are carbon-fiber reinforced epoxy resins which, apart from their high specific strength and stiffness properties, are also fatigue-tolerant and corrosion-resistant.

Inhibiting a wider range of applications are the small elongations to failure of epoxy resins, their susceptibility to environmental effects, and an as yet insufficient comprehension of the significance of damages occurring during the production process of structural parts, or in the course of their service. The disposition of such flaws as matrix cracks, delaminations, misdrilled holes, etc., by analytical means is as yet impossible for a lack of understanding of the mechanisms of damage progression. Consequently, the accept/reject decisions of damaged parts are normally made by time-consuming testing and often after extensive repairs. The knowledge thus gained is seldom transferrable to other cases as it provides no insight into the interpendence of many parameters affecting the response of damaged parts (9).

Anticipating a rapid increase of composite structures in the near future, the issue of damage mechanics was introduced as a major research program at the Institute for Structural Mechanics of the German Aerospace Research Establishment (DFVLR) (2). It must be fully recognized that the complexity of damage mechanics exceeds that of facture mechanics by far, partially because of the anisotropy and heterogeneity of the composite materials, and partially because of the much larger variety of possible kinds of damage.

TEST PROGRAM

Considering the large variety of parameters to be encountered, it stood to reason to commence the experimental investigations with flat laminates subject to unidirectional loading. The dominantly used material are 0.125 mm thick 914C/T300 autoclave-cured tape prepregs; all subsequent statements relate to that material unless otherwise noted. For the purpose of comparing their performance, test specimens are prepared without defects and with typical defects such as delaminations, holes and notches. The majority of the test specimens for tension and compression tests are from 10 mm to 40 mm wide and from 235 mm to 380 mm long, respectively. The substantial width of the larger specimens assures that the response of the centrally introduced defects is unaffected by the specimen boundaries. The stacking orders of the laminates are chosen such that they represent rib or spar chords, webs and skin panels of typical aerospace structures. Under compression loading the test specimens must be laterally supported by anti-buckling guides. In cyclic tests the specimen temperature may rise significantly due to internal and external friction and in dependence on the test frequency. In order to control the temperature effect the anti-buckling guides contain electrically activated cooling devices (3). The majority of the specimens are exposed to realistic environmental conditions including moisture, temperature and radiative effects, and are tested to eventual failure.

FAILURE ANALYSIS

In carbonfiber-reinforced laminates, different specimen configurations and different loading and environmental conditions lead to different failure modes. The dependency of the failure modes on the many possible parameter combinations of typical laminates is not well understood. In fact, it may be said that the investigation, classification and interpretation of failure modes is still in its infancy. Failure analysis techniques currently existing are: microscopic examination of fracture phenomena; non-destructive evaluation of macroscopic types of damage; and stress analysis of failed parts.

Microscopic Examinations

Failure modes observable on the microscopic scale include fiber pullout, fiber breakage, matrix micro-cracking, fiber-matrix debonding, and matrix deformations in the form of serrations and cleavage. Their subsequent progression may eventually cause fracture of the laminate. Fractographic techniques based on scanning electron beam microscopy can be applied to identify the fracture origin and the direction of propagation, as well as to analyse material parameters affecting the fracture process such as constituent properties, laminate configurations, fiber-matrix interface properties, loading and environmental conditions. A reliable characterization of the fracture phenomena may ultimately assist in establishing the cause of failure and thus suggest suitable modifications of the composite system.

Non-Destructive Evaluation

Non-destructive evaluation of all test specimens is mandatory in order to assure the absence of initial damage, and to detect and track various kinds of macroscopic defects. As no single procedure can satisfy this requirement, a combination of mutually supportive procedures must be employed. The techniques utilized by the Institute for Structural Mechanics include: High-precision ultrasonic test facilities with highly-vaporated focussing transducers and a narrow-band transmitter with variable pulse frequency; low-energy X-ray equipment with high lateral resolution; acoustic emission analysis and grid-reflection techniques for in-situ observations of the test specimens (8), (1), (4).

Stress Analysis

A reasonably accurate analysis of the three-dimenional state of stress around a discontinuity by a standard finite-element approach requires a large number of degrees of freedom so that the solutions may become prohibitively expensive, especially when the tracking of the damage progression involves an interative treatment (16). This recognition has led to the development of a new analysis approach which, although conceptually not novel, combines an unusual number of features in an economically organized computer program. Its basic component is a triangular hybrid shell element comprising bending and membrane action as well as normal and shearing stress capabilities on its upper and lower surfaces. By stacking several of these elements above one another, a multidirectional laminate can be modelled in great detail with a reasonably small number of degrees of freedom. A special condensation scheme is utilized capable of producing multilayer shell elements and substructures. Failure progression rules are appended to the finite element equation system in such a way that the tracing of damage progression will not require repeated triangularization of the global stiffness matrix (5).

MECHANISMS OF FRACTURE

In contrast to metals, where fracture under static or fatigue loads results from the nucleation and growth of a single dominant flaw, the fracture of fiber-reinforced composites is characterized by the initiation and progression of multiple failures of different modes such as matrix cracks, interfacial debonding, fiber breaks and delaminations between adjacent plies of the laminates. The kinds of occurring failures, their distribution, time sequence and possible interactions depend on many parameters such as the properties of the fiber/matrix system, the stacking order and curing process, the influence of the environment, etc. The problem is further complicated by different failure modes under static and dynamic load applications (12), and by the possibility of fatigue failure in the compressive as well as in the tensile load regime.

Close observation of unnotched specimens tested under cyclic tension loads indicates that the progression of events follows a more or less distinct pattern. The first discernable damage usually are matrix cracks at certain intervals in the crossplies of the laminates. With increasing cycles more matrix cracks develop which, at the interfaces with neighboring plies, tend to turn and to form small delaminations both inside and, especially, at the free edges of the laminate as indicated in Fig. 1. Additional delaminations may emanate from the locations of fiber bundle breaks.

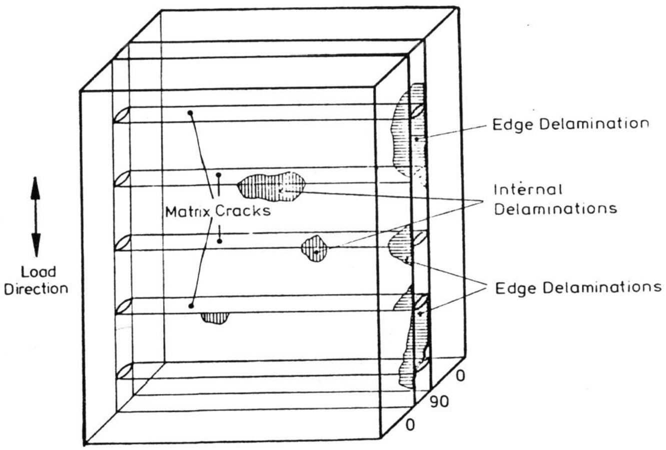


Fig. 1 Matrix cracks and incipient delaminations

With respect to compressive loads, critical conditions may arise in the presence of delaminations induced by lack of adhesion because of faulty manufacturing, or because of impact damage. Under sufficiently high compressive stresses the reduced bending stiffness of the separated sections will introduce local buckling and thereby a state of stress at the periphery of the delamination which tends to advance the crack front. Continuation of load cycling then leads to damage growth followed by massive separation and subsequent specimen failure.

Even in the case of very closely controlled tension-tension tests performed under identical parametric conditions, the scatter of the fatigue lives of the specimens is usually very significant. A possible explanation is that, at sufficiently high stress levels, the random distribution of micro-cracks, debonds, fiber breaks, etc., becomes denser with increasing cycles. Toward the end of the specimen life, adjacent failure modes tend to interconnect and form failure paths which, because of their stochastic nature, differ

from specimen to specimen and lead to discrepant life spans of the test specimens. A similar argument may apply to the fatigue performance of specimens subject to compressive loads where, of course, different kinds of failure modes interact differently but produce similarly scattered test results.

Accompanying the gradually increasing damage state is a reduction of the overall laminate stiffness. Depending on the stacking order, this reduction may be quite pronounced as shown in Fig. 2 for a matrix-controlled laminate, or more subtle in the case of fiber-controlled laminates. In both instances, however, a particularly critical combination of local failure modes develops which, finally, leads to a rapid deterioration of the stiffness in only a few additional cycles, and to what is commonly called "sudden death" of the specimen (13). Several of the dominant failure modes are addressed in more detail below.

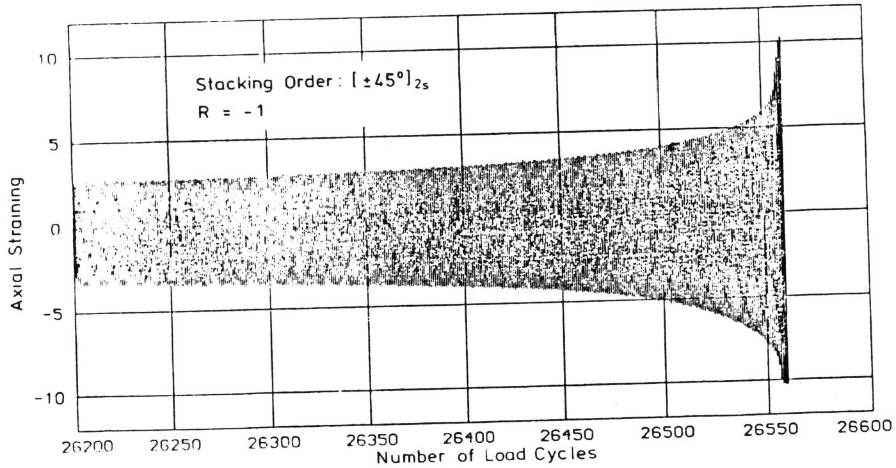


Fig 2. Stiffness decay shortly before failure

Matrix Cracks

The normally used epoxy resins have only limited tensile strain capabilities. This condition is aggravated by the introduction of tensile prestresses in the matrix resulting from the discrepant thermal elongations of the fibers and the matrix during the curing process. Consequently, the formation of cracks can be expected rather early in those plies of a laminate which are mechanically or thermally stressed beyond the critical strain values of the resin. Repeated exposures to high mechanical loads or to low temperatures will increase the state of damage (7). Figure 3 shows that in cross-plied specimens subjected to thermal cycles between +100°C and -155°C the cracks turn at the interfaces of adjacent plies and form local delaminations which tend to grow with increasing numbers of thermal cycles. It stands to reason that a similar effect occurs in specimens subjected to sufficiently high mechanical load cycles. Delaminations of this kind occur most severely along the free edges but are found in the interior of the test specimens as well. Considering that the strain value associated with the first crack in any one ply is often equated to the limit-load carrying capability of the structure, the urgent need for more ductile resin systems is self-evident.

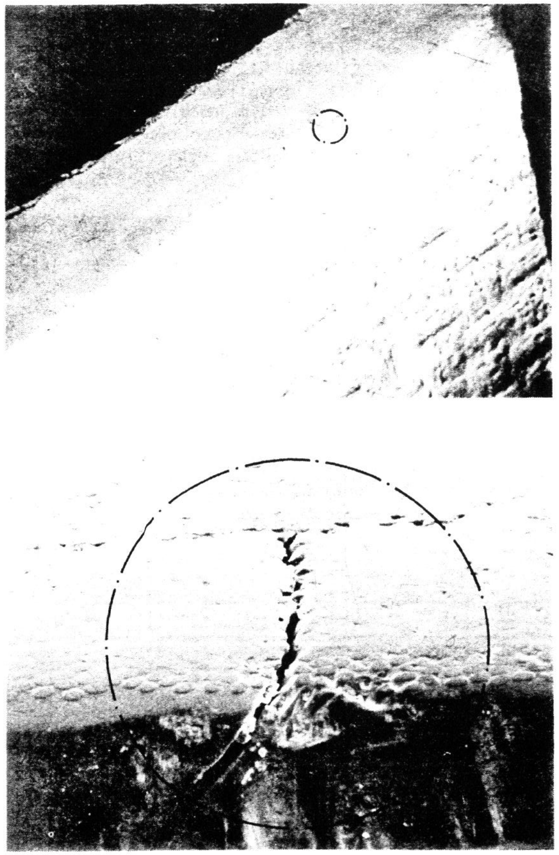


Fig. 3. Damage development due to thermal cycling (T3T F 178 material after 1170 cycles)

Edge Delaminations

The free edges of multidirectional laminates are ecpecially susceptible to the formation of cracks and delaminations because, under imposed axial strains, the enforced compatibility of the lateral contractions of the individual plies introduces interlaminar shearing stresses, as well as normal stresses, in the thickness direction. The resulting state of stress depends on the stacking order and on the load direction; Figure 4 summarizes the

results of a detailed finite-element analysis for laminates stacked $[0, \pm 45, 90]_s$ and $[90, \pm 45, 0]_s$. The numerical values of the linearly derived stresses account neither for curing prestresses nor for viscoelastic relaxations; however, their potentially dangerous trends can be reversed by altering the ply sequence (17). The question arises to what extent the actual strength of the laminates is affected by such ply rearrangements, considering that the commonly used lamination theory does not account for these internal states of stress.

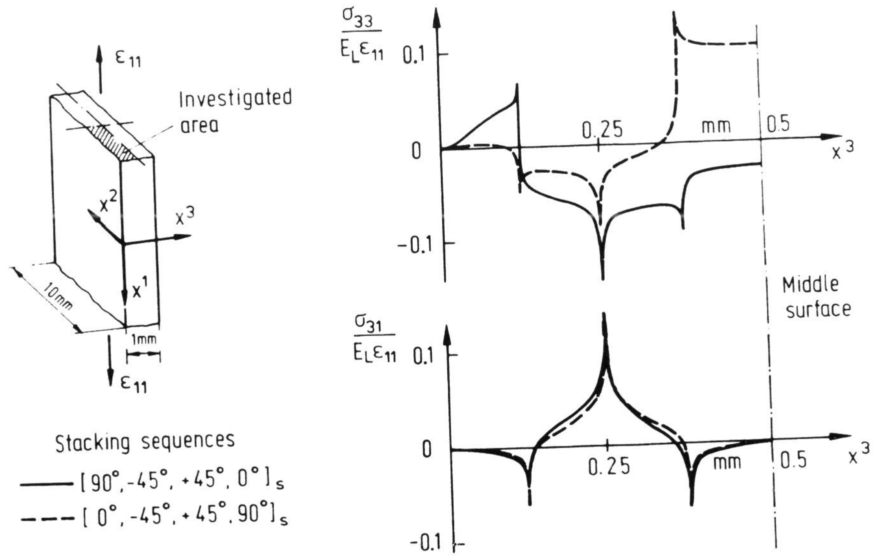


Fig. 4. Effect of stacking sequence on stress distributions in the vicinity of free edges ($x^2 \sim 0$)

Carefully conducted static tension tests confirm, indeed, a superiority of the $[90, \pm 45, 0]_s$-laminate over the other by approximately 10 %. Apart from the reversed crossply locations, the developing matrix crack patterns were comparable in both cases without noticeable evidence of edge delaminations.

A very different behavior of the two laminates was observed during fatigue loading with R = 0.1 and an upper stress level of 75 % of their respective static strengths. As expected, matrix cracking and edge delaminations occurred relatively early in the $[0, \pm 45, 90]_s$-specimens. Monitored by contrast-enhanced radiography, as shown in Fig. 5a, the delaminations proceeded from both sides toward the center of the specimen until, shortly before failure, they were separated only by the narrow trip recognizable in Fig. 5b. The $[90, \pm 45, 0]_s$-specimens, in contrast, exhibited relatively minor evidence of damage. A comparison of the crack patterns in the free edges of the two types of specimens, shortly before failure, is shown in Fig. 6. The onset of delaminations is recognizable between those plies where, according to Fig. 4, the internal peeling stresses are most severe.

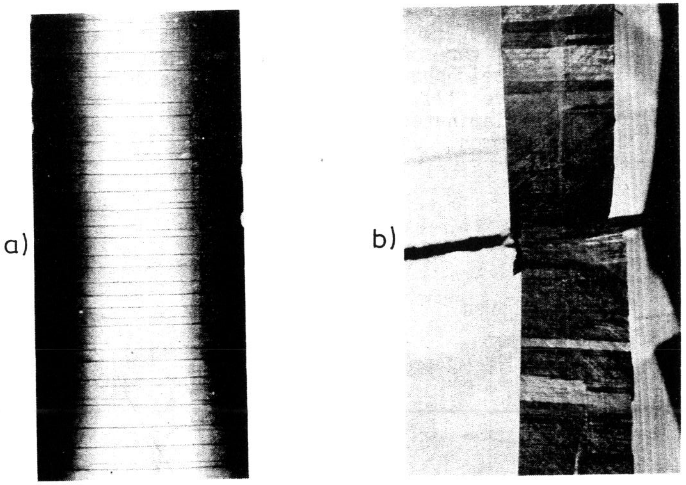


Fig. 5. Progression of edge delaminations

In spite of the different fracture behavior, the number of cycles to total failure was comparable for both types of laminates because the two separated halves of the $[0, \pm 45, 90]_s$-laminates were capable of maintaining the 75 % static strength level independently. Delaminations of this severity in tension/compression- or purely compression-loaded specimens, of course, would reduce the fatigue life drastically due to buckling of the separated sections. The point here is that an evaluation of test results without an accompanying failure analysis may lead to erroneous conclusions in regard to the performance characteristics of laminates.

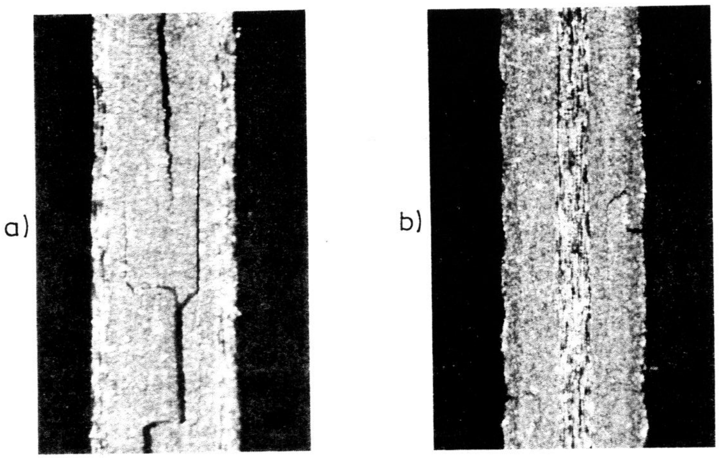


Fig. 6. Severity of edge delaminations

In actual applications the boundaries of structural components, such as panels, are often reinforced or less intensely stressed. The issue of edge effects, nevertheless, is of high significance as it also applies to the free boundaries of holes, notches or cutouts. More importantly, as the design allowables are normally defined on the basis of narrow test specimens, a superficial interpretation of test results may entail overly conservative design values.

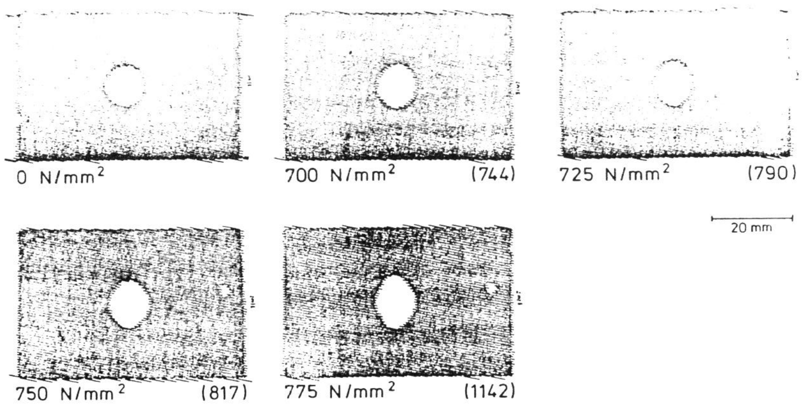
Central Delaminations

Apart from the free edges of a laminate, delaminations may occur in the central regions initiating from matrixcrack formations, or because of local lack of adhesion between adjacent plies caused either by a processing fault or by impact damage during service.

The introduction of delaminations in test specimens is possible, prior to curing, by the inclusion of an outgassing agent or by the imbedment of a very thin teflon disk or, after curing, by controlled impacting. The teflon disk approach has the advantage of providing a well-defined location and geometry and has been adopted for the majority of the studies. Numerous tests have proven that the somewhat blunted crack front at the perimeter of the disk does not significantly retard the eventual growth of the delamination.

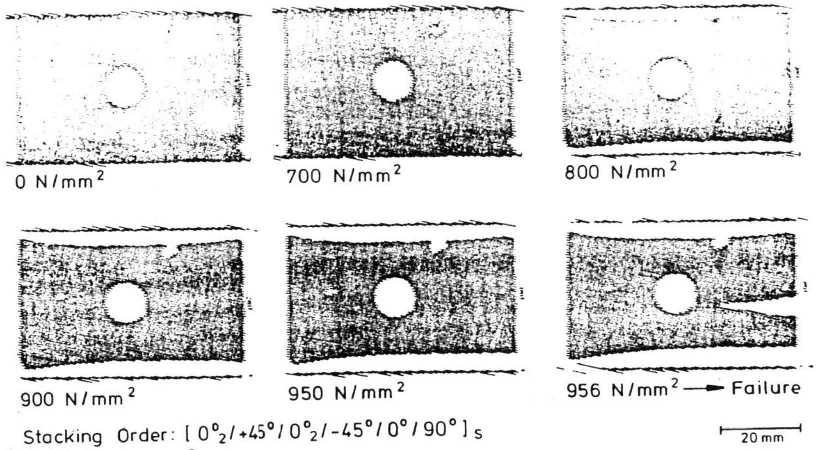
Figure 7 shows ultrasonic records of the progressive growth of a delamination under a gradually increasing compressive load in a standard test specimen. The 0.1 mm thick teflon disk was placed between the 90°-plies at the midplane of the specimen. Up to approximately 85 % of ultimate load the delamination is seen to be stable and to then grow in the direction of the fibers of the neighboring plies. The same kind of test specimen loaded in tension exhibits a very different behavior. Figure 8 shows that, while the central delamination remains unchanged up to failure of the specimen, edge delaminations occur along the free boundaries at approximately 80 % of ultimate load which subsequently gradually increase. Figure 9, finally, illustrates the response of a test specimen under cyclic load with R=1 and a stress level of ca. 50 % of its ultimate strength. After 20 000 cycles the first evidence of central delamination growth and onset of edge delaminations is noticeable, which gradually increase in severity until failure after 140 000 cycles (8), (12), (13). Figure 9 also indicates the formation and random distribution of an increasing number of local delaminations, not to be found under static loads and consistent with the argument offered previously.

Variations of the diameter of the delaminations or of their location within their stacking order, obviously, will produce different results. A major goal of the test program is to identify tolerance levels for delaminations below which no growth occurs, and to predict the rate of growth of delaminations above such tolerance levels by empirical/analytical procedures. Figure 10 summarizies some of the accumulated test data which indicate that the size of the delaminations is less significant than their location. A ready explanation is the increasing tendency of the thinner of the separated sections to locally buckle and to thereby aggravate the state of stress at the perimeter of the delamination (10).



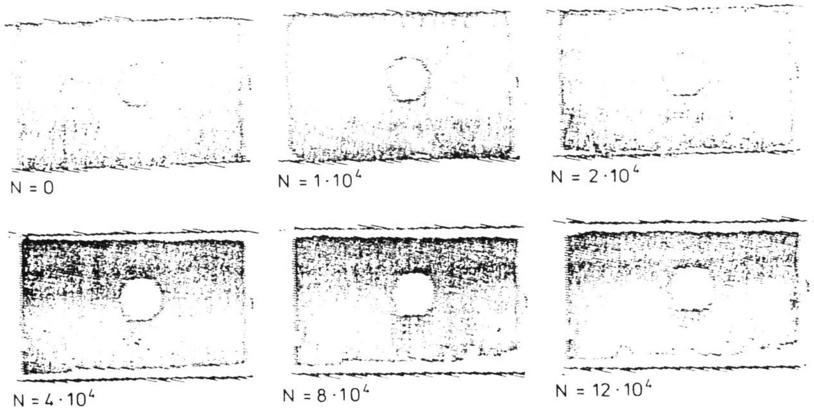
Stacking Order: $[0^\circ_2/+45^\circ/0^\circ_2/-45^\circ/0^\circ/90^\circ]_s$
Thickness: 2 mm
Delamination at Midplane

Fig. 7. Growth of central delamination under static tension load



Stacking Order: $[0^\circ_2/+45^\circ/0^\circ_2/-45^\circ/0^\circ/90^\circ]_s$
Thickness : 2 mm
Delamination at Midplane

Fig. 8. Growth of central delamination under static compression load



Stacking Order : $[0^\circ_2, +45^\circ, 0^\circ_2, -45^\circ, 0^\circ, 90^\circ]_s$
Thickness : 2mm
Delamination at Midplane
Dynamic Loading : $R = -1$, $\sigma = 400\,N/mm^2$

Fig. 9. Growth of central delamination under cyclic load

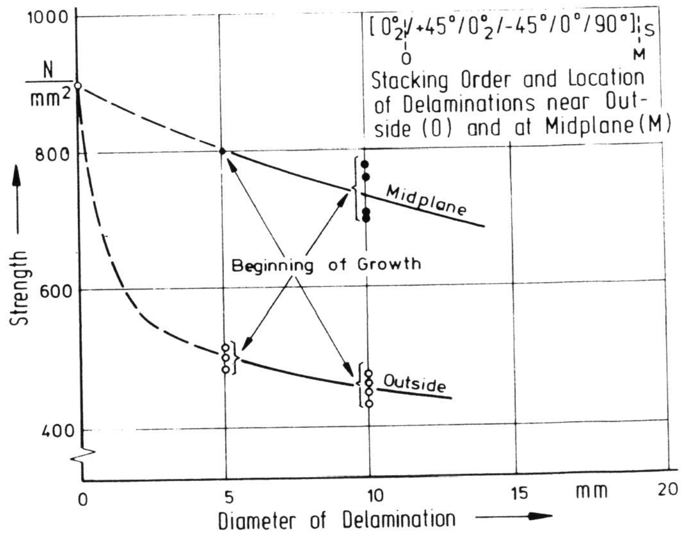


Fig. 10. Influence of delamination size and location on growth under static compression load

Fiber Breaks and Fiber Debonds

In highly stressed laminates fibers may rupture prematurely, individually or in small bundles, because of their imperfect shapes or imperfect alignment. Especially in fiber-controlled stacking orders the resulting redistribution of stresses in the vicinity of such discontinuities may initiate local failure modes which affect the fracture behavior of the laminate. Figure 11 depicts the observation of the break of a fairly massive fiber bundle on the specimen surface by the grid-reflection technique as well as an enlargement of the associated spalling and cracking of the affected zone.

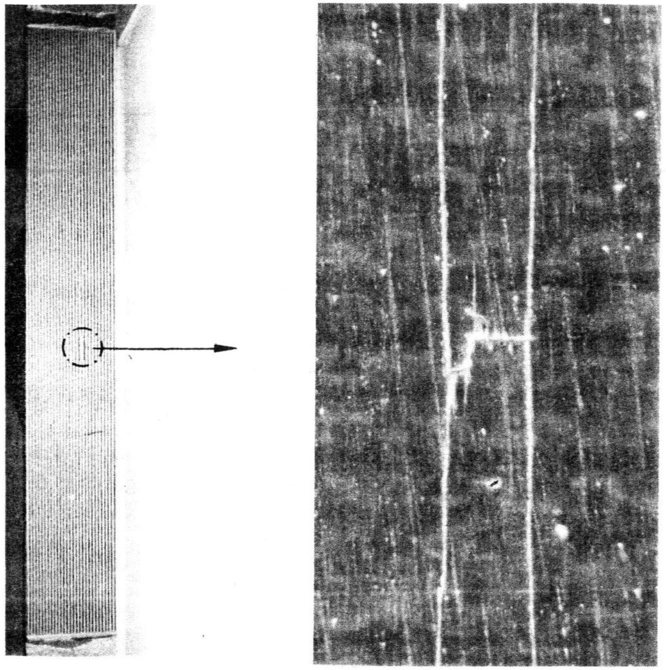
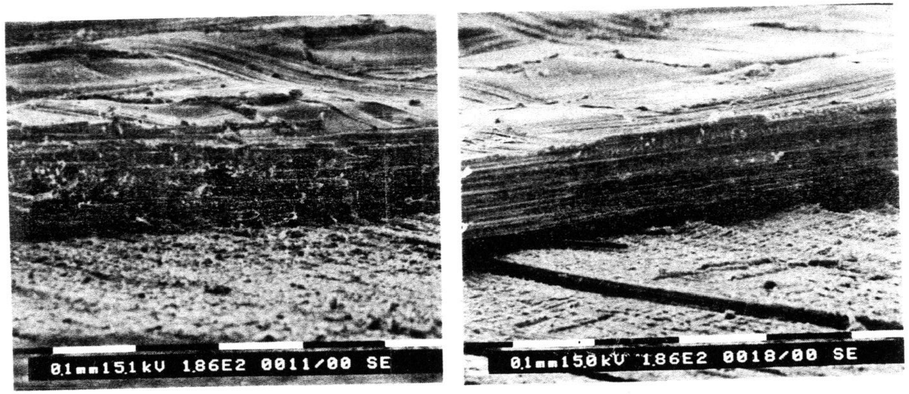


Fig. 11. Observation of fiber bundle break by grid reflection technique

The loss of adhesion between fiber and matrix is often referred to as debonding. The cause may be a locally faulty surface treatment of the fibers, or the gradual deterioration of an initially good bond by mechanically or thermally induced fatigue. An example of the latter is given in Fig. 12, showing the fracture surfaces of tension-loaded ±45-specimens before and after several thermal cycling. While prior to cycling the many specks of resin adhering to the fiber surfaces indicate a reasonably strong bond, the much smoother surfaces after cycling seem to signal the loss of it. It may be expected that similar degradations take place under mechanical loads. As a consequence of progressive debonding, a gradual deterioration of the laminate stiffness might be expected.



a) prior to cycling b) after 3480 thermal cycles

Fig. 12. Fracture surfuces of $[\pm 45]_{2s}$-specimens

ENVIRONMENTAL EFFECTS

The influence of the environment on the strength and stiffness of epoxy resins is a well-known phenomenon. Figure 13 shows, typically, the strength dependence of $[0, \pm 45, 0]$-laminates (Fiberite 934/T300) on both temperature and moisture (6), (3). The degrading trends are reversible upon drying of the laminate and/or by lowering of the temperature. Potential damage can be inflicted, however, by thermal shocking or by sustained exposure to high temperatures. Figure 14, for example, depicts the gradual loss of weight of epoxy laminates exposed to 100°C and 120°C for up to 25 000 hours. The tests were performed under atmospheric conditions and produced no visible changes of the surface properties. Additional tests with neat resins in and out of vacuum traced the weight loss to an oxidative process accompanied by significant stiffness degradations.

A different kind of degradation occurs after prolonged exposure of epoxy laminates to ultraviolet radiation. A slight increase in strength, probably caused by postcuring of the resin, is followed by a gradual decrease as a consequence of the erosive deterioration of the laminate surfaces. As a point of interest it may be mentioned that epoxy laminates subjected to 3 x 10 rads of electron beam irradiation, in vacuum, did not suffer noticeable strength or stiffness degradations in strength of stiffness, although the laminate surfaces exhibited a slight reddish tint (7).

Apart from laminate strength and stiffness, elevated temperatures as well as the presence of moisture affect significantly the strain capability of the epoxin resin. Figure 15 shows the matrix crack formation along the free edges of $[0,90]_s$-laminates tension-loaded to failure under different temperature and moisture conditions. In the dry state, the diminishing number of cracks at increasing temperature signals a higher degree of ductility, while in the moist state the onset of cracking is retarded by the relieving superposition of the swelling strains on the curing strains. From the damage-mechanical point of view it is essential that such considerations enter into the analysis of failure modes.

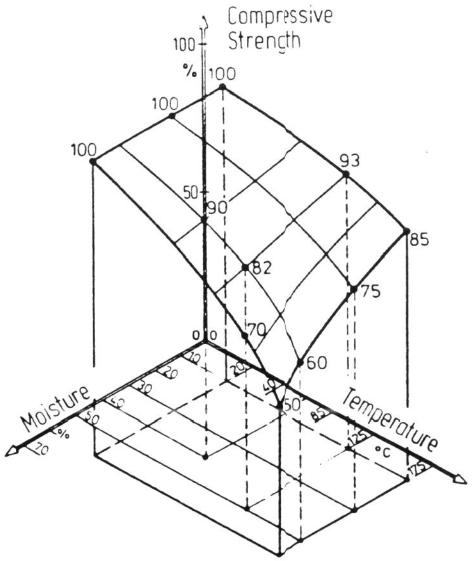


Fig. 13. Typical degradation of compressive strength due to temperature and moisture

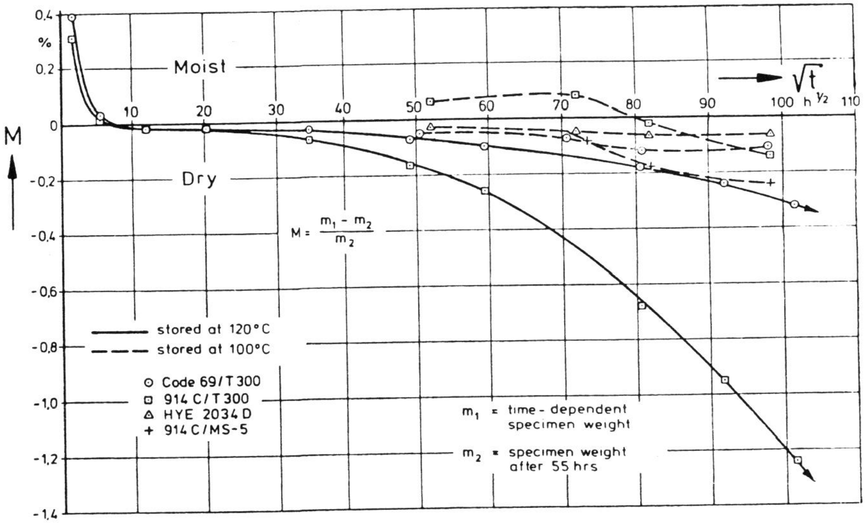


Fig. 14 Weight loss during sustained exposure at elevated temperatures

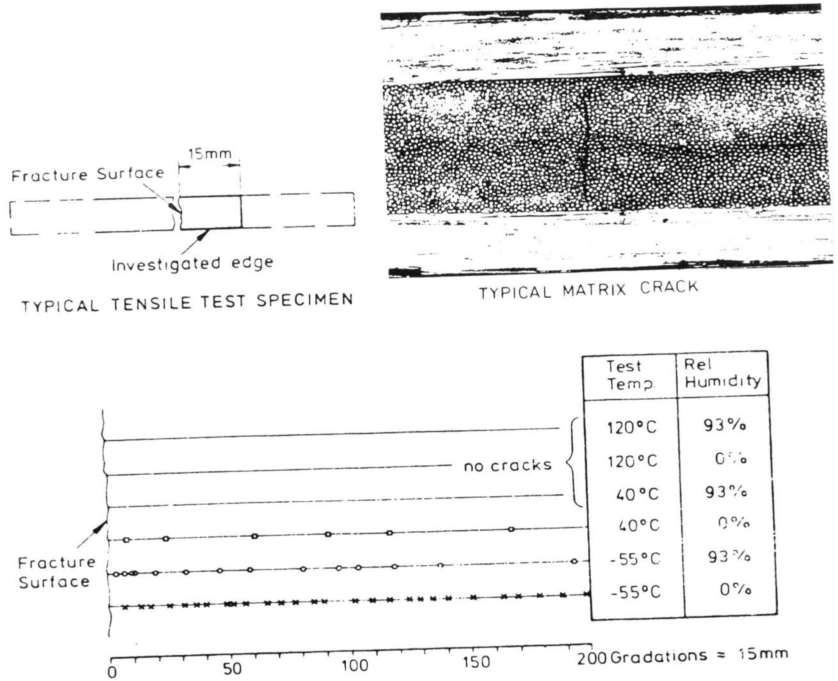


Fig. 15. Influence of temperatur and moisture on matrix crack formation

LIMITS OF FRACTURE MECHANICS

The complexity of the failure modes of fiber-reinforced laminates makes an adoption or modification of established fracture-mechanical principles difficult or impossible. Exceptions, perhaps, are such simple cases as cracks parallel to the fibers of unidirectional laminates or delaminations between adjacent plies.

Even the classical problems of a drilled hole or an elongated notch prove to be elusive. Several models based on fracture mechanics principles have been introduced for their pragmatic treatment, all based on the assumption that failure will occur when the crack tip damage reaches a critical value. This concept of critical damage zone size represents the complex crack tip damage as an "effective" crack length and stipulates that the damage growth can be modelled as a self-similar crack extension. All of these macroscopic fracture models are semi-empirical and require, for each application, a series of tests in order to correlate the model with the response of the test article. As they do not address, but rather by-pass, the micro-mechanical complexities in the crack extension process, the attempted generalizations of the models in regard to, e.g., stacking order or laminate dimensions, have not been fruitful.

A simple challenge to the validity of classical concepts is presented in Fig. 16, showing a laminate with a transverse notch and unidirectionally oriented fibers (10). Fracture-mechanical reasoning might idealize this laminate into an orthotropic plate with smeared homogeneity and, under static tensile load, expect a crack extension in the direction of the notch. In actuality the laminate behaves very differently. Emanating from the notch tips, cracks developing normal to the notch direction progress to the point of complete separation of the laminate with no growth in the notch direction at all.

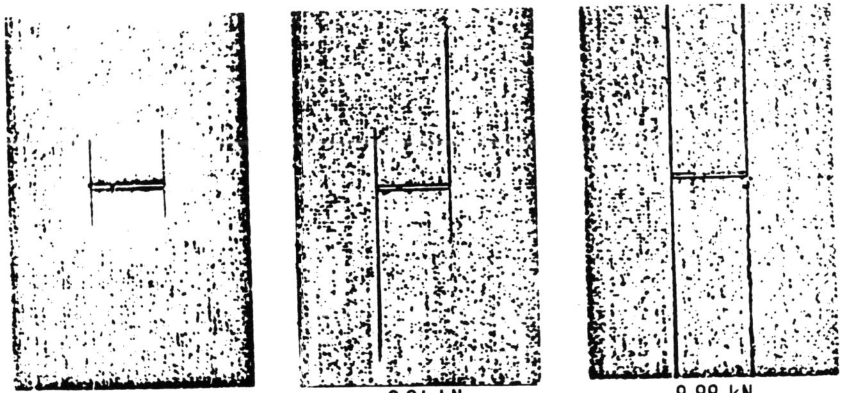


Fig. 16. Crack propagation in centrally notched $[0]_{16}$ -specimen

CONCLUSION

Evidently, the issue of damage mechanics is of inordinate complexity and little tangible progress has been made so far. The remaining volume of work seems to be overwhelming and the question is valid whether the effort is worth the gain. The DFVLR Institute for Structural Mechanics has adopted an affirmative position since, without the mastery of damage mechanics, the potential of composite construction cannot be fully exploited. Considering the highly competitive international market, the consequences of failing would be so grave that a relaxed stance in this matter can hardly be afforded.

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