ANALYSIS IMPLEMENTATION, VERIFICATION, VALIDATION AND PERFORMANCE OF A STRUCTURALLY-INTEGRATED TPS CONCEPT

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1. ABSTRACT

This paper describes the analysis implementation of a structurally-integrated thermal protection system (SITPS) concept in the HyperSizer structural sizing software. The software development is focused on integrating structural and thermal analysis methods for vehicle-level design of Highly Reliable Reusable Launch Systems (HRRLS) under the NASA Fundamental Aeronautics program. The unique feature of the SITPS concept is the AETB ceramic core which acts as an insulator between the hot outer surface and the cooler inner surface of the panel. The structural analysis is accomplished using panel homogenization. This results in an effective constitutive equation for the SITPS panel that is suitable for use in a full vehicle-scale finite element analysis. The thermal analysis of the SITPS concept is accomplished using an existing 1-D thermal analysis model that discretizes the structure and insulation into a series of thermal resistors and masses. Vehicle level sizing studies are included to compare the performance of SITPS to Gr/Ep and Al 2219 honeycomb sandwich concepts with traditional TPS shielding. These studies are used to establish accurate weight statements for a hypersonic SITPS vehicle concept. FEA verification is included in order to assess the accuracy of HyperSizer's eigenvalue predictions. Finally, the 1-D thermal analysis is validated by comparison of the results to published experimental data.

2. INTRODUCTION

During a three year NRA contract, Collier Research developed improved structural and thermal analysis methods for the design of a structurally-integrated TPS (SITPS) concept. The target application for this effort is the automated sizing of both stages of two-stage-to-orbit, air-breathing launch vehicle. The first stage must reach Mach 10 before flying back to base and the second stage is boosted out of the atmosphere and then re-enters at speeds exceeding Mach 25. This class of mission presents significant challenges in aerothermodynamics, structures and materials, and full-vehicle system integration. The SITPS panel concept, illustrated in Figure 1, is especially suited for hypersonic vehicle applications where the external aeroshell experiences mild aerodynamic loading and high temperatures during reentry. Due to its structural and thermal capability, the SITPS concept is potentially lighter weight and more durable than traditional panel concepts with external thermal insulation.

2.1 Description of Structurally Integrated TPS

Figure 1 illustrates the structurally integrated TPS (SITPS) panel concept. The unique feature of the SITPS concept is the Alumina Enhanced Thermal Barrier (AETB) ceramic core which acts as an insulator between the hot outer surface and the cool inner surface. The “hot” facesheet consists of a ceramic-matrix composite (CMC) while the bottom facesheet is a polymer-matrix composite (PMC). Rigid insulation bars are wrapped with CMC composite plies and stacked between the facesheets creating the stiffening core and directional stiffening webs.

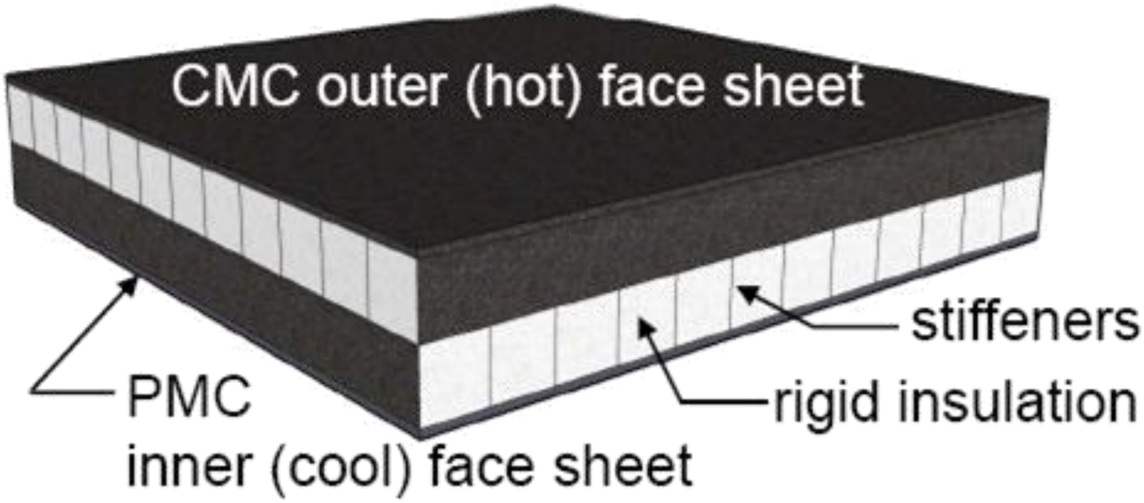


Figure 1. SITPS concept. The rigid insulation bars used in the current study are AETB ceramic insulation. The wrapped bars are stacked in a 0°/90° configuration. The entire stack is co-cured with the outer, CMC face sheet and a PMC bottom face sheet is bonded to the panel.

The potential benefits of a structurally integrated TPS concept over more traditional, parasitic TPS with cold structure are:

- In highly heated, low stressed areas of a re-entry vehicle, the SITPS can be less weight than a structure with a parasitic TPS
- SITPS may potentially be much more durable than traditional, parasitic, external thermal insulation

While showing promise, there are substantial design challenges associated with an structurally integrated TPS system. These include:

- CMC and PMC stiffness and allowable properties are very different from each other, creating highly asymmetric panel designs

- CMC is very brittle and possesses high stiffness, as well as a low strain allowables. As a result, the CMC material system performs very poorly in material strength.

3. IMPLEMENTATION

HyperSizer analyzes stiffened panels comprised of arbitrary composite laminates through stiffener homogenization, or “smearing”, techniques [1]. The result is an effective constitutive equation for the stiffened panel that is suitable for use in a full vehicle-scale finite element analysis. A key assumption for the thermo-elastic formulation of the SITPS panel concept is that the foam or insulation of the core does not affect the overall panel membrane stiffness and is completely ignored during the in-plane stiffness formulation.

The thermal analysis of the SITPS concept was accomplished using the existing 1-D thermal analysis model in the HyperSizer TPS analysis module. This analysis discretizes the structure and insulation into a series of thermal resistors and masses as shown in Figure 2.

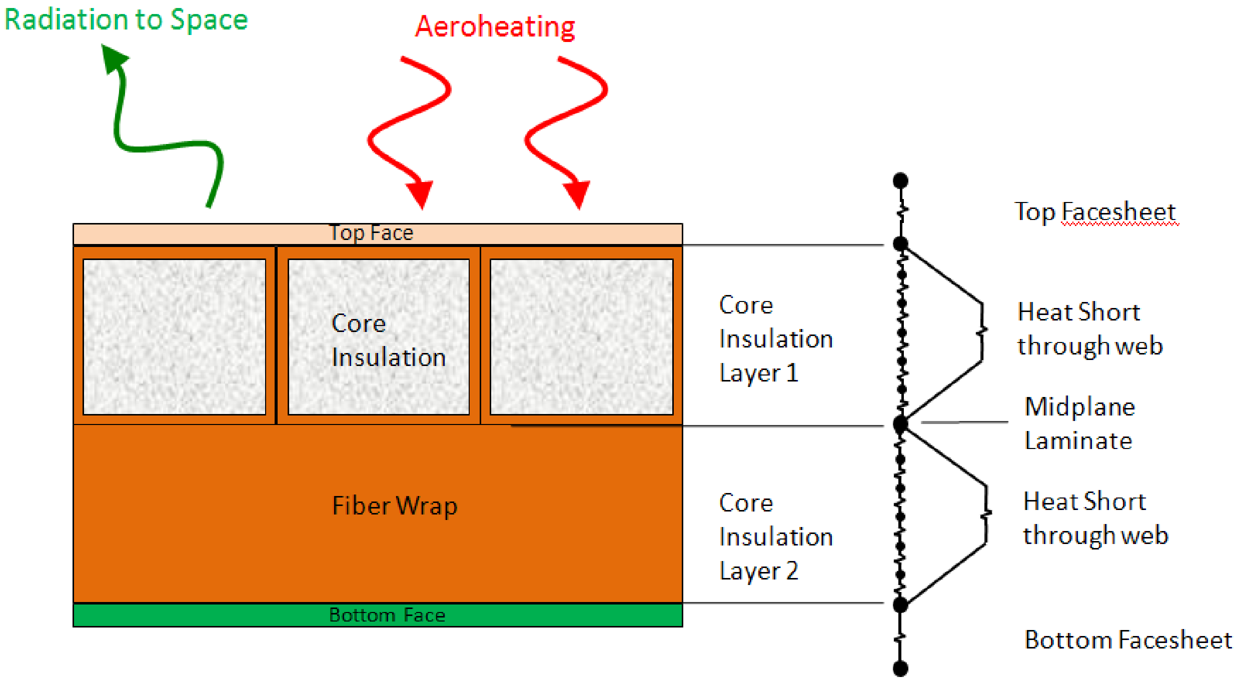


Figure 2. One-dimensional finite element thermal model of the SITPS panel. The facesheets and insulation were modeled as a series of thermal resistors and masses. The CMC insulation wraps were modeled as “heat shorts” or parallel heat paths around the insulation. The midplane was modeled as a lumped mass.

For this modeling technique, the mid-plane laminate is treated as a lumped mass in the TPS stack, able to absorb energy and slow the soak of energy through the TPS. Overall, this makes the TPS more thermally efficient. The validation studies presented in section 4 confirmed that the effect of the midplane on the TPS performance was substantial.

3.1 Sizing Variable Description

The sizing variables for the SITPS concept are illustrated in Figure 3.

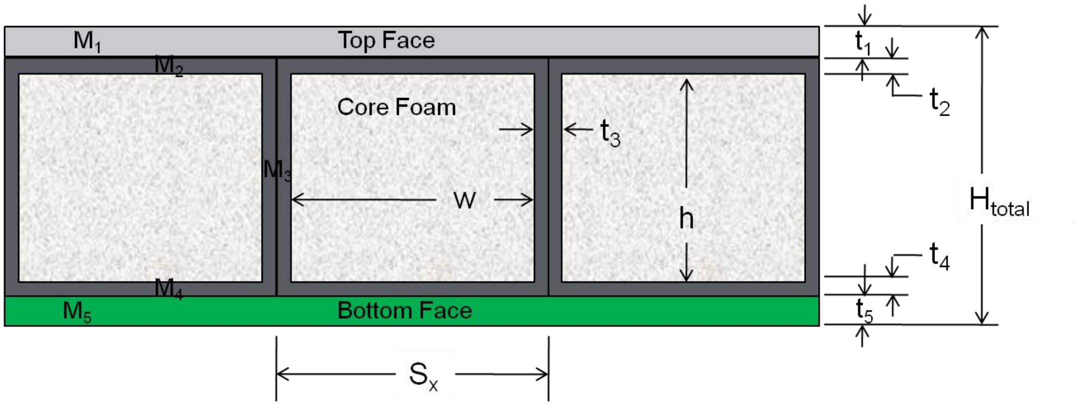


Figure 3. Sizing Variables for SITPS Concept

Variable	Description	Variable Name	Material
1	Top Face Thickness	t_1	✓ M_1
3	Web Thickness	t_3	✓ M_3
5	Bottom Face Thickness	t_5	✓ M_5
6	Web Spacing	S_x	
7	Panel Height	H_{Total}	✓ M_{foam}
	Dependent Variables		
2	Top Overwrap Thickness	$t_2=t_3/2$	✓ M_2
4	Bottom Overwrap Thickness	$t_4=t_3/2$	✓ M_4
9	Insulation Width	$w = S_x-t_3$	
10	Insulation Height	$h = H_{total}-(t_1+t_2+t_4+t_5)$	

There are two types of sizing variables represented: those that are independent and specified by the user and those that are functions of other sizing variables. Equations for the dependent variables are specified in the above table. The relationships between the independent and dependent materials are written qualitatively as:

Independent Materials

M_1	Top Face Laminate
M_3	Web Laminate
M_5	Bottom Face Laminate
M_{core}	Foam/Insulation material

Dependent Materials

M_2	Top overwrap laminate, assumed to be ½ of the M_3 laminate
M_4	Bottom overwrap laminate, assumed to be ½ of the M_3 laminate

3.2 Analysis Methods

Collier Research has developed improved structural analysis methods for the design of structurally-integrated TPS concepts [2]. These improved methods address the in-plane and out-of-plane deformation of the TPS due to thermal expansion. Additionally, they are capable of assessing the structural effectiveness and thermo-mechanical response of the integrated panels. The failure methods identified as applicable to the SITPS concept are listed in Table 1.

Table 1. Failure Modes for Structurally Integrated TPS Panel Configuration

Mode	Component(s)	Description/Method
Panel Buckling	Panel	• Based on panel-level ABD stiffness matrix and panel transverse shear flexibility (TSF) • Web and insulation homogenized to obtain panel TSF
Local Buckling	Web, Facesheets	• Plate with simple support on all edges • Fourier series solution of plate PDE, including N_y/N_x ratio • Support from insulation to web and facesheet included as buckling on an elastic foundation
Composite Strength	Web, Facesheets	• Based on loads (N, M, Q) on panel • Panel level Q goes into the web as in-plane shear force, N_{xy} • Insulation ignored for in-plane loads and bending moments • Many standard composite failure criteria (max stress/strain, Tsai-Hill, Hoffman, etc.)
Facesheet Wrinkling	Web, Facesheets	• Based on normal loads (N) in object • Core stiffness included in calculation of critical wrinkling stress • Interaction of X and Y wrinkling stresses
Crushing	Core	• Due to pressure crushing panel – localize P to determine crush stress in insulation, compare to allowable • Crush stress localized between insulation and web
Shear Crimping	Core	• Short wave buckling • Considers web and insulation to be a single homogenized core • Based on through-thickness shear moduli of core
Shear Strength	Foam	• Due to through-thickness shear force on panel, Q_x and Q_y • Localized to determine relative shear stress in web and shear stress in insulation • Compare shear stress in insulation to allowable stress • Check Q_x, Q_y, quadratic interaction

3.2.1 Out-of-plane loads

Though the SITPS sandwich has web reinforcements that provide out-of-plane (Qx and Qy) load paths, the out-of-plane shear load into the foam core material is a concern and potential failure mode. For this reason, HyperSizer uses a rule of mixtures approach for quantifying the out-of-plane (Qx) load path sharing between the web and the foam core [2]. The web is a more structurally efficient means for the SITPS to support out-of-plane load (Qx). However, in the transverse panel direction, without having a web running in this direction, the sandwich can only take a minimal amount of Qy load.

3.2.2 Buckling stability of the web

For typical HyperSizer panel concepts, local buckling of an analysis object is quantified using plate buckling equations with simple-simple boundary conditions. However, in the case of the SITPS panel, all of the local buckling objects are assumed to be reinforced by the rigid insulation core material. This complicates the buckling analysis from a simple flat plate buckling analysis to that of plate buckling on an elastic foundation. A method based on (Timoshenko, 1961) [3] was implemented to handle both normal (N_x, N_y) and shear (N_{xy}) buckling on each analysis object based on this method.

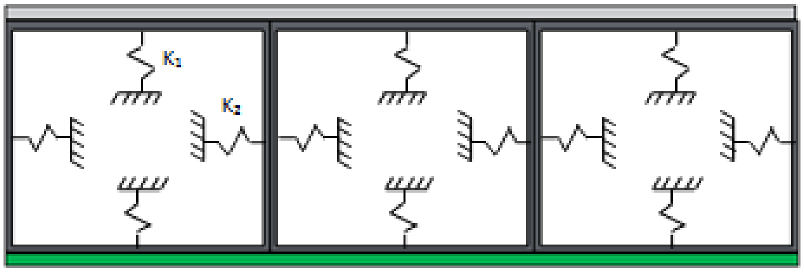


Figure 4. The local buckling objects of the panel are supported by the insulation material. The buckling analysis is performed by substituting the insulation with a spring constant K, which is a function of the modulus of the insulation and the spacing of the webs. Note that the webs are supported on both sides by insulation, whereas the top and bottom facesheets are only supported on one side, therefore the spring constant on the webs is multiplied by a factor of 2.

The solution for local buckling on an elastic foundation is based on the general governing partial differential equation for in-plane loading effects.

$$D_{11}\frac{\partial^4 w}{\partial x^4}+4D_{16}\frac{\partial^4 w}{\partial x^3\partial y}+2(D_{12}+2D_{66})\frac{\partial^4 w}{\partial x^2\partial y^2}+4D_{26}\frac{\partial^4 w}{\partial y^3\partial x}+D_{22}\frac{\partial^4 w}{\partial y^4}+Kw=N_x\frac{\partial^2 w}{\partial x^2}+N_y\frac{\partial^2 w}{\partial y^2}+2N_{xy}\frac{\partial^2 w}{\partial x\,\partial y} \qquad [1]$$

Where the pressure has been written as a stiffness *K* of the foundation, times the plate deflection, *w*. Two methods for determining the value of *K* have been implemented. An effective stiffness approach, based on the modulus and width of the foam and a second approach suggested by Hetenyi [4], based on the modulus of the foam and the flexural stiffness of the web. Three solutions are obtained using this method, these three solutions are the buckling solution for pure shear loading, and buckling for pure uniaxial loading in the N_x or N_y direction [2]. For the case of combined N_x, N_y, N_{xy} loading, the buckling margin of safety is determined using a quadratic interaction equation.

3.2.3 FEA Sensitivity and Verification Studies

Parametric studies were performed to assess the impact of cross-section geometry and insulation foam stiffness on the local buckling of the web [5]. Results are shown in Figure 5 in terms of percent difference between the analytical solution and linear FEA eigenvalues. Analytical predictions were performed with *K* set equal to zero. We see that the correlation is sensitive to the foam stiffness but rather insensitive to the relative cross-section geometry.

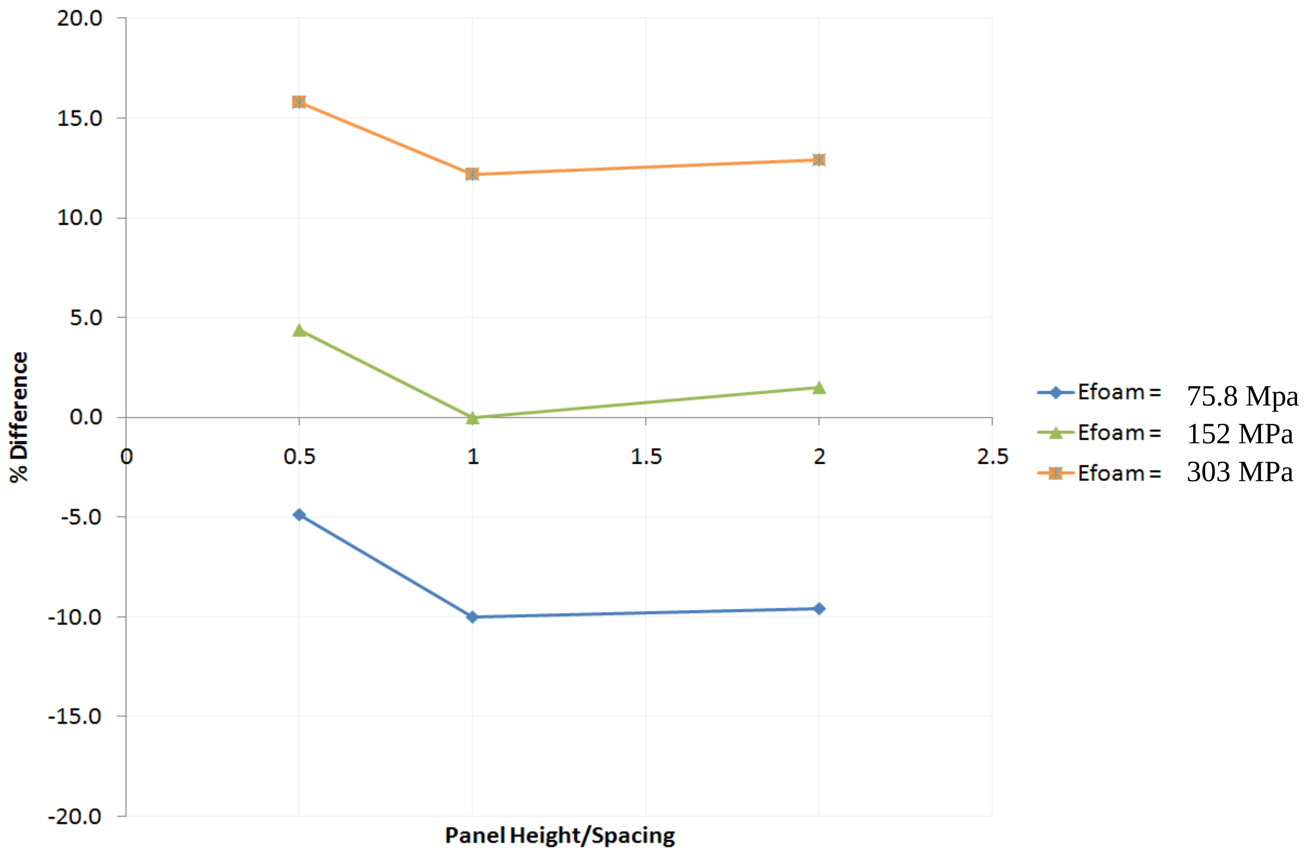


Figure 5. Difference between FEA and analytical predictions (K = 0) as a function of cross-section geometry and foam stiffness. Notice the sensitivity of the buckling eigenvalue to the foam stiffness.

3.2.4 Material Strength of the Ceramic Laminate

Though it has excellent high temperature capability relative to widely used polymer composite materials such as graphite/epoxy (IM7-977-2). The material strength of the CMC comprised of Hi-Nicalon™ fiber in a SiC matrix is quite weak. Strain and stress allowables of this CMC are at most ½ of those of PMC [2].

3.2.5 Synergistic Sizing Approach

A synergistic sizing approach is defined by the simultaneous sizing of a structure to mechanical and thermal loading to obtain a minimum weight "system" design [6]. For synergistic sizing, heat loads are input as a temperature profile and mechanical load sets are defined at a single point in the flight trajectory. For the structural analysis, the reference temperatures and thermal gradients are extracted for each mechanical load set based on the defined time in the trajectory and the optimum TPS configuration. The amount of synergy depends on where in the time dependent temperature profile the loading occurs. In some cases, for a synergistic sizing the system weight can be more than 10% lighter than the “best” uncoupled result.

4. VALIDATION

The 1-D thermal analysis approach was validated with published test data [6]. The primary objective of the test validation was to compare HyperSizer's 1-D thermal analysis to published experimental data for a typical HRRLS thermal load profile and NASA 1-D thermal predictions [7]. The test specimen used to validate HyperSizer’s 1-D thermal model is shown in Figure .

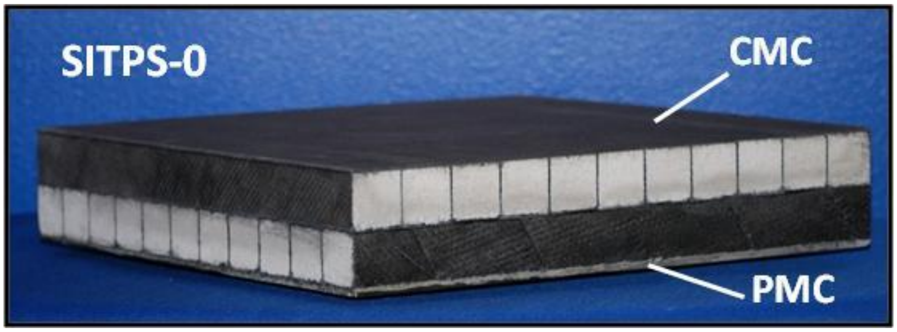


Figure 6. SITPS-0 test specimen, overall dimensions 292mm x 292mm x 57.15mm. 25.4 x 25.4 mm AETB-16 bars, wrapped with SiC fabric. PMC bottom facesheet bonded to panel.

Six total tests were reported [7]. The test conditions are summarized in [6]. The test configuration is illustrated in Figure 7.

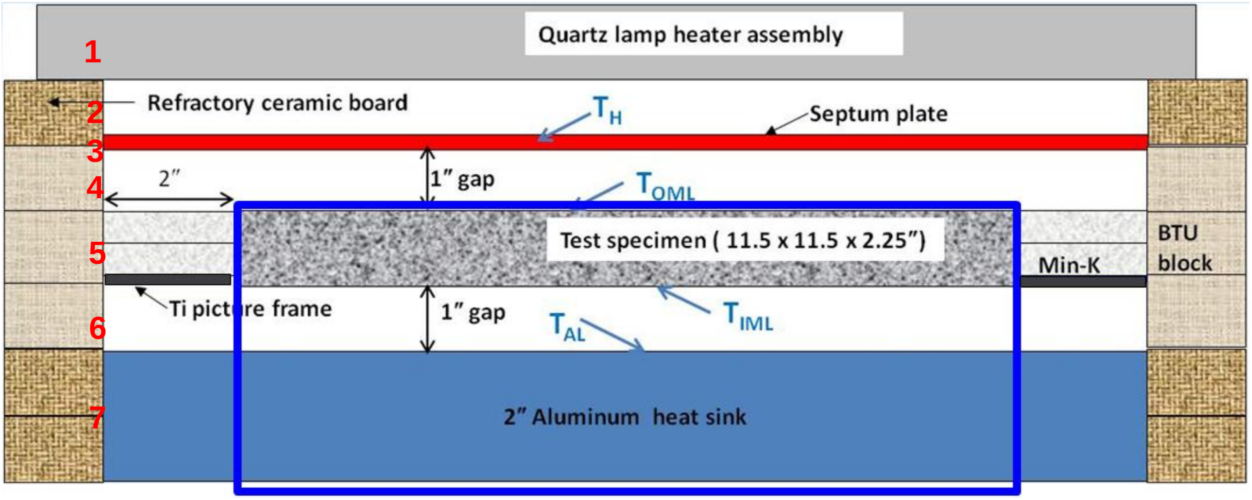
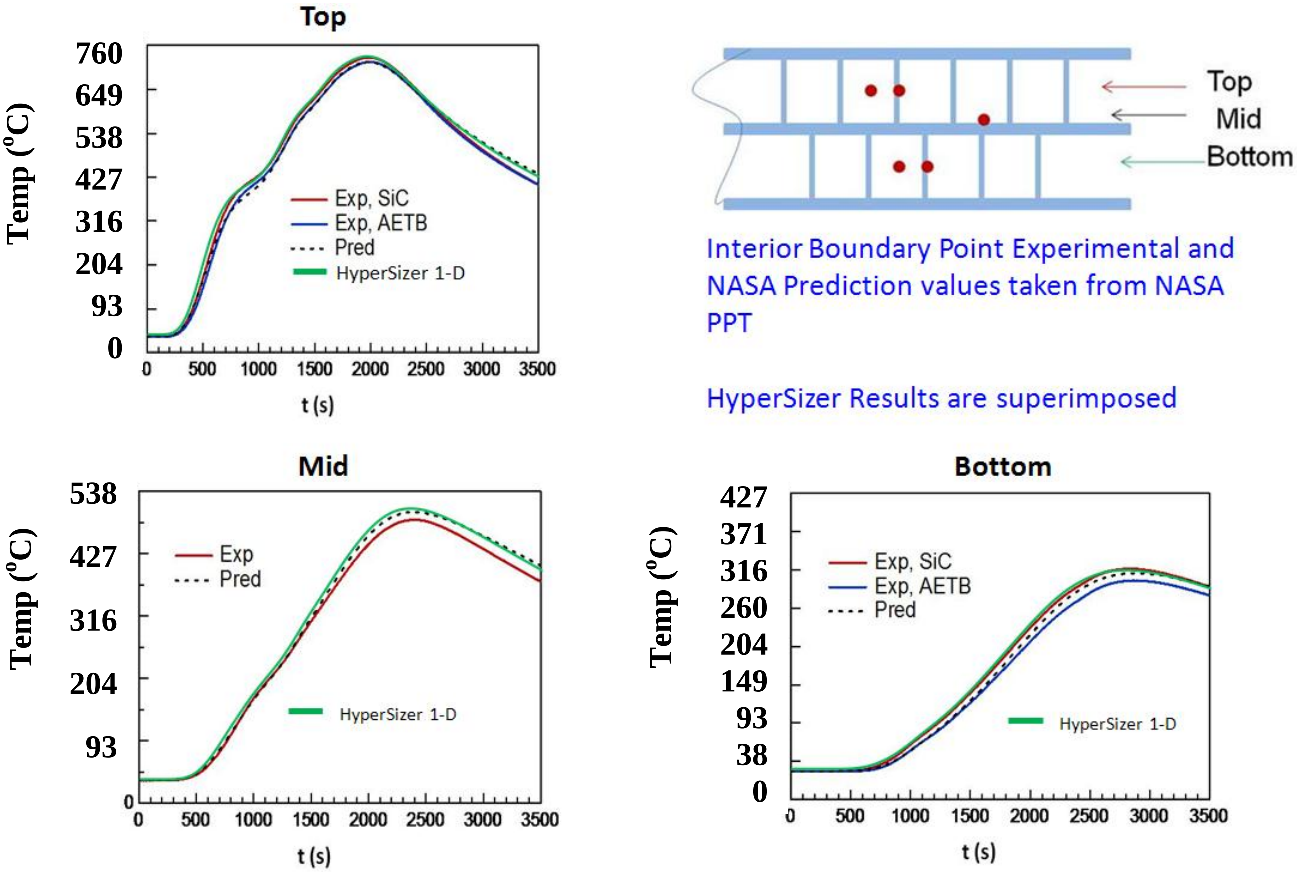


Figure 7. SITPS-0 test configuration. During the test, the heater heats up the septum plate, which radiates to the surface of the TPS test specimen. The OML surface temperature is measured to obtain a temperature vs. time heating profile and is imposed as a boundary condition to the analysis model.



Interior Boundary Point Experimental and NASA Prediction values taken from NASA PPT

HyperSizer Results are superimposed

Figure 8. HyperSizer and NASA test predictions through the thickness of the TPS. The temperature profile in the upper left represents a point in the midplane of the upper insulation. The profile in the bottom left represents the temperature at the midplane laminate and the profile in the lower right represents a point in the midplane of the lower insulation.

In Figure 8, the solid red lines show the temperature measurements for the SiC laminate. The point represented by red line is midway between the midplane laminate and the IML. This thermocouple is in the sidewall laminate. The blue lines show the temperature measurements for the AETB insulation. The point represented by the blue curve is vertically in the same position as the red line, however, this thermocouple is in the insulation away from the sidewall laminate. Neither the HyperSizer nor the NASA 1-D predictions make the distinction between these red and blue lines.

The green lines are HyperSizer's predictions and the dashed lines are the NASA 1-D predictions [7]. Both the NASA and HyperSizer 1-D predictions show of accuracy compared to this test data. The conclusion of the test correlation was that HyperSizer's 1-D thermal prediction is sufficiently accurate when compared to test data to go forward with the vehicle-level synergistic structure-TPS sizing activity, described in section 5.1.

5. PERFORMANCE

Failure envelopes of a demonstration SITPS design [2] were generated using HyperSizer. These failure envelopes quantify the load carrying capability of the panel under a combination of loads. They are useful in evaluating the relative structural performance of a panel design. The failure envelope represents four quadrants of loading. The upper right is a tension-tension loading and the bottom left a compression-compression loading. The bottom right is tension axial load (N_x) and compressive transverse load ($-N_y$). Three envelopes are for three different values of shear loading: 0%, 50%, and 100%. As shear load is increased, the axial and transverse allowables are reduced. The diamond markers represent results at room temperature and the square markers for elevated temperatures (1300 °C/2372F). As expected, a reduction in allowable strength can be observed.

These failure envelopes include structural failure modes such as: material strength based on damage tolerant allowables; and Tsai-Hahn quadratic stress criteria and max strain criteria; local buckling of the webs on elastic foundations; core crimping; etc. Figures 9 and 10 represent the load carrying capability of the panel for a 760mm panel span at the provided reference temperatures (22.2 deg and 1300 deg).

SITPS Demonstration Panel [2], Design (Proportional) Limit Material Properties

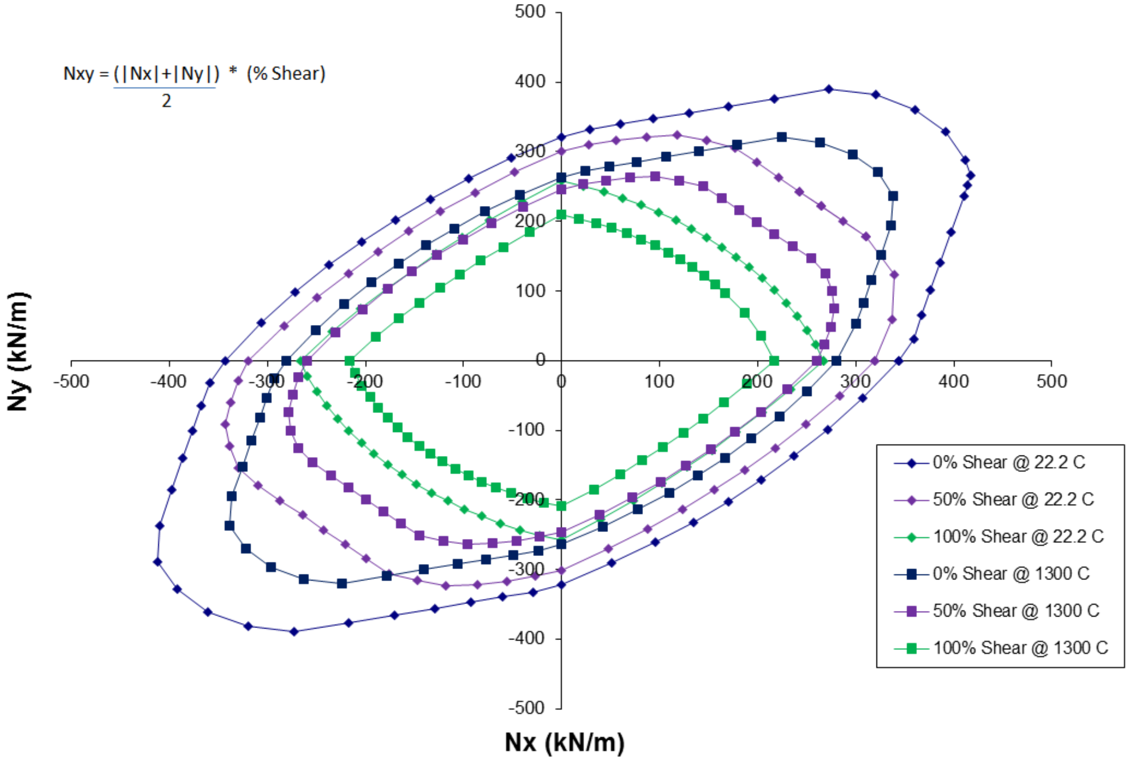


Figure 9. Performance Metric of SITPS with Proportional Limit, linear material data. Note that the benchmark SITPS with a unit weight of 15.9 (kg/m^2) comprised of the CMC laminates and the TPS foam insulation is able to support 262.7 (kN/m) uniaxial loading at 1300 ^{o}C and 332.7 (kN/m) at 22.2 ^{o}C.

SITPS Demonstration Panel [2], Ultimate Limit Material Properties

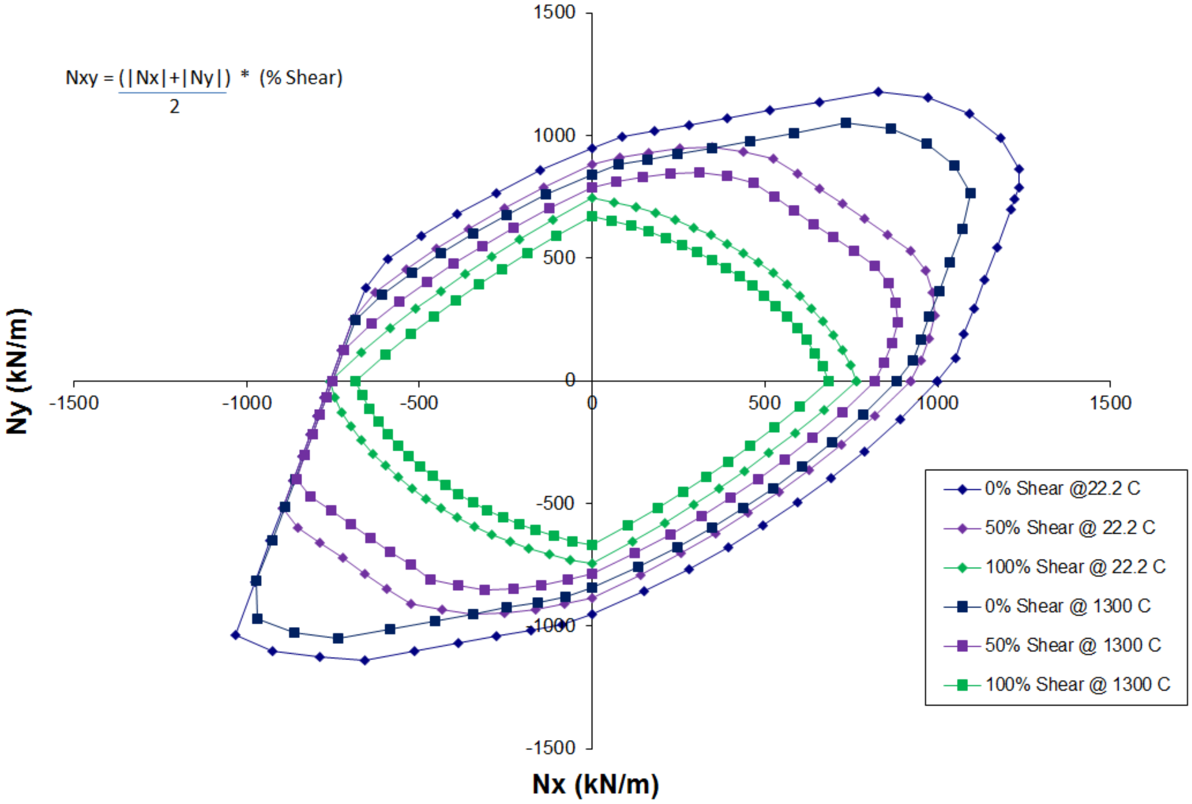


Figure 10. Performance Metric of SITPS with Ultimate Limit, non=linear material data. Using the more aggressive pristine non-linear material allowables the benchmark SITPS with a unit weight of <u>15.9 (kg/m^2)</u> comprised of the CMC laminates and the TPS foam insulation is able to support 805.6 (kN/m) uniaxial loading at 1300 ^{o}C and 945.6 (kN/m) at 22.2 ^{o}C.

5.1 Vehicle Sizing Optimization

Sizing studies of an air-breathing, two-stage to orbit, reusable hypersonic vehicle concept were performed to establish accurate weight comparisons between the SITPS panel concept and a traditional honeycomb sandwich concept with parasitic TPS [8]. The vehicle sizing results, reveal that the SITPS is a weight competitive panel concept for the full vehicle construction. Further studies reveal the high heat, low stressed areas of the vehicle to be as much as 20% lighter as SITPS concept.

5.1.1 Vehicle Dimensions

The vehicle concept for Highly Reliable Reusable Launch Systems (HRRLS) is a two-stage-to-orbit configuration with an air-breathing first stage and a rocket-based upper stage. The sizing studies were focused on the second stage, orbiter vehicle, shown in Figure 11, which is boosted out of the atmosphere in an orbital trajectory. When the orbiter re-enters the atmosphere at around Mach 25, it experiences significant heating loads. Vehicle dimensions for the orbiter are shown in Table 2. The orbiter is comparable in size to the NASA space shuttle orbiter vehicles.

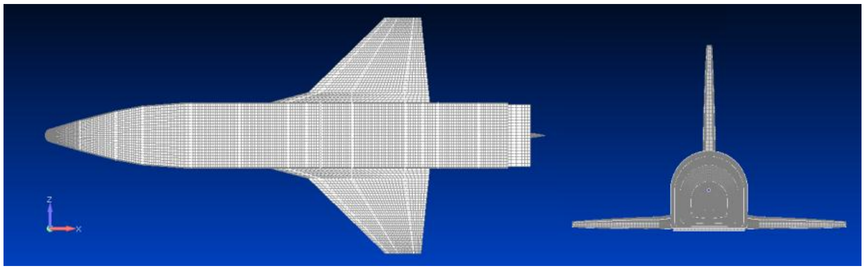


Figure 11. Two-Stage to Orbit (TSTO), second stage orbiter FE model

Table 2. TSTO second stage orbiter vehicle dimensions

Structure	**Dimensions (m)**
Wing Span	18.6
Wing Root Chord	9.6
Wing Tip Chord	2.7
Wing Root Max Thickness	0.7
Wing Tip Max Thickness	0.3
Vertical Tail Span	7.1
Vertical Tail Root Chord	6.4
Vertical Tail Tip Chord	2.0
Fuselage Height	5.2
Fuselage Width	5.0
LH2 Tank Length	14.5
LH2 Tank Height	4.9
LOX Tank Radius	2.4
Total Aero Shell Length	38.6
Structure	Surface Area (m^2)
Wings	188.8
Vertical Tail	64.1
Fuselage	578.2

5.1.2 Total Mass Comparison, all Sizing Studies

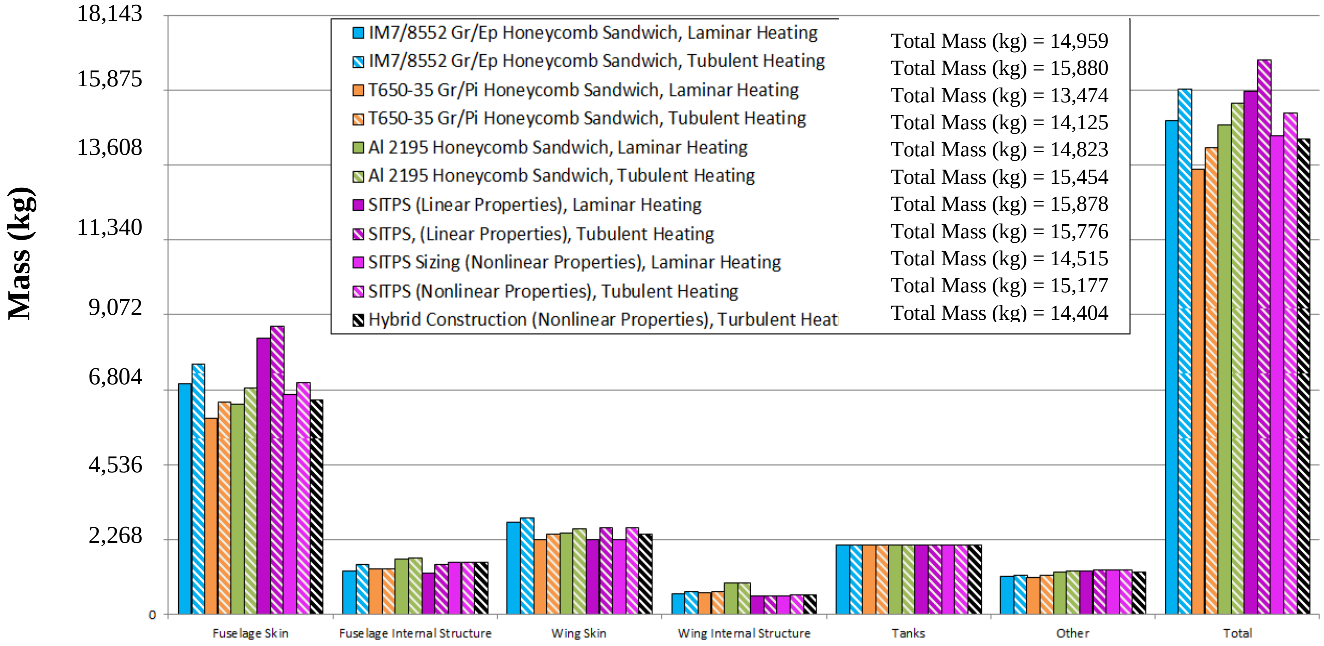


Figure 12. Total mass summary of all vehicle sizing studies.

For the vehicle sizing studies, summarized in Figure 12, SITPS, IM7/8552 Graphite Epoxy sandwich, T650-35 Graphite Polyimide sandwich, and Aluminum 2195 sandwich constructions were considered for the hot, outer aeroshell. Detailed ply layup schedules are provided for the SITPS concept [8]. For the SITPS concept, two sets of material properties were evaluated for the CMC composite to define the upper and lower performance bounds of the SITPS. Ultimate (non-linear) properties were used to approximate the lighter bound of the weight estimate and design (linear) properties are used to approximate the heaviest weight SITPS vehicle concept. For the sandwich concepts, traditional, stand-off TPS is used to handle the applied thermal loads. Three types of TPS are considered, a toughened uni-piece fibrous insulation (TUFI) coated ceramic tile (heaviest), tailorable advanced blanket insulation (TABI), and a low temperature blanket (lightest). Two heating profiles are considered for re-entry, one for laminar flow and the other for turbulent flow. The turbulent profile has substantially higher heating loads than the laminar flow heating profile. As a result, for all structural concepts, the outer aero-shell requires thicker TPS insulation when turbulent heating loads are used.

The sizing results shown in

Figure 12 reveal that the SITPS is a weight competitive panel concept for the full vehicle construction. Further studies reveal the high heat, low stressed areas of the vehicle to be as much as 20% lighter as SITPS concept. With this in mind, a hybrid vehicle construction was explored. The “Hybrid Construction” vehicle concept uses a combination of the SITPS concept in the highly heated areas on the windward side of the vehicle and IM7/8552 Gr/Ep sandwich with traditional TPS on the low heated areas on the leeward side. The "Hybrid Construction" was the lightest vehicle concept in the study, 10% lighter than the Gr/Ep sandwich concept and 7% lighter than the Aluminum sandwich concept.

6. CONCLUDING REMARKS

The outcome of this work is a production-ready analysis and sizing tool for the structurally integrated TPS concept. The structural analysis methods have been verified with FEA. The FEA verification studies reveal the analytical buckling methods accurately predict the buckling characteristics for the SITPS panel concept. Additionally, the 1-D thermal model has been validated with published test data. The conclusion of the test correlation was that HyperSizer's 1-D thermal prediction is sufficiently accurate enough for vehicle-level sizing studies. Sizing studies of an air-breathing, two-stage to orbit, reusable hypersonic vehicle concept were performed to establish accurate weight comparisons between the SITPS panel concept and a traditional honeycomb sandwich concept with traditional TPS. The vehicle sizing results reveal that the SITPS is a weight competitive panel concept for the full vehicle construction. Further studies show the highly heated, low stress areas of the vehicle to be as much as 20% lighter as SITPS concept.

7. REFERENCES

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