

# Engine Environmental Effects on Composite Behavior

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The NASA Lewis Research Center has conducted a series of programs intended to investigate and develop the application of composite materials to turbojet engines. A significant part of that effort was directed to establishing the impact resistance and defect growth characteristics of composite materials over the wide range of environmental conditions found in commercial turbojet engine operations. Both analytical and empirical efforts are involved. This paper summarizes the experimental programs and the analytical methodology development as well as an evaluation program for the use of composite materials as fan exit guide vanes.

## Introduction

THE development of implementation technology for more durable, weight efficient, cost effective engine structures is the objective of a recently expanded engine structures research program at the NASA Lewis Research Center. Coordinated programs involving in-house, university, and industry activities are being initiated to address difficult engine development problems and to effectively incorporate new analysis techniques and materials developments into currently evolving engine systems. These programs include a substantial effort to exploit the unique mechanical and manufacturing characteristics of newly developed composite material systems. Evaluations of graphite/epoxy composites and hybrid composites for fan blades, fan exit guide vanes (FEGV's), engine frames, nacelle components, engine ducts, and other relatively low-temperature structures are being, or have been, conducted.

A major part in these programs is the evaluation of the engine environmental effects (moisture and temperature) on composite material mechanical behavior. The objective of this paper is to summarize research being conducted and results obtained dealing with engine environmental effects on impact resistance, defect growth, and fracture of composites, and the fatigue resistance of composite FEGV's.

## High Velocity Impact

The experimental program on impact resistance has been conducted by General Electric under NASA Contract NAS3-21017. It involves evaluation of six composite systems, seven environmental conditions, and three test conditions. The composite systems consist of graphite-fiber/epoxy (T300/PR288) as the base line material, two graphite-S-glass/epoxy intraply hybrids (different fiber types within the same ply), one graphite-S-glass/polyimide, and two superhybrids (combination of metallic foils, and resin and metal matrix fiber composites adhesively bonded together). The intraply graphite-S-glass/epoxy systems used PR288 and SP313 as the matrix materials. The polyimide selected was NR150A2 and the superhybrids used PR288 and SP313 epoxy as matrix materials. The test conditions consisted of 70°F dry, wet, and wet spike; and 250°F dry, wet, and wet spike. Mechanical property test data included static flex, short-beam-shear, and high velocity impact strengths. The "wet spike" specimens were subjected to an abrupt temperature excursion from room temperature to 300°F followed by

cooling to test temperature. The cooling rate was slow relative to the heating rate but was sufficiently rapid to prevent a loss of moisture from the test specimens.

The PR288 epoxy was selected for its ease of processing, which is advantageous in making complex engine components such as fan blades. The SP313 epoxy was chosen because it is the most commonly used epoxy in structural applications and has about 100°F higher temperature capability than PR288. The NR150A2 polyimide was selected for its potential use in the hotter parts of the engine (parts operating at temperatures ranging from 300-500°F). The two superhybrids were selected for their unique material property characteristics, which provide high impact resistance combined with high strength, high stiffness, and moisture resistance. Both unidirectional and angleply specimens were tested. Unidirectional specimens were tested for moisture absorption and moisture-temperature strength degradation. Short beam (interlaminar) shear and three-point-bend specimens were tested for strength degradation. Degradation of impact resistance due to moisture and temperature was evaluated using angleply wedge specimens with multiples of 0/±35 deg plies symmetric about the midplane. Both epoxies were cured and post-cured according to the manufacturers specifications. The NR150A2 polyimide specimens were subjected to secondary pressure-temperature consolidation cycles which are described in detail in Ref. 1.

Experimental data on moisture absorption in composites made from the three different resin systems are shown in Fig. 1. All specimens were given a baseline drying treatment consisting of 250°F soak for 16 h prior to moisture exposure.

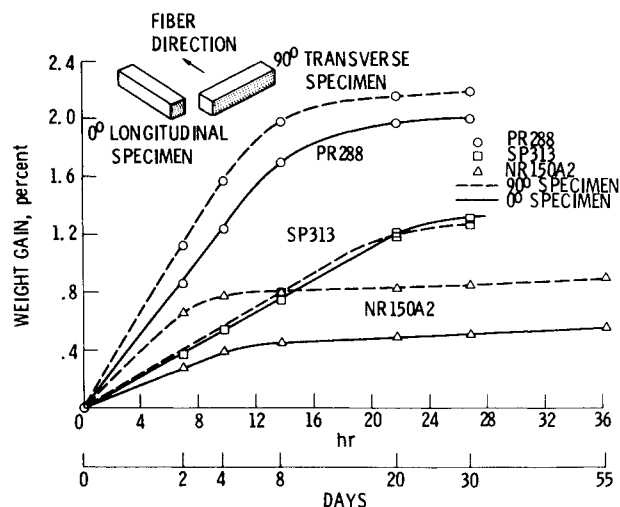


Fig. 1 Moisture absorption, S-glass flexural specimens, conditions 180°F/97% R.H.

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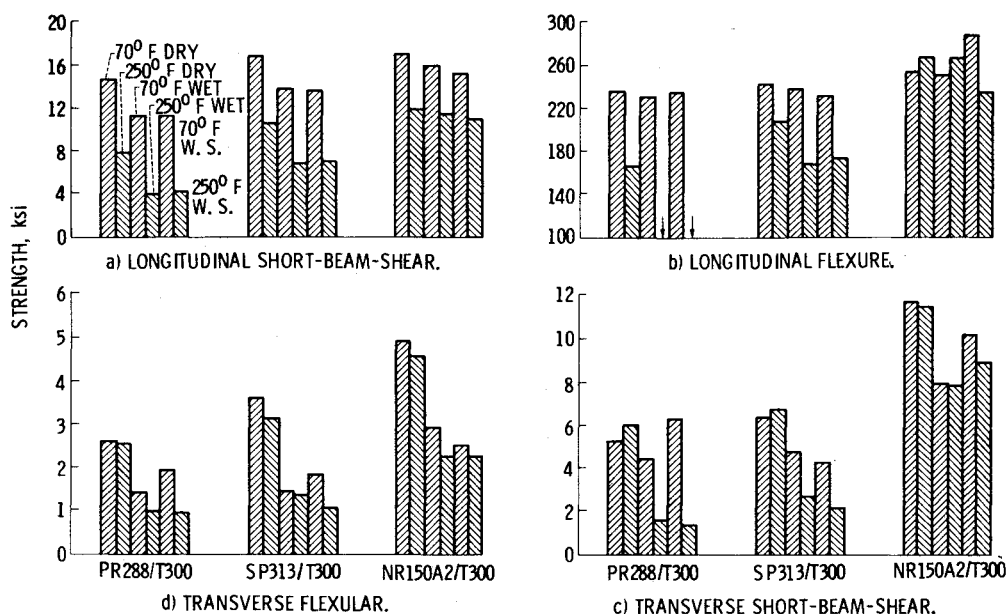


Fig. 2 Moisture/temperature effects on flexural and shear strengths of resin/T300 unidirectional composites.

The saturation moisture (curve leveling off) is about 2% for the composites with the PR288 resin, about 1.2% with the SP313 resin, and about 0.8% for the composites with the NR150A2 polyimide. As expected, the 90-deg specimens absorbed more moisture than the 0-deg specimens owing to greater interfacial surface exposure (more fiber ends at the surface). Although the data are not shown in Fig. 1, the superhybrid specimens absorbed no measurable moisture. Experimental data on the moisture-temperature effects (strength retention) of longitudinal shear specimens are shown in Fig. 2a in bar chart form. Tests were conducted in the wet and dry conditions at both 70 and 250°F. Wet spike tests consisting of an abrupt temperature excursion of wet specimens to 300°F followed by cooling to test temperatures of 70 or 250°F were also conducted. The composite with PR288 resin has the lowest strength retention for the combined wet and thermal conditions (250°F wet or wet spike) which is about 25% of the room-temperature dry strength. The corresponding strength retention was about 40% for the composite made with SP313 and about 70% for the composite with NR150A2.

Experimental data for moisture-temperature effect on longitudinal flexural strength are shown in Fig. 2b. The longitudinal flexural strength retention for the three resin composite systems at the 250°F wet and 250°F wet spike conditions (several cases) are as follows: PR288 composites about 30% of the 70°F (room temperature dry), about 70% for the SP313 composites, and nearly 100% for the NR150A2 composites.

Experimental data for transverse interlaminar (short-beam) shear strength are shown in Fig. 2c and for transverse flexural strength in Fig. 2d. The strength retention of the transverse interlaminar shear strength at the 250°F wet or 250°F wet spike condition is about 30% of the 70°F dry strength for the PR288 and SP313 composites, and about 45% for the NR150A2 composites. The corresponding transverse flexural strength retention is about 30% for the PR288 and SP313 composites and about 70% for the NR150A2 composites.

Taken collectively, the data in Fig. 2 show that the environmental conditions of 250°F wet or wet spike reduce substantially (as much as 75%) the shear and flexural strengths in epoxy composites while the corresponding reduction in the polyimide composites is only 30%, except for transverse intralaminar shear which is reduced about 60%. In addition, these data provide material strength characteristics which can be used in conjunction with the high velocity impact analysis to assess the environmental effects on impact resistance as will be described later.

IMPACT VELOCITY: 900 fps  
INCIDENCE ANGLE: 25° LEADING EDGE  
IMPACT PROJECTILE: 1 in. DIAM GELATINE (0.3 oz)

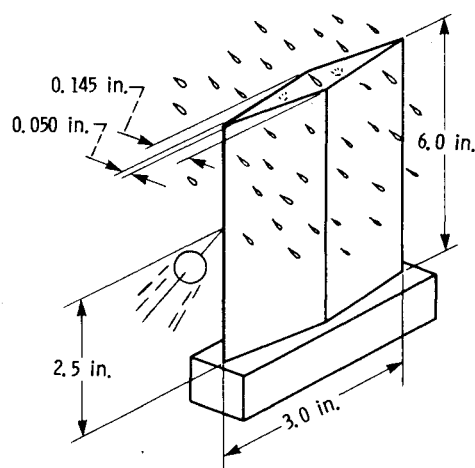


Fig. 3 Impact test conditions.

The high velocity impact test conditions and wedge specimen configuration are summarized on Fig. 3. The experimental data for environmental effects on impact resistance, as measured by area delamination (determined by C-scan measurements) are summarized in Fig. 4 for the impact conditions of 100 and 900 ft/s. The principal points established by the data of Fig. 4 are 1) the environmental and impact conditions investigated had an insignificant effect on the impact resistance of superhybrids, a minor effect on the polyimide composites and a severe effect on the epoxy composites, 2) the 250°F wet spike environmental impact conditions generally caused the greatest delamination in the epoxy composites, and 3) the 900 ft/s velocity impacts caused much more delamination than the 100 ft/s velocity impacts, especially in the epoxy composites.

Pertinent information about the high velocity impact analysis (composite mechanics<sup>2,4</sup> and NASTRAN<sup>5</sup>) is summarized in Fig. 5. Results obtained from this analysis are shown graphically in Fig. 6 for stresses near the impact point on the impact surface, and in Fig. 7 for stresses on the back surface. These stresses are for the PR288/T300 wedge specimen. They are typical of wedge specimen results from the analysis of other composite systems (including superhybrids).

Fig. 4 Damage comparison for 250°F environmental specimens.

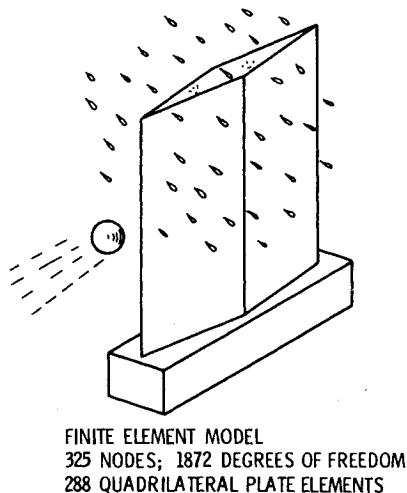
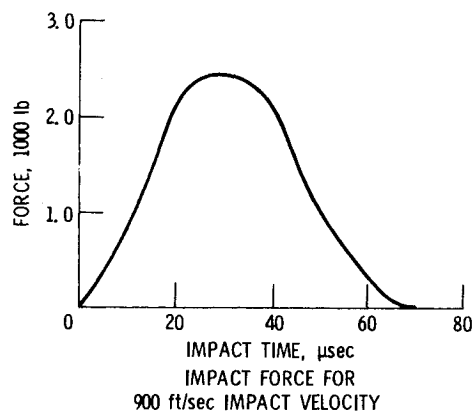
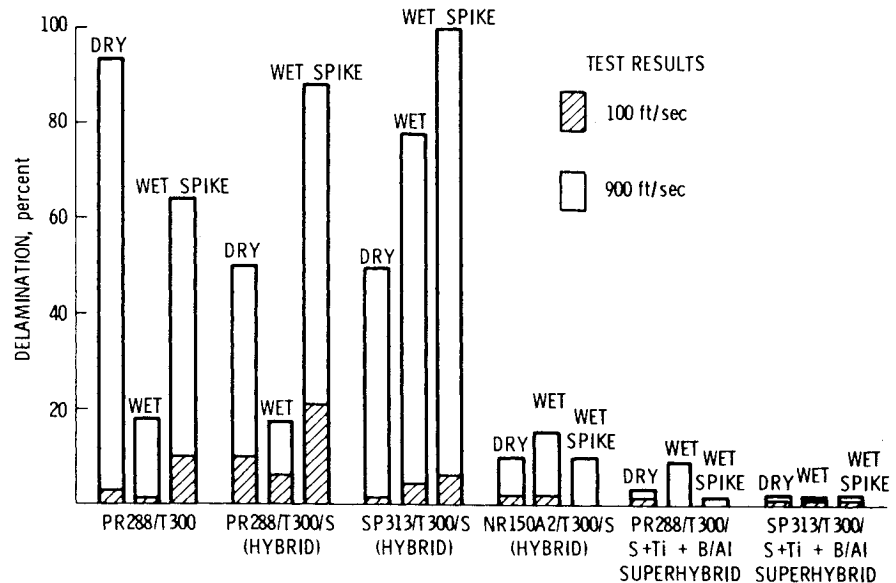


Fig. 5 Impact finite element analysis, NASTRAN direct time response.

All systems have approximately the same stresses early (first 100  $\mu\text{s}$ ) in the impact event. The analysis performed was linear. This linearity implies that the stresses shown in Figs. 6 and 7 are correct only prior to the onset of initial damage. This applies only early in the impact event and is the condition used for assessing the effects of moisture-temperature condition on impact resistance.

The inplane predicted stresses for initial damage for four test conditions—70°F dry, 250°F dry, 250°F wet, and 250°F wet spike—were determined (using the composite mechanics methods, Refs. 2-4). The results are shown as straight

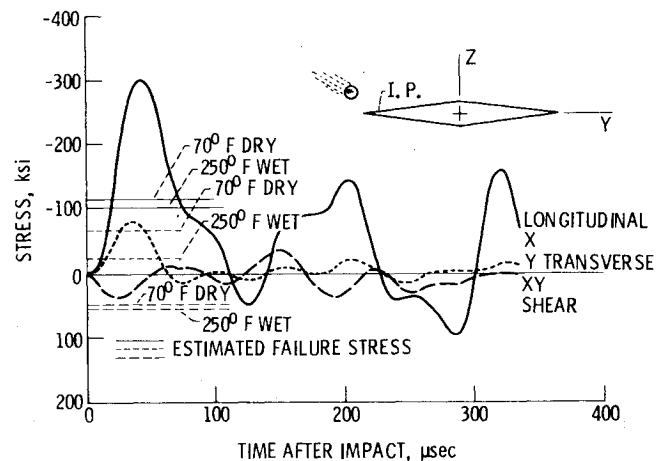


Fig. 6 Stresses near impact point, impact surface.

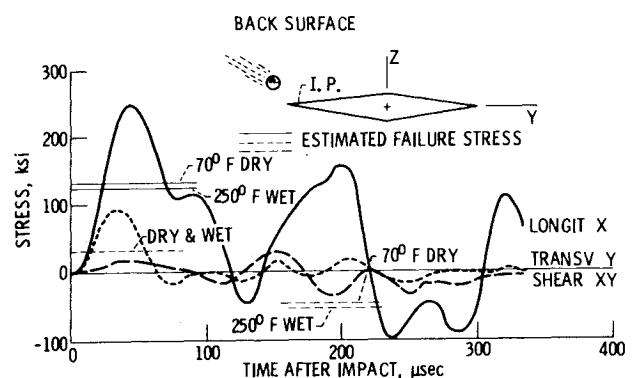


Fig. 7 Stresses near impact point, back surface.

horizontal lines in Figs. 6 and 7. The through-the-thickness shear stress (not shown on Figs. 6 and 7) is about 10 ksi compared to the short-beam shear strength of about 15 ksi for 70°F dry and 4 ksi for 250°F wet and wet spike conditions. The inplane and through-the-thickness predicted stresses for failure indicate that damage will occur very early in the impact event and will be at considerably lower transverse and interlaminar shear stresses (about 30%) for the 250°F wet compared to the 70°F dry case. However, the superhybrids will sustain only localized damage in the form of indentation since the moisture-temperature test condition does not

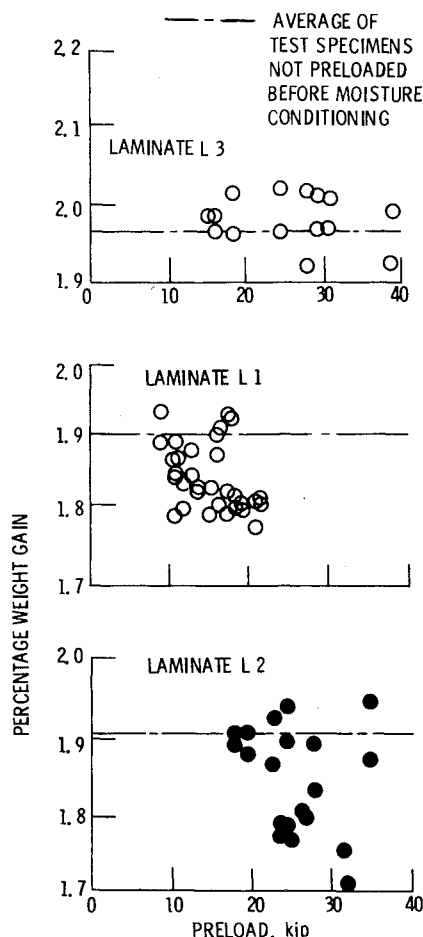


Fig. 8 Influence of preload on weight gain after eight weeks of 180°F water immersion.

seriously degrade the superhybrid mechanical properties. One conclusion from the foregoing discussion is that the impact damage of fiber-resin composites in moisture-temperature environments can be assessed using available finite element analysis methods and composite mechanics.

### Defect Growth and Fracture

The experimental program for environmental effects on defect growth in composites is being conducted by Boeing Aerospace under NASA Contract NAS3-20405. This program consists of the evaluation of 1) graphite-fiber/epoxy angleplied laminates with three different laminate configurations; 2) four environmental conditions; 3) three defect types; and 4) three test loading conditions. The graphite/epoxy angleplied laminates are made from T300/934 as follows: 1) baseline laminate,  $L_1$ ,  $[0/45-45/0/90/90/0/-45/45/0]_s$ ; 2) pressure vessel type laminate,  $L_2$ ,  $[(0_3/\pm 80_2)]_s$ ; and 3) fan blade type laminate,  $L_3$ ,  $[0/30/0^s/-30/0/30/0^s/-30/0]_s$ , where the  $0^s$  denotes S-glass/epoxy plies. The environmental conditions investigated consist of: 1) room temperature dry and wet and 2) 300°F-dry, -wet, and -wet spike. The defect types are: 1) full and half penetration holes; 2) full and half penetration slits; and 3) embedded delaminations. The test conditions are: 1) monotonic load to fracture (static); 2) cyclic load to fracture; and 3) cyclic load to fracture following preloading to 90% of the monotonic fracture load. Visual and ultrasonic methods and continuous crack opening displacement instrumentation are used to monitor the defect growth. The room-temperature dry fatigue and fracture data of this program have been previously reported in detail in Ref. 6. Testing of the high-moisture, high-temperature specimens is currently in progress. The effect of applying preloads up to

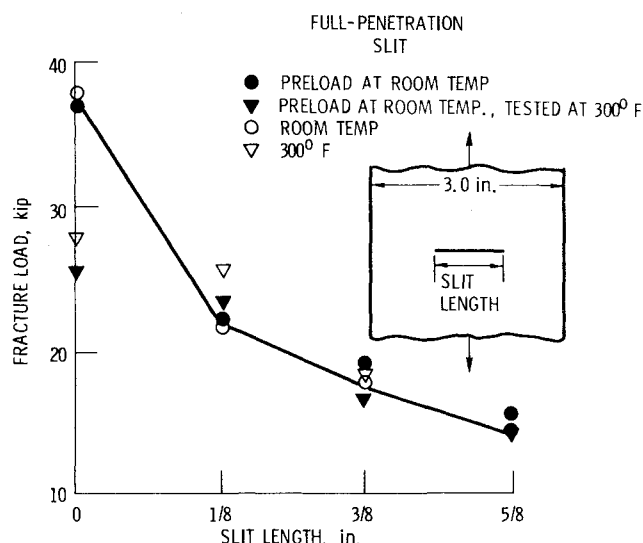


Fig. 9 Slit specimen static fracture data for laminate  $L_1$ .

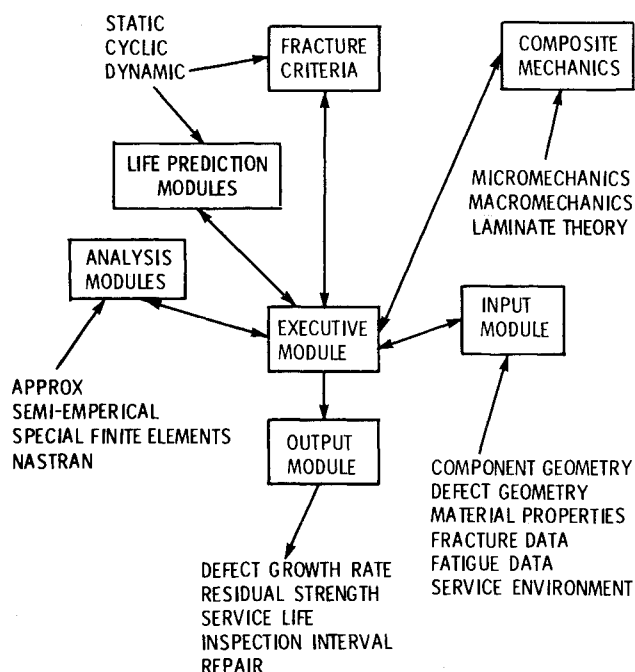


Fig. 10 CODSTRAN: Composite Durability Structural Analysis.

90% of the monotonic fracture load on the subsequent moisture absorption of the angleply composite specimens is shown in Fig. 8. After eight weeks of exposure consisting of complete immersion in 180°F water, the percentage weight gain for the preloaded specimens showed no definite correlation with preload level for any of the three laminate configurations investigated.

The environmental and preload effects on the fracture of the baseline laminate with slits are shown in Fig. 9. The results are essentially the same for the other two laminates. Also, these results are about the same for all three laminates with equal size holes, and may be considered to be representative of laminates with equal size, full penetration defects. It can be seen in Fig. 9 that: 1) elevated temperature (300°F), moisture (1.9 wt.%), and preload (about 90% of fracture) have no effect on the fracture load of laminates with defects and 2) elevated temperature decreases the fracture load (about 30%) of specimens without defects. The conclusion, therefore, is that moisture-temperature environments investigated have no significant effect on the fracture load of graphite/epoxy composites with defects.

A concurrent LERC in-house research effort is directed towards the development of the methodology required to predict the defect growth and propagation to fracture in composite structures subjected to environmental and mechanical loads. The objective of this in-house program is the development of an integrated computer program which is presently identified as CODSTRAN (Composite Durability Structural Analysis). The composition and scope of CODSTRAN is illustrated schematically in Fig. 10 and its initial form is described in some detail in Ref. 7. CODSTRAN was used to analyze specimens tested and data generated under the Boeing contract.

Typical results obtained using CODSTRAN are illustrated in Fig. 11. The predicted progressive damage in the slotted laminate is compared with an ultrasonic C-scan record. It can be seen from Fig. 11 that CODSTRAN predicts a damage pattern which is in essential agreement with that shown by the experimental C-scan data. This comparison is based on the 70°F dry specimen test data and the corresponding 70°F dry, composite mechanical property data for the CODSTRAN program. Modification of the CODSTRAN program by utilization of the matrix and fiber mechanical property data for the high-temperature, wet conditions is currently being accomplished and comparisons such as presented in Fig. 11 are planned to be made for the 300°F, fully wet conditions.

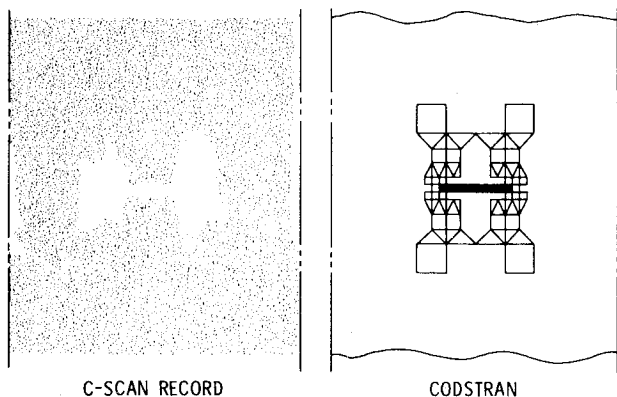


Fig. 11 C-scan/CODSTRAN defect growth comparisons, 50% fracture load.

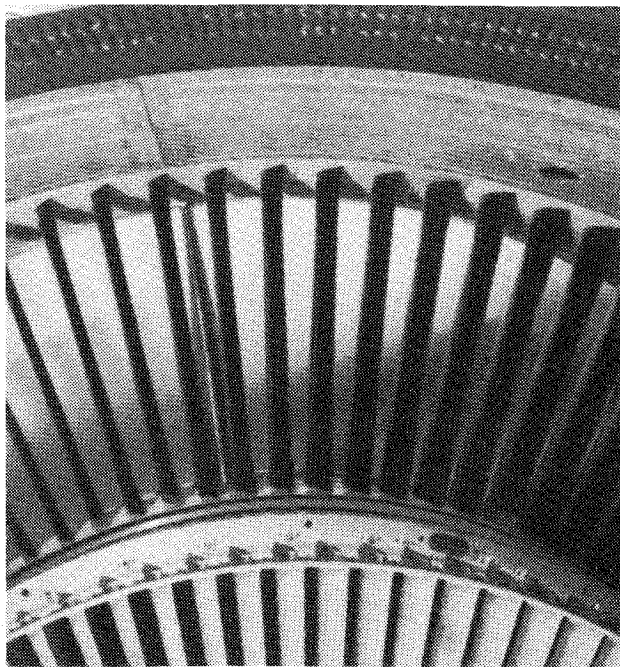


Fig. 12 Lightweight, composite fan-exit guide vanes for high-bypass-ratio turbofan engines.

### Fatigue of Fan Exit Guide Vanes

The engine environmental effects on composite fan exit guide vanes (FEGV's) were investigated by Pratt and Whitney under NASA Contract NAS3-21037. The engine application for the FEGV's is illustrated in Fig. 12, which shows composite FEGV's installed in a JT9D engine. Four different designs were evaluated involving two different fabrication procedures, pultrusion and hand-layup.

All four designs contained a high modulus graphite fiber core (Fortafil 5A) to provide adequate bending stiffness. Each fabrication process involved one all-graphite fiber vane design and one graphite core-fiberglass shell design. The pultrusion all-graphite vane used high modulus, 48 msi, Fortafil 5A fibers for both the core and shell. The hand-lay-up all-graphite vane used the high modulus Fortafil 5A fibers for the core and a lower modulus, 32 msi, AS-2 graphite fiber shell. The shell for the pultruded core was made from 6581 style S-glass cloth and the hand-layup vane shell was made from S-2 glass roving. The laminate configuration for the glass shells consisted of  $\pm 45$ -deg plies. For the graphite shells the configuration was  $\pm 35$  deg for pultrusion vane and  $\pm 30$  deg for the hand-layup vane. A detailed description of all fabrication steps of each vane design is contained in the appendices of Ref. 9.

The FEGV's were tested in simulated engine environments of moisture, temperature, and fatigue loading in addition to other mechanical tests required to qualify the FEGV's for a flight readiness test program. The results from the environmental fatigue testing effort are summarized in Fig. 13. The fatigue data obtained exceed the operational engine strain fatigue design requirement (about  $700 \mu\epsilon$  for  $10^7$  cycles) by at least a factor of 2. It can be seen in Fig. 13 that all fatigue failures, except one, occurred at strain levels about three times the design requirement. Also these failures occurred after several repetitions of  $10^7$  cycles at lower strain levels. The data also show that the environmental conditions imposed (0.8% moisture and 140°F temperature) had no discernible adverse effect on the fatigue life of the FEGV's. The conclusion, therefore, is that composite FEGV's can be designed and fabricated to meet the anticipated engine operation environmental conditions.

### Conclusions

The effects of engine environmental conditions of saturation moisture and elevated temperature (250 and 300°F) on composite structural performance were investigated in several programs conducted by the NASA Lewis Research Center. These programs were concerned with the effects on

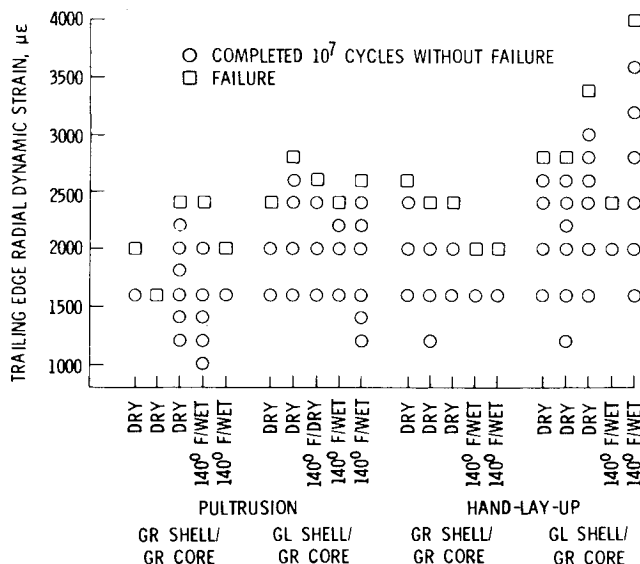


Fig. 13 Composite fan exit guide vane fatigue test sequence.

mechanical properties determined by flexural type specimens, impact resistance of angleply wedge specimens, defect growth and fracture of angle ply flat specimens, and fatigue resistance of fan exit guide vanes (FEGV's). The following important conclusions can be drawn from these programs.

1) The moisture absorbed in fiber composites depends on the resin systems, and amount of fiber ends exposed. Epoxy resin composites absorbed the most moisture (about 2 wt. %) while polyimide resin composites absorbed about 0.8% and superhybrid composites absorbed no moisture.

2) Both high moisture (saturation) and elevated temperature (250°F) conditions have severe effects on the flexural and interlaminar shear properties of unidirectional composites. Strength degradation ranges from about 30% for the polyimide composites to 70% for those made from the processible epoxy (PR288). The 250°F wet environment was the most severe condition.

3) The environmental and impact conditions (900-ft/s, 1 in.-diam, 0.3-oz gelatin ball, 25-deg incidence angle) produced insignificant damage to the superhybrid specimens (measured by delaminated area) and minor damage to the polyimide composites but severe damage to the epoxy composites. The 250°F wet spike impact condition caused the greatest delamination in the epoxy composites.

4) The impact damage to fiber composites in moisture-temperature environments can be assessed using available finite element analysis methods (such as NASTRAN) and composite mechanics analysis. The stress magnitudes near the impact region are very high relative to material allowables at early times of the impact event (about the first 100  $\mu$ s) and will induce significant damage in the resin composites. During this time interval, the stress magnitudes do not depend on the environmental conditions. However, the material allowables and the corresponding stresses at which initial damage occurs will depend on the environmental conditions, with the 250°F wet condition sustaining initial damage at lowest stress levels.

5) Preload, 1.9% moisture and 300°F temperature environmental conditions had no effect on the fracture load of

composites with slit type defects. CODSTRAN (an integrated computer program for Composite Durability Structural Analysis), predicts defect growth which is in reasonably good agreement with ultrasonic C-scan records for the 70°F dry test conditions and will be utilized for similar predictions at high-moisture, high-temperature conditions.

6) Engine operation environmental conditions of 0.8% moisture and 140°F temperature had no discernible effect on the fatigue resistance of composite fan exit guide vanes (FEGV's), and composite FEGV's can be designed to meet and exceed engine operational requirements.

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