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Research Article

Analysis of Unconventional Wing Structures of a Hyper-X Hypersonic Flight Research Vehicle for the Mach 7 Mission

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Abstract

Heat transfer, thermal stresses analyses were performed on the unconventional wing structures of a Hyper-X hypersonic flight research vehicle (designated as X-43) subjected to nominal Mach 7 aerodynamic heating. A wing mid span cross section was selected for the heat transfer and thermal stress analyses. Thermal stress analysis was performed on three regions of the upper wing skin; 1) a fore wing panel, 2) an aft wing panel, and 3) a unit panel at the middle of the aft wing panel. A fourth thermal stress analysis was performed on a mid-span wing segment. Thermal stress analysis and panel deformation results are presented.

Keywords: *Thermal stress, fore wing panel, aft wing panel, unit panel, mid wing.*

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1. Introduction

Hypersonic flight vehicles are subjected to severe aerodynamic heating during flights. The vehicle structure may be called “hot” structures or “warm” structures, depending on the operating temperature range. The hot structures are fabricated with high-temperature materials and are capable of operating at elevated temperatures exceeding 1000 °F. The warm structures are fabricated with light-weight materials such as aluminum and must be insulated so that the sub-structural temperatures will not exceed the operating temperature limit of 350 °F. An example of a recent hot structure is the new hypersonic flight research vehicle called Hyper-X (designated as the X-43 vehicle), which has unconventional wing structures with irregular-shaped wing panels.

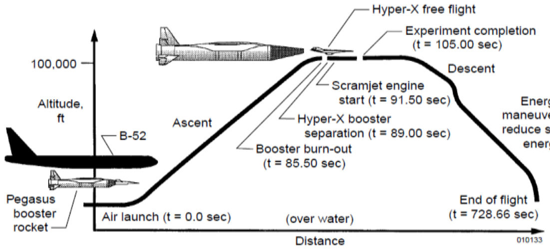

Figure 1 Hyper-X Flight Research Vehicle (Reference 8)

Hyper-X (designated as X-43) is a new hypersonic flight research vehicle (12 ft long, 5 ft span, 3,000 lb weight), designed to be flown at a range of Mach 7~10. The proposed flight trajectory of Hyper-X is shown in figure 1. The Hyper-X rides on a winged Pegasus booster rocket, which is carried under the wing of a B-52 aircraft up it, should be noted that the maximum Mach number reached during the nominal Mach 7 mission was 7.5 to a launch altitude of 17,000 ft. for the Mach 7 mission or 43,000 ft for the Mach 10 mission. After air launching from the B-52, the Pegasus booster rocket will accelerate and ascend to an altitude of approximately 100,000 ft, reaching the test velocity (of Mach 7 or Mach 10). After separation from the booster rocket, the cowl door of the Hyper-X scramjet engine opens to test the performance of the scramjet engine. Once the cowl door is open, fuel is injected, ignited and burned for about 8 seconds. The entire event from the opening to the closing of the cowl door lasts for 34 seconds.

The Hyper-X wing structure is fabricated with high-temperature Haynes 230 alloy (a nickel-chromium-tungsten-molybdenum alloy) which has relatively low thermal expansion characteristics. The design concept of its wing structures is entirely different from that of the conventional wing structures. The conventional spar and rib system is replaced with multiple radial stiffeners (spars, 0.25 in. wide) fanning out from the pivoting wing roots. To house the instrumentation inside the wing structure, upper and lower wing skins (0.090 inches thick) are divided into two separate wing panels (a fore wing panel and an aft wing panel). The wing panels are then butt-welded at their edges to the main wing frame, and line-welded to the radial reinforcing stiffeners without using conventional fastening screws or rivets. Because the edges of the heated wing panels are constrained, potential

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thermal buckling of the wing panels and possible shearing off of the line-welded sites are of great concern.

Thermal buckling analysis is to be performed on the following three regions of the wing skin panels (lower or upper): 1) the fore wing panel, 2) the aft wing panel, and 3) a unit panel at the middle of the aft wing panel. In addition, thermal buckling is also to be conducted for the wing segment. These analyses are being done to locate the thermal buckling initiation zone.

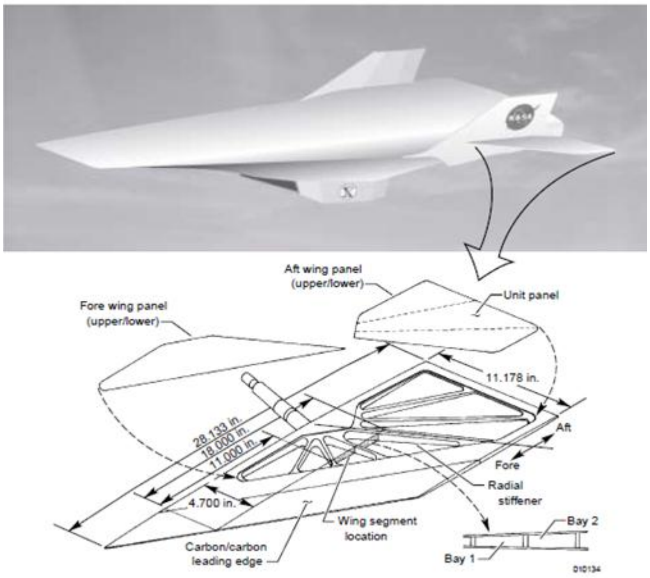


Figure 2 Unconventional wing structures of Hyper-X hypersonic flight research vehicle. (Reference 8)

I. Finite Element Modeling For Wing Mid-Span

The Hyper-X wing segment selected for the thermal buckling analysis is located at the wing mid-span, approximately 0.11938 m. from the wing root edge. The chord-wise region lies between the stream-wise distances 0.2794 m. and 0.4572 m. measured from the carbon/carbon leading edge, and spans over three neighbouring radial stiffeners (or spars). Thermal and material properties for thermal stress analysis are considered as follows:

E	1.682×10^{11} N / mm^2
ν	0.324
ρ	8968.28 kg / m^3
K	19.182
ϵ	0.85
c	469
α	7.9

A. Thermal Modeling

Thermal model is generated for full contact of welded site skin and spar contact as shown in fig. The material considered was Haynes 230 alloy. Outer structural mold lines use a 1.5 degree half-angle for both upper and lower skins. For the full contact, the wing skin panels are perfectly bonded to the full width (0.00635 m) of the stiffeners. The thermal models have a surface emissivity of $\varepsilon = 0.85$. The wing panels and the spars are modeled with 10 node solid 92, a tetrahedral element. The thermal model with 10 node solid 92 is converted to structural model such that the nodal coordinates of the finite-element structural model are made coincidental with those of the thermal model. Thus, the nodal temperature output from the thermal model can be used directly as temperature input to the structural model.

From reference 1, a structural performance and resizing (SPAR) finite-element thermal analysis computer program was used in the heat-transfer analysis of the space shuttle orbiter subjected to reentry aerodynamic heating. Three wing cross sections and one mid fuselage cross section were selected for the thermal analysis.

Mechanical and thermal buckling behavior of monolithic and metal-matrix composite hat-stiffened panels was investigated. The panels have three types of face-sheet geometry: flat face sheet, micro- dented face sheet, and micro bulged face sheet was analyzed in reference 3.

B. Finite Element Modeling for Wing Mid-Span

The Hyper-X wing segment selected for the thermal buckling analysis is located at the wing mid-span, approximately 0.11938m from the wing root edge. The chord-wise region lies between the stream-wise distances 0.2794m and 0.4572 m measured from the carbon/carbon leading edge, and spans over three neighboring radial stiffeners (or spars).

Element considered for meshing the model is solid 10node 92. SOLID92 has a quadratic displacement behavior and is well suited to model irregular meshes. The element is defined by ten nodes having three degrees of freedom at each node: translations in nodal x,y, and z directions. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

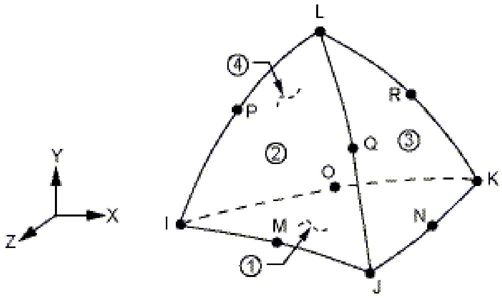


Figure 3 Solid92 geometry

C. Temperature Load

Average thermal load input for the thermal stress analysis has been taken from References [1], the thermal load input is based on the structural temperature distribution at time $t = 89$ sec (from launch of the Pegasus booster) obtained from the heat transfer analysis carried out by William L. Ko et.al Time $t = 89$ sec is the instant when the difference between the upper and lower skin peak temperatures reaches a maximum.

D. Uniform Temperature Loading on Panel

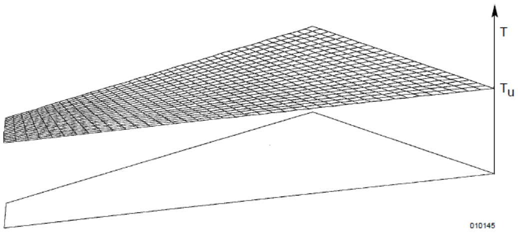


Figure 4 Uniform temperature loading

The simulated chord-wise thermal stresses induced in the wing-segment skins under free expansion (to simulate actual situation) is as shown in figure.

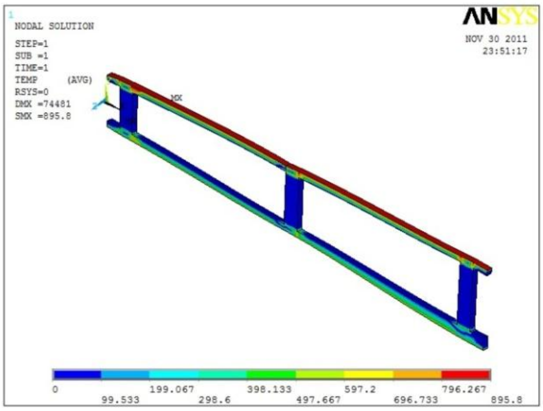


Figure 5 Nodal solution of wing cross-section

E. Boundary Conditions

Different support conditions listed below are considered for comparative studies of how the stress is distributed over wing panels.

Table 1 Definition Of Support Conditions.

	Panel Boundaries	**Panel and stiffener Welded sites**
SS – SS	Simply supported	Simply supported
SS – CL	Simply supported	Clamped
CL – SS	Clamped	Simply supported
CL – CL	Clamped	Clamped

Based on the fact that the Hyper-X wing panels are line-welded, the SS-SS condition listed in Table 1 could be the closest to the actual support condition of the Hyper-X wing panels. Because the chord – wise thermal expansion of the wing panels are restrained by the cooler wing frame (heat skin), both upper and lower wing panels of each bay are under compression. Even though the temperature distribution over the wing panel of each bay is non – uniform and arch – shaped the thermal stress induced in the wing panel of each bay is constant. This is the typical behaviour of hot structural panels.

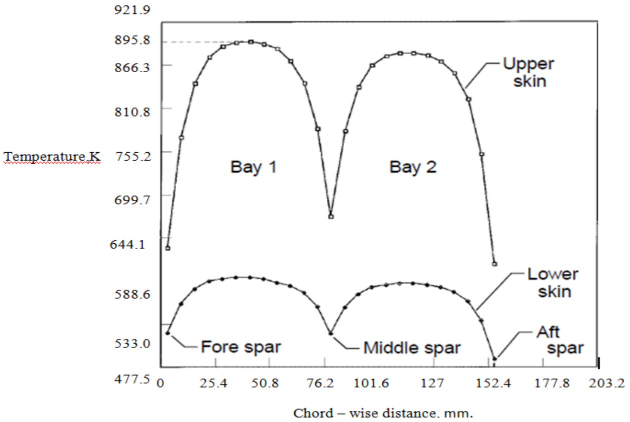


Figure 6 Chord wise distribution of Hyper – X wing segment skin temperatures; t = 89 sec

II. Thermal Stress Analysis on Fore Panel with Different Boundary Condition

A. Simply Supported – Simply Supported

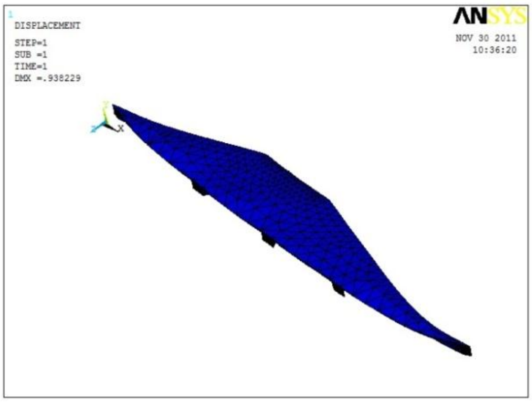


Figure 7 Deformation of wing aft panel at 483.10 K

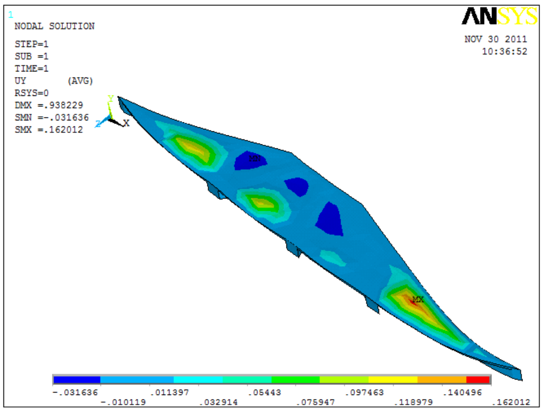


Figure 8 Stress on wing aft panel along the thickness at 483.10 K

When different temperatures 348.11 K, 353.11 K, 452.54 K, and 483.10 K were imposed on fore panel maximum stress of 0.16 N / mm^2 was obtained. At 483 K Haynes material can resist up to 170 MPa of stress. It is seen that stress obtained is within the permissible limit.

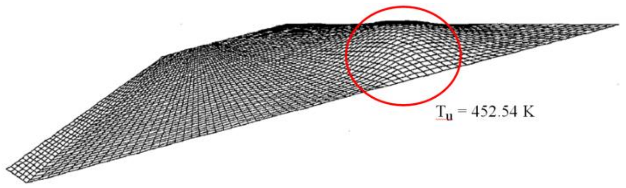
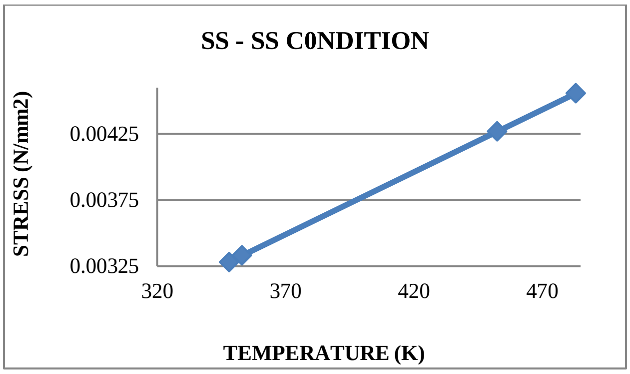


Figure 9 fore panel

When a uniform temperature of 452.54 K is experienced by fore panel maximum deformation and stress is obtained at near corner as shown. Position of maximum stress on fore panel is almost same.

Temperature and stress variation on fore panel with SS – SS condition

Graph 1 Stress Vs Temperature



III. Thermal Stress Analysis on AFT Panel With Different Boundary Condition

A. *Simply Supported – Simply Supported Condition*

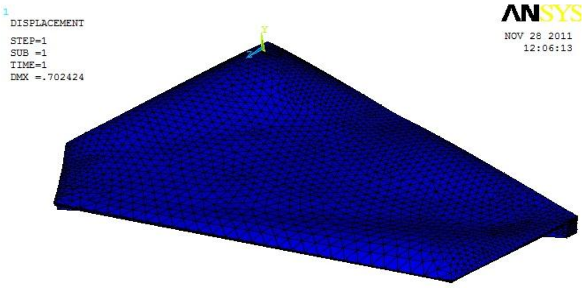


Figure 10 Deformation of wing aft panel at 418.66K

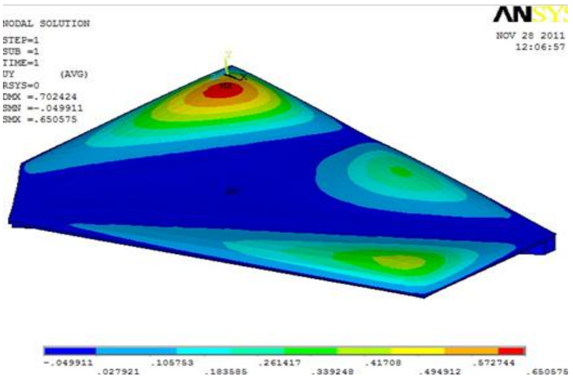


Figure 11 Stress on wing aft panel along the thickness at 418.66K

When uniform temperature of 418.66 K was applied on aft panel of wing maximum stress and deformation was obtained at the place shown in above figure. According to the analysis, value of maximum stress obtained was 0.65 N / mm^2. This value is less than the maximum stress of Haynes 230 alloy and the position of maximum stress is almost at same place. Minimum stress is obtained where radial stiffeners are passing bellow the aft panel.

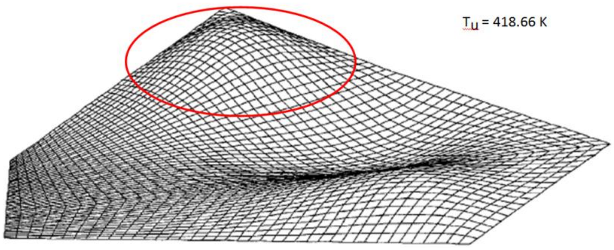
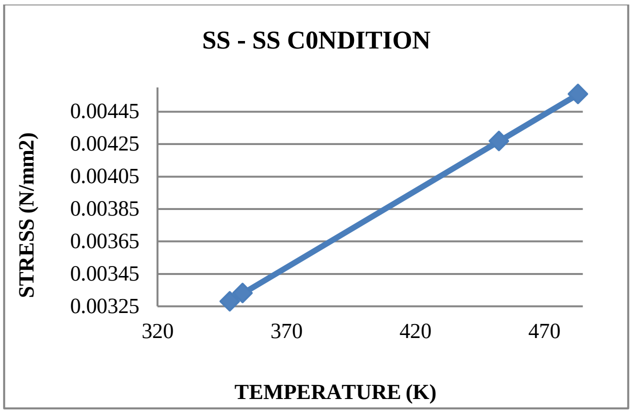


Figure 12 Aft panel

Graph 2 Stress Vs Temperature



IV. Thermal Stress Analysis on Unit Panel with Different Boundary Condition

A. *Clamped – Simply Supported Condition*

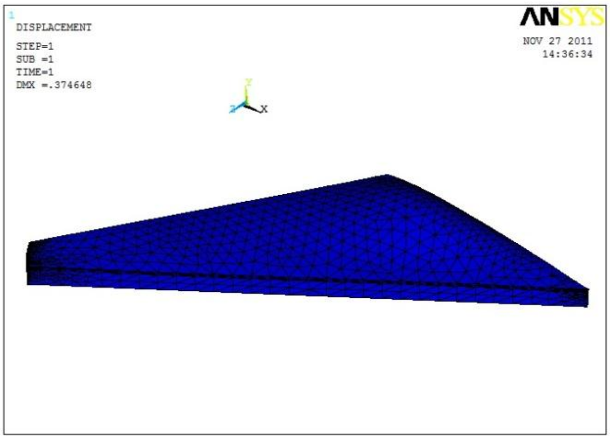


Figure 13 Deformation of wing aft panel at 419.21K

When uniform temperature of 419.21 K was applied on unit panel of wing maximum stress and deformation was

Table 2 Clamped – Simply supported condition

Temperature, K	Stress, N/mm^2
302.23	0.2703
318.67	0.3293
388.11	0.3557
419.21	0.3557

obtained at the place shown in above figure. According to the analysis, value of maximum stress obtained was 0.355 N / mm^2. This value is less than the maximum stress of Haynes 230 alloy and the position of maximum stress is almost at same place. Minimum stress is obtained between radial stiffeners unit panel which is a part of aft panel.

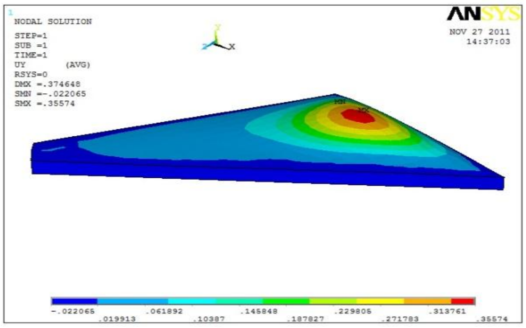
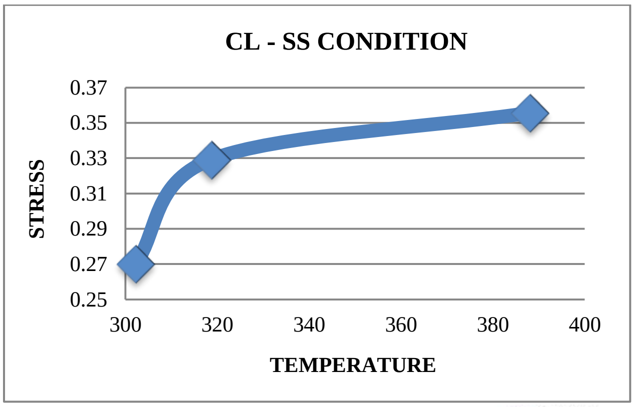


Figure 14 Stress on wing aft panel along the thickness at 419.21K

Table 3 Clamped – Clamped condition

Temperature, K	Stress, N/mm^2
322.56	0.5011
352.55	0.5590
359.78	0.6505
418.66	0.65057

Graph 3 Stress Vs Temperature



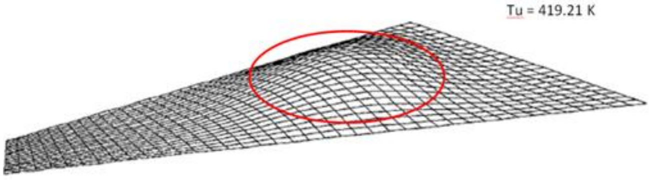


Figure 15 Maximum temperature on unit panel

Conclusions

Heat transfer, thermal stress, and thermal buckling analyses were performed on the Hyper-X wing structure for the Mach 7 mission.

- For fore panel with simply supported – simply supported condition and when it is exposed to different temperatures (348.11K, 353.11K, 452.54K, 483.10K) deformation & stress due to deformation is within the resistive value of Haynes 230 material which is used.
- For different boundary conditions considered for aft panel of wing is capable of resisting different uniform temperatures (322.56K, 359.78K, 352.55K, 418.66K) and 540 N/mm^2.
- Unit panel which is a part of aft panel whose edges are supported on stiffeners when is experiences a temperatures 302.23K, 388.11K, 318.67K, 419.21K and 540N/mm^2 its stress developed due to deformation is resistible and deformation is within the elastic limit.
- By identifying the unit panel region as the potential thermal buckling initiation zone, thermal buckling analysis of the Hyper-X wing panels may be reduced to the thermal buckling analysis of the unit panel without going through complex modeling of the entire wing structure.
- Material considered for the stiffener of the wing is capable of resisting the temperature imposed on it.

References

Ko, William L., Robert D. Quinn, and Leslie Gong, Finite-Element Reentry Heat Transfer Analysis of Space Shuttle Orbiter, *NASA Technical Paper 2657*, December 1986.

Robert D. Quinn and Leslie Gong Ames Research Center, Dryden Flight Research Facility. *Real – Time* Aerodynamic Heating and Surface Temperature Calculations for Hypersonic Flight Simulation.1990.

William L. KoDryden Flight Research Center Edwards, California,*Thermal and mechanical* Buckling Analysis of Hypersonic Aircraft Hat- Stiffened Panels with Varying Face Sheet Geometr and Fiber Orientatio

Ko, William L. and Raymond H. Jackson, Compressive Buckling Analysis of Hat-Stiffened Panel, *NASA 4310, August 1991.*

Ko, William L. and Raymond H. Jackson, *Shear* Buckling Analysis of Hat-Stiffened Panel, *NASA TM-4644, November 1994*

Ko, William L. and Raymond H. Jackson, Thermal Behavior of a Titanium Honeycomb-Core Sandwich Panel, *NASA TM-101732, January 1991.*

Ko, William L. and Raymond H. Jackson, Combined Compressive and Shear Buckling Analysis of Hypersonic Aircraft Structural Sandwich Panels, *NASA TM-4290, May 1991.* Also published as AIA

Paper No. 92-2487-CP, in the proceedings of the *33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structura Dynamics and Materials Conference*, Dallas, Texas, April 13-15, 1992.

William L. Ko and Leslie Gong NASA Dryden Flight Research Center Edwards, California, Thermostructural Analysis of Unconventional Wing Structures of a Hyper-X Hypersonic Flight Research Vehicle for the Mach 7 Mission.