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Homogenization of Integrated Thermal Protection System with Rigid Insulation Bars

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Integrated Thermal protection Systems (ITPS) are the features incorporated into a spacecraft's design to protect it from severe aerodynamic heating combining both the load bearing structure and the thermal protection system (TPS) into one single structure. Previous work studied an ITPS concept with a corrugated-core sandwich structure made of face sheets supported by webs and filled with low density insulation material. Analysis was carried out with both analytical and finite element based homogenization of the ITPS structure as an equivalent orthotropic plate. In this paper we extend the finite element based homogenization method to a new concept of ITPS to determine the equivalent stiffness properties. A micromechanics based approach is applied to obtain the inplane, bending and coupling stiffness of the panel. Because of the way the panel and insulation bars are arranged, transverse shear is more pronounced in the components of the new composite structure. A cantilever beam model is used along with shear deformable plate theory to determine the transverse shear stiffness. The three dimensional ITPS panel and the homogenized plate are analyzed under pressure loading and the responses are compared to assess the accuracy of the homogenized model.

Nomenclature

a	=	unit cell length, x direction
b	=	unit cell length, y direction
d	=	height of the sandwich panel (centerline to centerline)
$F_i^{(m)}$	=	nodal force in the finite element model
h	=	height of the insulation bar
L	=	length of the ITPS panel
M_i	=	moment resultant
n	=	number of insulation bars in the panel
N_i	=	force resultant
t_T	=	top face sheet thickness
t_B	=	bottom face sheet thickness
t_W	=	thickness of the wrap
q	=	pressure load per unit width
ε_o	=	mid-plane strain
κ	=	curvature
w	=	width of the insulation bar
u,v,w	=	displacement in the x, y and z directions
u_0,v_0,w_0	=	mid-plane plate displacements

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I. Introduction

To protect a space vehicle's structure from damage due to aerodynamic heating and extreme loading conditions such as aerodynamic pressure loads, small object high speed impacts and handling damages, an Integrated Thermal Protection System (ITPS) concept has been proposed. This concept fulfills both the thermal protection requirements during reentry and the structural requirements during the entire phase of the mission [1, 2]. The design was a corrugated core structure composed of face sheets with corrugated core and insulation made of different materials. The sandwich panel of the ITPS is a three layer element composed of two thin flat faces separated by a thick, lighter, and flexible core [3, 4]. The thin flat faces are high in stiffness when compared to the low average stiffness of the thick core. Empty spaces in between the webs were packed with insulation material (e.g., SAFFIL™) to block the internal radiation coming from the top face sheet also shown in Figure 1. The materials used were Titanium alloy (Ti-6Al-4V) for the top face sheet and corrugated core, Beryllium for the bottom face sheet and saffil foam for insulation making it a composite structure.

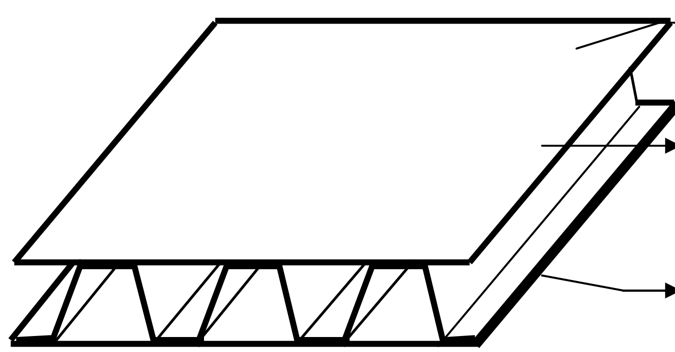


Figure 1. A corrugated-core sandwich structure concept for Integrated Thermal Protection System (ITPS)

In the earlier research work, analysis of the corrugated sandwich panel was performed using entirely shell finite elements (Figure 1). However, this method proved to be computationally intensive. It was proposed that homogenization of the composite structure as an equivalent two-dimensional orthotropic plate would reduce the computational cost tremendously [6, 7]. In general, homogenization is a process of approximating the behavior of heterogeneous structures as homogeneous and determining their equivalent stiffness properties. There are several approaches to homogenization: mechanics of materials approach, elasticity approach, energy methods and finite element analysis. All methods assume that there is a representative volume element (RVE) that repeats itself to form the structure.

Previous homogenization procedures of the ITPS panel used analytical models [8] and finite element based models [9] for determining the equivalent plate properties. Though the analytical model developed involved many approximations associated with the structural deformation of the panel, it provided a good estimate of the equivalent stiffness properties, the A, B and D matrices. Further a finite element based homogenization was developed [10]. This homogenization procedure proved to be more accurate than the analytical model. In this method, periodic boundary conditions are imposed on the RVE that corresponds to a given state of mid-plane strains and curvatures of the equivalent plate [11, 12]. In the present paper we use a similar homogenization procedure for calculating the stiffness matrices of the new IITPS panel. The terms unit cell and RVE are used interchangeably in this paper.

The new concept of ITPS consists of stacked rigid AETB (Alumina Enhanced Thermal Barrier foam) insulation bars that are spirally wrapped with a SiC/SiC cloth (see Figure 2).The bars are stacked orthogonally in two layers in a 0/90 configuration The bars are then supported by a top face sheet and a bottom face sheet made of SiC/SiC and polymer matrix composite (graphite/epoxy), respectively. The concept not only has material asymmetry but also geometric asymmetry as the rigid insulation bars are stacked orthogonally. Further, the design is complex because of the spirally wrapped cloth around the AETB insulation bar. In such a design, transverse shear between the insulation, the wraps and between the two layers of insulation would have a pronounced effect on the structure. Along with the inplane, bending and the coupling stiffnesses, the determination of transverse shear stiffness is also discussed here. The shear stiffness A_{44} and A_{55} are determined by combining FE based simulation of a cantilever beam under pressure load and plate theory solution for deflection of a cantilever plate. The stiffnesses ([*ABD*], A_{44} and A_{55}) are applied to the homogenized two-dimensional orthotropic plate and compared with the actual three-dimensional model to analyze the accuracy of the homogenization procedure.

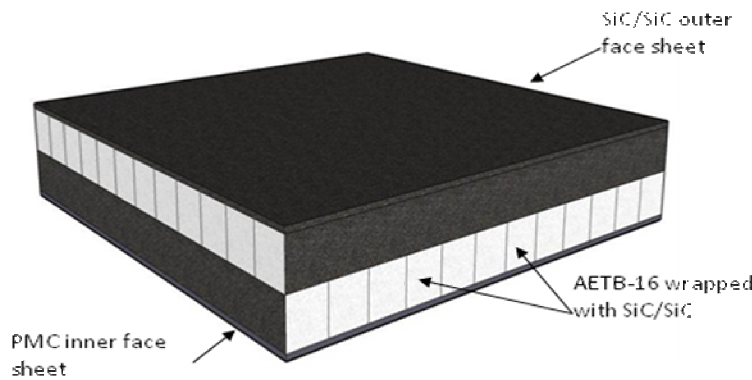


Figure 2. Schematic view of the ITPS design

In the earlier design the insulation material was Saffil foam which has relatively lower density than the other components and hence was neglected in the mechanical analysis. Unlike the model of the older concept, the foam (AETB) is not neglected in the FE model which makes it a solid structure composed of brick elements. In this paper, the first section discusses the new concept of ITPS, its finite element model and the second section demonstrates the homogenization procedures. The effective stiffness properties [*ABD*] of the homogenized model are predicted. The next section describes the method for obtaining the transverse shear stiffness of the model. The fourth section involves comparison of the 3D (solid) ITPS panel with the equivalent 2D (shell) plate. The accuracy of the homogenized model is assessed from the deflection of the panel under simply supported boundary conditions and pressure loading. The paper is concluded with summary and description of future work.

I. ITPS with rigid insulation bars

The new thermal protection system concept consists of stacked rigid insulation bars surrounded with wraps and supported by a top face sheet and bottom face sheet. The material properties and the fiber orientation of the laminate are given in Table 1 and 2. [13, 14, and 15]

Table 1. Components of ITPS, materials and fiber orientation

Component	Material	Fiber orientation	Thickness
TFS	**SiC/SiC laminate**	$[(0/90)_4]_S$	16 layers – 0.125 mm each
Foam	**AETB 8**	**-**	20 mm
BFS	**Gr/Ep laminate**	$[(0/90_4]_S$	16 layers – 0.125 mm each
Wrap	**SiC/SiC laminate**	$[0/90]_S$S	4 layers– 0.125 mm each

Table 2. Material Properties of the components of ITPS

Properties	SiC/SiC laminate	Graphite/Epoxy laminate	AETB foam
E_1 GPa	170	138	0.153
E_2 GPa	124	9	0.153
$v_{12} = v_{13}$	0.26	0.3	0.25
v_{23}	0.20	0.342	0.25
$G_{12}=G_{13}$ GPa	56	6.9	0.062
G_{23} GPa	60	3.58	0.062
α_1 x 10^{-6} /K	4	0.0032	1.77
α_2 x 10^{-6} /K	4	0.113	1.77

The key dimensions of the ITPS are the width w, and height of the h of the insulation bar, thickness of the top face sheet t_T, bottom face sheet t_B and wrap t_W and the number of bars n. The dimensions are shown in Figure 3and also in Table 3.

Table 3. Dimensions of the ITPS model

w	H	t_T	t_B	t_W	n
20.0 mm	20.0 mm	2.0 mm	2.0 mm	0.5 mm	12

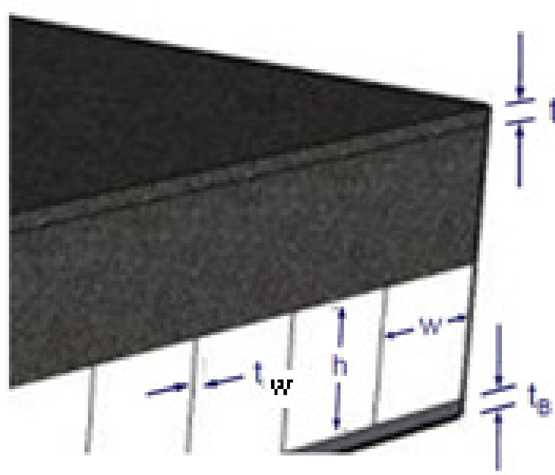


Figure 3.Dimensions of the ITPS

II. Homogenization of the ITPS panel

The homogenization method is micromechanics based approach where a representative volume element of the structure is forced to undergo deformations to predict the equivalent properties. The RVE, also referred to as the unit cell is basically the primary block of the structure that repeats itself. The unit cell is modeled using the commercial ABAQUS finite element software. As mentioned earlier, the unit cell is modeled using 20-node brick elements, C3D20R. Unlike the shell elements, the brick elements have only three degrees of freedom, the three displacements u, v, and w. The unit cell is subjected to six linearly independent deformations to determine the equivalent stiffness properties of the panel. The deformations are applied as periodic displacement boundary conditions (PBC) which includes three inplane strains $\left(\varepsilon_x, \varepsilon_y, \gamma_{xy}\right)$ and three curvatures $\left(\kappa_x, \kappa_y, \kappa_{xy}\right)$. The boundary conditions for the six cases are given in Table 4.

Table 4. Periodic boundary conditions for the six deformations

	u(a,y) – u(0,y)	***v(a,y) – v(0,y)***	***w(a,y) – w(0,y)***	***u(x,b) – u(x,0)***	***v(x,b) – v(x,0)***	***w(x,b) – w(x,0)***
$\varepsilon_{x0} = 1$	a	0	0	0	0	0
$\varepsilon_{y0} = 1$	0	0	0	0	b	0
$\gamma_{xy0} = 1$	0	$a/2$	0	$b/2$	0	0
$\kappa_x = 1$	az	0	$-a^2/2$	0	0	0
$\kappa_y = 1$	0	0	0	0	bz	$-b^2/2$
$\kappa_{xy} = 1$	0	$az/2$	$-ay/2$	$bz/2$	0	$-bx/2$

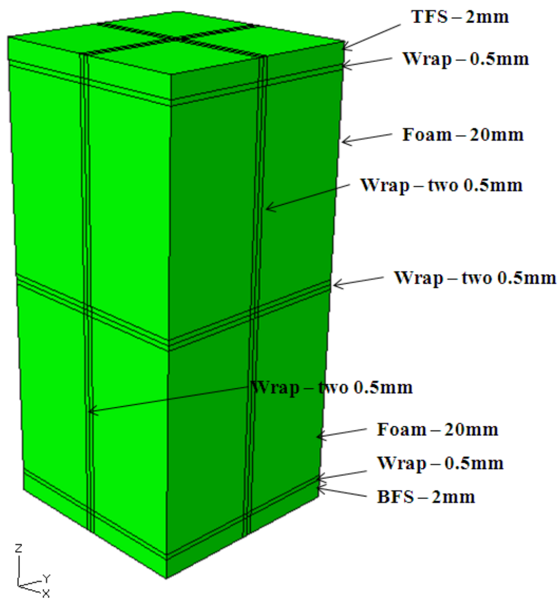


Figure 4. Finite element model of the unit cell

These deformations create inplane forces (N_x, N_y, N_{xy}) and moments (M_x, M_y, M_{xy}) in the unit cell. The constitutive relation between the inplane force, moments and strains and curvature gives the stiffness properties of the structure [16]. The constitutive relation is given as

$$\begin{bmatrix} N_x \\ N_y \\ Q_y \\ Q_x \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \left[\boxed{\begin{matrix} A_{11} \\ A_{12} \\ 0 \\ 0 \\ 0 \\ B_{11} \\ B_{12} \\ 0 \end{matrix}} \begin{matrix} A_{12} & 0 & 0 & 0 & B_{11} & B_{12} & 0 \\ A_{22} & 0 & 0 & 0 & B_{12} & B_{22} & 0 \\ 0 & A_{44} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{55} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{66} & 0 & 0 & B_{66} \\ B_{12} & 0 & 0 & 0 & D_{11} & D_{12} & 0 \\ B_{22} & 0 & 0 & 0 & D_{12} & D_{22} & 0 \\ 0 & 0 & 0 & B_{66} & 0 & 0 & D_{66} \end{matrix}\right] \begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \tag{1}$$

For instance when the unit cell is subjected to inplane strain ε_x in the *x*-direction, (Figure 5) one face of the unit cell is displaced by a distance *a* (width of the unit cell) in the *x*-direction. One of the corner nodes is fixed to prevent rigid body motion. This result in forces F_x , F_y generated on the displaced face (Figure 6a) from which the in-plane forces and moments can be calculated using Eqn (2). The in-plane forces would provide the in-plane stiffness matrix [A] and the moments would give the shear-bending coupling stiffness [B] (Eqn (2)) thus populating the first column of the matrix shown above. With all the strains and curvatures applied individually on the unit cell and the force and moment resultants for each case, the [ABD] matrix could be determined (*A* (in-plane stiffness), *B* (bending – stretching coupling stiffness) and *D* (bending stiffness)).

$$
\begin{aligned}
N_x &= \frac{1}{a}\sum_{i=1}^{n} F_x^{(i)}(a,y,z) \\
N_{xy} &= \frac{1}{a}\sum_{i=1}^{n} F_y^{(i)}(a,y,z) \\
M_x &= \frac{1}{a}\sum_{i=1}^{n} z\,F_x^{(i)}(a,y,z) \\
M_{xy} &= \frac{1}{a}\sum_{i=1}^{n} z\,F_y^{(i)}(a,y,z)
\end{aligned}
\tag{2}
$$

Figure 6 shows the deformation of the unit cell for each case of unit strain applied. Figure 6a shows how the unit cell would deform due to the PBC applied in Figure 5. These figures are just to show how the unit cells deform due to the periodic boundary conditions. [11, 12]

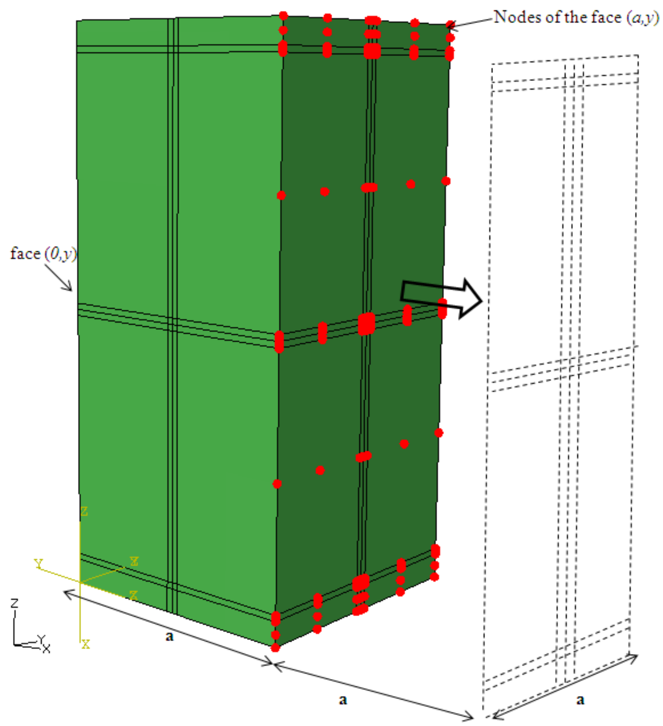


Figure 5. Periodic boundary condition applied on the unit cell for $\varepsilon_x = 1$

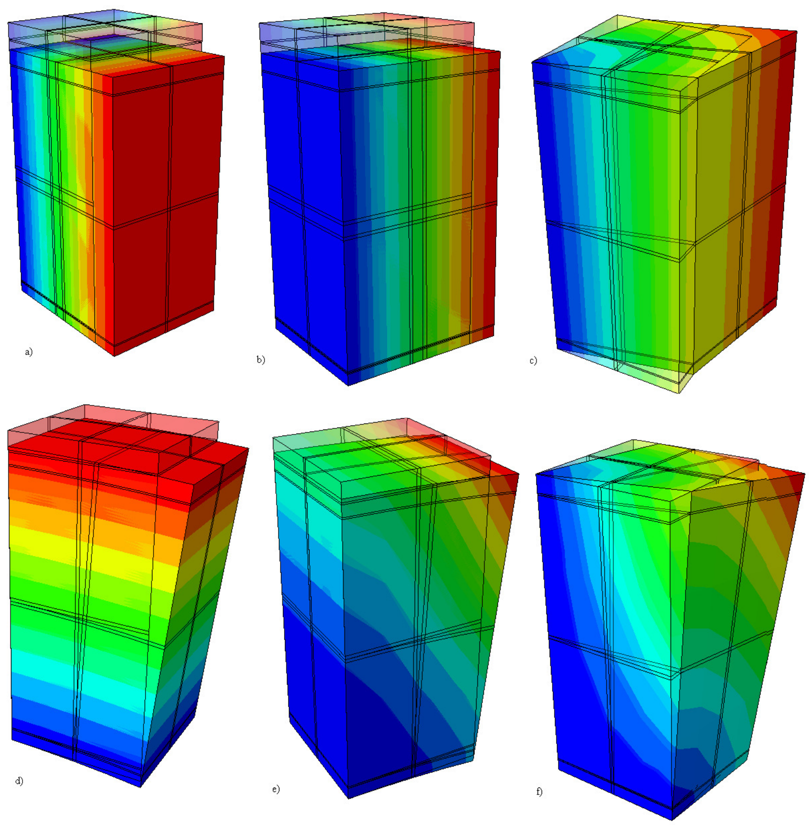


Figure 6. Unit Cell deformations for the six cases: (a) $\varepsilon_x = 1$; (b) $\varepsilon_y = 1$; (c) $\gamma_{xy} = 1$; (d) $\kappa_x = 1$; (e) $\kappa_y = 1$; (f) $\kappa_{xy} = 1$.

Initially the [*ABD*] matrix was predicted through homogenization method for an isotropic panel (E=129 GPa v=0.29). It was compared with the [*ABD*] matrix obtained analytically using the Classical Lamination Theory [17]. Both the analytical and FE values agreed well with less than 1% difference. Then the actual material properties were considered (Table 2) and the [*ABD*] matrix was determined shown in the matrix (Eqn (3)) below. The coefficients A_{16}, A_{26}, B_{16}, B_{26}, D_{16}, D_{26} would be zero because each of the individual layers of the ITPS is orthotropic.

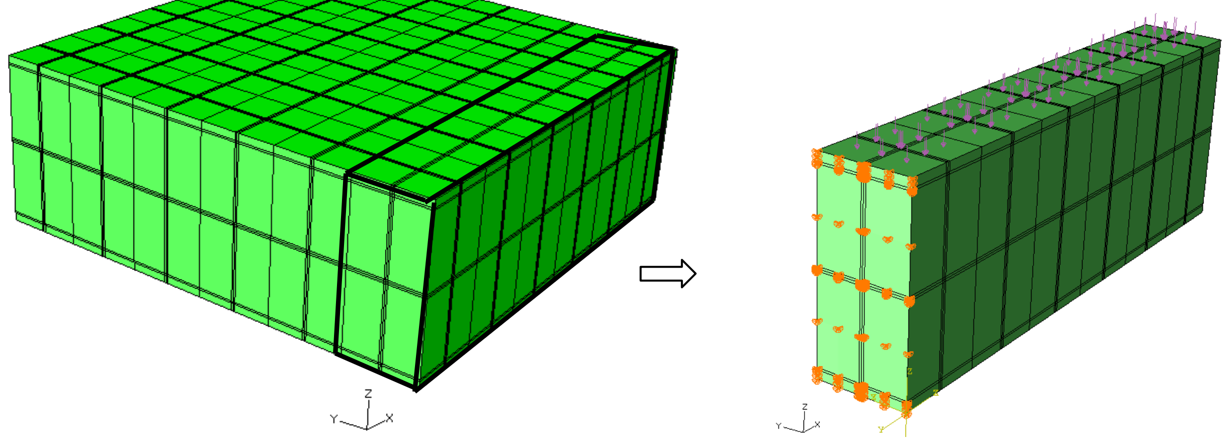
Table 5. Comparison of [A] and [D] matrices calculated using the analytical method and finite element method. The ITPS panel is assumed to be made of titanium alloy

Stiffness	Analytical	FE Analysis	% diff.
A11[N/m]	6.499×10^9	6.499×10^9	0.0
A12[N/m]	1.884×10^9	1.884×10^9	0.0
A22[N/m]	6.499×10^9	6.499×10^9	0.0
A66[N/m]	2.309×10^9	2.307×10^9	0.08
D11[Nm]	1.146×10^6	1.146×10^6	0.0
D12[Nm]	0.332×10^6	0.332×10^6	0.0
D22[Nm]	1.146×10^6	1.146×10^6	0.0
D66[Nm]	0.407×10^6	0.406×10^6	0.24

$$ABD = \begin{bmatrix} 914.06\text{ x }10^6 & 143.01\text{ x }10^6 & 0 & 5.02\text{ x }10^6 & 1.37\text{ x }10^6 & 0 \\ 143.01\text{ x }10^6 & 912.99\text{ x }10^6 & 0 & 1.37\text{ x }10^6 & 2.07\text{ x }10^6 & 0 \\ 0 & 0 & 240.73\text{ x }10^6 & 0 & 0 & 2.16\text{ x }10^6 \\ 5.02\text{ x }10^6 & 1.37\text{ x }10^6 & 0 & 309.64\text{ x }10^3 & 50.51\text{ x }10^3 & 0 \\ 1.37\text{ x }10^6 & 2.07\text{ x }10^6 & 0 & 50.51\text{ x }10^3 & 309.74\text{ x }10^3 & 0 \\ 0 & 0 & 2.16\text{ x }10^6 & 0 & 0 & 85.96\text{ x }10^3 \end{bmatrix} \tag{3}$$

III. Transverse shear stiffness of the ITPS panel

The design with face sheets, insulation bars with wraps would cause pronounced shear deformation of the ITPS panel. To effectively homogenize the 3D structure into an equivalent 2D orthotropic plate, transverse shear stiffness should be determined. In order to obtain the shear stiffness, the panel is considered such that it forms a one-dimensional plate with unit cells in one direction, say *x*-direction. Transverse shear stiffness obtained from smaller length plate would predict very high stiffness which might not be the actual stiffness in the material. A 1-D cantilever plate was constructed with a length/height ratio equal to 9.3 (20 unit cells) after experimenting with various *L/H* ratios. One face of the beam is constrained in all three directions and a pressure load is applied on the top surface of the beam. Both the sides of the plate along the *x*-direction are given plane strain conditions.



a) **b)**

Figure 7. a) ITPS panel considered as b)One dimensional Cantilever plate with unit cells in x-direction

The deflection of the 1-D plate due to pressure load would have two components, one due to bending and other one due to transverse shear [17]. The deflection w of a cantilever plate of length L due to pressure load (per unit width q) can be derived as:

$$w(x) = \frac{qx^4}{8D'_{11}} + \frac{q(L-x).x^3}{3D'_{11}} + \frac{q(L-x)^2.x^2}{4D'_{11}} + \frac{q(L-x)x}{A_{55}} + \frac{qx^2}{2A_{55}} \tag{4}$$

$$D'_{11} = D_{11} - \frac{B_{11}^2}{A_{11}} \tag{5}$$

The first three components of deflection are due to bending of the beam, the other two components are due to the transverse shear. From the length of the beam, pressure load and the bending stiffness, the bending deflection could be determined analytically. The finite element cantilever beam would provide the total deflection of the beam. Using the above equation, the deflection due to transverse shear and hence the transverse shear stiffness A_{55} can evaluated.

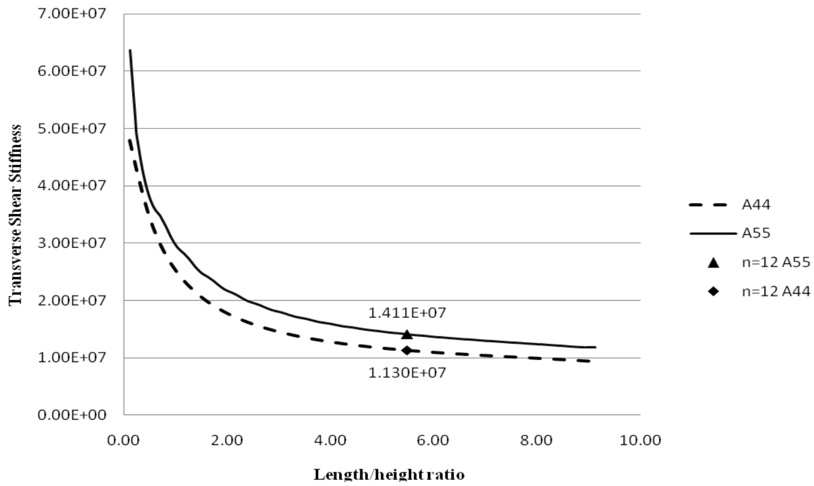


Figure 8: Transverse shear stiffness A44 and A55 along the length of the panel. The value of n=12 indicates that 12 unit cells were used in the 1-D plate model.

The shear stiffness A_{44} is evaluated similarly but by considering the 1D cantilever plate with unit cells in the y-direction (the values of stiffness A_{22}, B_{22} and D_{22} in the y-direction is considered for this case).

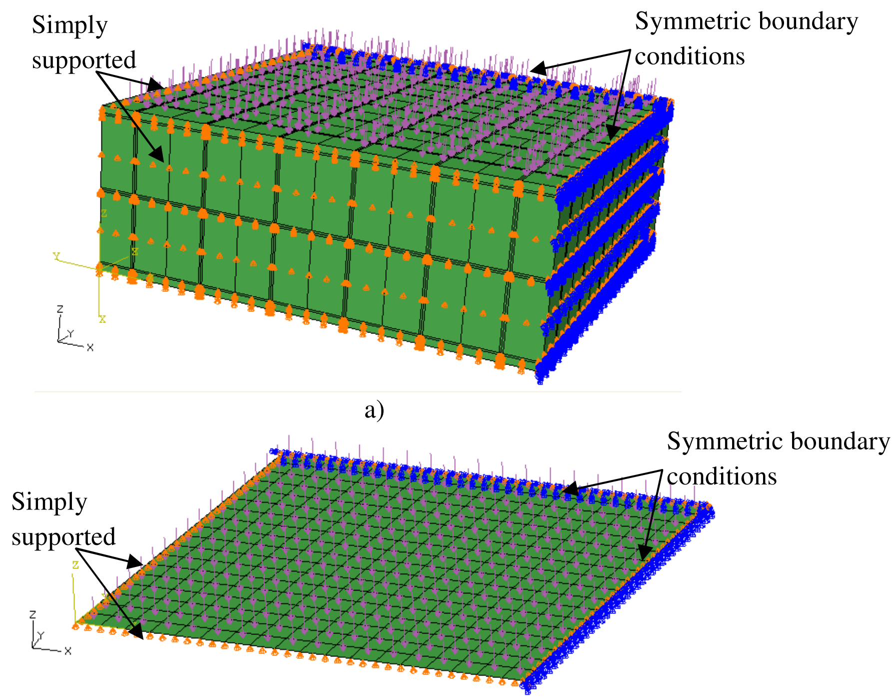
The transverse shear stiffness A_{44} and A_{55} are cross sectional properties and hence are supposed to be a constant for a given microstructure. However, for homogenization to be valid the structure (the 1D plate in this case) should have a minimum number of unit cells. When the number of unit cells is less than that minimum, the structure cannot be idealized as an equivalent orthotropic plate. When the number of unit cells is small, the deflections are also small making the apparent shear stiffness much larger. It is observed that both A_{44} and A_{55} decrease along the length of the panel (Figure 8). Ideally the shear stiffness should reach a steady state value as the length increases. However, as the length increases shear deformation becomes negligible compared to the bending deflection, thus making estimating the shear stiffness a difficult task. In the present study the shear stiffness corresponding to 12 unit cells is being considered for further calculations.

Table 6. Transverse Shear stiffness A44 and A55

A_{44} (Nm)	A_{55} (Nm)
11.30×10^6	14.11×10^6

IV. Comparison of 3D ITPS panel and equivalent 2D plate

The ITPS panel is subjected to various combinations of loads when installed on the exterior of the space vehicle. Pressure, temperature, inplane and impact loads are the various loads that act on the panel during flight. As a part of homogenization it is desirable to compare the response of the panel to that of the homogenized plate to assess the effectiveness of homogenization procedure. The 3D ITPS panel is simply supported and subjected to 100,000 Pa (approximately 1 atmosphere) pressure load. Due to symmetry, only one quarter of the plate is analyzed. The two dimensional plate with the equivalent stiffness properties obtained from homogenization is also simply supported and subjected to the same pressure load. The deflections along the length of the panel are compared. Figure 9 below shows the boundary conditions and loads applied on the two finite element models.



a)

b)

Figure 9. Boundary conditions and pressure load on the (a) 3D model; (b) 2D model

The deflection obtained from the finite analysis is plotted in Figure 10. The 2D plate is analyzed with the homogenized stiffness properties including the transverse shear stiffnesses A_{44} and A_{55}. It also analyzed without including the shear stiffnesses (the model was assigned infinite shear stiffness).

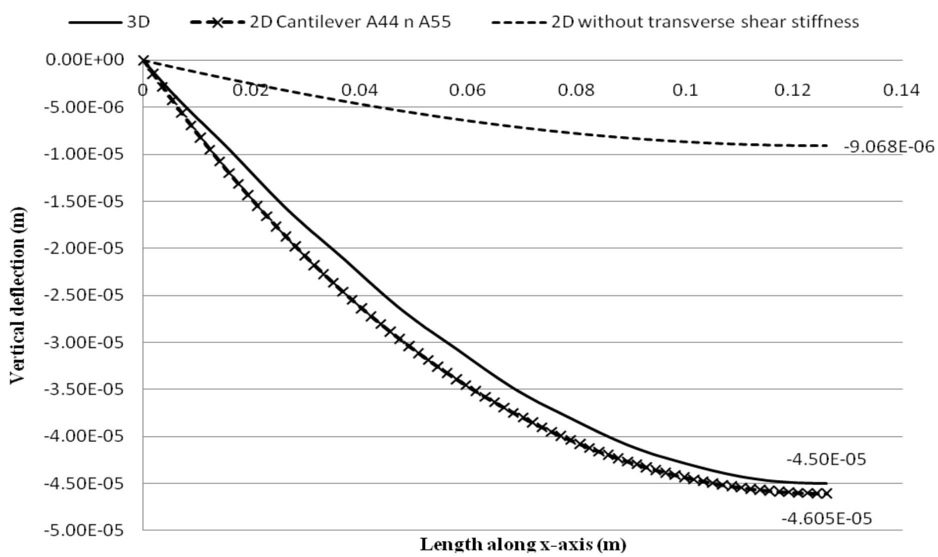


Figure 10Comparison of deflection between 3D panel and 2D plate with (A_{44} and A_{55})and without transverse shear stiffness

One can note that the classical lamination theory which assumes infinitely large transverse shear stiffness makes the plate very stiff, and the deflections are significantly smaller than the deflections from the 3D analysis. The error in the 2D deflection without considering transverse shear is 78.6 %. This demonstrates the effect of shear on the panel proving that it is an important stiffness property that cannot be neglected. When the transverse shear stiffness terms A_{44} and A_{55} were included, the maximum 2D plate deflection is about 2% less than that from 3D analysis. The results show that the proposed homogenization procedure can be used to approximate the ITPS as a homogenous orthotropic plate for the purpose of calculating maximum deflection.

V. Summary

The homogenization of a new concept for an ITPS panel as a two dimensional (2D) orthotropic plate was performed. A representative volume element/unit cell of the panel was analyzed to obtain the equivalent stiffness properties of the 2D plate. The unit cell was subjected to six linearly independent deformations and the equivalent stiffness properties of the composite structure were obtained through finite element based homogenization. A method is also proposed to estimate the transverse shear stiffness of the equivalent plate. The quarter size of the panel was analyzed under pressure load and the deflection was compared to that of an equivalent 2D plate. The deflections of 2D plate with and without shear stiffness demonstrated the effect of transverse shear on the model. The deflection without shear was 78.6% less than that of 3D deflection indicating that the model is predominantly shear deformable. The homogenization procedure that includes transverse shear effects proved to be accurate as the deflections between the 3D and 2D model agreed well.

VI. Future Work

Future work will include thermal loading in addition to pressure loading and also development of a reverse homogenization procedure to recover the detailed stress filed from the plate deformations such as mid-plane strains and curvatures obtained in the 2D plate analysis.

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