3PC SOLVER005

Analysis of Sandwich Panels Subjected to Hygrothermal and Mechanical Loads

3P COMPOSITES

1/30/2023

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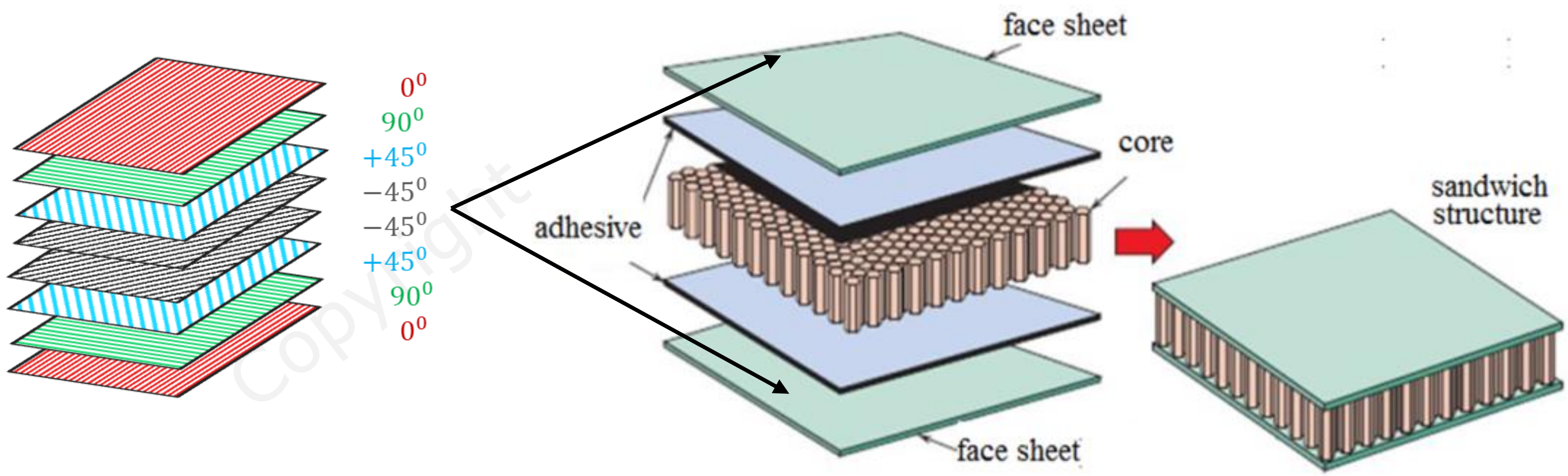
Sandwich Structures

- Sandwich panels are generally the most efficient way of providing high flexural (or bending) stiffness at lowest weight to resist transverse normal loads due to pressure and/or concentrated force(s). They provide large increase in moment of inertia without weight penalty. Sandwich panels are also one of the most efficient ways to provide acoustic damping

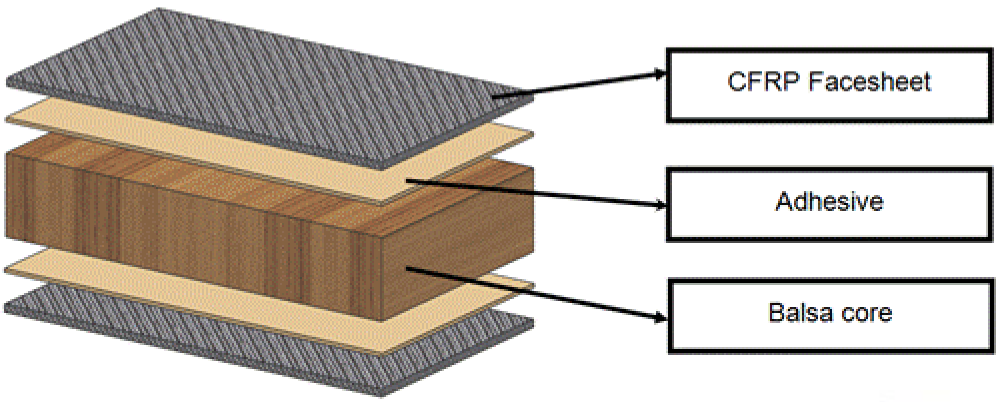
- The key components of a sandwich structure are the two facesheets, one on the top and other on the bottom, and a core that separates the two facesheets by an optimal distance to provide the required flexural stiffness. An adhesive layer is placed at the interfaces of the facesheets and the core to ensure good bond between them. A typical sandwich panel is shown below:



Picture Reference:
"Analysis of Sandwich Structures by the FEM" **Peter Sivák, Ingrid Delyová, Patrícia Diabelková,** AJME, 2017, 5(6),243-246 doi:10.12691/ajme-5-6-2

Sandwich Structures

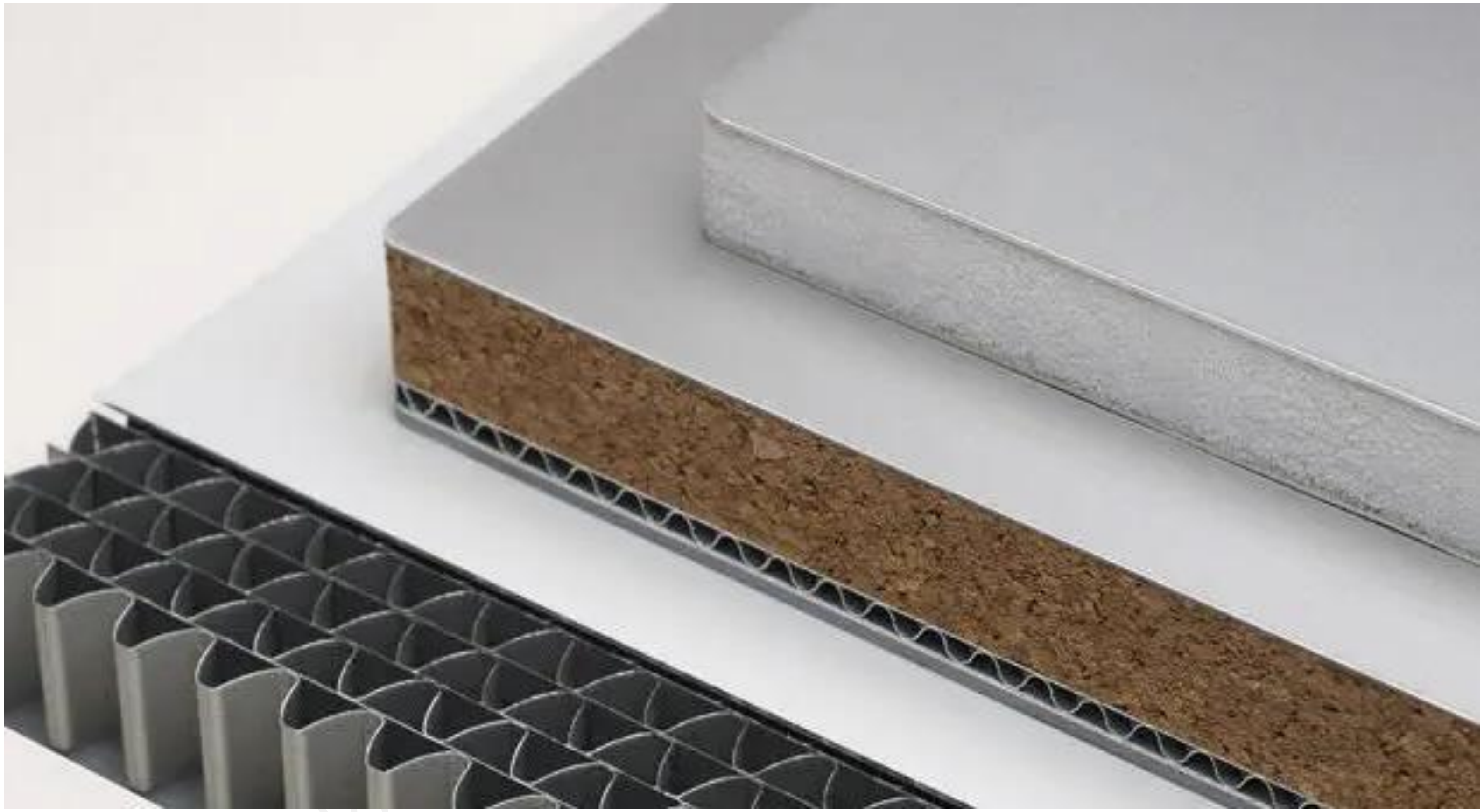
- The facesheets can be fabricated from metallic or composite materials. The core can be any metallic or non-metallic material. With many possible combinations. Sandwich structures offer numerous possibilities to design various structures for optimal performance, lightest weight and cost. A few examples of sandwich constructions are shown below:



Picture Reference:
https://www.researchgate.net/figure/The-CFRP-Balsa-sandwich-structure_fig1_317224037, DOI: 10.15376/biores.12.2.2673-2689

Picture Reference:
http://www.topolocfrt.com/pvc-foam-sandwich-panel/

Sandwich Structures



Picture Reference:
https://www.directindustry.com/prod/metawell-gmbh-metal-sandwich-technology/product-193280-1971936.html

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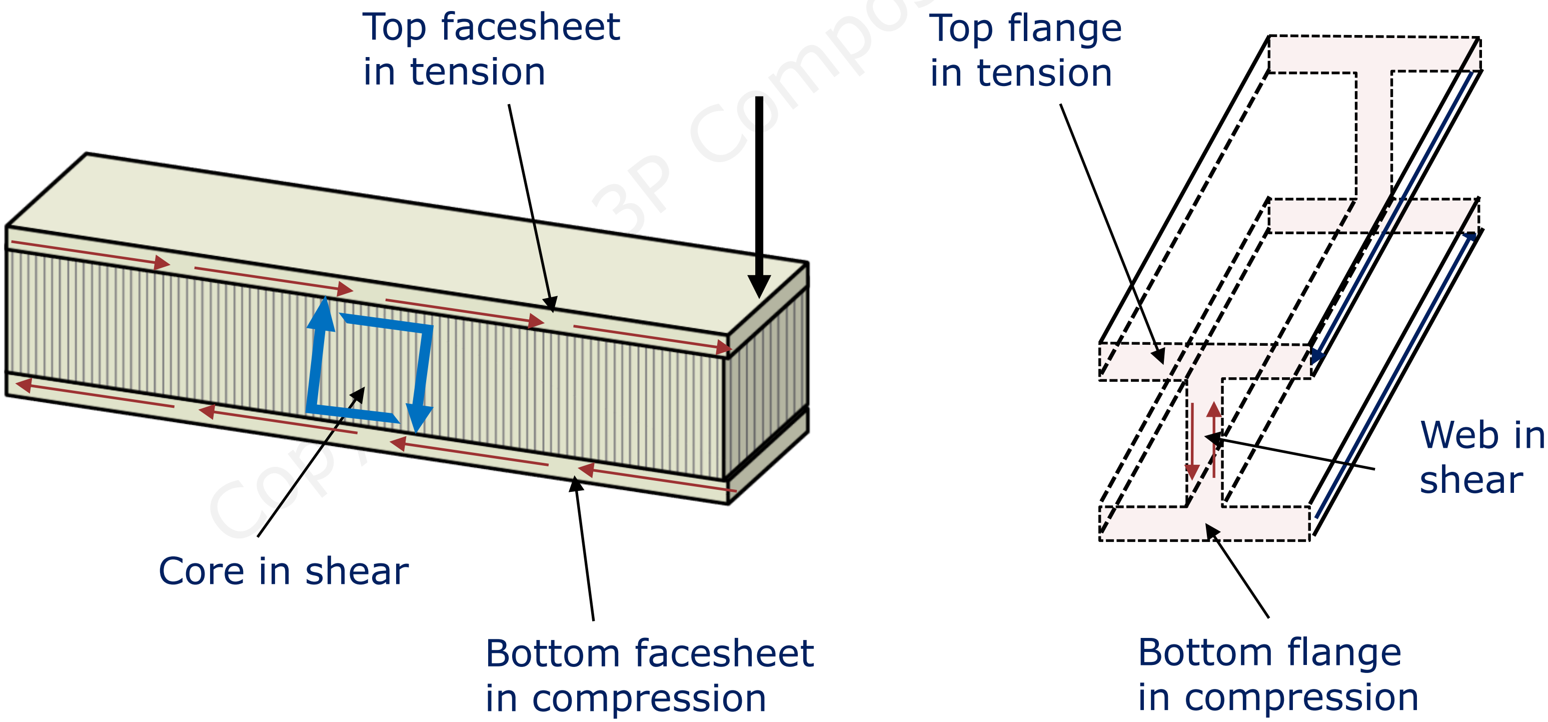
Sandwich Structures

Picture Reference:
https://aerospaceengineeringblog.com/sandwich-panel/

Picture Reference :
https://www.avient.com/products/advanced-composites/continuous-fiber-composite-panels

Analysis of Sandwich Structures

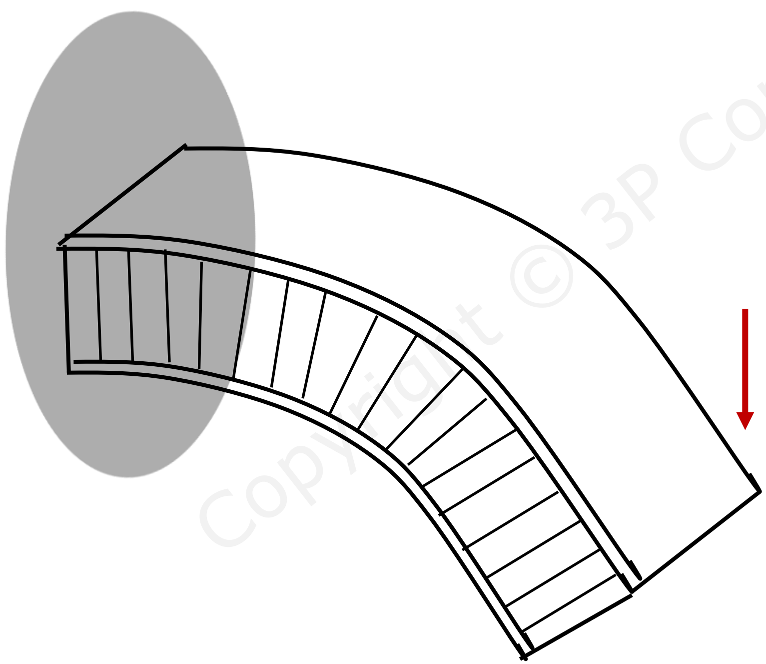
❖ Sandwich structures are analogous to traditional I-beams. In I-beams, beam flanges react the bending moment as axial tension and compression forces, and beam web resists the shear loads manifesting from the transverse bending. Sandwich structures behave very similar to I-beams in that the stiff/strong facesheets reacting the bending moment as axial tension and compression forces manifesting from the couple, and relatively less stiff or softer core resisting the transverse shear loads. A schematic comparison of the two is shown below:



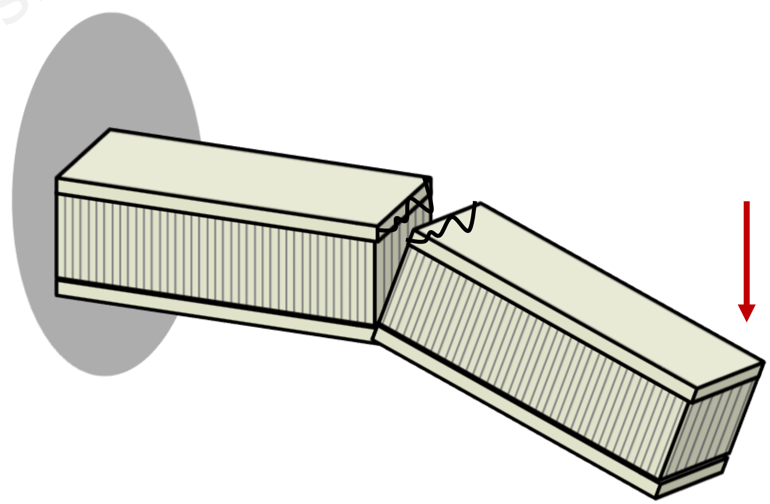
Analysis of Sandwich Structures

❖ The types of failure modes in a sandwich structure are strongly dependent upon the types of (i) loading, (ii) face sheets materials, and (iii) core materials. For example, facesheets bonded to a honeycomb core would have different kinds of failure modes than those bonded to a solid foam or balsa core. Typical failure modes in a sandwich structure are shown below:

1: Excessive deflection

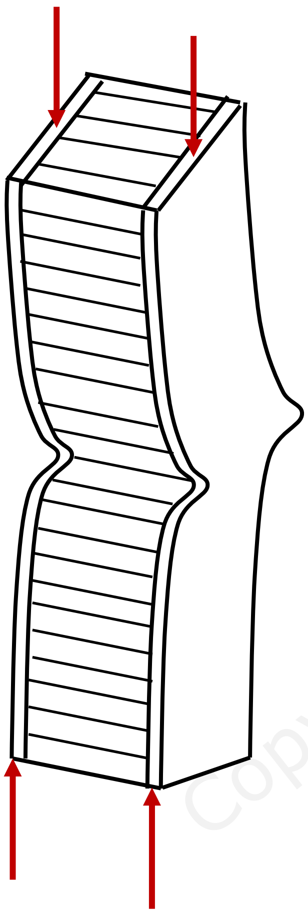


2: Strength failure of facesheets (Tension or Compression)

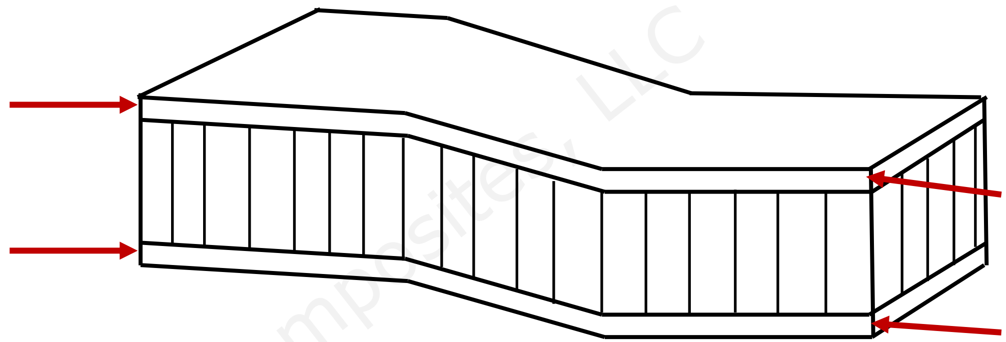


Analysis of Sandwich Structures

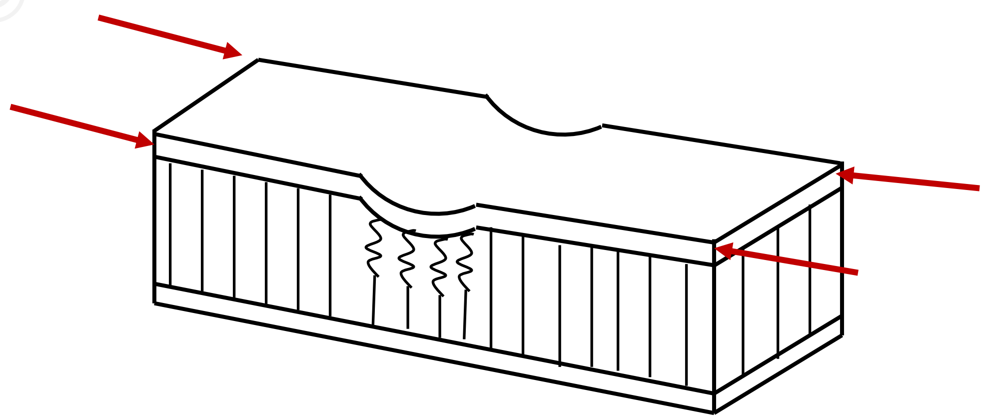
3: Global panel buckling



4: Shear crimping

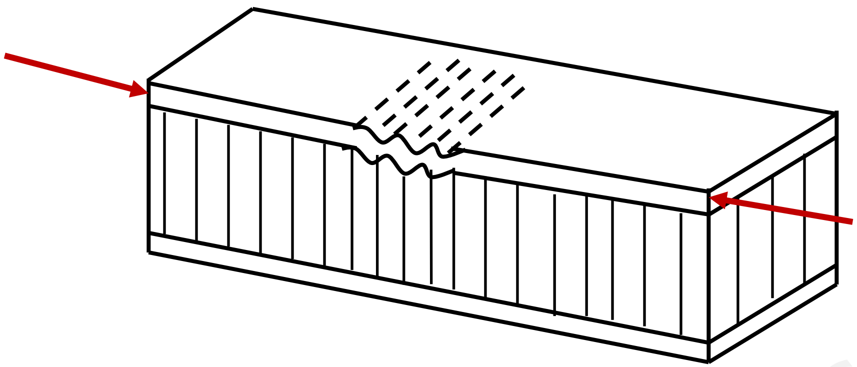


5: Facesheet wrinkling

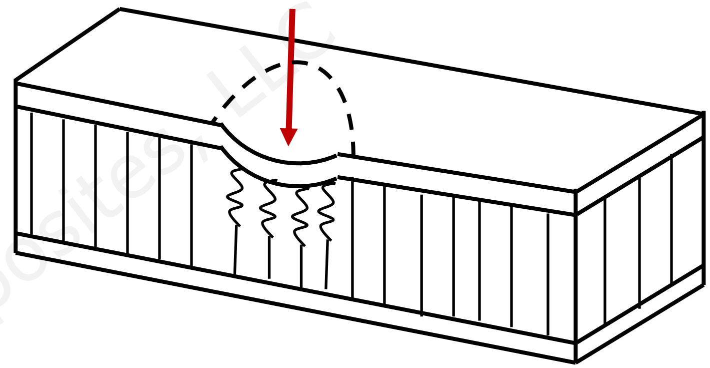


Analysis of Sandwich Structures

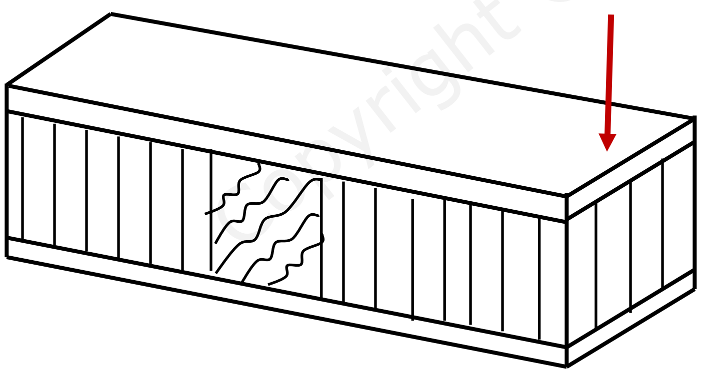
6: Intracellular buckling/Dimpling



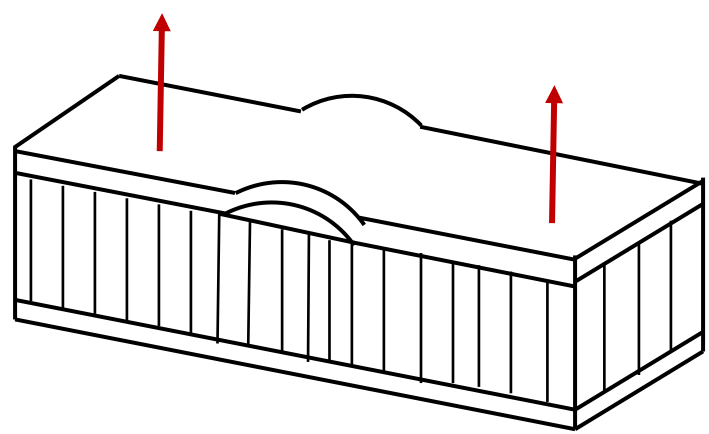
7: Local compression/Core crush



8: Core shear

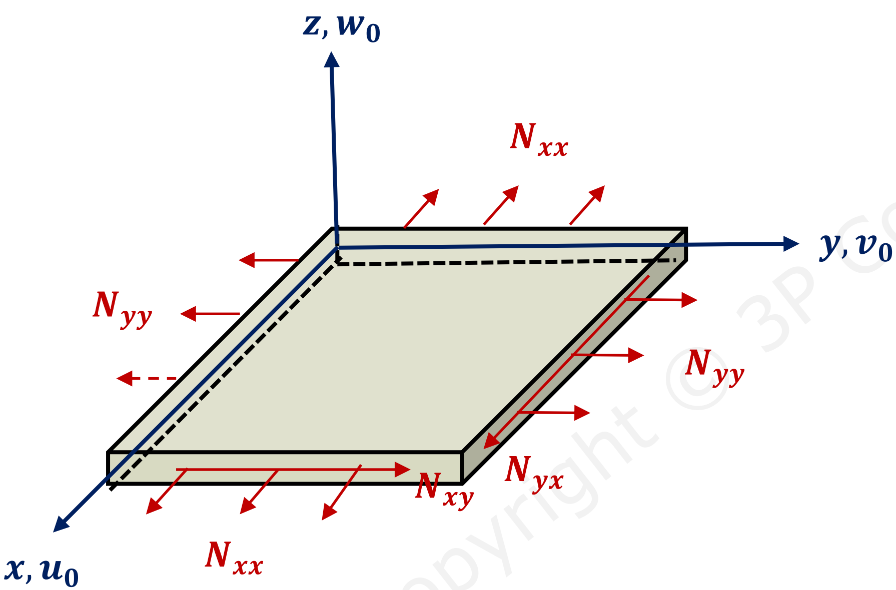


9: Facesheet disbond

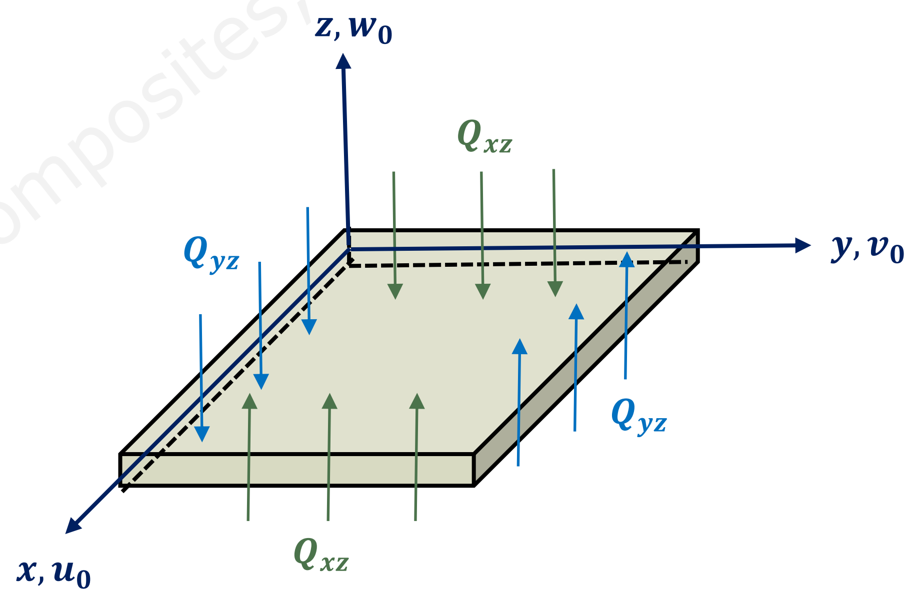


Solver Overview

- Each of the failure modes shown above sets a criteria in the design of a sandwich structure. 3pcsolver005 performs stress analysis of sandwich panels subjected to static forces and moments per unit length, uniform temperature and moisture variations. Furthermore, it performs checks for all failure modes shown on Slides 9-11 except 1 and 3. Positive sign conventions for applied force and moment resultants are shown below:

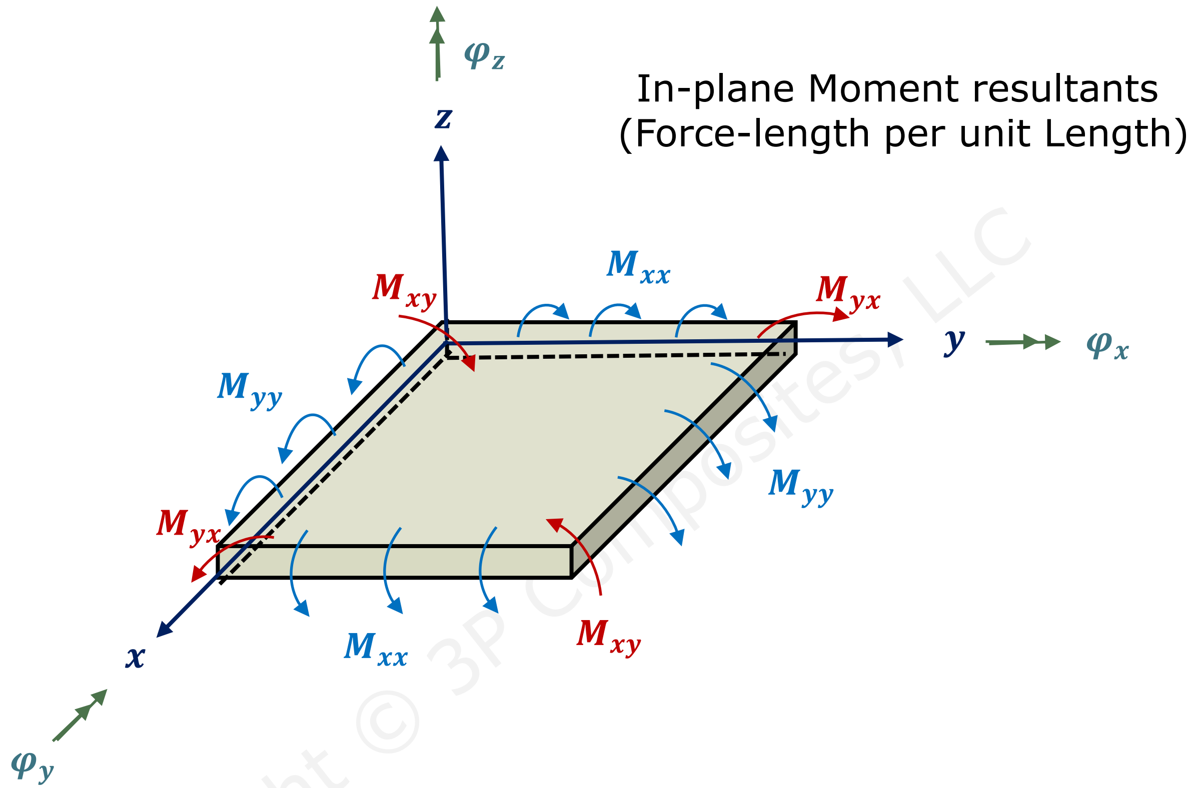


In-plane Force resultants
(Force per unit Length)



Transverse Force resultants
(Force per unit Length)

Solver Overview



- Generally, the plies or laminae and the core in the sandwich panel are laid-up or stacked from bottom-to-top. Hence, the positive moments M_{xx} and M_{yy} would result in tension in the top face sheet plies and compression in the bottom face sheet plies. Similarly, positive twisting moment M_{xy} results in a positive shear strain in top face sheet and a negative shear strain in the bottom face sheet

Applications

- The analysis is applicable to the sandwich panels manufactured from face sheets that are either fiber-reinforced laminates or metallic sheets and a core that is either isotropic or orthotropic. The face sheets can consist of single-material laminate(s) or hybrid (multi-material) laminates, one or multiple broad forms of lamina type or fiber types or single or multiple materials systems or their combinations
- Core of the sandwich structure can be isotropic or orthotropic, and
  - Metallic such as Aluminum, Titanium, etc.
  - Non-metallic such as Nomex, Balsa wood, Rohacell, Foam core, Glass Fiber, Kevlar, etc.
- Face sheets of the sandwich structure can have LAMINA that
  - has any kind of FIBER such as boron, carbon, graphite, glass, Kevlar, Aramid, polyester, natural fibers, etc.,
  - is in any type of broad form such as unidirectional, bi-directional 2D textile weaves like plain weave, twill and harness, biaxial and triaxial braids, chopped random continuous fibers, non-crimp, nonwoven fabrics, etc.
  - Is impregnated with any RESIN/MATRIX, thermoset or thermoplastic systems such as epoxy, polyester, vinyl ester, polyurethane, phenolic, cyanate ester, bis-maleimide, polyimides, benzoxazine, Acrylic, ABS, Polylactic acid PLA, Polybenzimidazole PBI, Polyether sulfone PES, Polyoxymethylene POM, Polyether ether ketone PEEK, Polyetherimide PEI, Polyphenylene oxide PPO, Polyphenylene sulfide PPS, Polystyrene PS, Polypropylene PP, Polyvinyl chloride PVC, Teflon PTFE, etc.
  - is cured using any MANUFACTURING PROCESS such as Autoclave, Resin Transfer Molding like VARTM, SQRTM, RIM, SRIM, Filament Winding, Pultrusion, Compression Molding, Wet-lay up, etc.

Theoretical Background

- **3pcsolver005** solver is based on Mindlin-Type First-Order Shear Deformation Theory (FSDT) of laminated plates. Based on such theory, the constitutive law for the sandwich panels is given as

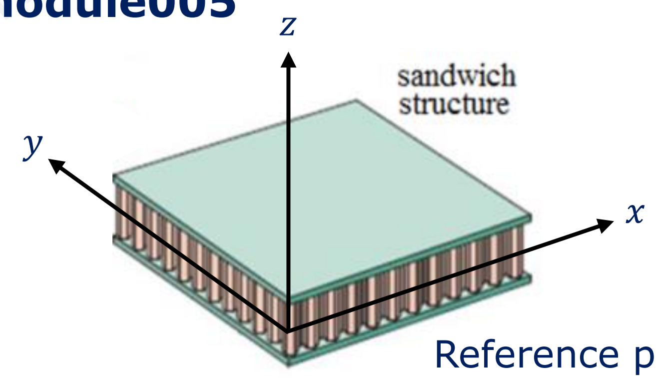
$$\begin{Bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{Bmatrix} + \begin{Bmatrix} N_{xx}^T \\ N_{yy}^T \\ N_{xy}^T \\ M_{xx}^T \\ M_{yy}^T \\ M_{xy}^T \end{Bmatrix} + \begin{Bmatrix} N_{xx}^M \\ N_{yy}^M \\ N_{xy}^M \\ M_{xx}^M \\ M_{yy}^M \\ M_{xy}^M \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{66} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \gamma_{xy}^0 \\ \kappa_{xx}^0 \\ \kappa_{yy}^0 \\ \kappa_{xy}^0 \end{Bmatrix}$$

$$\begin{Bmatrix} Q_{yz} \\ Q_{xz} \end{Bmatrix} = \begin{bmatrix} A_{44} & A_{45} \\ A_{45} & A_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{yz}^0 \\ \gamma_{xz}^0 \end{Bmatrix}$$

- In the equations given above, N_{ij}'s are the in-plane force resultants, M_{ij}'s are the moment resultants, and Q_{ij}'s are the transverse force resultants. Superscripts T and M denote thermal and moisture resultant terms that are dependent upon the coefficients of thermal expansions and moisture absorptions, respectively, of the face sheets and the core. ε_{xx}^0, ε_{yy}^0 and γ_{xy}^0 are the in-plane extensional and shear strains, γ_{yz}^0 and γ_{xz}^0 are the transverse shear strains, and κ_{xx}^0, κ_{yy}^0 and κ_{xy}^0 are bending and twisting curvatures of the reference surface of the sandwich panel (usually the middle surface, equidistant from top and bottom surfaces of the sandwich panel)

Theoretical Background

❖ Given the sandwich panel stack up, face sheet laminate stack-up, lamina/ply material properties and allowables, core material properties and allowables, **3pcsolver005** solver calculates reference surface (by default, the midplane of the sandwich panel) strains and curvatures, ply-by-ply strains and stresses in the top and bottom face sheets, transverse shear stresses in the core, and failure indices/Margin of Safeties for face sheet laminates and core, and for sandwich structure specific failure modes such as wrinkling, dimpling, shear crimping, core shear, flatwise tension, core crush, etc. subjected to Hygro-thermo-mechanical loads. The solver uses widely established laminated plate theories, and strain and stress transformations equations to compute [A], [B], [D] stiffness matrices, effective in-plane and flexural engineering constants, and effective hygrothermal engineering constants for the face sheet laminates and overall sandwich panel. Details of the theoretical approach along with numerous verification and application examples are provided in the training module **3pcmodule005**



Reference plane/Mid-Surface $x - y$

Inputs

- All inputs should be in consistent units. Use either (N, m, kg, Celsius, N/mm N-m/m) OR (N, mm, Kg, Celsius, N/mm, N-mm/mm) or (lbs, in, Fahrenheit, lb/in, lb-in/in) consistently. Inputs in scientific notation (0.0+e) are acceptable

- Input process is intuitive and uses the following logical order of user's input:

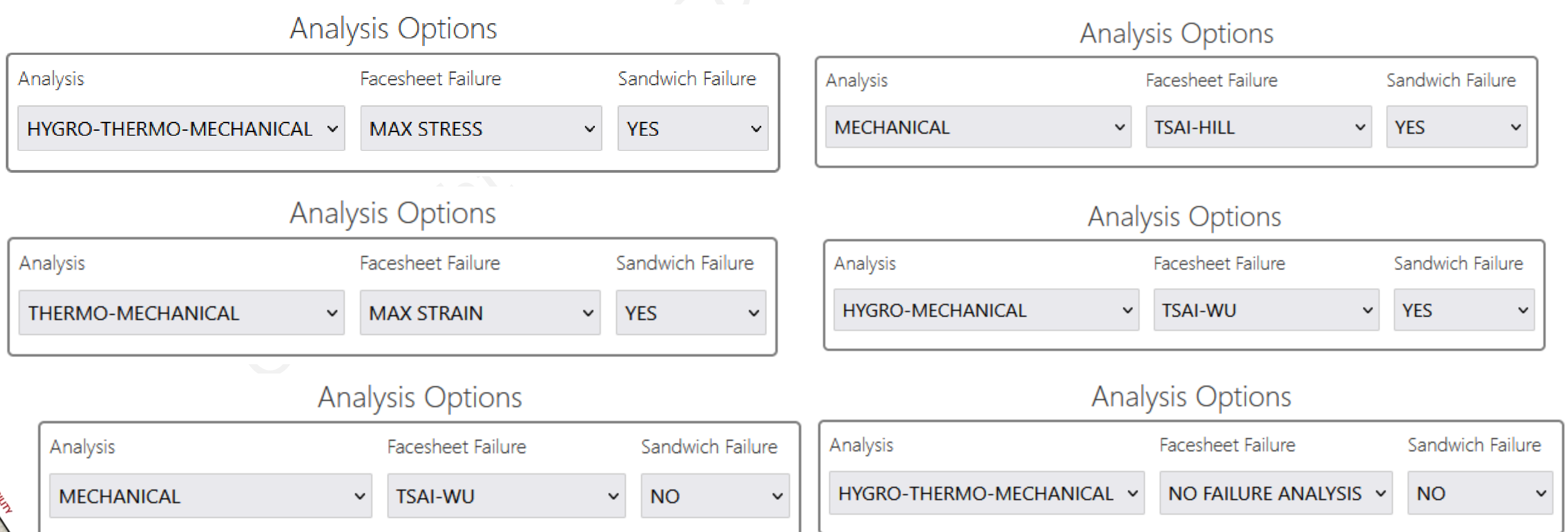
  - Analysis Options
  - Materials
  - Plies / Laminae
  - Cores
  - Laminates
  - Sandwich Panels
  - Loads

- The type of analysis selected dictates the required inputs. In general, the loads are applied to the sandwich panels, which are built from top and bottom face sheets and a core

Inputs: Analysis Options

❖ Analysis Options:

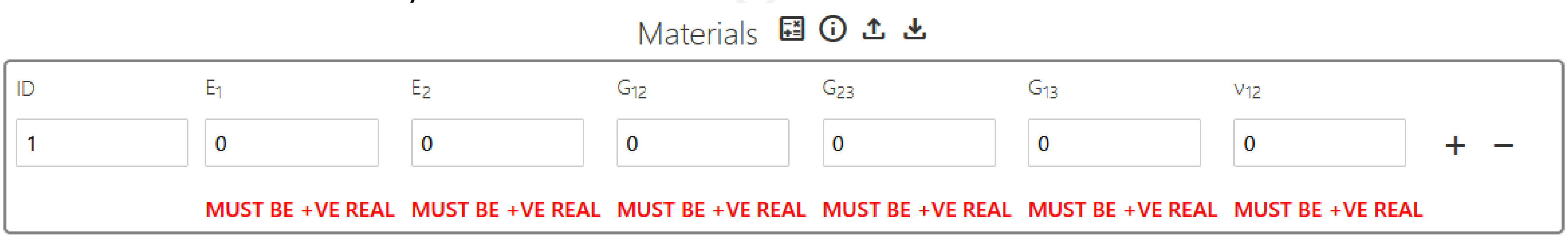
Four types of analyses can be performed using this solver, viz. (i) Mechanical (ii) Thermo-mechanical (iii) Hygro-mechanical, and (iv) Hygro-thermo-mechanical, In addition, Failure analysis of the face sheet laminates can be performed using First-ply failure criteria using one of the four commonly used composite failure theories, viz. (i) Maximum Stress (ii) Maximum Strain (iii) Tsai-Hill, and (iv) Tsai-Wu. Additionally, and core shear failure and local and global sandwich panel failure modes shown on Slides 9-11 can also be analyzed using 3pcsolver005. In total there are **Forty** (40) possible ways of using this solver to perform analysis of sandwich panels subjected to Hygro-thermo-mechanical loads. A few combination of analyses are shown below:

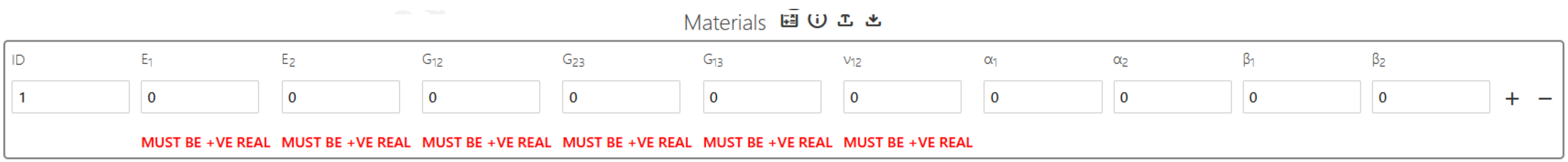


Inputs: Materials

❖ Material Properties:

In the SI system, MPa or Pa, and in the US system Psi are used to input the orthotropic lamina Moduli E_1, E_2, G_{12}, G_{13} and G_{23}. Coefficient of thermal expansions α_1 and α_2 are expressed in mm/mm or m/m per degree Celsius in SI system, and in/in per Fahrenheit in the US system. Similarly, Coefficient of moisture expansions β_1 and β_2 are in mm/mm per Kg/Kg or m/m per Kg/Kg in SI system and in/in per lb/lb in the US system. Coefficients of Thermal and Moisture expansions are required to perform hygrothermal analysis due change in temperature and/or moisture content. ν_{12} is major Poison's ratio. Multiple lamina types and lamina materials can be input by simply clicking the '+' sign on the extreme right. Based on the type of analyses selected, the required material inputs for an orthotopic Lamina can vary as shown below:





Inputs: Materials

❖ Material Allowables:

Additional inputs are required to perform face sheet laminate failure analysis. Depending upon the type of failure theory selected for an orthotropic lamina, either strength (σ_{11}^{T}, σ_{11}^{C}, σ_{22}^{T}, σ_{22}^{C} and τ_{12}) or strain (ε_{11}^{T}, ε_{11}^{C}, ε_{22}^{T}, ε_{22}^{C} and γ_{12}) based material allowables, in tension, compression and shear should be input as shown below:

Allowables ⓘ

ID	$\sigma_{11}{}^{T}$	$\sigma_{11}{}^{C}$	$\sigma_{22}{}^{T}$	$\sigma_{22}{}^{C}$	τ_{12}
1	0	0	0	0	0

Allowables ⓘ

ID	$\varepsilon_{11}{}^{T}$	$\varepsilon_{11}{}^{C}$	$\varepsilon_{22}{}^{T}$	$\varepsilon_{22}{}^{C}$	γ_{12}
1	0	0	0	0	0

Allowables ⓘ

ID	$\sigma_{11}{}^{T}$	$\sigma_{22}{}^{T}$	τ_{12}
1	0	0	0

Strength allowables are input as MPa or Pa in SI system, and in Psi in the US systems, and should be consistent with the unit system used for input of Moduli

Inputs: Plies

❖ **Plies/Laminae:**

Types of plies in a face sheet laminate are required as input. Each ply type is defined by its angle (or orientation) in degrees, material type and its thickness. Material of a ply/lamina can be selected from a predefined list of materials that are input in the Material Properties Section above. The thickness of the ply or lamina is in mm or m in the SI system or inch in the US system. Multiple ply or lamina types can be input by simply clicking the '+' sign on the extreme right. The required ply/lamina type inputs with few examples are shown below:

Plies

ID	Angle (deg)	Material	Thickness		
1	0	Uni	0.005	+	–
2	45	PW	0.010	+	–
3	90	Uni	0.005	+	–

Plies

ID	Angle (deg)	Material	Thickness		
1	0	CEP	0.005	+	–
2	30	Flax	0.010	+	–
3	60	CEP	0.005	+	–

Plies

ID	Angle (deg)	Material	Thickness		
1	0	CEP	0.005	+	–
2	45	CEP	0.005	+	–
3	-45	CEP	0.005	+	–
4	90	CEP	0.005	+	–
5	0	Flax	0.01	+	–

Inputs: Cores

❖ Cores:

Types of cores are required as input. Each core type can be defined by its orientation angle in degrees, material type (isotropic or orthotropic) and its thickness. If option to analyze sandwich failure modes is selected, core compression shear modulus E_c, core allowable transverse shear strengths S_{xz} & S_{yz} and core allowable flatwise tension strength F_{WT} and compression strength F_{WC} are required as input. Strength allowables are input as MPa or Pa in SI system, and in Psi in the US systems, and should be consistent with the unit system used for input of Moduli

For isotropic core wrinkling factor k_1 (suggested value of $k_1 = 0.63 - 0.75$) is a user input. Effect of initial imperfection on Facesheet wrinkling can also be accounted through user's input of δ_0 value

Multiple core types can be input by simply clicking the '+' sign on the extreme right. A few examples of the core type inputs are shown below:

Cores

ID	Angle (deg)	Material	Thickness	Core Cell Size	E_c	S_{yz}	S_{xz}	FwT	δ_0	Core Type	k_1		
1	0	ortho core	0.5	0.125	20000	500	300	400	0	Orthotropic	0	+	−
2	0	Iso core	1.0	0.125	50000	1000	1000	600	0	Isotropic	0.65	+	−
3	90	ortho core	0.5	0.125	20000	500	300	400	0	Orthotropic	0	+	−

Inputs: Laminates

❖ Laminates:

Multiple faces sheet laminates can be quickly created by defining their stacking sequences using the plies defined in the previous step. Hybrid laminates can be defined using different ply and material combinations established in the previous steps. Additional laminates can be added by simply clicking the '+' sign on the extreme right. A few examples of laminates and their inputs are shown below:

Laminates

ID	Stacking Sequence	Stacking Sequence (Angle)	Offset		
CEP-QI	2,3,1,4,4,1,3,2	45,-45,0,90,90,0,-45	Middle	+	−
CEP-Cross Ply	1,4,1,4,1,4,1,4	0,90,0,90,0,90,0,90	Bottom	+	−
CEP-Angle Ply	2,3,2,3,2,3,2,3	45,-45,45,-45,45,-45	Top	+	−
CEP-Flax Hybrid	1,2,3,4,5	0,45,-45,90,0	Middle	+	−

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Inputs: Sandwich Panels

❖ Sandwich Panels:

Sandwich Panels are defined using the input definitions of laminates and cores. A sandwich panel has two face sheets, top (or upper) and bottom (or lower) and a core. Each sandwich panel has a unique ID that facilitates its analyses for multiple load cases. Sandwich panel analysis uses middle surface as reference plane. Additional sandwich panels can be added by simply clicking the '+' sign on the extreme right (see below):

Sandwich Panels

ID	Bottom Facesheet	Core	Top Facesheet		
1	1	1	1	+	−
2	1	2	1	+	−
3	1	3	1	+	−

Inputs: Loads

❖ Loads:

Hygrothermomechanical loads can be applied to the sandwich panels. Single or multiple sandwich panels can be analyzed for single or multiple load cases (up to 100 max). For analyses of sandwich panels subjected to mechanical loads, in-plane force and moment resultants, and transverse force resultants are provided as inputs. For thermomechanical analysis, temperature change is required as input. For hygromechanical analysis, change in moisture absorption is required as input. Examples of the load inputs for typical mechanical or a complete hygrothermomechanical analyses are shown below. Additional load cases can be added by simply clicking the '+' sign on the extreme right as shown below:

Loads

ID	Panel	N_{xx}	N_{yy}	N_{xy}	M_{xx}	M_{yy}	M_{xy}	Q_{yz}	Q_{xz}	
1	1	100	0	25	0	0	0	0	0	+ −
2	1	0	0	0	20	-10	0	0	0	+ −
3	2	10	-10	100	2	-1	-3.2	0	0	+ −
4	3	0	30	5.5	0	0	0	2.2	10	+ −
5	3	0	0	0	0	-10	0	5.2	0	+ −
6	4	20	0	0	-10	20	0	0	0	+ −
7	4	0	-10	15	0	0	2.5	0	0	+ −

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Inputs: Loads

Loads

ID	Panel	N_{xx}	N_{yy}	N_{xy}	M_{xx}	M_{yy}	M_{xy}	Q_{yz}	Q_{xz}	ΔT	ΔC
1	1	100	0	25	0	0	0	0	0	0	0
2	1	0	0	0	20	-10	0	0	0	0	0
3	2	10	-10	100	2	-1	-3.2	0	0	0	0
4	3	0	30	5.5	0	0	0	2.2	10	0	0
5	3	0	0	0	0	-10	0	5.2	0	0	0
6	4	20	0	0	-10	20	0	0	0	0	0
7	4	0	-10	15	0	0	2.5	0	0	0	0
8	1	50	0	0	0	10	0	0	0	-100	0
9	2	-10	0	20	0	0	0	0	0	0	1.5

In-plane force and transverse force resultants are input as N/mm or N/m in SI system, and lb/in in provided as inputs. Moment resultants are input in N-mm/mm or N-m/m in SI system, and lb-in/in in the US system. Differential Temperature is input in degree Celsius in SI system, and in Fahrenheit in the US system. Difference in moisture absorption is prescribed as Kg/Kg in SI system and lb/lb in the US system

Outputs

❖ Analysis Outputs:

Once all the Input steps viz., Analysis Options, Materials, Plies / Laminae, Laminates, Cores, Sandwich Panels and Loads are completed, analyses can be run by clicking the "submit" button. Maximum 100 Load Cases can be analyzed at one time

Submit

Upon completion of analyses, an output is displayed for each Load ID in the window underneath

Output

Depending upon the analysis option selected, the analyses output contains the following information at minimum.

- Material Properties and Facesheet Laminate Information
- Facesheet Laminate [A], [B], [D] stiffness matrices
- Effective Facesheet laminate in-plane and flexural engineering constants
- Effective Sandwich hygrothermal engineering constants
- Applied Hygro-thermo-mechanical loads
- Sandwich panel Reference plane strains and curvatures
- Ply-by-Ply in-plane strains and Stresses (TOTAL, MECHANICAL OR RESIDUAL) in global and ply coordinate systems for Facesheet
- Core transverse shear strains and stresses
- Face sheet Laminate/Lamina failure analysis– Failure Indices or Margins of Safety
- Sandwich Failure Modes Analysis

Outputs

❖ **Analysis Outputs:**

Note that all output is consistent with the unit system used during the material, lamina, Face sheet laminate, and loads Inputs.

- Top and Bottom Face sheets Laminate [A] stiffness matrices N/m or N/mm or lb/in
- Top and Bottom Face sheets Laminate [B] stiffness matrices N-m/m or N-mm/mm or lb-in/in
- Top and Bottom Face sheets Laminate [D] stiffness matrices N-m or N-mm or lb-in
- Top and Bottom Face sheets Effective laminate in-plane, flexural and hygrothermal engineering constants- same as material property inputs
- Sandwich Panel Reference plane strains – in/in, m/m, mm/mm
- Sandwich Panel Reference curvatures – 1/in, 1/mm, 1/m
- Face sheet Laminate Ply-by-Ply strains – in/in, m/m, mm/mm
- Face sheet Laminate Ply-by-Ply Stresses – Psi, MPa, Pa
- Face sheet Laminate/Lamina failure analysis– Failure Indices or Margins of Safety – Dimensionless
- Core Transverse Shear failure analysis– Failure Indices or Margins of Safety – Dimensionless
- Margins of Safety for overall Sandwich local and global failure modes

Outputs: Facesheet Stiffnesses

```
3pc-solver005, v1.0b0
LOADS ID  PANEL ID
1         28
                         MATERIAL PROPERTIES
ID          E1          E2          G12         G23         G13         v12
Pagano      2.50e+07    1.00e+06    5.00e+05    0.00e+00    0.00e+00    0.2500
PagaCor     4.00e+04    4.00e+04    1.60e+04    6.00e+04    6.00e+04    0.2500

   BOTTOM FACESHEET LAMINATE GEOMETRY
STACKING SEQUENCE (PLY ANG): [+0.0        ]
STACKING SEQUENCE (PLY MAT): [Pagano      ]

 CORE GEOMETRY
 CORE ANG: +0.0        CORE MAT: PagaCor      THICKNESS: 4.8000
CORE TYPE: isotropic CORE MODULUS Ec: 2.00e+05      CORE SHEAR MODULUS Gc: 6.00e+04      CORE CELL SIZE:
0.1250       INITIAL IMPERFECTION DELTA0: 0.0000       FLATWISE TENSION ALLOWABLE: 300.00       WRINKLING
PARAMETER K1: 0.63         ALLOWABLE SHEAR SXZ: 150.00       ALLOWABLE SHEAR SYZ: 250.00

    TOP FACESHEET LAMINATE GEOMETRY
STACKING SEQUENCE (PLY ANG): [+0.0        ]
STACKING SEQUENCE (PLY MAT): [Pagano      ]
TOTAL THICKNESS: 0.6000

BOTTOM FACESHEET LAMINATE PROPERTIES
             A MATRIX
+15037593.98  +150375.94   +0.00
+150375.94    +601503.76   +0.00
+0.00         +0.00        +300000.00

             B MATRIX
+0.00         +0.00        +0.00
+0.00         +0.00        +0.00
+0.00         +0.00        +0.00

             D MATRIX
+451127.82    +4511.28     +0.00
+4511.28      +18045.11    +0.00
+0.00         +0.00        +9000.00
```

Outputs: Sandwich Stiffnesses

TOP FACESHEET LAMINATE PROPERTIES

A MATRIX

+15037593.98	+150375.94	+0.00
+150375.94	+601503.76	+0.00
+0.00	+0.00	+300000.00

B MATRIX

+0.00	+0.00	+0.00
+0.00	+0.00	+0.00
+0.00	+0.00	+0.00

D MATRIX

+451127.82	+4511.28	+0.00
+4511.28	+18045.11	+0.00
+0.00	+0.00	+9000.00

SANDWICH LAMINATE PROPERTIES

A MATRIX

+30279987.97	+351951.88	+0.00
+351951.88	+1407807.52	+0.00
+0.00	+0.00	+676800.00

A MATRIX - TRANSVERSE SHEAR

+288000.00	+0.00
+0.00	+288000.00

B MATRIX

+0.00	+0.00	+0.00
+0.00	+0.00	+0.00
+0.00	+0.00	+0.00

D MATRIX

+220543591.94	+2299807.76	+0.00
+2299807.76	+9199231.04	+0.00
+0.00	+0.00	+4539456.00

Outputs: Applied Loads and Strains

EFFECTIVE BOTTOM FACESHEET LAMINATE INPLANE AND FLEXURAL ENGINEERING CONSTANTS

Ex	Ey	Gxy	vxy	vyx	Efx	Efy	Gfxy	vfxy	vfyx	
+2.50e+07	+1.00e+06	+5.00e+05	+0.2500	+0.0100	+2.50e+07	+1.00e+06	+5.00e+05	+0.2500	+0.0100	

EFFECTIVE TOP FACESHEET LAMINATE INPLANE AND FLEXURAL ENGINEERING CONSTANTS

Ex	Ey	Gxy	vxy	vyx	Efx	Efy	Gfxy	vfxy	vfyx
+2.50e+07	+1.00e+06	+5.00e+05	+0.2500	+0.0100	+2.50e+07	+1.00e+06	+5.00e+05	+0.2500	+0.0100

MECHANICAL LOADS AND MOMENTS

NX	NY	NXY	MX	MY	MXY	QXZ	QYZ	
+0.00	+0.00	+0.00	+985.50	+9.29	+0.00	+0.00	+0.00	+0.00

SANDWICH REFERENCE PLANE STRAINS AND CURVATURES

EPSX0 (x 1E-6)	EPSY0 (x 1E-6)	GAMMAXY0 (x 1E-6)	KAPPAX0 (x 1E-6)	KAPPAY0 (x 1E-6)	KAPPAXY0 (x 1E-6)	GAMMAYZ0 (x 1E-6)	GAMMAXZ0 (x 1E-6)
-0.00	-0.00	+0.00	+4.47	-0.11	+0.00	+0.00	+0.00

BOTTOM FACESHEET LAMINATE PLY BY PLY INPLANE STRAINS (TOTAL) FAILURE ANALYSIS - MAX STRAIN

ANGLE	Z	EPS1 (x 1E-6)	EPS2 (x 1E-6)	GAMMA12 (x 1E-6)	EPSX (x 1E-6)	EPSY (x 1E-6)	GAMMAXY (x 1E-6)	MS1	MS2	MS12
+0.0	-3.00000	-13.41	+0.32	+0.00	-13.41	+0.32	+0.00	+73.58	NA	NA
	-2.70000	-12.07	+0.29	+0.00	-12.07	+0.29	+0.00	+81.86	NA	NA
	-2.40000	-10.73	+0.26	+0.00	-10.73	+0.26	+0.00	+92.22	NA	NA

TOP FACESHEET LAMINATE PLY BY PLY INPLANE STRAINS (TOTAL) FAILURE ANALYSIS - MAX STRAIN

ANGLE	Z	EPS1 (x 1E-6)	EPS2 (x 1E-6)	GAMMA12 (x 1E-6)	EPSX (x 1E-6)	EPSY (x 1E-6)	GAMMAXY (x 1E-6)	MS1	MS2	MS12
+0.0	+2.40000	+10.73	-0.26	+0.00	+10.73	-0.26	+0.00	+92.22	NA	NA
	+2.70000	+12.07	-0.29	+0.00	+12.07	-0.29	+0.00	+81.86	NA	NA
	+3.00000	+13.41	-0.32	+0.00	+13.41	-0.32	+0.00	+73.58	NA	NA

Outputs: Strains and Stresses

BOTTOM FACESHEET LAMINATE TRANSVERSE SHEAR STRAINS

ANGLE	Z	GAMMA23	GAMMA13	GAMMAYZ	GAMMAXZ
		(x 1E-6)	(x 1E-6)	(x 1E-6)	(x 1E-6)
+0.0	-3.00000	+0.00	+0.00	+0.00	+0.00
	-2.70000	+0.00	+0.00	+0.00	+0.00
	-2.40000	+0.00	+0.00	+0.00	+0.00

CORE TRANSVERSE SHEAR STRAINS

ANGLE	Z	GAMMA23	GAMMA13	GAMMAYZ	GAMMAXZ
		(x 1E-6)	(x 1E-6)	(x 1E-6)	(x 1E-6)
+0.0	-2.40000	+0.00	+0.00	+0.00	+0.00
	+0.00000	+0.00	+0.00	+0.00	+0.00
	+2.40000	+0.00	+0.00	+0.00	+0.00

TOP FACESHEET LAMINATE TRANSVERSE SHEAR STRAINS

ANGLE	Z	GAMMA23	GAMMA13	GAMMAYZ	GAMMAXZ
		(x 1E-6)	(x 1E-6)	(x 1E-6)	(x 1E-6)
+0.0	+2.40000	+0.00	+0.00	+0.00	+0.00
	+2.70000	+0.00	+0.00	+0.00	+0.00
	+3.00000	+0.00	+0.00	+0.00	+0.00

BOTTOM FACESHEET LAMINATE PLY BY PLY INPLANE STRESSES (TOTAL)

ANGLE	Z	SIG1	SIG2	TAU12	SIGX	SIGY	TAUXY
+0.0	-3.00000	-335.98	-3.04	+0.00	-335.98	-3.04	+0.00
	-2.70000	-302.38	-2.73	+0.00	-302.38	-2.73	+0.00
	-2.40000	-268.79	-2.43	+0.00	-268.79	-2.43	+0.00

TOP FACESHEET LAMINATE PLY BY PLY INPLANE STRESSES (TOTAL)

ANGLE	Z	SIG1	SIG2	TAU12	SIGX	SIGY	TAUXY
+0.0	+2.40000	+268.79	+2.43	+0.00	+268.79	+2.43	+0.00
	+2.70000	+302.38	+2.73	+0.00	+302.38	+2.73	+0.00
	+3.00000	+335.98	+3.04	+0.00	+335.98	+3.04	+0.00

Outputs: Strains and Stresses

BOTTOM FACESHEET LAMINATE TRANSVERSE SHEAR STRESSES

ANGLE	Z	TAU23	TAU13	TAUYZ	TAUXZ
+0.0	-3.00000	+0.00	+0.00	+0.00	+0.00
	-2.70000	+0.00	+0.00	-0.00	-0.00
	-2.40000	+0.00	+0.00	-0.00	-0.00

CORE TRANSVERSE SHEAR STRESSES

ANGLE	Z	TAU23	TAU13	TAUYZ	TAUXZ
+0.0	-2.40000	+0.00	+0.00	+0.00	+0.00
	+0.00000	+0.00	+0.00	+0.00	+0.00
	+2.40000	+0.00	+0.00	+0.00	+0.00

TOP FACESHEET LAMINATE TRANSVERSE SHEAR STRESSES

ANGLE	Z	TAU23	TAU13	TAUYZ	TAUXZ
+0.0	+2.40000	+0.00	+0.00	-0.00	-0.00
	+2.70000	+0.00	+0.00	-0.00	-0.00
	+3.00000	+0.00	+0.00	+0.00	+0.00

Outputs: Sandwich Specific Failure Analysis

ADDITIONAL SANDWICH FAILURE MODES

INTRACELLULAR BUCKLING / DIMPLING
BOTTOM FACESHEET LAMINATE
APPLIED NXX: -181.43 APPLIED NYY: -1.64
ALLOWABLE (LOADS PER UNIT LENGTH): -138586466.17 MS: -763854.19
TOP FACESHEET LAMINATEAPPLIED NXX: +181.43
APPLIED NYY: +1.64
ALLOWABLE (LOADS PER UNIT LENGTH): -138586466.17
MINIMUM MS: NA

WRINKLING

BOTTOM FACESHEET LAMINATE
APPLIED NXX: -181.43
APPLIED NYY: -1.64
ALLOWABLE NXX: +74534085.63 ALLOWABLE NYY: +14906817.13
MINIMUM MS (NO INTERACTION): +410811.84
FAILURE INDEX (INTERACTION): +0.00

TOP FACESHEET LAMINATE
APPLIED NXX: +181.43 APPLIED NYY: +1.64
ALLOWABLE NXX: +74534085.63 ALLOWABLE NYY: +14906817.13
MINIMUM MS (NO INTERACTION): NA
FAILURE INDEX (INTERACTION): NA

SHEAR CRIMPING
APPLIED NXX: +0.00 APPLIED NYY: +0.00 APPLIED NXY: +0.00
ALLOWABLE NXX: +364500.00 ALLOWABLE NYY: +364500.00 ALLOWABLE NXY: +364500.00
MINIMUM MS: NA

Inputs and Outputs: Consistent Units

Quantity	SI System 1	SI system 2	US System
$E_1, E_2, G_{12}, G_{13}, G_{23}$ $E_x, E_y, G_{xy}, E_{fx}, E_{fy}, G_{fxy}, E_c$	$MPa\ (N/mm^2)$	$Pa\ (N/m^2)$	$Psi\ (lb/in^2)$
$\alpha_1\ ,\ \alpha_2\ ,\ \alpha_x\ ,\ \alpha_y,\ \alpha_{xy}$	$mm/mm/$°C	$m/m/$°C	$in/in/$°F
$\beta_1, \beta_2\ ,\ \beta_x\ ,\ \beta_y, \beta_{xy}$	$mm/mm/Kg/Kg$	$m/m/Kg/Kg$	$in/in/lb/lb$
$\sigma_{11}^T, \sigma_{11}^C, \sigma_{22}^T, \sigma_{22}^C\ \tau_{12}^S, \sigma_1, \sigma_2, \tau_{12}, \tau_{23}, \tau_{13},$ $\sigma_x, \sigma_y, \tau_{xy}, \tau_{yz}, \tau_{xz}, S_{xz}, S_{yz}, F_{WT}, F_{WC}$	$MPa\ (N/mm^2)$	$Pa\ (N/m^2)$	$Psi\ (lb/in^2)$
$\varepsilon_{11}^T, \varepsilon_{11}^C, \varepsilon_{22}^T, \varepsilon_{22}^C, \gamma_{12}, \varepsilon_1, \varepsilon_2, \gamma_{12}, \gamma_{13}, \gamma_{23}, \varepsilon_{x0},$ $\varepsilon_{y0}, \gamma_{xy0}, \gamma_{yz0}, \gamma_{xz0}\ \varepsilon_x, \varepsilon_y, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}$	mm/mm	m/m	$in/$in
$\kappa_{x0}, \kappa_{y0}, \kappa_{xy0}$	$1/mm$	$1/m$	$1/in$
$N_{xx}, N_{yy}, N_{xy}, N_{xx}^T, N_{yy}^T, N_{xy}^T,$ $N_{xx}^H, N_{yy}^H, N_{xy}^H$, [A]	N/mm	N/m	lb/in
$M_{xx}, M_{yy}, M_{xy}, M_{xx}^T, M_{yy}^T, M_{xy}^T,$ $M_{xx}^H, M_{yy}^H, M_{xy}^H$, [B]	$N-mm/mm$	$N-m/m$	$lb-in/in$
[D]	$N-mm$	$N-m$	$lb-in$
ΔT	°C	°C	°F
ΔC	Kg/Kg	Kg/Kg	lb/lb
Ply Angle, θ	Degree	Degree	Degree
Ply or Laminate thickness or Offset, w, δ_0	mm	m	in

3P COMPOSITES PRODUCIBILITY PERFORMANCE PROFITABILITY

Other Features

❖ Upload/Download:

Users can upload and download material properties, Cores, Plies, Laminates, Sandwich Panels and Loads data files (*.jso using the upload and download buttons next to these inputs. Sample input and output files can be downloaded from the 3p Composites website at www.3pcomposites.com

❖ Additional Output:

Users can review a few intermediate calculations such as minor Poison's ratios ν_{21}, Q_{ij} for each ply type and laminate ABD by using the calculation button . Examples are shown below:

Materials

E_1	E_2	G_{12}	G_{23}	G_{13}	ν_{12}	α_1	α_2	β_1

ID	v21
GMS4020 PW	0.05
GMS4020 Tape	0.0254
2024-T3	0.3
Rastogi_Fiberglass	0.02667
Tuttle	0.01662

Other Features

Plies

ID	Angle (deg)	Material	Thickness
1	0	Tuttle	0.0075
2	90	Tuttle	0.0075

ID	Q	Q44	Q55	Qbar	Q44bar	Q45bar	Q55bar
1	[[22627882.74, 376125.7, 0.0], [376125.7, 1106252.04, 0.0], [0.0, 0.0, 640000.0]]	640000	640000	[[22627882.74, 376125.7, 0.0], [376125.7, 1106252.04, 0.0], [0.0, 0.0, 640000.0]]	640000	0	640000
2	[[22627882.74, 376125.7, 0.0], [376125.7, 1106252.04, 0.0], [0.0, 0.0, 640000.0]]	640000	640000	[[1106252.04, 376125.7, 0.0], [376125.7, 22627882.74, 0.0], [0.0, 0.0, 640000.0]]	640000	0	640000
3	[[22627882.74, 376125.7, 0.0], [376125.7, 1106252.04, 0.0], [0.0, 0.0, 640000.0]]	640000	640000	[[6761596.54, 5481596.54, 5380407.67], [5481596.54, 6761596.54, 5380407.67], [5380407.67, 5380407.67, 5745470.85]]	640000	0	640000
4	[[22627882.74, 376125.7, 0.0], [376125.7, 1106252.04, 0.0], [0.0, 0.0, 640000.0]]	640000	640000	[[6761596.54, 5481596.54, -5380407.67], [5481596.54, 6761596.54, -5380407.67], [-5380407.67, -5380407.67, 5745470.85]]	640000	0	640000

Laminates

ID	Stacking Sequence	Stacking Sequence (Angle)	Offset
1	1,1,1,1,1,1,1,1	0,0,0,0,0,0,0,0	Middle
2	1,2,1,2,2,1,2,1	0,90,0,90,90,0,90,0	Middle
3	3,4,3,4,4,3,4,3	45,-45,45,-45,-45,45	Middle

ID	Thickness	A	B	D	A44	A45	A55
1	0.06	[[1357672.96, 22567.54, 0.0], [22567.54, 66375.12, 0.0], [0.0, 0.0, 38400.0]]	[[0.0, 0.0, 0.0], [0.0, -0.0, 0.0], [0.0, 0.0, 0.0]]	[[407.3, 6.77, 0.0], [6.77, 19.91, 0.0], [0.0, 0.0, 11.52]]	38400	0	38400
2	0.06	[[712024.04, 22567.54, 0.0], [22567.54, 712024.04, 0.0], [0.0, 0.0, 38400.0]]	[[0.0, 0.0, 0.0], [0.0, -0.0, 0.0], [0.0, 0.0, 0.0]]	[[286.24, 6.77, 0.0], [6.77, 140.97, 0.0], [0.0, 0.0, 11.52]]	38400	0	38400
3	0.06	[[405695.79, 328895.79, 0.0], [328895.79, 405695.79, 0.0], [0.0, 0.0, 344728.25]]	[[0.0, -0.0, 0.0], [-0.0, -0.0, 0.0], [0.0, 0.0, -0.0]]	[[121.71, 98.67, 36.32], [98.67, 121.71, 36.32], [36.32, 36.32, 103.42]]	38400	0	38400

3P COMPOSITES

General Information

- Subscription fee to access 3pcsolver005 is $39/year per for a single-login license

- Training module 3pcmodule005 supports the solver 3pcsolver005. Users' can buy the training module 3pcmodule001 online at

  https://www.3pcomposites.com/

- 3P Composites, LLC can conduct online or in-class trainings for the 3pcsolver005 and 3pcmodule005. The training can be adapted to meet the requirements of individual needs and/or industrial applications

- For questions, issues, comments, suggestions, trainings, please contact us at 3pcomps@gmail.com. Your feedback is appreciated in helping us continuously improve the product

Example: Strength Analysis of a Sandwich Plate

- Lamina Properties: $E_1 = 1.68e7\ psi, E_2 = 1.16e6\ psi, G_{12} = G_{13} = 8.0e5\ psi, G_{23} = 6.0e5\ psi, \nu_{21} = 0.35$, $t_{ply} = 0.00525\ in$, $\varepsilon_{11}^{T} = 5000\ \mu\varepsilon, \varepsilon_{11}^{C} = -5000\ \mu\varepsilon, \varepsilon_{22}^{T} = 20000\ \mu\varepsilon$, $\varepsilon_{22}^{C} = -20000\ \mu\varepsilon, \gamma_{12} = 20000\ \mu\varepsilon$;

Core Properties: $E_1 = E_2 = 1000\ psi, E_3 = E_c = 10000\ psi, G_{12} = 10\ psi, G_{13} = 13000\ psi, G_{23} = 6000\ psi, \nu_{21} = 0.1, t_{core} = 0.5\ inch$, Angle = 0, Type: orthotropic, Core Cell Size = 0.125 in, Initial imperfection = 0.0, Flatwise Tension Allowable = 350.00 Psi, Wrinkling Parameter K1 = 0, Allowable Shear Strength $S_{23} = 250\ Psi$ and $S_{13} = 150\ Psi$

- Plate Dimensions: L = 15 in., W = 10 in., Aspect Ratio $\frac{L}{W} = 1.5$

- Facesheet Laminates: Bottom - $[0/90/\pm45/0/90]_T$,Top - $[90/0/\mp45/90/0]_T$

- Load Cases: M_{xx} = 321.40 lb-in/in, M_{yy} = 392.7 lb-in/in , Q_{yz} = 80 lb/in. Laminate Failure Criteria: Maximum Strain, Sandwich Failure Modes

- MATLAB scripts are used to plot transverse displacement w, moment resultants M_{xx} ,M_{yy} and M_{xy} and the transverse shear force resultants Q_{xz} and Q_{yz} in the laminated plate subjected to transverse loading

Strength Analysis of Sandwich Plate

❖ BOTTOM FACESHEET LAMINATE PROPERTIES:

A MATRIX

+248285.53	+49895.58	+0.00
+49895.58	+248285.53	+0.00
+0.00	+0.00	+62197.49

B MATRIX

-434.75	+0.00	-108.69
+0.00	+434.75	-108.69
-108.69	-108.69	+0.00

D MATRIX

+23.25	+1.41	-0.00
+1.41	+23.25	+0.00
-0.00	+0.00	+2.42

TOTAL THICKNESS: 0.0315

❖ TOP FACESHEET LAMINATE PROPERTIES:

A MATRIX

+248285.53	+49895.58	+0.00
+49895.58	+248285.53	+0.00
+0.00	+0.00	+62197.49

B MATRIX

+434.75	+0.00	+108.69
+0.00	-434.75	+108.69
+108.69	+108.69	+0.00

D MATRIX

+23.25	+1.41	+0.00
+1.41	+23.25	+0.00
+0.00	+0.00	+2.42

TOTAL THICKNESS: 0.0315

Strength Analysis of Sandwich Plate

- SANDWICH PLATE PROPERTIES

A MATRIX

+497076.11	+99841.67	+0.00
+99841.67	+497076.11	+0.00
+0.00	+0.00	+124399.97

A MATRIX - TRANSVERSE SHEAR

+3000.00	+0.00
+0.00	+6500.00

B MATRIX

-0.00	+0.00	-0.00
+0.00	+0.00	-0.00
-0.00	-0.00	+0.00

D MATRIX

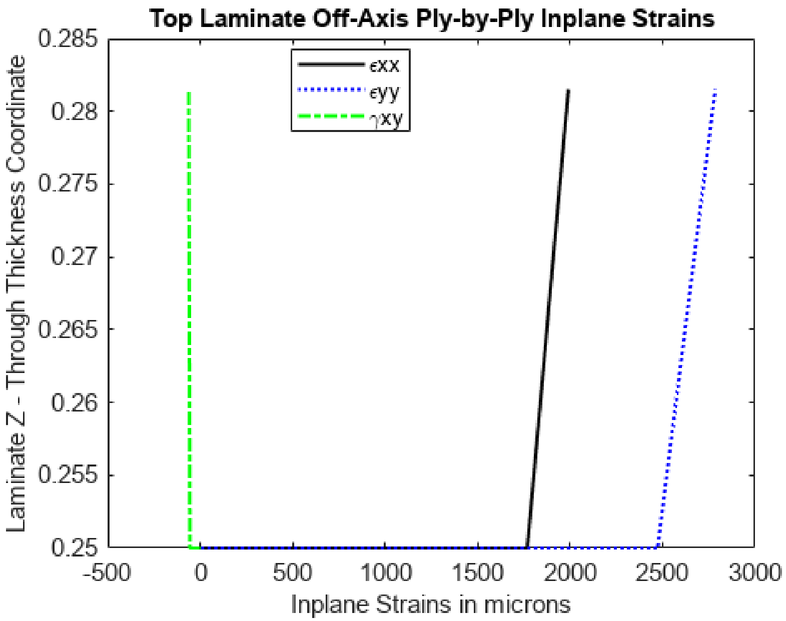
+35588.53	+7051.42	+115.54
+7051.42	+34664.25	+115.54
+115.54	+115.54	+8790.11

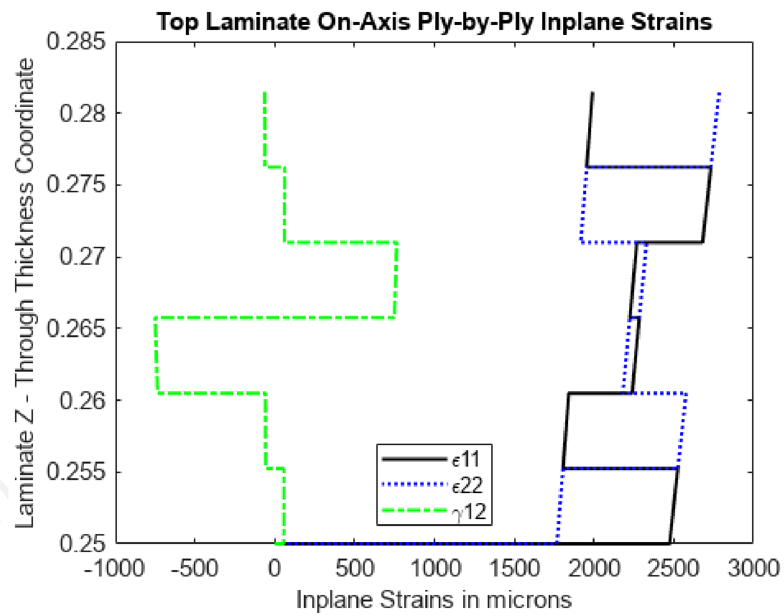
TOTAL THICKNESS: 0.5630

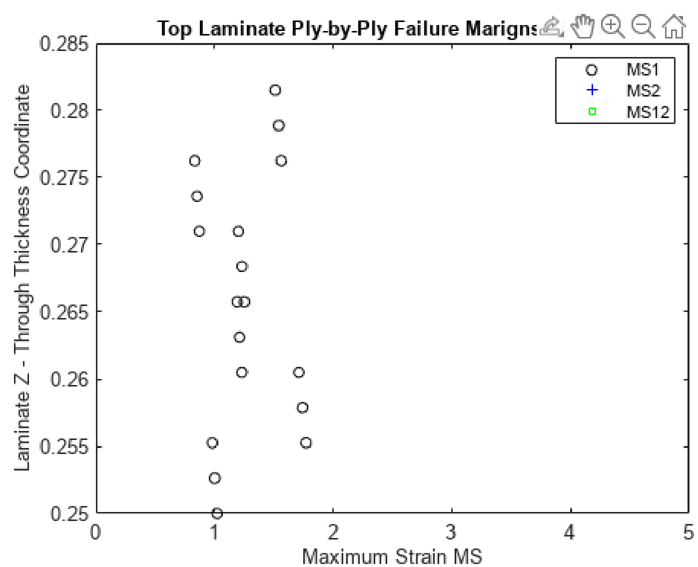
- Mid Plane Strains and Curvatures:

$\varepsilon_{x0} = \varepsilon_{y0} = \gamma_{xy0} = 0.0\ \mu\varepsilon$, $\kappa_{x0} = 0.007072$ 1/in, $\kappa_{y0} = 0.009891$ 1/in, $\kappa_{xy0} = -0.000223$

Ply-by-Ply Strains & MS -Top Facesheet

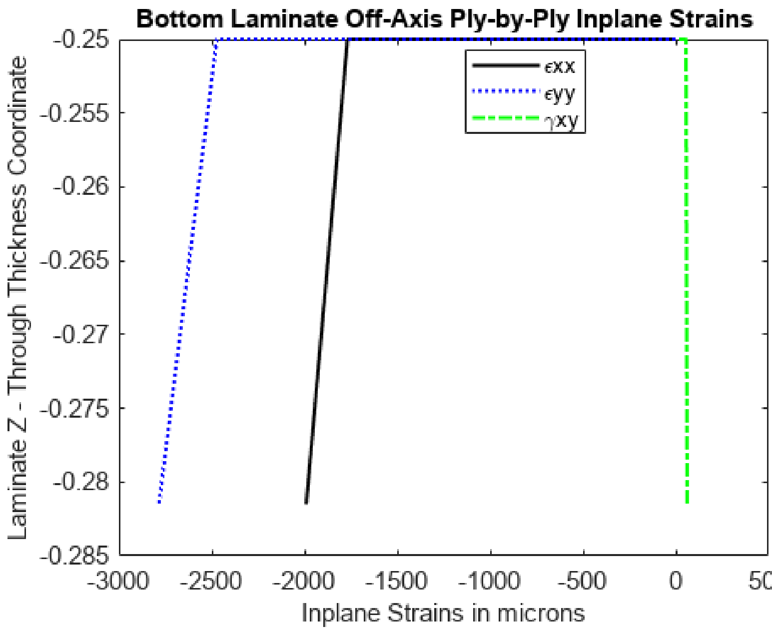


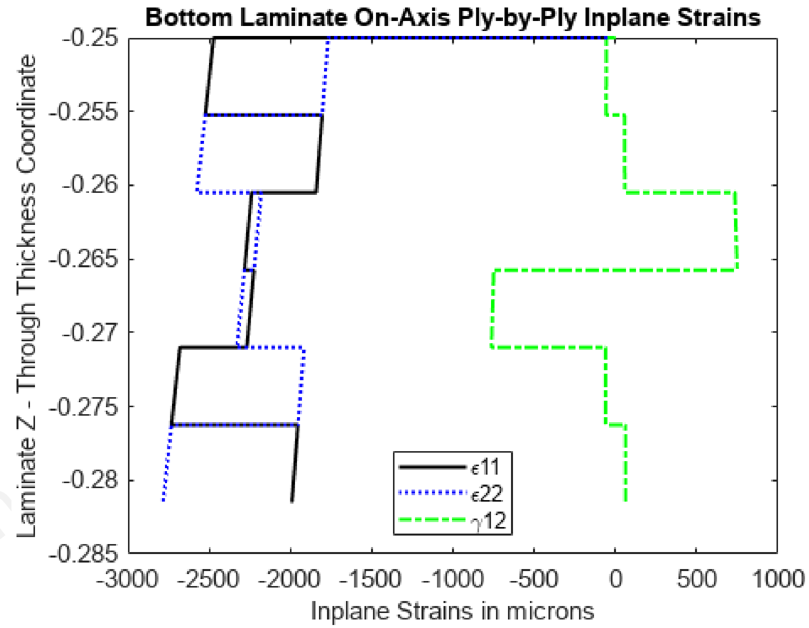


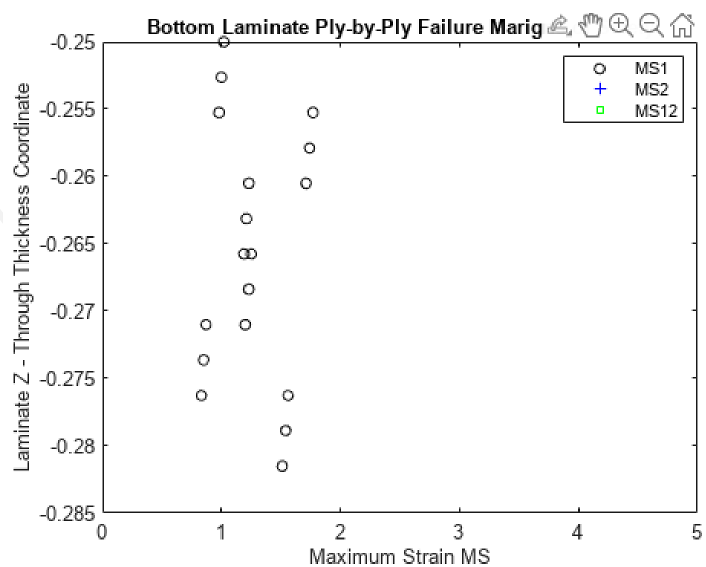


3P COMPOSITES
PRODUCIBILITY PERFORMANCE PROFITABILITY

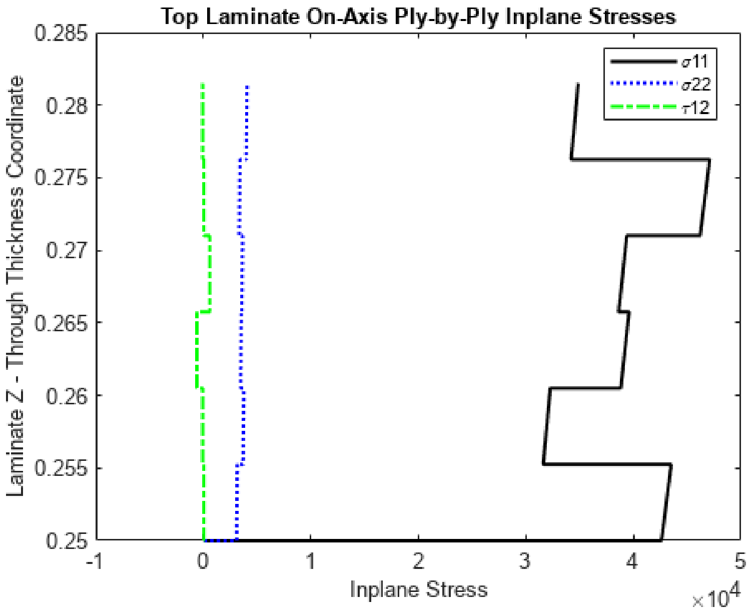
Ply-by-Ply Strains & MS - Bottom Facesheet

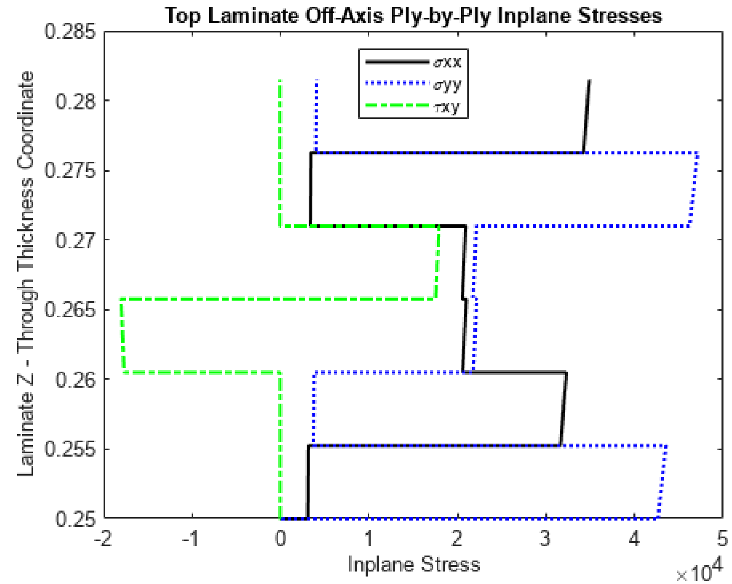


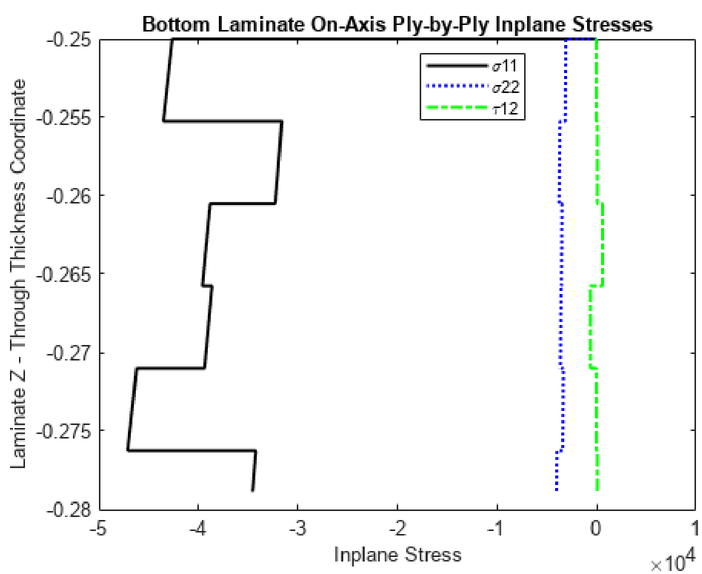


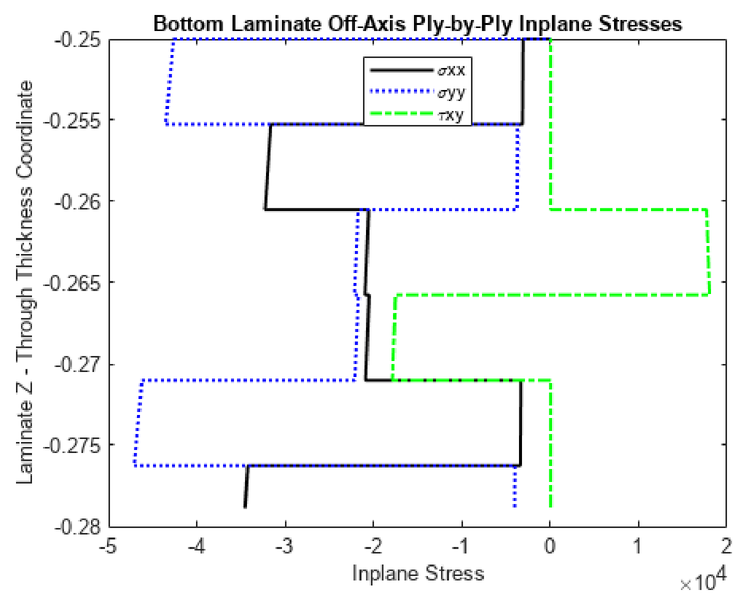


Face sheets Ply-by-Ply Stresses



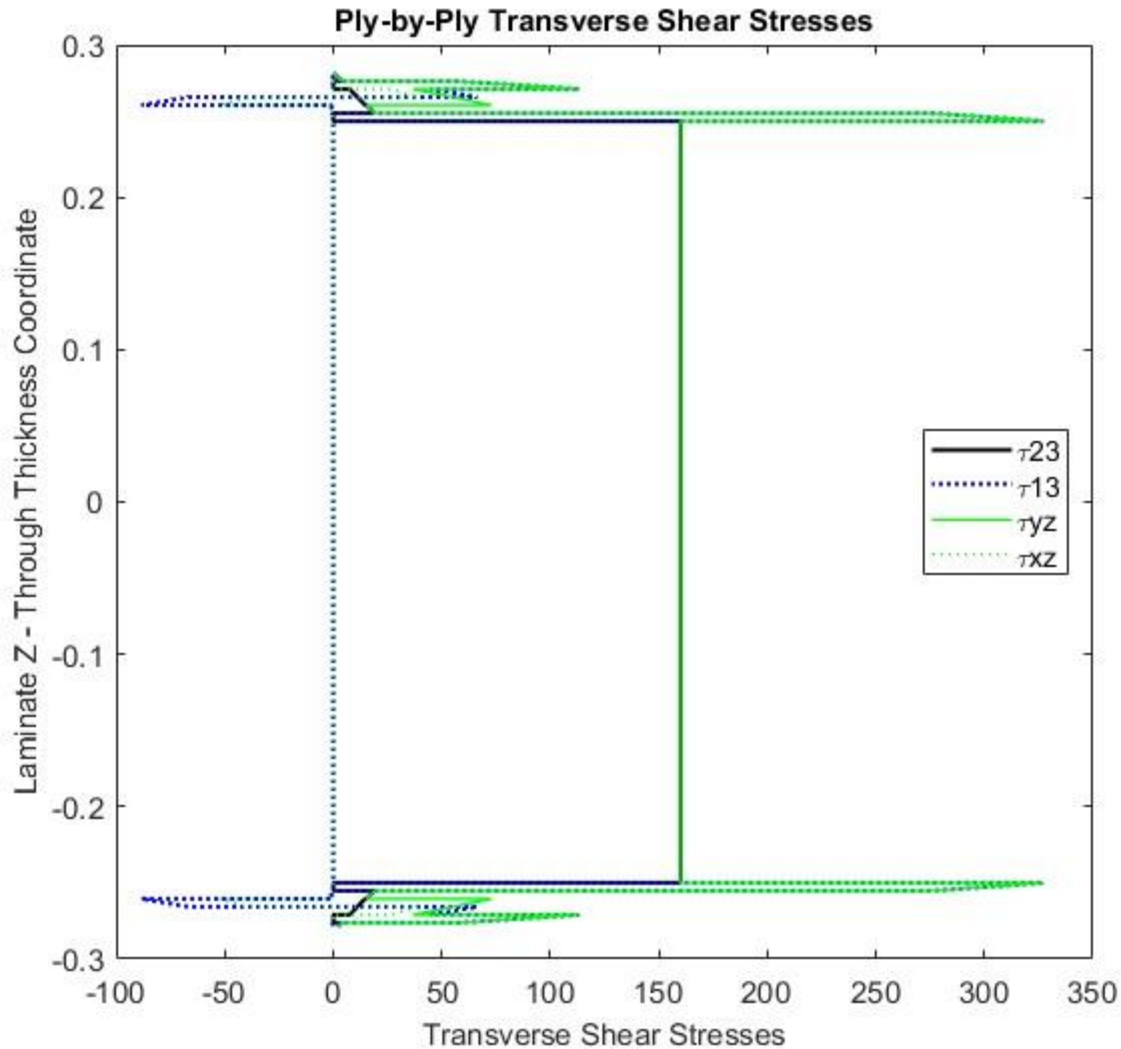






3P COMPOSITES
PRODUCIBILITY PERFORMANCE PROFITABILITY

Transverse Shear Stresses in Sandwich

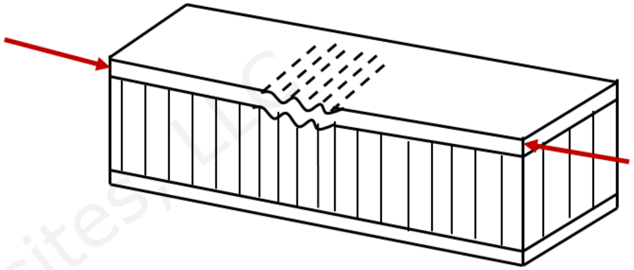


Additional Sandwich Failure Modes

❖ INTRACELLULAR BUCKLING / DIMPLING

BOTTOM FACESHEET LAMINATE

APPLIED NXX: -600.82
APPLIED NYY: -742.06
ALLOWABLE (LOADS PER UNIT LENGTH): -31534.25
MS: +41.50

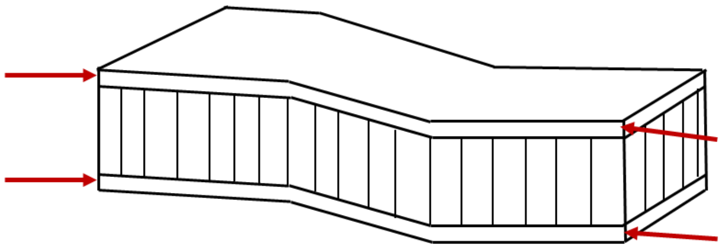


TOP FACESHEET LAMINATE

APPLIED NXX: +600.82
APPLIED NYY: +742.06
ALLOWABLE (LOADS PER UNIT LENGTH): -31534.25
MINIMUM MS: NA (since Top Facesheet is in tension)

❖ SHEAR CRIMPING

APPLIED NXX: +0.00
APPLIED NYY: +0.00
APPLIED NXY: +0.00
ALLOWABLE NXX: -7344.80
ALLOWABLE NYY: -3389.91
ALLOWABLE NXY: +4989.81
MINIMUM MS: NA

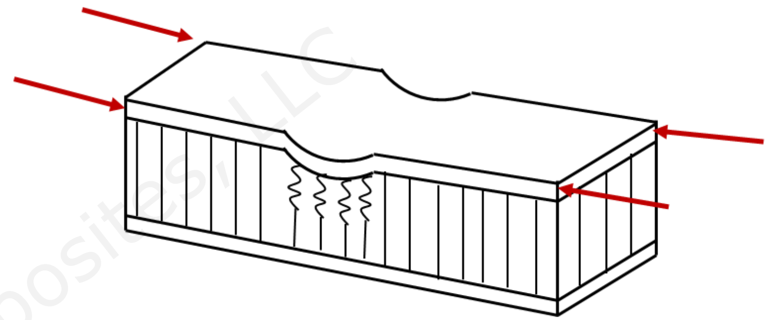


Additional Sandwich Failure Modes

❖ WRINKLING

BOTTOM FACESHEET LAMINATE

APPLIED NXX: -600.82
APPLIED NYY: -742.06
ALLOWABLE NXX: -1933.43
ALLOWABLE NYY: -1933.43
MINIMUM MS (NO INTERACTION): +1.61
FAILURE INDEX (INTERACTION): +0.35



TOP FACESHEET LAMINATE

APPLIED NXX: +600.82
APPLIED NYY: +742.06
ALLOWABLE NXX: -1933.43
ALLOWABLE NYY: -1933.43
MINIMUM MS (NO INTERACTION): NA (since Top Facesheet is in tension)
FAILURE INDEX (INTERACTION): NA

❖ CORE TRANSVERSE SHEAR STRESSES

ANGLE	Z	TAU23	TAU13	TAUYZ	TAUXZ	MS
+0.0	-0.25000	+160.00	+0.00	+160.00	+0.00	
	-0.00000	+160.00	+0.00	+160.00	+0.00	**-0.06**
	+0.25000	+160.00	+0.00	+160.00	+0.00