Nonlinear Response of a Skin Panel Under Combined Thermal and Structural Loading

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Abstract: Future hypersonic vehicle will operate in an extreme environment, which includes extreme aerodynamic heating, fluctuating pressure and acoustic loading. Hypersonic vehicle must be reusable, lightweight and affordable in such environment. For hypersonic flight, the structure experiences complex aero-acoustic loads. The design of structure depends on the ability to predict response and life of structure in extreme environment. This paper presents a detailed investigation of the interactions and interplay among these parameters as evidenced by the nonlinear response of the panel.

A representative panel was selected as part of ramp skin panel on a blend wing body hypersonic vehicle concept. This paper focuses on the nonlinear response of the skin panel under combined thermal and structural loading. Thermal buckling, snap-through, and snap-buckling behaviors have been investigated by using different structural boundary conditions. Future work includes trajectory-dependent coupled thermal-structural loading study. The long-term goal of this research includes capturing fluid structure interaction as well as developing design curves for nonlinear response of the panel.

Keywords: Hypersonic vehicle, skin panel, nonlinear response, buckling, boundary condition

1. Introduction

Development of next generation hypersonic platform depends on the ability to predict the response and life of structure. This study focuses on the nonlinear response of a representative skin panel under combined thermal and structural loading. Since the vehicle skin is a load-bearing structure, due to severe thermal loading the vehicle skin may thermally buckle into flow and cause local shock, which may result in snap-through and snap-buckling behavior. Consequently, the fatigue life of the aircraft structure may be reduced because of the large deformation oscillation. This paper presents results related to the transient behavior of the skin panel under combined loading condition. Thermal buckling, snap-through, and snap-buckling behaviors have been investigated. There are six sections in this paper. Followed by this section, representative skin panel used will be introduced. In the 3rd section, results by nonlinear post-buckling analysis will be present and then snap-through and snap-buckling behaviors are performed and discussed. After that, different type of boundary condition ware proposed and analyzed. At last, some conclusions are derived.

2. Representative skin panel model

The vehicle skin in a hypersonic platformis a thermal and acoustic barrier so that panel level analysis is necessary after the development of reference vehicle (G. Tzong 2010). For representative skin panel selection, a critical panel is supposed to located in the region, where combination of loadings drives the design of the vehicle. A representative skin panel used in the study is derived from the one presented in (A.J. Culler 2009). The panels were designed with actively cooled features to remove excessive heat from engine combustion and reduce temperature to outer face sheet of a sandwich structure (G. Tzong 2010).

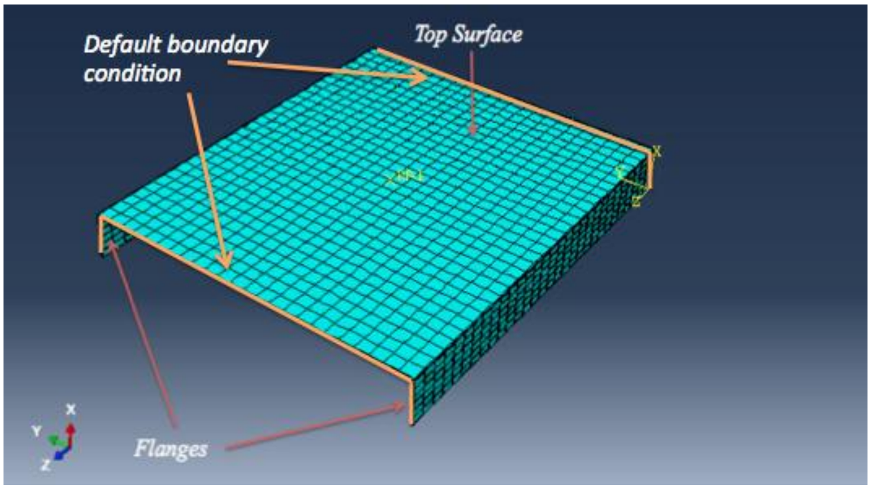

Figure 1. Representative skin panel used with Default Boundary Conditions

The dimensions of this representative panel used in this paper are 12 in. by 10 in., which corresponds to the stiffened area of the ramp panel. The thickness of the stiffener is considered a half of the original dimensions due to symmetry. The skin panel is made of Inconel-718 and the material properties are shown in Table 1 (Inconel alloy 718 2007), which are assumed constant as the temperature changes.

Table 1. Material properties of the Inconel-718 panel at 200 °F (Inconel alloy 718 2007)

Density	7.6666×10^{-4}	Lb/in^3
Thermal Conductivity	86	$BTU\bullet in/ft^2\bullet h\bullet°F$
Thermal Expansion Coefficient	7.31×10^{-6}	in/in/°F
Specific Heat	0.104	Btu/ lb °F
Elastic Modulus	2.84×10^{7}	psi
Poisson’s Ratio	0.288	

3. Nonlinear post-buckling analysis

When a thermally buckled panel is subject to increasing pressure, the pressure magnitude is the critical parameter for emergence of saddle-node bifurcation. To understand this behavior, the panel under static, coupled loading was considered first. Default boundary condition in the following analysis is shown in Figure 1. Two flanges and two edges at both leading and trailing edge are constrained in rotation and z-translation.

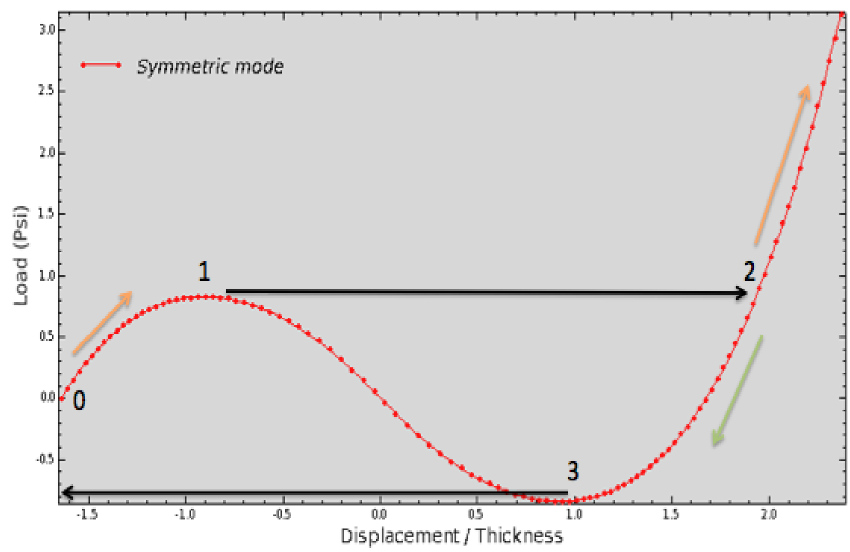

Figure 2. Equilibrium path of the buckled panel under normal pressure

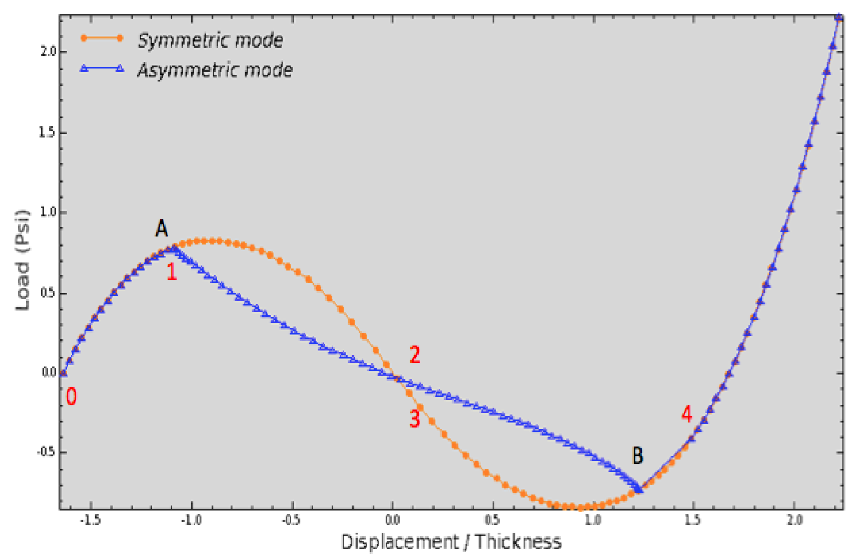

Figure 3. Bifurcation diagram of thermally buckled panel under static pressure: symmetric mode and asymmetric mode

Figure 2 shows the equilibrium load-deflection path of the panel as obtained using nonlinear post-buckling analysis based on static Riks Method (Abaqus Theory Manual 6.10 2010). As seen in Figure 2, Pt.1 and 3 are two critical load points. From Pt.0 to Pt.1, the magnitude of the pressure increases and the stiffness of the panel decreases and then drops to zero. When the load reaches the critical value at Pt.1, structure under static loading will directly snap into a shape, corresponding to Pt.2. Also, for a reverse loading direction, a similar situation is present. If the load is decreased from Pt.2 to Pt.3 then the jump happens at a different displacement level.

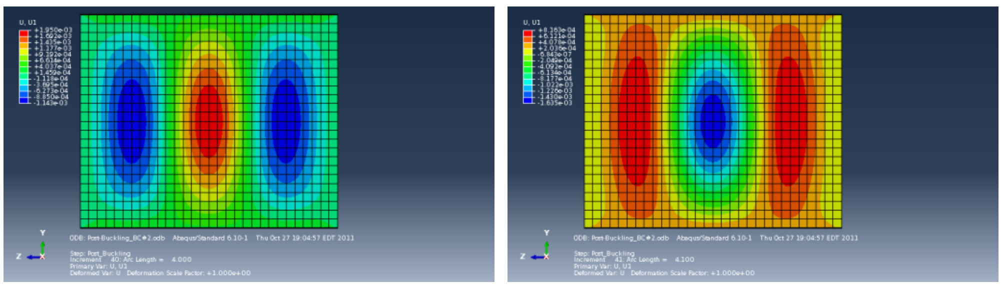

Figure 4. Deformed shapes of symmetric mode at key points 2 and 3

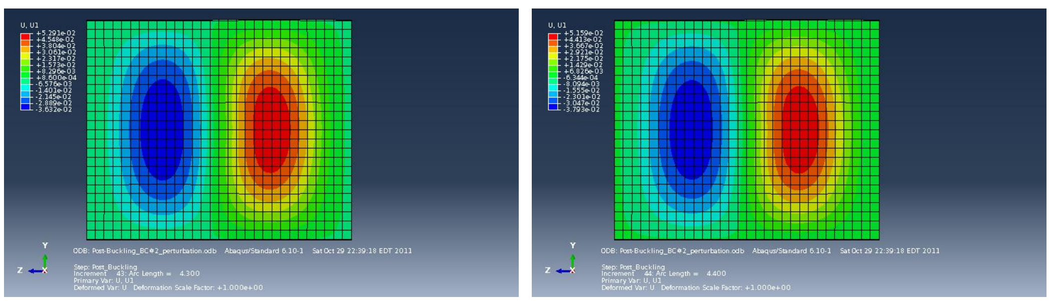

Figure 5. Deformed shapes of asymmetric mode at key points 2 and 3

To investigate the effect of asymmetric mode on the thermal buckling response we introduce a perturbation of additional point force applied to a node on the top surface of the panel, with magnitude of 0.01 lbs. Figure 4 shows two branches of the resulting load-deflection curve. There are two equilibrium modes of the panel: symmetric and asymmetric in the vicinity of two bifurcation Pts. A and B. The curve, which corresponds to symmetric mode, is same as the curve in Figure 2. Another curve, which corresponds to asymmetric mode due to small perturbation, connects two bifurcation points, Pts. A and B. Deformed shapes of the panel along the load path at key points 2 and 3 marked in Figure 4 are shown in Figure 4 and 5. It is obvious that in the first case (as in Fig. 4) the configuration is symmetric. However, in the second case, the configuration is transformed from symmetric mode to asymmetric mode. These two results indicate that under combined loading condition, skin panel may exhibit symmetric and asymmetric mode deformation. To under this phenomenon, snap-through and snap-buckling behavior are investigated in the next section.

4. Static snap-through and snap-buckling analysis

Snap-through occurs when the elastic stiffness of the structure is negated by the effect of compressive stress within the structure, under a symmetric mode of deformation. When a structure loses its stability under a symmetric and an asymmetric mode, it is known as *snap-buckling* (T.S. Sankar 1971).

Table 2. Loading cases for coupled analysis

ΔT (° F)	30	38	60	85	200
Pressure/Time (psi/s)	2	2	2	2/4	2/4

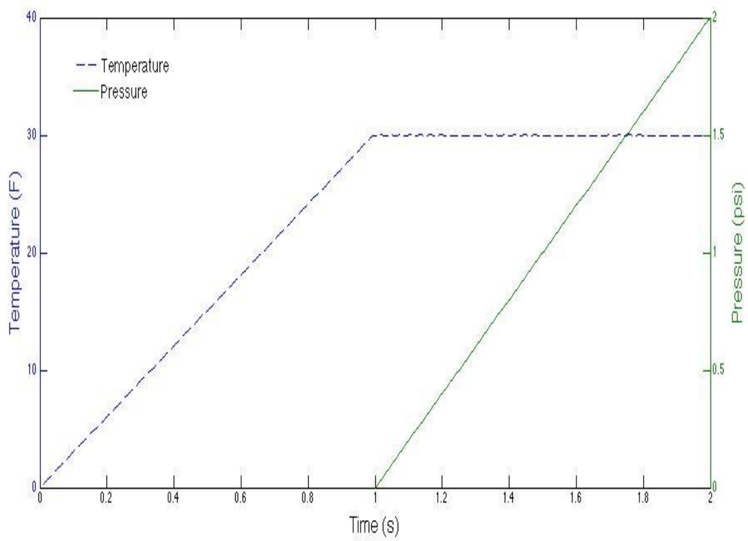

Figure 6. Amplitude of pressure and temperature loading profile

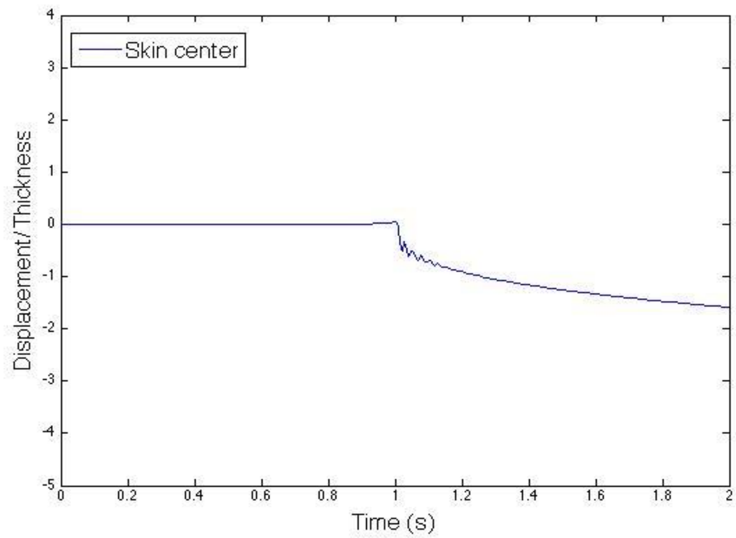

Figure 7. Response of skin panel when ΔT =30 ° F, Pressure/ Time = 2

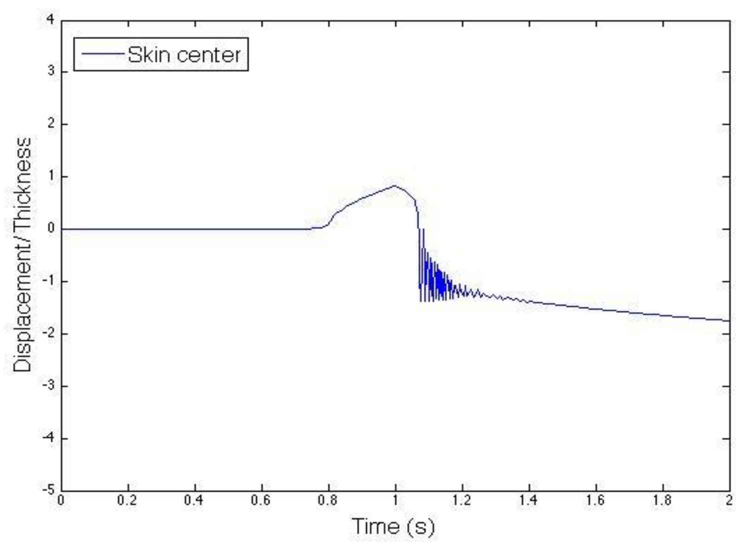

Figure 8. Response of skin center when ΔT =38 ° F, Pressure/ Time = 2

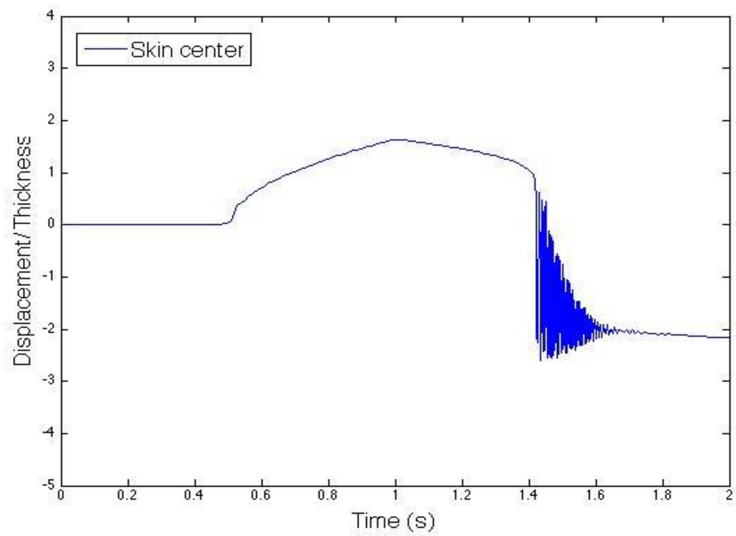

Figure 9. Skin center response when ΔT =60 ° F, Pressure/ Time = 2

It was observed that snap-through and snap-buckling could occur for a combined loading scenario. Various temperature and pressure case are considered as shown in Table 2. Temperature is linearly increased to a predefined value listed in Table 2 in [0-1 s] and then kept constant in the [1-2 s]. Also, the pressure is applied during [1-2 s] and increases linearly to predefined values in Table 2. This loading profile is shown in Fig. 6. Skin panel center is used to observe unstable response. When ΔT =30 ° F, which is lower than the first critical thermal buckling temperature (30.392 ° F), pressure with magnitude of 0.00988 psi can make the panel suddenly snap to a lower position, which corresponded to half of the thickness of the panel as in Figure 7 even if the panel is not initially thermally buckled. The natural frequency was also found to drop to zero when snap-through occurred. The configuration of the panel is still symmetric so that no snap-buckling occurred. When ΔT =38 ° F, which is between first and second thermal buckling temperature, when pressure increases to 0.13 psi, the panel jumps to a position, which is corresponds to 1.5 times the thickness (Figure 8). After that, oscillation was also observed and last about 0.15 second. The configuration of skin panel is also symmetric when and after it loses stability. When ΔT =60 ° F, which is between the second and third critical thermal buckling temperature, at critical pressure magnitude 0.85 psi, the panel snap to a position, which is approximately 2 times the thickness (Figure 9). A significant transient response is seen. In this case, two additional references points are also used to observe the snap-buckling behavior, which are respectively located between the leading edge and skin center, trailing edge and skin center. The responses of these two points are shown in Figure 10 (a) and (b), where Figure 10(b) shows enlarged view of the snap-buckling highlighting transient oscillations. It is obvious that two references points move out of phase to each other during snap-buckling and oscillation. The configuration of panel is transformed from symmetric mode to asymmetric mode when snap-buckling occurred and is still changing during oscillation and then is transformed to symmetric mode again.

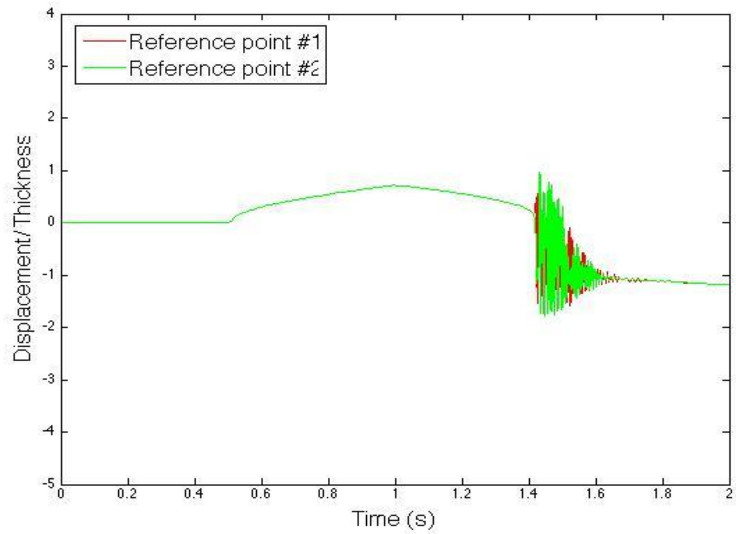

Figure 10(a). Reference points response when ΔT =60 ° F, Pressure/ Time = 2

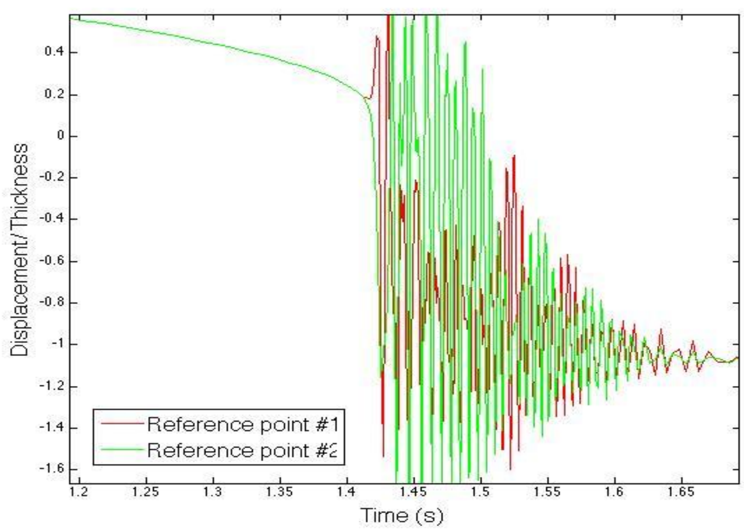

Figure 10(b). Reference points response when ΔT =60 ° F, Pressure/ Time = 2

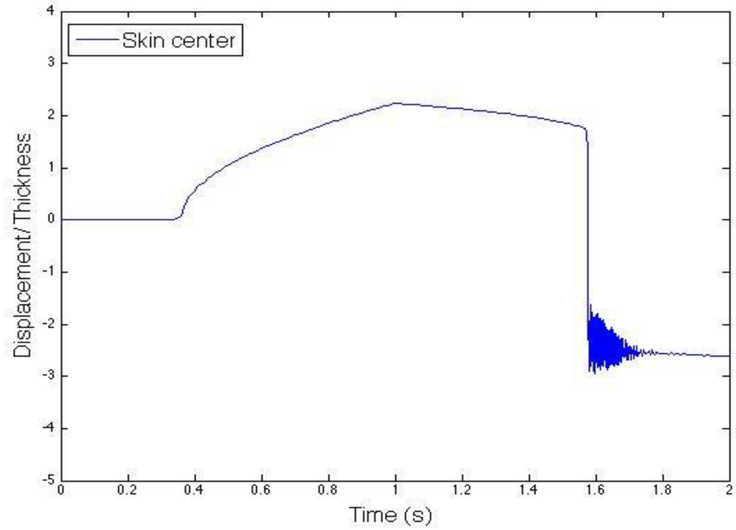

Figure 11. Skin panel response when ΔT =85 ° F, Pressure/ Time = 2

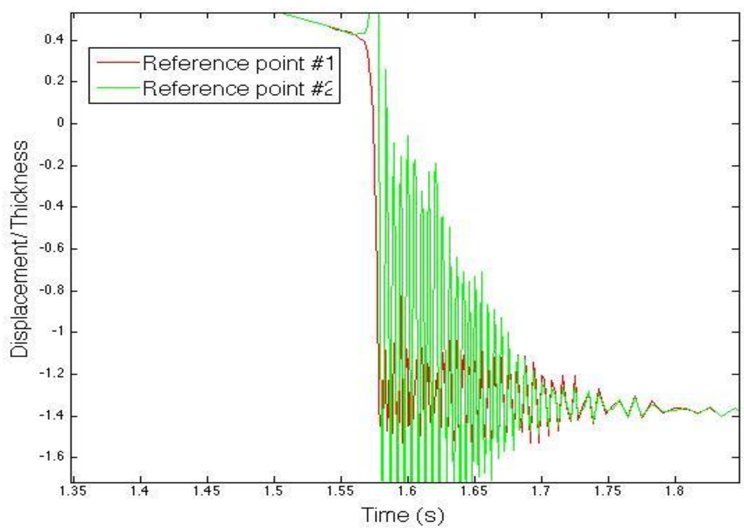

Figure 12. Reference points response when ΔT =85 ° F, Pressure/ Time = 2

Another case was performed when ΔT =85 ° F, which is between the third and fourth critical thermal buckling temperature. Under the effect of pressure on top surface, the response of skin center is shown in Figure 11. Two reference points exhibit different response and asymmetric deformed shapes were also observed during snap-buckling shown in Figure 12.

Table 3. Comparison of results when ΔT = 85 ° F

Pressure/Time	End Displacement / Thickness			Max amplitude of oscillation / Thickness			Duration of oscillation (s)
	Skin center	Ref Pt.1	Ref Pt.2	Skin center	Ref Pt.1	Ref Pt.2	
2	**-2.615**	**-1.43**	**-1.43**	**1.5**	**0.7**	**2**	**0.1**
4	**-2.86**	**-1.66**	**-1.66**	**2.5**	**3.2**	**1.2**	**0.2**

The ratio of pressure and time, which equals to 4, was also considered. The comparison of these two cases when ΔT = 85 ° F are listed in Table 3. It is shown that larger ratio of pressure and time results in larger displacement. In addition, transient oscillations also increases in severity as the pressure is increased to a larger value.

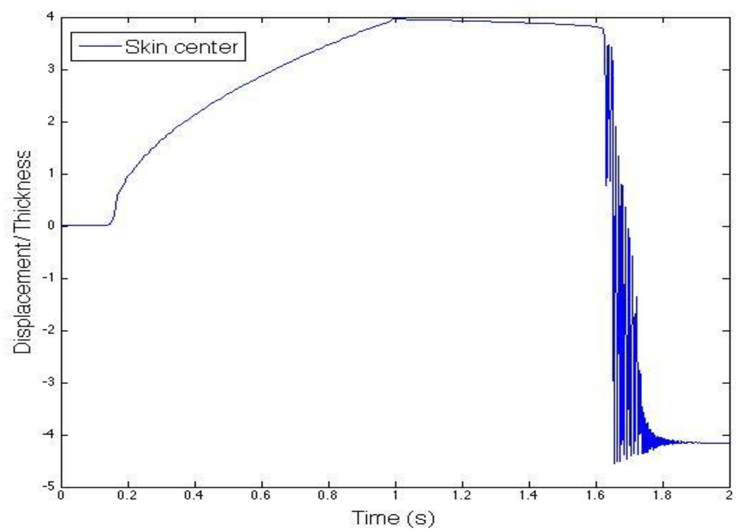

Figure 13. Reference points response when ΔT =200 ° F, Pressure/ Time = 2

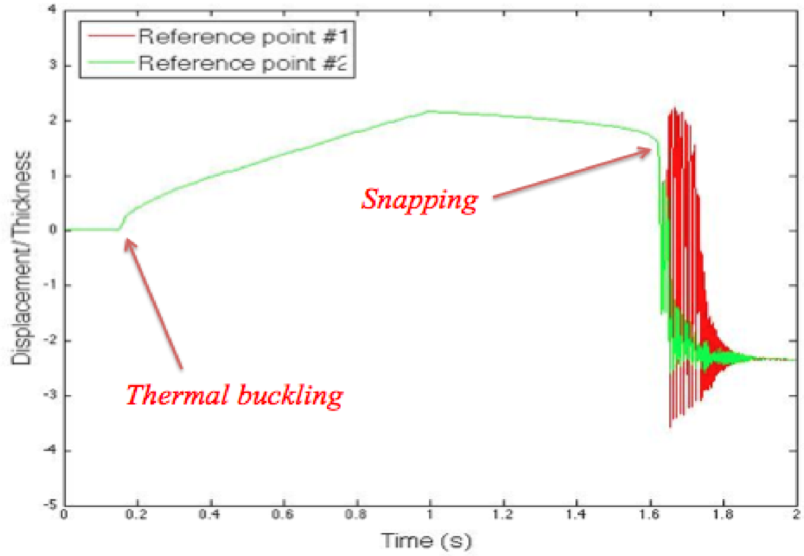

Figure 14(a). Reference points response when ΔT =200 ° F, Pressure/ Time = 2

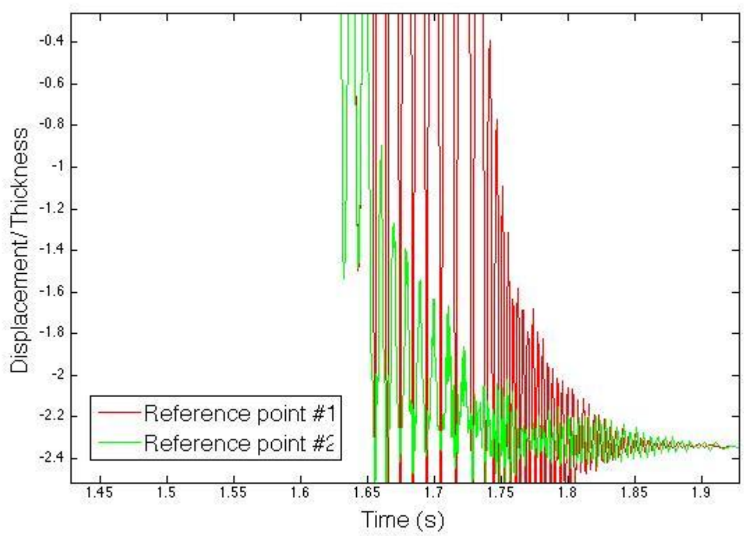

Figure 14(b). Reference points response when ΔT =200 ° F, Pressure/ Time = 2

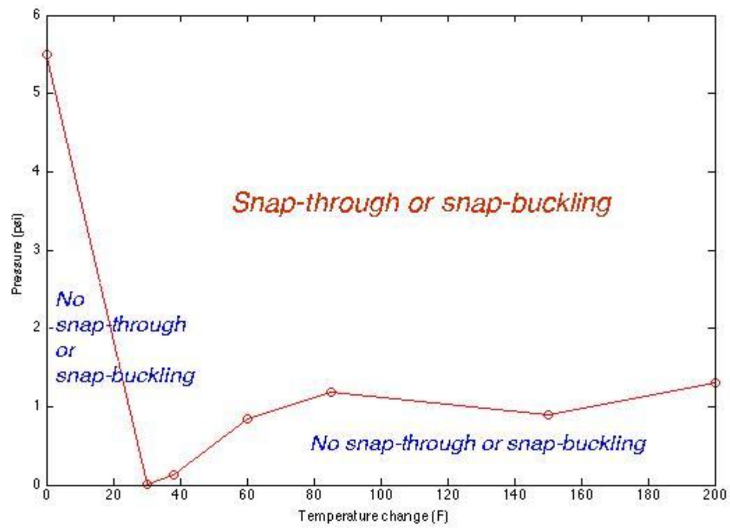

Figure 15. Boundary of snap-through and snap-buckling

At ΔT =200 ° F, it is seen from Figure 13 that snap-buckling occurred at approximated 1.65 s.

Responses of two reference points are shown in Figure 14. As in previous case, asymmetric configuration was observed during snap-buckling and oscillation. Compared to previous case, it was found that larger static pressure amplitude does not greatly effect the magnitude and duration of transient oscillation during and after snap-buckling as shown in Table 4.

Table 4. Comparison of results when ΔT = 200 ° F

Pressure/Time	End Displacement / Thickness			Max amplitude of oscillation / Thickness			Duration of oscillation (s)
	Skin center	Ref Pt.1	Ref Pt.2	Skin center	Ref Pt.1	Ref Pt.2	
2	-4.15	-2.35	-2.35	6	5	2.5	0.2
4	-4.28	-2.52	-2.52	6	5	2.5	0.2

Based on the results above, a boundary of snap-through and snap-buckling behavior of the skin panel can be found and is shown in Figure 15. Without thermal loading, the panel may buckle when pressure increases to about 5.5 psi. When the skin panel is thermally buckled, exceeding a critical pressure value may result in snap-through or snap-buckling behavior. As the heating temperature increases, the critical pressure also increases. The configuration of the panel gets asymmetric when heating temperature is high.

5. Coupled temperature-displacement skin panel analysis

To understand the effect of boundary condition on the nonlinear response of the skin panel, six boundary condition cases are proposed and are shown in Table 5. Boundary condition case A and B are clamped type boundary condition. In case A, two flanges at both leading and trailing edge are constrained in rotation and z-translation but two edges are set free. However, in case B, two edges are also constrained in the same way. Aside from clamped type boundary condition, spring type boundary conditions were also considered. Same as case A, the flanges are constrained in rotation and x-translation. In addition, seven linear springs are assigned on both leading and trailing edge. In each case, different stiffness value of springs were included and are respectively10%, 20%, 50%, and 100% of the product of elastic modules and the thickness of the panel in order to find out the effect of stiffness value on the panel response.

Table 5. Boundary condition cases

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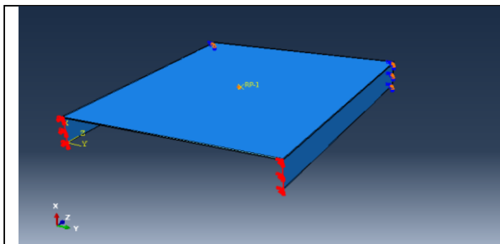
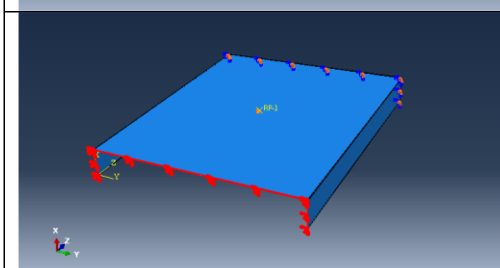
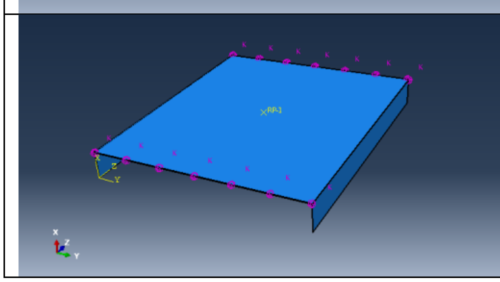
<tr><td></td><td colspan="3">Case A
Cross-sections of two flanges are constrained in rotation and z-translation.</td></tr>
<tr><td></td><td colspan="3">Case B
Cross-sections of flanges and two edges are constrained in rotation and z-translation.</td></tr>
<tr><td rowspan="4"></td><td rowspan="4">Flanges are clamped same as Case A.</td><td>Case C</td><td>K = 184600 lbs/in (10%)</td></tr>
<tr><td>Case D</td><td>K = 369200 lbs/in (20%)</td></tr>
<tr><td>Case E</td><td>K = 932000 lbs/in (50%)</td></tr>
<tr><td>Case F</td><td>K = 1846000 lbs/in (100%)</td></tr>
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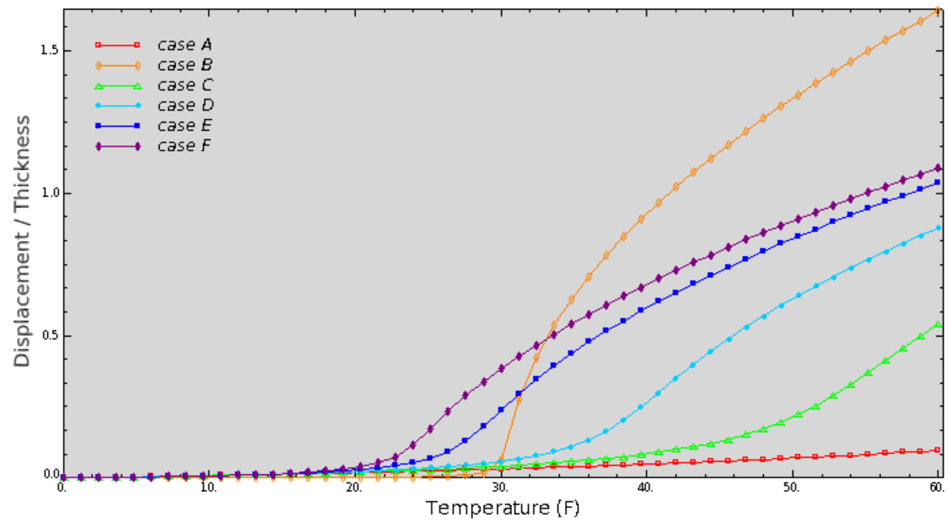

Figure 17. Displacement of skin panel center versus temperature change

Transient coupled temperature-displacement analysis was performed for all six proposed boundary cases. Second-order element C3D20T was used. Skin panel center was used to observe the transient behavior under thermal loading.

Transient thermal analysis of panel for case A and B were performed first and thermal buckling was observed. From Figure 17, we can see that panel in case B buckled suddenly at a relatively low temperature change, 30 °F degree. Since the panel is constrained only at flanges in Case A, the displacement of the skin center increases slowly as the temperature goes up and buckled at a relatively high temperature (ΔT =100 °F). The comparison of case A and B concludes that the boundary condition at two edges of the panel makes a significant effect on the critical temperature and response of the panel due to thermal loading.

For spring type boundary condition cases from C to F, with larger stiffness value of springs, the panel would buckle at a lower temperature. For instance, case C, where 10% spring is used buckled at approximately 55 °F but for case F, where 100% spring is used, the panel buckled even earlier than case B at approximated 25 °F This comparison of these results may conclude that the boundary condition at leading and trailing edges make a significant effect on the thermal buckling temperature and response of the panel and as the stiffness of the constraints at two edges increases, the critical buckling temperature will decrease.

6. Conclusion

This paper presents part of author's recent work related on nonlinear response of the skin panel under combined loading condition. Based on the results above, following conclusion can be derived:

i) The skin panel may exhibit symmetric and asymmetric mode under combined loading condition.

ii) When the panel thermally buckled at higher temperature, it will snap to lower position with larger amplitude of oscillation under same pressure loading.

iii) When ΔT is high, the transient response is significant.

Future work includes applying coupled static and dynamic thermal-mechanical loading on the structural based on trajectory of the mission.

7. References

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