

# Structural Adhesive Behavior: Experimental and Numerical Study

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# Outline

- Introduction
- Objective
- Mechanical Properties
- Material Models
- Material Model Validation
- Summary & Conclusion

# Outline

- **Introduction**

- Objective

- Mechanical Properties

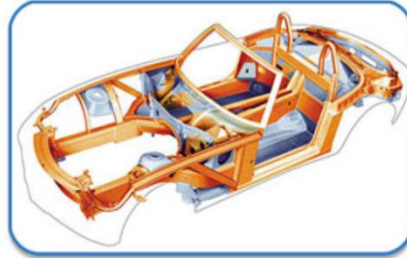
- Material Models

- Material Model Validation

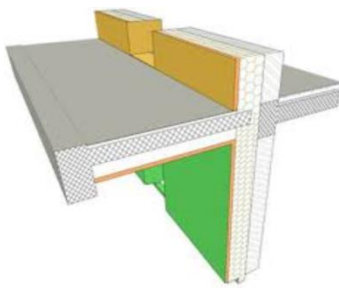
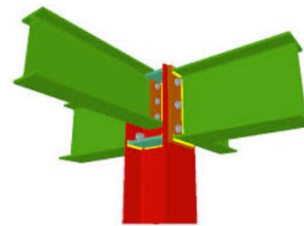
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## Structural Adhesive Applications:

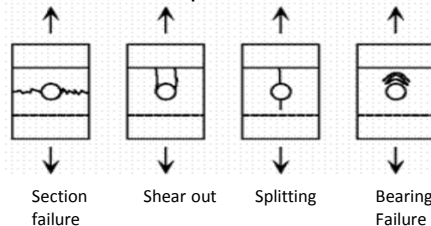
- Adhesive joints are being increasingly used due to their unique characteristics and advantages. They have been widely used in the fields of aerospace, automotive and electronic packages.



- Civil infrastructure applications have considered utilizing adhesive for joining load-bearing components as an excellent candidate for replacing the traditional joining methods such bolting and riveting, especially for scenarios involving joining Fiber Reinforced Polymers (FRP) composites.



Bolting create stress concentrations which lead to premature failure

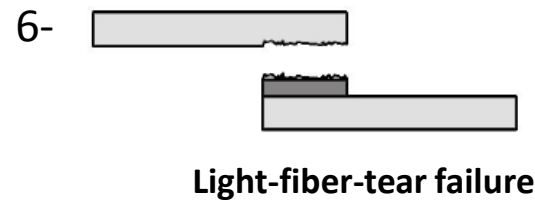
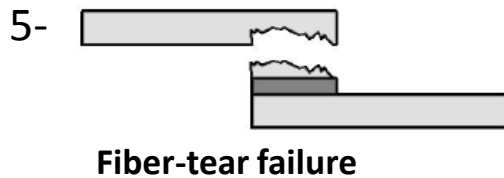
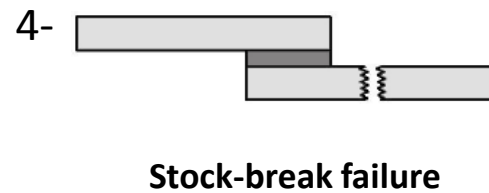
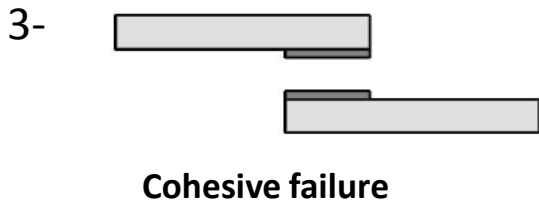
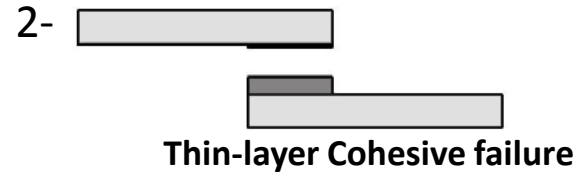
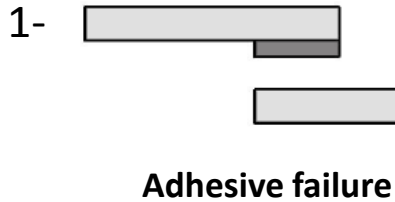


Adhesive joints for civil infrastructure applications are in its infancy due to the lack of understanding bonded joint behavior and lack of design guidelines..

## **Advantages:**

- High joint efficiency and dimensional stability
- Adhesive distribute load across the entire joint area
- Fewer stress concentrations
- No need to dig holes and damage the adherends; holes are points where moisture ingress can occur, which can affect durability
- Low structural weight
- Low fabrication cost and improved damage tolerance
- Rot resistance
- Ease of use

## Failure Modes of Adhesive Joints:



- The properties of the bulk adhesive
- The adhesion properties at the interface

## Design Parameters for Adhesively Bonded Joints

- Structural Adhesive:
  - Mechanical Property: property of the bulk adhesive and adhesion at the interface
  - Requirement for curing
  - Resistance to environmental parameters
  
- Joints:
  - Geometry: surface area and bondline thickness
  - Parameters concerning loading and environment
  
- Fabrication:
  - Preparation before bonding: surface treatment
  - Curing and post-curing: clamping pressure and control environment

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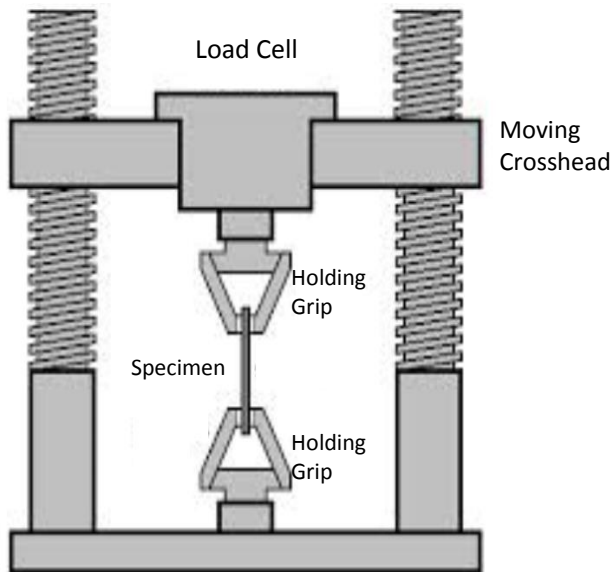
- Characterize adhesive's mechanical property under tensile and shear loadings, at low and high rates (static and dynamic)
- Create FEA material model for the adhesive that can describe the adhesive behavior accurately
- Validate material model experimentally and computationally at coupon level (coupon tension and shear) and sub-system level (four-point bend and dynamic ball drop)

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## Tensile and Shear testing:

Adhesives are viscoelastic materials, therefore their mechanical properties depend upon loading mode and rate.

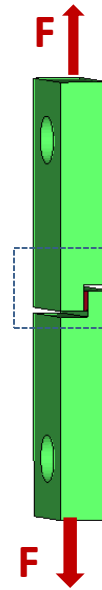


Tensile specimen

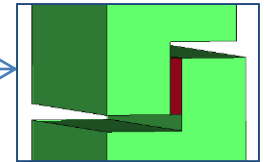


100mm x 20mm x 2mm

Shear specimen



150mm x 20mm x 16mm



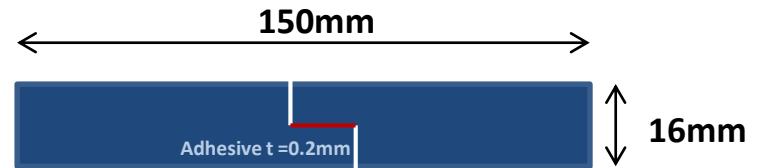
Adhesive:  
10mm x 20mm x 0.2mm

- *It is important to prepare bulk specimens that is in a suitable size for testing, and can accurately represent the properties of the thin layer of the adhesive in a bonded joint.*

## Determination of Tensile & Shear Behavior at Quasi-Static Rate

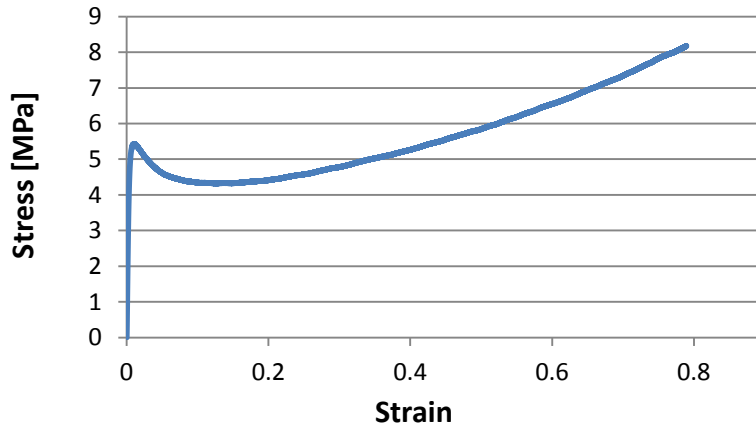


100mm long x 20mm wide x 2mm thick

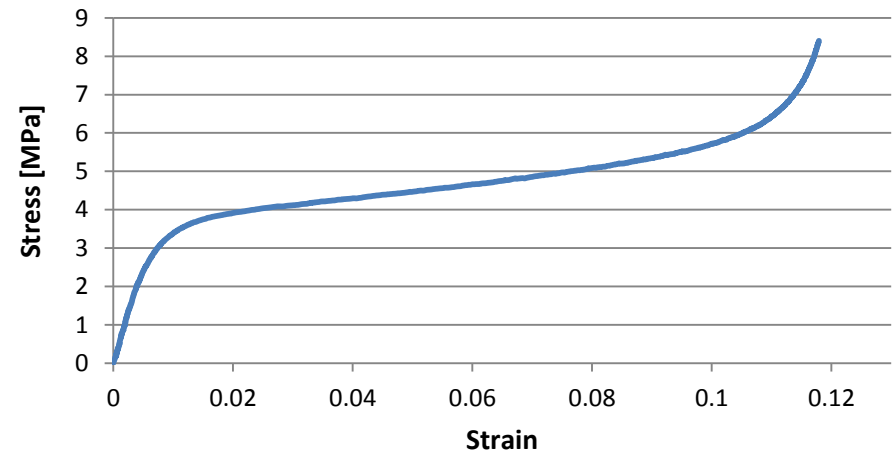


150mm long x 16mm thick x 20mm wide

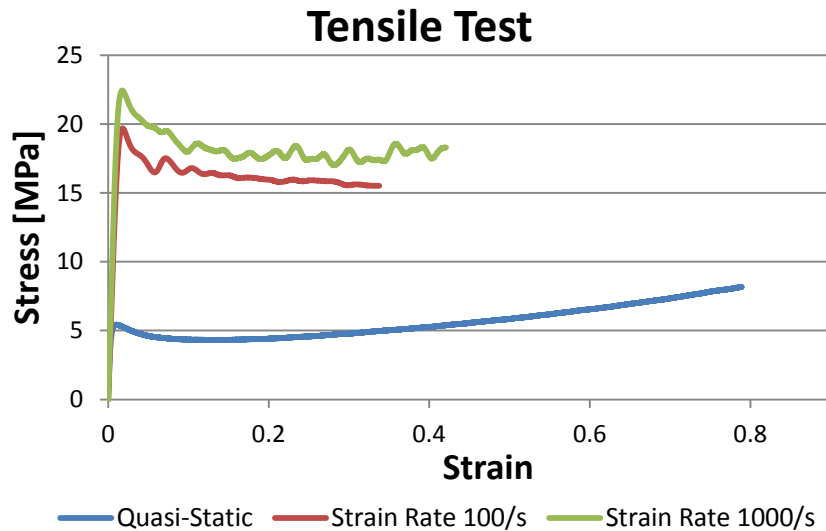
### Tensile Test



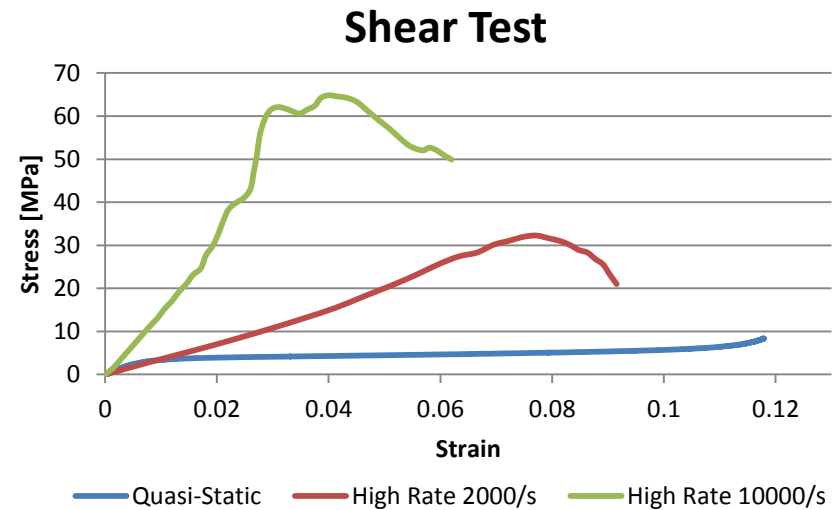
### Shear Test



## Determination of Tensile & Shear Behavior at High Rates



	QS	HR-100/sec	HR-1000/sec
Young Modulus (MPa)	1566	3960	5040
Stress @ yield (MPa)	5.2	19.6	22.4
Elongation @ yield (%)	1.2	1.2	1.16
Elongation @ fail (%)	79	33	42

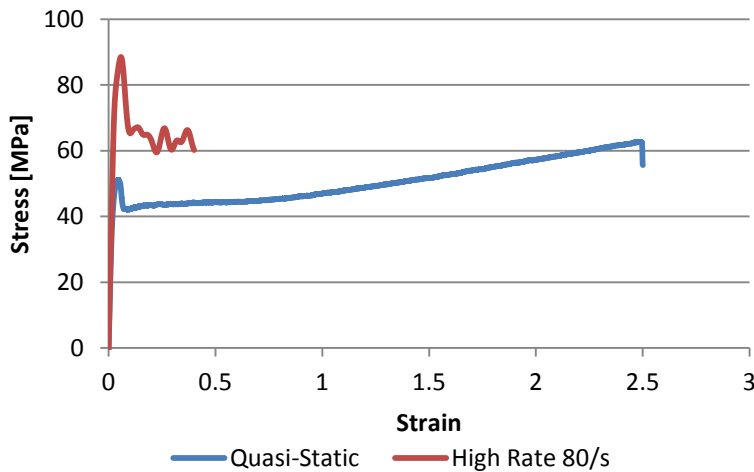


	QS	HR- 2000/sec	HR-10000/sec
Shear Modulus [Mpa]	630	756	1314
Max. Shear Stress [Mpa]	9	32	64
Shear Strain @ fail [%]	11	9	6

Both linear and non-linear properties of adhesives are dependent on the loading rate.

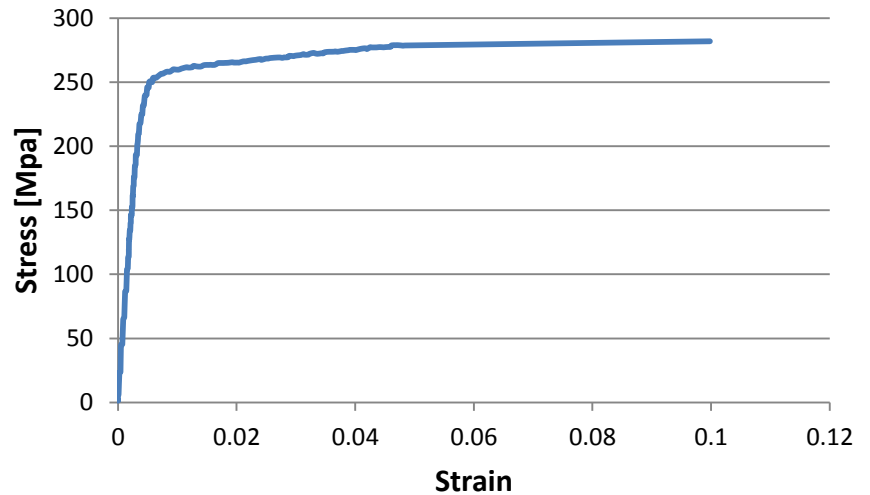
## Tensile Test for Adherends (Al & PC):

Polycarbonate



	Modulus [GPa]	Yield Stress [MPa]
Quasi-static	2.9	50
High Rate 80/s	2.9	88

Al-6061-T6



Modulus [GPa]	Yield Stress [MPa]
67	271

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## Material Modeling approaches:

### ➤ Linear Elastic

- Elastic response fully specified by Young's modulus, E, and Poisson's ratio,  $\nu$

### ➤ Linear Elastic – Plastic

- Conversion of nominal stress-strain to true (Cauchy) stress-strain using relations:

$$\sigma_{true} = \sigma_{nom} (1 + \varepsilon_{nom})$$

$$\varepsilon_{true} = \ln(1 + \varepsilon_{nom})$$

- Plasticity model assumed isotropic yield and hardening behavior.
- Plastic data in terms of true stress, true plastic strain.
- From strain decomposition, true plastic strain to be obtained from

$$\varepsilon_{true}^p = \varepsilon_{true}^t - \varepsilon_{true}^e$$

$$\varepsilon_{ln}^p = \ln(1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E}$$

### ➤ Linear Elastic – Viscoelastic

$$G(\tau) = G_0 \left( 1 - \sum_{i=1}^N \bar{g}_i^p (1 - e^{-\tau/\tau_i^G}) \right), \text{ material coefficient are } \bar{g}_i^p \text{ and } \tau_i^G$$

## Material Modeling approaches:

Linear Elastic		Linear Elastic - Plastic		Linear Elastic - Viscoelastic
A	B	C	D	E
<i>*Elastic</i>	<i>*Elastic</i>	<i>*Elastic</i>	<i>*Elastic</i>	<i>*Elastic</i>
$E = 1566 \text{ MPa}$	$E = 5040 \text{ MPa}$	$E = 1566 \text{ MPa}$	$E = 5040 \text{ MPa}$	$E = 1566 \text{ MPa}$
		<i>*Plastic</i>		<i>*Viscoelastic</i>
		<p>True Stress –true strain: 0.01/s, 100/s and 1000/s</p> <p>The hardening curve data are required in the tabular form of yield stress with plastic strain where the first pair of numbers must correspond to the initial yield stress at zero plastic strain.</p>		<p>In Abaqus <math>G(t)</math> and <math>K(t)</math> are specified in one of four different ways:</p> <p>Prony series curve fit from experimental stress relaxation test data:</p> <p><b>*VISCOELASTIC, TIME=RELAXATION TEST DATA</b> Prony series curve fit from experimental creep test data: <b>*VISCOELASTIC, TIME=CREEP TEST DATA</b> Prony series coefficients specified directly by the user: <b>*VISCOELASTIC, TIME=PRONY</b> Defined from frequency-dependent cyclic test data: <b>*VISCOELASTIC, TIME=FREQUENCY DATA</b></p>

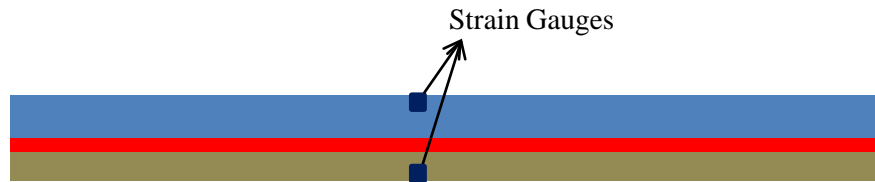
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- **Material Model Validation**
  - **Sandwich Structure**
  - **Quasi-Static Bend Test**
  - **Dynamic Bend Test**
  - **FEM model**
  - **Quasi-Static Bend Simulation**
  - **Dynamic Bend Simulation**
- Summary & Conclusion

## □ Sandwich Structure

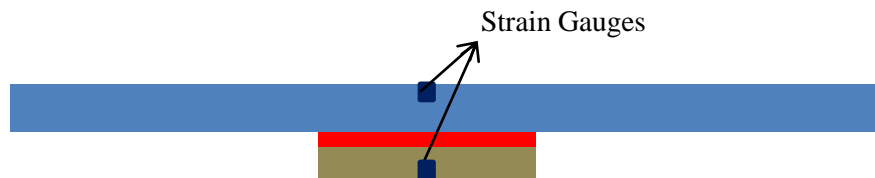
Sandwich structures were constructed where the adhesive was sandwiched between two substrates (Al and PC); two configurations were considered as shown in figure-1.

Configuration-1: Equal length adherends



Plates: 70mmX20mmX1mm  
Adhesive: 70mmX20mmX0.2mm  
Top Span: 35mm  
Bottom Span: 60mm

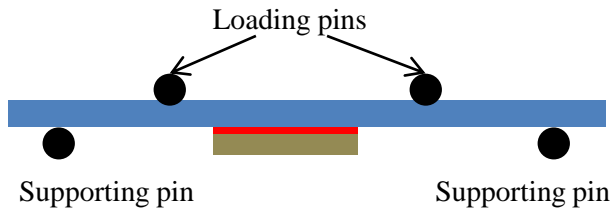
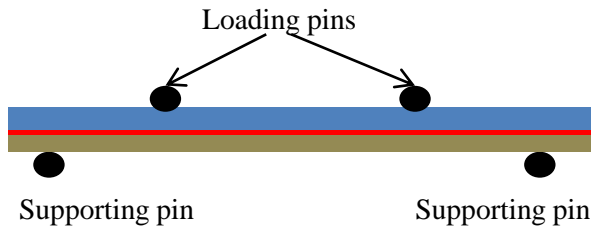
Configuration-2: Unequal length adherends



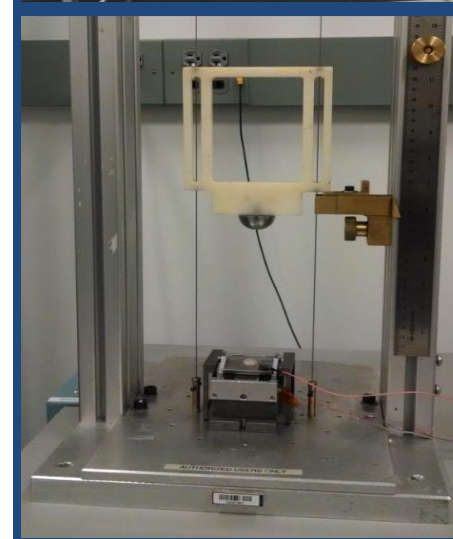
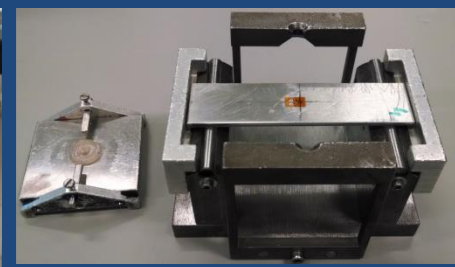
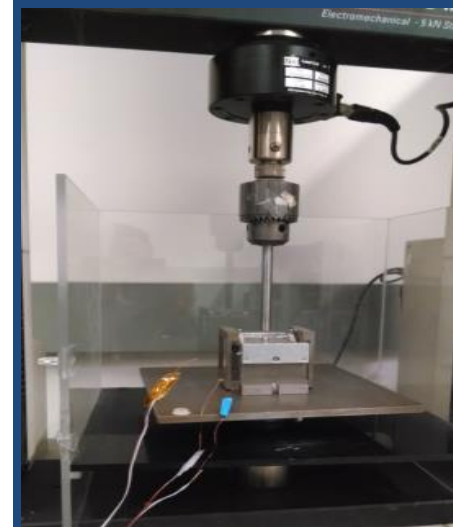
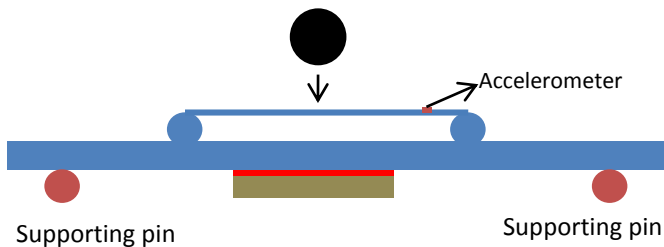
Big Plate: 70mmX20mmX1mm  
Small Plate: 20mmX20mmX1mm  
Adhesive: 70mmX20mmX0.2mm  
Top Span: 35mm  
Bottom Span: 60mm

## Quasi-Static & Dynamic Testing:

### ➤ Quasi-Static Bend Test



### ➤ Dynamic Bend Test



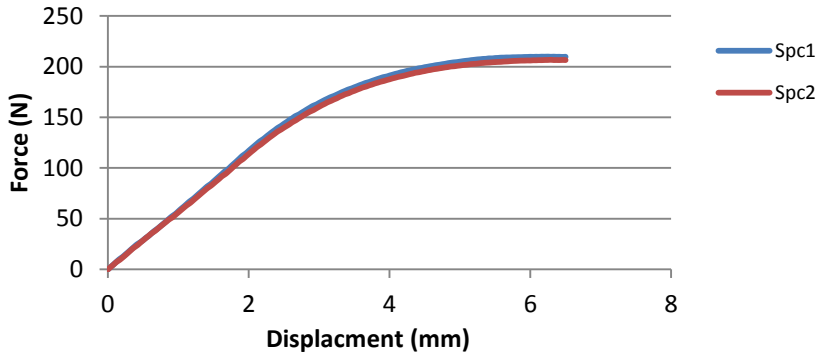
➤ Two strain gauges for each sandwich structure were used. One at the center of the top plate and one at the center of the bottom plate

➤ Accelerometer was placed at the top fixture in dynamic testing in order to extract acceleration and use it as input in the computational study

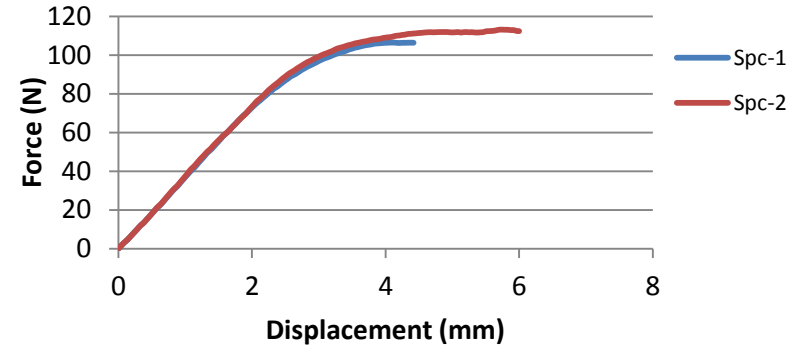
## Quasi-Static Test Results:



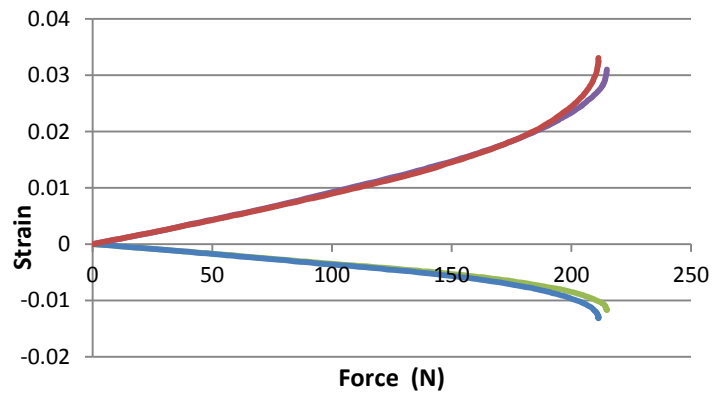
**Force - Displacement**



**Force vs Displacement**

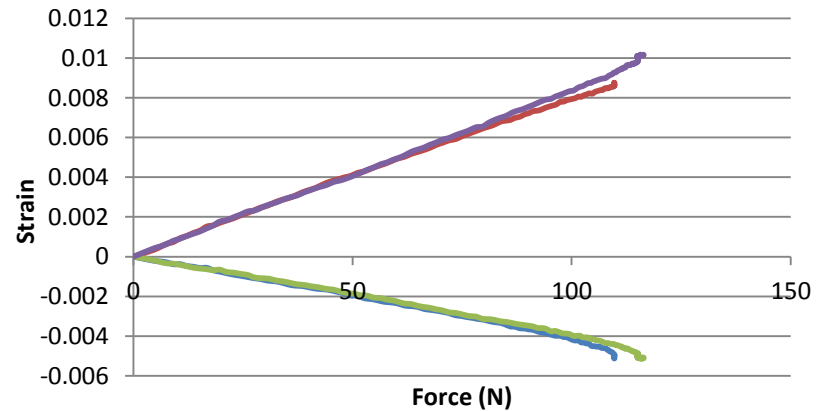


**Force vs Strain**



— Spc1- Top Strain    — Spc1- Bottom Strain  
— Spc2- Top Strain    — Spc2- Bottom Strain

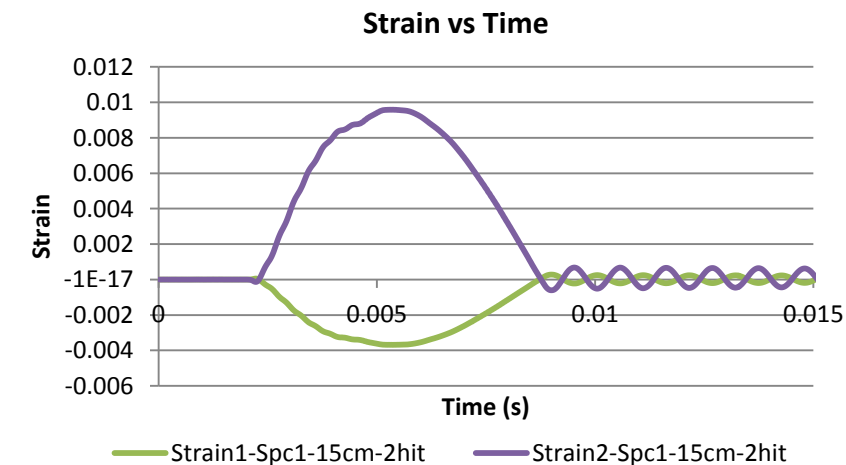
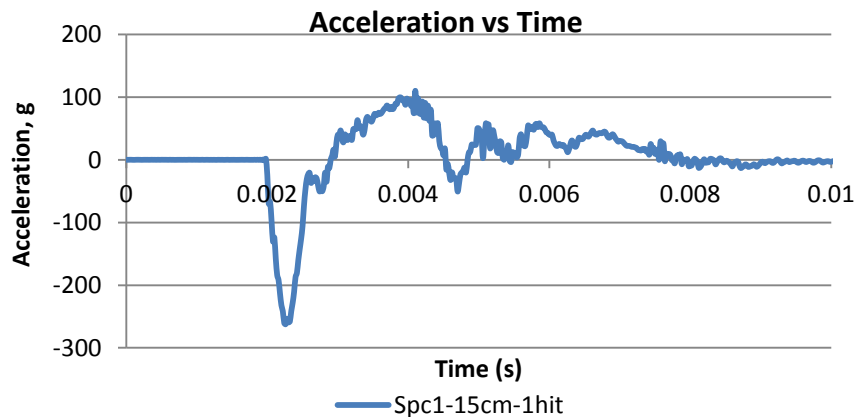
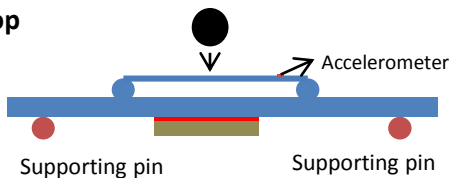
**Force vs Strain**



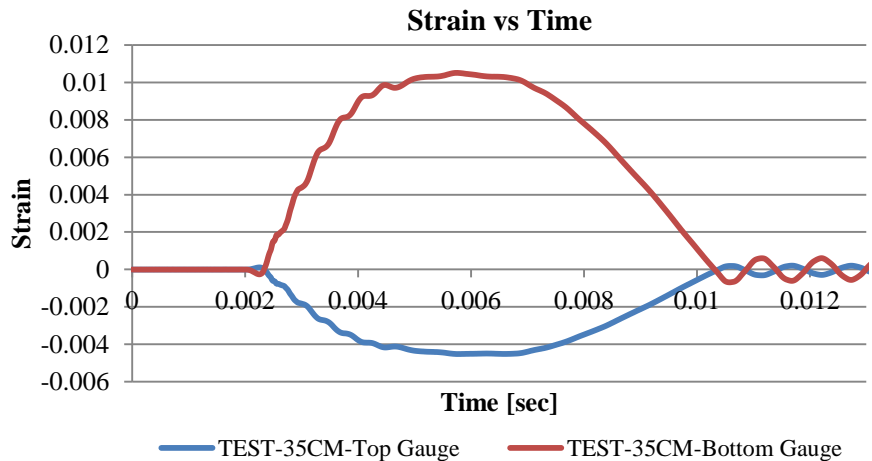
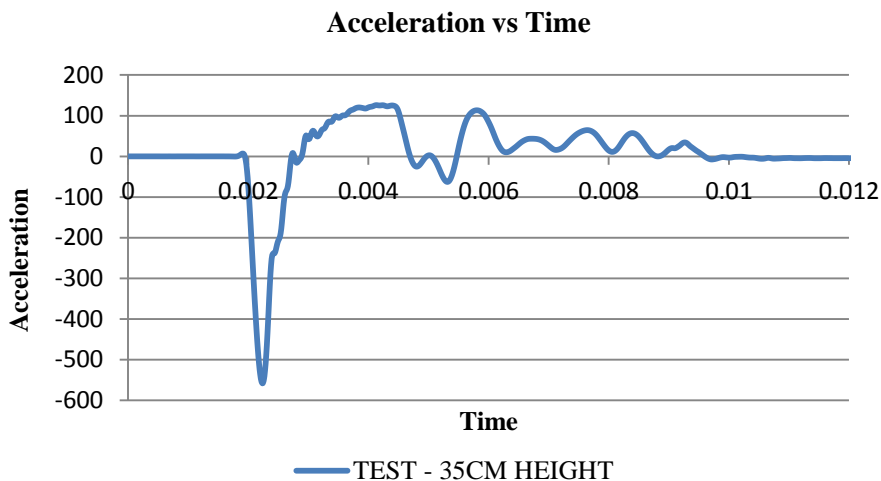
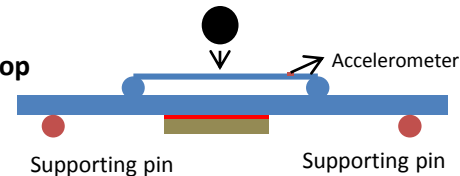
— Spc 1 - Top Strain    — Spc 1 - Bottom Strain  
— Spc 2 - Top Strain    — Spc 2 - Bottom Strain

## Dynamic Test Results:

### 15 cm Ball Drop

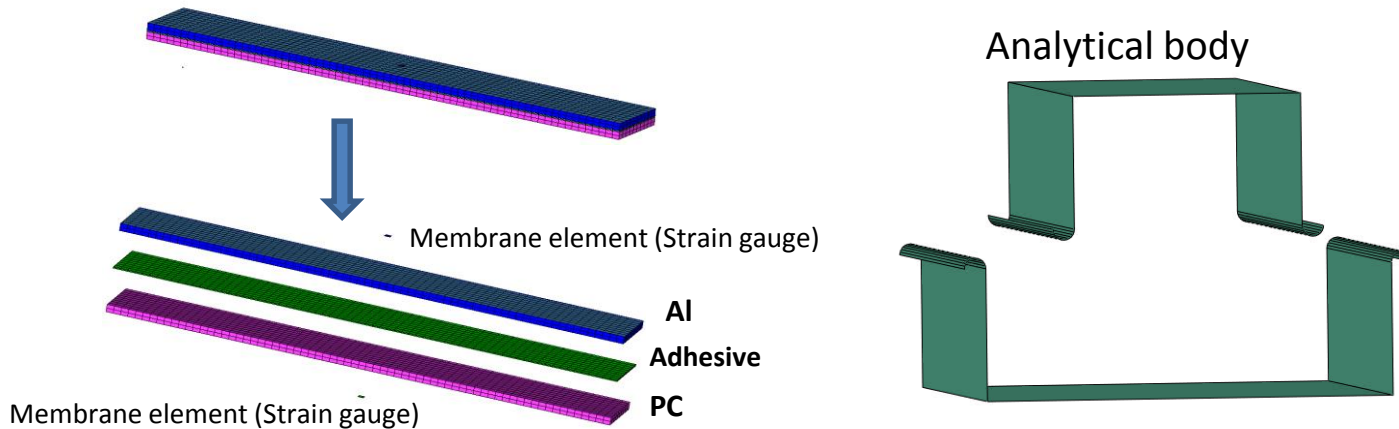


### 30 cm Ball Drop

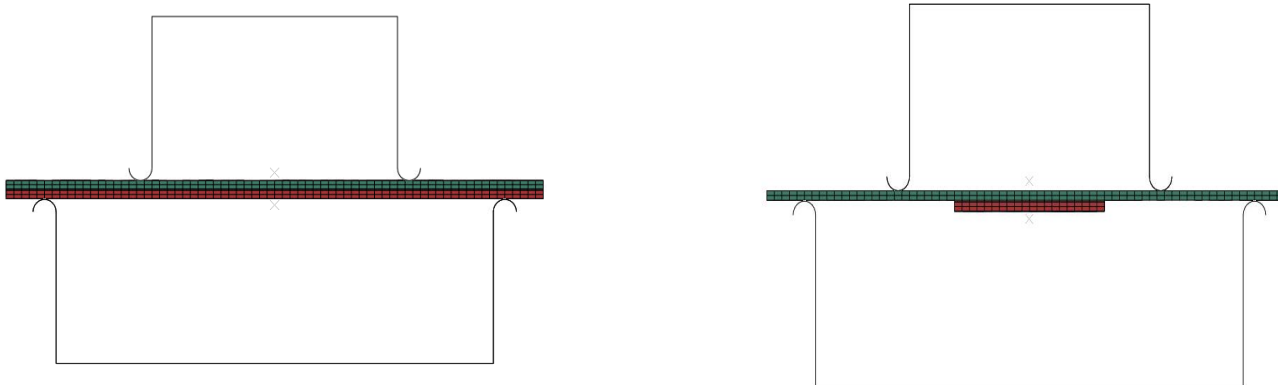


## □ Finite Element Analysis Model

A full three-dimensional finite element model of the sandwiched structure (Al plate, Adhesive and PC plate), and the supports of the four-point bend fixture were built using the modeling software ABAQUS. The Plates and the adhesive were modeled with full-integration brick elements. The two strain gauges were modeled as two membrane elements [0.8x0.8mm]. Supports of the four-point bend fixture were modeled using analytical rigid surfaces.



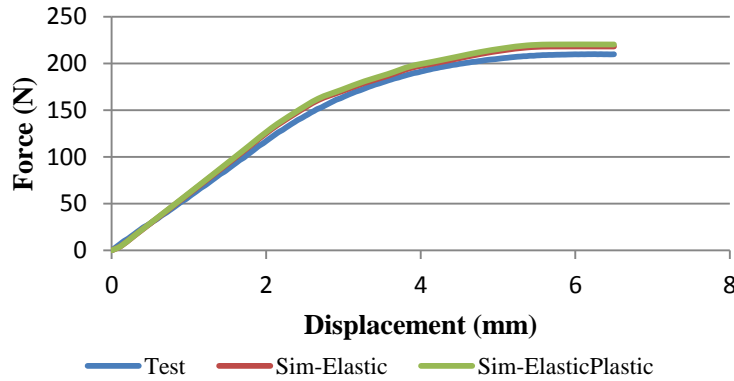
Appropriate contact definitions were defined between the rollers and plates surfaces. The bottom support was constrained in all directions in order to prevent rigid body motion. The top support was also constrained in every direction except the vertical direction.



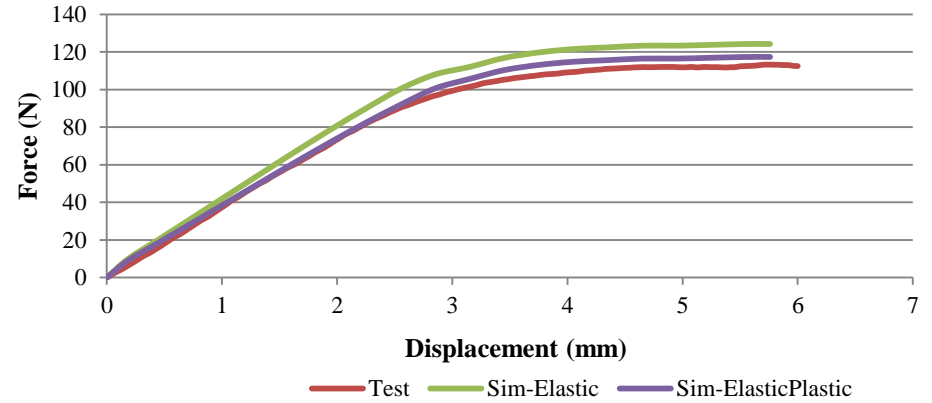
## Quasi-Static Bend Simulation



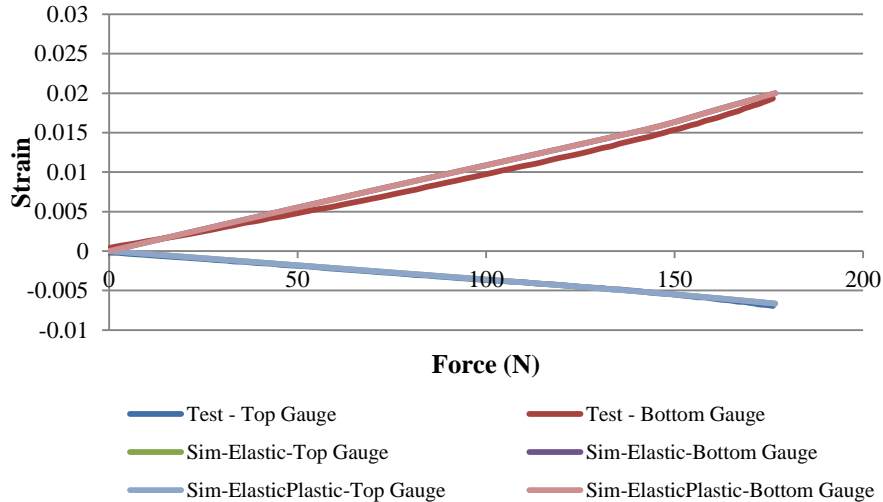
**Force - Displacement**



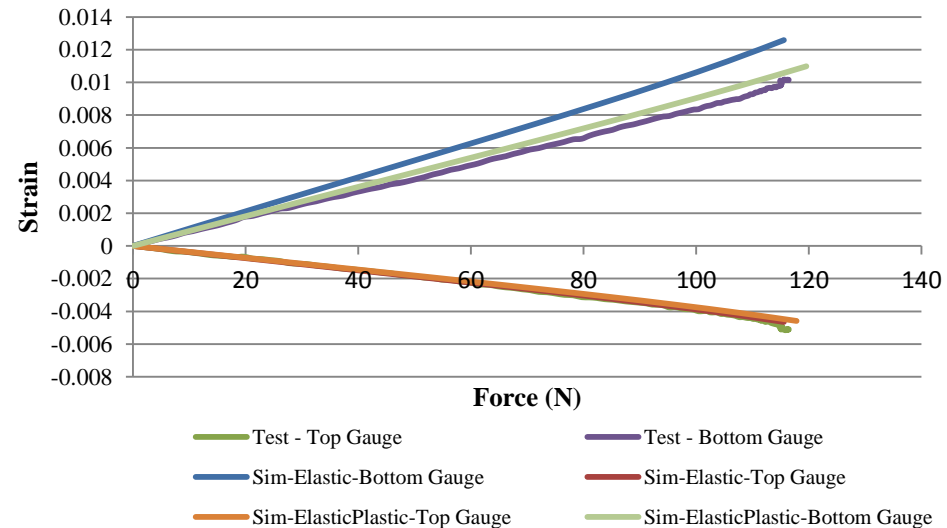
**Force - Displacement**



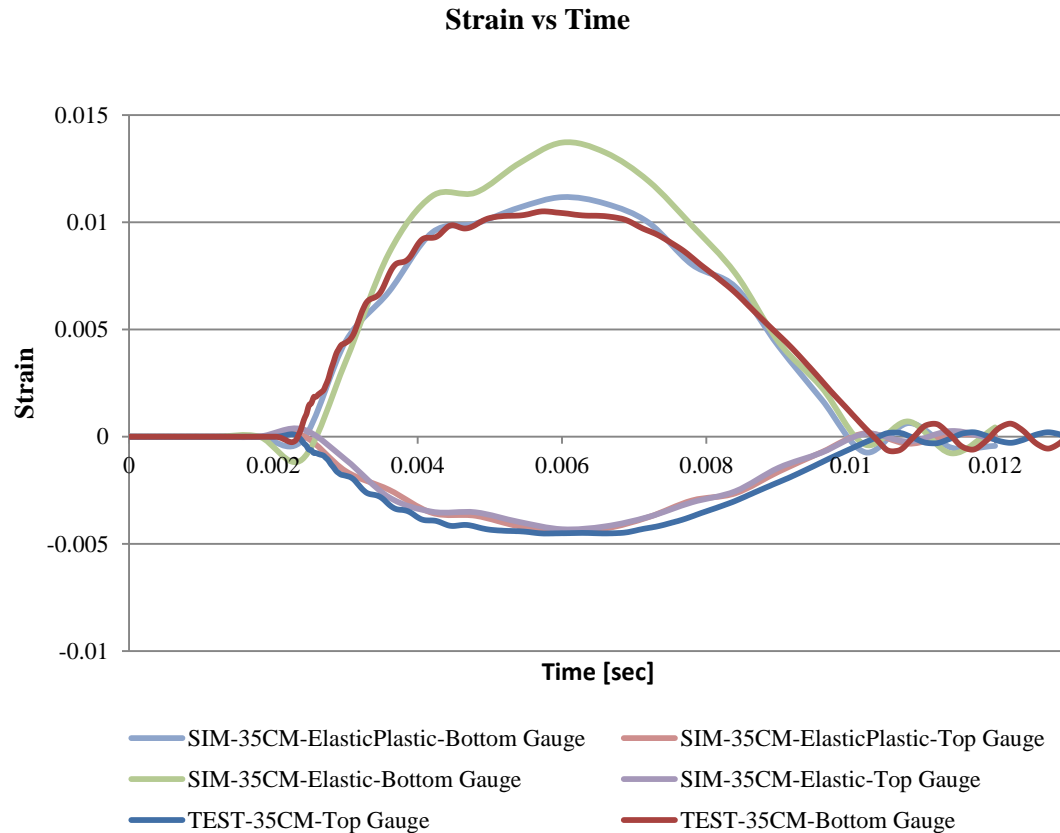
**Force - Strain**



**Force - Strain**



## Dynamic Bend Simulation



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- The sandwich structure with **unequal-length plates** is able to capture the sensitivity to the adhesive material modeling approaches. However, the sandwich structure with **equal-length plates** is insensitive to the adhesive layer and failed as a configuration for capturing or investigating adhesive behavior and properties
- Force-displacement and force-strain results in quasi-static bend test show that the **linear-elastic** material model will over predict the stiffness of the sandwich structure where the **elastic-plastic** material model mimics the experimental results much better.
- Dynamic bend simulations with unequal-length-plate sandwich structure show that the overall behavior of the structure is sensitive to the adhesive material modeling approach. The elastic-plastic material modeling approach predicts the testing results very well, unlike the elastic material modeling approaches which correlate poorly with experimental results because they do not account for plasticity.

- Adhesive material property is **sensitive to rate of loading**, stiffness increases with the increase of the loading rate even in the elastic region.
- Determination of adhesive property over wide range of strain rate is needed to enable predictions under dynamic loading.
- Although both of the elastic and plastic phases of this specific adhesive are loading rate dependent, **plastic behavior** of the adhesive has bigger impact than its elastic behavior on the overall sandwich structure behavior. This is due to the fact that the adhesive will start deforming while the adhered substrates are still in their elastic regions.
- The accuracy of the computational calculations is dependent on the **validity of the material models** used in the analysis to describe the material behavior and the availability of suitable test data for these models.