

Predicting Snap-through of a Thin-walled Panel due to Thermal and Acoustic Loads

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Abstract: Under contract from Wright-Patterson AFB (WPAFB), ATA Engineering, Inc., (ATA) has performed a study of “snap-through buckling” of a panel on a hypersonic vehicle under the influence of fluctuating pressures. Snap-through occurs when the elastic stiffness of the structure is cancelled by the effects of compressive stress within the structure. If this effect causes the structure to suddenly displace a large amount in a direction normal to the load direction then it is classical bifurcation buckling. If there is a sudden large movement in the direction of the loading it is snap-through buckling.

The analysis was performed by applying aerothermal loads and fluctuating pressure loads on a thin-walled panel. Representative metallic (Inconel X-750) panel structures have been defined. Uncoupled nonlinear computational structural dynamics (NLCS) using Abaqus/Explicit simulations performed on these panels include their quasi-static deformation under the vehicle’s aerothermal loads and their vibratory response to aerodynamic fluctuating pressure loads. The latter analysis has captured the phenomenon of snap-through response between two stable buckling equilibrium positions.

The presenters will show the methods used and the results of this study, especially as it relates to the use of Abaqus.

Keywords: Aircraft, Buckling, Coupled Analysis, Dynamics, Heat Transfer.

1. Introduction

The Air Force Research Lab, Structural Sciences Center, has identified multidisciplinary coupled analysis capability as an enabling technology for the design of future high-speed vehicles that must withstand extreme aerothermal and aeroacoustic environments. The expected benefit of such a tool is a more accurate response prediction and life of the aerothermoelastic phenomena of panel hot spots, snap-through, and/or flutter, to enable designs that do not carry a weight penalty due to overspecification of thermal protection systems.

The design of such combined environment structures requires a time-resolved definition of the vehicle’s aerothermal environments along a given trajectory and mission for two reasons: (1) the solution is path-dependent, not allowing for the superposition of loads at prespecified trajectory points, and (2) a detailed, time-accurate history of the response will be required for life prediction.

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The vehicle's thermal-vibro-acoustic behavior must be coupled to a mission profile (Culler, 2010). High temperatures along the trajectory require unconventional lightweight materials to be used for vehicle skin panels, such as fiber-reinforced composites, metal matrix composites, and inter-metallic compounds (Vaicaitis, 1994). As the vehicle accelerates, aerodynamic heating takes place on the panels due to several phenomena. In the supersonic region, the bow shock continuously deforms along the trajectory, with large temperature and pressure gradients across it. The increasing kinetic energy of the flow heats the panel, deforming it into the flow and further inducing spatial temperature gradients that can feed back on local deformations, causing dangerous "hot spots" (Culler, 2009). Panel deformations can also induce local shocks due to effective curvature changes, resulting in shock-boundary layer interactions (SBLI) and strong aerothermoelastic coupling, which may result in dangerous panel flutter or snap-through responses (Wieting, 2010). Additional loading scenarios on vehicle skin panels include local flow separation, strong shocks, and shock impingement on downstream control surfaces.

This paper presents selected results generated in ATA Engineering, Inc.'s (ATA) Phase I Air Force Research Laboratory (AFRL)-sponsored SBIR program for the "Development of a Multiphysics, Coupled Analysis Framework for Hypersonic Vehicle Structures." The long-term goal of this research project is to develop a physics simulation capability that encompasses a set of coupled software tools that could be used for vehicles exposed to launch, flight in air at sustained hypersonic velocities, and re-entry, and for stealth aircraft with buried engines and ducted exhaust.

In Phase I a typical hypersonic vehicle forebody was defined, as shown in Figure 1. The forebody was similar to the vehicle described in Blevins et al. (Blevins, 2009), with a typical mission profile to Mach 15 at constant dynamic pressure of 1000 lb/ft². This is an example of a candidate hypersonic cruise mission envelope for a blended wing body (BWB) aircraft. Typically, such a vehicle design requires more propulsion system/airframe integration than conventional military and commercial aircraft.

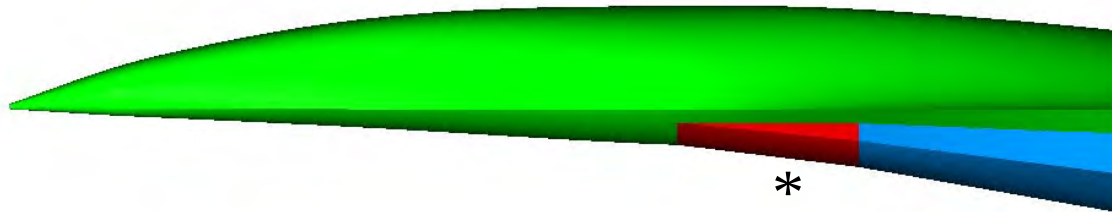


Figure 1. Typical hypersonic vehicle forebody. In steady, level-flight, vehicled underbody ramps are compression surfaces of 3, 7, and 11 degrees. Approximate panel location is 55 ft (16.8 m) from the nose, shown by an asterisk.

Additionally, the salient characteristics of structures at the panel level and extreme environments that necessitate a multiphysics, coupled analysis were identified. This has led to the development of a conceptual framework that will (in Phase II) couple state-of-the art computational fluid dynamics (CFD) and nonlinear computational structural dynamics (NLCSD) tools to simulate the response of high-speed vehicle structures in those environments.

2. Thin-walled Panel Definition

The first objective was to define a metallic panel geometry and material properties that were consistent with the hypersonic vehicle and trajectory. The panel definition was chosen to lend itself to phenomena such as snap-through and/or flutter during parts of the mission. A typical location for these panels is about 55 feet from the nose of the vehicle, on the first vehicle compression ramp, as depicted by the asterisk in Figure 1 above.

A flat Inconel X-750 panel definition was based on a communication by Wright-Patterson AFB (Spottswood, 2009). The metallic panel length and width are 12 inches by 18 inches, with a nominal thickness of 0.060 inch. An Abaqus finite element model (FEM) was created, as depicted in Figure 2. Square elements having a length of 0.5 inches were chosen, resulting in a 24-element by 36-element mesh. Panel geometric dimensions and boundary conditions are given in Table 1.

The material properties for Inconel X-750 are based on MIL-HDBK-5J and are presented in Appendix A.

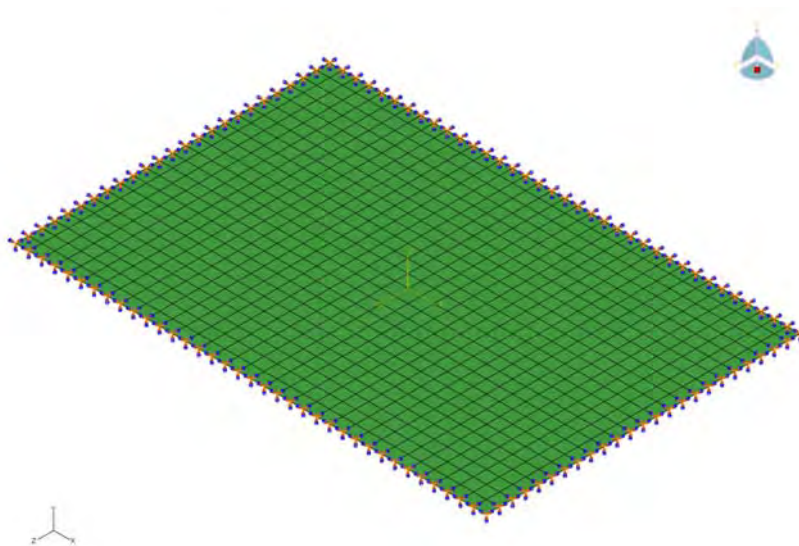


Figure 2. Representative panel FEM with clamped edge constraints. Ramp panel construction is similar with initially assumed dimensions given based on information contained in Spottswood, 2009.

Table 1. Inconel X-750 representative panel geometry.

Nominal Thickness	0.060 inch
Width (flow direction)	12 inch
Length (transverse direction)	18 inch
Stiffener height	not modeled
Stiffener thickness	not modeled
Stiffener spacing (transverse direction)	not modeled
Boundary conditions	clamped on 4 sides, pinned on 4 sides, in-plane springs with vertical restraints w/ and w/out rotational restraints

3. Nonlinear Quasi-steady Panel Thermal Analysis

A quasi-one-dimensional aero-heating analysis was next performed at a location 55 feet from the nose on the windward side of the BWB using the NASA Langley MINIVER code (Engel, 1988) in order to characterize the aero-heating loads on the panel as a function of time. Using these aero-heating loads, a one-dimensional transient thermal analysis was performed to compute the temperature history of the Inconel X-750 structure. The initial temperature of the panel was 68 °F (20 °C). Radiative heat transfer was modeled assuming the exterior of the panel radiates to a constant sink temperature of 68 °F (20 °C). The simulation was performed over the entire trajectory. The analysis indicates that the Inconel X-750 ramp panel reaches a peak temperature of 1852 °F (1011 °C), as shown in Figure 3.

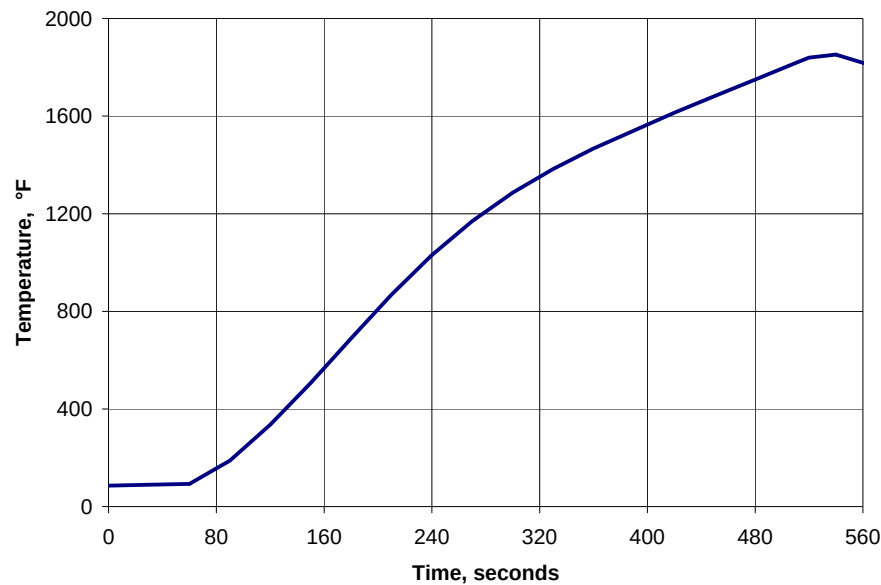


Figure 3. Temperature versus time at ramp panel location for ascent portion of trajectory.

These temperatures were then applied uniformly in space to the Abaqus structural models of the Inconel X-750 panel. Deformation of the plate was computed based on a fully nonlinear structural transient due to thermal loading. To reduce analysis time, the thermal loading was scaled to go from the initial temperature to the peak temperature in 2.16 simulation seconds, instead of 540 simulation seconds. This shortened analysis used an integration time step of approximately 2 microseconds.

Initially, clamped and pinned boundary conditions were applied to the edges of the panels. However, these boundary conditions cause a majority of the panel to yield, as shown in Figure 4. This problem occurs because metallic structures are designed for thermal growth. Fixed in-plane boundary conditions constrain this thermal growth and are therefore overly restrictive. Ideally, the underlying supporting structure would be modeled to account for compliance and thermal growth. The compliance of the structure was thus modeled using in-plane springs that could be tuned to prevent the panel from yielding during thermal expansion and could also induce out-of-plane deformations.

To remove this problem, translational springs were added to each node on the edge of the panel and were attached to ground. The spring stiffness was modified so that the peak von Mises stress was approximately half of the yield stress of 31,200 psi at 1852 °F. This stress limit was chosen to allow for dynamic behavior that would not necessarily yield the material. The rotation of the nodes on the edge was rigidly restrained.

After several iterations, a spring stiffness of 571 lb/in (100,000 N/m) was selected for the dynamic analyses. With these springs, the panel had a peak deformation of 0.15 inches and a peak stress of 16,620 psi (53% of yield stress), as shown in Figure 5 and Figure 6, respectively.

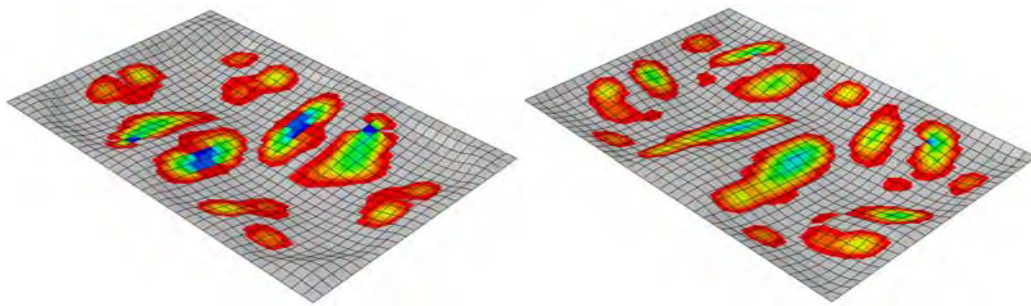


Figure 4. Stress for flat plate Inconel X-750 with clamped boundary conditions (top) and pinned boundary conditions (bottom). The areas in gray have exceeded the yield stress of the material.

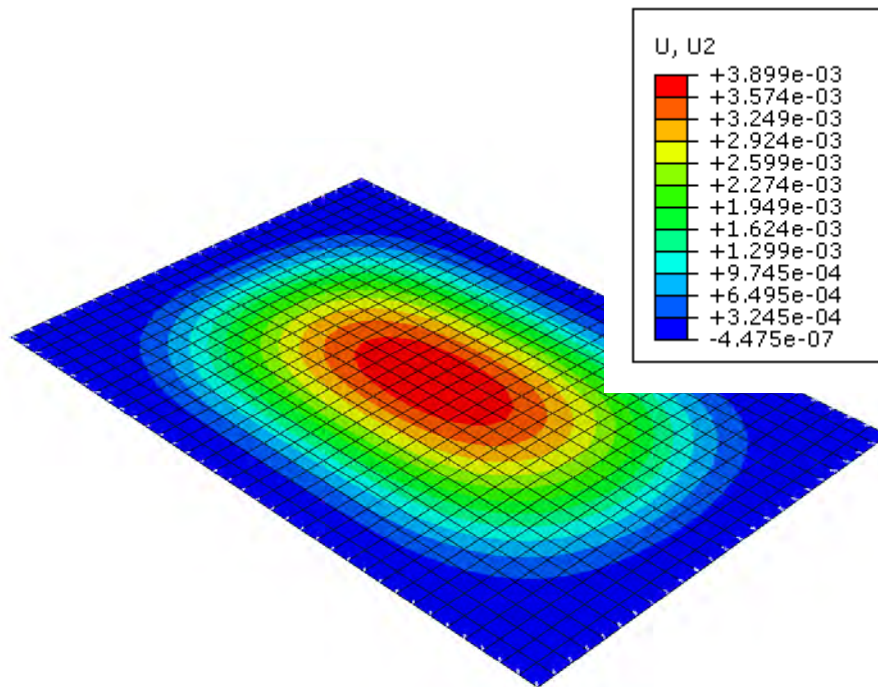


Figure 5. Flat plate thermal deformations at peak temperature. Contours show normal displacement in meters. The peak normal deformation is 0.15 inches (3.9 mm).

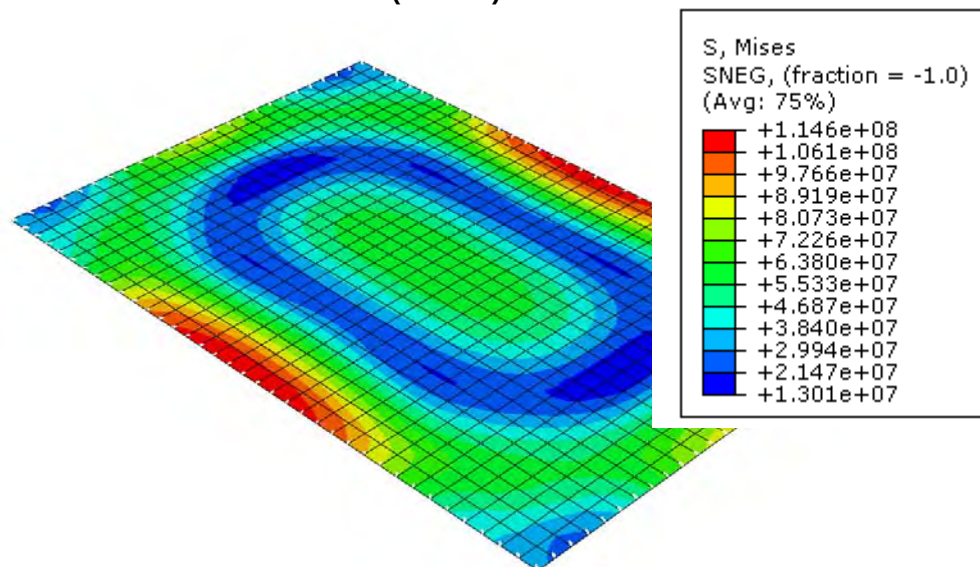


Figure 6. Flat plate thermal stresses at peak temperature. Contours show von Mises stress in Pascal. The peak von Mises stress is 16,620 psi (114.6 MPa).

Using a Gaussian random pressure load with a spectrally flat spectrum from 0–1500 Hz, a spatially uniform, transient pressure load was next generated as an excitation. This excitation is similar to that used in Przekop and Rizzi (Przekop, 2007), and again the assumption of complete spatial correlation of the pressure was used for simplicity.

The fluctuating pressure load was applied to the thermally deformed Abaqus model at the peak temperature. Multiple 2.138-second transient simulations using different FPL values were performed using an integration time step of 1 microsecond. The displacement at the center node was graphed to determine if the panel exhibits snap-through behavior.

At 148 dB, the flat panel snaps through only once (Figure 7). At 150 dB, there are multiple snap-through events (Figure 8), and at 152 dB (Figure 9), the snap-through behavior is similar to the observations of Przekop and Rizzi (Przekop, 2007).

At input levels of 158 dB and above, there is a change in the behavior of the center node. At 158 dB (Figure 10), there appears to be less snap-through behavior than at lower input levels. At 168 dB (Figure 11), there is a distinct drift towards a new equilibrium point. At 178 dB (Figure 12), there is rapid growth of the equilibrium point, increasing from 0.15 inches to 1 inch normal to the surface of the panel.

For the FPLs at and above 158 dB, the change in response at the center is due to plastic deformation of the panel. The edges of the panel yield and allow for plastic deformation, causing the center of the panel to bulge (see Figure 13 to Figure 15). The bulge tends to stabilize the structure, reducing the snap-through effect.

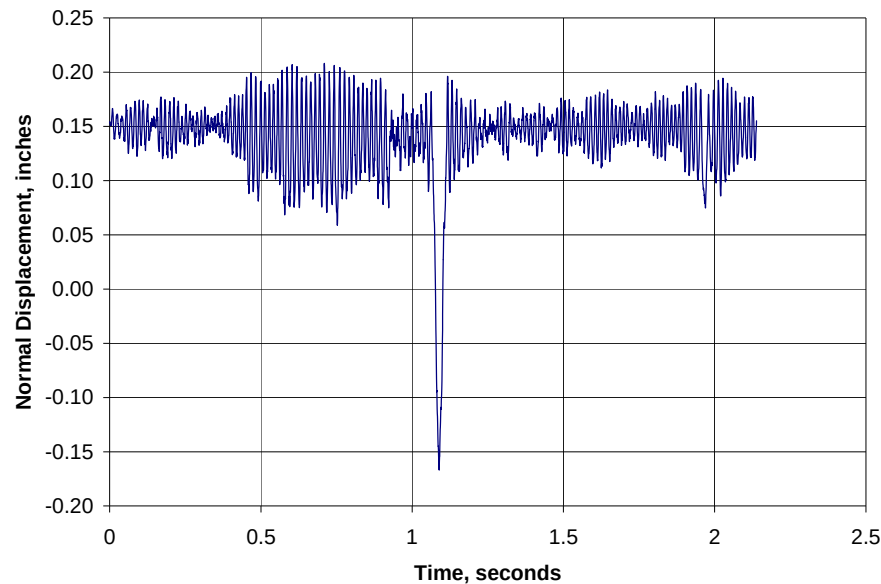


Figure 7. Response of center of a flat plate due to a 148 dB acoustic excitation. The center fluctuates ± 0.2 inches (± 5 mm).

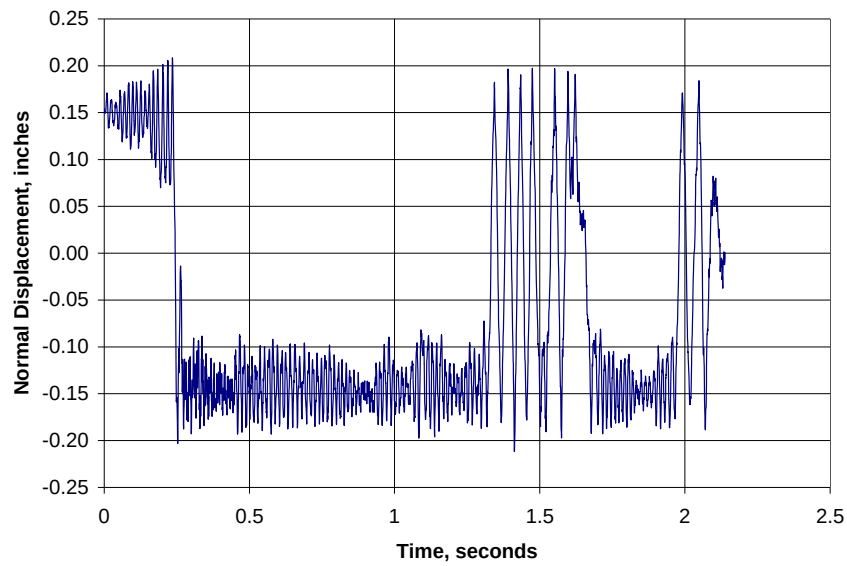


Figure 8. Response of center of a flat plate due to a 150 dB acoustic excitation. The center fluctuates ± 0.2 inches (± 5 mm)

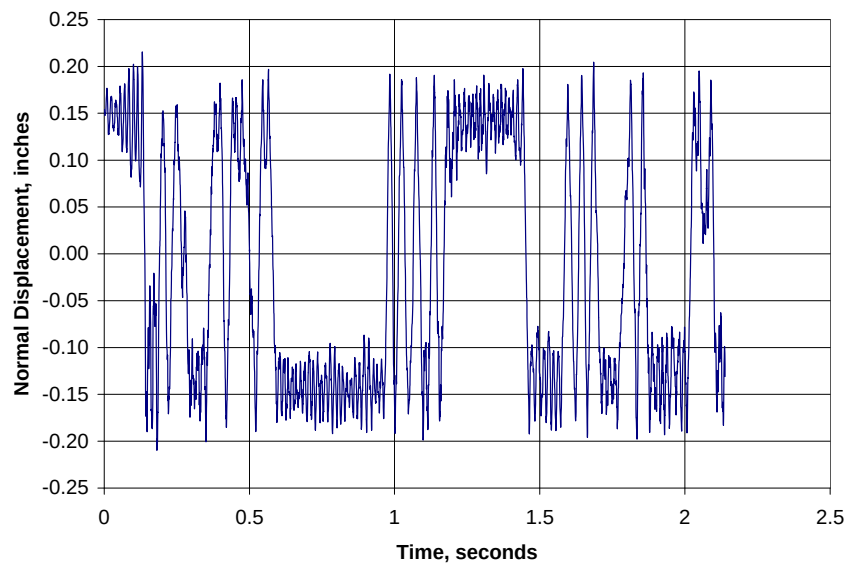
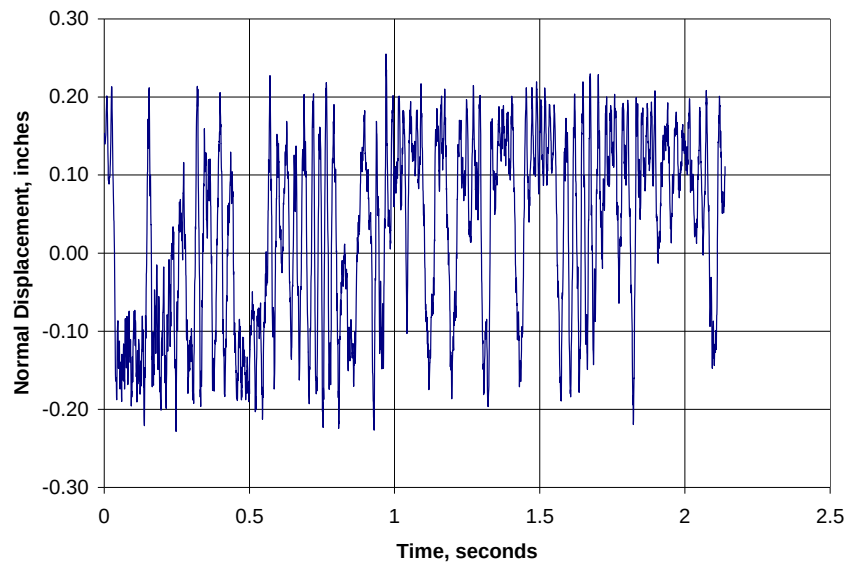
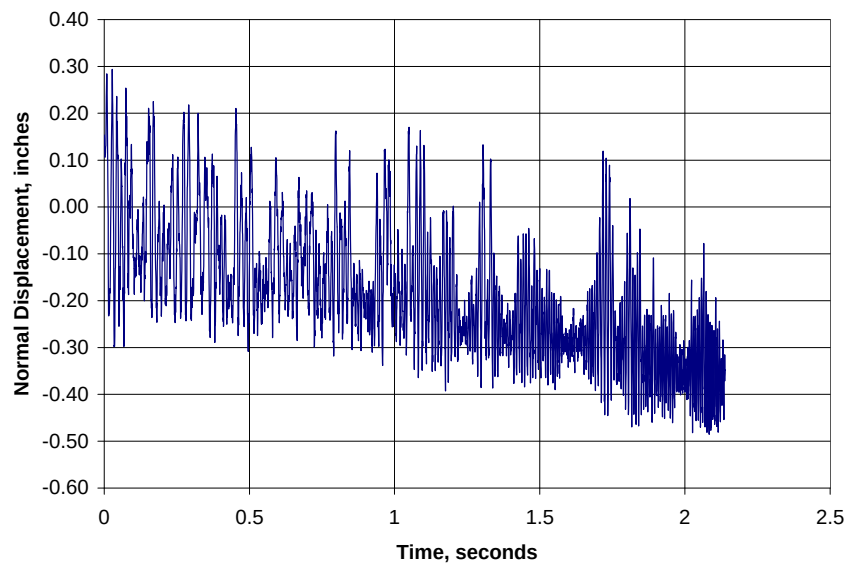


Figure 9. Response of center of a flat plate due to a 152 dB acoustic excitation. The center fluctuates ± 0.2 inches (± 5 mm).



**Figure 10. Response of center of a flat plate due to a 158 dB acoustic excitation.
The center fluctuates ± 0.2 inches (± 5 mm).**



**Figure 11. Response of center of a flat plate due to a 168 dB acoustic excitation.
The center node appears to be drifting towards a new equilibrium position.**

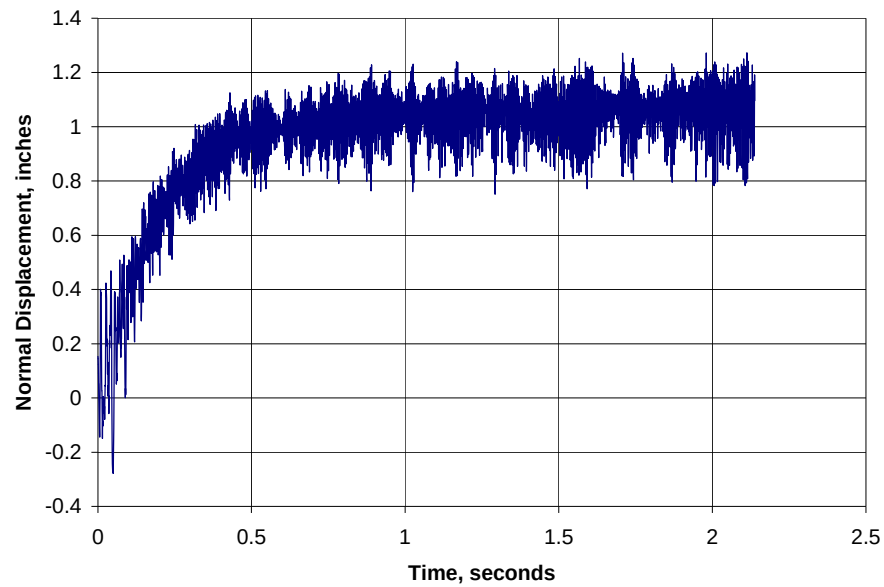


Figure 12. Response of center of a flat plate due to a 178 dB acoustic excitation. The center node moves rapidly to a new equilibrium position.

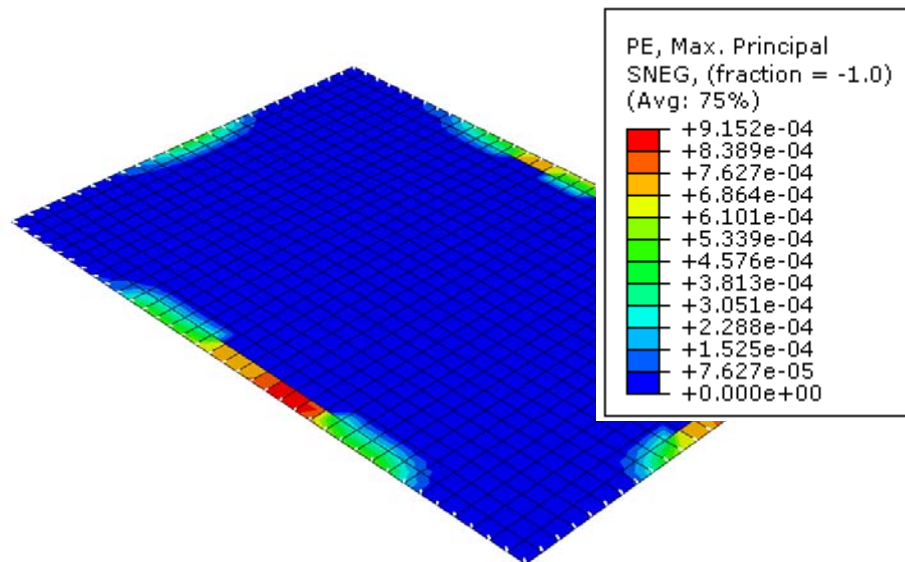


Figure 13. Plastic strain due to a 158 dB acoustic excitation on a flat plate. Peak plastic strain is 0.09%.

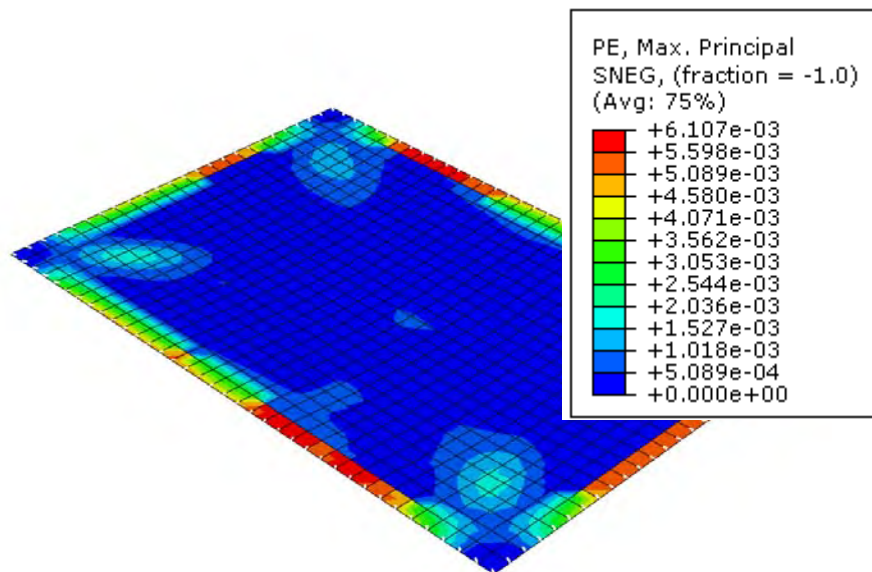


Figure 14. Plastic strain due to a 168 dB acoustic excitation on a flat plate. Peak plastic strain is 0.6%.

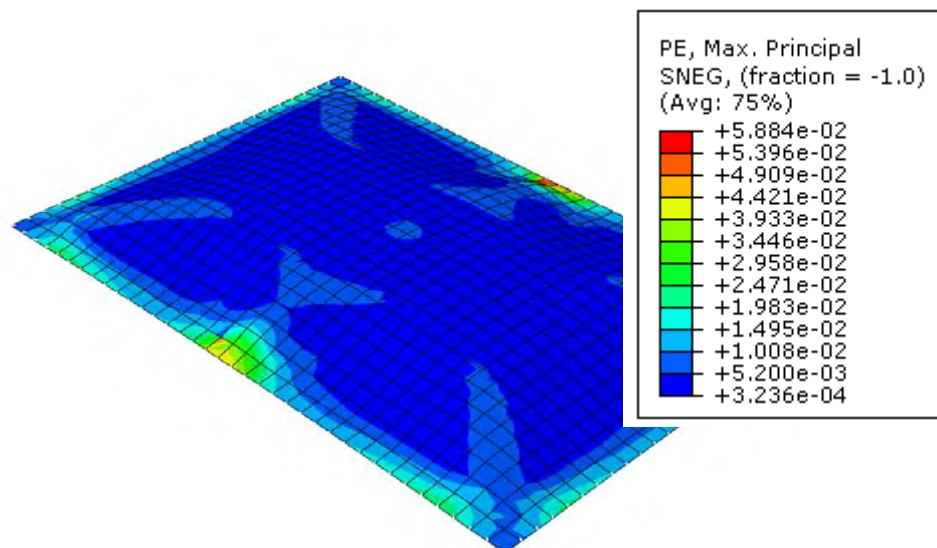


Figure 15. Plastic strain due to a 178 dB acoustic excitation on a flat plate. Peak plastic strain is 5.8%.

4. Conclusions

ATA Engineering has completed a multiphysics analysis of an Inconel X-750 panel on a hypersonic vehicle which included deformations due to mechanical, thermal, and acoustic loads. The results of the study for flat plates show that under the right thermal and acoustical conditions the panel will exhibit snap-through that may result in failure of the panel over time.

ATA Engineering has been awarded a Phase II SBIR contract to continue this work. Future efforts will focus on the development of a framework to couple mechanical, thermal, CFD, and acoustic loads into an integrated analysis for hypersonic vehicle structures..

5. References

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6. Appendix A – Inconel X-750 Material Properties Used in Analysis

These are the properties of Inconel X-750 that were used in the above analysis. They are based on data found in MIL-HDBK-5J.

Table 2. Inconel X-750 constant properties.

Density	0.298 lb/in ³
Poisson's Ratio	0.3

The data in the figures below were linearly extrapolated in the temperature range of 1600 to 2000 °F. The stress-strain curves in Figure 16 assume linear stress-strain variation up to the yield stress data shown in Figure 17. The plastic portion of the curve was assumed to begin at the yield stress and continue to the ultimate stress (also shown in Figure 17). At the ultimate stress, the strain was assumed to be 0.2. The coefficient of thermal expansion (CTE), thermal conductivity, and specific heat are plotted as functions of temperature in Figure 18 and Figure 19.

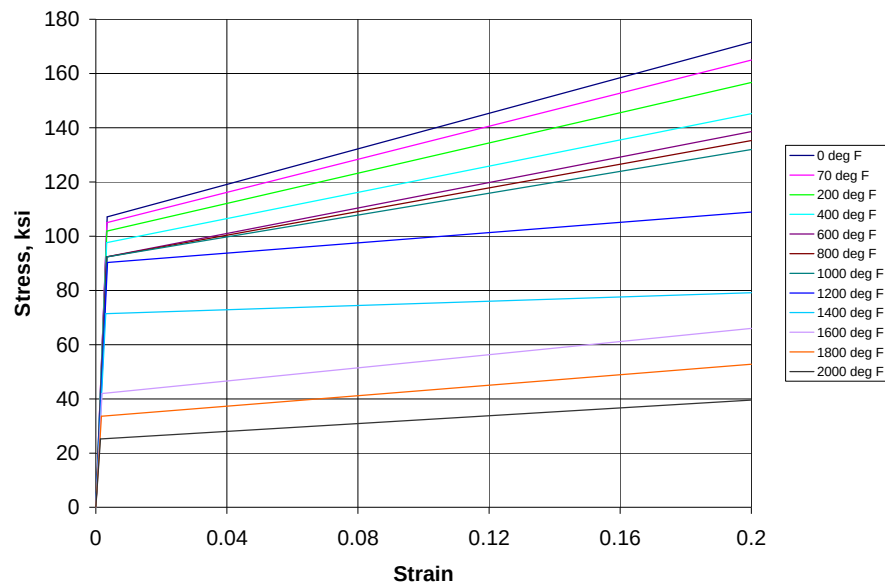


Figure 16. Stress-strain versus temperature for Inconel X-750.

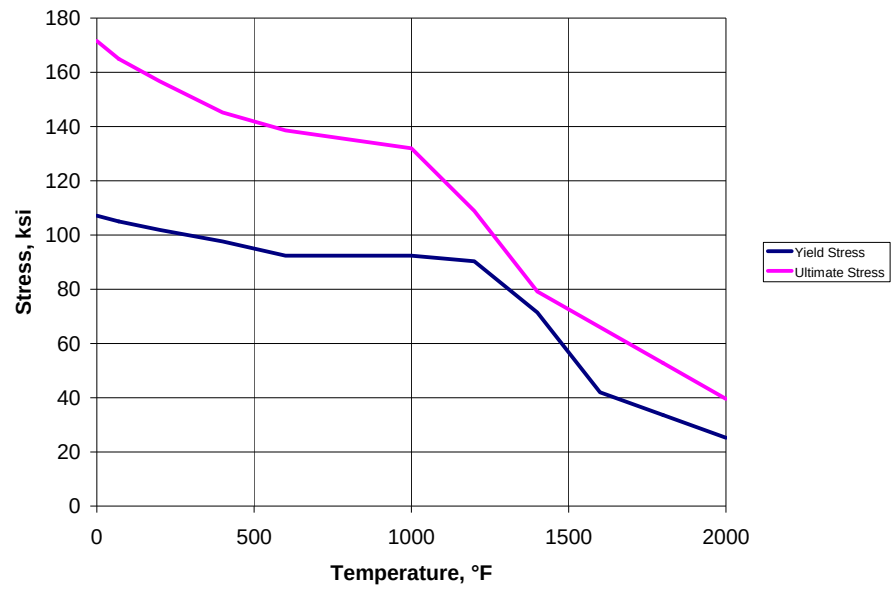


Figure 17. Yield and ultimate stress versus temperature for Inconel X-750.

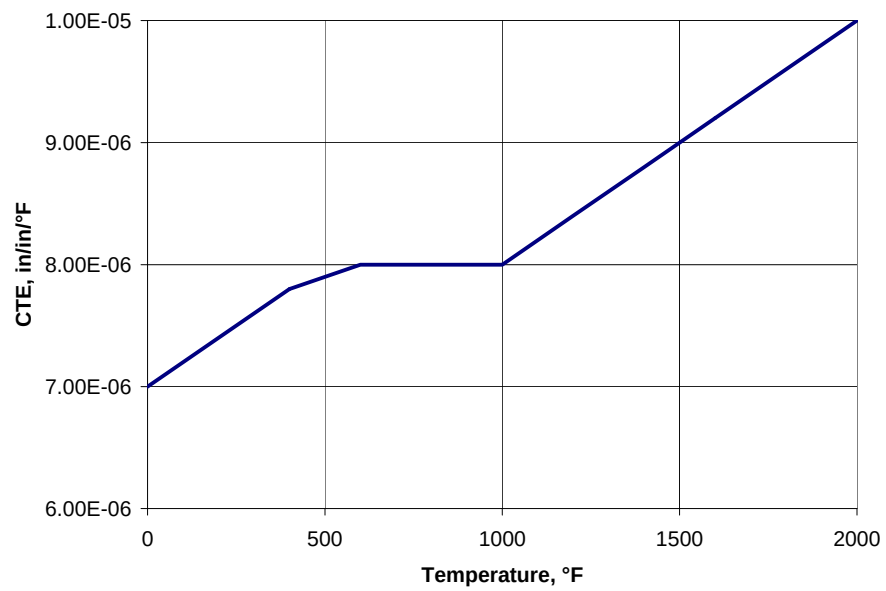


Figure 18. Coefficient of thermal expansion (CTE) versus temperature for Inconel X-750.

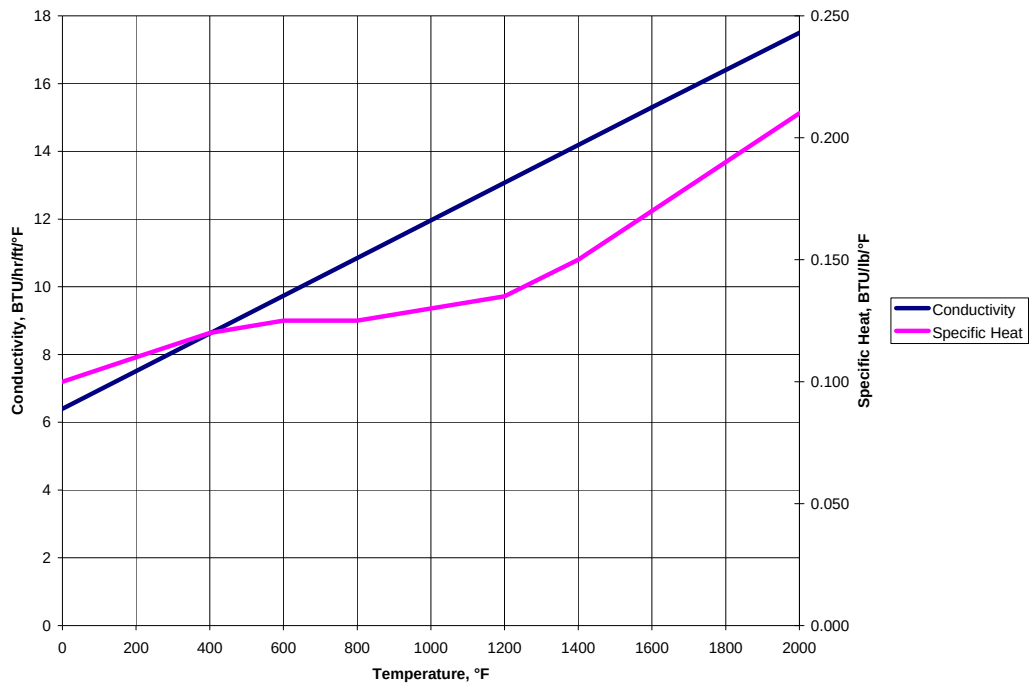


Figure 19. Thermal conductivity and specific heat versus temperature for Inconel X-750.

7. Acknowledgments

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