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LOADING RATE SENSITIVITY OF OPEN HOLE COMPOSITES IN COMPRESSION

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INTRODUCTION

The high strength-to-weight ratio of composites makes these materials ideally suited for aerospace applications where they are used in aircraft secondary structures and are under consideration for heavily loaded primary structures. Previous research has shown that the composite compressive strength is reduced by local discontinuities such as holes and impact damage [1]. A new generation of toughened polymer matrix materials have improved the compressive strength and impact damage tolerance of composites [2,3,4]. However, the behavior of these viscoelastic polymers under long term loading is not clearly understood, particularly when reinforced by relatively rigid fibers in a composite structure.

This paper presents the experimental results of an exploratory study on the compressive, time-dependent behavior of fiber reinforced polymer composites. Matrix materials tested in this study were the epoxies 5208, 5245C, 1808 and 8551-7, as well as the thermoplastics Ultem and APC2 (Table 1). The effect of loading rate on open hole compressive strength was determined for the six different material systems at 75 degrees F (21 degrees C) and 220 degrees F (104 degrees C). A new screening method is described and used to evaluate the loading rate sensitivity of the material systems. The slope of the strength versus elapsed-time-to-failure curve can be used as an alternate to creep testing for ranking the viscoelastic response of material systems. For the thermoplastic AS4/APC2, the effects of laminate thickness and hole size were also determined.

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EXPERIMENTAL PROCEDURES

Specimens

Several types of fiber/matrix combinations were studied. These materials, ranging from brittle epoxies (thermosets) to toughened epoxies and thermoplastics, are listed in Table 1, along with the laminate stacking sequence and resin manufacturer. The specimens were six inches long by one inch wide. The gage length was 1.5 inches. A hole was ultrasonically machined on the centerline of each specimen using a diamond impregnated core drill. Several laminate thicknesses and hole sizes were tested for the APC2 material. Except for 1808, all of the specimens were 48 ply quasi-isotropic containing a 1/4 inch (0.64 cm) diameter hole. The 1808 was a 40 ply quasi-isotropic layup with a 1/16 inch (0.16 cm) diameter hole. The thermoplastic interleave in the 1808 increased the thickness of the laminate, requiring fewer plies to achieve the same thickness as a 48 ply laminate without interleaf. Specimens were tested at both room temperature (70 degrees F or 21 degrees C) and high temperature (approximately 220 degrees F or 104 degrees C).

Test Fixture

The compressive strength of composites is affected by both the unsupported gage length and the fixture used. As part of the current study, an improved compression fixture was developed to address the problem of transverse motion of the fixture during compressive failures, as well as to satisfy the desire to observe the micro behavior when notch effects were introduced into the specimen [5] (Figure 1). The notable features of this fixture are: the incorporation of linear bearings to maintain alignment and resist lateral motion of the fixture; end loading of the specimen to prevent slippage at high loads; and rigid specimen clamping plates which restrain buckling. The serrated gripping surfaces of the clamping plates also contribute to load introduction through shear forces on the faces of the specimen. This loading reduces the possibility of Poisson's deformations (brooming) on the ends of the specimen. The open design of the fixture allows observation of damage development during compression loading.

Test procedure

In a preliminary study of long term compressive loading, a standard creep test was performed. A load equal to 80 - 98 percent of ultimate open hole strength was applied to the specimen in 0.5 sec, then held until failure. The result was that some specimens failed instantaneously, while others never failed. This method was abandoned due to the erratic results as well as a concern over the length of time spent waiting for specimens to fail. An alternate method was developed which was more suitable for evaluating a large number of specimens. In this new procedure, open-hole specimens were loaded to failure at different load rates using a servo-hydraulic testing machine in load control. The strengths decreased with increasing time to failure. The rate at which the strength declined with time-to-failure is a measure of the viscoelastic response under compressive loading.

High temperature testing was performed with an environmental chamber positioned around the test fixture. Specimen heating was achieved using a combination of direct heating through plates attached to the grips and hot air to maintain a uniform temperature on the specimen surface. Initially, the internal specimen temperature was monitored with thermocouples mounted in shallow holes drilled into the specimen edge. The specimen temperature equaled the temperature of the fixture within ten minutes due to the thermal mass of the compression fixture. For convenience, the temperature of subsequent specimens was determined from thermocouples taped to the specimen with heat resistant tape.

A digital storage oscilloscope was used to monitor and collect data. Ring gages were used to measure the displacement between the top and bottom of the 1/4 inch (0.64 cm) diameter hole (Figure 2). The onset of damage around the hole was indicated by the beginning of non-linearity of the stress-displacement curve, as shown in Figure 3.

RESULTS AND DISCUSSION

Loading Rate Effects

Figures 4 and 5 are semi-logarithmic graphs of the failure stresses versus elapsed-time-to-failure, along with a least-squares regression curve through each set of data. The effect of loading rate can clearly be seen. All the materials tested showed a lower failure strength for the slower loading rates (longer elapsed-time-to-failure). For a given material system the strength at room temperature was greater than the strength at the higher temperature (approximately 220 degrees F or 104 degrees C) as seen when comparing the data in Figures 4 and 5. Since the compressive behavior is dominated by the matrix properties and the polymer matrix material is weaker at elevated temperatures compared to room temperature, it is not surprising that at elevated temperatures the strength of the composite is lower.

Additional information was obtained from the rate of strength decrease. The slope of the regression line was used as a measure of the material's sensitivity to loading rate effects. A comparison of this sensitivity for different materials is shown in Figure 6 where the slopes of the strength-life curves from Figures 4 and 5 have been displayed on a bar graph. It should be noted that the slope of the regression curve was used to represent the response of the material systems.

At room temperature the majority of the materials had roughly the same sensitivity (rate of strength decrease) as shown in Figure 6. The large sensitivity of the 5245C data could be due to the laminate being made from prepreg which exceeded the recommended shelf life by two years. AS4/1808, an interleaved laminate, is also included in this figure to compare the trends, although the data is for a 40 ply specimen with a 1/16 inch (0.16 cm) diameter hole instead of 48 ply with a 1/4 inch (0.64 cm) diameter hole. Even with the thermoplastic interleave, the AS4/1808 specimens behaved much like a typical brittle thermoset (e.g. 5208) in all regards.

At the higher temperature Ultem and 8551-7 showed more sensitivity to loading rate than the other three systems (Figure 6). Ultem, an amorphous thermoplastic, showed the greatest sensitivity which can be expected considering the noncrystalline nature of the matrix material. 8551-7, a toughened matrix, displayed a similar sensitivity. 8551-7 achieves its toughness by second-phase rubber precipitates at the ply interface; these rubber particles may be responsible for the increased loading rate sensitivity at the higher temperature. The remaining three materials had similar slopes indicating the same sensitivity at the higher temperature.

From a design viewpoint, the sensitivity to time under load could result in a lower allowable stress for applications with sustained loading. Figure 7 is a projection of this strength decrease for a 1,000,000 second (12 day) test compared to a more typical test of 60 seconds. The regression lines in figure 4 and 5 were used to extrapolate the strengths. The resultant ranking of the materials is similar to those obtained using the slope of the strength-life curve. At room temperature most materials showed a strength decrease of 11 to 12 percent. The APC2 was slightly lower (7 percent) while the 5245C was almost double at 20 percent. At the higher temperature the strength decrease of Ultem and 8551-7 (17 to 21 percent) was about twice those of the remaining materials. This potential for lower compressive strengths points out a need for a better characterization of the long term compressive creep behavior of composite materials, particularly the newer generation matrices at high temperatures.

Effect of Specimen Geometry

The effect of specimen geometry on the time dependent behavior was explored by testing 24, 32 and 48 ply APC2 specimens with 1/16 inch (0.16 cm) and 1/4 inch (0.64 cm) holes. Figures 8, 9 and 10 are semi-logarithmic graphs of the failure stresses versus elapsed-time-to-failure. The solid lines are the least-squares regression curve for each set of data at room temperature, while the broken lines are the regression curve for the high temperature tests. For all configurations, the strength is less for the slower loading rates (longer time under load). At room temperature net compressive strength increases with both increasing number of plys and decreasing hole size. At elevated temperatures the same effect occurs with one exception; the strength of the 24 ply material is higher than the 32 ply for the 1/4 inch (0.64 cm) diameter hole. The reason may be data scatter, since the coefficient of variation is large for this particular specimen geometry. Scatter in the APC2 data was greater than that for the other materials, emphasizing the need for more specimens in follow up studies.

Figure 11 is a bar graph of the slopes of the strength-life curves of Figures 8, 9, and 10 showing the relative sensitivity to loading rate effects due to specimen geometry. At room temperature the trend is decreasing sensitivity for both increasing number of plies and increasing hole size. At the higher temperature the same trend is evident, with the 48 ply material with a 1/4 inch (0.64 cm) diameter hole being the only exception. For both hole sizes there is less sensitivity at the higher temperature compared to room temperature. This may be a consequence of the lower failure strength in general for polymer composites at high temperatures.

Damage Characterization

In these compression tests, a damage zone, similar to a fatigue crack in metals, initiates at the edges of the hole and propagates across the width of the specimens resulting in final failure. The damage zone is virtually symmetric about the hole (ignoring asymmetries due to load introduction and imperfections in the specimen.) The damage is initiated by local fiber buckling at the edges of the hole and was not detected until loads exceeded 88 percent of the failure load. The length or size of the damage zone grows with increasing compressive load. Figure 12 shows the initiation and propagation of this damage zone across the specimen's width. This damage zone was observed only in the ductile materials systems (APC2, ULTEM and 8551-7). Growth of the damage zone in the brittle systems occurs quickly and is difficult to observe prior to catastrophic failure. The ring gage measurements for the 32 and 48 ply APC2 showed the displacement across the 1/4 inch (0.64 cm) hole averaged 6000 to 8000 microinches (0.15 to 0.20 mm) prior to catastrophic failure.

Figures 13 through 17 show edge views of several failed specimens. For these figures, specimen (a) was tested at room temperature, while specimen (b) was tested at the higher temperature. The T300/5208 specimen (Figure 13) exhibited failures typical of a brittle epoxy at both temperatures with extensive longitudinal delamination. AS4/APC2 (Figure 14), a toughened thermoplastic, had similar brittle behavior at room temperature; at the higher temperature the failure mode changed to shear crippling with few signs of longitudinal delamination. C12000/ULTEM (Figure 15), an amorphous thermoset, failed predominately due to shear crippling accompanied by small amounts of longitudinal delamination at room temperature. At the higher temperature the failure mode was exclusively shear crippling. IM7/8551-7 (Figure 16), an epoxy toughened with rubber precipitates, had areas of shear crippling in the failures at both temperatures, however fewer longitudinal delaminations occurred at the higher temperature. The interleaved material AS4/1808 (Figure 17) is noted for improved impact resistance [3,4], however the failure surface of the open hole compression specimen was almost identical to that of the T300/5208 in Figure 13, at both room and high temperatures.

For all but the most brittle materials, the failure mode at the higher temperature contained shear crippling and fewer interply delaminations. (A discussion of the role of fiber kinking and shear crippling is contained in reference 6). At room temperature the amount of shear crippling was related to the amount of toughening employed to improve the matrix material. The toughening results in a lower matrix stiffness which gives less support to the fiber and increases the occurrence of shear crippling. A detailed examination of the through-the-thickness damage of open hole compressive failures can be found in a separate article by the second author in reference 7.

The damage zone growth and failure modes for these specimens closely resembles the failures reported by Williams [8] using larger 5 by 10 inch panels from reference 9. Thus the new compression test fixture reported in this paper has the additional advantage of requiring less material for compression and notch effect studies.

CONCLUSIONS

The effect of loading rate on open hole compressive strength was determined for the epoxies 5208, 5245C, 1808 and 8551-7 and the thermoplastics Ultem and APC2 at 75 degrees F (21 degrees C) and 220 degrees F (104 degrees C). For the AS4/APC2 material system the effects of laminate thickness and hole size were determined by testing 24, 32 and 48 ply specimens with 1/16 inch (0.16 cm) and 1/4 inch (0.64 cm) diameter holes. A new screening method was described and used to evaluate the loading rate sensitivity of the material systems.

All the materials exhibited loading rate effects at both 70 and 220 degrees F (21 and 104 degrees C). All the polymer matrix materials tested had greater strength at room temperature than the same material at the higher temperature. Strength for a 1,000,000 second (12 day) test was compared to a more typical 60 second test to project the long term design implications. At room temperature the strength decrease due to decreased loading rate was 11 to 12 percent. The decrease for APC2 was slightly lower (7 percent) while that for the 5245C was almost double (20 percent). At the higher temperature the strength decrease for Ultem and 8551-7 was about twice that of the other materials (17 to 21 percent compared to 9 percent).

The slope of the strength versus elapsed-time-to-failure curve was used to rank the loading rate sensitivity of the six materials. At room temperature the loading rate sensitivity was about the same for the majority of the materials. The loading rate sensitivity was less for 220 degrees F (104 degrees C) than for 70 degrees F (21 degrees C). However, ULTEM and

IM7/8551-7 were notably more sensitive to loading rate than the other materials at the higher temperature.

AS4/APC2 specimens in several laminate thicknesses and hole sizes were evaluated. The trend for both room and elevated temperature was higher net compressive strength with both increasing number of plys and decreasing hole size. For loading rate sensitivity, the trend is lower sensitivity with both increasing number of plys and increasing hole size. Loading rate sensitivity was less at the higher temperature compared to room temperature for the same specimen configuration. Scatter in the APC2 data was greater than that for the other materials.

During compressive loading, a damage zone, similar to a fatigue crack in metals, initiates at the edges of the hole and propagates across the width of the specimens, resulting in specimen failure. Failed specimens contained both longitudinal splitting and shear crippling, with the amount of each related to both the test temperature and the toughening employed in the matrix.

The compressive loading rate effects identified in this study reflect viscoelastic behavior of the resins, particularly the toughened resins. Long term stability of composites loaded in compression must be considered, especially at elevated temperatures.

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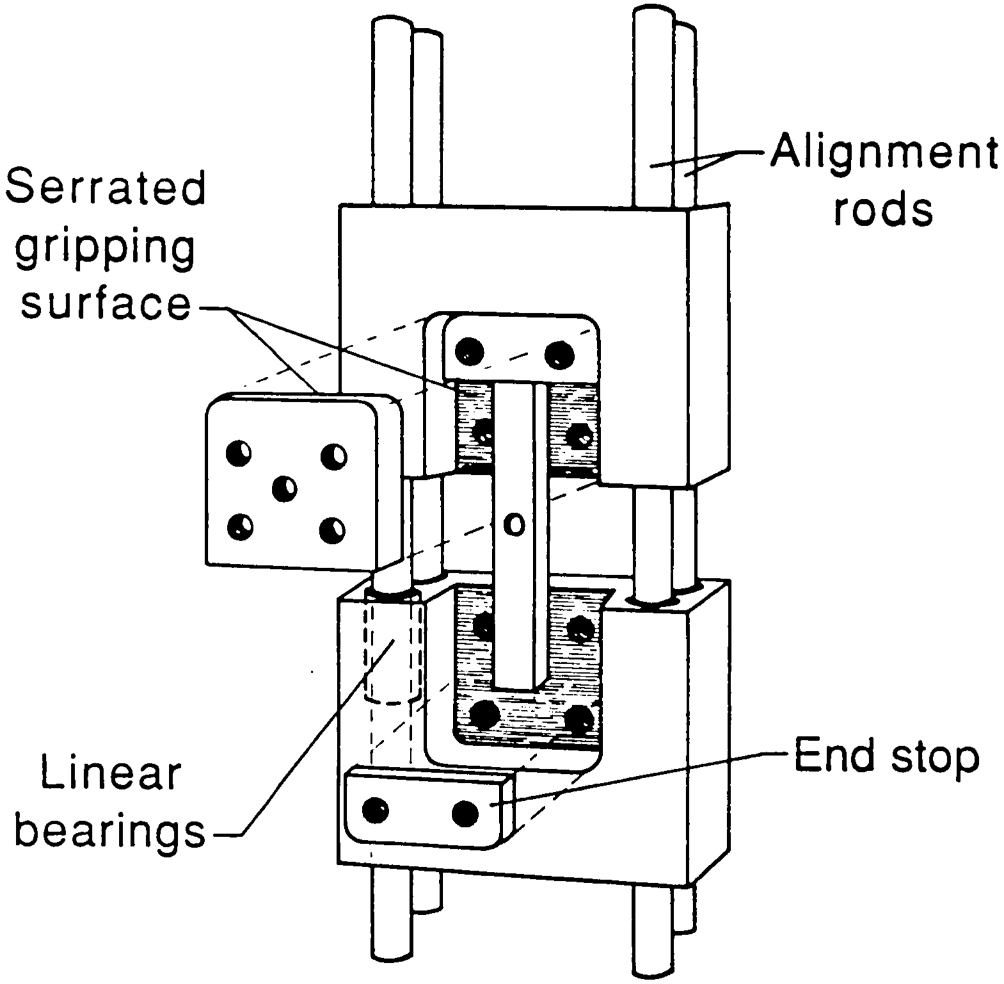

Figure 1 - Compression test figure.

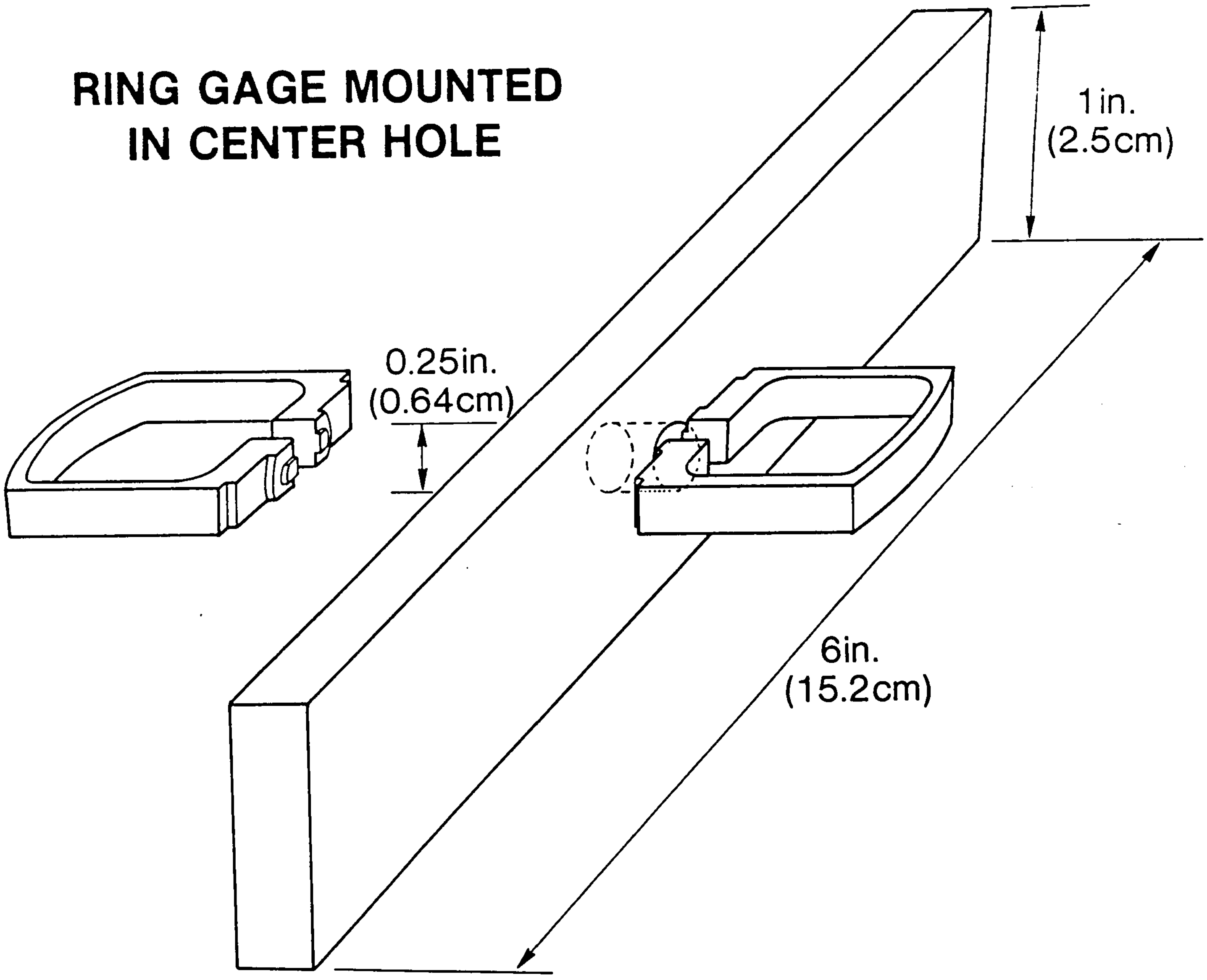

Figure 2 - Ring gages installed in 1/4 in. (0.64 cm) diameter center hole.

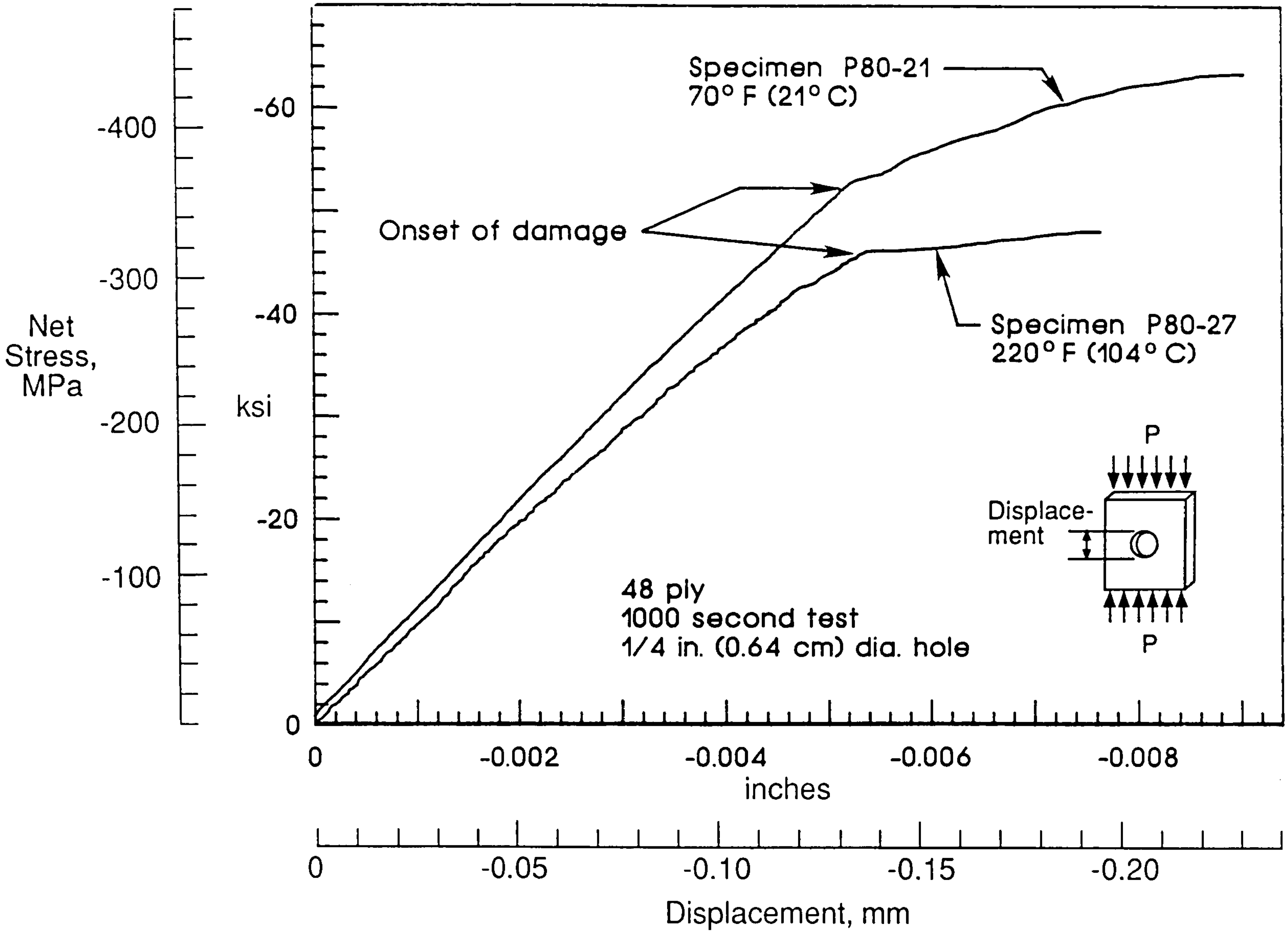

Figure 3 - Typical clip gage displacement versus net stress for 1000 second compression test. This data is for two 48 ply AS4/APC2 specimens with a 1/4 in. (0.64 cm) diameter hole.

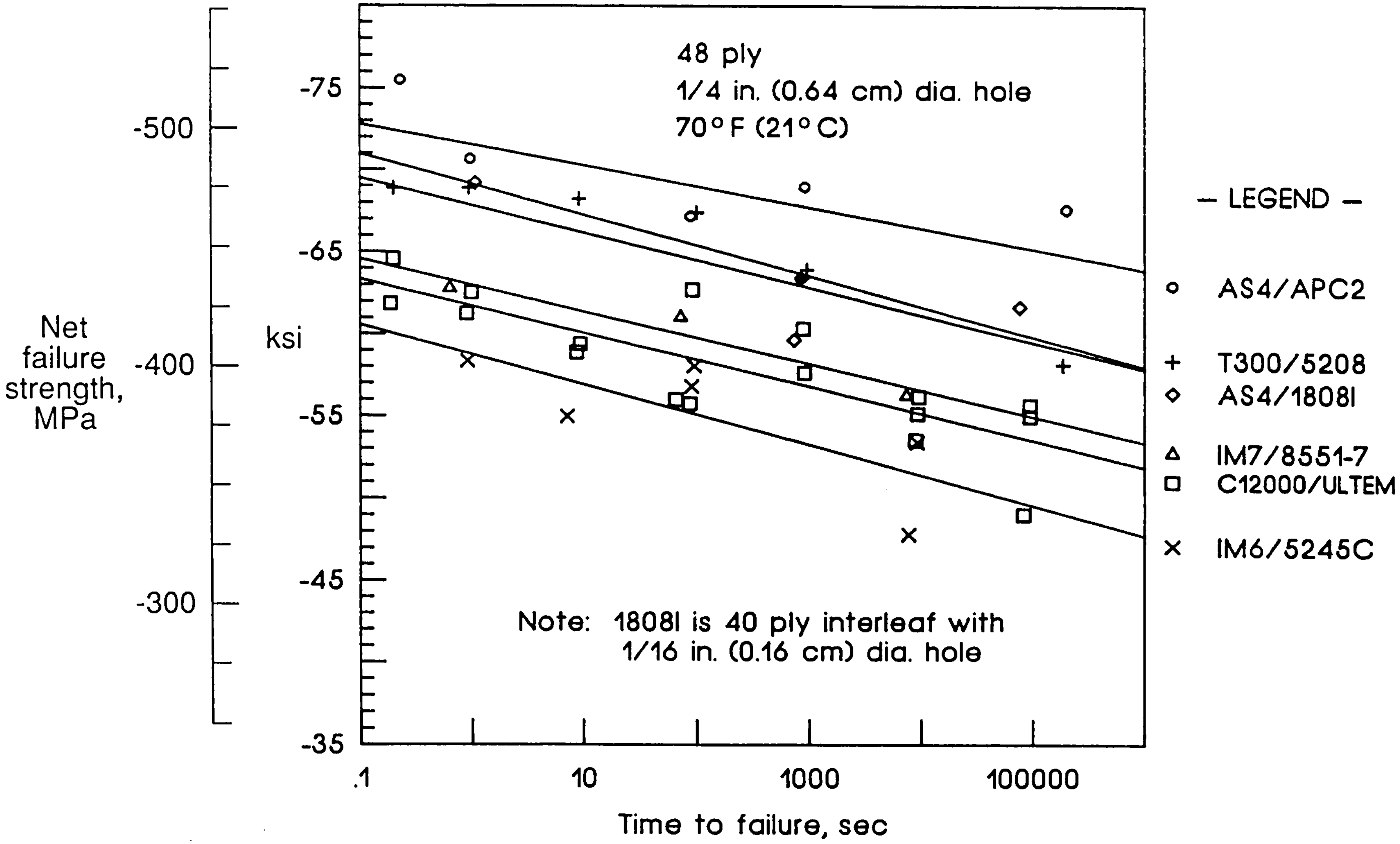

Figure 4 - Room temperature compressive strength versus elapsed-time-to-failure for 48 ply specimens.

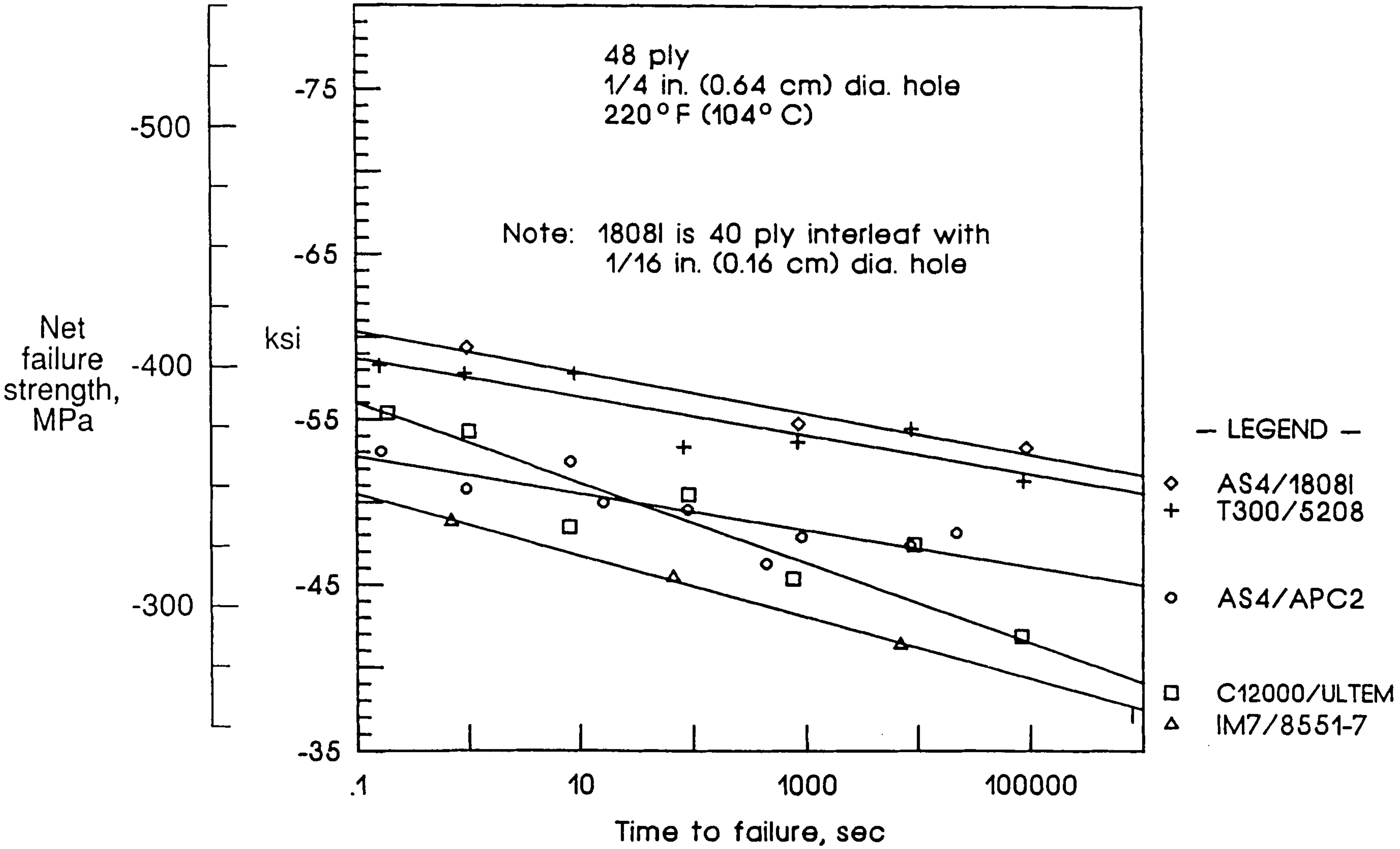

Figure 5 - High temperature compressive strength versus elapsed-time-to-failure for 48 ply specimens.

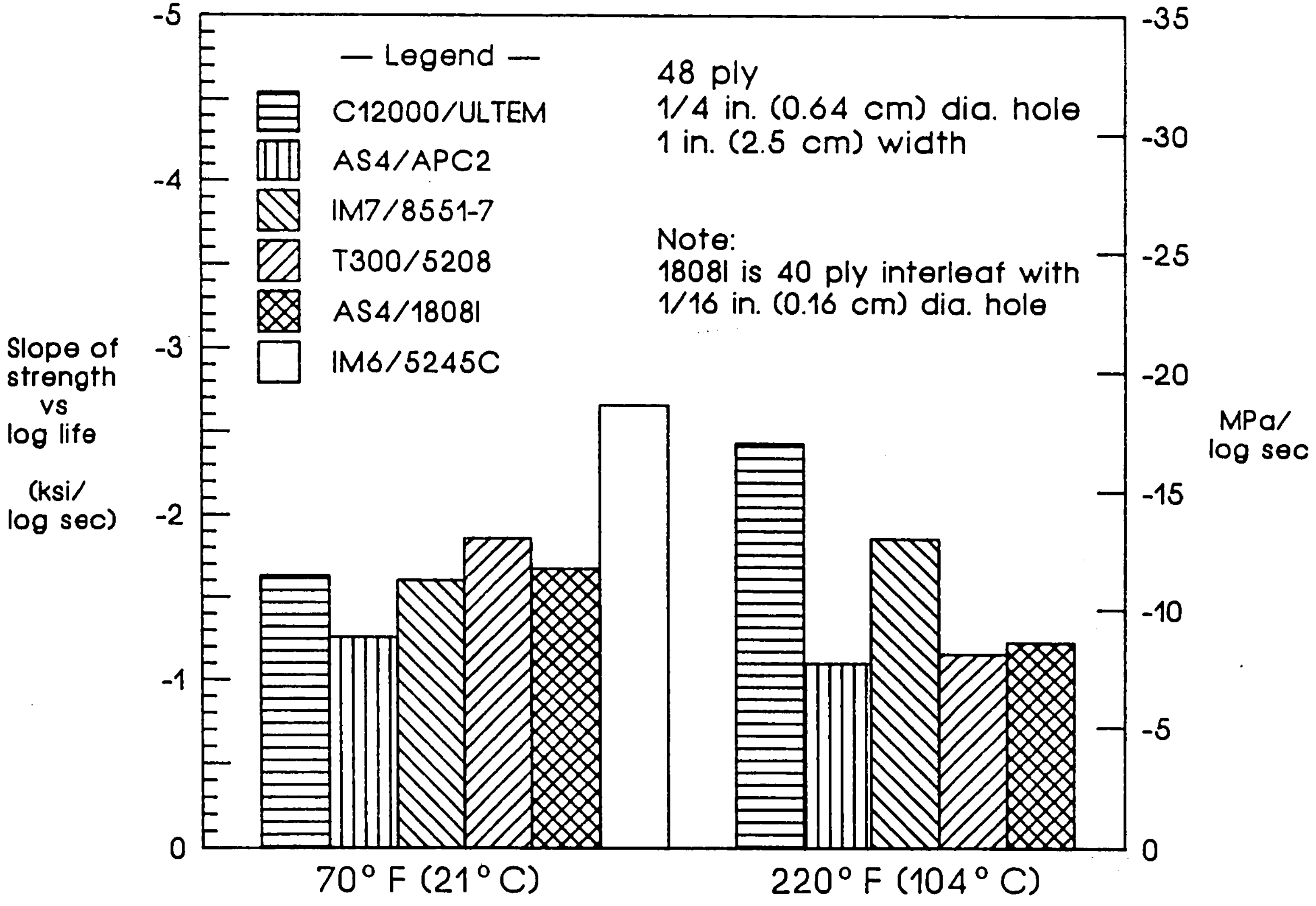

Figure 6 - Slope of the strength-life curve from figure 5 showing the relative sensitivity to loading rate.

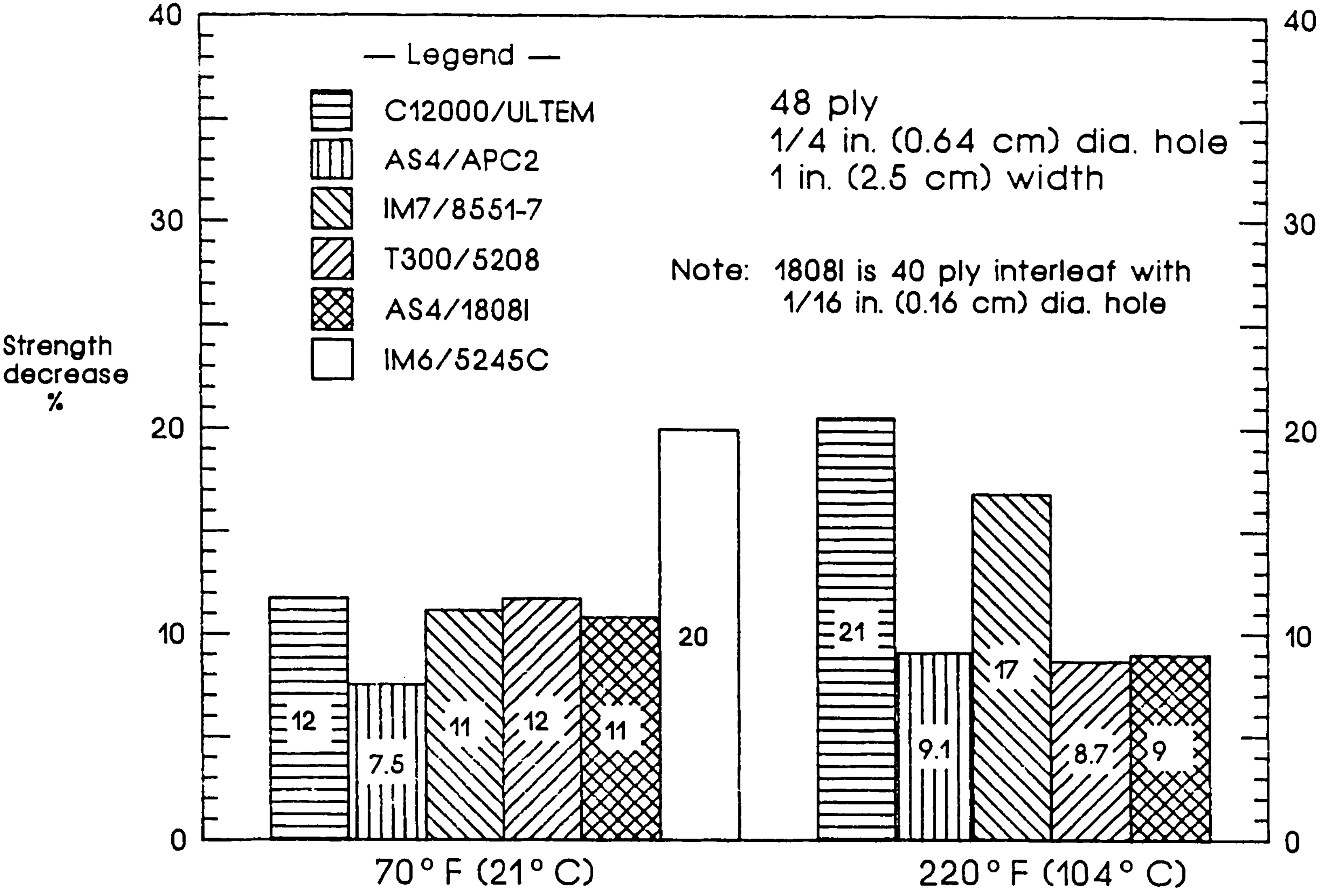

Figure 7 - Decrease in compressive strength for a 1,000,000 second test compared to a 60 second test.

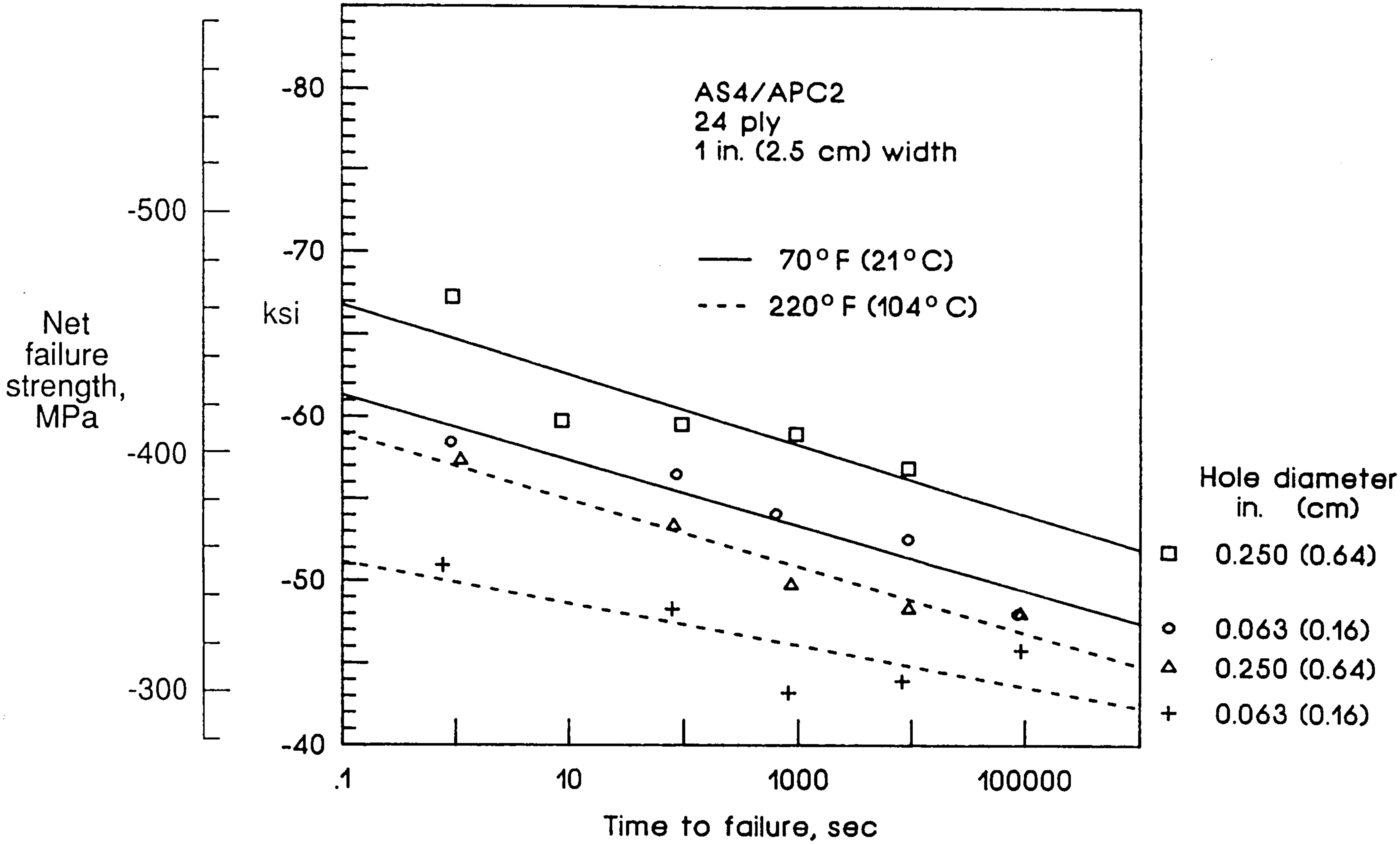

Figure 8 - Compressive strength versus elapsed-time-to-failure for 24 ply AS4/APC2 specimens.

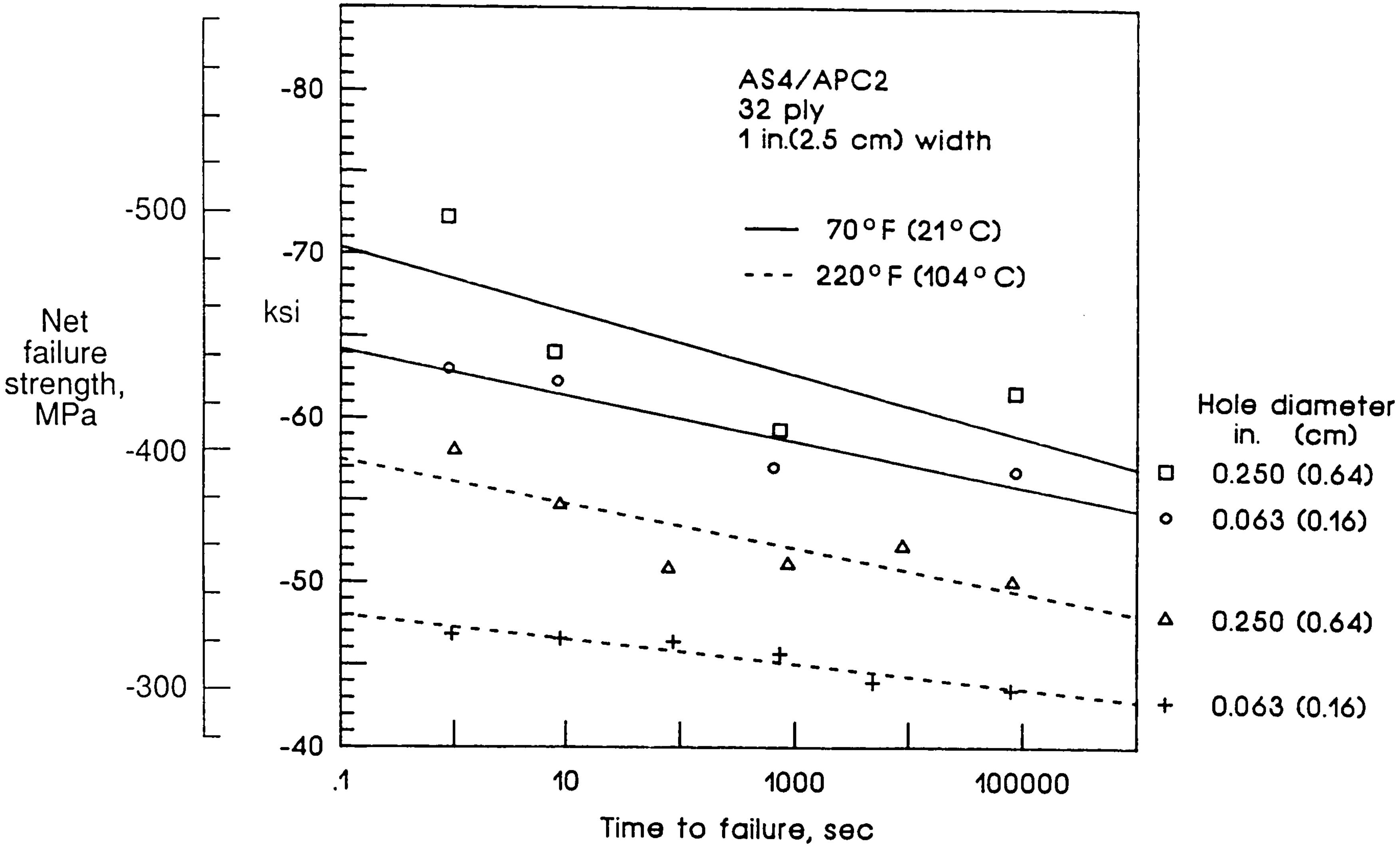

Figure 9 - Compressive strength versus elapsed-time-to-failure for 32 ply AS4/APC2 specimens.

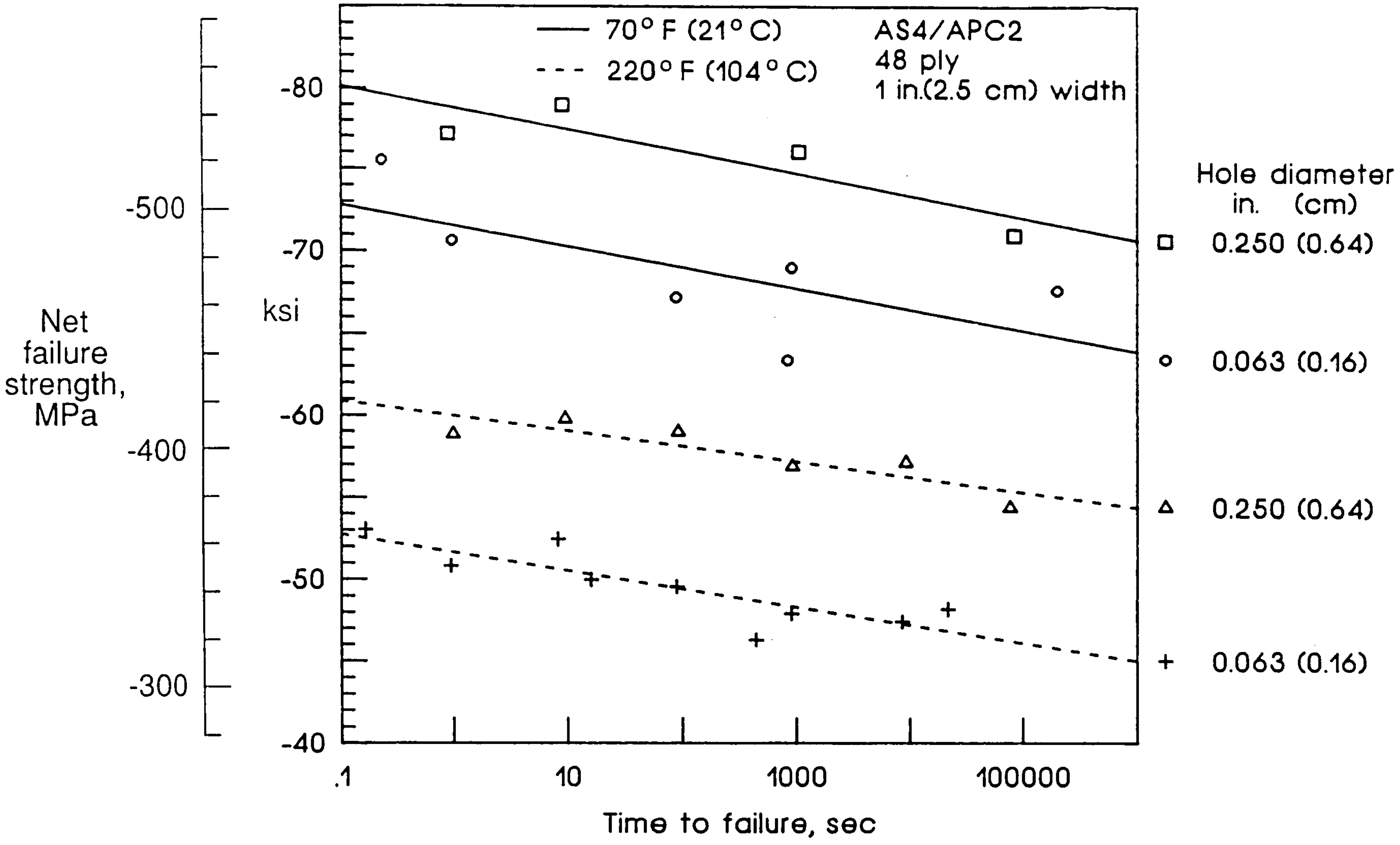

Figure 10 - Compressive strength versus elapsed-time-to-failure for 48 ply AS4/APC2 specimens.

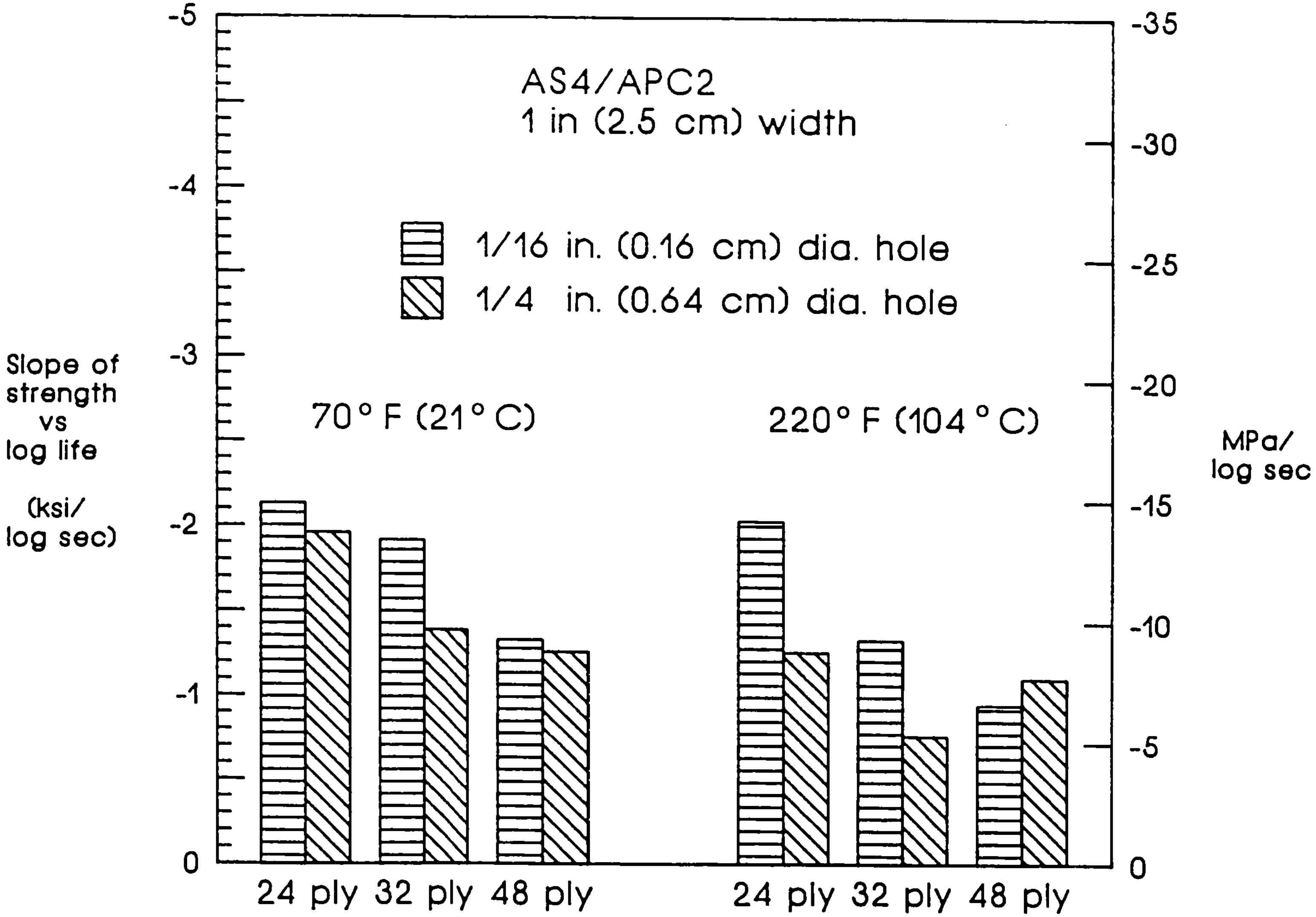

Figure 11 - Slope of the strength-life curve from figures 8, 9, and 10 showing the relative sensitivity to loading rate.

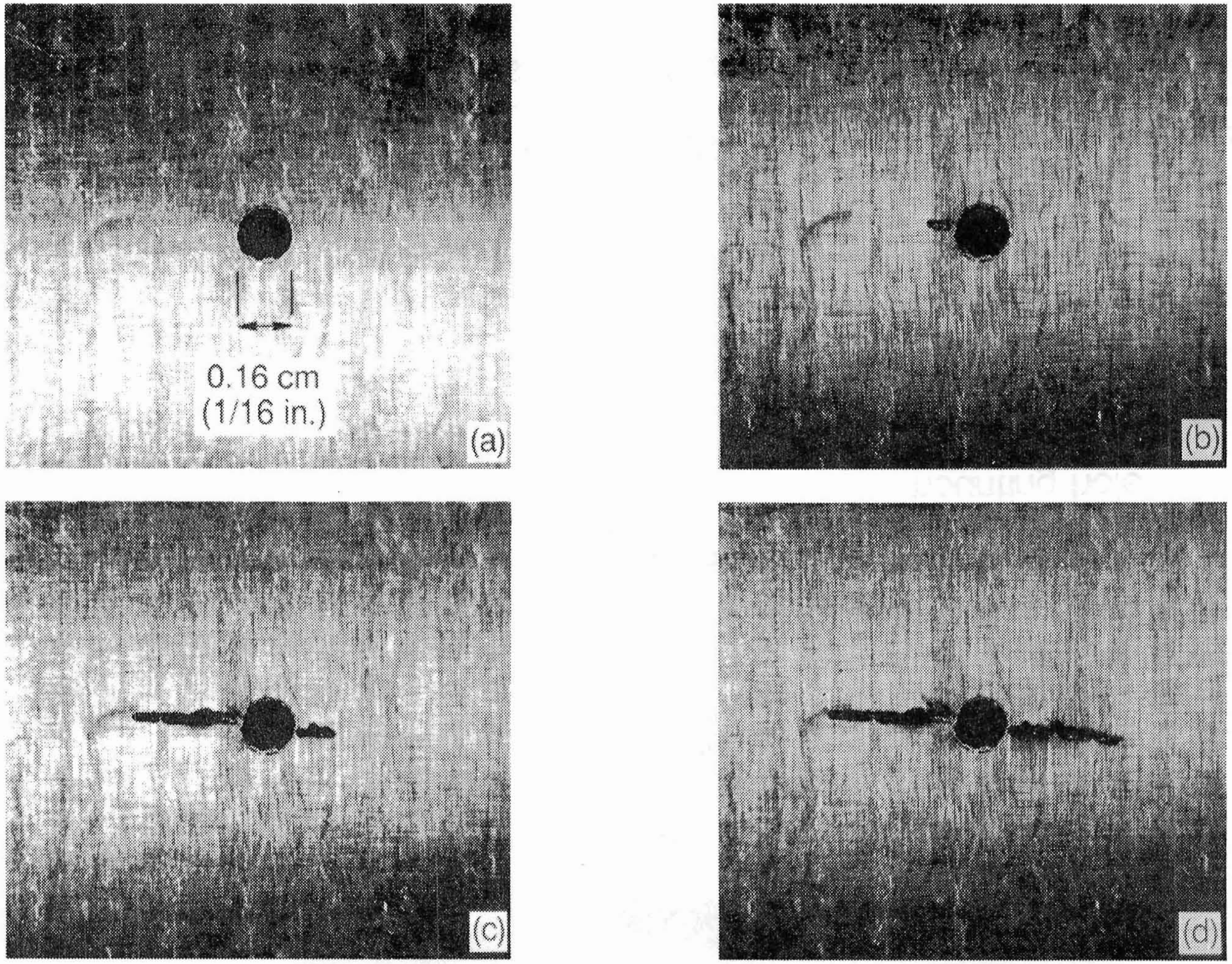

Figure 12 - Initiation and propagation of damage zone prior to compressive failure in an AC4/APC2 specimen. Hole diameter is 1/16 in. (0.16 cm). Damage zone lengths are:
(a) 0.020 in. (0.05 cm),
(b) 0.030 in. (0.08 cm),
(c) 0.050 in. (0.13 cm) and 0.120 in. (0.30 cm),
(d) 0.140 in. (0.36 cm) and 0.140 in. (0.36 cm).

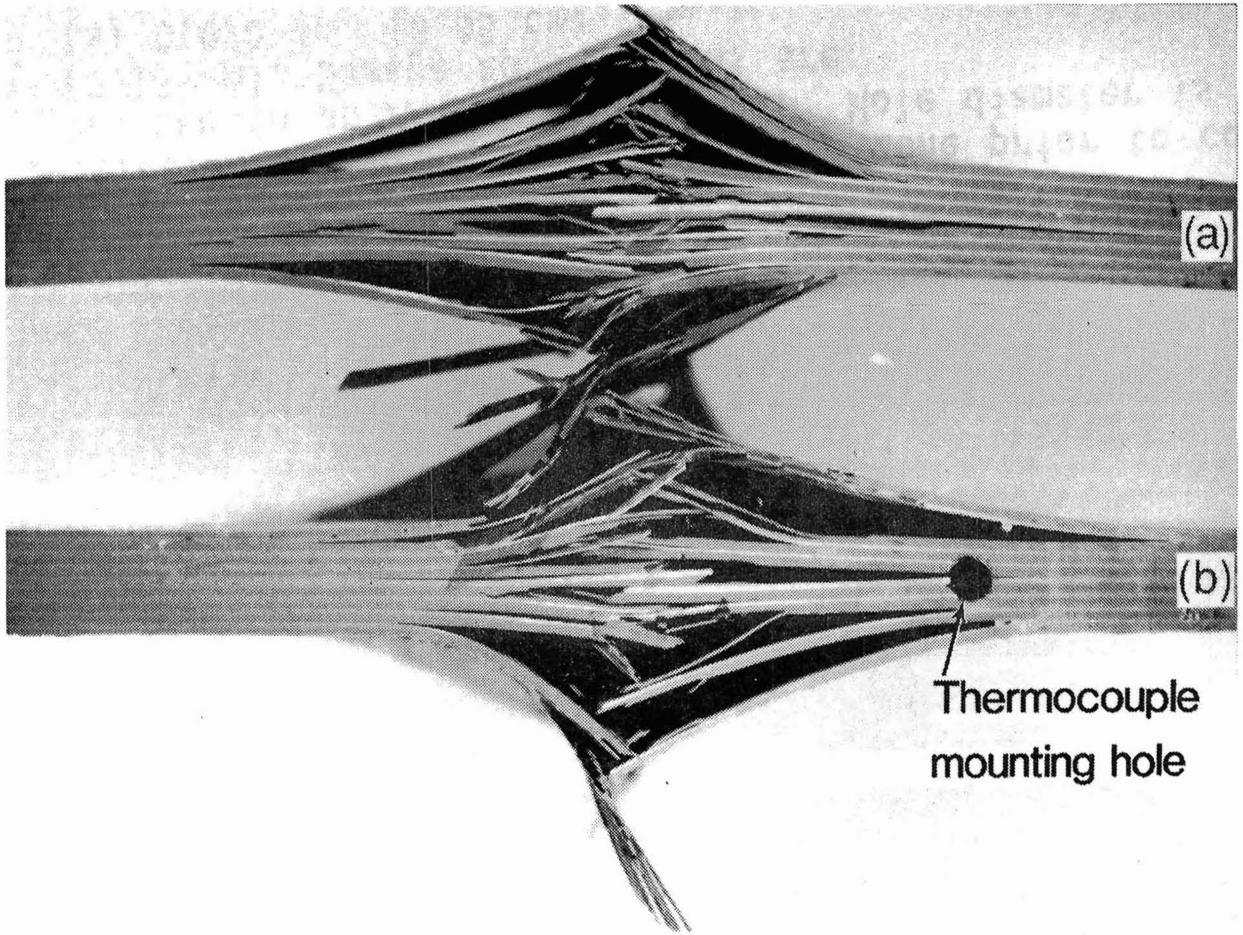

Figure 13 - Edge view of failed T300/5208 compression specimen.
(a) 70 degrees F (21 degrees C).
(b) 220 degrees F (104 degrees C).

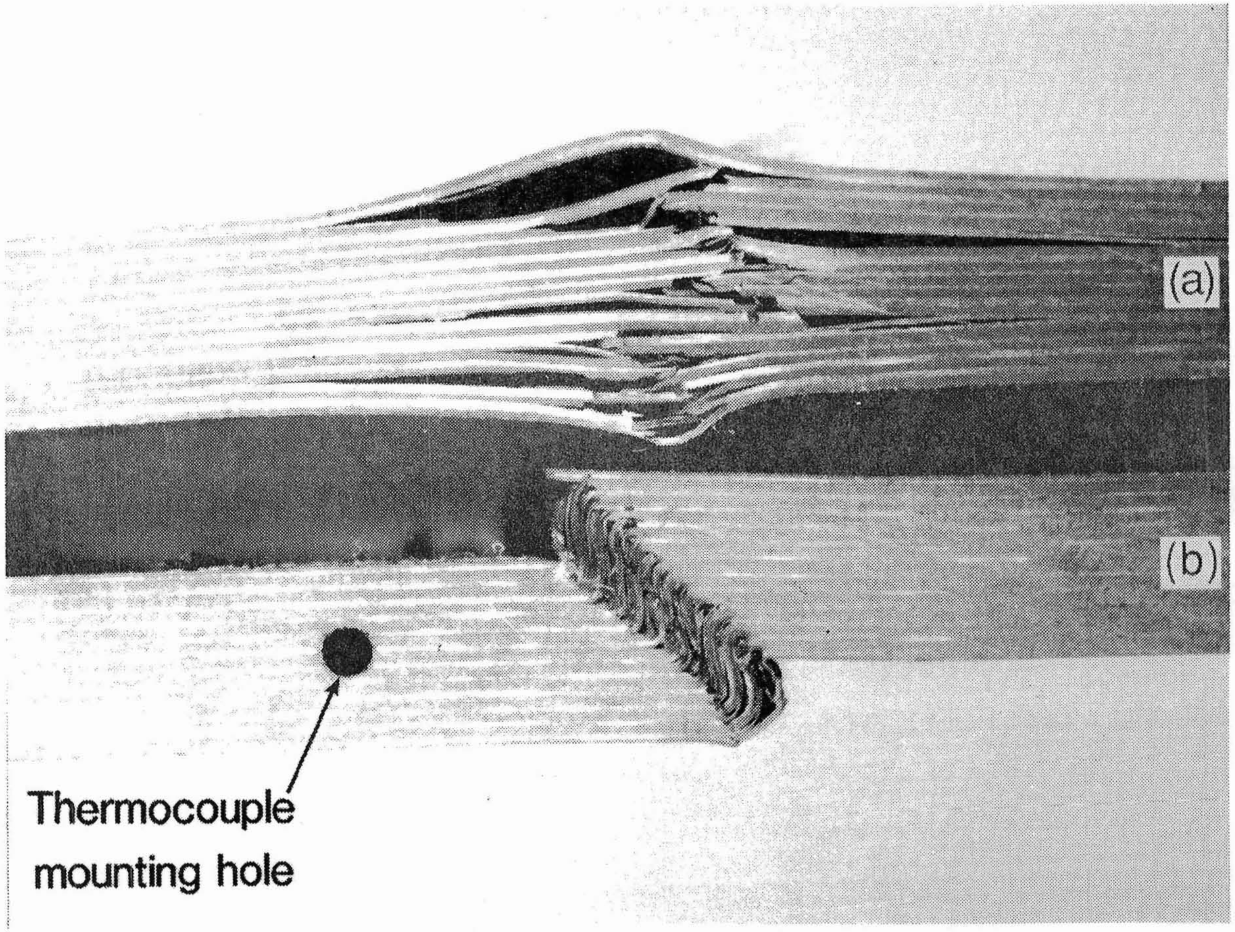

Figure 14 - Edge view of failed AS4/APC2 compression specimen.
(a) 70 degrees F (21 degrees C).
(b) 220 degrees F (104 degrees C).

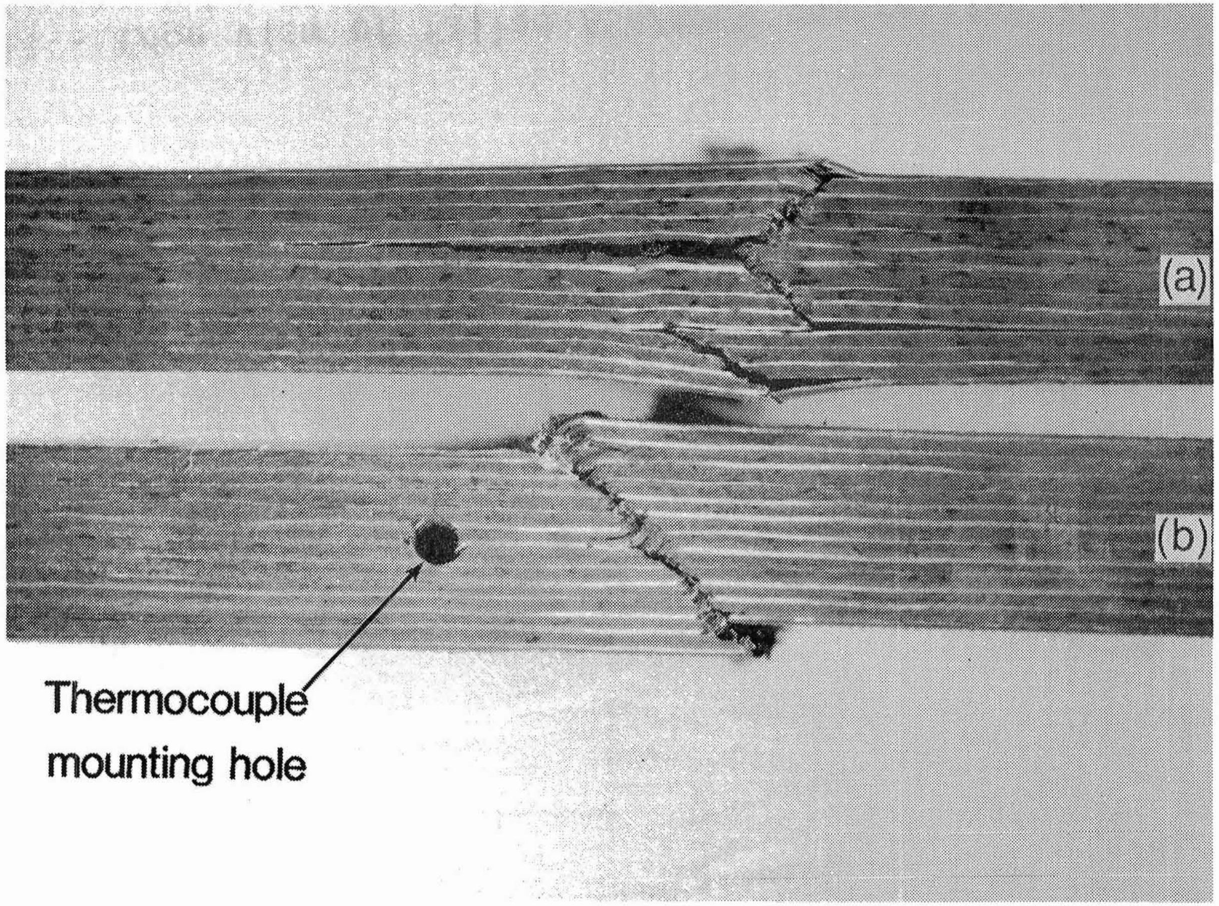

Figure 15 - Edge view of failed C12000/ULTEM compression specimen.
(a) 70 degrees F (21 degrees C).
(b) 220 degrees F (104 degrees C).

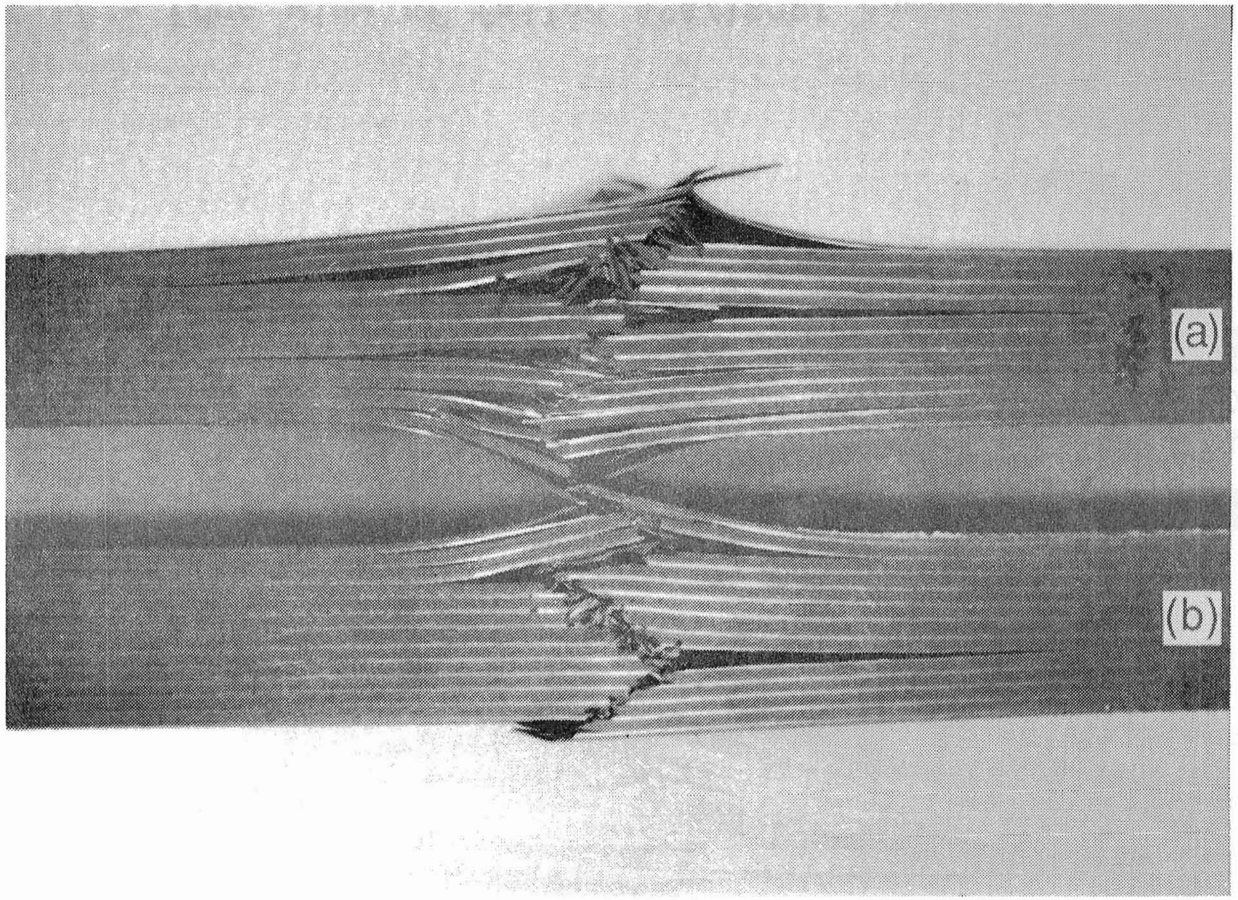

Figure 16 - Edge view of failed IM7/8551-7 compression specimen.
(a) 70 degrees F (21 degrees C).
(b) 220 degrees F (104 degrees C).

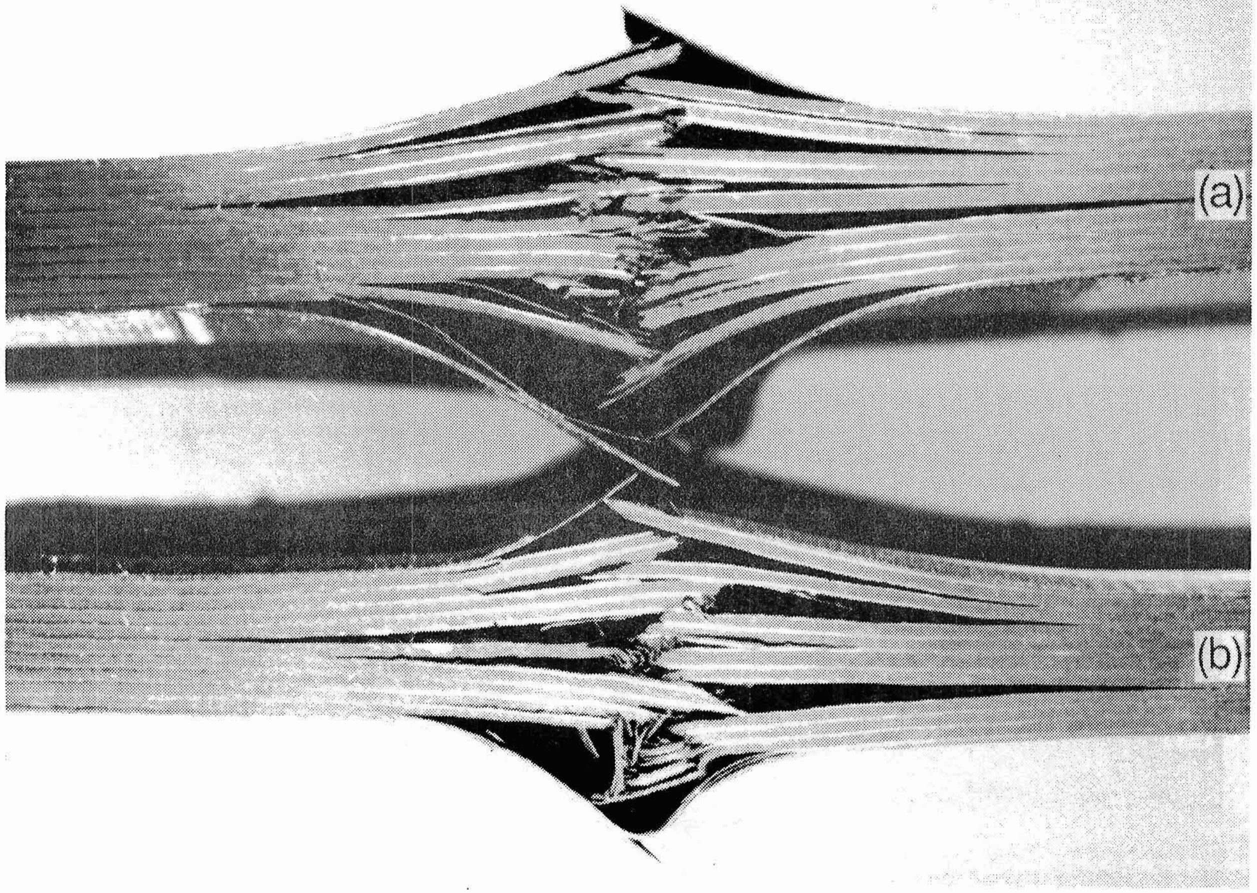

Figure 17 - Edge view of failed AS4/1808I compression specimen.
(a) 70 degrees F (21 degrees C).
(b) 220 degrees F (104 degrees C).

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15. Supplementary Notes

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16. Abstract

This paper reports the results of an experimental study on the compressive, time-dependent behavior of graphite fiber reinforced polymer composite laminates with open holes. The effect of loading rate on compressive strength was determined for six material sytems ranging from brittle epoxies to thermoplastics at both 75° and 220°. Specimens were loaded to failure using different loading rates. The slope of the strength versus elapsed time-to-failure curve was used to rank the materials' loading rate sensitivity. All of the materials had greater strength at 75° compared to the same material at 220°F. All of the materials showed loading rate effects in the form of reduced failure strength for longer elapsed-time-to-failure. Loading rate sensitivity was less at 220° than the same material at 70°F. However, C12000/ULTEM and IM7/8551-7 were more sensitive to loading rate than the other materials at the 220°F AS4/APC2 laminates with 24, 32, and 48 plies and 1/16 and 1/4 inch diameter holes were tested. The sensitivity to loading rate was less for either increasing number of plies or larger hole size. The failure of the specimens made from brittle resins was accompanied by extensive delaminations while the failure of the toughened systems was predominantly by shear crippling. Fewer delamination failures were observed at the higher temperature.

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