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STRAIN ENERGY RELEASE RATE AS A FUNCTION OF TEMPERATURE AND PRELOADING HISTORY UTILIZING THE EDGE DELAMINATION FATIGUE TEST METHOD

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**Title and Subtitle**
Strain Energy Release Rate as a Function of Temperature and Preloading History Utilizing the Edge Delamination Fatigue Test Method

**Abstract**
Static laminate and tension-tension fatigue testing of IM7/8551-7 composite materials was performed. The Edge Delamination Test (EDT) was utilized to evaluate the temperature and preloading history effect on the critical strain energy release rate (G_c). Static and fatigue testing was performed at room temperature and 180°F (82°C). Three preloading schemes were used to precondition fatigue test specimens prior to performing the normal tension-tension fatigue EDT testing. Computer software was written to perform all fatigue testing while monitoring the dynamic modulus to detect the onset of delamination and record the test information for later retrieval and reduction.
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OF TEMPERATURE AND PRELOADING HISTORY
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RICHARD S. ZIMMERMAN
DONALD F. ADAMS

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TECHNICAL REPORT
NASA-LANGLEY RESEARCH CENTER
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This final report presents the results of a research program, initiated in July 1986, sponsored by the National Aeronautics and Space Administration under Grant No. NAG-1-674 (University of Wyoming Project No. 5-32474). The NASA Technical Monitor was Dr. T. Kevin O'Brien, Fatigue and Fracture Branch, Materials Division, NASA-Langley Research Center.

All work was performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming. Co-principal investigators were Mr. Richard S. Zimmerman, Staff Engineer, and Dr. Donald F. Adams, Professor. Making significant contributions to this program were Mr. Michael Borgman and Ms. Janice Atkins, undergraduate students in Mechanical Engineering and members of the CMRG.

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SECTION 1
INTRODUCTION

The edge delamination test (EDT) is a mixed-mode fracture test method comprised of components of a tensile mode and a sliding or interlaminar shear mode of delamination (Mode I and Mode II). It was initially developed by Pagano and Pipes to characterize interlaminar fracture toughness in composite laminates and provide a method to determine their relative damage tolerance and toughness [1,2]. The EDT has been further developed by O'Brien and most recently has been proposed as a standard test method by the American Society for Testing and Materials (ASTM) [3,4].

The edge delamination specimen develops interlaminar normal stresses at the free edges when loaded in tension. These stresses, caused by large Poisson's ratio mismatches between plies, cause the specimen to delaminate at the ply interface with the highest interlaminar normal stress. The delamination is controlled by a combination of Mode I and Mode II. Several different laminate types have been used to perform this test, with varying percentages of Mode I and Mode II components based on the layup and material system [2,3]. O'Brien has also developed a finite element computer program to quantify the contribution of each mode in the EDT for the purpose of predicting material behavior related to damage tolerance and fracture toughness [3].

The EDT method is normally performed under static tensile loading but can be performed under tension-tension fatigue loading. Fatigue loading allows the determination of dynamic fracture toughness
properties due to the cyclic loading. The purpose of this study was to 
measure effects of temperature and preloading history on critical strain 
ergy release rate ($G_c$) determined using the edge delamination test 
method (EDT) in tension-tension fatigue. Tension-tension fatigue 
testing at two test temperatures was performed on IM7/8551-7 carbon 
fiber-reinforced epoxy composite specimens laid up in the $[\pm 35/0/90]_{s}$ 
orientation. Some edge delamination specimens were fatigue tested with 
no preconditioning while others were preconditioned using one of two 
methods, i.e., a high mean load for 1000 cycles or a high spike load. 
Static tests to determine in-plane lamina properties and static edge 
delamination tests were also performed on IM7/8551-7 material.
SECTION 2
SUMMARY

All test specimens were fabricated and tested by the Composite Materials Research Group (CMRG) from cured panels supplied by NASA-Langley. The complete test matrix is given in Tables 1 and 2.

Static lamina testing was performed to generate in-plane material properties necessary to calculate the critical strain energy release rate \( (G_C) \) values measured in edge delamination tests (EDT). Static EDT were conducted to allow comparisons with dynamic EDT results. Transverse coefficient of thermal expansion (CTE) tests were also performed. Tension-tension fatigue testing was performed using the EDT method with three types of preconditioning of the test specimens.

Average axial and transverse tensile, edge delamination, and in-plane Iosipescu shear results are presented in Figures 1 through 4 as a function of test temperature. Average tabulated data are given in Section 4 and individual specimen data and stress-strain plots are presented in Appendix A.

Figure 1 shows the axial tensile test results for the IM7/8551-7 carbon fiber-reinforced/epoxy material. Figures 1a through 1c show that there were minimal differences in the longitudinal material properties between the two test temperatures. Figure 2 presents the transverse tensile material properties measured. Slightly more variation was seen in the transverse tensile material properties because of specimen configuration and material variations at the two test temperatures. These differences are discussed in detail in Section 4. Critical strain energy release rate \( (G_C) \) calculated from the static EDT results
### TABLE 1
Test Matrix for Static Tests

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Test Temperature (°F)</th>
<th>Test Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>5</td>
</tr>
<tr>
<td>Axial Tension</td>
<td></td>
<td></td>
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<tr>
<td>Transverse Tension</td>
<td></td>
<td></td>
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<tr>
<td>In-Plane Iosipescu Shear</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[±35/0/90]_s Edge Delamination</td>
<td></td>
<td></td>
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<tr>
<td>Transverse Coefficient of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Expansion (-40°F to 250°F)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                            | 5 | 5 |

#### TABLE 2
Test Matrix for Edge Delamination
Fatigue Tests at 10 Hz, R = 0.1

<table>
<thead>
<tr>
<th>Fatigue Curve Type</th>
<th>Test Temperature (°F)</th>
<th>Specimen Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Sine Wave (no preconditioning)</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>20</td>
</tr>
<tr>
<td>High Load Spike in 1st Cycle (70 percent of ultimate load)</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>20</td>
</tr>
<tr>
<td>High Mean Load Sine Wave (First 1000 cycles at 70 percent of ultimate peak load)</td>
<td>75</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>20</td>
</tr>
<tr>
<td>(First 1000 cycles at 60 percent of ultimate peak load)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Runout to 10^6 Cycles Typical          | 120 Specimens         |
| Runout to 10^7 Cycles One Test/Curve   |                       |
Figure 1. Average Static Axial Tensile Results for the IM7/8551-7 Carbon/Epoxy Unidirectional Composite as a Function of Temperature.
a) Static Transverse Tensile Strength

b) Static Transverse Tensile Modulus

c) Static Transverse Tensile Ultimate Strain

Figure 2. Average Static Transverse Tensile Results for the IM7/8551-7 Carbon/Epoxy Unidirectional Composite as a Function of Temperature.
decreased slightly at the higher test temperature, as seen in Figure 3. In-plane Iosipescu shear properties are shown in Figure 4. Shear strength and modulus values decreased slightly at the higher test temperature. Ultimate shear strain variation with temperature could not be determined due to saturation of the strain gage rosettes at both test temperatures. Transverse CTE was measured for the IM7/8551-7 material.

Six complete fatigue curves were generated using EDT specimens. Three fatigue curves were generated at room temperature and three at 180°F (82°C), all at 10 Hz, using a sinusoidal waveform and a load ratio R equal to 0.1. Three preconditioning load histories (described in Section 3) were used to determine their effects on $G_C$. A laminated plate computer program (AC3) was used to calculate the sub-laminate modulus required for the calculation of the stiffness contribution in the strain energy release rate equation [12]. Cycles to delamination were reduced significantly after specimens had been preconditioned with the 1000 cycle high mean loading. Less effect on number of cycles to delamination was measured when a high spike loading precondition was performed prior to the fatigue loading. Values of $G_C$ were higher at the elevated test temperature when the same precondition history fatigue curves were compared. This effect on $G_C$ was the reverse of that seen in the static $G_C$ data.

Section 3 discusses the test procedures and test apparatuses for all testing performed. Section 4 presents average test results for static and fatigue testing performed. Conclusions are given in Section 5. Individual test results are given in Appendices A and B.
STRAIN ENERGY RELEASE RATE

Figure 3. Average Static Critical Strain Energy Release Rate for IM7/8551-7 Carbon/Epoxy Unidirectional Composite as a Function of Temperature.
Figure 4. Average In-plane Iosipescu Shear Results for IM7/8551-7 Carbon/Epoxy Unidirectional Composite as a Function of Temperature.
SECTION 3
SPECIMEN FABRICATION AND TEST PROCEDURES

3.1 Material

The material system chosen by NASA-Langley for this study was IM7/8551-7 carbon fiber-reinforced epoxy. It is a relatively new material system manufactured by Hercules Aerospace, Salt Lake City, Utah. The IM7 is a high strength, medium modulus carbon fiber (683 ksi (4.71 GPa), 41.0 Msi (283 GPa)) [4]. The 8551-7 is a rubber-toughened epoxy with good $G_{IC}$ toughness properties (5.5 in-lb/in$^2$ (958 J/m$^2$)) [5]. All materials used in this program were supplied by NASA-Langley in flat plate form. Six inch (152.4 mm) square panels were supplied in the edge delamination test layup ($[\pm 35/0/90]_s$) and three different thickness unidirectional layups ($[0]_8$, $[0]_{12}$, and $[0]_{20}$). Enough material was supplied to complete six edge delamination fatigue curves and all required static tests.

3.2 Static Test Procedures

All specimens were cut from the supplied panels utilizing an abrasive cut-off wheel mounted on a surface grinder. Water cooling was used to ensure that the material did not overheat during the cutting process.

Acid digestion fiber volume determinations were performed on all panels. The procedure given in ASTM Standard Test Method D3171-76 was followed, where a 70% nitric acid was used to dissolve the matrix from the fibers using a hot plate to heat the samples to approximately 170°F (75°C) to speed up the reaction time [6]. The 8551-7 toughened epoxy
dissolved at a slower rate than usually seen in this procedure on previously studied epoxies.

All static tests were conducted using a computer-controlled Instron Model 1125 electromechanical testing machine. A BEMCO Model FTU 3.0 environmental chamber was used to achieve the 180°F (82°C) test temperature. A crosshead rate of 0.08 in/min (2 mm/min) was used for all static testing except the edge delamination testing, which was performed at 0.04 in/min (1 mm/min).

3.2.1 Static Tension

Guidelines in ASTM Standard Test Procedure D3039-76 were followed for all static tension testing [7]. Conventional wedge action grips were utilized to load specimens for all static tension testing. Static axial tension test specimens were 6 in. (152 mm) long, 0.5 inch (12.7 mm) wide, and approximately 0.04 in. (1.0 mm) thick. Longer specimens are normally used for axial tension (9 in. (229 mm)) but the supplied panels limited the specimen length to the smaller dimension. Glass/epoxy circuit board material end tabs 1.5 in. (38 mm) long were bonded to each specimen using a two-part epoxy adhesive. The adhesive was Techkits A-12 (Techkits, Inc., Demarest, New Jersey). It is used extensively for bonding tabbing material to composite specimens and has good material properties up to 350°F (177°C). Axial strains were measured using a 2 inch (50.8 mm) gage length Instron extensometer, allowing complete stress-strain curves to be generated. Lateral strains were measured with a 0.5 inch (12.7 mm) gage length extensometer on the axial tension test specimens, allowing for the calculation of Poisson's ratio.
Transverse tension test specimens were 6 in. (152 mm) long, 0.75 in. (19 mm) wide, and 0.115 in. (2.9 mm) or 0.040 in. (1.0 mm) thick. Not all transverse tension specimens could be cut from the same thickness panel due to the small panel dimensions. None of the supplied panels were large enough to accommodate all the required ten transverse tension specimens. The five room temperature test specimens were cut from the 0.115 in. (2.9 mm) thick $[0]_{20}$ panel while the five elevated temperature test specimens were cut from a 0.04 inch (1.0 mm) thick $[0]_6$ panel. End tabs were not used with these specimens. Axial strains were measured using a 2 inch (50.8 mm) gage length Instron extensometer, allowing complete stress-strain curves to be generated. Transverse strains were not measured on the transverse tension specimens.

Edge delamination test (EDT) specimens were 6 in. (152 mm) long, 0.5 inch (12.7 mm) wide, and approximately 0.04 in. (1.0 mm) thick. This specimen geometry was used for previous edge delamination testing for NASA-Langley at the University of Wyoming [10]. Other geometries can be used for this test method as described by O'Brien and Carlsson and Pipes in references [3,14]. The smaller specimen configuration was used in this program to allow more specimens to be fabricated. Approximately 1.0 inch (25.4 mm) of each end of the EDT specimens was held in the grip area, leaving 4 in. (102 mm) between the grips. Axial strains were measured using a 2 inch (50.8 mm) gage length Instron extensometer, allowing complete stress-strain curves to be generated. Lateral strains were measured with a 0.5 inch (12.7 mm) gage length extensometer, allowing for the calculation of Poisson's ratio for the static EDT tests.
3.2.2 **In-Plane Iosipescu Shear**

In-plane Iosipescu shear test specimens were 3 in. (76.2 mm) long, 0.75 in. (19.1 mm) wide, and approximately 0.06 in. (1.6 mm) thick. Opposing 90° notches were cut on each edge of the specimens to a depth of 0.15 in. (3.8 mm). The notches were cut using a silicon-carbide grinding wheel dressed to the 90° angle with a 0.05 in. (1.3 mm) radius at the bottom of the notch.

Loads were applied to all in-plane shear specimens using a Wyoming Iosipescu shear test fixture. Shear strains were measured with a Measurements Group No. EP-13-062TH-120 two-element rosette strain gage mounted between the notches of the specimens. Complete shear stress-shear strain curves were generated for all Iosipescu shear specimens.

3.2.3 **Transverse Coefficient of Thermal Expansion (CTE)**

The transverse CTE test specimens were 5 in. (127 mm) long, 0.375 in. (9.5 mm) wide, and 0.115 in. (2.9 mm) thick. No axial coefficient of thermal expansion specimens were tested in this program.

Transverse CTE tests were performed using a microprocessor-controlled quartz-tube dilatometer in conjunction with a linear-variable differential transformer (LVDT). The specimens were exposed to thermal excursions between -40°F (-40°C) and 250°F (120°C). Data were acquired on the heat-up portion of the thermal cycles only. Two thermal cycles each were completed on the three specimens tested.

3.3 **Tension-Tension Edge Delamination Fatigue Procedure**

All fatigue tests were performed on an Instron Model 1321 biaxial servo-hydraulic testing machine using a 10 Hz sinusoidal excitation
waveform and a load ratio $R$ (ratio of minimum to maximum applied cyclic loading) approximately equal to 0.1. Axial strains were measured using a 2 inch (50.8 mm) gage length Instron extensometer. The extensometer knife edges were bonded to the EDT specimens using Devcon 5-minute two-part epoxy to ensure that the measured strains were not affected by slippage of the knife edges on the specimens' surface during the fatigue test.

Model 647.02S hydraulic grips manufactured by MTS, Inc., Minneapolis, Minnesota, were used to grip specimens for all edge delamination fatigue testing. The grips were equipped with special high temperature seals and actuating fluid system to allow usage up to 350°F (177°C). They have a load capacity of 5500 pounds (25 kN), which was sufficient to perform all EDT fatigue testing.

An Applied Test Systems, Inc. Series 2911 environmental chamber was used to achieve the required 180°F (82°C) test temperature. Chamber temperature was measured using a Type "E", Chromel-Constantan, thermocouple placed near the test specimen. Figure 5 shows the tension-tension fatigue test configuration used with the environmental chamber in place.

Six complete fatigue curves were generated using the EDT method while monitoring the dynamic modulus of the specimens. Three fatigue curves were generated at room temperature and three at elevated temperature, 180°F (82°C). The three fatigue curves at each temperature were generated using different preloading schemes prior to the normal sinusoidal fatigue test. One curve at each test temperature consisted of a normal sinusoidal loading to specimen delamination with no preload history (normal baseline curve). One curve at room temperature was
Figure 5. Edge Delamination Fatigue Test Configuration Showing Extensometer Mounted on EDT Specimen, Hydraulic Grips, Environmental Chamber, Instron Model 1321 Testing Machine, and Controls Cabinet.
generated with normal sinusoidal loading to delamination after the specimens had been subjected to a high cyclic load to 70 percent of ultimate load for 1000 cycles (high mean load curve). The elevated temperature fatigue curve with a high mean load for 1000 cycles was performed to only 60 percent of ultimate load because the EDT specimens delaminated before the 1000 cycles were completed at 70 percent of ultimate load. This precluded the possibility for further fatigue loading. The third fatigue curves at both test temperatures were generated after the EDT specimens had been subjected to a maximum load of 70 percent of ultimate load for one cycle (spike load curve).

The fatigue test procedure for all testing was quite complicated and required a great deal of time and effort to perfect. The application computer programs necessary to calibrate and perform the testing were written by the CMRG in Fortran 77 computer language on a PDP 11/24 minicomputer. The application programs interfaced with an Instron Machine Driver (IMD) to perform the required subroutine calls to control the test machine and to acquire the data during each fatigue test. The Instron Machine Driver is written in the Macro-11 computer language and is supported by Instron Corporation, Canton, Massachusetts. It consists of numerous machine control subroutines and data acquisition subroutines interfaced with the Instron testing machine hardware. Data recorded during each fatigue test were load, strain, stroke, and cycle count.

The application computer programs also performed many calculations and decisions based on the status of the fatigue test, such as to continue with the test if the specimen was intact, or stop the test if the specimen had delaminated causing a loss of stiffness. The decision
to continue or suspend testing was based on the dynamic modulus calculated during the test. The dynamic modulus was calculated using a linear regression curve-fit technique. The lowest stress level during a cycle \( (\sigma_{\text{min}}) \) was found and the slope of the stress-strain curve was calculated over the next 20 data stress-strain pairs. If the calculated dynamic modulus had decreased by 5 percent or more from the initial calculated modulus, signifying delamination, then the computer would stop the fatigue test. Storage of data was accomplished using a logarithmic scheme similar to that used in previous modulus decay fatigue testing for NASA-Langley [8,9]. Table 5 gives the data storage progression used in this program.

There were five major steps required to prepare for and perform an EDT fatigue test. Step 1 was to calibrate the load, strain, and stroke

<table>
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<tr>
<th>Table 5</th>
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<td><strong>DATA STORAGE PROGRESSION</strong></td>
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<td>Cycle Range</td>
</tr>
<tr>
<td>1 to 100</td>
</tr>
<tr>
<td>101 to 1000</td>
</tr>
<tr>
<td>1001 to 10,000</td>
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<tr>
<td>10,001 to 100,000</td>
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<tr>
<td>100,001 to 1,000,000</td>
</tr>
<tr>
<td>1,000,001 to 10,000,000</td>
</tr>
</tbody>
</table>

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transducers to the appropriate values required. This step was performed periodically during the testing to verify that calibration values had not changed for the three transducers and their respective amplifiers.

Step 2 was to calibrate the computer with the three transducer outputs. This step was performed to ensure the computer had stored the current transducer calibrations before each fatigue test.

Step 3 was to perform a preliminary fatigue test using a square wave excitation on a specimen with similar stiffness to the actual test specimen. A square wave excitation was used to set the load transducer gain level for optimum control and response of the Instron test machine at each load level as described in the Instron Machine Operation Manual [11]. Step 3 was critical because of the limited load control response of the Instron 1321 at the 10 Hz cycling frequency. After setting the gain level to the optimum level, the computer program calculated the appropriate amount of computer control overprogramming necessary to ensure the loads transmitted to the specimen were close to the desired values. The mass of the torsional actuator below the linear actuator was very detrimental to the performance of the Instron Model 1321 test machine at the 10 Hz cycling frequency, but was fully compensated for by this load command overprogramming in the application computer program. The stiffness of the composite material specimens being tested was low enough and the inertia of the load frame actuator high enough to require a command overprogramming of 10 to 20 percent for all fatigue tests.

Step 4 was performed on only those specimens subjected to a pretest load history. The high mean load EDT specimens were tension-tension fatigue tested for 1000 cycles at a maximum peak load equal to 70 percent of ultimate load in the room temperature case, and 60 percent of
ultimate load in the 180°F (82°C) case. The lower peak load precondition used for the elevated temperature specimens was necessary to prevent the delamination of the specimens prior to completing the full 1000 cycles. The spike load EDT specimens were cycled once to a peak load of 70 percent of ultimate prior to being subjected to the normal sinusoidal loading. It was not necessary to reduce the spike peak load level for the elevated temperature specimens because they did not delaminate during the one cycle at the 70 percent peak load level.

Performance of the actual tension-tension fatigue test on the edge delamination specimen at a particular stress level was Step 5. This step included performing the fatigue test between two predetermined stress values until delamination occurred and the specimen calculated dynamic modulus had decreased by at least 5 percent from the initial calculated value. Figure 6 shows a typical modulus decay curve. All modulus decay curves are included in Appendix B. When the dynamic modulus decreased to less than 95 percent of the original calculated value, the computer suspended the fatigue test and ramped to zero load. As Figure 6 shows, the drop in modulus was easily determined from the data. The critical strain value ($\varepsilon_c$) used in the $G_c$ calculation was determined by looking at these curves and picking the location of the onset of delamination as the point where the modulus started to decrease to the minimum value for that test. At least one specimen for each fatigue curve was tested to $10^7$ cycles to investigate material behavior at longer than normal fatigue test runout (typically $10^6$ cycles). Optical inspection of test specimens, after the computer had suspended the tests, always revealed they had delaminated on one or both free edges.
Figure 6. Typical Modulus Decay Curve Used to Determine Onset of Delamination.
Specimen data files were then transferred from the PDP11/24 to a VAX 11/750 minicomputer for reduction and plotting after test completion. Complete test results are presented in Section 4.

3.4 Dye-Enhanced X-Ray and Optical Photography

Dye-enhanced x-ray and optical photographs were taken of some of the specimens, to document the extent of the delaminations. A PANTEK Model HF75 Industrial X-ray unit was used to take all radiographs. This unit was designed especially for low density materials such as composites. The dye was the same used for previous work for NASA-Langley [10]. The mixture formula used is as follows:

60 gm ZnI₂ (Zinc Iodide)  
10 ml Isopropyl Alcohol  
10 ml Deionized Water  
1 ml Kodak "Photo-Flo", Wetting Agent

Polaroid Type 55 sheet film was used for all x-ray photographs. Settings on the x-ray controls were adjusted to result in good contrast for better interpretation of the photographs. The control settings were 17 kilovolts (kV), 12 milliamps (mA), 20 seconds exposure time, and 17 inch (432 mm) film focal distance (FFD). Two specimens from each EDT fatigue curve were radiographed. These radiographs are presented in Section 4.
3.5 **Temperature and Relative Humidity Measurement**

Temperature and relative humidity measurements were recorded during most of the fatigue testing phase in the test laboratory using a Cole-Parmir Model 8368-50 hygrothermograph. Charts were changed periodically during the testing phase. Relative humidity ranged from 12 to 20 percent while laboratory temperature ranged from 68° to 86°F (20° to 30°C).
SECTION 4

TEST RESULTS

4.1 Fiber and Void Volume Results

All IM7/8551-7 panels supplied by NASA-Langley had a fiber volume of approximately 60 percent. The \([0]_8\) and \([\pm 35/0/90]_8\) panels had slightly higher fiber volumes than the \([0]_{12}\) and \([0]_{20}\) panels (62 percent versus 59 percent). Void volumes were typically less than 1 percent except for the EDT panels where 1.2 to 4.7 percent voids were measured. Individual tabulated fiber and void volume data are given in Appendix A.

4.2 Static Tension Test Results

All average static test results are given in Table 4. Individual static test results are given in Appendix A. Static tensile test results for the two test temperatures indicate the moderate elevated temperature, i.e., 180°F (82°C), had some effect on the material behavior.

A slight decrease in axial tensile strength, and axial Young's modulus, and an increase in ultimate axial tensile strain and major Poisson's ratio were measured at the elevated test temperature, possibly due to the higher test temperature causing slight softening of the matrix material.

Transverse tensile test results indicate that the IM7/8551-7 material had lower strength and stiffness properties at the elevated test temperature. Because the specimens tested at the two different
## TABLE 4

Average Static Test Results for IM7/8551-7
Carbon Fiber-Reinforced Epoxy Composite Material

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Test Temperature (°F)</th>
<th>Ultimate Strength (ksi) (MPa)</th>
<th>Modulus (Msi) (GPa)</th>
<th>Ultimate Strain (percent)</th>
<th>Poisson's Ratio</th>
<th>Stress at Delamination (ksi) (MPa)</th>
<th>Strain at Delamination (percent)</th>
<th>Strain Energy Release Rate (in-lb) (J) (in²) (m²)</th>
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<tr>
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<td>1.08</td>
<td>7.4</td>
<td>0.56</td>
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<td>104</td>
<td>0.83</td>
<td>5.7</td>
<td>11.50</td>
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<tr>
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<td>88</td>
<td>0.75</td>
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<td>11.30</td>
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<td>Edge Delamination</td>
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<td>0.20</td>
<td>81</td>
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<td>[±35/0/90]_s</td>
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<td>754</td>
<td>9.99</td>
<td>68.9</td>
<td>1.45</td>
<td>0.45</td>
<td>74</td>
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</tbody>
</table>
temperatures were cut from different panels and were of different thicknesses, an independent temperature effect could not be determined. The overall effect of specimen configuration and test temperature was seen as a decrease in transverse tensile strength and modulus and ultimate transverse tensile strain values at the higher test temperature.

Static EDT results indicate that the IM7/8551-7 material was almost 20 percent tougher at room temperature than at the elevated test temperature. Critical strain energy release rate \( (G_C) \) values were slightly lower at the elevated temperature due to the lower measured critical strain at delamination \( (\varepsilon_c) \) and the lower stiffness values for the laminates. Equation (1) was used to calculate \( G_C \):

\[
G_C = \frac{1}{2} \varepsilon_c t (E_{\text{lam}} - E^*)
\]

where

- \( G_C \) = critical strain energy release rate
- \( \varepsilon_c \) = axial strain at delamination onset
- \( t \) = laminate thickness
- \( E_{\text{lam}} \) = initial laminate modulus
- \( E^* \) = laminate modulus if completely delaminated along one or more interfaces

Strain at delamination onset \( (\varepsilon_c) \) was determined from the EDT stress-strain curves at the point where the curve began to deviate from linear behavior. \( E_{\text{lam}} \) was determined by calculating the initial tangent modulus for the static EDT specimens. Values for \( \varepsilon_c \) and \( E_{\text{lam}} \) are given in Table 4. The delaminated modulus \( (E^*) \) was calculated using Equation (2):
No $[±35/0]_S$ sub-laminate material was supplied to measure the stiffness values required to calculate the $G_C$ values. Laminated Plate Theory Program AC3 was used to calculate the stiffness values for the sub-laminate used in the $E^*$ calculations [12]. The $E_{22}$ value was determined by calculating the initial tangent modulus from the transverse tensile tests. Appropriate values for each test temperature were used in all calculations.

4.3 In-Plane Iosipescu Shear Test Results

Average in-plane shear test results are presented in Table 4. Individual tabulated results and plotted results are given in Appendix A. Significant differences were seen in shear test results at the two test temperatures. Shear strength decreased by 25 percent and shear modulus decreased by 10 percent at the higher test temperature. Ultimate shear strains could not be determined due to saturation of the strain gage rosettes used to measure shear strain on the Iosipescu shear test specimens. Shear strains measured were quite nonlinear for this material system at both test temperatures.

4.4 Transverse Coefficient of Thermal Expansion (CTE) Results

Average transverse CTE results are presented here. Individual tabulated and plotted transverse CTE results are presented in Appendix A. The average transverse CTE value for the IM7/8551-7 material was 19.4 $με/°F$ (34.8 $με/°C$). This value is quite typical for most carbon fiber/epoxy material systems. No unusual behavior was seen.
in the thermal expansion testing results. No axial thermal expansion testing was conducted in this program due to the dilatometer equipment not being able to adequately measure the extremely small displacements in the axial direction for carbon fiber/epoxy composites.

4.5 **Tension-Tension Edge Delamination Fatigue Results**

Six complete fatigue curves were generated using the EDT method subjected to sinusoidal excitation loading at 10 Hz, \( R = 0.1 \), at various stress levels. Three of the fatigue curves were generated at room temperature and three at elevated temperature, 180°F (82°C). Three different specimen preconditioning methods were used to prepare the EDT test specimens for cyclic fatigue loading. One curve at each test temperature was generated using a normal sinusoidal loading to specimen delamination with no pretest load history (baseline curves). One curve at room temperature was generated with normal sinusoidal loading after the specimen had been subjected to a high cyclic load to 70 percent of ultimate load for 1000 cycles (high mean load curves). The elevated temperature precondition, with the high mean load for 1000 cycles, was performed to only 60 percent of ultimate load. The EDT specimens delaminated before the 1000 cycles were completed at 70 percent, precluding the need for further fatigue loading. The third fatigue curve at both test temperatures was generated after the EDT specimens had been subjected to 70 percent of ultimate load for one cycle only (spike load).

Figures 7 through 9 illustrate the temperature effect on \( G_C \) for each of the three load preconditions. Figure 7 shows the two normal fatigue curves generated at different temperatures. Figures 8 and 9
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

Figure 8. Critical Strain Energy Release Rate for IM7/8551-7 [-35/0/90]s Laminates with High Spike Load Precondition as a Function of Temperature.
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

Figure 9. Critical Strain Energy Release Rate for IM7/8551-7 [±35/0/90] laminates with high mean load for 1000 cycles precondition as a function of temperature.
show the high spike and high mean load precondition fatigue curves at the two test temperatures, respectively. The elevated temperature curve in all three of these figures indicates that higher dynamic $G_C$ values were calculated independent of precondition method, for comparable cycles to delamination.

Comparisons of room temperature fatigue $G_C$ values at low numbers of cycles with static $G_C$ data (Table 4) indicate that the dynamic $G_C$ values are much lower (a factor of two) than those generated under static loading at room temperature. Elevated temperature dynamic $G_C$ values at a low number of cycles to delamination indicate much more consistent values compared with elevated temperature static $G_C$ values.

The normal, high spike load, and high mean load curves at the room test temperature and elevated test temperature are plotted in Figures 10 and 11, respectively. Figure 10 indicates that there are significant effects due to the preloading history at room temperature. The two precondition loading curves indicate that damage incurred by the specimen is worse for the high mean load precondition than for the high spike precondition. At room temperature, nearly three decades fewer cycles were seen in the high mean precondition curve than the normal curve data. The spike precondition curve at room temperature indicates that approximately two decades fewer cycles to delamination were measured compared to the normal fatigue curve. Precondition comparisons in Figure 11 show that the effects were reduced significantly at the higher test temperature. Little difference could be seen between the three fatigue curves at the 180°F (82°C) test temperature after passing 10-100 cycles.
Figure 10. Critical Strain Energy Release Rate for IM7/8551-7 [+]35/0/90]s Laminates at Room Temperature as a Function of Precondition.
Figure 11. Critical Strain Energy Release Rate for IM7/8551-7 [+35/0/90] Laminates at Elevated Temperature (180°F (82°C)) as a Function of Precondition.
4.6 X-ray and Optical Photograph Results

Dye-penetrant enhanced x-rays and optical photographs were taken of some of the failed EDT specimens to document the extent of the delaminations. The x-ray opaque dye was composed of the materials listed in Section 3.5 at the given mixing ratios. Figures 12 through 17 are dye-penetrant enhanced x-rays of two specimens from each fatigue curve. At least two specimens from each fatigue curve were x-rayed to see if there were any differences in delamination zones due to temperature or the load history variations used for the fatigue testing. One specimen with less than 100 cycles and one with more than 10,000 cycles were x-rayed from each fatigue curve. The delamination zones appear as darkened areas in the radiographs. Number of cycles to delamination, temperature, and load precondition did not seem to affect the delamination zone size or appearance. Darkened areas at the points of extensometer attachment were due to the glue lines absorbing the dye and are not caused by actual damage to the specimens.

Optical photographs were taken of specimen edges to document the delamination crack at the free edge. Figures 18 and 19 are optical photographs of two specimen edges showing typical edge delamination cracks. The delamination occurred at the 0/90 interfaces in all cases, and wandered back and forth between the 0° plies within the 90° plies along the length of the specimens. This behavior was as expected for the [±35/0/90]s layup used in this program. No variations in delaminations were seen between the different test temperatures or preloading history specimens to indicate any visible effect on the delamination crack path.
Figure 12. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at Room Temperature, No Precondition.

Top: Specimen No. LFLESA - 36 Cycles to Delamination.
Bottom: Specimen No. LFLLSD - 950 Cycles to Delamination.
Figure 13. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at Room Temperature, High Spike Load Precondition.

Top: Specimen No. LFLDPA - 1 Cycle to Delamination.
Bottom: Specimen No. LFLNPB - 1000 Cycles to Delamination.
Figure 14. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at Room Temperature, High Mean Load Precondition.

Top: Specimen No. LFLDMB - 66 Cycles to Delamination.
Bottom: Specimen No. LFLLMA - 3300 Cycles to Delamination.
Figure 15. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at 180°F (82°C), No Precondition.

Top: Specimen No. LFHESA - 51 Cycles to Delamination.
Bottom: Specimen No. LFHMSB - 210,000 Cycles to Delamination.
Figure 16. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at 180°F (82°C), High Spike Load Precondition.

Top: Specimen No. LFHEPA - 1 Cycle to Delamination.
Bottom: Specimen No. LFHMPA - 70,000 Cycles to Delamination.
Figure 17. Dye-enhanced X-ray Photograph of Two EDT Fatigue Failed Specimens at 180°F (82°C), High Mean Load Precondition.

Top: Specimen No. LFHFMA - 1 Cycle to Delamination.
Bottom: Specimen No. LFHMMA - 890,000 Cycles to Delamination.
Figure 18. Optical Photograph of Failed EDT Fatigue Specimen Showing a Crack at the Free Edge in the 90° Plies.
Figure 19. Optical Photograph of Failed EDT Fatigue Specimen Showing a Crack on the Free Edge in the 90° Plies.
Static lamina, static edge delamination, and tension-tension fatigue edge delamination testing was performed on IM7/8551-7 carbon fiber-reinforced/epoxy. Static lamina test results indicated some reduction in material properties from the elevated test temperature on this material system. Matrix-dependent material properties (shear, transverse tension, and EDT) measured at the elevated test temperature were typically lower than those measured at room temperature. Higher test temperatures could be used for future testing to identify an upper use temperature for this material system. The IM7/8551-7 performed well at the 180°F (82°C) test temperature. Static test results indicated that the $G_C$ of this material system was quite good compared to other material systems previously tested [5,6]. Results from this test program should allow the finite element analysis used by O'Brien to predict the contributions of $G_{IC}$ and $G_{IIc}$ to $G_C$ for this material [3].

At room temperature, EDT fatigue results indicated lower $G_C$ values (half of static values) were measured compared to static $G_C$ values. All three preconditions resulted in lower $G_C$ at room temperature. EDT fatigue testing at the 180°F (82°C) test temperature indicated that comparable values of $G_C$ were measured compared to static EDT values.

Effects on $G_C$ at elevated temperature due to preconditioning test specimens were minimal. Only at the high stress level/low number of cycles portion of the fatigue curves was there much variation in $G_C$ between the different load preconditioning data. The high mean load and high spike load curves resulted in $G_C$ values lower than the no
precondition curve values up to about 100 cycles. Elevated temperature data from the three precondition curves approached the same $G_C$ value at runout ($10^7$ cycles).

The room temperature $G_C$ values at equal number of cycles from the three precondition curves were quite different after 10,000 cycles. The three room temperature curves showed a strong influence of the precondition method used with the high mean load having the lowest $G_C$ values and the no precondition $G_C$ values being the highest values at greater than 10,000 cycles. Number of cycles to delamination was reduced by three to four decades compared with the no precondition case after specimens had been preconditioned at room temperature by the high mean level method. Two to three fewer decades of cycles to delamination were measured after preconditioning with the single high spike loading compared with the no precondition case.

Optical photographs showed that the delamination crack on the free edge of specimens did not vary due to test temperature or precondition. Dye-enhanced radiographs taken of delaminated specimens showed that no discernible differences could be attributed to the two different test temperatures or three preconditions.
REFERENCES


APPENDIX A

INDIVIDUAL STATIC TEST RESULTS
## Table A1

**Individual Fiber and Void Volume Results for IM7/8551-7 Composites**

<table>
<thead>
<tr>
<th>Plate Layup</th>
<th>Fiber Volume ($V_f$) (Percent)</th>
<th>Void Volume ($V_v$) (Percent)</th>
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</thead>
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</tr>
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Table A2

Individual Static Axial Tensile Results
for IM7/8551-7 Composites

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<th>Specimen Name</th>
<th>Test Temperature (°F)</th>
<th>Tensile Strength (ksi)</th>
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<th>Ultimate Strain (Percent)</th>
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*Not included in Average or Standard Deviation
Table A3
Individual Static Transverse Tensile Results
for IM7/8551-7 Composites

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<th>Specimen Name</th>
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<th>Tensile Strength (ksi)</th>
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<td>7.56</td>
<td>1.15</td>
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| NTTD21        | 180              | 3.84*                  | 1.07                  | 7.4                      | 0.37*                    |
| 22            |                  | 4.72                   | 1.05                  | 7.2                      | 0.46                     |
| 23            |                  | 5.05                   | 1.05                  | 7.2                      | 0.53                     |
| 24            |                  | 6.20                   | 1.08                  | 7.4                      | 0.60                     |
| 25            |                  | 6.50                   | 1.11                  | 7.6                      | 0.62                     |
| 26            |                  | 6.63                   | 1.09                  | 7.5                      | 0.65*                    |
| 27            |                  | 6.19                   | 1.09                  | 7.5                      | 0.60                     |
| Average       |                  | 5.88                   | 1.08                  | 7.4                      | 0.56                     |
| Std. Dev.     |                  | 0.80                   | 0.02                  | 0.2                      | 0.07                     |

*Not included in Average and Standard Deviation
Table A4

Individual In-Plane Iosipescu Shear Results for IM7/8551-7 Composites

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*Not included in Average or Standard Deviation
Table A5

Individual Static Edge Delamination Test Results for ID7/8551-7 Composites

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<th>Strength Delamination</th>
<th>Critical Strain Energy Release Rate</th>
<th>Strain at Delamination</th>
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*Not included in Average or Standard Deviation
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<td>$E_{22}$</td>
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[±35/0/90]₀ (Predicted Properties From AC3)

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<td>$E_x$</td>
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[±35/0]₀ (Predicted Properties From AC3)

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<td>$v_{xy}$</td>
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$E^*$ = 9.18 Msi (63.3 GPa) 8.41 Msi (58.0 GPa)  
(Calculated Using AC3 and Equation 2)

$E_{lam}$ = 9.85 Msi (67.9 GPa) 9.99 Msi (68.9 GPa)  
(Measured Static EDT Initial Tangent Modulus)
AXIAL TENSION 23 DEG C

STRESS (GPa)

STRAIN (x 10E-03)
AXIAL TENSION 82 DEG C

![Graph showing stress-strain relationship]
AXIAL TENSION 82 DEG C

AXIAL TENSION 82 DEG C

![Graph showing strain vs. strain for an axial tension test at 82 degrees Celsius.](image-url)
TRANSVERSE TENSION 23 DEG C

![Graph showing stress vs. strain for transverse tension at 23 degrees C. The x-axis represents strain (x 10E-03), and the y-axis represents stress (MPa and ksi). The graph includes multiple data points and lines indicating stress-strain behavior.]
TRANSVERSE TENSION 82 DEG C

![Graph showing stress-strain relationship for transverse tension at 82 degrees Celsius.](image)

- **X-axis**: STRAIN (x 10E-03)
- **Y-axes**: STRESS (MPa) and STRESS (ksi)
IOSIPESCU SHEAR 23 DEG C

![Graph showing stress-strain relationship](image)
IOSIPESCU SHEAR 23 DEG C
IOSIPESCU SHEAR 82 DEG C

![Graph showing stress-strain relationship](Image)
EDGE DELAMINATION 23 DEG C

![Graph showing stress-strain relationship for edge delamination at 23 degrees Celsius.](image-url)
EDGE DELAMINATION 23 DEG C

T. STRAIN (x 10E-03)

STRAIN (x 10E-03)
EDGE DELAMINATION 82 DEG C

![Graph showing stress-strain relationship for edge delamination at 82 degrees Celsius.](image)
EDGE DELAMINATION 82 DEG C

![Graph showing strain versus temperature for edge delamination at 82 degrees Celsius.](image)
NL0TD2.TEN
ULT. STRESS = 372.000 ksi
TEMP = 23.0 DEG. C  MOD = 23.894 Msi

![Graph showing stress-strain relationship with labeled axes and values]
NL0TD2.TEN
ULT. STRESS = 372.000 ksi
TEMP = 23.0 DEG. C  NU = 0.168

T. STRAIN (x 10E-03)

0  3  6  9  12  15
0  1  2  3  4  5

STRAIN (x 10E-03)
ULT. STRESS = 382.500 ksi
TEMP = 23.0 DEG. C  MOD = 23.844 Msi

\[ \text{STRAIN (x 10E-03)} \]

\[ \text{STRESS (6Pa)} \]

\[ \text{STRESS (ksi)} \]
NLOTD3.TEN
ULT. STRESS = 382.500 ksi
TEMP = 23.0 DEG. C    NU = 0.186

T. STRAIN (x 10E-03)

STRAIN (x 10E-03)
NLOTD4.TEN
ULT. STRESS = 340.700 ksi
TEMP = 23.0 DEG. C MOD = 21.679 Msi

STRESS (GPa)

1.5

1.0

0.5

0.0

0 5 10 15 20 25
STRAIN (x 10E-03)

2.0

2.5

300

200

100

0
NLOTD4.TEN
ULT. STRESS = 340.700 ksi
TEMP = 23.0 DEG. C   NU = 0.174
ULT. STRESS = 231.200 ksi
TEMP = 23.0 DEG. C MOD = 24.672 Msi
NLOTD5.TEN
ULT. STRESS = 231.200 ksi
TEMP = 23.0 DEG. C   NU = 0.200

T. STRAIN (x 10E-03)

0.0
0.5
1.0
1.5
2.0
2.5

0 2 4 6 8 10
STRAIN (x 10E-03)
NLOTD6.TEN
ULT. STRESS = 358.300 ksi
TEMP = 23.0 DEG. C MOD = 22.318 Msi
NL0TD6.TEN
ULT. STRESS = 358.300 ksi
TEMP = 23.0 DEG. C    NU = 0.189
NLFSH1.TEN
ULT. STRESS = 320.800 ksi
TEMP = 82.0 DEG. C MOD = 22.138 Msi

![Graph showing stress-strain relationship](image-url)
NLFSH1. TEN
ULT. STRESS = 320.800 ksi
TEMP = 82.0 DEG. C   NU = 0.419

![Graph showing stress-strain relationship with marked values of stress, temperature, and Poisson's ratio.](image-url)
NLFSH2.TEN
ULT. STRESS = 364.300 ksi
TEMP = 82.0 DEG. C MOD = 21.357 Msi
NLFSH2.TEN
ULT. STRESS = 364.300 ksi
TEMP = 82.0 DEG. C  NU = 0.404

![Stress-Strain Diagram]

**Stress (ksi)**

**Strain (x 10E-03)**

**T. STRAIN (x 10E-03)**

**STRAIN (x 10E-03)**
NLFSH3.TEN
ULT. STRESS = 366.700 ksi
TEMP = 82.0 DEG. C MOD = 21.345 Msi

![Graph showing stress-strain relationship](image-url)
NLFSH3.TEN
ULT. STRESS = 366.700 ksi
TEMP = 82.0 DEG. C
NU = 0.345
NLFSH4.TEN
ULT. STRESS = 368.500 ksi
TEMP = 82.0 DEG. C  MOD = 21.787 Msi

![Stress-Strain Diagram]

- Stress (GPa) vs. Strain (x 10E-03)
- Stress (ksi) on the y-axis
- Strain on the x-axis

[Graph showing a linear relationship between stress and strain]
NLFSH4.TEN
ULT. STRESS = 368.500 ksi
TEMP = 82.0 DEG. C  NU = 0.345

T. STRAIN (x 10E-03) vs STRAIN (x 10E-03) graph.
NLFSH5.TEN
ULT. STRESS = 372.300 ksi
TEMP = 82.0 DEG. C MOD = 22.448 Msi

![Graph showing stress-strain relationship with axes labeled.]
NLFSH5.TEN
ULT. STRESS = 372.300 ksi
TEMP = 82.0 DEG. C  NU = 0.337

![Graph showing strain vs. strain with values and labels]
NLTTDO.TEN

ULT. STRESS = 6.838 ksi
TEMP = 23.0 DEG. C  MOD = 1.186 Msi

![Graph showing stress-strain relationship with axes labeled Stress (MPa) and Strain (x 10E-03).]
NLTDD1.TEN

ULT. STRESS = 7.560 ksi

TEMP = 23.0 DEG. C  MOD = 1.149 Msi

STRAIN (x 10E-03)

STRESS (MPa)

STRESS (ksi)

0  1.5  3.0  4.5  6.0  7.5

0  3  6  9

0  15  30  45  60  75
ULT. STRESS = 7.607 ksi
TEMP = 23.0 DEG. C
MOD = 1.205 Msi

![Stress-Strain Diagram]
NLTTD3.TEN
ULT. STRESS = 2.801 ksi
TEMP = 23.0 DEG. C MOD = 1.152 Msi

![Graph showing stress-strain relationship]
ULT. STRESS = 7.397 ksi
TEMP = 23.0 DEG. C MOD = 1.211 Msi
NLTTD5.TEN
ULT. STRESS = 7.304 ksi
TEMP = 23.0 DEG. C MOD = 1.269 Msi

![Stress-Strain Graph](image)
ULT. STRESS = 3.843 ksi
TEMP = 82.0 DEG. C  MOD = 1.067 Msi
NTTD22.TEN
ULT. STRESS = 4.722 ksi
TEMP = 82.0 DEG. C MOD = 1.051 Msi
NTTD23.TEN
ULT. STRESS = 5.053 ksi
TEMP = 82.0 DEG. C MOD = 1.053 Msi

STRESS (ksi) 6
5
4
3
2
1
0

STRAIN (x 10E-03)
0.0 1.5 3.0 4.5 6.0 7.5

STRESS (MPa) 50
40
30
20
10
0

STRAIN (x 10E-03)
NTTD24.TEN
ULT. STRESS = 6.200 ksi
TEMP = 82.0 DEG. C MOD = 1.076 Msi

![Graph showing stress-strain relationship with data points and axes labeled for stress (MPa) and strain (x 10E-03).]
NTTD25.TEN
ULT. STRESS = 6.504 ksi
TEMP = 82.0 DEG. C MOD = 1.106 Msi

STRESS (MPa)

STRAIN (x 10E-03)

0 1.5 3.0 4.5 6.0 7.5

0 10 20 30 40 50

0 2 3 5 6
ULT. STRESS = 6.631 ksi
TEMP = 82.0 DEG. C  MOD = 1.094 Msi

[Graph showing a linear relationship between stress and strain]
NTTD27.TEN
ULT. STRESS = 6.192 ksi
TEMP = 82.0 DEG. C MOD = 1.088 Msi

Graph showing the relationship between stress (MPa) and strain (x 10E-03), with a linear trend line.
NFIRD1. IOS
ULT. STRESS = 16.140 ksi
TEMP = 24.0 DEG. C MOD = 0.863 Msi

The diagram shows a stress-strain curve with the following labels:
- X-axis: STRAIN (x 10E-03)
- Y-axis: STRESS (MPa)
- Stress at various strain levels is plotted, indicating the material's behavior under stress.

The curve peaks at a stress level of approximately 150 MPa and a strain level of 150 x 10E-03.
STRESS (MPa)

STROKE in (x 10E-03)

NFIRD1.IOS
NFIRD2.IOS
ULT. STRESS = 14.910 ksi
TEMP = 24.0 DEG. C MOD = 0.873 Msi

![Stress-Strain Graph](image-url)
NFIRD3.IOS

ULT. STRESS = 15.770 ksi
TEMP = 24.0 DEG. C MOD = 0.828 Msi

![Graph showing stress-strain relationship with labeled axes and data points.]
NFIRD3.IOS

Graph showing stress plotted against stroke in (x 10E-03).
NFIRD4.IOS
ULT. STRESS = 15.480 ksi
TEMP = 24.0 DEG. C  MOD = 0.831 Msi

STRESS (MPa)

STRAIN (x 10E-03)
ULT. STRESS = 12.820 ksi
TEMP = 24.0 DEG. C MOD = 0.756 Msi

STRAIN (x 10E-03)
NFIRD5.IOS

![Graph showing stress vs. stroke](image-url)
NFIHD1.IOS

ULT. STRESS = 12.390 ksi
TEMP = 82.0 DEG. C  MOD = 0.811 Msi

![Stress-Strain Diagram](image-url)
NFIHD1.IOS

![Graph showing stress-strain relationship with units in MPa and ksi.](image-url)
NFIHD2.IOS
ULT. STRESS = 10.110 ksi
TEMP = 82.0 DEG. C MOD = 0.772 Msi
NFIHD3.IOS
ULT. STRESS = 13.250 ksi
TEMP = 82.0 DEG. C  MOD = 0.764 Msi

Graph showing stress-strain relationship with axes labeled:
- Stress (MPa) on the vertical axis
- Strain (x 10E-03) on the horizontal axis
NFIHD3.IOS

![Graph showing stress vs. stroke. The x-axis represents stroke in microns (x 10E-03), and the y-axis represents stress in MPa (left) and ksi (right). The graph shows a curve that increases with stroke.]
NFIHD4.IOS
ULT. STRESS = 13.060 ksi
TEMP = 82.0 DEG. C MOD = 0.780 Msi
NFIHD4.IOS

![Graph showing stress vs. stroke](image)

- **Stress (MPa)** on the y-axis.
- **Stroke in (x 10E-03)** on the x-axis.
- The graph plots stress against stroke, with a notable increase in stress as stroke increases.
NFIHD5.I0S
ULT. STRESS = 12.270 ksi
TEMP = 82.0 DEG. C MOD = 0.615 Msi
NLTD1.EDT

ULT. STRESS = 107.500 ksi
TEMP = 23.0 DEG. C  MOD = 8.969 Msi
NLDTD1.EDT
ULT. STRESS = 107.500 ksi
TEMP = 23.0 DEG. C  NU = 0.196

STRAIN (x 10E-03)

STRAIN (x 10E-03)
NLDTD2.EDT
ULT. STRESS = 98.660 ksi
TEMP = 23.0 DEG. C MOD = 9.573 Msi

STRESS (MPa)

STRAIN (x 10E-03)
NLDTD2.EDT
ULT. STRESS = 98.660 ksi
TEMP = 23.0 DEG. C  NU = 0.138
NLDTD3.EDT
ULT. STRESS = 98.510 ksi
TEMP = 23.0 DEG. C MOD = 9.735 Msi

![Stress-Strain Graph]

- Stress (MPa) vs. Strain (x 10E-03)
- Legend: Q
NLDTD3.EDT
ULT. STRESS = 98.510 ksi
TEMP = 23.0 DEG. C NU = 0.168
NLDTD4.EDT
ULT. STRESS = 120.000 ksi
TEMP = 23.0 DEG. C  MOD = 10.061 Msi

![Graph showing stress-strain relationship with a linear plot.
The X-axis represents strain (x 10E-03) ranging from 0 to 15.
The Y-axis represents stress (GPa) ranging from 0 to 1.0.
The graph includes several data points indicating a linear relationship.
The ultimate stress is indicated as 120.000 ksi.
Temperature is 23.0 DEG. C.
Modulus is 10.061 Msi.]
NLDTD4.EDT
ULT. STRESS = 120.000 ksi
TEMP = 23.0 DEG. C  NU = 0.211

![Graph showing stress-strain relationship](image)
NLDTD5.EDT

ULT. STRESS = 93.990 ksi
TEMP = 23.0 DEG. C MOD = 10.191 Msi

![Graph showing stress-strain relationship with Y-axis labeled 'Stress (MPa)' and X-axis labeled 'Strain (x 10E-03)']
NLDTD5.EDT
ULT. STRESS = 93.990 ksi
TEMP = 23.0 DEG. C  NU = 0.183

T. STRAIN (x 10E-03)

0  3  6  9  12  15
0  1  2  3  4  5

STRAIN (x 10E-03)
NLDTD6.EDT
ULT. STRESS = 115.400 ksi
TEMP = 23.0 DEG. C MOD = 9.577 Msi

0.0 0.2 0.4 0.6 0.8 1.0

0 3 6 9 12 15

0 30 60 90 120

STRESS (GPa) vs STRAIN (x 10E-03)
NLDTD7.EDT
ULT. STRESS = 108.100 ksi
TEMP = 23.0 DEG. C  MOD = 9.926 Msi

![Stress-Strain Curve](image)

**Stress (MPa)**

**Strain (x 10E-03)**
NLDTD7.EDT
ULT. STRESS = 108.100 ksi
TEMP = 23.0 DEG. C
NU = 0.232

T. STRAIN (x 10E-03)

0 3 6 9 12 15
0 2 4 6 8 10

STRAIN (x 10E-03)
NLDTD8.EDT
ULT. STRESS = 110.700 ksi
TEMP = 23.0 DEG. C MOD = 10.769 Msi

![Graph showing stress-strain relationship with specific values and labels.](image-url)
NLDTD8.EDT
ULT. STRESS = 110.700 ksi
TEMP = 23.0 DEG. C  NU = 0.267

T. STRAIN (x 10E-03)

0  2  4  6  8  10
0  2  4  6  8  10

STRAIN (x 10E-03)
NLTD21.EDT
ULT. STRESS = 112.400 ksi
TEMP = 82.0 DEG. C MOD = 9.882 Msi

STRAIN (x 10E-03)

STRESS (GPa)

STRESS (ksi)

0.00 0.20 0.40 0.60 0.80 1.00

0 2 4 6 8 10

0 30 60 90 120
NLTD21.EDT
ULT. STRESS = 112.400 ksi
TEMP = 82.0 DEG. C  NU = 0.388
NLTD22.EDT
ULT. STRESS = 108.800 ksi
TEMP = 82.0 DEG. C MOD = 10.789 Msi

![Stress-Strain Graph]

Stress (GPa) vs. Strain (x 10E-03)
NLTD22.EDT
ULT. STRESS = 108.800 ksi
TEMP = 82.0 DEG. C JPEG NU = 0.564

![Graph showing stress-strain relationship with labeled axes and data points.](image-url)
NLTD23.EDT
ULT. STRESS = 107.900 ksi
TEMP = 82.0 DEG. C MOD = 10.141 Msi

[Graph showing stress-strain relationship]
NLTD23.EDT
ULT. STRESS = 107.900 ksi
TEMP = 82.0 DEG. C  NU = 0.471

T. STRAIN (x 10E-03)

0  5  10  15  20  25
0  3  6  9  12  15

STRAIN (x 10E-03)
NLTD24.EDT
ULT. STRESS = 107.700 ksi
TEMP = 82.0 DEG. C  MOD = 9.421 Msi
NLTD24.EDT
ULT. STRESS = 107.700 ksi
TEMP = 82.0 DEG. C
NU = 0.421

![Graph showing T. STRAIN vs. STRAIN with specific values indicated.]
ULT. STRESS = 110.100 ksi
TEMP = 82.0 DEG. C MOD = 9.733 Msi

![Graph showing stress-strain relationship]
NLTD25.EDT
ULT. STRESS = 110.100 ksi
TEMP = 82.0 DEG. C   NU = 0.415

T.STRAIN (x 10E-03)

0 5 10 15 20 25
STRAIN (x 10E-03)
IM7/8551-7 90 DEG NO. 1

ALPHA = +3.618E-05 / C

![Graph showing temperature vs. strain with data points and a linear trend line.](image-url)
IM7/8551-7 90 DEG NO. 2

ALPHA = +3.471E-05 / C

STRAIN (E-03)

TEMPERATURE DEG. C
IM7/8551-7 90 DEG NO. 3

ALPHA = +3.365E-05 / C
Naming Convention for Edge Delamination Fatigue Specimens

Specimen name = 123456.FTG - six characters with .FTG extension

Character Meaning:

1. L - NASA-Langley
2. F - Fatigue Specimen
3. L or H - Test Temperature
   L = Low 75°F (25°C)
   H = High 180°F (82°C)
4. Maximum Load Value where:
   A = 95% of Ultimate Load
   B = 90%
   C = 85%
   D = 80%
   E = 75%
   F = 70%
   G = 65%
   H = 60%
   I = 55%
   J = 50% of Ultimate Load
   K = 45%
   L = 40%
   M = 35%
   N = 30%
   O = 25%
   P = 20%
   Q = 15%
   R = 10%

5. - Precondition Type
   S = No precondition (Normal)
   M = High Mean Load (1000 cycles)
   P = Spike Load (One cycle)

6. - Specimen Number 0-9, A-Z

Example - LFLESA.FTG

Explanation - LF = NASA-Langley Fatigue Program
L = Low temperature 75°F (25°C)
E = 75% of Ultimate Load
S = No Precondition
A = Specimen No. A

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Table B1

Individual Tension-Tension Edge Delamination Fatigue Results for IM7/8551-7 Composites at Room Temperature No Precondition

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Thickness (in)</th>
<th>Peak Stress (ksi)</th>
<th>Initial Modulus (MPa)</th>
<th>Final Modulus (GPa)</th>
<th>R Ratio</th>
<th>Cycles to 5% Modulus Decay</th>
<th>Cycles to Delamination</th>
<th>Delamination Strain (in)</th>
<th>Gc</th>
<th>Gc (J/m²)</th>
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<tbody>
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<td>1.12</td>
<td>79.1</td>
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<td>9.34</td>
<td>64.35</td>
<td>8.86</td>
<td>61.05</td>
<td>0.113</td>
<td>66</td>
</tr>
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<td>0.044</td>
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<td>81.8</td>
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<td>64.56</td>
<td>8.26</td>
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<td>507</td>
<td>10.12</td>
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<td>9.55</td>
<td>65.80</td>
<td>0.139</td>
<td>56</td>
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<td>61.18</td>
<td>0.107</td>
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<td>9.52</td>
<td>65.59</td>
<td>8.99</td>
<td>61.94</td>
<td>0.112</td>
<td>8,600</td>
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### Table B2

Individual Tension-Tension Edge Delamination Fatigue Results for IM7/8551-7 Composites at High Temperature No Precondition

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Thickness (in)</th>
<th>Peak Stress (ksi)</th>
<th>Initial Modulus (MPa)</th>
<th>Final Modulus (MPa)</th>
<th>R Ratio</th>
<th>Cycles to 5% Modulus Decay</th>
<th>Cycles to Delamination</th>
<th>Delamination Strain (percent)</th>
<th>Gc (in$^2$)</th>
<th>Gc (J/m$^2$)</th>
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<tbody>
<tr>
<td>LFLSPA 90%</td>
<td>0.044</td>
<td>74.2</td>
<td>511</td>
<td>9.14</td>
<td>62.97</td>
<td>8.68</td>
<td>59.81</td>
<td>0.138</td>
<td>330</td>
<td>11</td>
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<tr>
<td>LFLSPB 90%</td>
<td>0.045</td>
<td>73.9</td>
<td>509</td>
<td>9.50</td>
<td>65.46</td>
<td>9.01</td>
<td>62.08</td>
<td>0.109</td>
<td>36</td>
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<tr>
<td>LFLCPA 85%</td>
<td>0.044</td>
<td>70.6</td>
<td>486</td>
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<td>70.42</td>
<td>9.71</td>
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<td>59.67</td>
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<td>750</td>
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<td>53.7</td>
<td>370</td>
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<td>61.11</td>
<td>8.37</td>
<td>57.67</td>
<td>0.118</td>
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<td>9,900</td>
</tr>
<tr>
<td>LFLHDA 60%</td>
<td>0.043</td>
<td>50.9</td>
<td>351</td>
<td>9.16</td>
<td>63.11</td>
<td>8.70</td>
<td>59.94</td>
<td>0.104</td>
<td>5,800</td>
<td>9,400</td>
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<td>LFLIDA 55%</td>
<td>0.045</td>
<td>42.0</td>
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<td>8.45</td>
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<td>323</td>
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<td>70.14</td>
<td>9.63</td>
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<td>0.099</td>
<td>24,000</td>
<td>3,200</td>
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<td>LFLIIPB 50%</td>
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<td>58.70</td>
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<tr>
<td>LFLKPA 45%</td>
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<td>LFLLPA 40%</td>
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<td>68.21</td>
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<td>64.77</td>
<td>0.104</td>
<td>7,900</td>
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<tr>
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<td>32.8</td>
<td>226</td>
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<td>61.73</td>
<td>8.51</td>
<td>58.63</td>
<td>0.118</td>
<td>960,000</td>
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<td>Thickness (in)</td>
<td>Peak Stress (ksi)</td>
<td>Initial Modulus (MPa)</td>
<td>Final Modulus (GPa)</td>
<td>R Ratio</td>
<td>Cycles to 5% Modulus Decay (percent)</td>
<td>Cycles to Delamination (lb f in)</td>
<td>Gc (J/m²)</td>
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<td>65.04</td>
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<td>61.60</td>
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<td>8.81</td>
<td>60.70</td>
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<td>57.53</td>
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<td>58.91</td>
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<td>9.71</td>
<td>66.90</td>
<td>9.21</td>
<td>63.46</td>
<td>0.096</td>
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<td>1.12</td>
<td>12.6</td>
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<td>65.94</td>
<td>9.12</td>
<td>62.84</td>
<td>0.102</td>
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</table>
Table B4

Individual Tension-Tension Edge Delamination Fatigue Results for IM7/8551-7 Composites at High Temperature High Spike

<table>
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<tr>
<th>Specimen Name</th>
<th>Thickness (in)</th>
<th>Peak Stress (ksi)</th>
<th>Initial Modulus (MPa)</th>
<th>Final Modulus (GPa)</th>
<th>R Ratio</th>
<th>Cycles to 5% Modulus Decay</th>
<th>Cycles to Delamination</th>
<th>Delamination Strain (lb/in)</th>
<th>Gc (in²)</th>
<th>Gc (J/m²)</th>
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<td>Cycles to 5% Modulus Decay</td>
<td>Cycles to Delamination Strain</td>
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<td>Gc (lb, in)</td>
<td>Gc (J/m²)</td>
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<tr>
<td>Specimen Name</td>
<td>Thickness (in)</td>
<td>Peak Stress (ksi)</td>
<td>Initial Modulus (MPa)</td>
<td>Final Modulus (GPa)</td>
<td>R Ratio</td>
<td>Cycles to 5% Modulus Decay</td>
<td>Cycles to Delamination</td>
<td>Delamination Strain (lb-in)</td>
<td>Gc (in²)</td>
<td>Gc (J/m²)</td>
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<td>64.69</td>
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<td>27.5</td>
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<td>2,000,000</td>
<td>0.31</td>
<td>0.321</td>
<td>56.20</td>
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STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

ROOM TEMPERATURE (75 F)
NO PRECONDITIONING

Cycles to Delamination

Gc (in-lb/in**2)

Gc (J/m**2)
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

HIGH TEMPERATURE (180 F)
NO PRECONDITIONING

Cycles to Delamination

\[ \text{gc (u/m^2)} \]

\[ 10^{-1} \quad 10^{0} \quad 10^{1} \quad 10^{2} \quad 10^{3} \quad 10^{4} \quad 10^{5} \quad 10^{6} \quad 10^{7} \]

0.0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0 \quad 2.5 \quad 3.0 \quad 3.5 \quad 4.0
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

ROOM TEMPERATURE (75 F)

PRECONDITION WITH SINGLE SPIKE @ 70% EDGE DELAMINATION STRENGTH

Cycles to Delamination

Gc (in-lb/in**2)

10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7

0.0 0.5 1.0 1.5 2.0 2.5 3.0

Gc (J/m**2)
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

HIGH TEMPERATURE (180 F)
PRECONDITION WITH SINGLE SPIKE @ 70% EDGE DELAMINATION STRENGTH

Graph showing Cycles to Delamination vs. Gc (in-lb/in**2)
STRAIN ENERGY RELEASE RATE
AT ONSET OF DELAMINATION

ROOM TEMPERATURE (75 F)
PRECONDITIONED WITH 1000 CYCLES
@ 70% EDGE DELAMINATION STRENGTH

Cycles to Delamination

\[ \text{GC} \text{ (j/m}^{2}) \]

\[ \text{GC} \text{ (in}-\text{lb} / \text{in}^{2}) \]
STRAIN ENERGY RELEASE RATE AT ONSET OF DELAMINATION

HIGH TEMPERATURE (180 F)
PRECONDITIONED WITH 1000 CYCLES
@ 60% EDGE DELAMINATION STRENGTH
Edge Delam. Tension/Tension Fatigue

IM7/8551-7 [+35, 0, 90]s
R = 0.1
Tested at Room Temperature

Legend:
- ☐ Single Spike @ 70% Edge Delam. Strength
- + 1000 Cycles @ 70% Edge Delam. Strength
- ✫ No Precondition

Peak Stress (ksi)

Cycles to 5% Modulus Decay
Edge Delam. Tension/Tension Fatigue

IM7/8551-7  [-35, 0, 90]s
R = 0.1
Tested at High Temperature (82 C)

LEGEND
- Single Spike @ 70% Edge Delam. Strength
+ 1000 Cycles @ 60% Edge Delam. Strength
* No Precondition

Peak Stress (ksi)

Cycles to 5% Modulus Decay
Edge Delam. Tension/Tension Fatigue

IM7/8551-7  [-35, 0, 90]°s
R = 0.1
Tested at Room Temperature (23°C)

Graph showing the relationship between Peak Stress (ksi) and Cycles to 5% Modulus Decay.
Edge Delam. Tension/Tension Fatigue

IM7/8551-7 \([-35, 0.90]\)s

R = 0.1

Preconditioned with Single Spike
@ 70% Edge Delamination Strength
Tested at Room Temperature (23C)
Edge Delam. Tension/Tension Fatigue

IM7/8551-7 \([\pm 35, 0, 90]\)s

R = 0.1

Preconditioned at 1000 Cycles

@ 70% Edge Delamination Strength

Tested at Room Temperature (23C)
Edge Delam. Tension/Tensión Fatigue
IM7/8551-7 [+-35, 0, 90]s
R = 0.1
Tested at High Temperature (82C)
Edge Delamination Tension/Tension Fatigue

IM7/8551-7  [+/-35, 0, 90]s
R = 0.1
Preconditioned with Single Spike
@ 70% Edge Delamination Strength
Tested at High Temperature (82C)

Peak Stress (ksi)

Cycles to 5% Modulus Decay
Edge Delam. Tension/Tension Fatigue

IM7/8551-7  [+-35, 0, 90]s  
R = 0.1
Preconditioned with 1000 Cycles
@ 60% Edge Delamination Strength
Tested at High Temperature (82°C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)

MODULUS (Msi) vs CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23°C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)

MODULUS (Msi)

LFHDPDA

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)

LFHHHPA

MODULUS (Msi)

10.0
9.0
8.0
7.0

10
100
1000
10000
100000
1000000
10000000

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 °C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82°C)
MODULUS DECAY CURVE
IM 7 / 8551-7
SINGLE SPIKE AT 70% ULTIMATE - HIGH TEMPERATURE (82 C)

MODULUS (Msi)

LFHQPBB

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82°C)

MODULUS (Msi)

0 8.0

LFHCSB

CYCLES
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)

MODULUS (Msi)

CYCLES

LFHGSAL
MODULUS DECAY CURVE
IM 7 / 8551-7
1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23°C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23°C)

LFLOMA
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)

LFLQMA
MODULUS DECAY CURVE

IM 7 / 8551-7

SINGLE SPIKE AT 70% ULTIMATE - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)

LFHISA
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE – HIGH TEMPERATURE (82°C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)

LFHEMA

MODULUS (Msi)

8.0

7.0

10^0  10^1  10^2  10^3  10^4  10^5  10^6  10^7

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 50% ULTIMATE - HIGH TEMPERATURE (82°C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)

MODULUS (Msi)

LFHIMC

CYCLES

10^0  10^1  10^2  10^3  10^4  10^5  10^6  10^7
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)

MODULUS (Ms1)

LFHJMA

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

1000 CYCLES AT 60% ULTIMATE - HIGH TEMPERATURE (82 C)

LFHMMC
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 °C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - ROOM TEMPERATURE (23 C)

MODULUS (Msi)

LFLDSB

CYCLES

10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)

MODULUS (Msi)

LFLESA

CYCLES

10^0  10^1  10^2  10^3  10^4  10^5  10^6  10^7
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7
NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE
IM 7 / 8551-7
NO PRECONDITIONING - ROOM TEMPERATURE (23 C)

MODULUS (Msi)

CYCLES
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)
MODULUS DECAY CURVE

IM 7 / 8551-7

NO PRECONDITIONING - ROOM TEMPERATURE (23 C)