JOURNAL OF AIRCRAFT
Vol. 29, No. 6, Nov.-Dec. 1992

Acoustic Testing of High-Temperature Panels

J. D. Leatherwood,* S. A. Clevenson,† C. A. Powell,‡ and E. F. Daniels*
NASA Langley Research Center, Hampton, Virginia 23665

This paper summarizes recent thermoacoustic test activities at NASA Langley Research Center. The Langley Thermal Acoustic Fatigue Apparatus facility is described and results of two experiments to measure dynamic strain response of advanced structural panels at ambient and elevated temperatures are presented. The first study investigated techniques for measuring the dynamic strain of superalloy honeycomb thermal protection system panels subjected to combined thermal and acoustic loads. Results illustrating the linear response of these panels as a function of sound pressure level and temperature are presented. The second study was a joint NASA/General Dynamics test of two flat and two blade-stiffened carbon-carbon panels. These panels were tested to failure at an acoustic excitation level of 160 dB. Failure times ranged from several minutes to about 3 h. The flat panels failed due to development of edge-cracks, and the blade-stiffened panels due to delamination. Results showed that the carbon-carbon panels tested at elevated temperatures had significantly longer fatigue life. Strain data from both types of panels were obtained, although difficulties were encountered in returning reliable strain measurements on the carbon-carbon panels.

Introduction

THE NASA, DARPA, and USAF are engaged in a joint program to investigate technology requirements for a single-stage-to-orbit hypersonic vehicle called the National Aero-Space Plane (NASP). The NASP flight envelope encompasses a range of cruise speeds and altitudes that poses a significant challenge to the airframe designer. A typical NASP structural element may encounter any or all of the following conditions: 1) extremely hot surface temperatures; 2) large temperature gradients; 3) transient heating; 4) very high acoustic pressures; and 5) long-duration exposures to these environments. As a consequence of these adverse conditions, a NASP structural component may experience one or more of the following 1) possibly large static (thermal) stresses superimposed on dynamic stresses; 2) changes in material properties that manifest as changes in strength and modulus of elasticity; 3) accentuation of nonlinear behavior; 4) changes in fatigue behavior; 5) complex thermal and structural boundary conditions that may be difficult to simulate experimentally; and 6) difficulty in obtaining reliable experimental structural response measurements (e.g., static and/or dynamic strain).

A candidate for certain NASP structural components is carbon-carbon (c-c) composites. Carbon-carbon composites exhibit desirable strength to weight properties, especially at elevated temperatures, and may be used in environments having temperatures exceeding 1000°F. Unfortunately, little information is available describing the structural response and sonic fatigue characteristics of this material under combined thermal-acoustic loading. This is further complicated by the difficulty in measuring static and/or dynamic surface strains on this material at elevated temperature. This is partly due to the difficult task of bonding the strain gauges to the silicon carbide (SiC) surface.[1]

A concept that has recently been studied[2] for possible use as a thermal protection system (TPS) for surfaces of future space transportation systems (Space Shuttle, for example), employs a superalloy honeycomb configuration. Results from a variety of verification tests[3] of superalloy honeycomb TPS systems indicate they are viable over a temperature range of 700–2300°F. These verification tests included vibration, acoustic, aerothermal, environmental exposure, and lightning strike tests. However, no combined thermal-acoustic tests were conducted and strain response data at elevated temperature has not been obtained for these panels.

This article presents results of a series of thermal-acoustic tests conducted in the NASA Langley Research Center thermal-acoustic fatigue apparatus (TAFA) to 1) investigate techniques for obtaining strain measurements on metallic and c-c materials at elevated temperature; 2) document the dynamic strain response characteristics of several superalloy honeycomb TPS panels at elevated temperature (up to 1200°F); and 3) determine the strain response and sonic fatigue behavior of four c-c panels at both ambient and elevated temperatures. The four c-c panels were tested under a joint agreement with General Dynamics, Ft. Worth Division, who supplied the panels and support fixtures. A key element in all of these tests was evaluation of the performance of resistance strain gauge within the severe thermoacoustic test environment.

Experimental Setup and Procedures

Acoustic Test Facility

The TAFA facility is a grazing incidence progressive wave tube driven by a pair of electropneumatic modulators, each with an acoustic power output of 30 kW. The modulators are coupled to a 5 × 5 ft panel test section through an exponential horn with a 25 Hz low-frequency cutoff. For these tests, a bank of 12 quartz heater lamps (2500 W each) located 12 in. from the test panels, was used to provide an incident heat flux of about 4 Btu/ft^2-s over the approximately 12 × 12 in. test panels used in the present studies. The acoustic level at a test panel can be varied from about 135–169 dB overall sound pressure level (OASPL) for broadband noise in the range of 30–500 Hz.

Description of Test Panels

The superalloy honeycomb TPS panels were constructed of individual Inconel and titanium honeycomb sandwich panels

Presented as Paper 90-3939 at the AIAA 13th Aeroacoustics Conference, Tallahassee, FL, Oct. 22–24, 1990; received Feb. 10, 1991; revision received Nov. 15, 1991; accepted for publication Nov. 22, 1991.

*Aerospace Engineer, Structural Acoustics Branch, Acoustics Division.

†Aerospace Engineer, Structural Acoustics Branch, Acoustics Division. Associate Fellow AIAA.

‡Supervisory Aerospace Engineer, Structural Acoustics Branch, Acoustics Division.

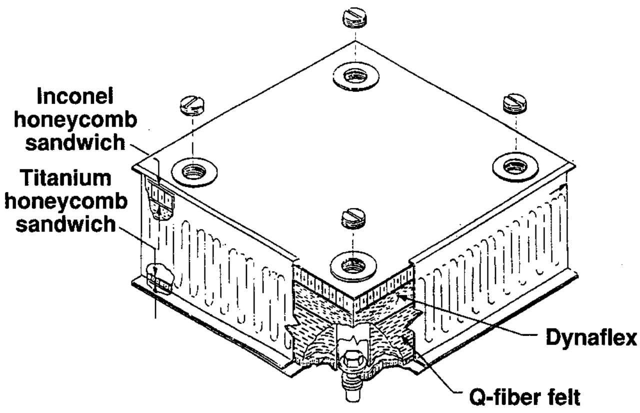


Fig. 1 Thermal protection system panel.

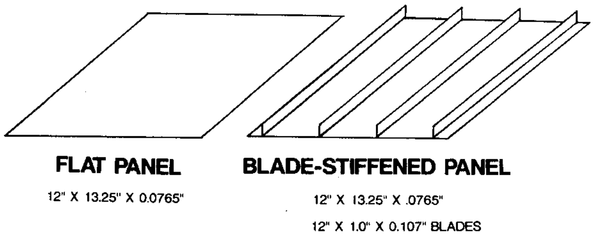


Fig. 2 Schematic of c-c test panels.

separated by two layers of fibrous insulation material (Dynaflex and Q-fiber felt) as shown in Fig. 1. The panels were mounted by means of four through-panel fasteners to an aluminum plate (representing the substructure) that was attached to the wall of the test section. Three panels with different face-sheet thicknesses (0.0025, 0.005, and 0.010 in. for the Inconel and 0.003, 0.006, and 0.014 in. for the titanium) were tested. Inconel honeycomb panel core thickness was 0.280 in. and titanium panel core thickness was 0.170 in. Total TPS panel thickness was about 2.35 in.

Four c-c panels having dimensions of 13.25 × 12.0 in. were tested. Two were simple flat panels containing 7 plies with a total thickness of 0.0765 in. The remaining two panels contained equally spaced blade stiffeners in the short (12 in.) direction and also contained 7 plies except for two additional plies at the base of the stiffeners. The stiffeners were 1.0-in.-high and 0.107-in.-thick. The two types of panel (shown schematically in Fig. 2) were tested at room temperature and at elevated temperature. All panels were coated with silicon carbide and sealed with sodium silicate.

Instrumentation

The test panels were instrumented with high-temperature strain gauges and type J or K thermocouples. Thermocouples were placed on both sides of the test panels to determine surface and through-panel temperature gradients. Strain gauges were generally located in pairs to measure surface strains along the two major panel axes. They were placed at the center, edges, and intermediate locations, and on both sides of the TPS panels and one side (that facing the acoustics and radiant heat flux) of the c-c panels. All strain gauge bridge outputs were high-pass filtered at 5 Hz to block temperature-dependent apparent strain voltage outputs that ranged from 10,000–20,000 microstrain at temperatures of 1000°F.

Attachment of resistance-type strain gauges to the faces of the TPS panels was relatively straightforward although great care had to be taken to prevent lead wire motion and scrubbing under acoustic loading. Attachment of strain gauges to the high-temperature c-c panels was not straightforward and proved to be a separate research issue within itself. Throughout the tests the gauge installation technique was modified as problem areas were discovered and corrective measures taken. The general procedure involved a series of steps that included microblasting of the surface, baking, application of ceramic adhesives, curing, and plasma spray application of various coatings. It was also necessary to firmly secure the lead wires to the panel surface in order to maintain lead-wire attachment in the dynamic environment and prevent chafing and lead-wire breakage.

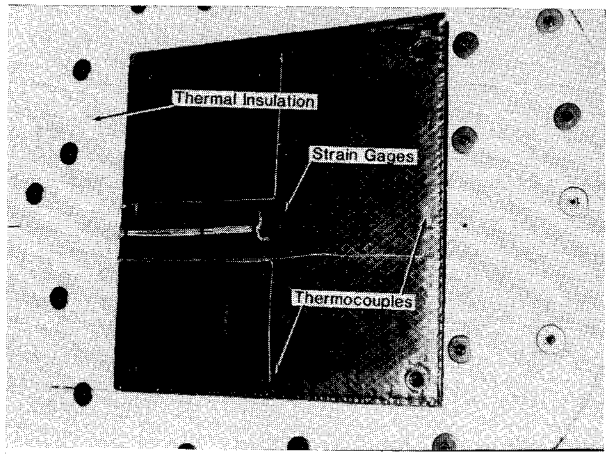


Fig. 3 TPS panel in test section.

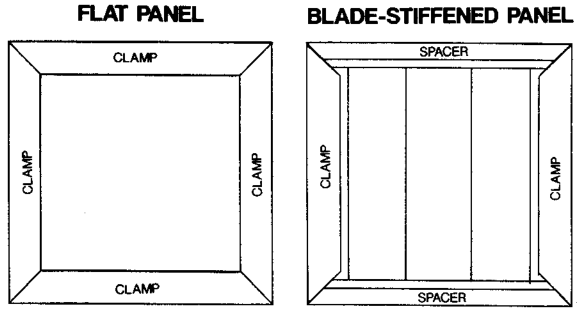


Fig. 4 c-c panel test fixture.

Gauge installation on the room temperature panels was simpler since ceramic cements and plasma spraying were not required. However, lead-wire management requirements were the same as for high-temperature installations.

Microphones were installed in the test section wall at locations near the upstream and downstream edges of the test panels. Earlier noise surveys conducted in the test section, indicated that the acoustic pressures at these locations were coherent over the frequency range of interest, and differed by no more than 1–2 dB.

Test Setup and Procedure

TPS Panels

The TPS panels were installed in the wall of the test section so that the surface of the outer Inconel sandwich panel was nearly flush with the test-section wall. A photograph of a typical installation is presented in Fig. 3. The steel-section wall surrounding the panel was shielded with insulating material to prevent excessive wall temperature buildup. The panels were tested with broadband (50–500 Hz) noise at levels of 140, 150, and 160 dB at both ambient and elevated temperatures. The ambient temperature tests required approximately 1 min/test point and the elevated temperature tests took slightly longer due to the time required to stabilize the temperature when the sound pressure level was changed.

c-c Panels

The c-c panel boundary conditions and test procedure differed significantly from that used in the TPS tests. A picture frame clamping-bar arrangement (see Fig. 4) was used to support the flat panels on all four sides and the blade-stiffened

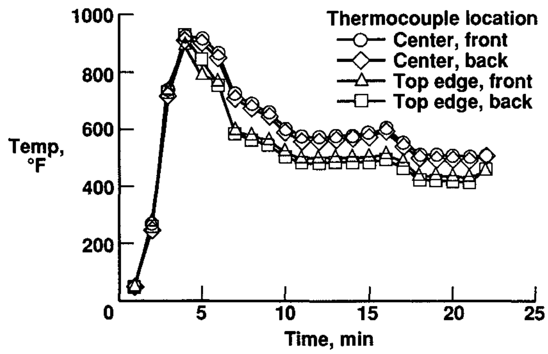


Fig. 5 Typical c-c panel thermal response.

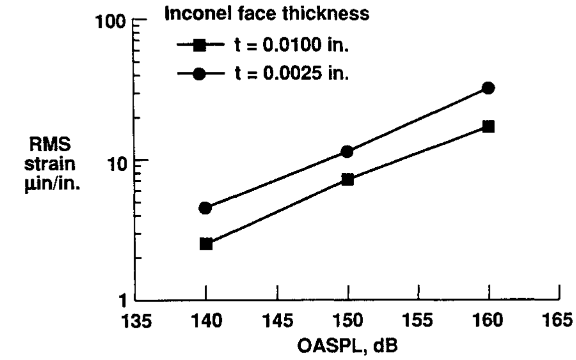


Fig. 6 Relationship of overall rms strain to overall sound pressure level.

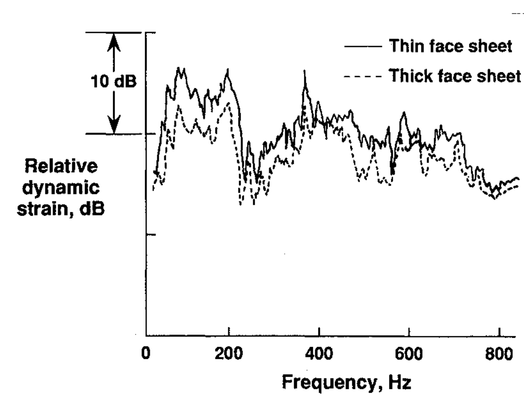


Fig. 7 Measured rms strain spectra at the center of the TPS Inconel face sheets at 160 dB.

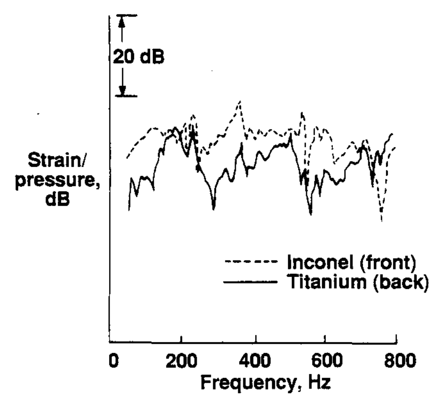


Fig. 8 Strain-to-pressure transfer functions of center of front and back TPS panel surfaces (thin face-sheet panel).

panels on two sides. The blade-stiffened panels were mounted in the frame with the stiffeners oriented vertically and the upstream and downstream edges (those parallel to the stiffeners) clamped within the frame; the remaining two edges were free. The test panels were thermally isolated from the clamping frame by means of flexible insulation blanket that was wrapped over the clamping bars, into the jaws of the clamp, around the panel edges, and out of the back side. The jaws of the clamp were closed to a fixed gap, compressing the insulation uniformly against the panel with moderate pressure. The installation procedure was the same for both ambient and elevated temperature panels.

The four c-c panels were tested at a broadband (30–500 Hz) noise level at 160 dB. One panel of each type was tested at ambient temperature and the second panel of each type at elevated temperature. The tests were conducted in 15-min test segments. After each test segment the panels were visually and thermographically inspected for damage. A test was terminated if visual damage was detected and/or panel response frequency decreased by 20% from its initial value. Strain-time series data were recorded at the beginning, middle, and near the end of a test segment. Panel frequency response changes were monitored as the tests progressed. Thermocouple output was recorded at 1 min intervals.

The elevated temperature panel test procedure was as follows: modulator airflow was established without modulation and the lamp bank turned on. This produced c-c panel temperatures between 900–1000°F. Modulation was then applied resulting in panel temperature drop to about 825°F. As each 15 min test segment progressed, the high acoustic levels in the facility would cause some of the heat lamps to fail, resulting in further temperature decreases. The final steady-state temperatures ranged between 350–600°F depending upon the number of lamp failures. This produced a typical panel thermal response illustrated in Fig. 5. Note that the thermal gradient through the panel thickness was small compared to the surface gradient.

The recorded data were analyzed to obtain rms strain spectra, strain power spectral density, transfer functions between acoustic pressure (measured near the panel edges) and panel strains, strain histograms, and limited circle fits of the strain response and acoustic pressure data.

Results and Discussion

TPS Panel Response

Strain Response

The TPS panel gauge installations performed well under both ambient and elevated temperatures up to 1200°F and returned reliable and repeatable dynamic strain measurements under the applied thermal and acoustic loads. No attempt was made to measure static (or thermal) strains on these panels.

Strain data obtained from the three TPS panels indicated that the measured strains were generally small and that strain response varied linearly with the level of the applied acoustic loads. Figure 6 shows examples of the overall rms strains at the center of the Inconel honeycomb sandwich panels as a function of noise level. Maximum observed rms strain level was approximately 33 microstrain (at 160 dB) for the thinnest face sheet. Spectra of rms strain obtained at the 160 dB test condition of Fig. 6 are presented in Fig. 7. Note that both TPS panels responded primarily at the lower frequencies (approximately 70–180 Hz) with the exception of a narrow peak at about 340 Hz. Furthermore, the thin-face-sheet-panel response was uniformly higher at all frequencies.

Differences in strain response were also observed between the front (Inconel) and back (titanium) TPS panel surfaces. This is illustrated in Fig. 8 in terms of strain-to-pressure transfer functions measured at the center of the thin-face-sheet TPS panel. These data show the Inconel surface strains to be higher than those of the titanium surface, due to the increased thickness of the titanium face sheets relative to the Inconel face sheets.

Temperature Effects

The effects of temperature on TPS panel responses are summarized in Fig. 9 for the TPS panel with the thickest Inconel and titanium face sheets. Also shown are the rms strain spectra measured at the center of the Inconel honeycomb sandwich panel for temperatures of 60 (ambient), 500, and 1000°F, and an applied acoustic level of 150 dB. Strain response generally increased with rising temperatures, with substantial increases occurring at frequencies above about 600 Hz. This elevation of strain responses could result in significant reductions in fatigue life due to high-cycle fatigue effects.

c-c Panel Response

Strain Gauge Performance

Overall performance of the gauge installations on the c-c panels was considered fair. Generally the gauges on the room temperature panels performed best and experienced the fewest failures. Factors affecting gauge performance included 1) microcrack growth on the silicon carbide coating; 2) poor strain transmission through the ceramic adhesive; and 3) gauge convolute failure due to shearing forces transmitted up through the adhesive. The gauges on the elevated temperature panels experienced a significant failure rate (about 30%) and many of the remaining gauges indicated low (5–20 microstrain) strain levels. These low strains were thought to be indicative of poor performance of the gauge installations. However, recent (unpublished) theoretical nonlinear analyses of similar c-c panels have predicted surprisingly low strains at panel locations where higher strains were expected. The predicted low strains were possibly due to nonlinear stiffening. Dynamic strain results are presented only for the two c-c flat panels since they exhibited the best strain gauge performance.

Flat-Panel Strain Response

Measured overall rms strain levels for selected gauges on the flat panels are shown in Fig. 10 as a function of test duration. Strains measured on the room temperature are indicated by RT and those on the elevated temperature panel by HT. The room temperature (RT) data terminate at 41 min due to panel failure (to be discussed later). The high temperature (HT) data terminate due to gauge failures.

With the exception of gauge 1 on both flat panels, the data indicate that rms strain levels generally increased as test duration increased. The highest strains were obtained at gauges 2 and 5 (120–140 microstrain) on the room temperature panel and at gauge 7 (160 microstrain) on the elevated temperature panel. These levels were approximately one-half of the levels predicted in a preliminary analysis. The observed increases in surface strains with test duration could have been due to loss of panel stiffness produced by gradual debonding (or delamination) as the tests progressed. This loss of stiffness would also tend to reinforce any nonlinear response effects. Evidence of nonlinear response of these panels is presented in Fig. 11, which shows rms strain spectra at acoustic excitation levels of 135 and 160 dB. The panel response at 160 dB exhibits the peak-shifting and peak-broadening behavior typical of a nonlinear system.

A parameter often used to indicate failure onset is the percentage change in frequency of the first panel mode measured relative to its pretest value. For these tests the first mode frequencies were determined from the strain to pressure transfer functions. These frequencies are presented in Fig. 12 as a function of test duration for the room temperature and elevated temperature flat panels. A decrease in the first mode frequency of the room temperature flat panel from 126 to 100 Hz is evident during the first 38 min of testing. In the remaining 2–3 min this frequency quickly dropped to about 71 Hz and the test was stopped due to detection of a rapidly propagating edge crack.

The first mode frequency of the flat panel tested at elevated temperature remained relatively constant for the 151 min that strain data were available. Failure of all gauges by this time prevented determination of whether the response frequencies decreased significantly near the end of the test, that was also stopped, due to detection of an edge crack.

The rms spectra measured on the room temperature flat panel at the start of the test (2 min), when a small crack

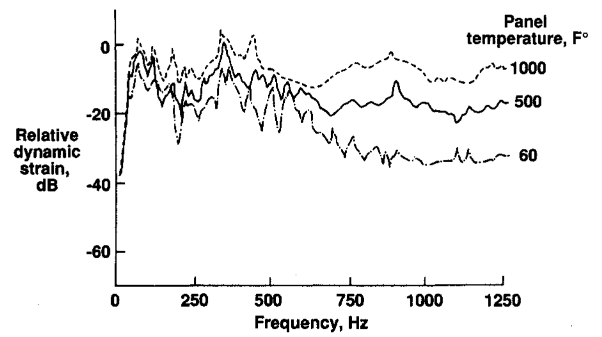


Fig. 9 Effect of temperature on TPS panel strain response (thick face-sheet panel).

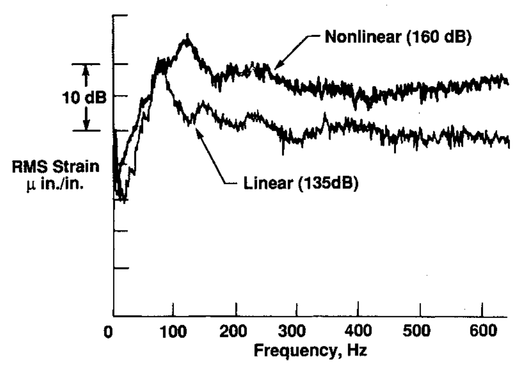


Fig. 11 c-c flat-panel rms strain response indicating nonlinear behavior at high-acoustic levels.

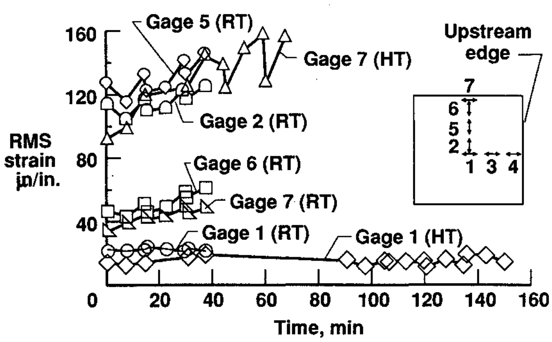


Fig. 10 Relationship of rms strain and cumulative test time for c-c panels tested at room temperature (RT) and high temperature (HT).

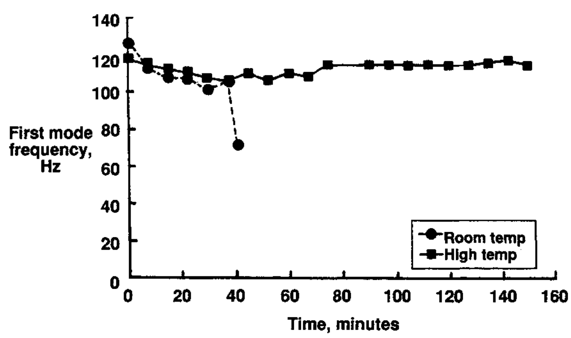


Fig. 12 Relationship between first mode frequency and cumulative test time for the flat c-c panels.

appeared (38 min), and just prior to stopping the test (41 min) are presented in Fig. 13. These spectra show the downward shifts in first mode frequency from 126 to 71 Hz accompanied by increases in peak strain response amplitudes. This was due to the increasingly large panel deflections resulting from loss of panel stiffness. Similar data for the flat-panel tested at elevated temperature and the two blade-stiffened panels were not obtained due to gauging problems.

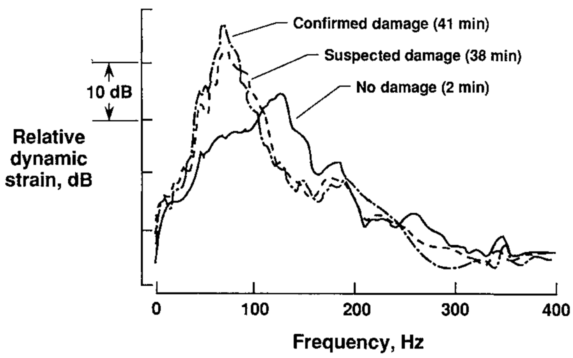
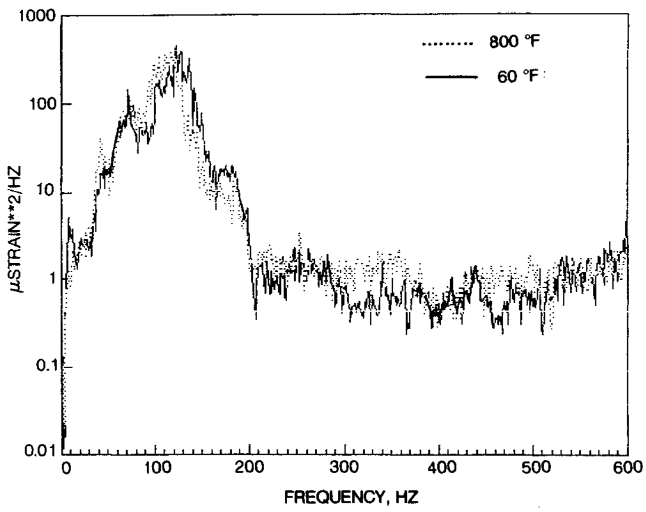
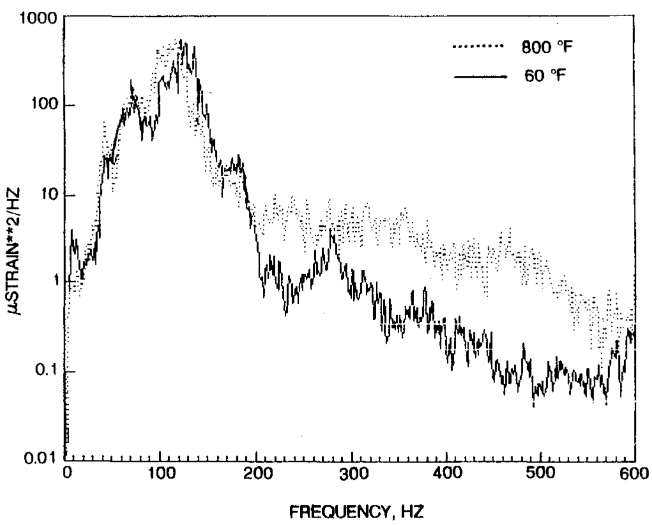


Fig. 13 Effects of panel failure on strain response of c-c flat-panel tested at room temperature.



a) Gauge 2



b) Gauge 5

Fig. 14 Comparison of c-c flat-panel strain response at ambient and elevated temperature.

Temperature Effects on Strain Response

Comparisons of room temperature and elevated temperature data measured at corresponding locations on the flat panels (for 150 dB acoustic excitation) are shown in Figs. 14a and 14b. Power spectral density (psd) curves obtained at the start of each test for gauges 2 and 5 (see Fig. 10) are shown. All spectra exhibit broad-response peaks consistent with the nonlinear response behavior described earlier. The strain response data at room and elevated temperature are similar for frequencies below 200 Hz, and gauge 5 on the elevated temperature panel indicated increased strain response at frequencies above 200 Hz. Both figures show a slight downward shift in peak response frequency for the hot panels. Similar results were obtained for the other gauges on the flat panels.

c-c Panel Failures

Flat Panels

As described earlier, the flat panel tested at room temperature, experienced a reduction in first mode frequency from 126 to 100 Hz after 38 min of testing and a gradual increase in strain level (Fig. 10). At 38 min of accumulated test time, the insulation near the center of the downstream vertical edge of the panel began to tear and come out around the clamping bar. Shortly thereafter, a crack became visible, growing out from the clamping bar horizontally for about 1 in. and then turning downward for about 3 in. At this point the test was terminated (41 min); the failure is shown in Fig. 15. Upon removal of the panel from the clamping frame, it was observed that the panel had delaminated from corner to corner along the edge where the crack started, and in an area along the length of the crack.

The test of the flat panel at elevated temperature was terminated at 192 min cumulative test time. Inspection of the panel revealed a crack on the rear of the panel that had originated at the upstream panel edge. This crack was hidden behind the clamping bar and hence was not easily detected by the video monitor during the test; this crack is shown in Fig. 16. Detailed inspection of the panel showed the delamination had begun at the panel edge and that the crack extended through the panel thickness. The insulation blanket had disintegrated in the vicinity of the crack in a manner similar to that observed on the room temperature panel.

Blade-Stiffened Panels

The test of the blade-stiffened panel at room temperature was stopped after 9 min when a crack through the outer ply along the length of a center rib-root radius was observed on the video monitor. Later examination of the video indicated the crack likely occurred within the first minute of the test.

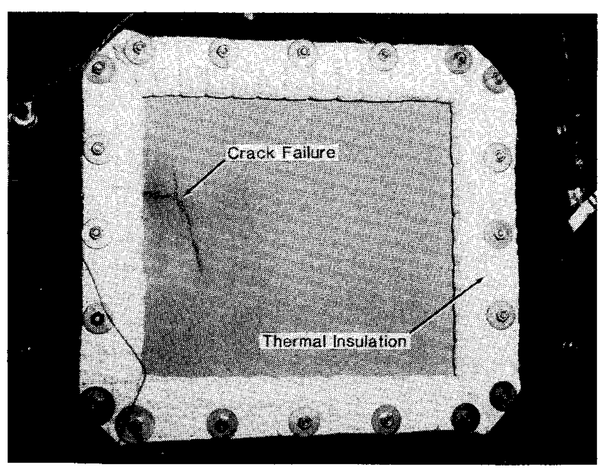


Fig. 15 Sonic fatigue failure of flat c-c panel tested at room temperature.

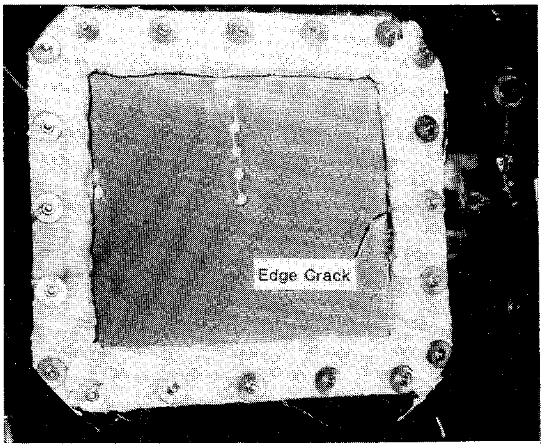


Fig. 16 Sonic fatigue failure of flat c-c panel tested at elevated temperature.

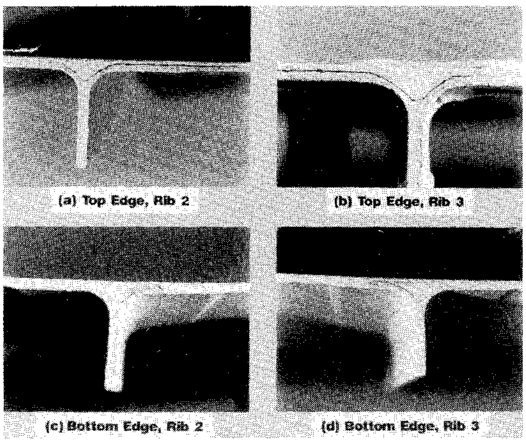


Fig. 17 Sonic fatigue failure of blade-stiffened c-c panel tested at elevated temperature.

The test of the blade-stiffened panel at elevated temperature was terminated after 75 min of cumulative test time at 160 dB. Although no visible damage was evident, panel stiffness (observed by pressing on the panel between test runs) had decreased substantially from its pretest value. Removal of the panel from the test fixture and detailed inspection revealed extensive delamination extending from the top to bottom edges (in direction of stiffeners) and from the panel centerline to a stiffener fillet. Views of the top and bottom panel edges at each interior stiffener are shown in Fig. 17. Subsequent enhancement of thermal images taken at the end of each 15 min test segment indicated that the delamination started at the panel center during the third test segment (30–45 min) and spread toward the stiffeners in successive test segments.

Panel Failure Times

Total cumulative test times for each panel are represented by the solid bars in Fig. 18. These times, however, do not necessarily correspond to the times of actual failure onset. The earliest times at which failures were detected and confirmed by posttest analyses are represented by the hatched bars. Since the flat-panel edge cracks developed within the clamped areas, they were not detectable until they spread beyong the clamping bars. Consequently, the cumulative test times and failure detection times differed only slightly for these panels. The first-mode frequency shifts described earlier, however, provide some evidence that the flat-panel failures may have begun sooner. The blade-stiffened panel failures were readily confirmed to have occurred much sooner than the test termination times. Consequently, the lack of good strain data and the absence of visible damage on these

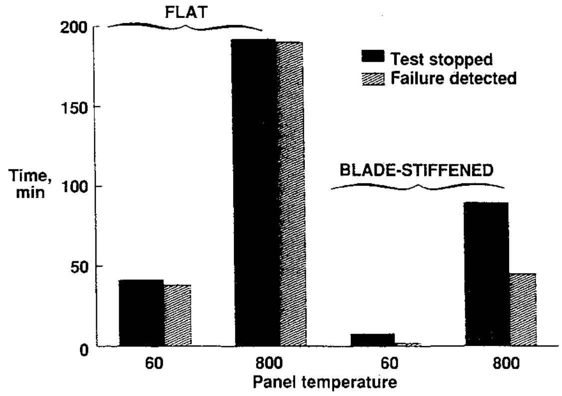


Fig. 18 Summary of c-c panel failure times.

panels resulted in these tests extending far beyond the actual failure points.

Both panels tested at room temperature failed much earlier than the corresponding panels at elevated temperature, implying that c-c may be more fatigue-resistant at elevated temperature. If this were true, it could minimize high-temperature test requirements for this material. However, the small number of panels tested does not provide conclusive evidence that this will always be so. Additional testing, particularly at temperatures closer to the operating limits of the material, will be required to validate this result.

Figure 18 also indicates that the blade-stiffened panels failed much earlier than the flat panels. This is very likely due to the boundary conditions applied to these panels. Since these panels were clamped along the two edges parallel to the stiffeners, the stiffeners did not provide any additional stiffness but rather only a line of mass-loading and additional stress along that line. This was conducive to the development of large response amplitudes under the applied acoustic loading and would act to reduce fatigue life.

Concluding Remarks

Dynamic strain measurements on three superalloy honeycomb TPS panels subjected to intense acoustic loads at ambient and elevated temperatures (up to 1200°F) were obtained. TPS panel strain responses were found to be relatively low and to vary linearly with the level of acoustic excitation in the range of 140–160 dB. Results of elevated temperature testing of these panels indicated an overall increase in dynamic strain at high temperatures, especially at frequencies above 200 Hz. This effect would tend to reduce fatigue life of TPS panels placed within environments containing simultaneously applied thermal and acoustic loads for significant lengths of time.

Attempts to obtain accurate and reliable dynamic strain measurements on the c-c panels met with limited success. Room temperature gauges performed reasonably well and provided useful strain frequency and amplitude data. Success with the elevated temperature gauges was not as good. Gauge outputs were generally low and failure rates were relatively high. Lead-wire management was critical, requiring great care to secure the wires at the panel surfaces and edges. Based upon knowledge and experience gained in the c-c panel tests, it is anticipated that future c-c test efforts will provide strain data of improved accuracy and reliability.

Measured strains on all c-c panels were lower than those estimated by preliminary analysis. Flat-panel strains were approximately one-half of the predicted levels that may have been partially due to nonlinear effects, i.e., nonlinear stiffening at large displacement amplitudes. Blade-stiffened panel strains were much lower than expected (5–20 microstrain) and reasons for this are unclear at present. For example, it is difficult to ascertain whether the low strains were due to the gauge installations or if they were influenced by the nonlinear response behavior. Because of the differences in boundary conditions, the blade-stiffened panel deflection response was greater than the flat-panel deflection response. This could have accentuated nonlinear effects, further reducing strain response. Additional nonlinear analyses of these panels to study their behavior under the experimental test conditions would be helpful.

Temperature effects on flat-panel strain response indicated the primary effect to be a slight decrease in first mode frequency and, in some cases, increased strain response at high frequencies. Temperature effects on blade-stiffened panel strain response could not be determined because of c-c gauging problems. However, both types of panels experienced much longer fatigue lives at elevated temperature. This increased fatigue resistance at elevated temperature implies that it may be sufficient to conduct fatigue and/or qualification testing of c-c panels at room temperature. This would greatly simplify the test requirements and increase the reliability and confidence in the obtained fatigue data. However, this temperature effect must be validated with additional testing at temperatures closer to the operating limits of c-c composites.

Conclusions related to the sonic fatigue behavior of these panels must remain tentative. The panels were designed to be weak enough to fail within a reasonable time in the applied thermoacoustic environment. Thus, the relatively short fatigue lives of these panels should not be used to imply that c-c composites have a sonic fatigue problem. Further, thermal isolation of these panels from the support fixture, introduced uncertainty in the boundary conditions that could have significantly affected panel responses. Future test efforts should pay particular attention to achieving improved thermal and mechanical boundary conditions.

References

[1]Moore, T. C., "High Temperature Strain Gage Installation Techniques for Carbon/Carbon with Silicon Carbide Surfaces," *Seventh National Aero-Space Plane Symposium*, Paper 92, Cleveland, OH, Oct. 1989.

[2]Shideler, J. L., Kelly, N. H., Avery, D. E., Blosser, M. L., and Adelman, H. E., "Multiwall TPS—An Emerging Concept," NASA TM 83133, May 1981.

[3]Shideler, J. L., Webb, G. L., and Pittman, C. M., "Verification Tests of Durable Thermal Protection System Concepts," *Journal of Spacecraft and Rockets*, Vol. 22, No. 6, 1985, p. 598.