Finite Element Analyses of Adhesively Bonded Composite-Steel Joints for Lightweighting Applications

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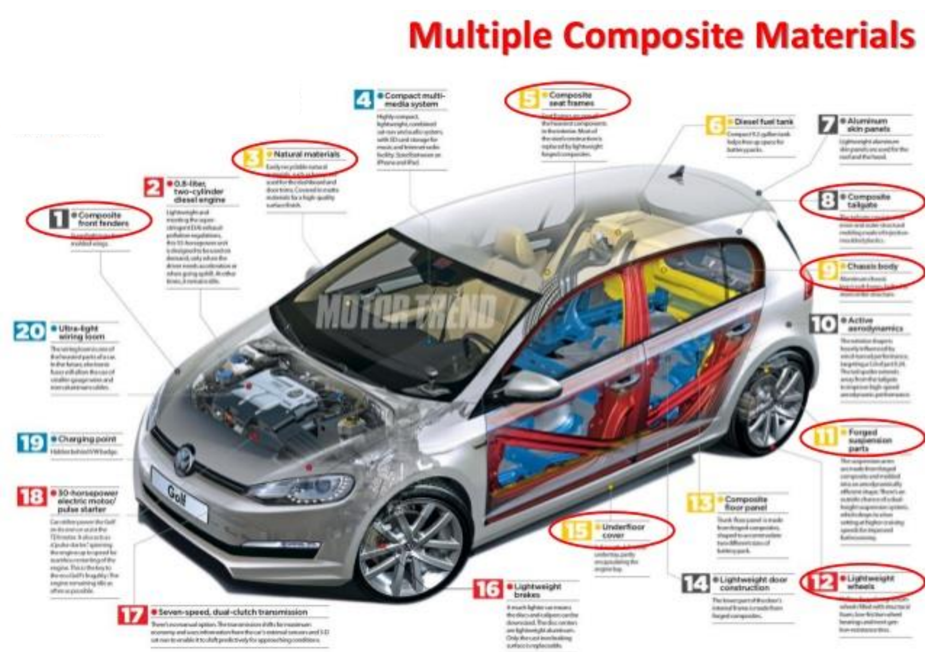
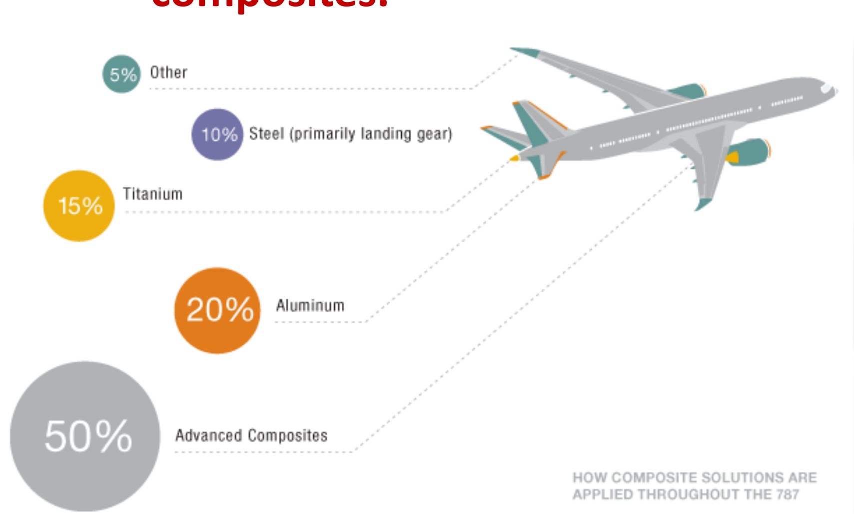
Introduction

- Manufacturers of planes, trains, automobiles, trucks, and tractors are seeking new materials that improve efficiency and reduce weight.



50% of airplane material is composites.



https://www.slideshare.net/ratnachatterjee/advanced-future-applications-of-composite-fibres-in-the-automotive-industry

http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html

Challenge and Solution

- Engineering plastics and carbon-fiber composites are popular choices, but they create challenges when they have to be joined to dissimilar materials, such as aluminum, steel, or titanium.
- To assist the design of a bonded joint system for a composite-metal interface, a three-dimensional (3D) finite-element computational procedure was developed.
- This analysis procedure was used to predict stress and strain distributions, joint strength, and failure modes of an adhesive-bonded composite joint during loading.

Design Verification Approach

Model Design

Material properties
Bond line thickness
Environmental effects
Joint concepts

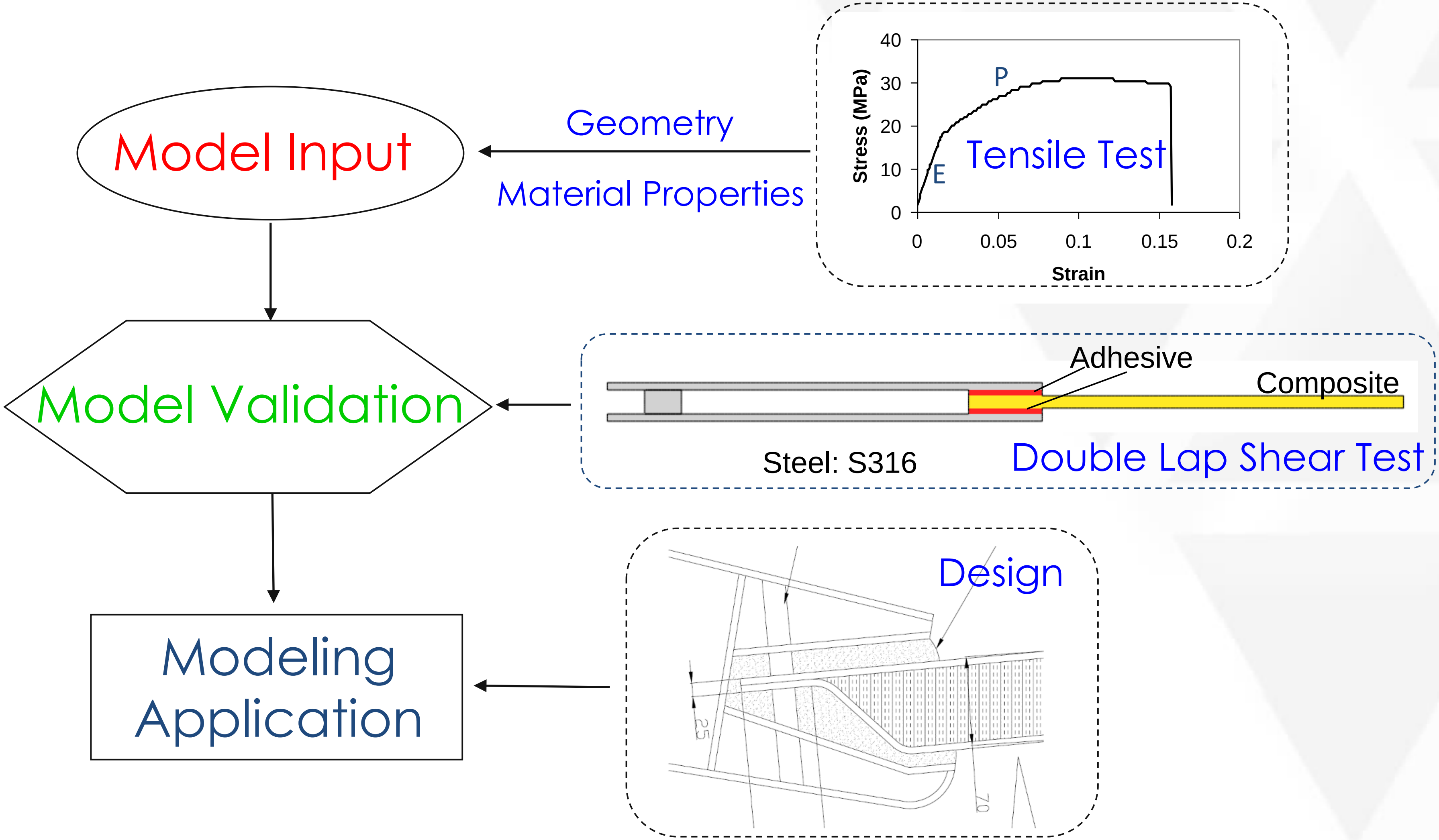
Measure Material Properties

- Tensile
- Modulus
- Cure effects
- Lap shears
- Surface preps

Confirming Structure

- Build full scale joints
- Test against parameters
- Verify – static and fatigue
- NDE development

Modeling Approach



Modeling Procedure and Input

Model Input: Material Properties

- Metal properties can be obtained from public literature.
- Composite material properties can be obtained from material suppliers.
- Adhesive material properties depend on the adhesive process conditions and were prepared by tensile testing.

Modeling Procedures

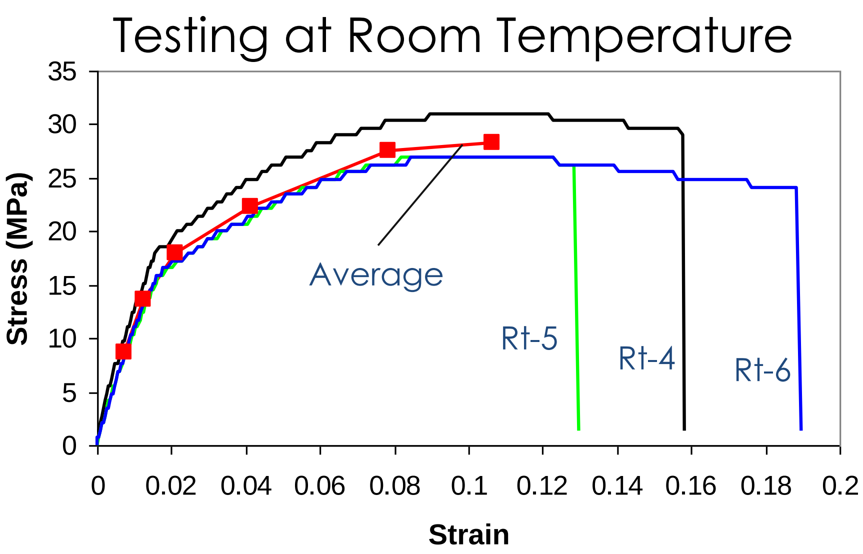
- The computational procedure was developed based on commercial finite element software, ABAQUS, and 3D models were conducted for the analysis.
- Metal and adhesive were meshed with solid brick elements and the composite was meshed with both solid brick elements and cohesive elements.
- Isotropic elastic and plastic material properties were assumed for both the metal and the adhesive.
- Orthotropic elastic material properties were assumed for the composite.
- Progressive damage and failure were modeled by defining failure criteria (damage initiation and evolution) to the adhesive and composite.

Adhesive Properties Testing

- The adhesive for the exterior joint is 3M™ Scotch-Weld™ 2216 Translucent Epoxy Adhesive to which an accelerant was added to boost its cure rate and temperature resistance.
- Tensile tests were conducted from cast specimens configured as in ASTM D638 Type I "dogbones."
- Tensile properties were measured at a room temperature (23°C) and at an elevated temperature (60 °C).
- The strain rate was kept constant at 12.5 mm/min. Both 1.5- and 6-mm thick specimens were cast and tested.

Material Properties of Adhesive at Room Temperature

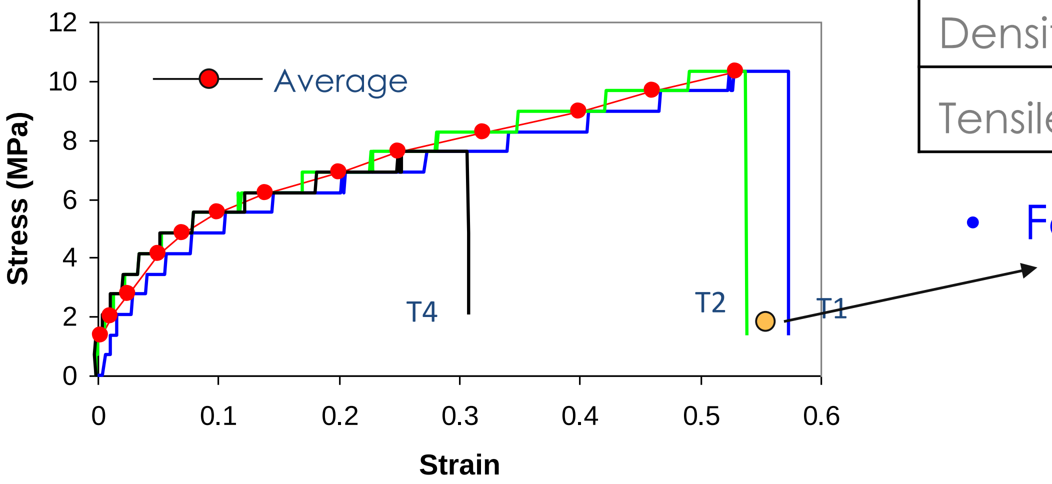
- Material properties from tensile tests.
- Averaged data was input to model.



Poisson's Ratio	0.38
Density (kg/mm^3)	1.13E-06
Tensile Modulus (GPa)	1.3

Material Properties of Adhesive at a High Temperature

- Tensile tests show that the failures were caused by stretching the adhesive to the material limit (most deformation is plastic).

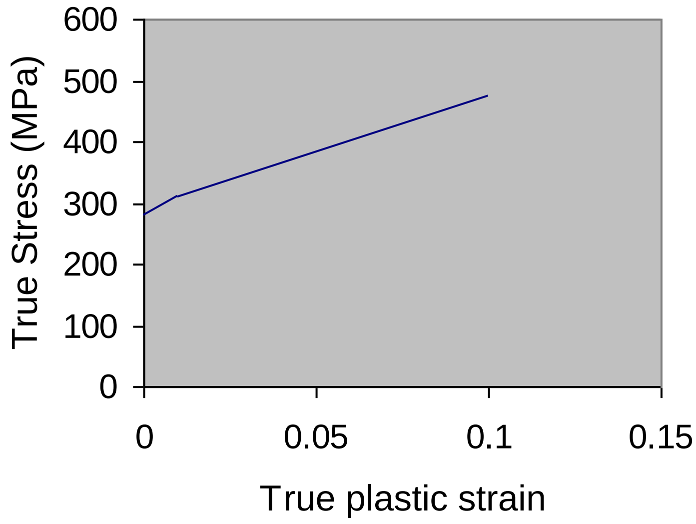


Poisson's Ratio	0.38
Density (kg/mm^3)	1.13E-06
Tensile Modulus (GPa)	0.177

- Failure criteria:
  - Average plastic strain:
    - 56.5%

Model Input: Material Properties of Steel

- Isotropic elastic and plastic material properties were assumed for steel.
- Material properties from literature.



Poisson's Ratio	0.3
Density (kg/mm^3)	7.98E-06
Tensile Modulus (GPa)	195.6

Model Input: Composite Material Properties

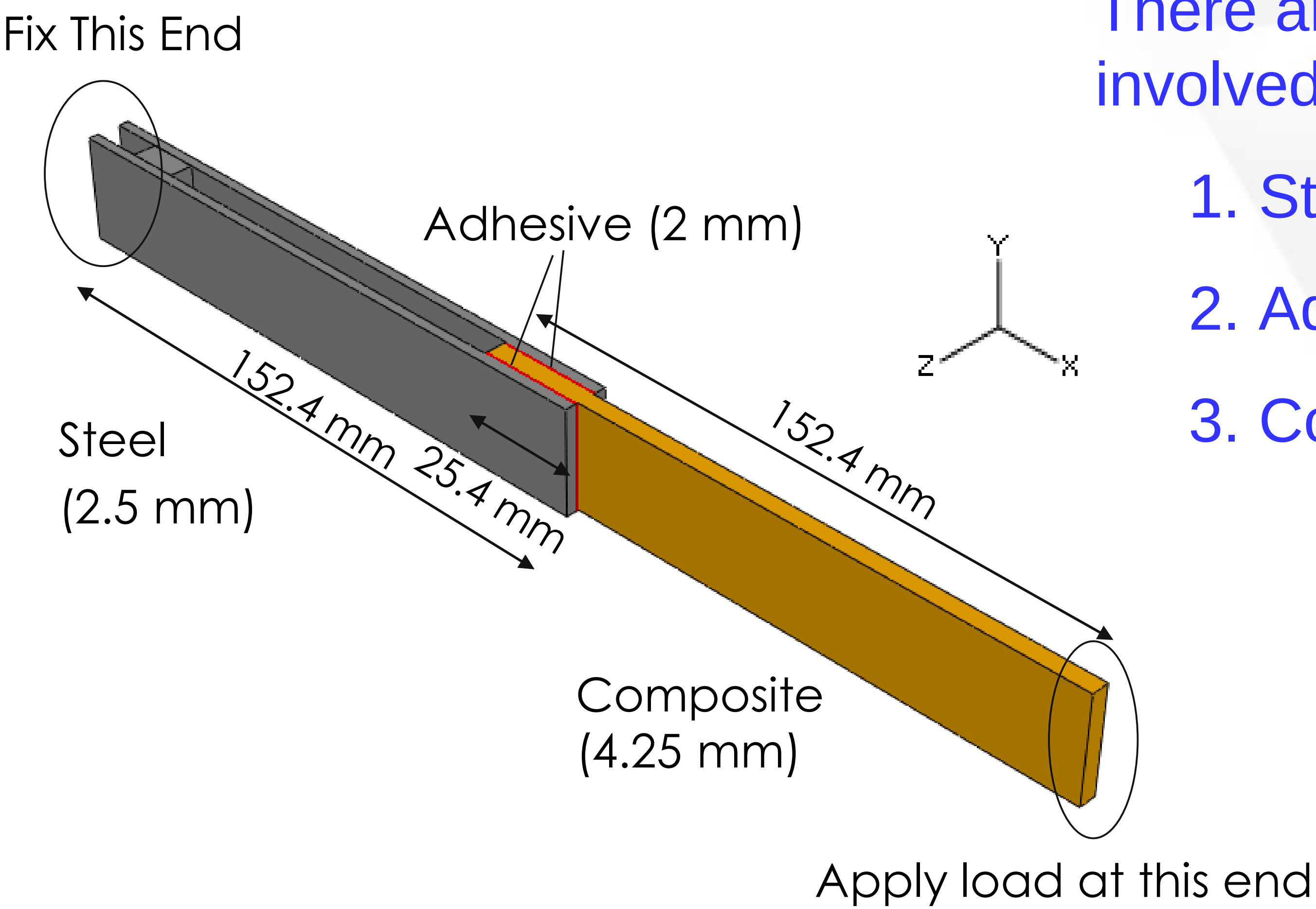
- Orthotropic material properties were assumed for composite.
- Data provided by a material supplier.

Elastic Modulus		GPa
Tensile	Ex	17.5
	Ey	17.5
	Ez	3.0
Shear	Gxy	6.9
	Gxz	6.9
	Gyz	6.9
Poisson Ratio	Vxy	0.3
	Vxz	0.3
	Vyz	0.3

Strength	MPa
Tensile strength	399.0
Compressive strength	337.9
Shear strength	34.5
Tensile strain	1.8%
Compressive strain	1.6%
Shear strain	1.6%
Density (Kg/mm^3)	1.6E-6

Model Validations

Model Validation: Double Lap Shear



There are three materials involved in the design:

1. Steel
2. Adhesive
3. Composite

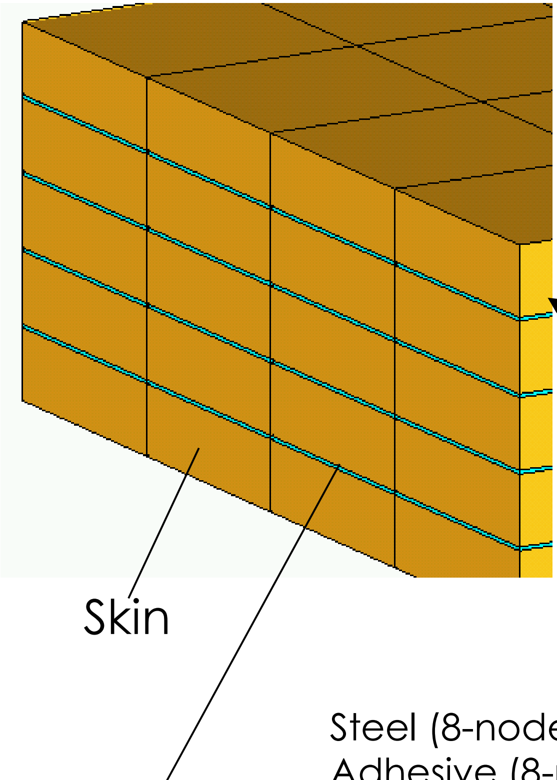
Double Lap-Shear (DLS) Testing

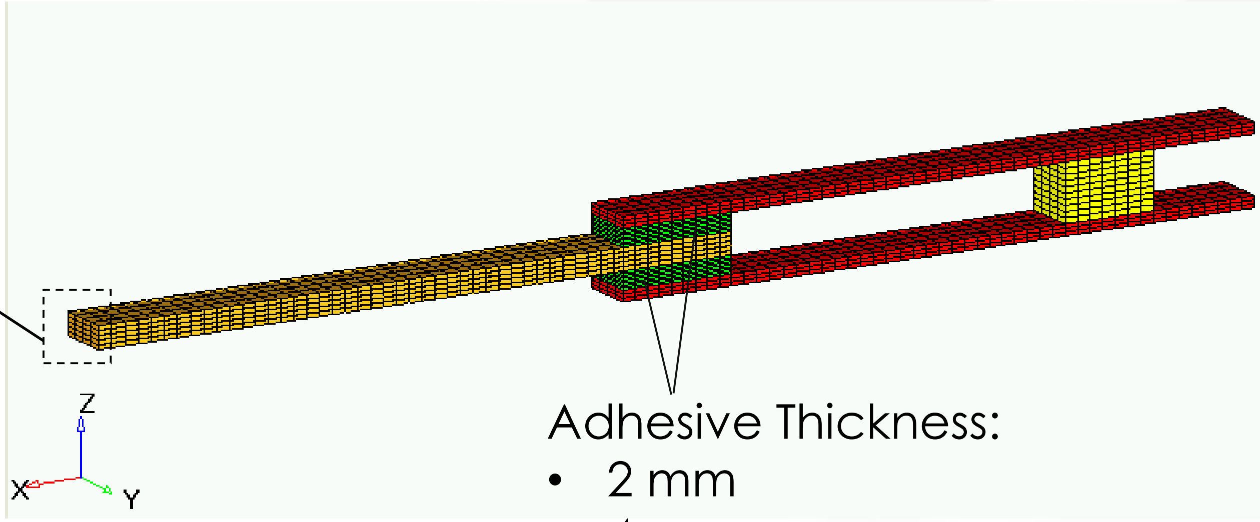
- The chosen DLS specimen configuration is taken from ASTM 3528, Type A.
- A single large bonded plate about 300 mm wide was produced and individual 25 mm test specimens were cut from that plate.
- The adhesive cured for at least one week at room temperature prior to testing.
- The samples were tested at a strain rate of 12.5 mm/min. Stress-strain curves were obtained to compare with the modeling results.

Double Lap-Shear (DLS) Testing *(continued)*

- Ten specimens were tested for each environmental condition, except for the salt-fog test specimens where five each were used after each exposure time.
- The DLS specimens were tested after exposure to:
  - Room temperature, dry (23°C) (Modeled)
  - Elevated temperature, dry (60°C) (Modeled)
  - Elevated temperature, wet (ETW – stored 60 days at 60°C/98–100% RH, tested at RT)
  - After 500 hour salt-fog exposure (ASTM B117 – tested RT)
  - After 1500 hour salt-fog exposure (ASTM B117 – tested RT).

Double Lap Shear: Model Details





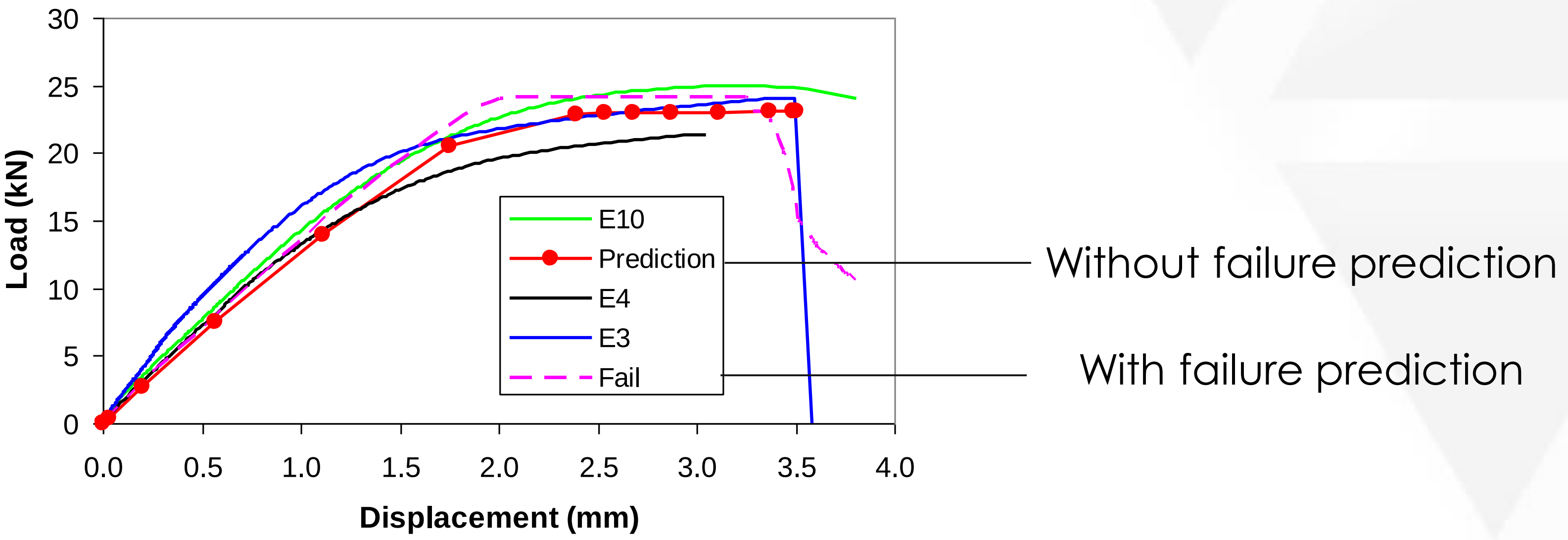
Adhesive Thickness:

- 2 mm
- 4 mm

Steel (8-node brick element): 2040 nodes and 1200 elements
Adhesive (8-node brick element): 900 nodes and 576 elements
Shim (8-node brick element): 1340 nodes and 856 elements
Composite skin (8-node brick element): 2550 nodes and 1000 elements
Composite cohesive (8-node cohesive element): 2040 nodes and 800 elements

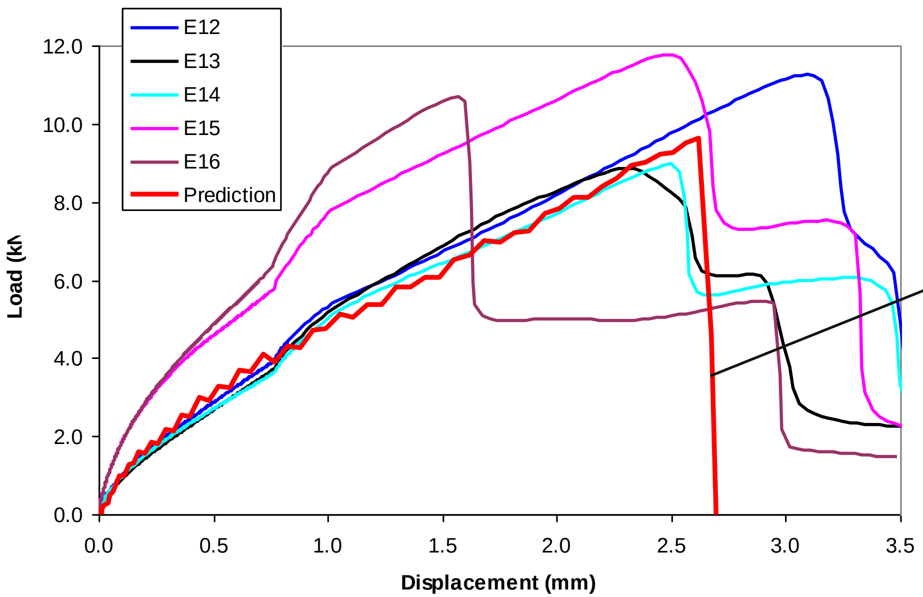
Failure Prediction of Double Lap Shear Specimen at 23°C

- Load responses were compared between model predictions (red line) and experiments (E3, E4, and E10) at room temperature.
- Comparison shows that the model is accurate to predict the load response at room temperature.



Comparison of Model and Experiment — 60°C

- Figure shows the comparison of load responses between model predictions (red dot line) and experiments (E12, E13, E14, E15, and E16) at a high temperature (60°C).
- Comparison shows that the model is accurate to predict the load response at the temperature (60°C)



Analysis with failure prediction and failure criteria: effective plastic strain 56.5%.

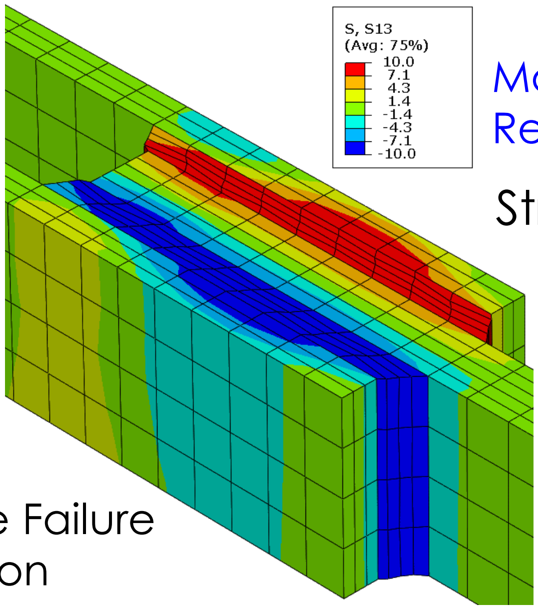
Shear Stress at Failure

Shear Strength From Testing

Specimen Identification	Test Temperature		Ultimate Load		Ultimate Strength		Displacment at Maximum Load		Failure Location
	(°C)	(°F)	(N)	(lbf)	(MPa)	(psi)	(mm)	(in.)	
E12**	60	140	11290	2529	8.2	1186.2	3.429	0.135	Cohesive
E13**	60	140	8893	1992	6.3	908.8	2.565	0.101	Cohesive
E14**	60	140	8996	2015	6.8	989.3	2.743	0.108	Cohesive
E15**	60	140	11813	2646	8.9	1289.9	3.251	0.128	Cohesive
E16**	60	140	10728	2403	8.7	1263.9	2.362	0.093	Cohesive
E17	60	140	12161	2724	9.5	1371.2	3.251	0.128	Cohesive
E18	60	140	10040	2249	7.6	1104.0	2.946	0.116	Cohesive
E19	60	140	9313	2086	6.9	998.7	2.718	0.107	Cohesive
E20	60	140	10205	2286	7.9	1145.9	3.023	0.119	Cohesive

Shear Stress Is Comparable Between Experiment and Modeling

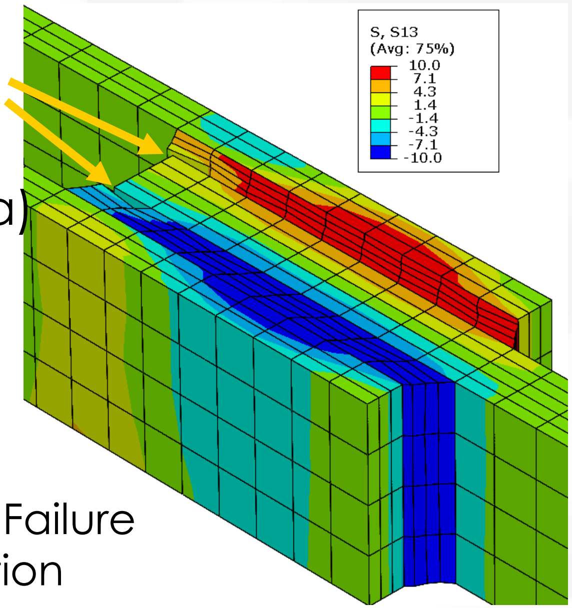
Shear Stress:
Red: 7.1-10MPa;
Blue: –1.7 to –10MPa



Before Failure Initiation

Material Removed

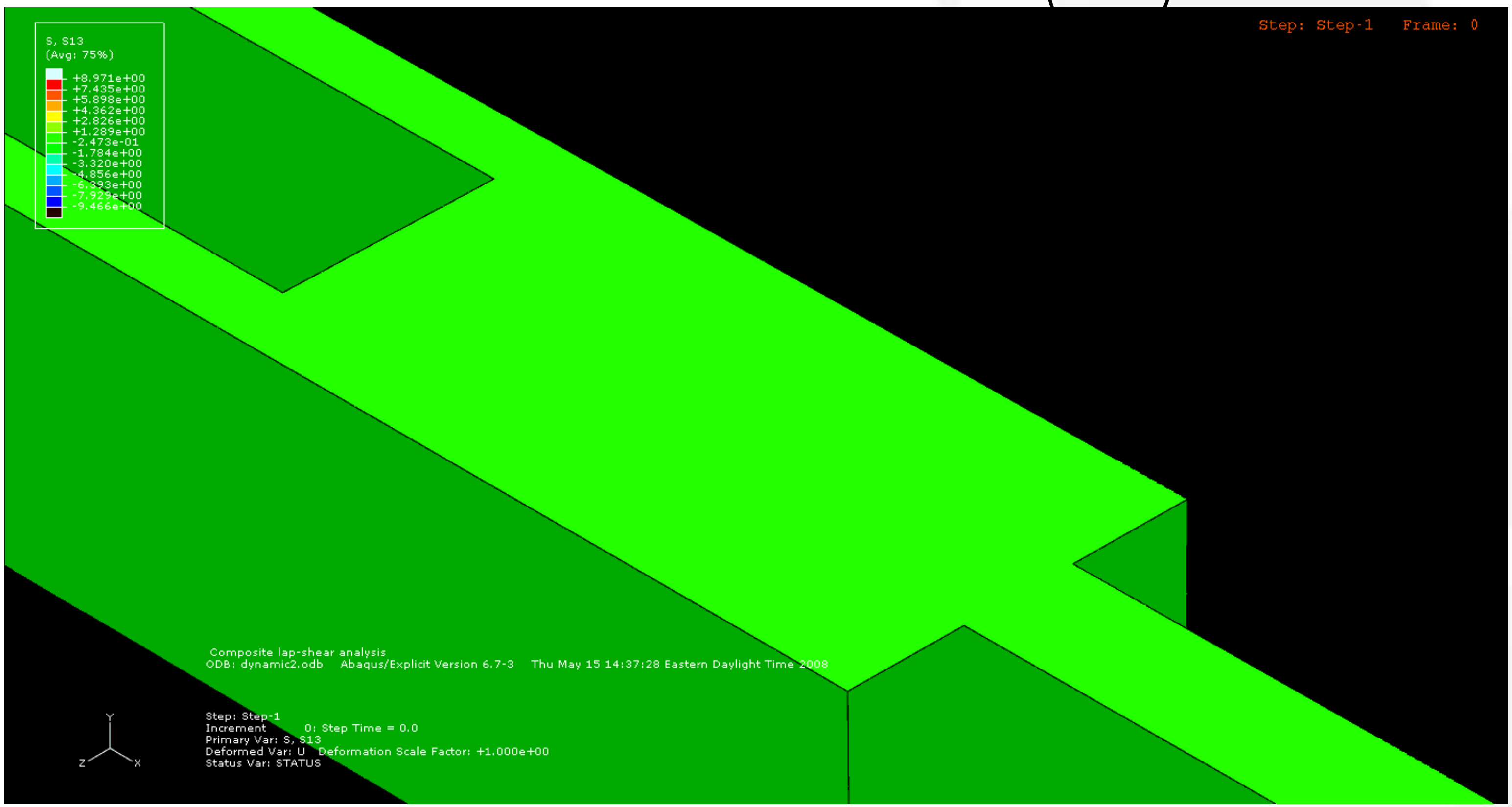
Stress (MPa)



After Failure Initiation

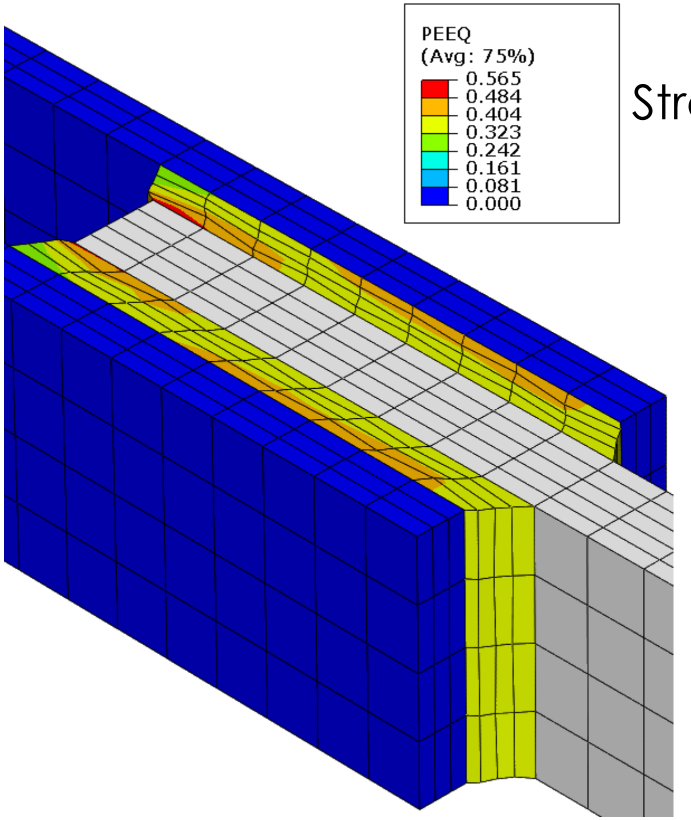
Shear Stress Evolution during Loading

Stress (MPa)



Effective Plastic Strain at Failure

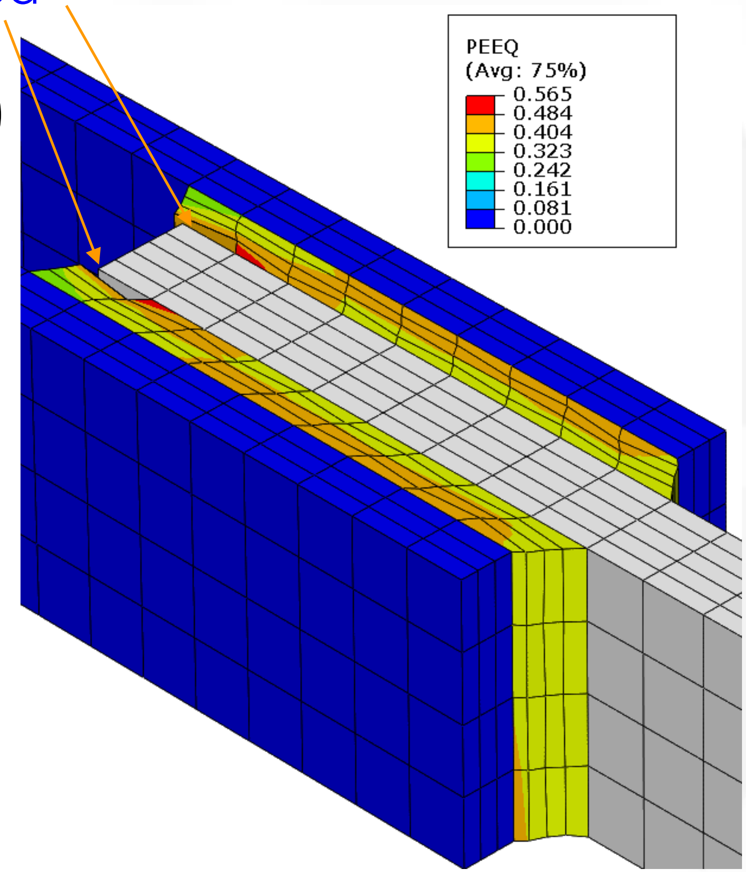
Before Failure Initiation



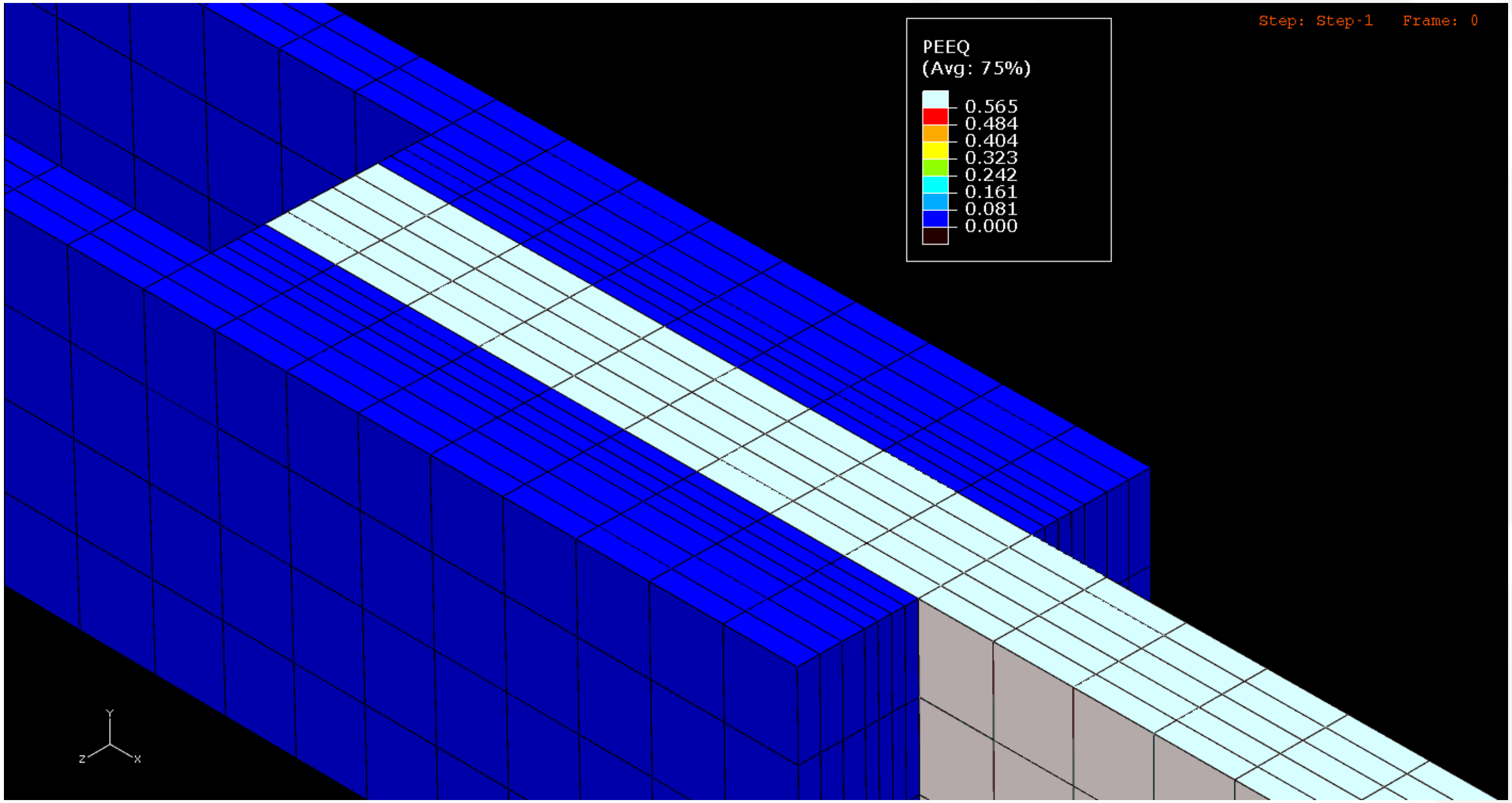
Stress (MPa)

Material Removed

After Failure Initiation

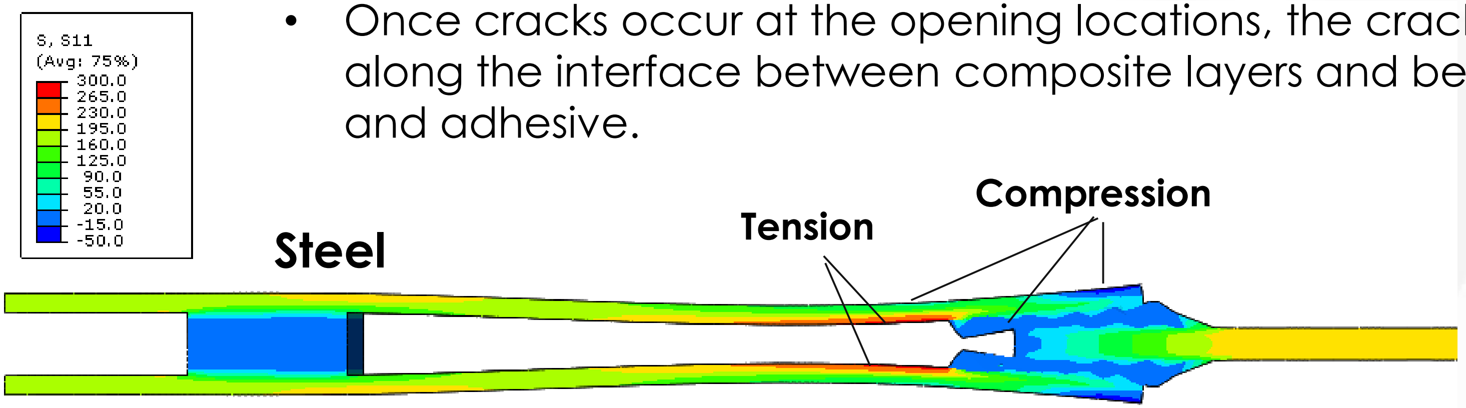


Shear Strain Evolution during Loading

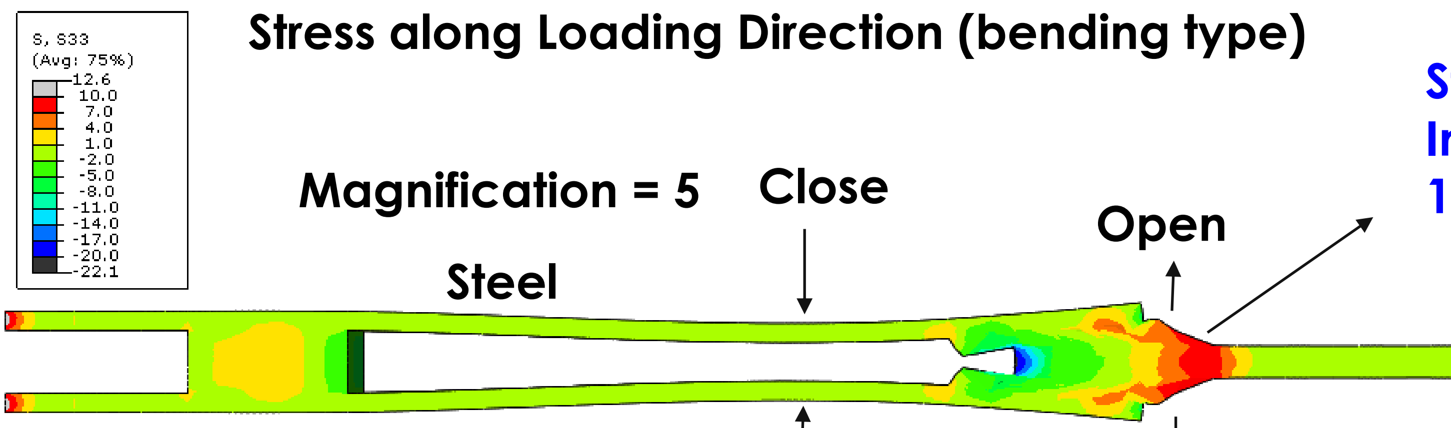


Model Validation: Broken Mechanism Analysis for 23°C Tests

- Both experimental and modeling results show the bending deformation of steel parts.
- The bending tends to open the joint as shown in the following figure.
- Once cracks occur at the opening locations, the crack will propagate along the interface between composite layers and between the steel and adhesive.



Stress along Loading Direction (bending type)

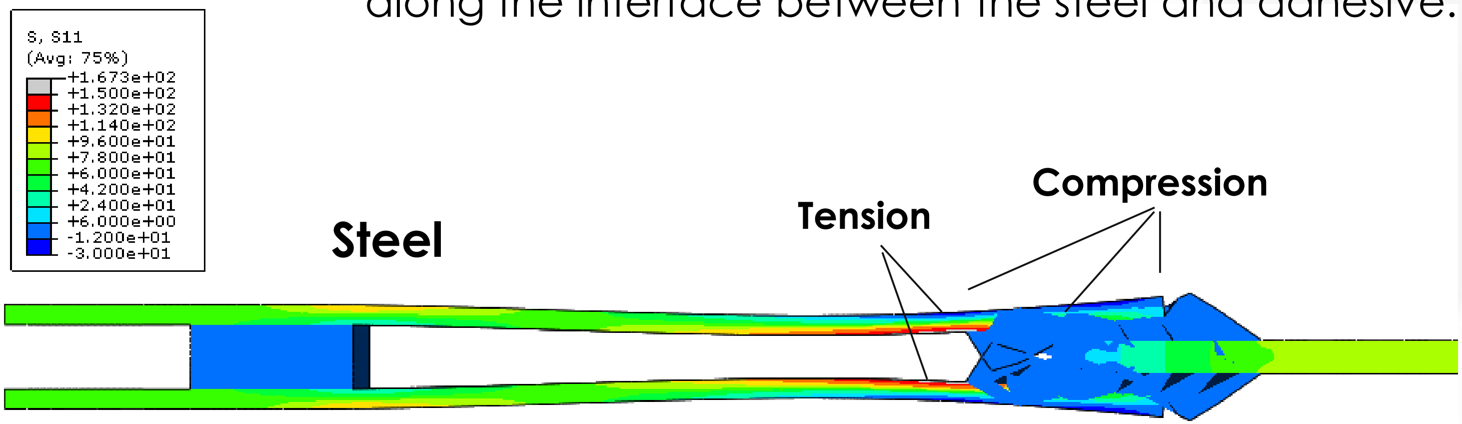


Stress at Crack Initiation is 12.3 MPa

Stress along Thickness Direction

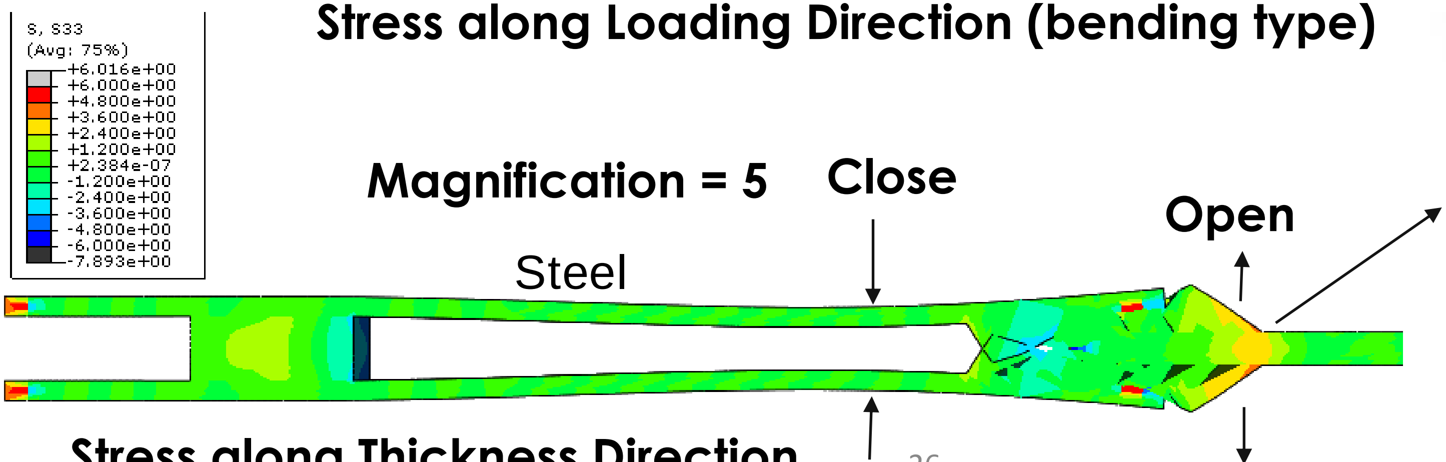
Model Validation: Broken Mechanism Analysis for 60°C Tests

- Similar broken mechanism as the RT tests for crack initiation.
- Most deformation appears in the adhesive as shown in the figure.
- Once cracks occur at the opening locations, the crack will propagate along the interface between the steel and adhesive.



Stress (MPa)

Stress along Loading Direction (bending type)



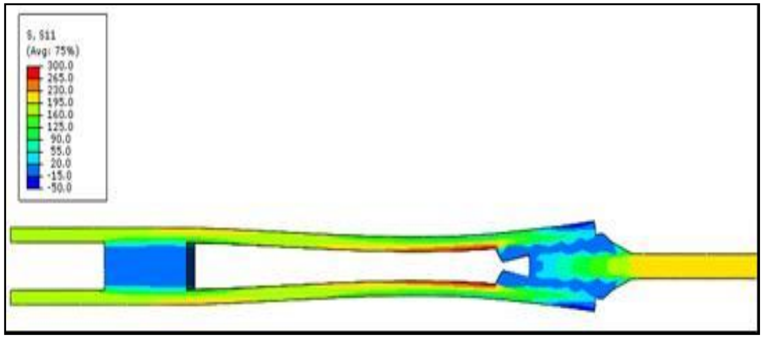
Stress at Crack Initiation is 4.3 MPa

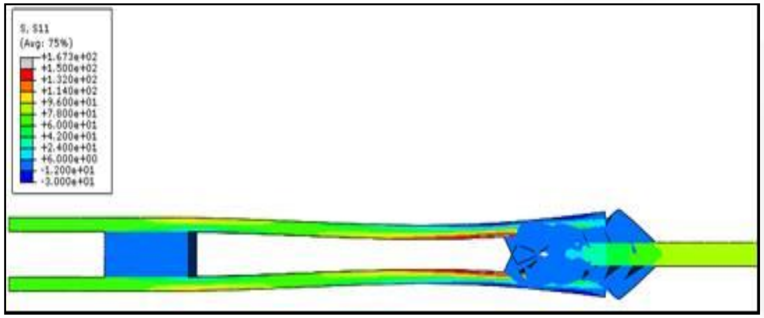
Stress along Thickness Direction

Verification of Model

23°C

60°C





Axial Stress with Displacements × 10

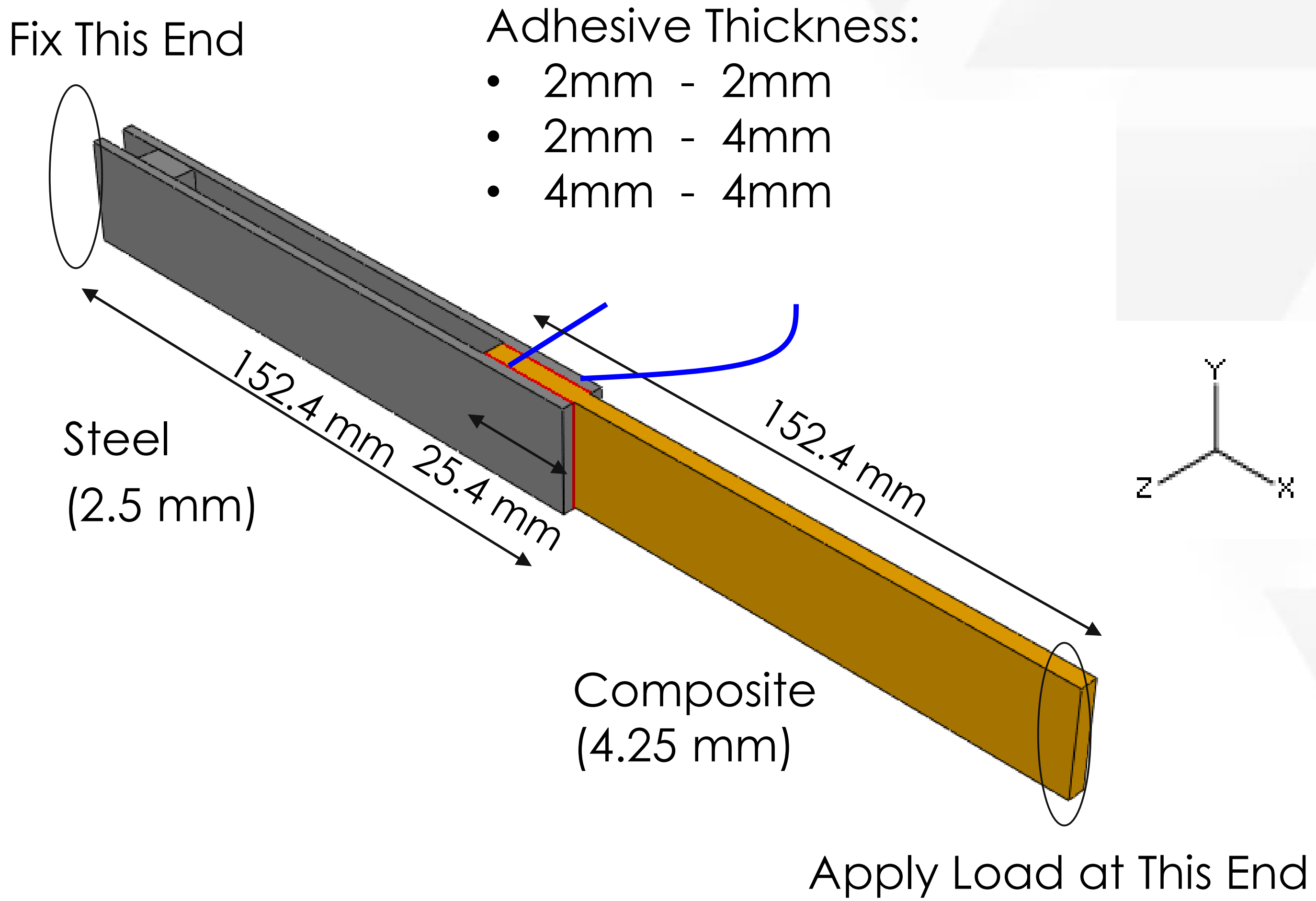
Model Application 1

Effect of adhesive material thickness on the load capacity of an adhesive joint

Three Adhesive Thicknesses

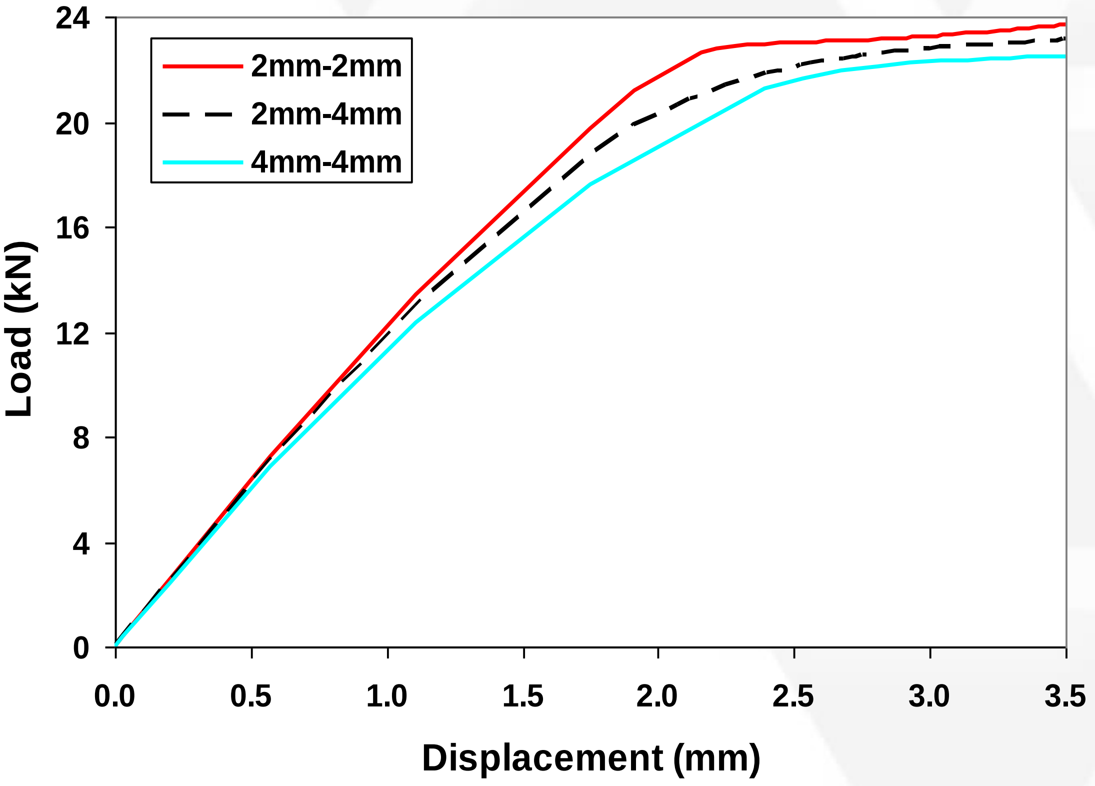
Adhesive Thickness:

- 2mm - 2mm
- 2mm - 4mm
- 4mm - 4mm



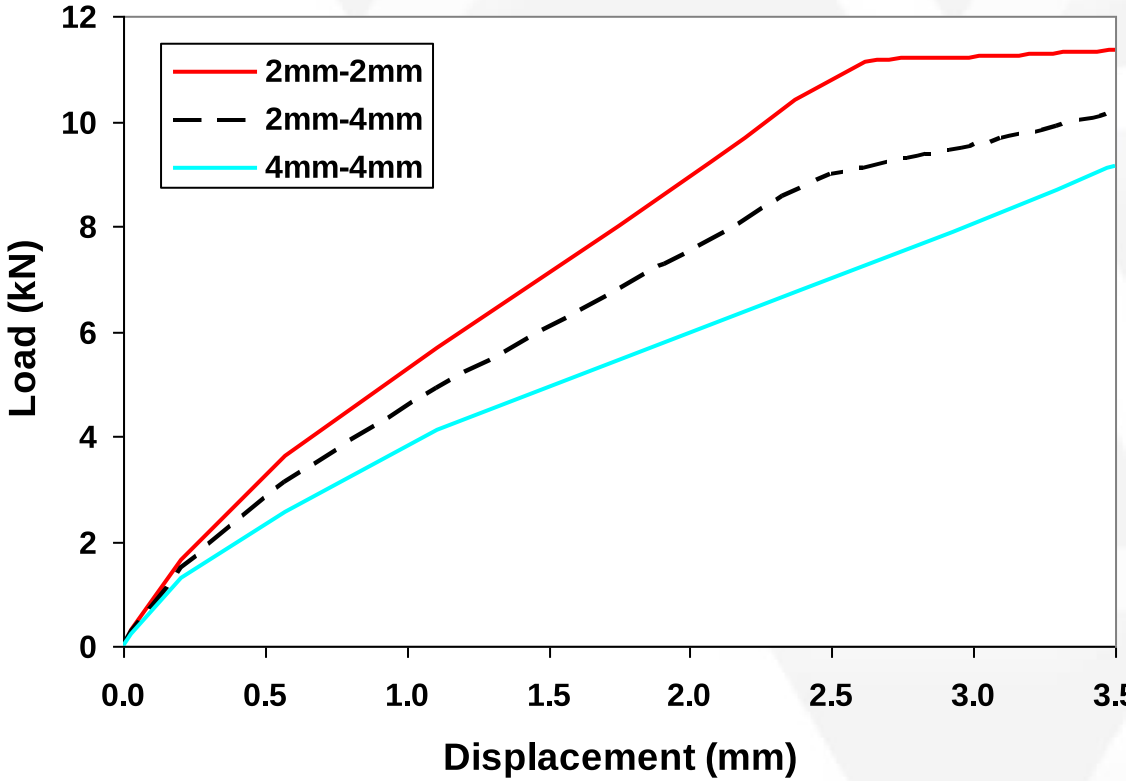
Predicted Load-Displacement Curves at Room Temperature

- The adhesive material has a low elastic modulus.
- The thicker the adhesive layer, the more flexible it becomes.
- As a result, for the same load, the elongation goes up as the thickness increases.



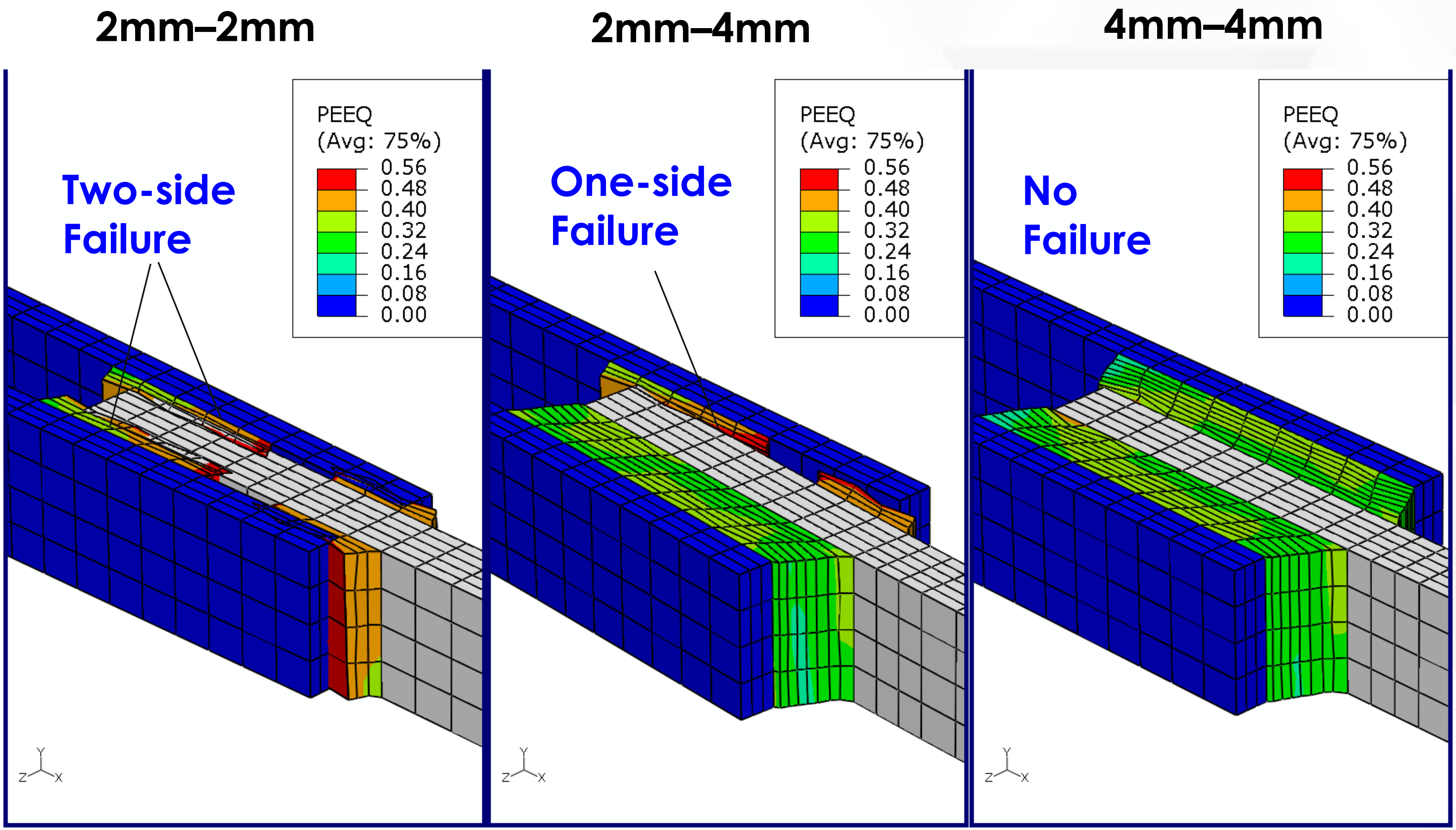
Predicted Load-Displacement Curves at 60°C

- Strength of the adhesive material drops significantly as the temperature is increased from the room temperature to 60 °C.
- For the same load, the displacement increases largely as the temperature rises.



Effect of Adhesive Thickness On Joint Failures

Effective plastic strain distribution after applying 3.5 mm displacement.



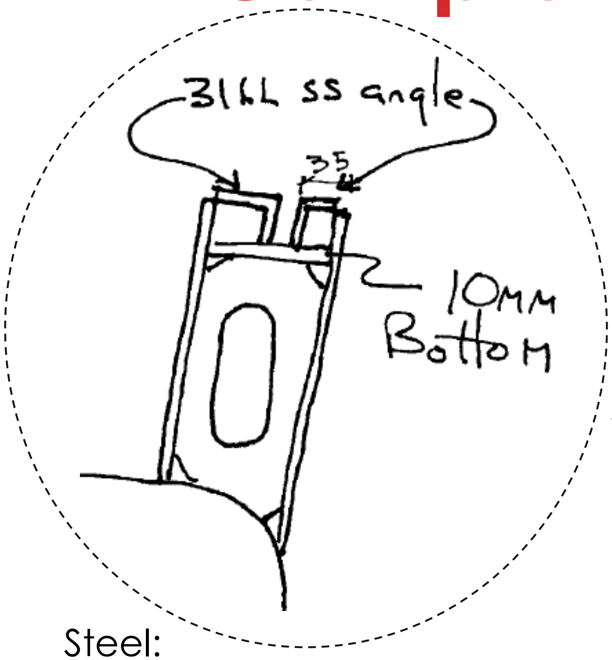
Discussion

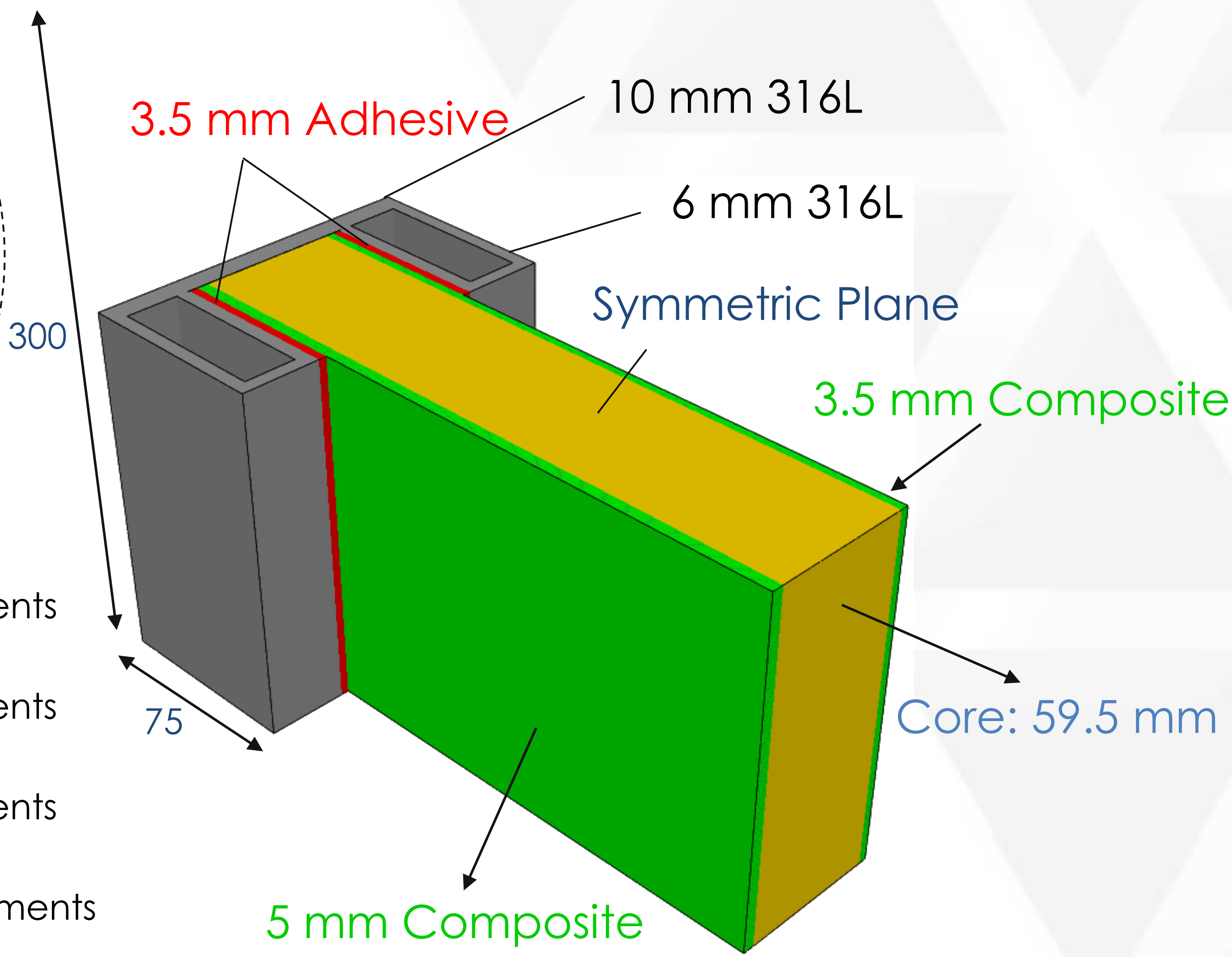
- Effect of adhesive material thickness on the joint strength has been studied at RT and 60°C.
- It was found that the thicker the adhesive layer, the more flexible it becomes.
- As a result, for the same load, the elongation goes up as the thickness increases.

Model Application 2

A complex geometry

A Complex Geometry





Steel:
20560 nodes and 15990 elements
Adhesive:
29120 nodes and 25350 elements
Composite:
55120 nodes and 38688 elements
Core:
100360 nodes and 83148 elements

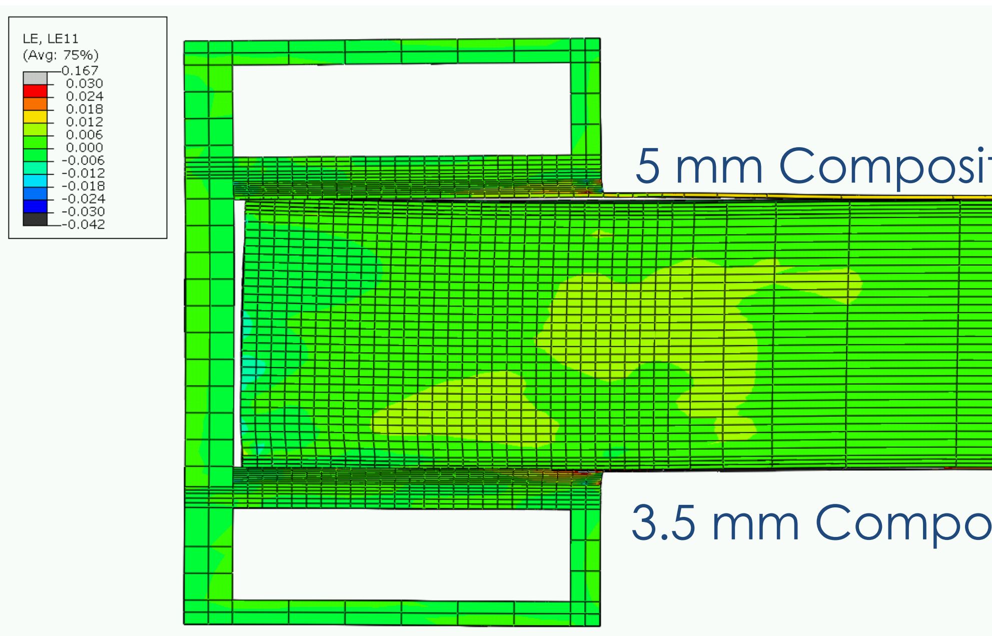
Element type:
Linear 8-nodes brick element

Model Input: Material Properties of H200 Core

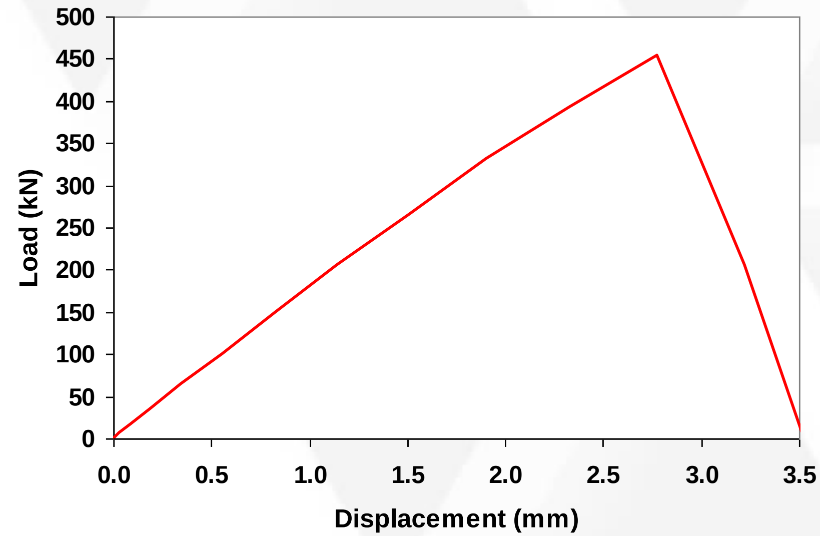
- Isotropic elastic and plastic material properties were assumed for H200 Core.

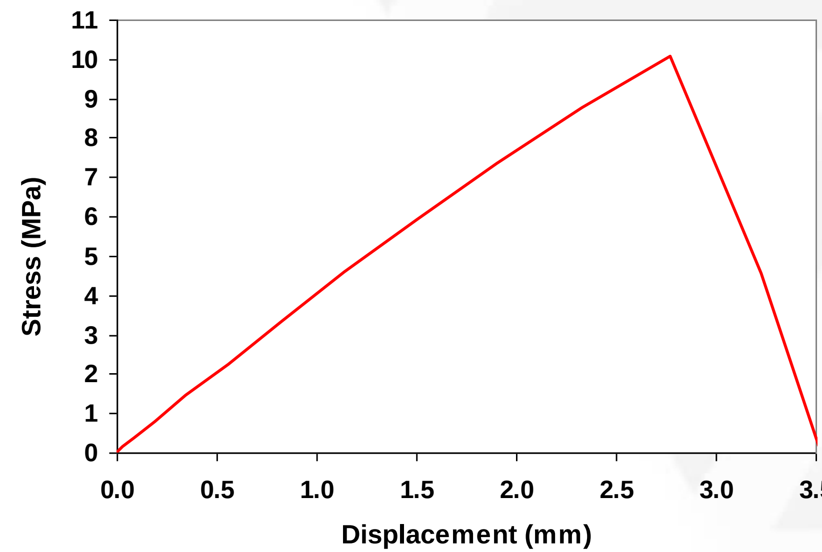
Poisson's Ratio	0.32
Density (kg/mm^3)	2.00E-07
Tensile Modulus (GPa)	0.23
Yield Stress (MPa)	1.6
Tensile Strength (MPa)	6.4
Failure Strain	0.33

Analysis of the Complex Geometry at RT

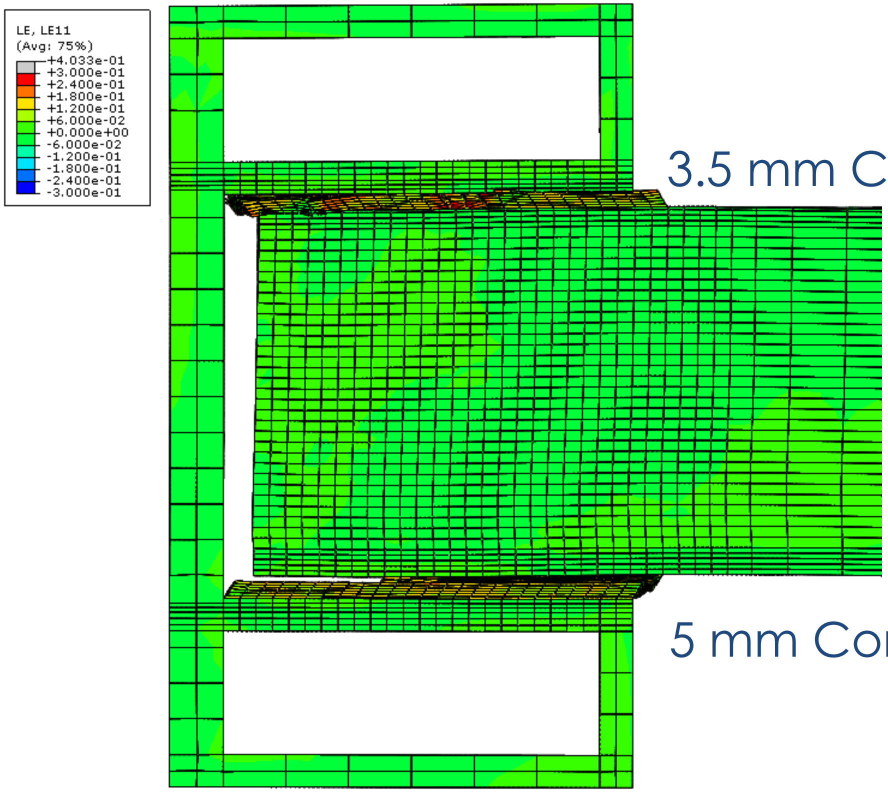


Mag = 1





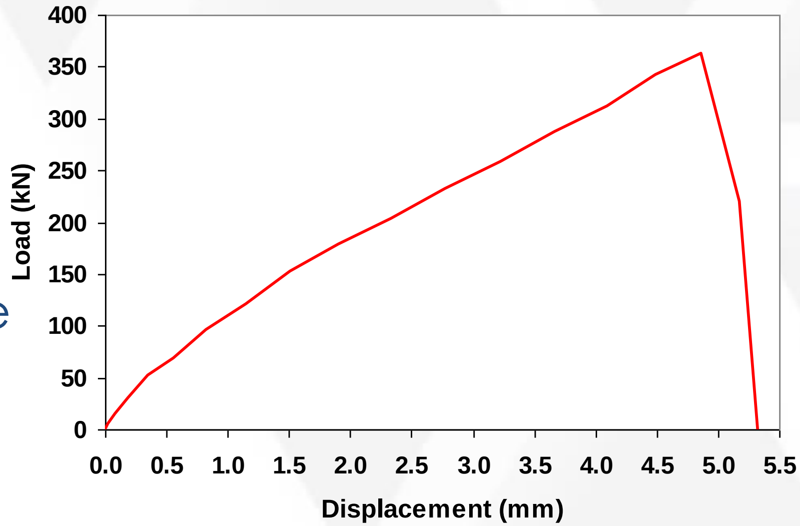
Analysis of the Complex Geometry at 60°C

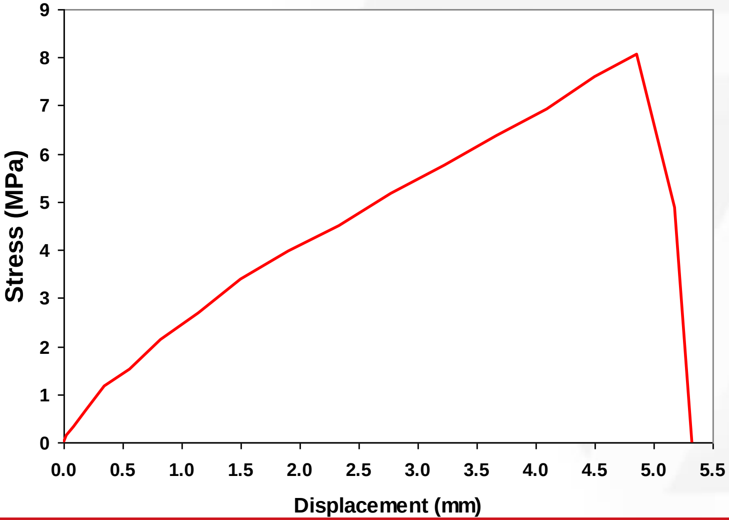


3.5 mm Composite

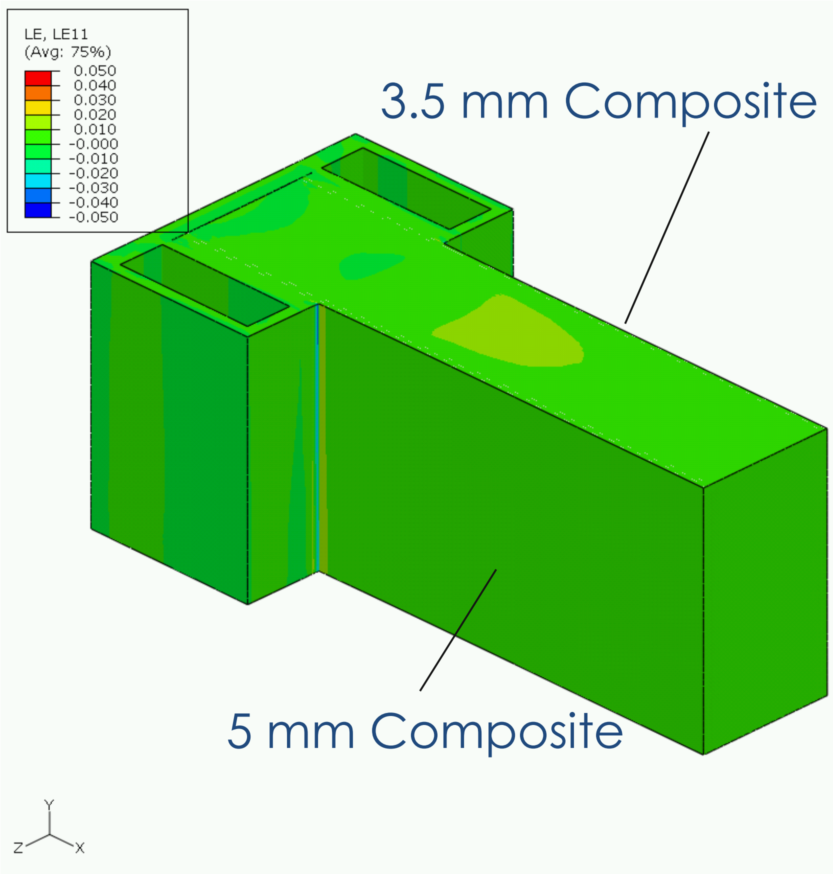
5 mm Composite

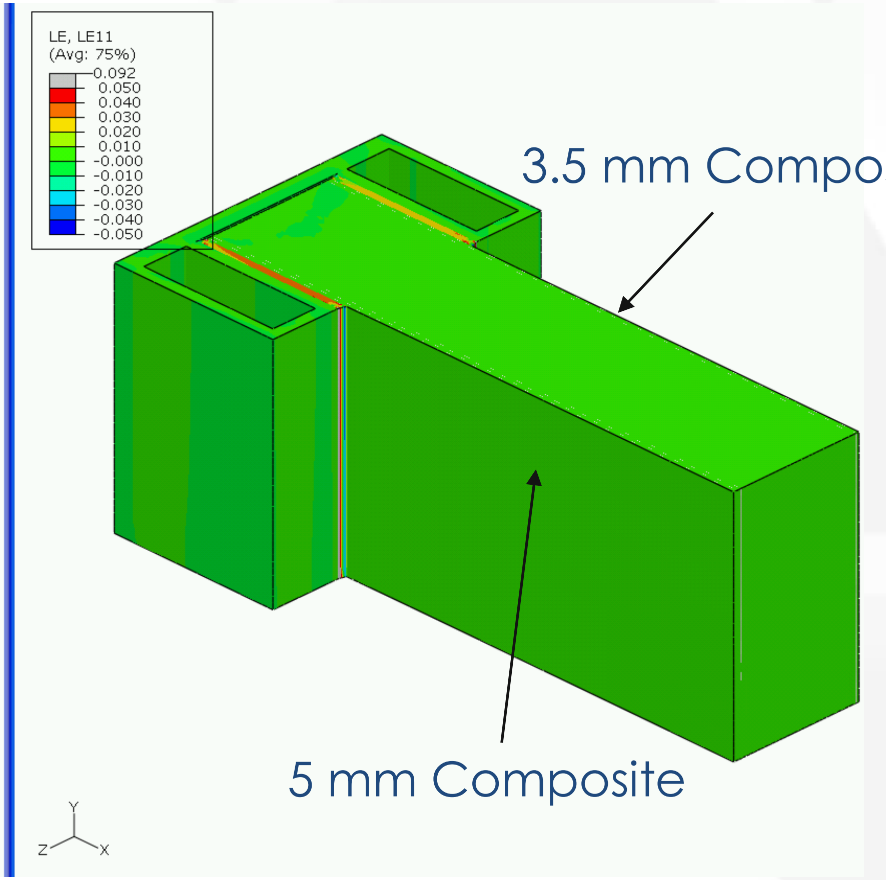
Mag = 1





Total Strain Comparison between RT and 60°C





- Adhesive has more deformation at 60°C than RT.
- Adhesive deformation has some differences between thin-composite side and thick-composite side.

Summary

- A model has been developed to predict the mechanical performance of an adhesive joint between composite to steel.
- The model has been validated with double lap shear testing.
- The model can be used in assisting the adhesive joint design.

Acknowledgments

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- Dr. Yu-Ping Yang, Modeling
- Dr. Junde Xu, Modeling
- Dr. Wei Zhang, Modeling
- Susan Fiore, MS, Program Manager

Thank You!