A Comparison of Composite Modeling Techniques

Allison Hutchings
Michael Palodichuk
ATA Engineering

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Average Analysts Have Little Background Using Increasingly Popular Composite Materials

- Composite materials are made from two or more constituent materials
  - These materials have different physical or chemical properties
  - When combined they produce a material with characteristics different from the individual components
- As more industries and applications begin to use composites, more analysis is being done by analysts of varying backgrounds

Disassembled composite fuselage of a Boeing Dreamliner. (Source: Wikipedia)

A 2012 PLM World Presentation Highlighted The Challenges Of Composite Analysis

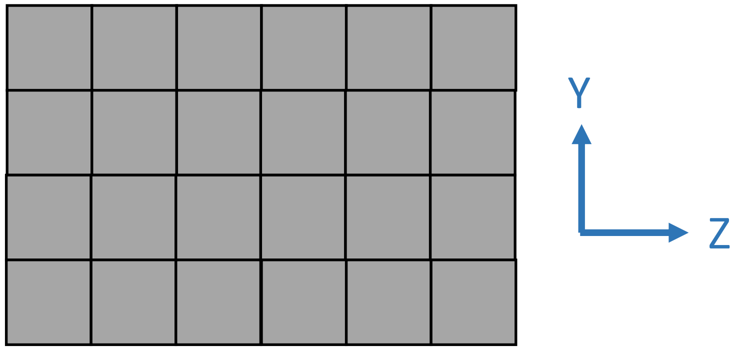
- Analysis of composites can be extremely time consuming
- There is often a lack of material (stiffness and strength) data from testing or manufacturing
- There are many failure modes to study
- The selection of element types is specialized for analysis
  - Failure often may happen thru the thickness, but plates or layered PCOMP may not capture that well
- High stresses in bonds or joints are often at singular locations
  - Refining the mesh increases the stress as the mesh gets smaller and smaller
  - Stresses obtained may not be meaningful without normalization to element size or testing

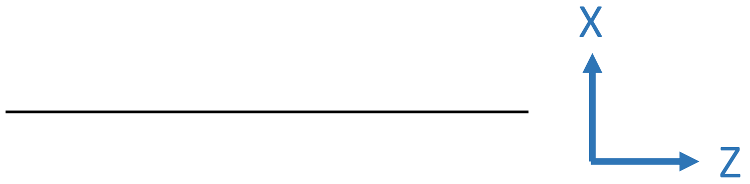
Agenda

- **Review of Typical Composite Modeling Techniques**
  - Shell elements with PSHELL/PCOMP properties
  - 3D elements with PSOLID properties
  - 3D elements with PCOMPS properties
- **Closed Form Verification**
- **Representative Test Cases**
  - Single-Lap-Joint (ASTM 1002)
  - Peel Resistance (ASTM 1876)
- **Summary and Observations**

Composite Modeling Techniques (1 of 3)
2D Elements with PSHELL or PCOMP properties

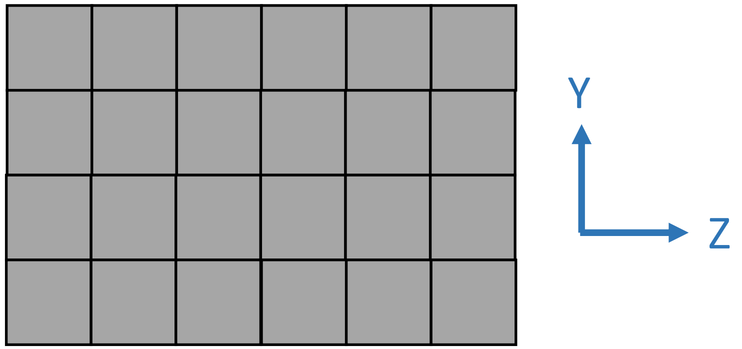
- The PSHELL method can be used to "directly input membrane, bending, membrane-bending coupling, and transverse shear constitutive relationships"
  - Good for defining simpler composites but quickly gets complex with more detailed laminates
  - You can only directly recover smeared element data (post-recovery can be used for ply-by-ply results)
- The PCOMP/PCOMPG method can be used to define the laminate via a ply-by-ply method and the software will compute the equivalent PSHELL and MAT2 entries. This method uses classical lamination theory.
  - The user defines thickness, orientation, and the material properties for each lamina
- Can be applied to CQUAD4, CQUAD8, CQUADR, CTRIA3, CTRIAR and CTRIA6 elements

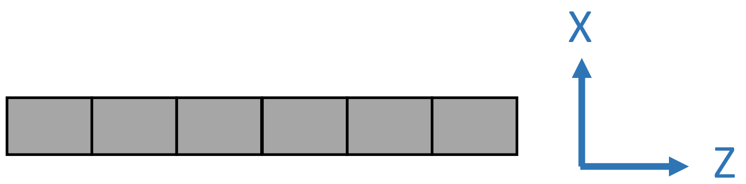




Composite Modeling Techniques (2 of 3)
3D Elements with PCOMPS properties

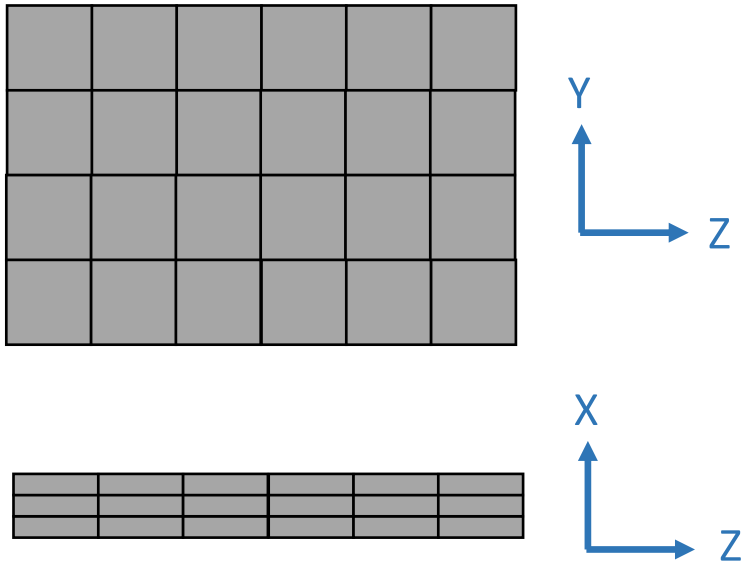
- Similar to the PCOMP method, the PCOMPS method uses ply-by-ply properties but applies them to 3D elements (CHEXA and CPENTA)
  - It is not based on classical lamination theory so is useful for modeling thick laminates where interlaminar and normal stresses may be important
  - The user defines thickness, orientation, and the material properties for each lamina
- Note: The MAT11 card is a newer material definition for Orthotropic Solid Materials





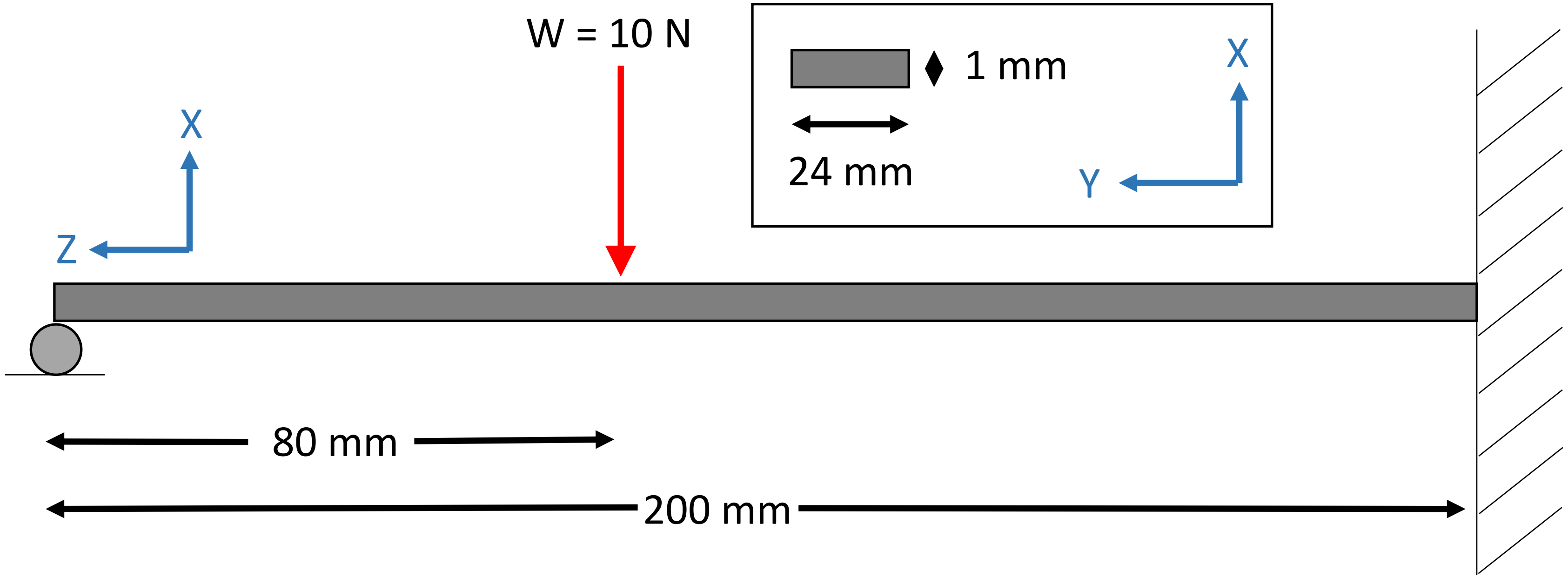
Composite Modeling Techniques (3 of 3)
3D Elements with linear bricks

- A final method is to model your lamina with individual layers of linear bricks with the appropriate material data and directionality



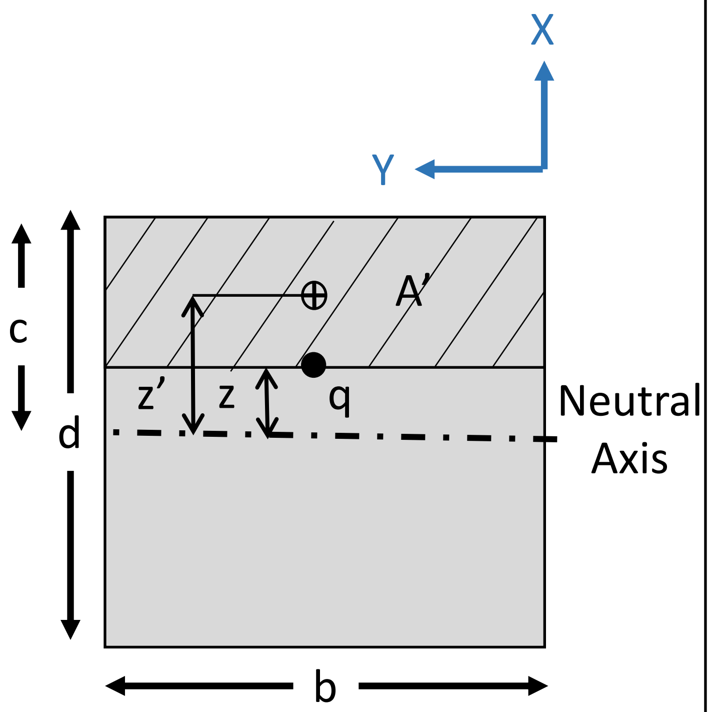
For Closed Form Verification Can Look at a Simply Supported Cantilever Beam With Point Load

- Simple closed form example
- Using properties for aluminum (AL 2024 T3)



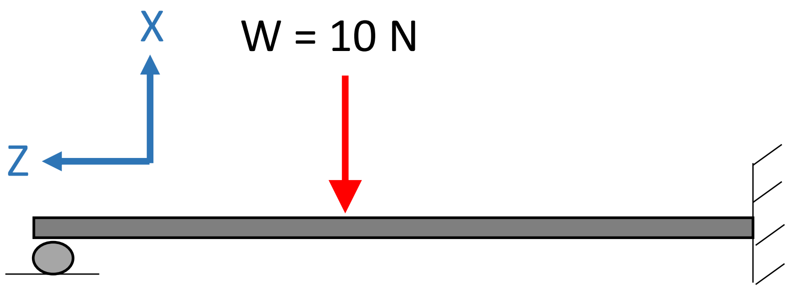
- We will compare the element types with this simple test case first
  - Note, we are starting with isotropic so that we can compare element formulations without material orientation as an additional variable

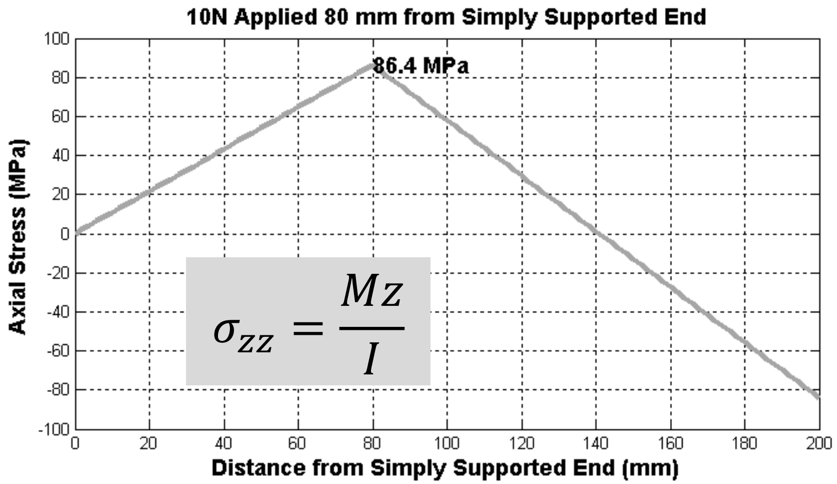
The Exact Solutions for Displacement, Axial Stress, & Axial-Normal Shear Stress Can All Be Found

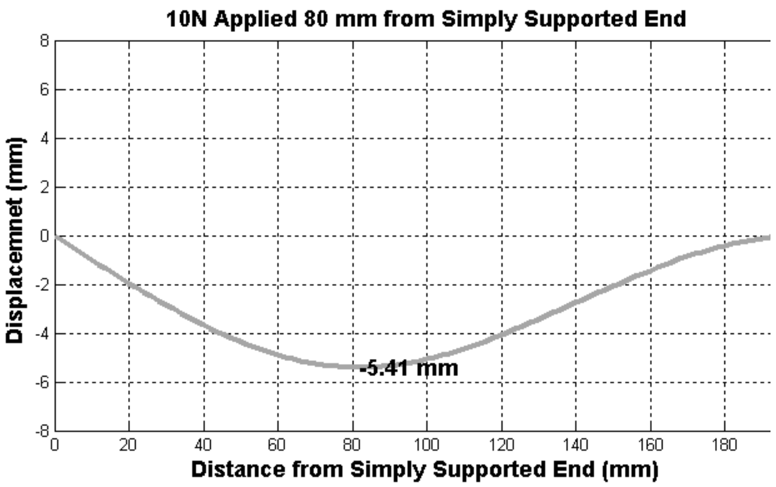


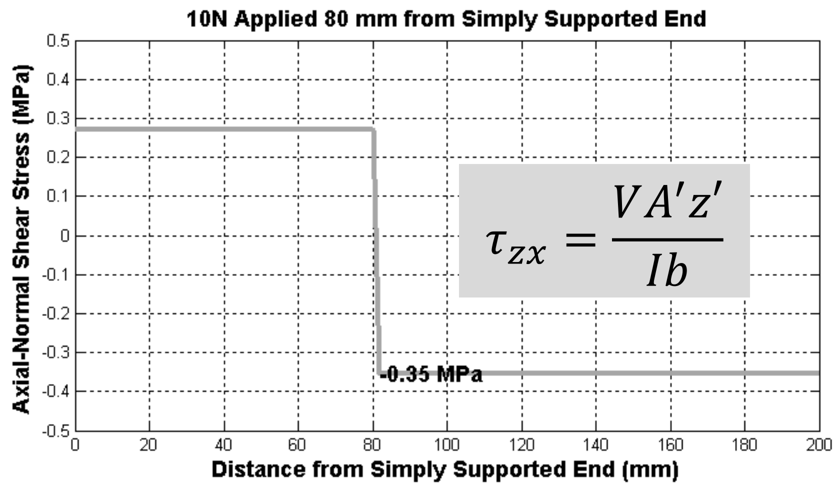
σ_{max} at top/bottom surface

τ_{max} at neutral axis

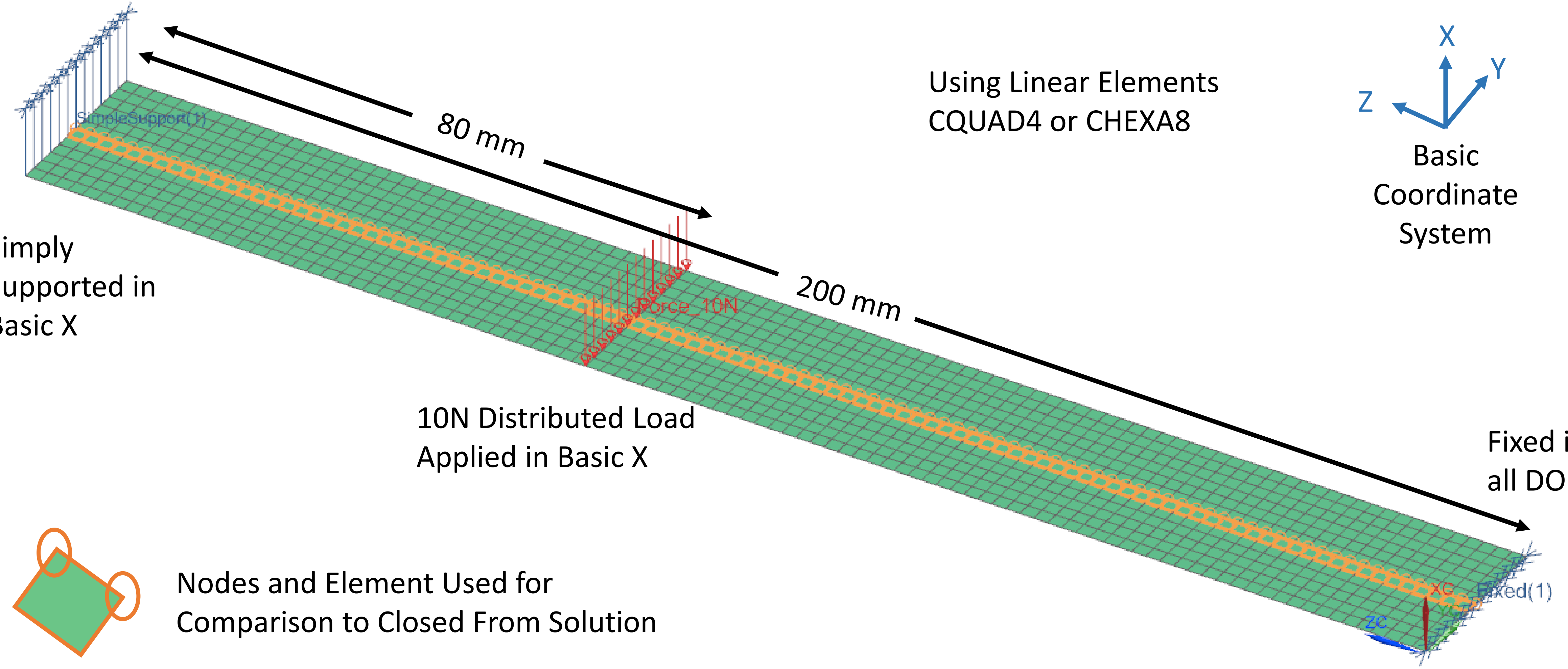








Example Model Using CQUAD4 Elements



Using Linear Elements
CQUAD4 or CHEXA8

Basic Coordinate System

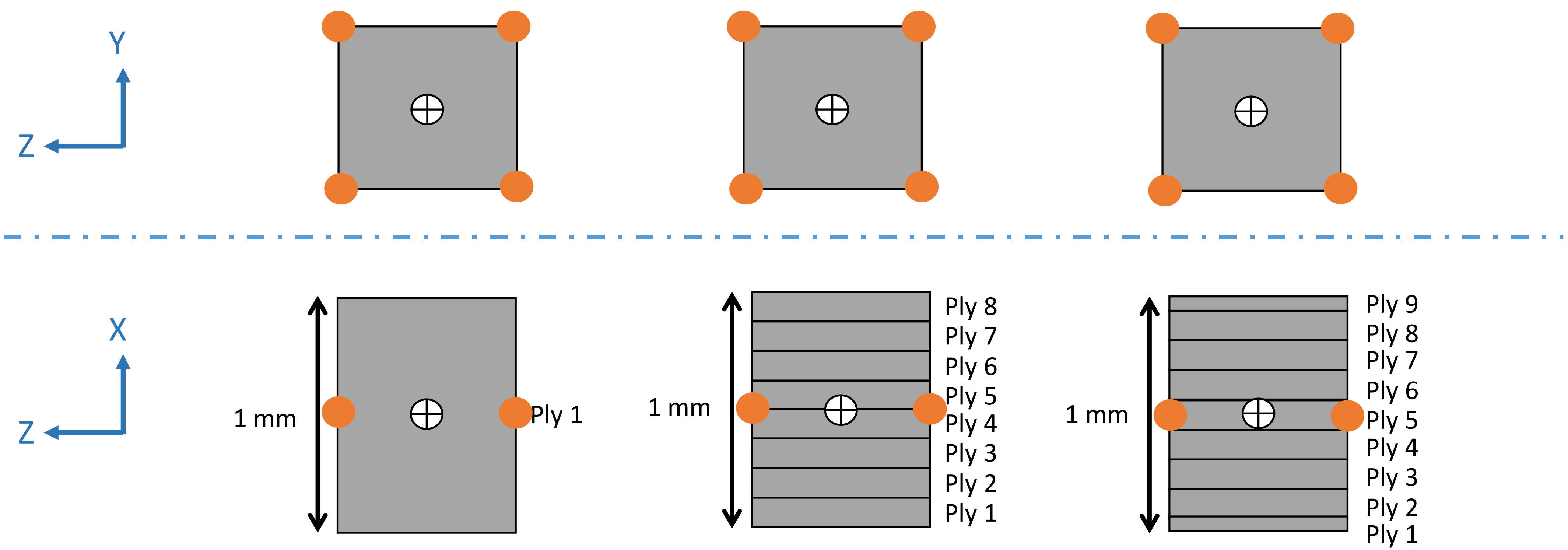
Simply Supported in Basic X

10N Distributed Load Applied in Basic X

Fixed in all DOF

Nodes and Element Used for Comparison to Closed From Solution

Example of Ply Layups for a CQUAD4 Element



Example of a 1 Ply Model
Single ply is 1 mm

Example of an 8 Ply Model
Each ply is 0.125 mm

Example of a 9 Ply Model
Each inner ply is 0.13 mm
Each outer ply is 0.045 mm

The closed form solution is used as the benchmark for displacement and axial stress comparisons

			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
Closed Form Solution			**5.41**		**86.4**				0.36			
PBEAM	--	--	5.41	0.0%	86.4	0%	--	--	**0.29**		--	--
PSHELL	1	--	5.37	0.7%	84.0	3%	84.3	2%	--	--	--	--
PCOMP	1	1	5.37	0.7%	--	--	0.0	100%	--	--	0.00	100%
PCOMP	1	8	5.37	0.7%	--	--	73.8	15%	--	--	0.28	4%
PCOMP	1	9	5.37	0.7%	--	--	80.5	7%	--	--	0.28	5%
PSOLID	1	--	5.37	0.8%	83.9	3%	0.0	100%	0.19	36%	0.19	36%
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PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%

- Closed form solution and PBEAM model are within 1% agreement for displacement and axial stress.

The PBEAM estimate is used as the benchmark for axial-normal shear comparison

			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
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- Closed form solution assumes axial-normal shear stress is uniform across the width of the beam
- Exact analysis shows that shear stress varies across the width with max intensity occurring at ends of neutral axis for a rectangular cross section

Results are enveloped through the thickness over all elements and plies

			Displacement		Axial Stress				Axial-Normal Shear Stress			
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- Exclude results near the applied boundary conditions
- For axial-normal shear also exclude results near the applied load

2D Element Ply results are located at the element centroid only

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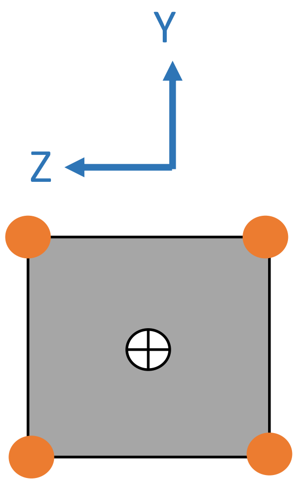

2D Element ply results are reported at the middle of the ply

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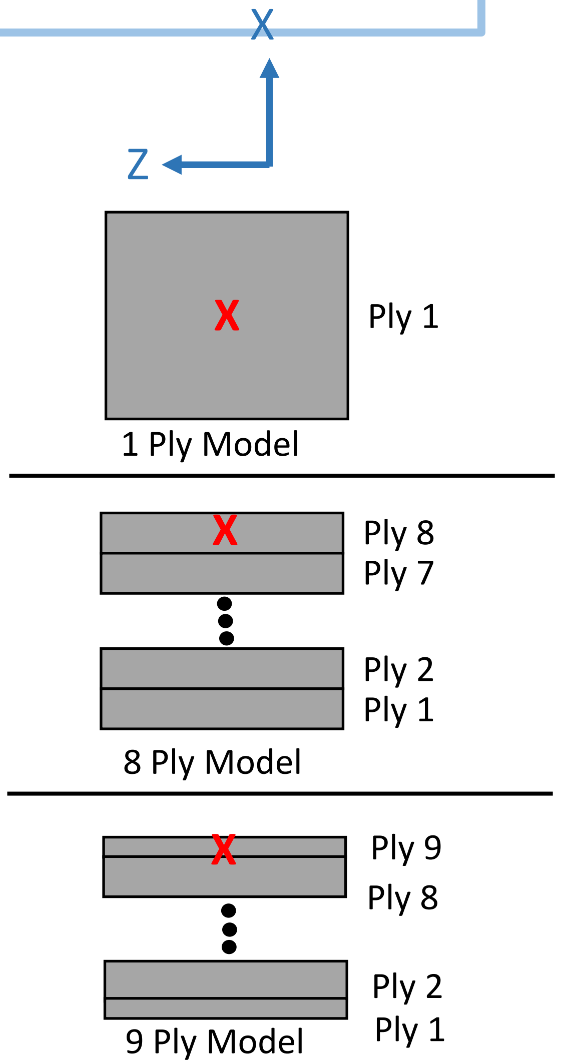

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- Axial stress is maximum at the outer surface
- 2D element ply results are reported at the middle of the ply
- High inaccuracy estimating axial stress using a single ply

- Potential inaccuracies using thick plies
- Improvement in axial stress accuracy with more plies/thinner outer ply

2D Element interlaminar results are reported at the top of the ply

			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
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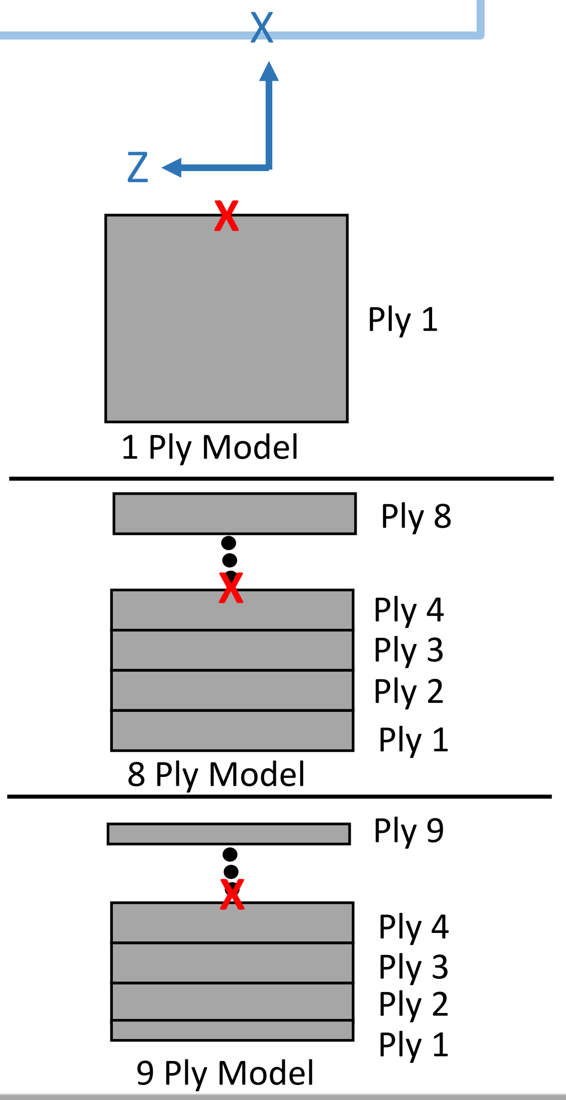

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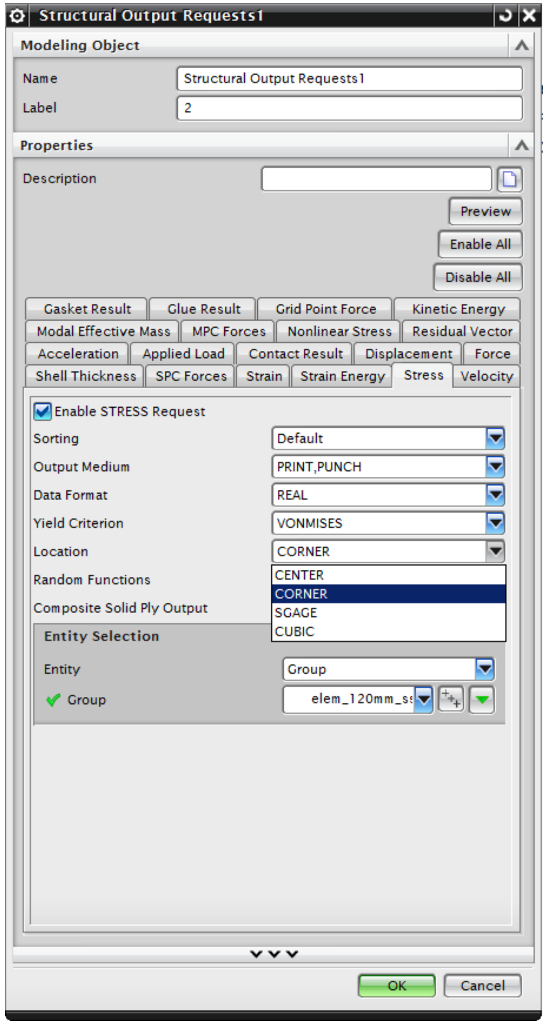
PCOMPS	1	1	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	8	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	9	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PSOLID	8	--	5.36	0.9%	83.9	3%	73.7	15%	0.27	7%	0.28	5%
PCOMPS	8	1	5.36	0.9%	84.3	2%	84.3	2%	0.28	5%	0.28	5%
PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%

- Axial-normal shear stress is maximum at the neutral axis
- 2D element interlaminar results are reported at the top of the ply
- High inaccuracy estimating axial-normal shear stress using a single ply

- Improvement in axial-normal shear stress accuracy dependent on recovery location

3D Element Ply results are located at the element centroid and at the element nodes (if requested)

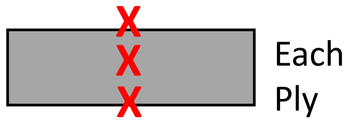
			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
Closed Form Solution			**5.41**		**86.4**				0.36			
PBEAM	--	--	5.41	0.0%	86.4	0%	--	--	**0.29**		--	--
PSHELL	1	--	5.37	0.7%	84.0	3%	84.3	2%	--	--	--	--
PCOMP	1	1	5.37	0.7%	--	--	0.0	100%	--	--	0.00	100%
PCOMP	1	8	5.37	0.7%	--	--	73.8	15%	--	--	0.28	4%
PCOMP	1	9	5.37	0.7%	--	--	80.5	7%	--	--	0.28	5%
PSOLID	1	--	5.37	0.8%	83.9	3%	0.0	100%	0.19	36%	0.19	36%
PCOMPS	1	1	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	8	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	9	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PSOLID	8	--	5.36	0.9%	83.9	3%	73.7	15%	0.27	7%	0.28	5%
PCOMPS	8	1	5.36	0.9%	84.3	2%	84.3	2%	0.28	5%	0.28	5%
PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%



There are multiple options for reporting 3D Element Ply results

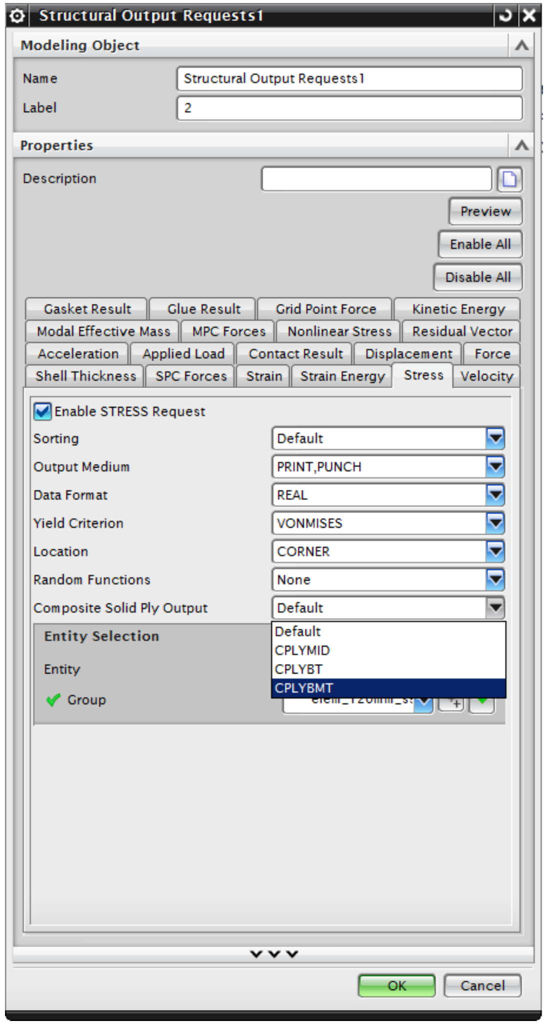
			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
Closed Form Solution			**5.41**		**86.4**				0.36			
PBEAM	--	--	5.41	0.0%	86.4	0%	--	--	**0.29**		--	--
PSHELL	1	--	5.37	0.7%	84.0	3%	84.3	2%	--	--	--	--
PCOMP	1	1	5.37	0.7%	--	--	0.0	100%	--	--	0.00	100%
PCOMP	1	8	5.37	0.7%	--	--	73.8	15%	--	--	0.28	4%
PCOMP	1	9	5.37	0.7%	--	--	80.5	7%	--	--	0.28	5%
PSOLID	1	--	5.37	0.8%	83.9	3%	0.0	100%	0.19	36%	0.19	36%
PCOMPS	1	1	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	8	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	9	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PSOLID	8	--	5.36	0.9%	83.9	3%	73.7	15%	0.27	7%	0.28	5%
PCOMPS	8	1	5.36	0.9%	84.3	2%	84.3	2%	0.28	5%	0.28	5%
PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%

- 3D Element Ply results can be reported at:
  1. middle of the ply
  2. the top and bottom of the ply
  3. the top, middle, and bottom of the ply
- Results are shown using option (3) leading to high accuracy in axial stress estimate



There are multiple options for reporting 3D Element Ply results

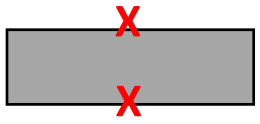
			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
Closed Form Solution			**5.41**		**86.4**				0.36			
PBEAM	--	--	5.41	0.0%	86.4	0%	--	--	**0.29**		--	--
PSHELL	1	--	5.37	0.7%	84.0	3%	84.3	2%	--	--	--	--
PCOMP	1	1	5.37	0.7%	--	--	0.0	100%	--	--	0.00	100%
PCOMP	1	8	5.37	0.7%	--	--	73.8	15%	--	--	0.28	4%
PCOMP	1	9	5.37	0.7%	--	--	80.5	7%	--	--	0.28	5%
PSOLID	1	--	5.37	0.8%	83.9	3%	0.0	100%	0.19	36%	0.19	36%
PCOMPS	1	1	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	8	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	9	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PSOLID	8	--	5.36	0.9%	83.9	3%	73.7	15%	0.27	7%	0.28	5%
PCOMPS	8	1	5.36	0.9%	84.3	2%	84.3	2%	0.28	5%	0.28	5%
PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%



3D Element Interlaminar results are reported at the top and bottom of the ply

			Displacement		Axial Stress				Axial-Normal Shear Stress			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
Closed Form Solution			**5.41**		**86.4**				0.36			
PBEAM	--	--	5.41	0.0%	86.4	0%	--	--	**0.29**		--	--
PSHELL	1	--	5.37	0.7%	84.0	3%	84.3	2%	--	--	--	--
PCOMP	1	1	5.37	0.7%	--	--	0.0	100%	--	--	0.00	100%
PCOMP	1	8	5.37	0.7%	--	--	73.8	15%	--	--	0.28	4%
PCOMP	1	9	5.37	0.7%	--	--	80.5	7%	--	--	0.28	5%
PSOLID	1	--	5.37	0.8%	83.9	3%	0.0	100%	0.19	36%	0.19	36%
PCOMPS	1	1	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	8	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PCOMPS	1	9	5.37	0.8%	84.3	2%	84.3	2%	0.19	36%	0.19	36%
PSOLID	8	--	5.36	0.9%	83.9	3%	73.7	15%	0.27	7%	0.28	5%
PCOMPS	8	1	5.36	0.9%	84.3	2%	84.3	2%	0.28	5%	0.28	5%
PSOLID	16	--	5.36	0.9%	84.3	2%	79.3	8%	0.28	4%	0.28	4%

- 3D Element interlaminar results are reported at the top and bottom of the ply



Each Ply

- Observe no improvement in accuracy using layered composite element than with single solid element

First Representative Test Case is the Single-Lap-Joint

- ASTM 1002 – Single-Lap-Joint
  - This test method covers the determination of the apparent shear strengths of adhesives for bonding metals
  - Bonded lap joint under tensile loading
    - The specimens are placed in the grips of the testing machine so that the outer ends are in contact with the jaw
    - The long axis of the test specimen coincides with the direction of applied pull through the center line of the grip assembly

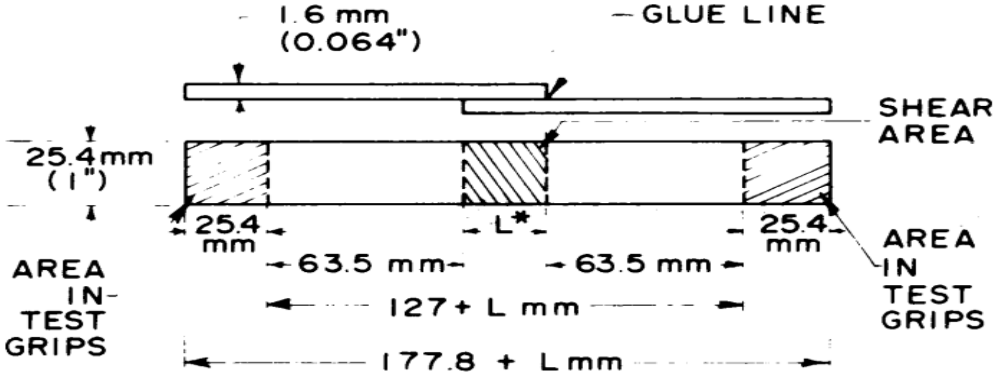


FIG. 1 Form and Dimensions of Test Specimen

ASTM 1002 – Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)

Single-Lap-Joint Test Will Use an Adhesive and Two Different Adherands

- Adhesive: Hysol EA 9394
  - Common two-part structural paste adhesive
- Adherand 1: AL 2024 T3 (because this is what the tests for Hysol EA 9394 use)
  - At 77^{o}F/25^{o}C the failure stress is 28.9 MPa
  - A = 25.4 mm x 1.62 mm = 41.148 mm^2
  - Force at failure = stress*area = 28.9 x 1E6 Pa*4.1148E-5 m^2 = **1,189 N**
- Adherand 2: T300 Uniaxial Tape
  - Use the same load and boundary conditions

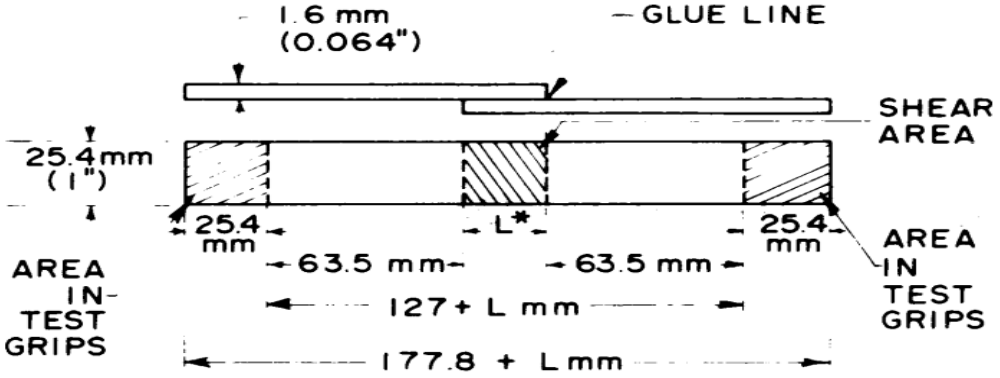
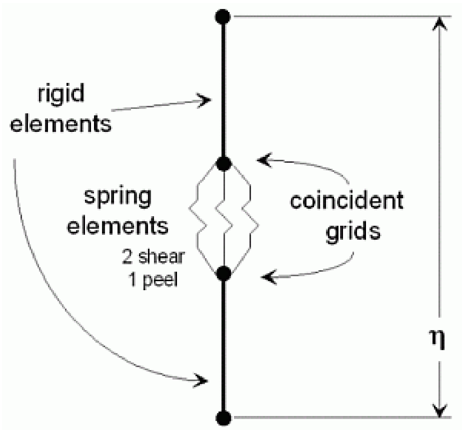


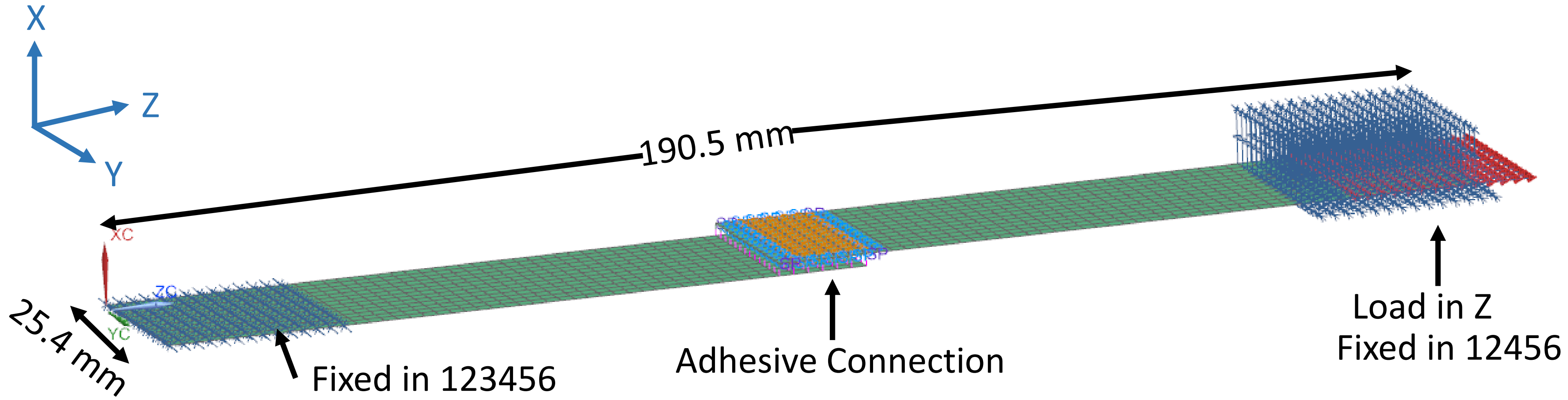
FIG. 1 Form and Dimensions of Test Specimen

ASTM 1002 – Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)

Dimensions Used Were Exactly The Same For the 2D and 3D Models

- The elements were set to ~2 mm in length and width
- For shell element connections the adhesive was modeled with springs
  - Connected with constraint elements to coincident springs per the FEMCI method* of modeling adhesive in a bonded joint
  - The springs have varying stiffness based on material properties of adhesive, element areas, and adhesive thickness

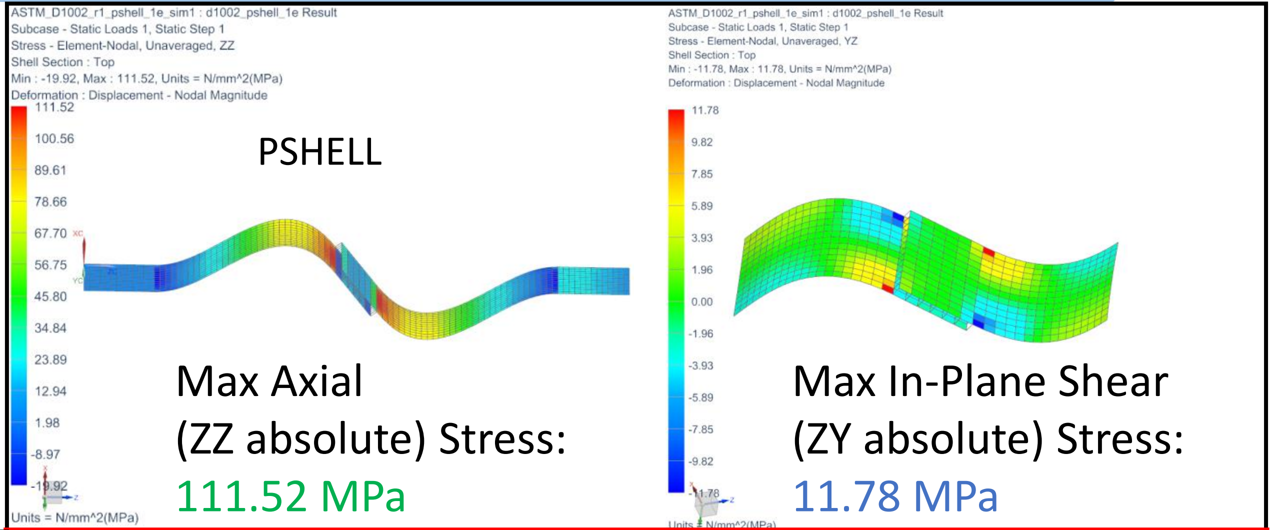


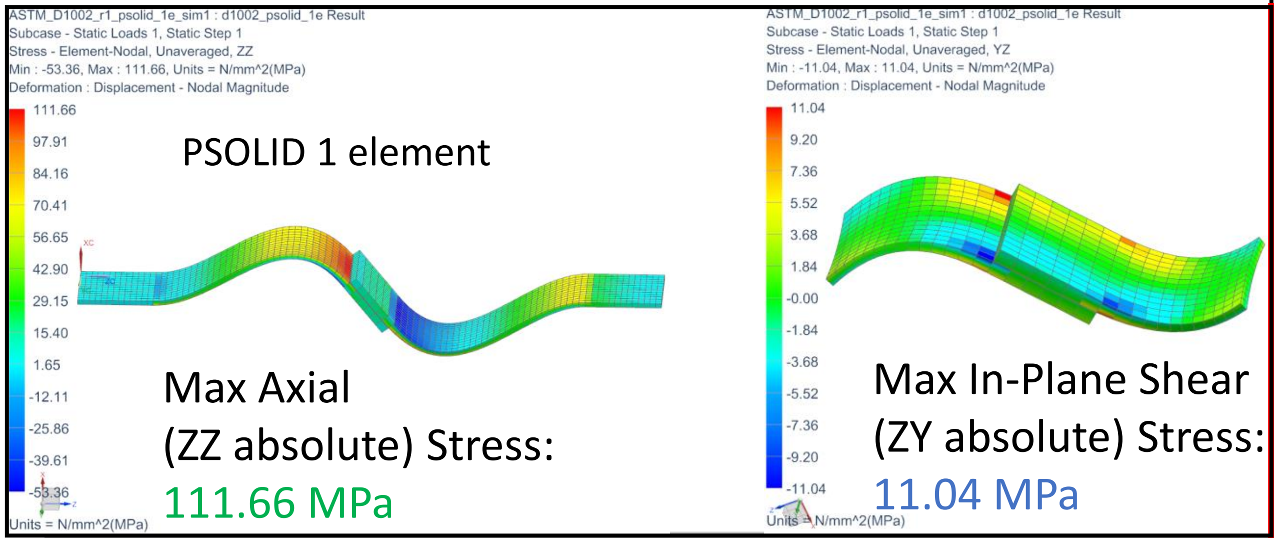


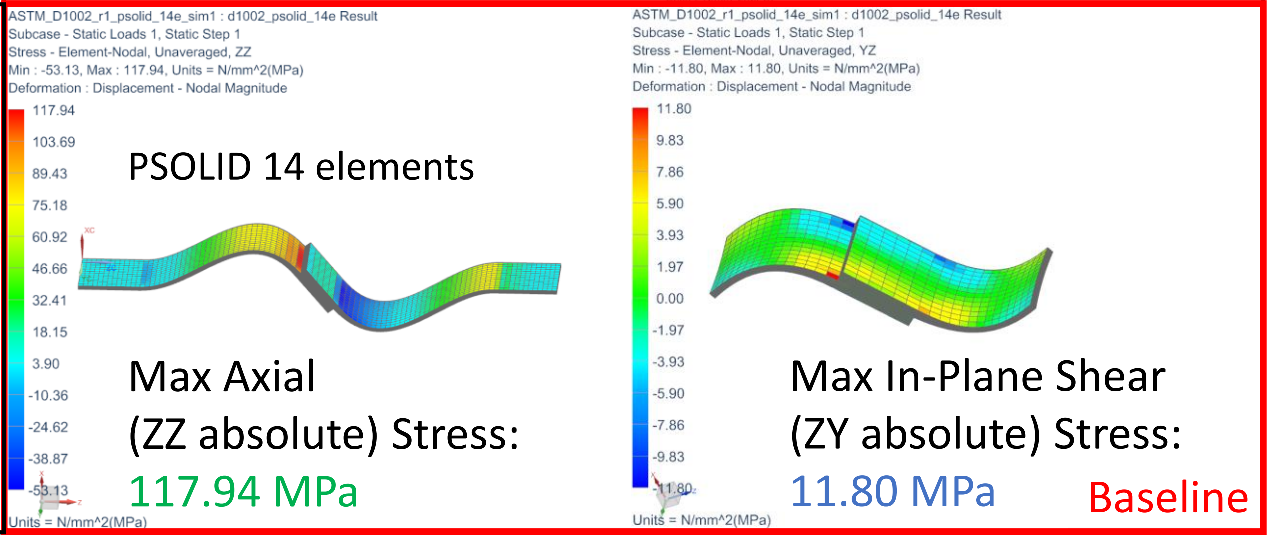
*See source in appendix

Axial and In-Plane Shear Stress Match Well Between PSHELL and PSOLID Models

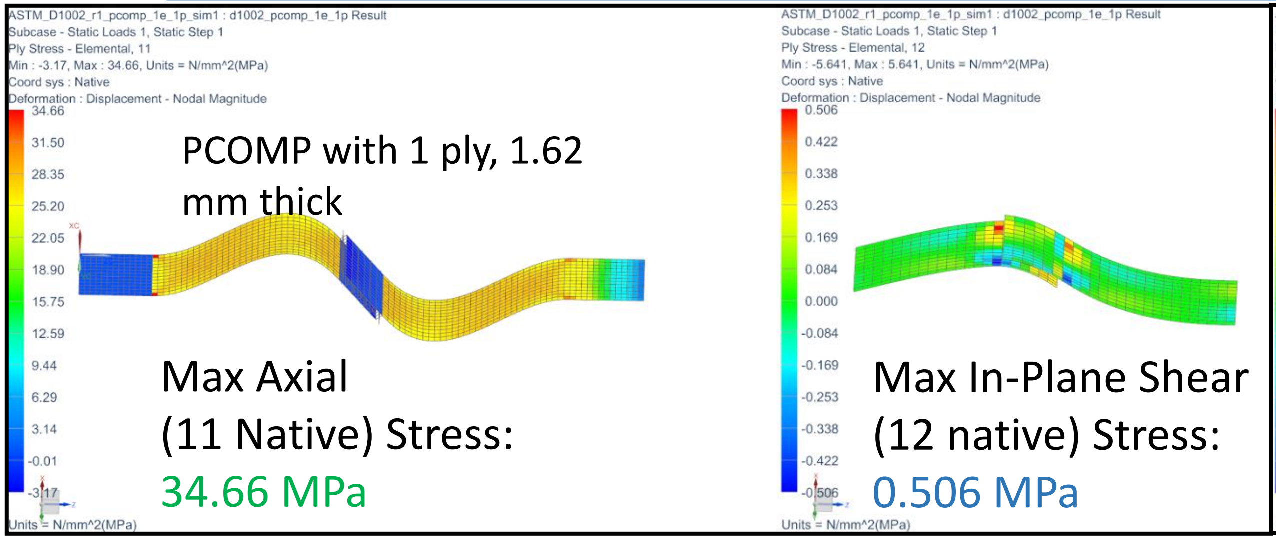
- Interested in the axial stress and the in-plane shear
- For shear looking at elements near the center to avoid boundary condition effects
- The 14 element through the thickness model is likely to provide the most accurate results and we will use this as the baseline

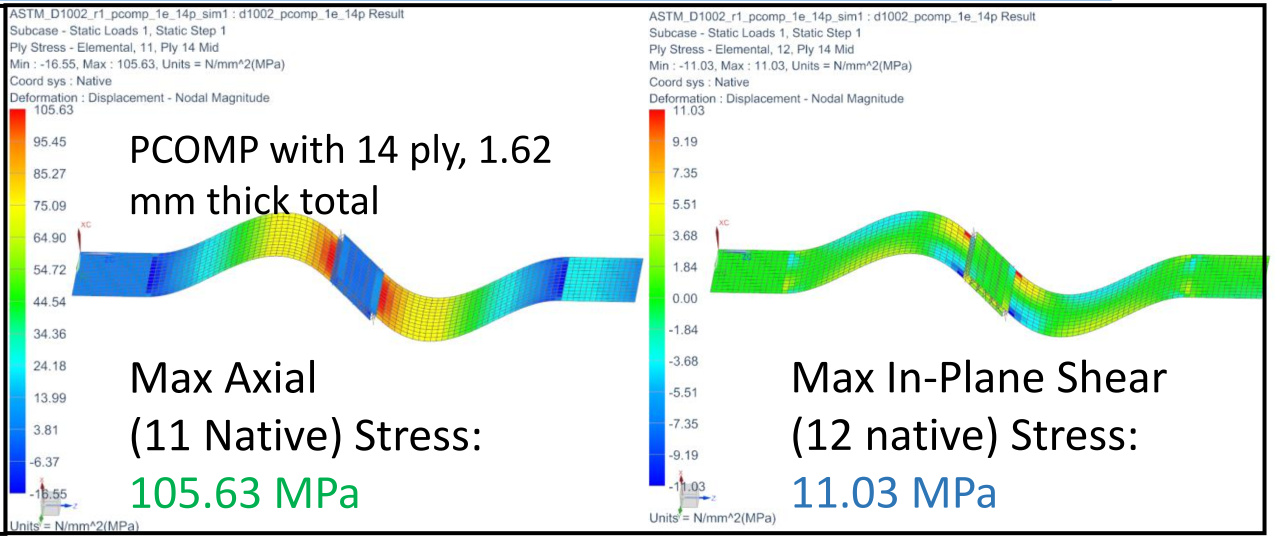






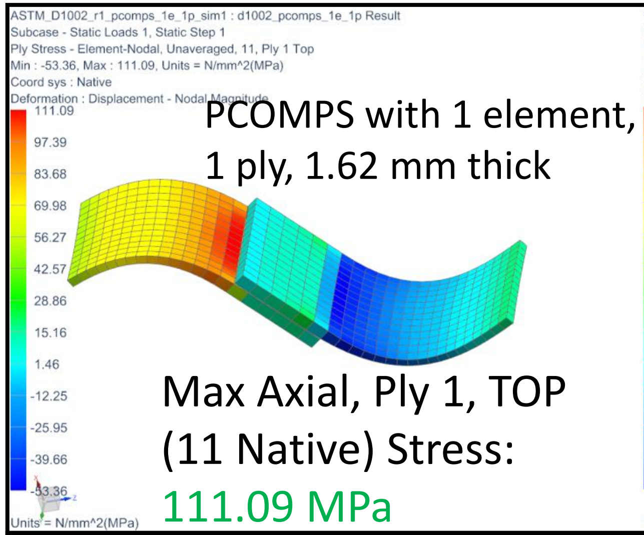
PCOMP With 14 Plies Is Close To The Baseline

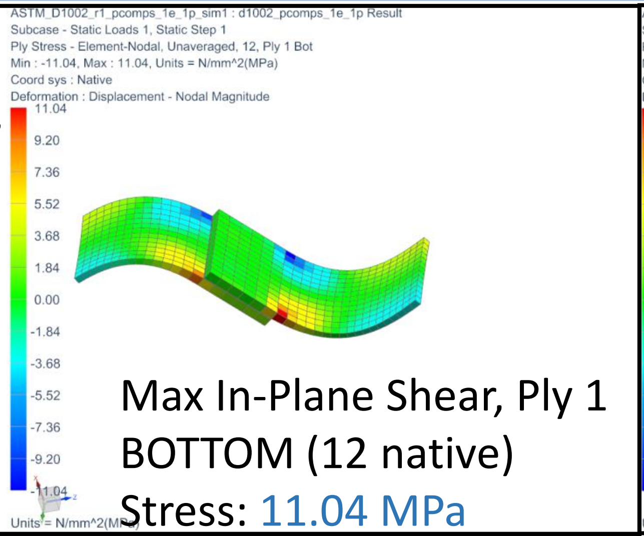


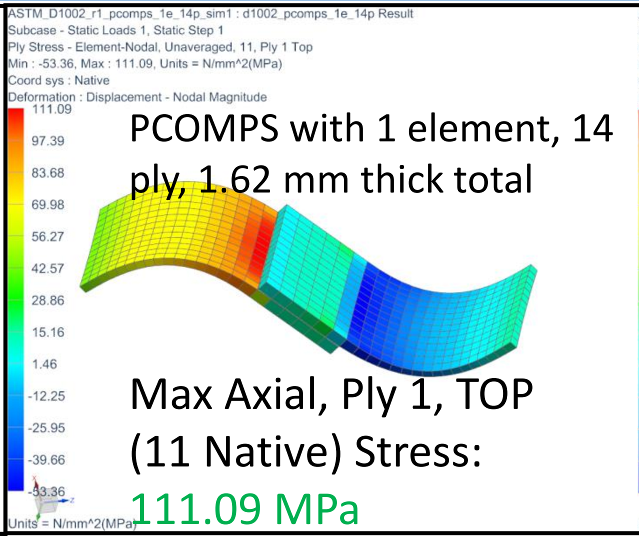


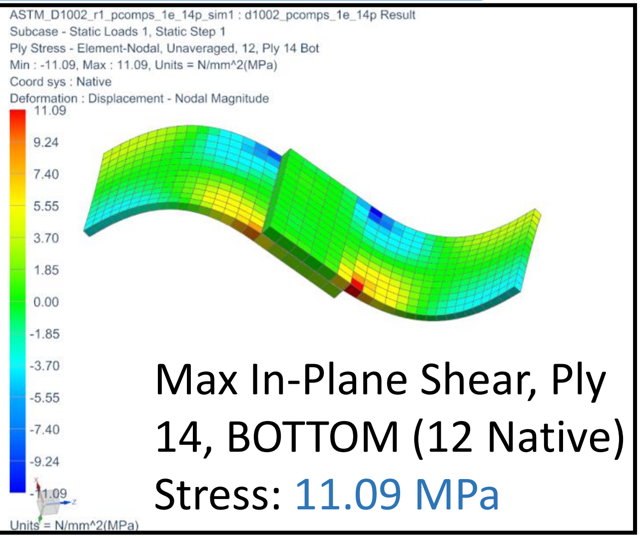
- Stress is recovered for both stress results at the mid plane of each ply, not at the top or bottom
- Cannot request nodal-elemental values for PCOMP results so must look at elemental (centroid)
- One way to address the poor results for the 1 ply (or improve the 14 ply results) is to request shell resultants, then NXLC can compute ply stresses at the outer fiber of 2d elements

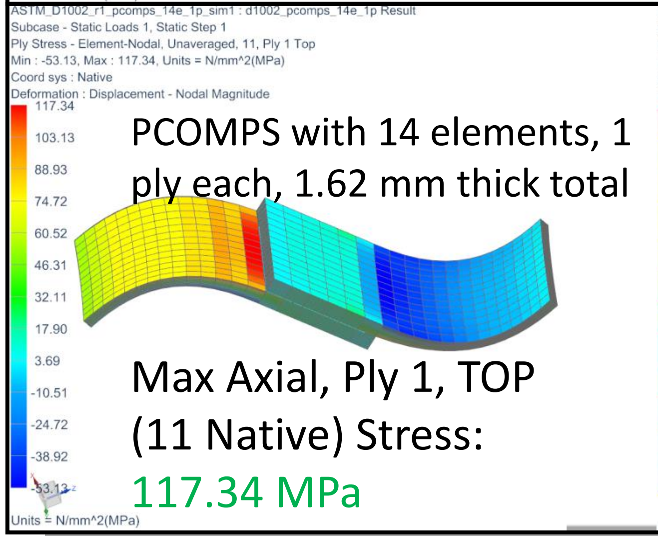
Modeling layers using PCOMPS yields a slight error compared to modeling all the layers explicitly

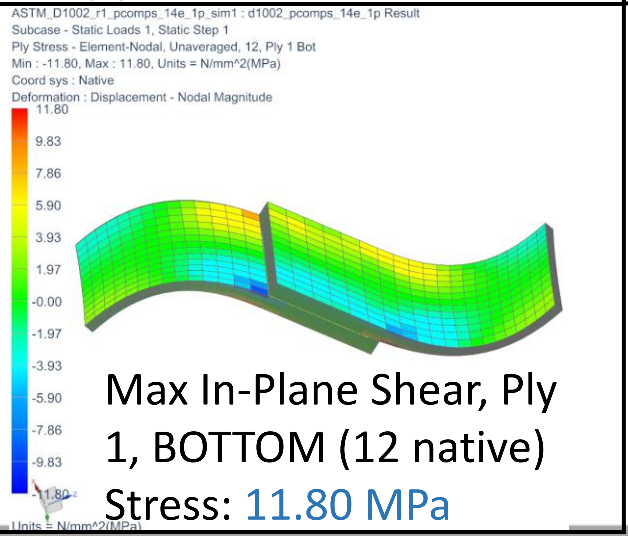












- Modeling layers with the same material using PCOMPS yields a slight error compared to modeling all the layers explicitly with CHEXAs (PSOLID)
- Error of PCOMPS Model With 14 Plies On A Single Layer Is Small Compared to PSOLID Model With 14 Elements
- Have To Be Extremely Careful With Data Requests and Comparison

All Displacements Across Physical Property Types Match Within 4%

- All results in the table are being compared relative to the PSOLID with 14 elements through the thickness, nodal-peak results

Physical Property Type	Elements Through Thickness	Plies Per Element	Displacement		Normal - ZZ/11 Stress (MPa)				In Plane Shear - ZY/12 Stress (MPa)			
			Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
PSOLID	14	--	0.289	0.00%	**117.94**	0.00%	**110.21**	6.55%	**11.8**	0.00%	**10.7**	9.32%
PSHELL	1	--	0.278	3.81%	111.52	5.44%	111.5	5.44%	11.8	0.17%	11.8	0.17%
PCOMP	1	1	0.278	3.81%	--	--	34.7	70.61%	--	--	0.5	95.71%
PCOMP	1	14	0.278	3.81%	--	--	105.6	10.44%	--	--	11.0	6.53%
PCOMPS	1	1	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.0	6.44%	11.0	6.44%
PCOMPS	1	14	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.1	6.02%	11.1	6.02%
PCOMPS	14	1	0.289	0.00%	117.3	0.51%	117.3	0.51%	11.8	0.00%	11.8	0.08%
PSOLID	1	--	0.29	-0.35%	111.66	5.32%	34.8	70.47%	11.0	6.44%	5.7	51.48%

- All Displacements match within 4%

Stress Error For PCOMPS With 1 Element Through The Thickness Compared To Layered PSOLID Is Within 7%

- All results in the table are being compared relative to the PSOLID with 14 elements through the thickness, nodal-peak results

			Displacement		**Normal - ZZ/11 Stress (MPa)**				**In Plane Shear - ZY/12 Stress (MPa)**			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
PSOLID	14	--	0.289	0.00%	**117.94**	0.00%	**110.21**	6.55%	**11.8**	0.00%	**10.7**	9.32%
PSHELL	1	--	0.278	3.81%	111.52	5.44%	111.5	5.44%	11.8	0.17%	11.8	0.17%
PCOMP	1	1	0.278	3.81%	--	--	34.7	70.61%	--	--	0.5	95.71%
PCOMP	1	14	0.278	3.81%	--	--	105.6	10.44%	--	--	11.0	6.53%
PCOMPS	1	1	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.0	6.44%	11.0	6.44%
PCOMPS	1	14	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.1	6.02%	11.1	6.02%
PCOMPS	14	1	0.289	0.00%	117.3	0.51%	117.3	0.51%	11.8	0.00%	11.8	0.08%
PSOLID	1	--	0.29	-0.35%	111.66	5.32%	34.8	70.47%	11.0	6.44%	5.7	51.48%

- Using PCOMPS with 1 element through the thickness and 14 plies displacement matches within 1%

- Stress error in particular might be problem dependent
  - Loading, number of layers, materials, etc

To Get Most Accurate Through-the-Thickness Results Need to Model All of the Layers Explicitly With Elements

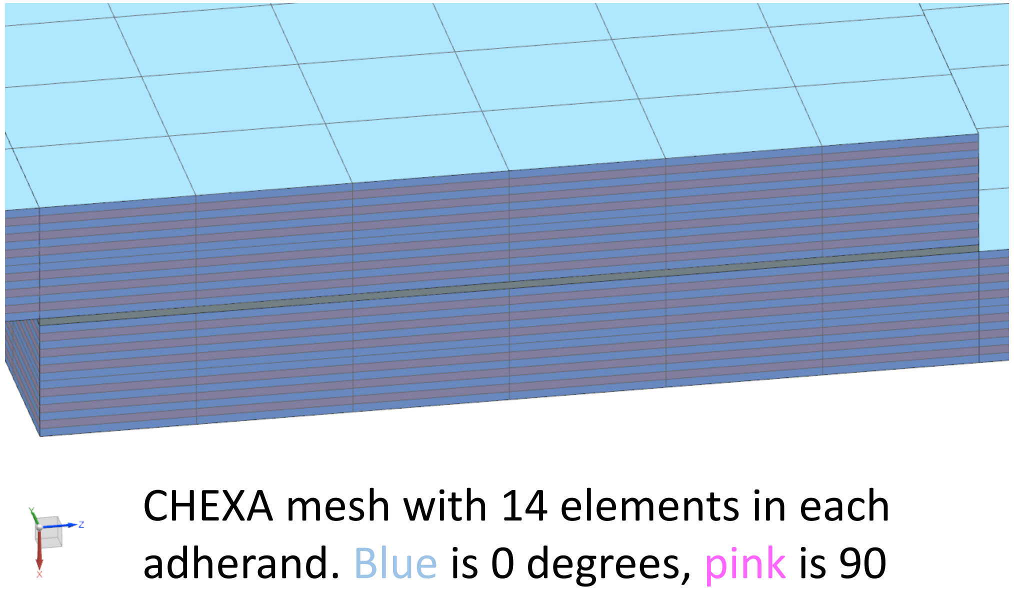
- All results in the table are being compared relative to the PSOLID with 14 elements through the thickness, nodal-peak results

Physical Property Type	Elements Through Thickness	Plies Per Element	Displacement		Normal - ZZ/11 Stress (MPa)				In Plane Shear - ZY/12 Stress (MPa)			
			Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
PSOLID	14	--	0.289	0.00%	**117.94**	0.00%	**110.21**	6.55%	**11.8**	0.00%	**10.7**	9.32%
PSHELL	1	--	0.278	3.81%	111.52	5.44%	111.5	5.44%	11.8	0.17%	11.8	0.17%
PCOMP	1	1	0.278	3.81%	--	--	34.7	70.61%	--	--	0.5	95.71%
PCOMP	1	14	0.278	3.81%	--	--	105.6	10.44%	--	--	11.0	6.53%
PCOMPS	1	1	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.0	6.44%	11.0	6.44%
PCOMPS	1	14	0.29	-0.35%	111.1	5.81%	111.1	5.81%	11.1	6.02%	11.1	6.02%
PCOMPS	14	1	0.289	0.00%	117.3	0.51%	117.3	0.51%	11.8	0.00%	11.8	0.08%
PSOLID	1	--	0.29	-0.35%	111.66	5.32%	34.8	70.47%	11.0	6.44%	5.7	51.48%

- If modeling every layer explicitly is computationally or "modeling time" prohibitive, a closer approximation can be still be had by modeling at least a few element layers
- 3 elements: axial stress is 115.30 MPa and shear stress is 11.50 MPa
- 5 elements: axial stress is 116.89 MPa and shear is 11.62 MPa

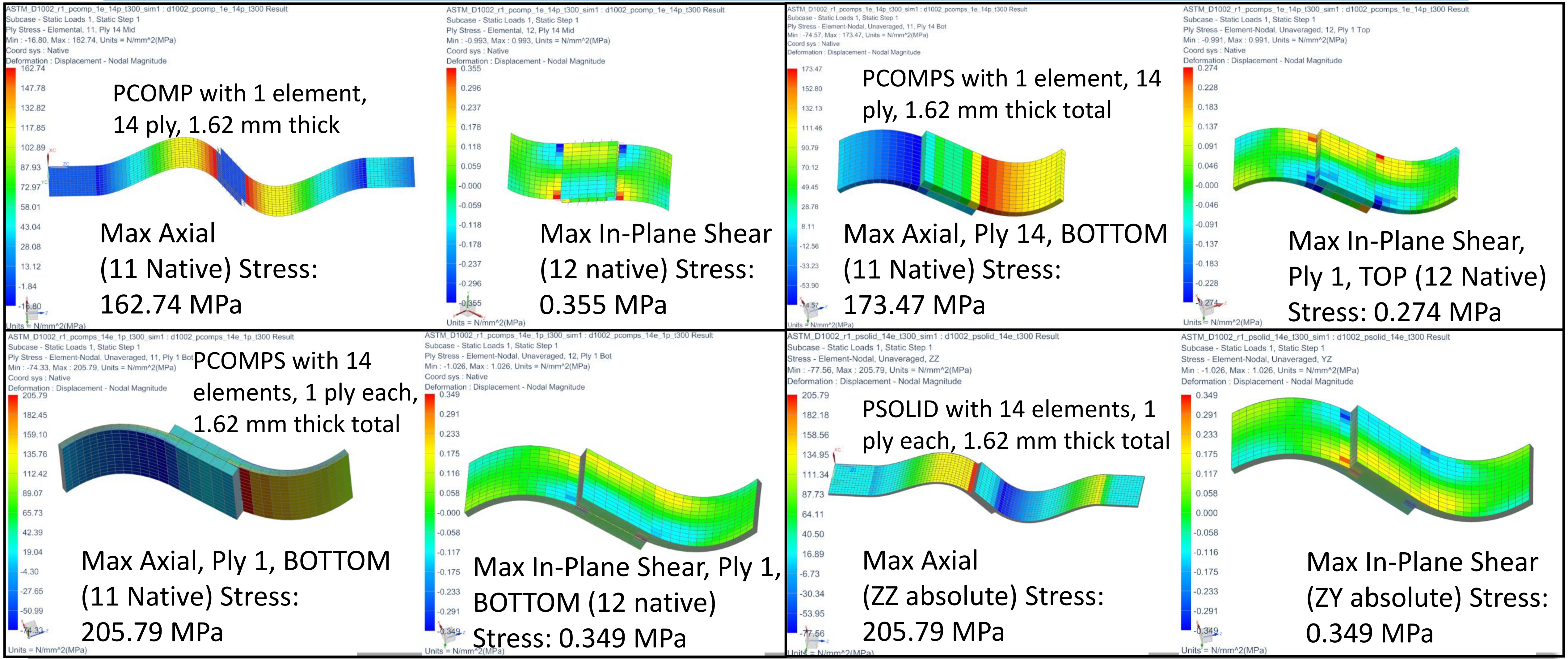
Moving to Composites: Using T300 Uniaxial Tape

- As an example we chose 14 layers of T300 uniaxial tape at [0, 90, 0, 90, 0, 90, 0, 0, 90, 0, 90, 0, 90, 0]
  - PCOMP with 14 plies
  - PCOMPS with 1 element, 14 plies
  - PCOMPS with 14 elements, 1 ply each
  - PSOLID with 14 elements
- Each layer is 1.62 mm/14 plies = 0.11571 mm which is close to the actual thickness of the tape



CHEXA mesh with 14 elements in each adherand. Blue is 0 degrees, pink is 90 degrees, grey is adhesive

Both PCOMP and PCOMPS With 1 Element Through The Thickness Underestimate Max Axial Stress



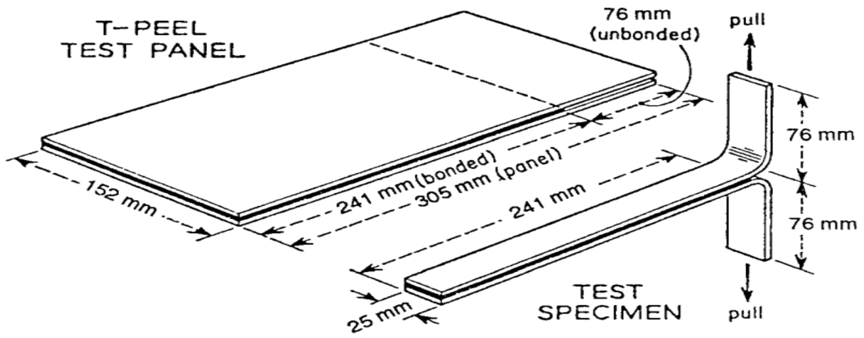
Stress Error For the PCOMPS Results With 1 Element Through The Thickness Is Higher In Composite Example

- PCOMPS with 14 element layers matches the PSOLID 14 element results
- PCOMPS with 1 element but 14 plies is off by at least 16% for axial stress and more for the in-plane shear

			Displacement		**Axial - ZZ/11 Stress (MPa)**				**In Plane Shear - ZY/12 Stress (MPa)**			
Physical Property Type	Elements Through Thickness	Plies Per Element	Nodal		Nodal Peak		Element Centroidal		Nodal Peak		Element Centroidal	
			(mm)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)	(MPa)	(% Diff)
PSOLID	14	--	0.261	0.00%	**205.79**	0.00%		100.00%	**0.349**	0.00%		100.00%
PCOMP	1	14	0.227	13.03%	--	--	162.7	20.92%	--	--	0.355	-1.72%
PCOMPS	1	14	0.252	3.45%	173.5	15.71%	173.1	15.89%	0.274	21.49%	0.274	21.49%
PCOMPS	14	1	0.261	0.00%	205.8	0.00%	205.8	0.01%	0.349	0.00%	0.343	1.72%

Second Representative Test Case is Peel Resistance

- ASTM 1876 – Peel Resistance
  - This test method is primarily intended for determining the relative peel resistance of adhesive bonds between flexible adherends
  - Two bonded, flexible adherends are progressively separated
    - The bent, unbonded ends of the test specimen are clamped in the grips of the tension testing machine
    - A load at a constant head speed is applied
- Goal of this test often is to establish an adhesive stress allowable (via normalization to specific mesh sizing)



METRIC EQUIVALENTS

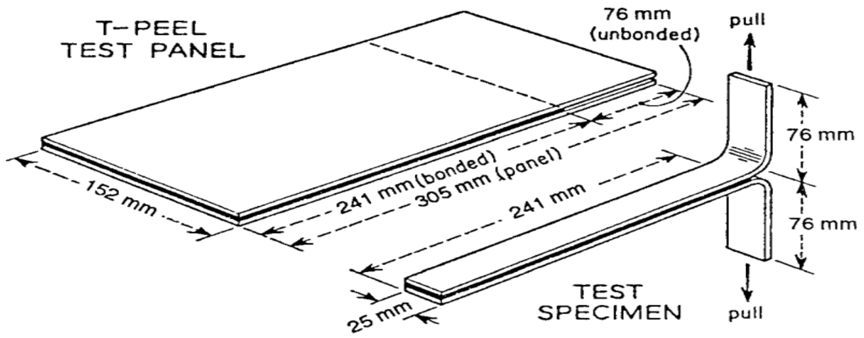
in.	1	3	6	9	12
mm	25	76	152	229	305

FIG. 1 Test Panel and Test Specimen

ASTM 1876 – Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)

Peel Test Will Use an Adhesive and an Adherand

- Adhesive: Hysol EA 9394
  - Common two-part structural paste adhesive
- Adherand 1: AL 2024 T3 (per test spec for Hysol EA 9394)
  - At 77°F/25°C the failure occurs at 22.2 N/25 mm
  - W = 25 mm
  - Force at failure = W * Failure Force = 22.2 N/25 mm * 25 mm = **22.2 N**



METRIC EQUIVALENTS

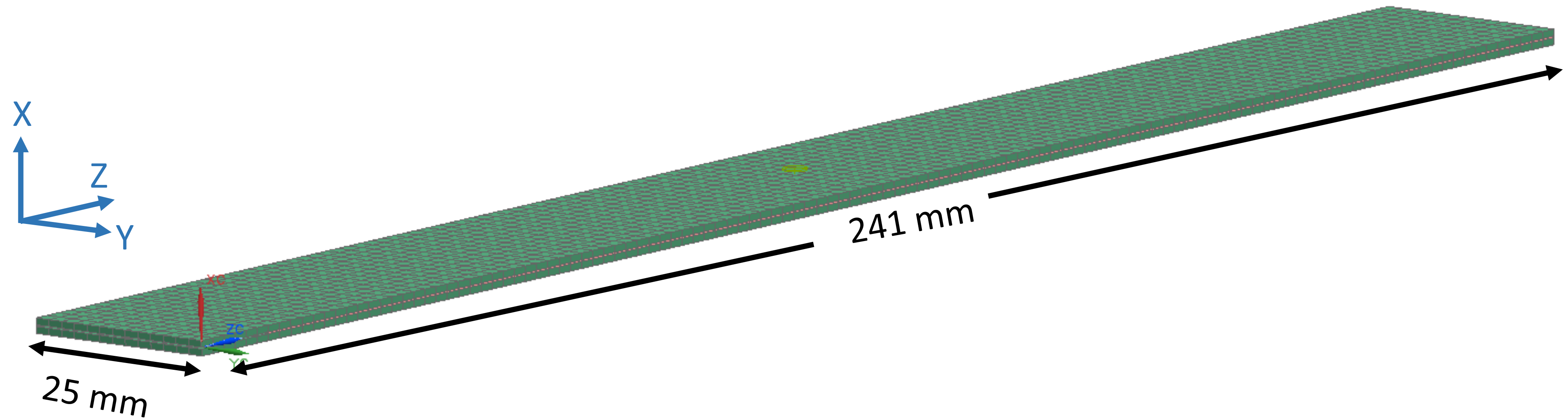
in.	1	3	6	9	12
mm	25	76	152	229	305

FIG. 1 Test Panel and Test Specimen

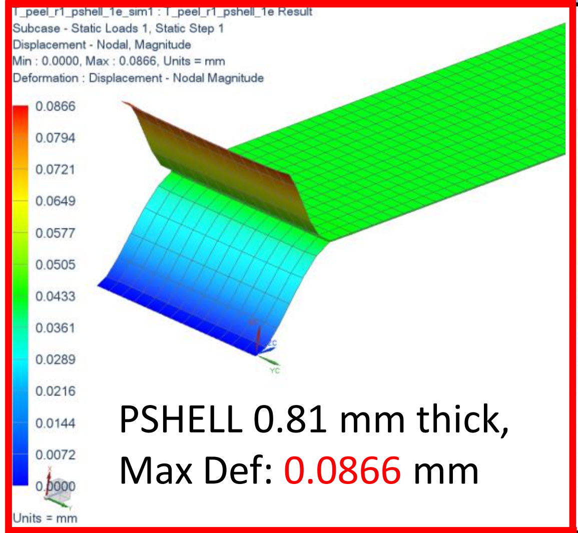
ASTM 1876 – Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)

Dimensions Used Were Exactly The Same For the 2D and 3D Models

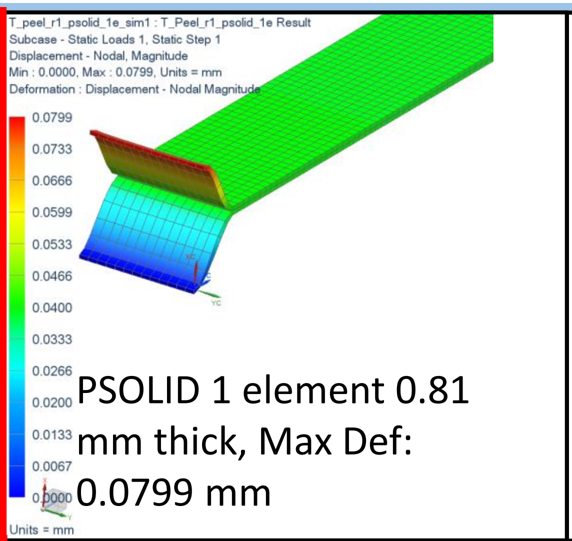
- The elements were set to ~2 mm in length and width
- Adhesive is modeled with CHEXA elements for both 2D and 3D models (for the adherands)
- To simplify this test FEM even more we looked at only the bonded flat region
- Interested in the peel stress (XX, through the thickness) stress



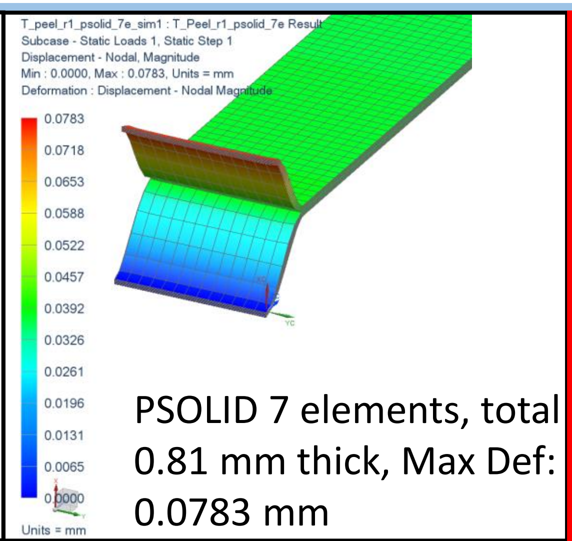
Maximum Deflection Varies With Mesh Type, 2D Properties All Match



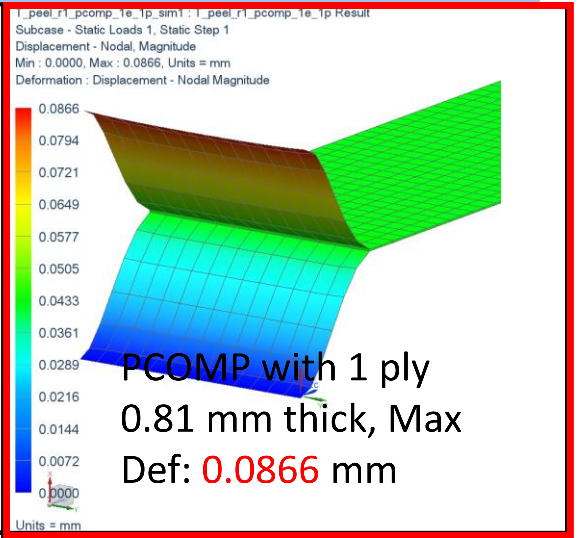
PSHELL 0.81 mm thick, Max Def: 0.0866 mm



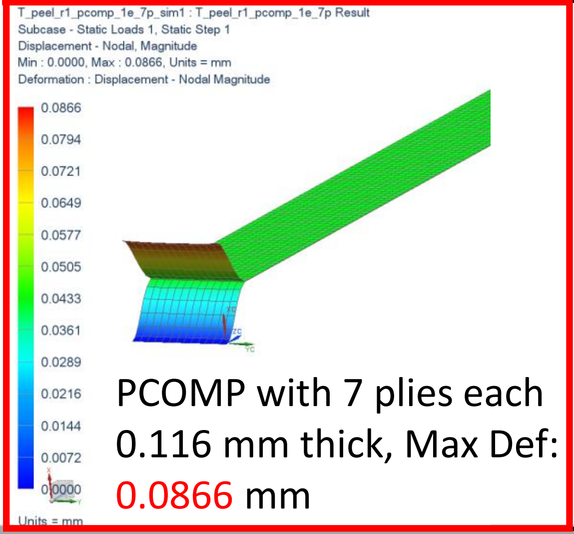
PSOLID 1 element 0.81 mm thick, Max Def: 0.0799 mm



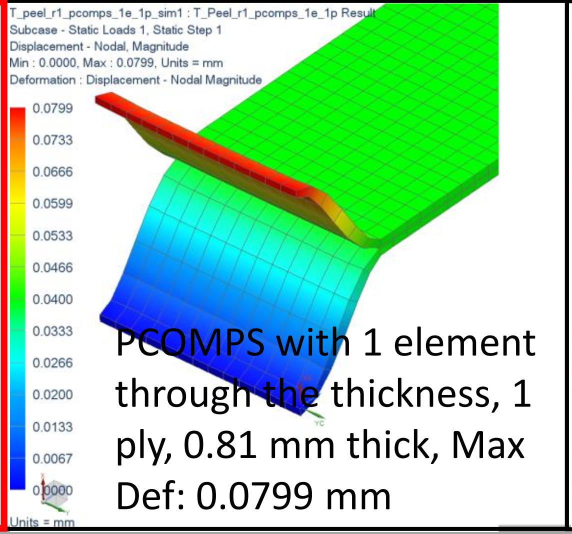
PSOLID 7 elements, total 0.81 mm thick, Max Def: 0.0783 mm



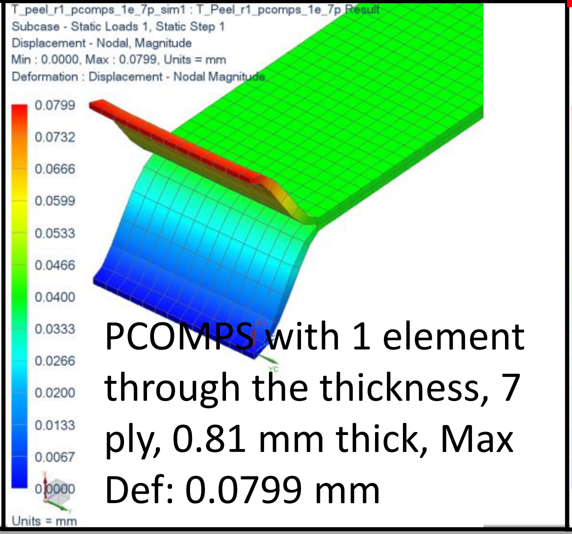
PCOMP with 1 ply 0.81 mm thick, Max Def: 0.0866 mm



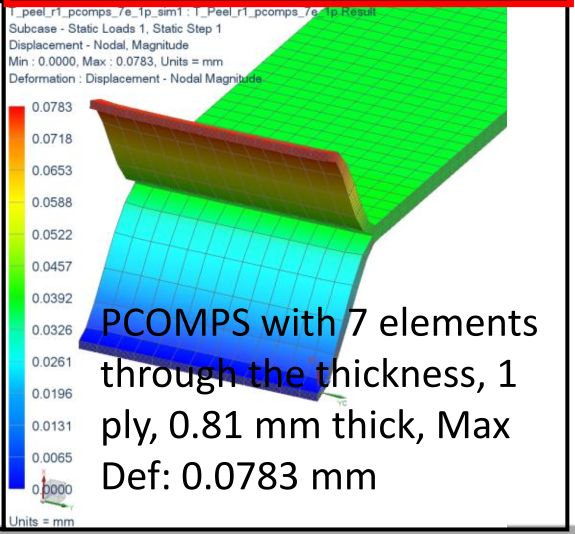
PCOMP with 7 plies each 0.116 mm thick, Max Def: 0.0866 mm



PCOMPS with 1 element through the thickness, 1 ply, 0.81 mm thick, Max Def: 0.0799 mm

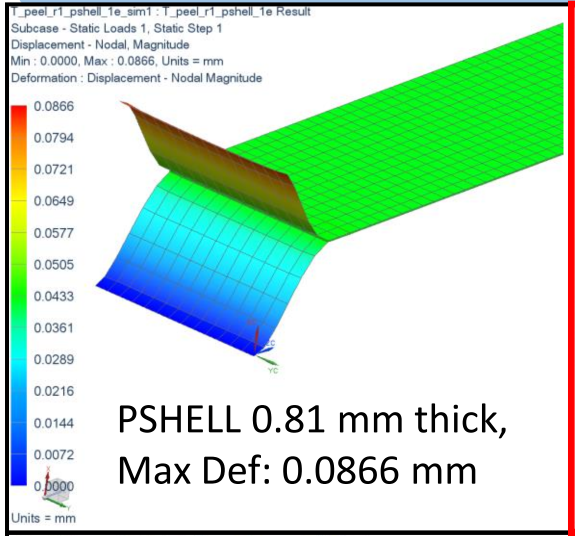


PCOMPS with 1 element through the thickness, 7 ply, 0.81 mm thick, Max Def: 0.0799 mm

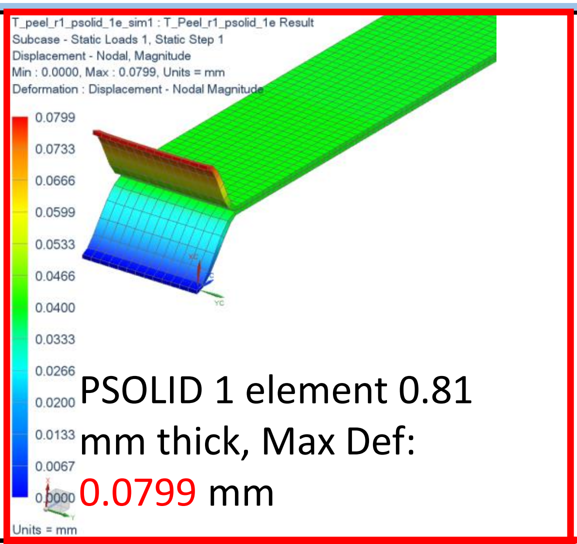


PCOMPS with 7 elements through the thickness, 1 ply, 0.81 mm thick, Max Def: 0.0783 mm

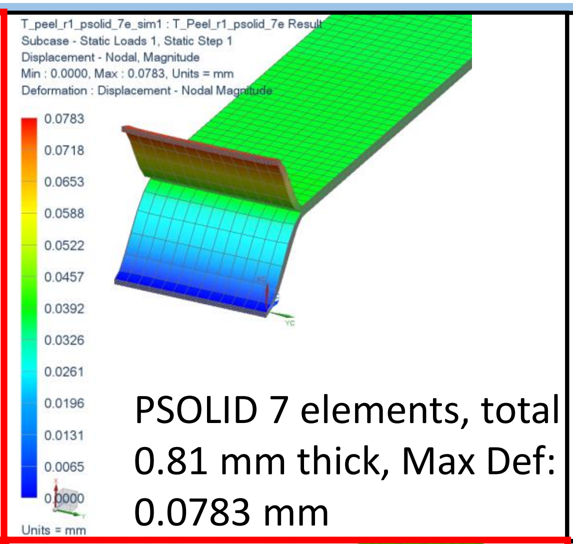
Maximum Deflection Varies With Mesh Type, 3D Elements With 1 Element Through-the-Thickness All Match



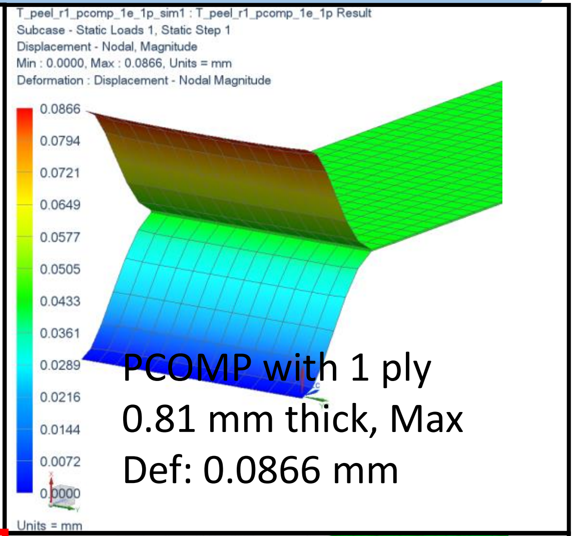
PSHELL 0.81 mm thick, Max Def: 0.0866 mm



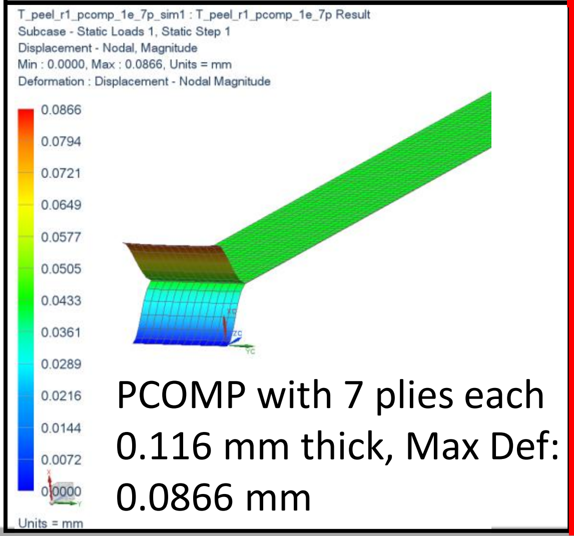
PSOLID 1 element 0.81 mm thick, Max Def: 0.0799 mm



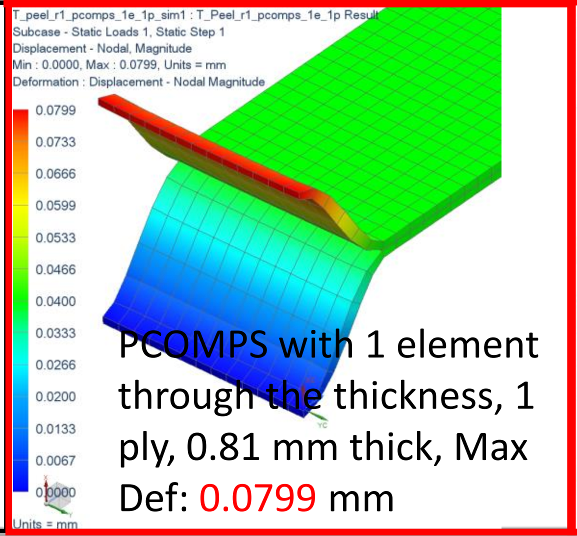
PSOLID 7 elements, total 0.81 mm thick, Max Def: 0.0783 mm



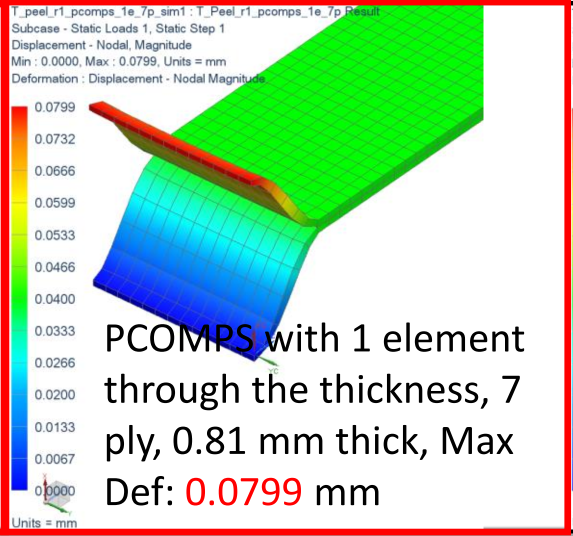
PCOMP with 1 ply 0.81 mm thick, Max Def: 0.0866 mm



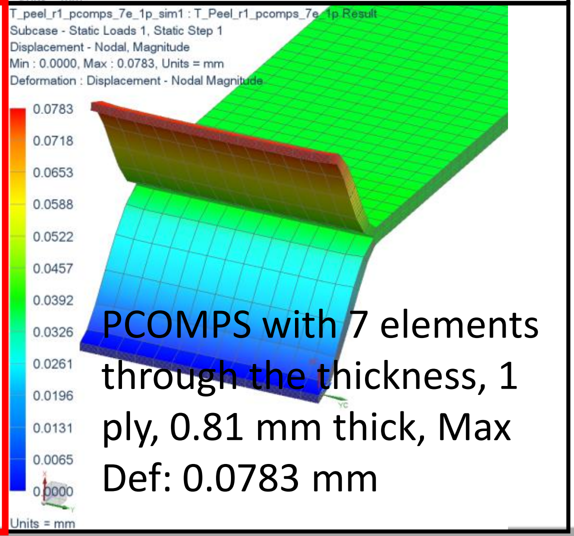
PCOMP with 7 plies each 0.116 mm thick, Max Def: 0.0866 mm



PCOMPS with 1 element through the thickness, 1 ply, 0.81 mm thick, Max Def: 0.0799 mm

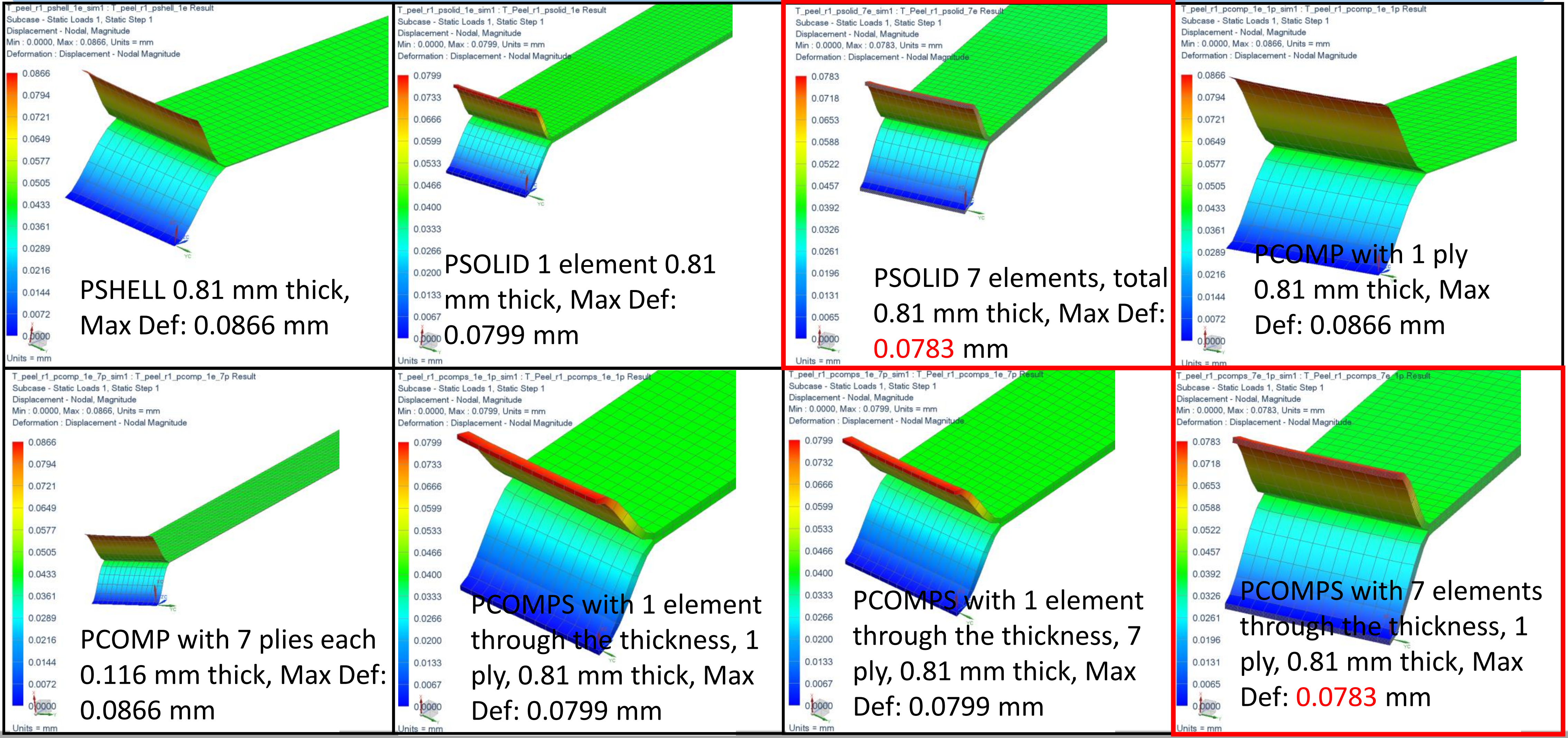


PCOMPS with 1 element through the thickness, 7 ply, 0.81 mm thick, Max Def: 0.0799 mm

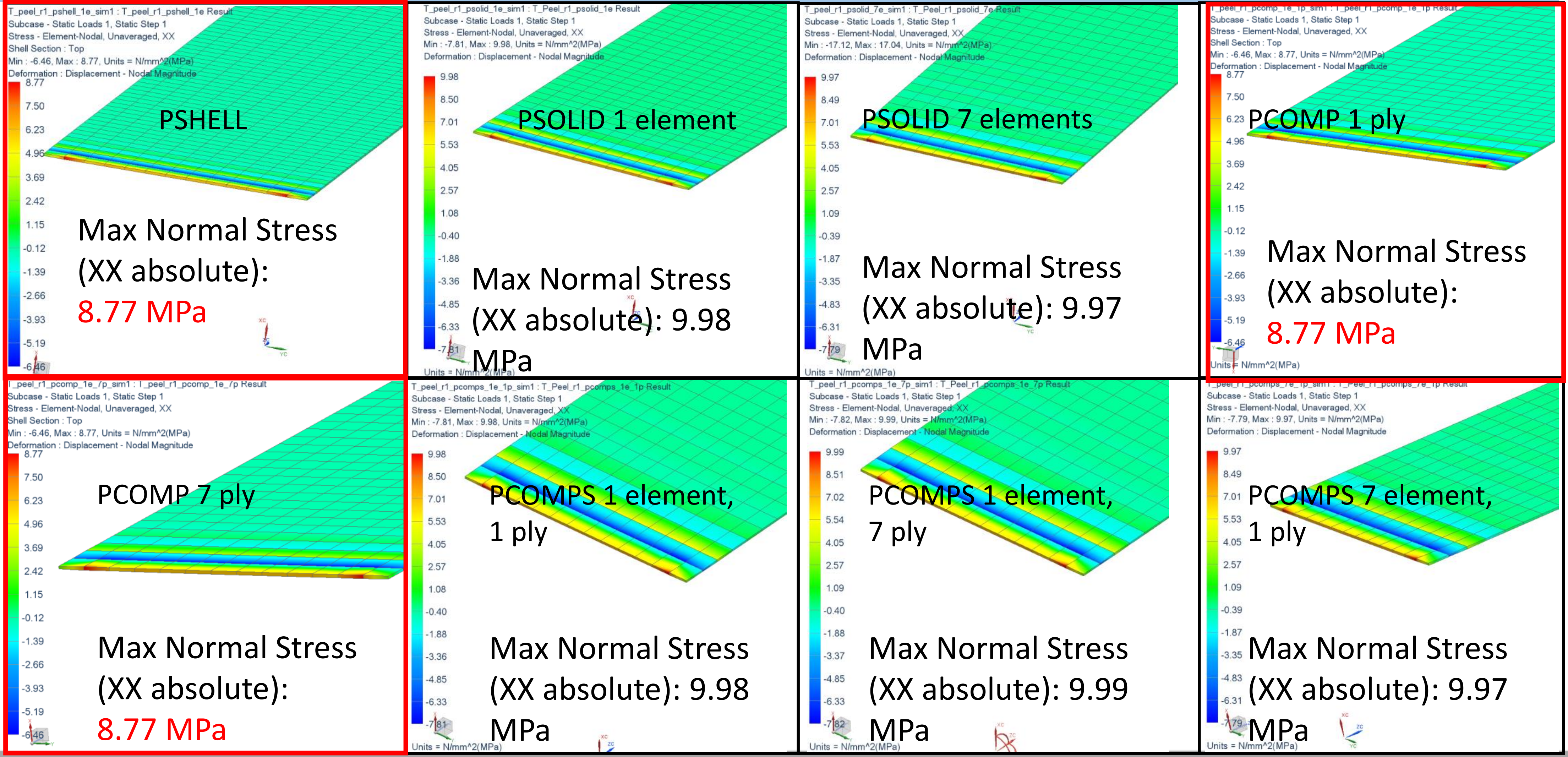


PCOMPS with 7 elements through the thickness, 1 ply, 0.81 mm thick, Max Def: 0.0783 mm

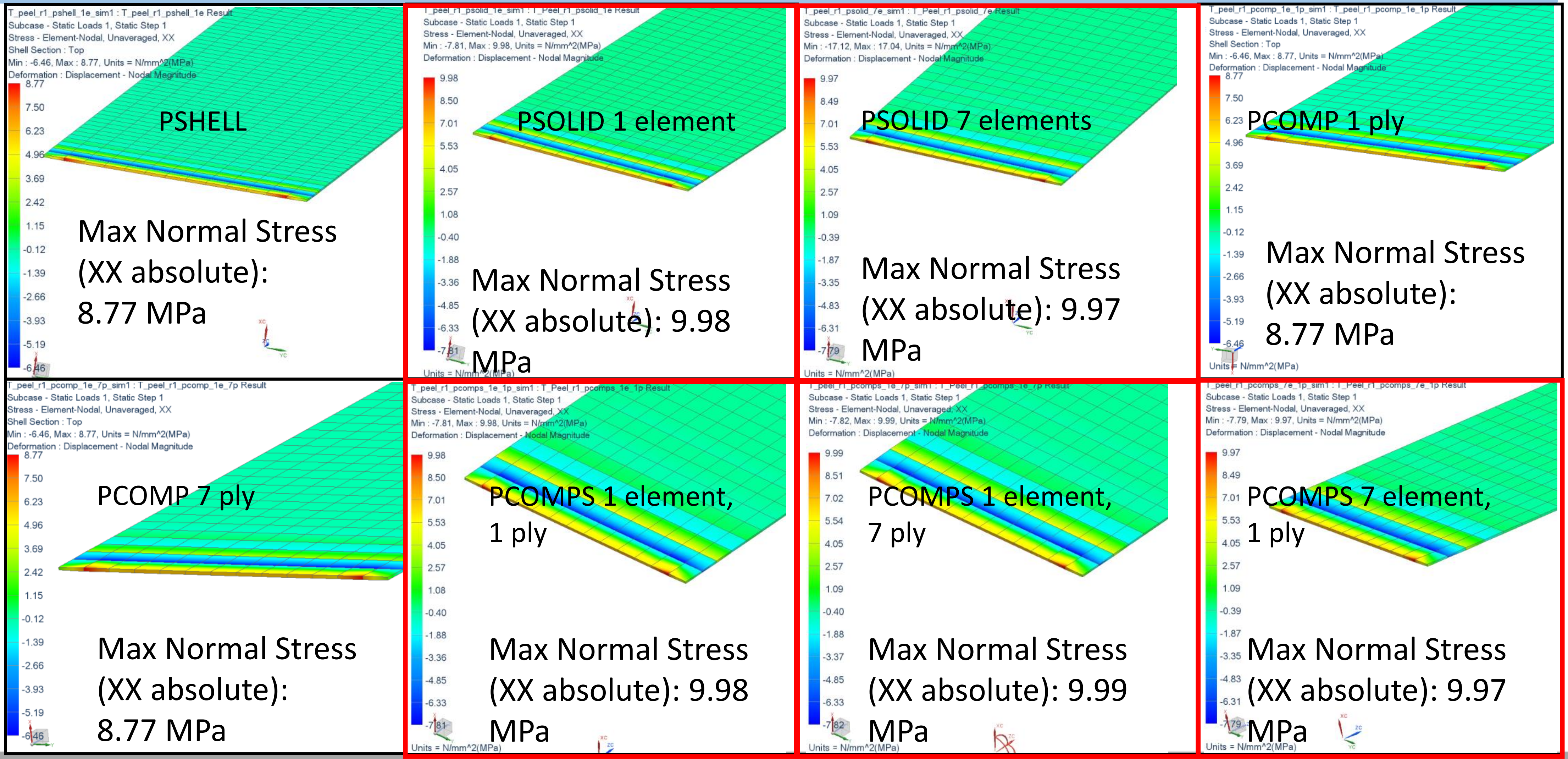
Maximum Deflection Varies With Mesh Type, 3D Elements With 7 Element Through-the-Thickness All Match



Adhesive Solid Stress Varies As Expected Based On Differences In Displacements Due To Different Adherands



Adhesive Solid Stress Varies As Expected Based On Differences In Displacements Due To Different Adherands



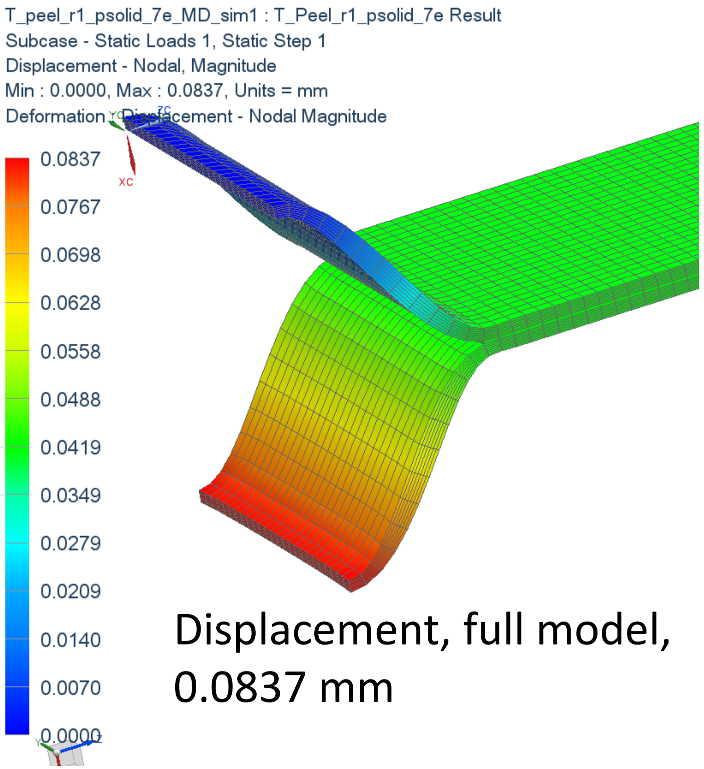
2D Models Differ From The Baseline Through The Thickness By As Much As 12%

- The 2D adherand elements fail to match displacement or elemental-nodal normal stress compared to that predicted by the full 3D models

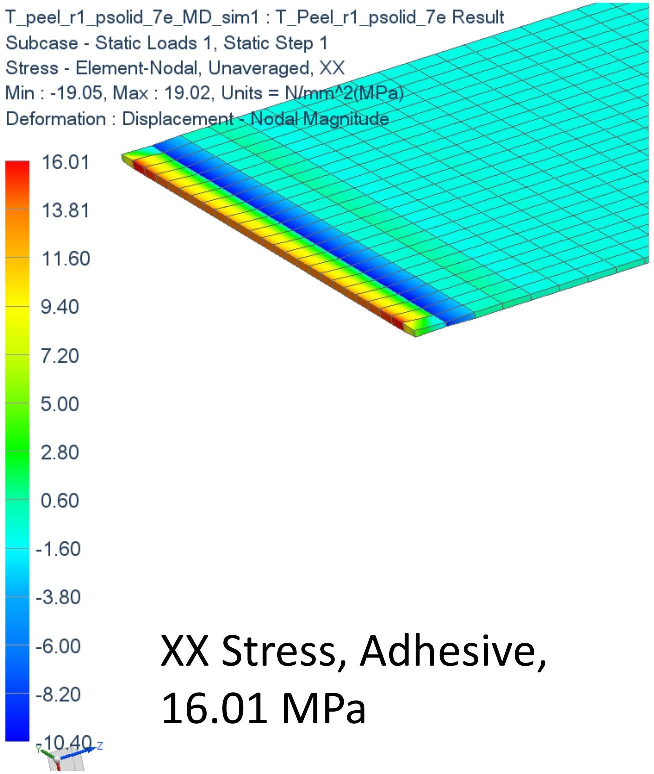
Physical Property Type	Elements Through Thickness	Plies Per Element	Displacement Nodal (mm)	Displacement Nodal (% Diff)	Normal - XX/33 Stress (MPa) Elemental-Nodal (MPa)	Elemental-Nodal (% Diff)	Elemental (MPa)	Elemental (% Diff)
PSOLID	7	--	0.0783	--	**9.97**	--	**3.606**	--
PSHELL	1	--	0.0866	-10.60%	8.77	12.04%	3.454	4.22%
PCOMP	1	1	0.0866	-10.60%	8.77	12.04%	3.454	4.22%
PCOMP	1	7	0.0866	-10.60%	8.77	12.04%	3.454	4.22%
PCOMPS	1	1	0.0799	-2.04%	9.980	-0.10%	3.656	-1.39%
PCOMPS	1	7	0.0799	-2.04%	9.990	-0.20%	3.657	-1.41%
PCOMPS	7	1	0.0783	0.00%	9.970	0.00%	3.606	0.00%
PSOLID	1	--	0.0799	-2.04%	9.980	-0.10%	3.656	-1.39%

Recall Stresses Obtained May Not Be Meaningful Without Normalization To Element Size And Testing

- As a quick test the 3D PSOLID mesh with 7 elements through the thickness was re-meshed with elements that were one half of the size (1 mm x 1 mm)
- The displacement is similar (within 7%) but not exact
  - This indicates a mesh refinement may be necessary to gain accurate results
- The stress on the other hand scales inversely with element size
  - It increased by 60%!
- It is important to normalize your limit stresses to test data and element size



Displacement, full model, 0.0837 mm



XX Stress, Adhesive, 16.01 MPa

Composite Modeling Application: How Do You Choose Element & Property Type?

- Have to pick element & property type for your specific application
  - Solids are the most general but also the most time consuming

Interest	Application/Needs	Common Property Types
Displacements	Global modeling of test displacements	PSHELL, PCOMP/PCOMPG, PCOMPS, PSOLID
Smeared In Plane Stresses	Failure due to axial or bending loads, lots of layers but they are not important, honeycomb, dynamics models (not detailed layered stresses)	PSHELL, PSOLID
Ply-by-Ply In Plane Stresses	Driven by in-plane ply theory, want to compute ply failure indices	PCOMP/PCOMPG, PCOMPS
Interlaminar Stresses	Peel Behavior (Flatwise Tension) Near Bond, Accurate interlaminar stress required	PCOMPS, PSOLID

Summary: Composite Modeling Requires Tracking Of Many Details & Good Knowledge Of The End Goal

- Make sure you recover stress where the high stress is going to occur (or recover at all points if you are not sure)
  - You can request elemental-nodal results for PCOMPS properties
  - You can request bottom, mid, or top for PCOMPS properties
- All stress results improve via more elements through the thickness
  - But depending on your stress states of interest (ie, axial in a simple beam bending problem) the error may be acceptable with less elements through the thickness
- Normalization to element size and testing is recommended
  - This allows establishment of allowables that relate to your specific mesh density