INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

Surge Project Report

"Two-Scale Thermo-Mechanical Analysis of Integrated Thermal Protection System Panels for Reusable Launch Vehicles"

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ABSTRACT

We aim at mitigating thermal energy transfer-induced deformations in reusable launch vehicles (RLVs). Launch vehicles experience substantial thermal energy transfer during reentry, leading to thermal expansion and structural deformation, particularly in corrugated panels.
To address this issue, an Integrated Thermal Protection System (ITPS) is employed to impede heat transfer and safeguard various components of the RLV. Leveraging existing data and codes pertaining to the thermal and mechanical behaviors of corrugated structures, our research aims to homogenize these characteristics into a singular plate.
This homogenization process will involve extrapolating the thermal transfer, bending, and other pertinent properties from the complex 3D corrugated structure to a simplified 2D plate configuration. By establishing a mean representation of heat transfer within the plate, our objective is to facilitate the translation of findings onto actual components of the RLV.
Central to our investigation is the transfer of thermal characteristics from a single corrugated structure to a broader segment of the RLV, ensuring enhanced structural integrity and performance under extreme thermal conditions. Through this, we aim to contribute novel insights towards the advancement of thermal management strategies, ultimately bolstering the reliability and resilience of future launch vehicle systems.

1. INTRODUCTION

Today, reducing the extremely high costs of space and air travel is crucial. When a spacecraft enters a planetary atmosphere, it often travels at hypersonic speeds exceeding Mach 20, and sometimes reaching up to Mach 40. These high-energy, high-velocity flights subject the vehicle to intense aerodynamic heating and pressures. To prevent damage from this heating, the vehicle's structure must be adequately protected. The design features that enable a vehicle to withstand such aerodynamic heating and safeguard it from damage are referred to as Thermal Protection Systems (TPS).

Efforts are on to develop a robust load-bearing TPS structure called *Integral Thermal Protection System*, ITPS. The ITPS has both the thermal protection and load-bearing capabilities integrated into one structure.

The main challenge of an Integrated Thermal Protection System (ITPS) is that the needs of a load-bearing structure and a thermal protection system are opposite. A TPS should have low thermal conductivity and withstand high temperatures, which is why ceramic materials are used. However, ceramics have poor structural qualities like low impact resistance and tensile strength. On the other hand, a strong load-bearing structure needs high tensile strength, fracture toughness, and impact resistance, typically found in metals and metallic alloys. These materials have high conductivity and lower temperature limits. Also, strong load-bearing structures are usually dense, making them poor heat insulators, while a good TPS is usually lightweight. The challenge is to create a structure that can do both.

Integrated thermal protection systems (ITPS) for reusable launch vehicles (RLVs) often use a corrugated core sandwich structure, which experiences varying temperatures at different thicknesses depending on its location. The sandwich structure can be optimized for specific locations on the RLV using finite element method (FEM) simulations. However, these simulations can be computationally difficult due to the vast difference in size between the overall RLV components and the detailed features of the sandwich structure. To overcome this, we can simplify the analysis by treating the complex 3D structure as a homogenized 2D plate, making the calculations more manageable.

OBJECTIVE

Our goal is to accurately determine the temperature distribution through the thickness of the 2D unit cell model of the Integrated Thermal Protection System (ITPS). To achieve this, we will apply appropriate heat loads to the model.

Once we have this temperature field, we will use it to perform a detailed unit cell analysis, which involves studying how the material responds to the thermal load. This analysis will help us observe the stress concentration within the 3D unit cell model of the ITPS. By identifying areas where stress is highest, we can better understand potential failure points and make informed improvements to enhance the ITPS's thermal and structural performance.

2. HEAT CONDUCTION IN ITPS

Finite element heat transfer analysis helps determine the peak bottom face sheet temperature, which is required to impose the temperature constraint in the ITPS design optimization, and provides the temperature distribution in the panel that can be used for buckling, stress and deflection analyses. This FEM analysis is carried out on ABAQUS®.

2.1 2-D UNIT CELL MODEL

Using the ABAQUS CAE we modelled the unit cell and conducted the analysis.

The geometry and design variables:

1. Thickness of top face sheet, t_T
2. Thickness of webs, t_W,
3. Thickness of bottom face sheet, t_B,
4. Angle of corrugations, θ,
5. Height of the sandwich panel (centre-to-centre distance between top and bottom face sheets), h,
6. Length of a unit-cell of the panel, $2p$.

t_T	2.0 mm
t_W	3.0 mm
t_B	6.0 mm
h	140.0 mm
p	75.0 mm
θ	82.0 mm

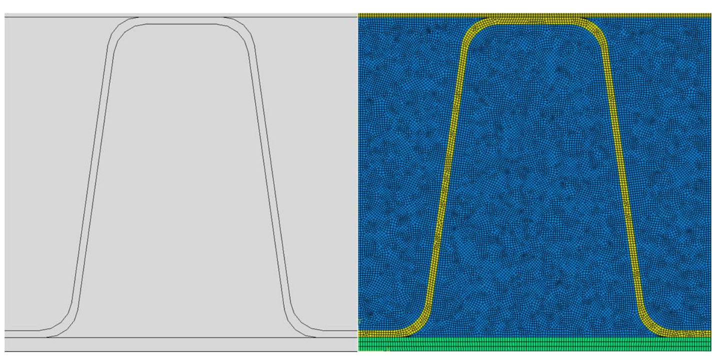


Figure 1: (a) a 2-D unit cell, (b) a 2-D mesh of the unit cell

The material properties of different parts of the unit cell:

1. Top Face Sheet: Titanium Alloy: Ti-6Al-4V
2. Bottom Face Sheet: Beryllium Alloy

3. Webs: Titanium Alloy: Ti-6Al-4V
4. Insulation Material: SAFFIL®

Initial temperature of the structure is assumed as 295 K. Heat flux is incident on the top surface of the top face sheet. A large portion of this heat is radiated out to the ambient by the top surface. The remaining heat is conducted into the ITPS. It is also assumed that there is no lateral heat flow out of the unit cell, that is, the heat flux incident on a unit cell is completely absorbed by that unit cell only. The thermal loading is divided into four load steps. In the first two steps there is heat flux input and heat loss through radiation. In the third step there is no heat flux input and only heat loss through radiation. In the fourth step the vehicle has come to rest and there is only heat loss due to convection and radiation.

STEPS	**TIME PERIOD**	**HEAT FLUX INPUT**	**TIME STEP SIZE**	**AMBIENT TEMPERATURE**
STEP 1	0 – 450 sec	0.0 - 34069.0 W/m^2 Ramp Linearly	30 sec	213 K
STEP 2	450 – 1575 sec	34069.0 - 39748.0 W/m^2 Ramp Linearly	25 sec	243 K
STEP 3	1575 – 2175 sec	39748.0 - 0.0 W/m^2 Ramp Linearly	30 sec	273 K
STEP 4	2175 – 5175 sec	-	50 sec	295 K

Parameters:

- Emissivity of top surface: 0.8
- Coefficient of convective heat transfer: 6.5 Wm-2K-1
- Stefan-Boltzmann Constant σ = 5.67 × 10-8 W/m2-K4
- Absolute Zero Temperature = 0K

2.2 **RESULTS**

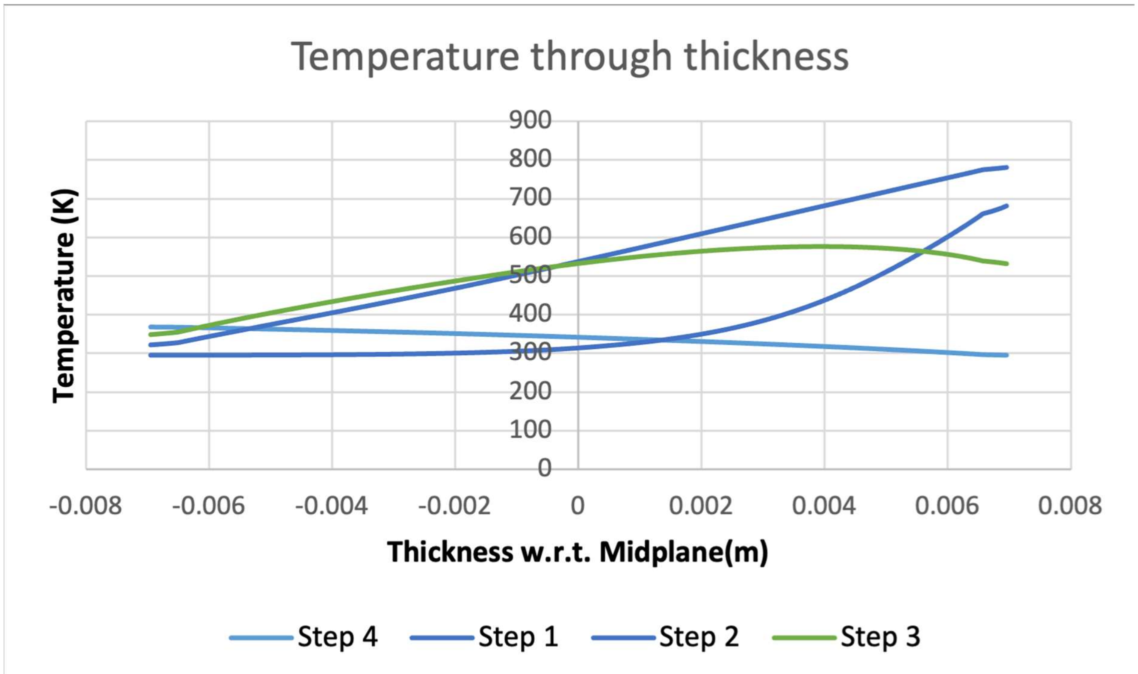


Figure 2: Temperature distribution through the thickness of the ITPS 2D unit cell

The temperature field for the second step is approximately linear. This field is used further to carry out the thermo-mechanical unit cell analysis of 3D unit cell.

3. THERMO-MECHANICAL UNIT CELL ANALYSIS

3.1 3D UNIT CELL MODEL

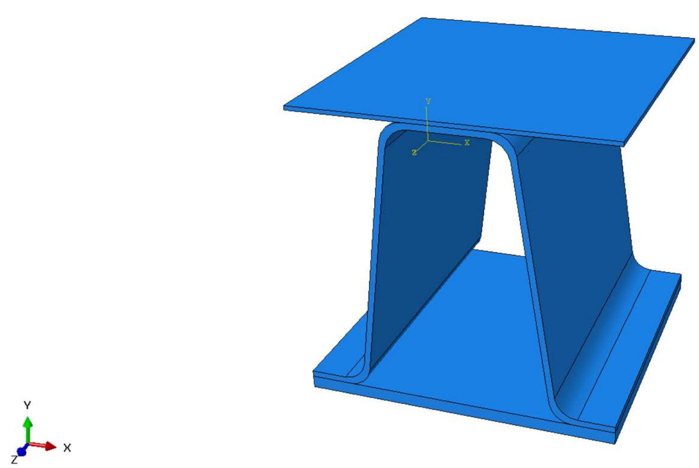
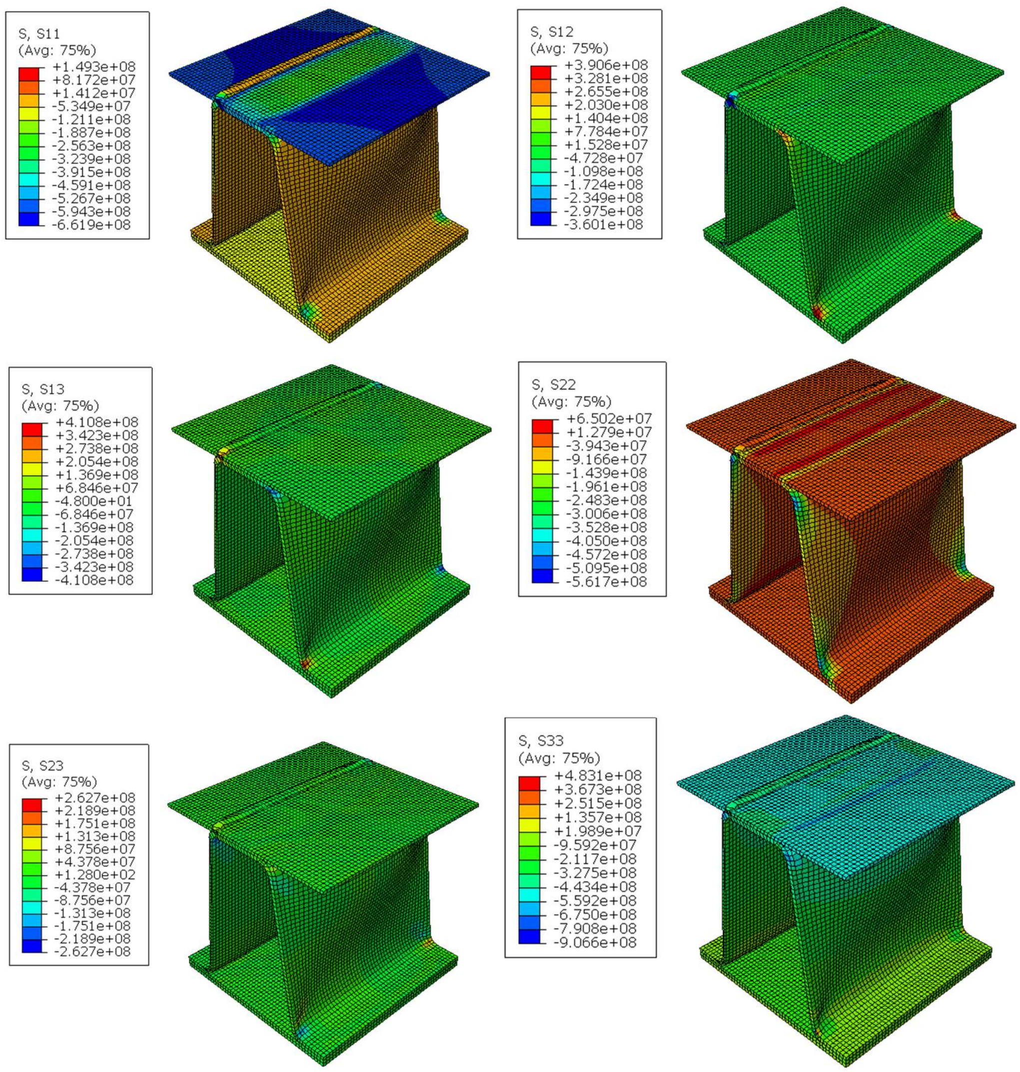


Figure 3: 3D unit cell

All the six displacement and rotational degrees of freedom of the 3D unit cell are restricted and the temperature field obtained in the heat transfer analysis is applied to obtain the stress distribution and deformations over the unit cell.

3.1 RESULTS



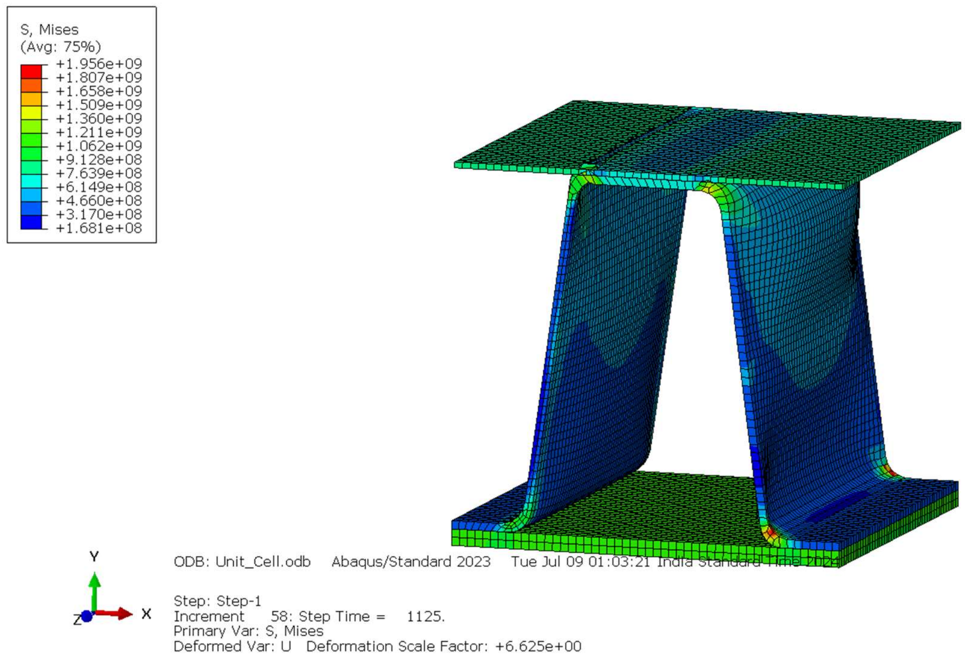


Figure 4: Stress distribution, S11, S12, S13, S22, S23, S33 and Mises Stress respectively

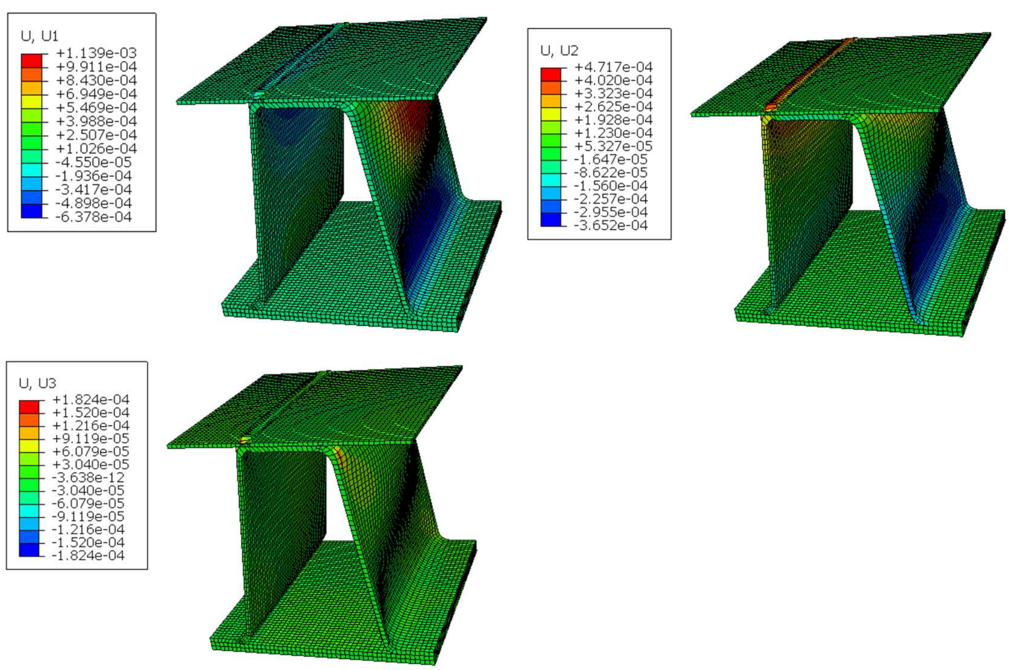


Figure 5: Deformations in 3D unit cell, U1, U2, U3 respectively

4. CONCLUSION

In conclusion, our study successfully obtained the temperature distribution across the thickness and analysed stress concentrations within the 3D unit cell of the Integrated Thermal Protection System (ITPS). This comprehensive analysis provides valuable insights into potential failure points within the structure. By identifying areas susceptible to higher stresses, we can prioritize design enhancements and material optimizations to improve the overall reliability and durability of the ITPS. These findings are crucial for advancing thermal management strategies in reusable launch vehicles (RLVs), ensuring enhanced performance and safety during extreme operational conditions.

FUTURE PLANS

These results can be used to conduct thermo-mechanical analysis to determine the ABD matrix, capturing thermal-mechanical coupling.
In future the 3D corrugated structure can be homogenised into a 2D plate representation for easier application on RLV components.

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