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Certification of Discontinuous Fiber Composite Forms for Aircraft Structures

2013 Technical Review

Brian Head and Mark Tuttle
University of Washington

Predicting Modulus and Membrane-Bending Coupling in Discontinuous Fiber Composites

- Motivation and Key Issues
  - Certification of DFC parts currently achieved by testing large numbers of individual parts (certification by “point design”)
  - Desire to transition to certification based on analysis supported by experimental testing

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Predicting Modulus and Membrane-Bending Coupling in Discontinuous Fiber Composites

- Motivation and Key Issues (continued)
  - Previous modeling of HexMC parts over predicted buckling loads by more than 20%
  - Suspected cause of errors include local stiffness variation and membrane bending coupling effects
- Objective
  - Develop a method of predicting modulus variation and Membrane-Bending Coupling (MBC) effects in HexMC
  - Use the method to better understand the disparity between predictions and experiments

Predicting Modulus and Membrane-Bending Coupling in Discontinuous Fiber Composites

- Approach
  - By comparison of measured stiffness variations and out of plane displacements to predictions, determine modeling parameters
  - Using modeling parameters determined by comparison to coupon testing, apply modeling method to more complex geometries, to evaluate method

Predicting Modulus and Membrane-Bending Coupling in Discontinuous Fiber Composites

- Principal Investigators & Researchers (UW):
  - PI: Mark Tuttle
  - Grad Students: Brian Head and Michael Arce
  - (Prior to 2011 Prof. Paolo Feraboli and his grad students also participated)
- FAA Technical Monitor
  - Lynn Pham
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Boeing: Bill Avery
  - Hexcel: Bruno Boursier, David Barr, Marcin Rabiega and Sanjay Sharma

Testing - Setup

- Two thicknesses of flat specimens were cut 1.5” x 13” (0.157” and 0.097” thick)
  - Specimens of each thickness came from two different plates, four plates total
- 9 inch gauge length
- In total 20 tests were run
  - Nine specimens of each thickness
  - One specimen of each thickness was tested twice, observing each side one time

Testing - Setup

- Specimens were speckled for DIC
- Tested to 12.7 ksi at 0.02 in/min
  - 1847 lbf for thin
  - 3000 lbf for thick

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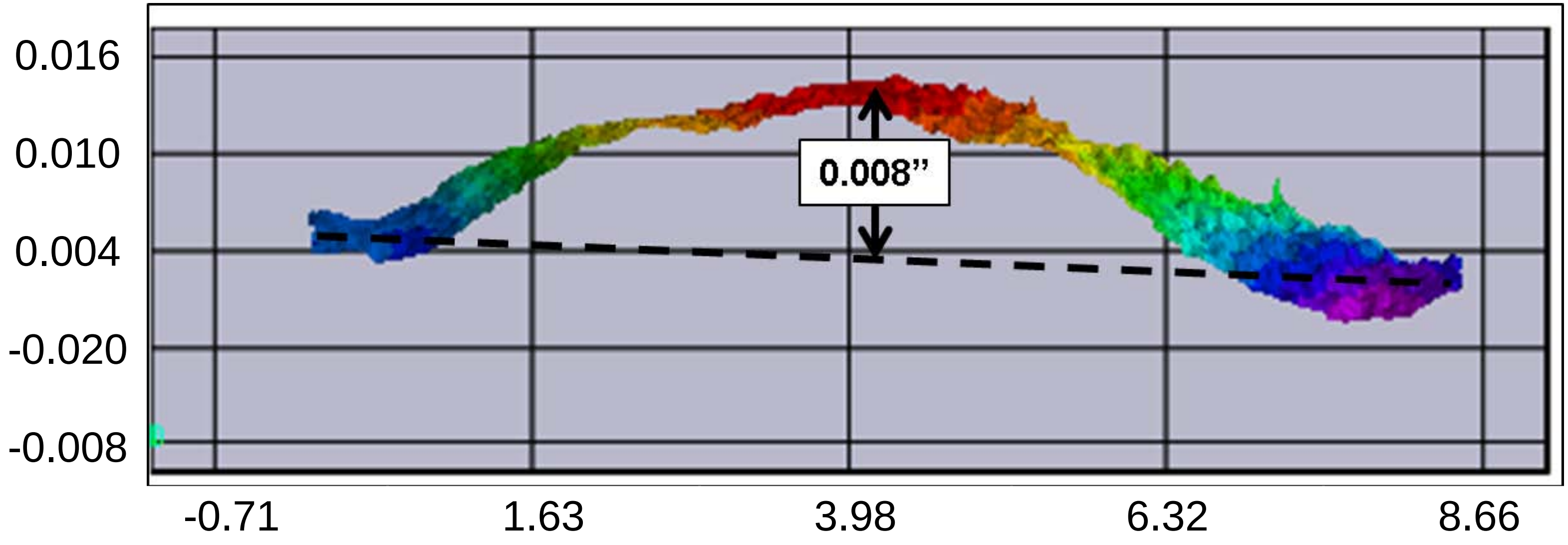
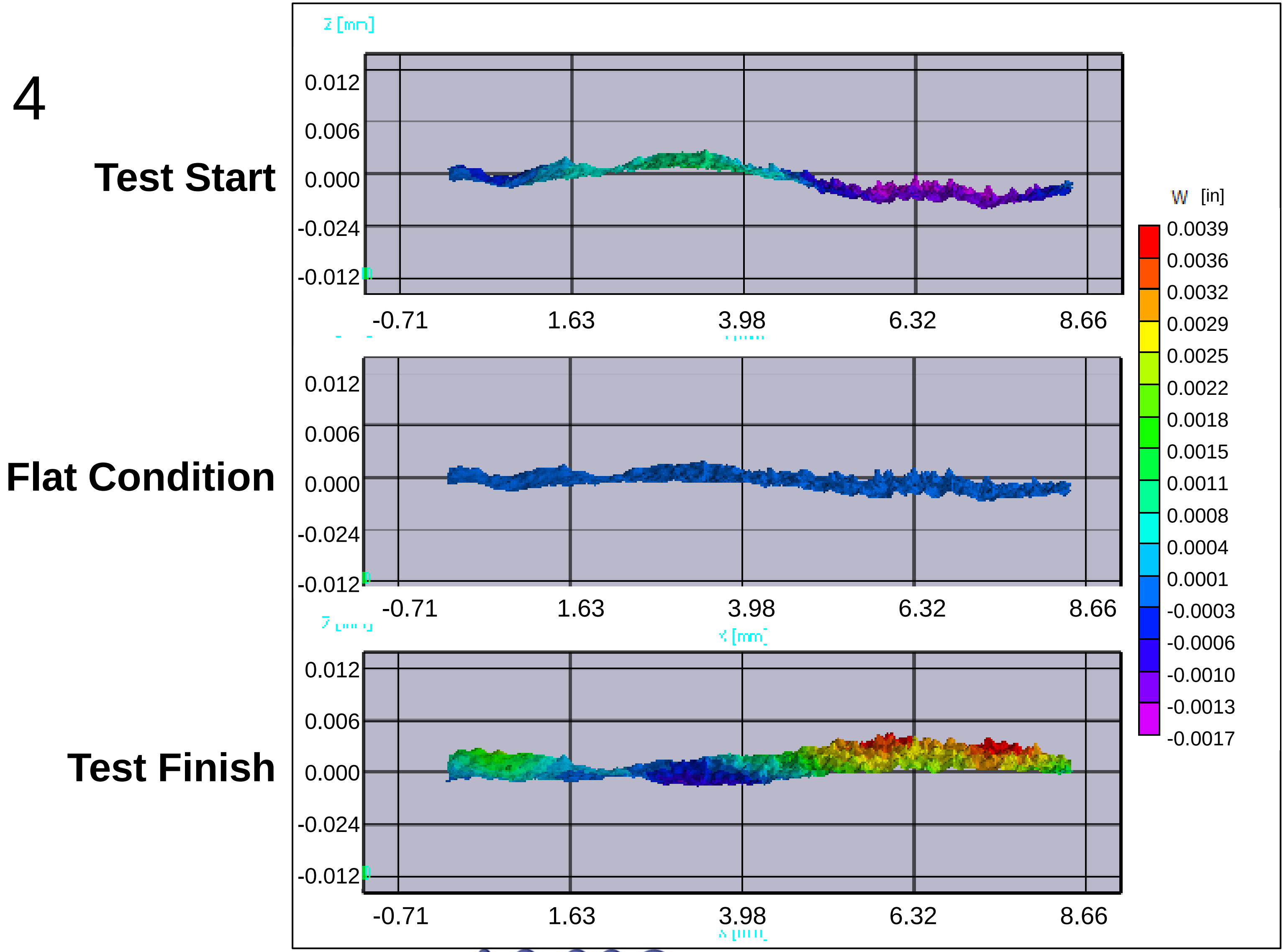
Coupling - Measurement

- Specimens did not start out flat
- Used minimum of standard deviation of out of plane position to establish when the specimen was flat



Coupling

Spec 4



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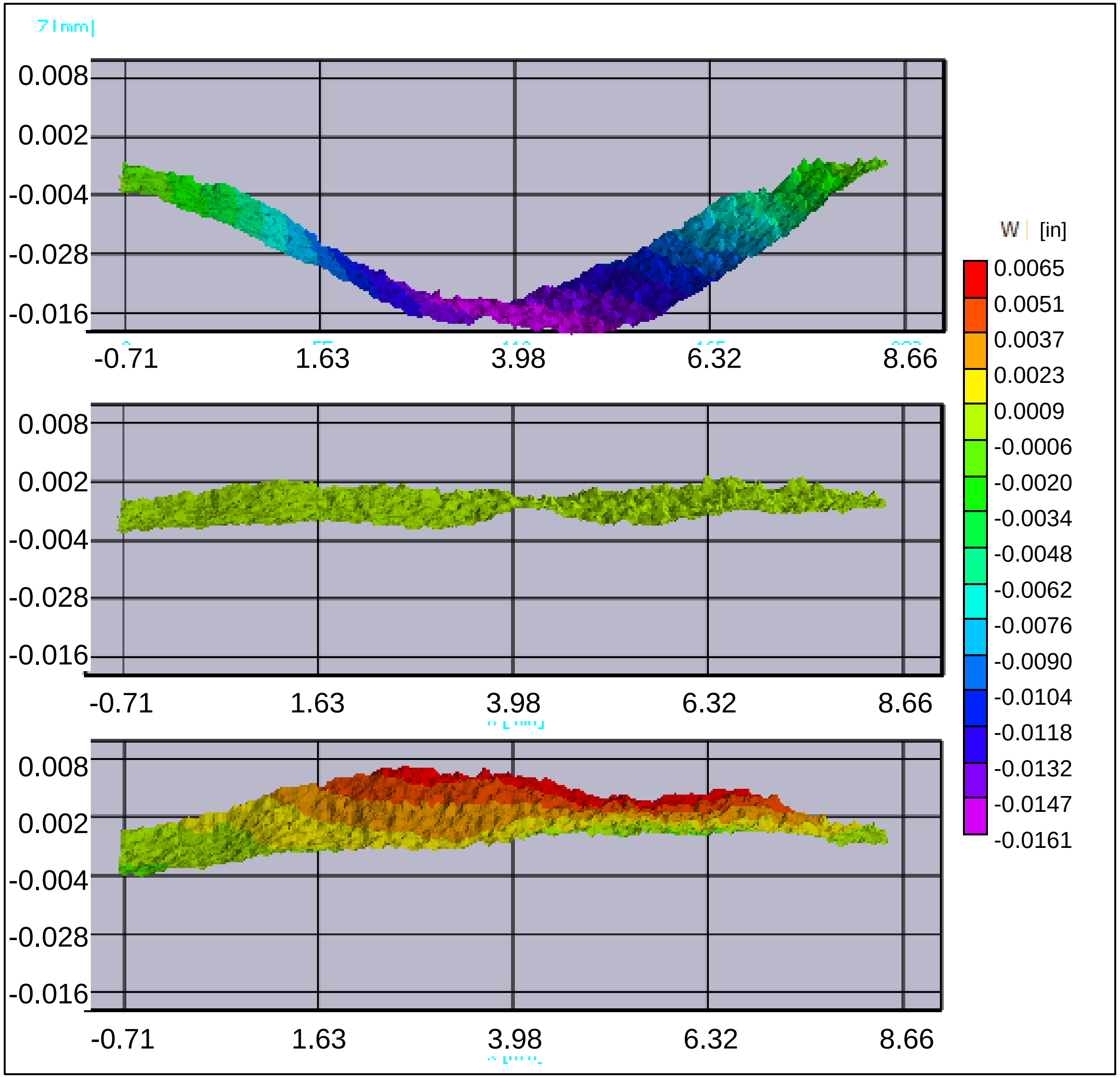
Coupling

Spec 14

Test Start

Flat Condition

Test Finish



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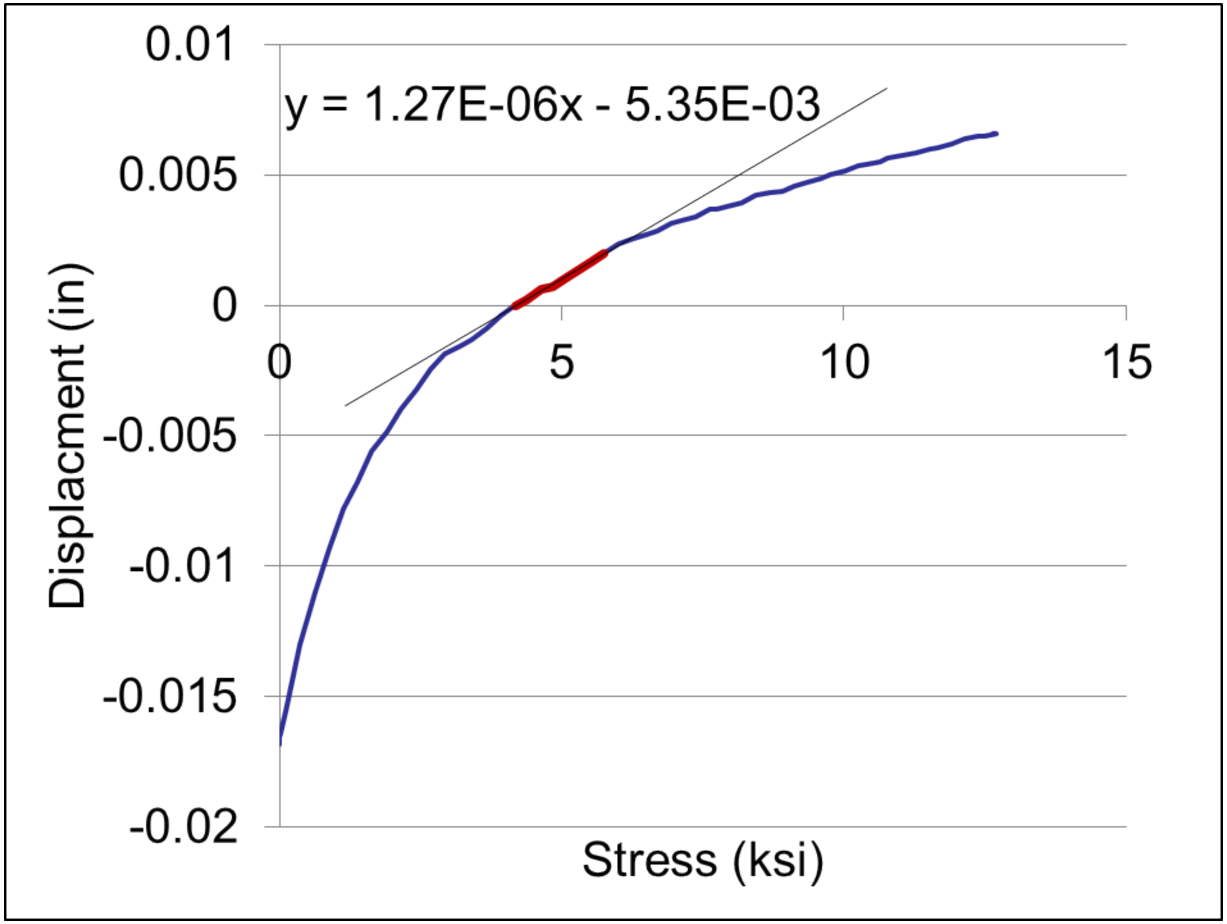
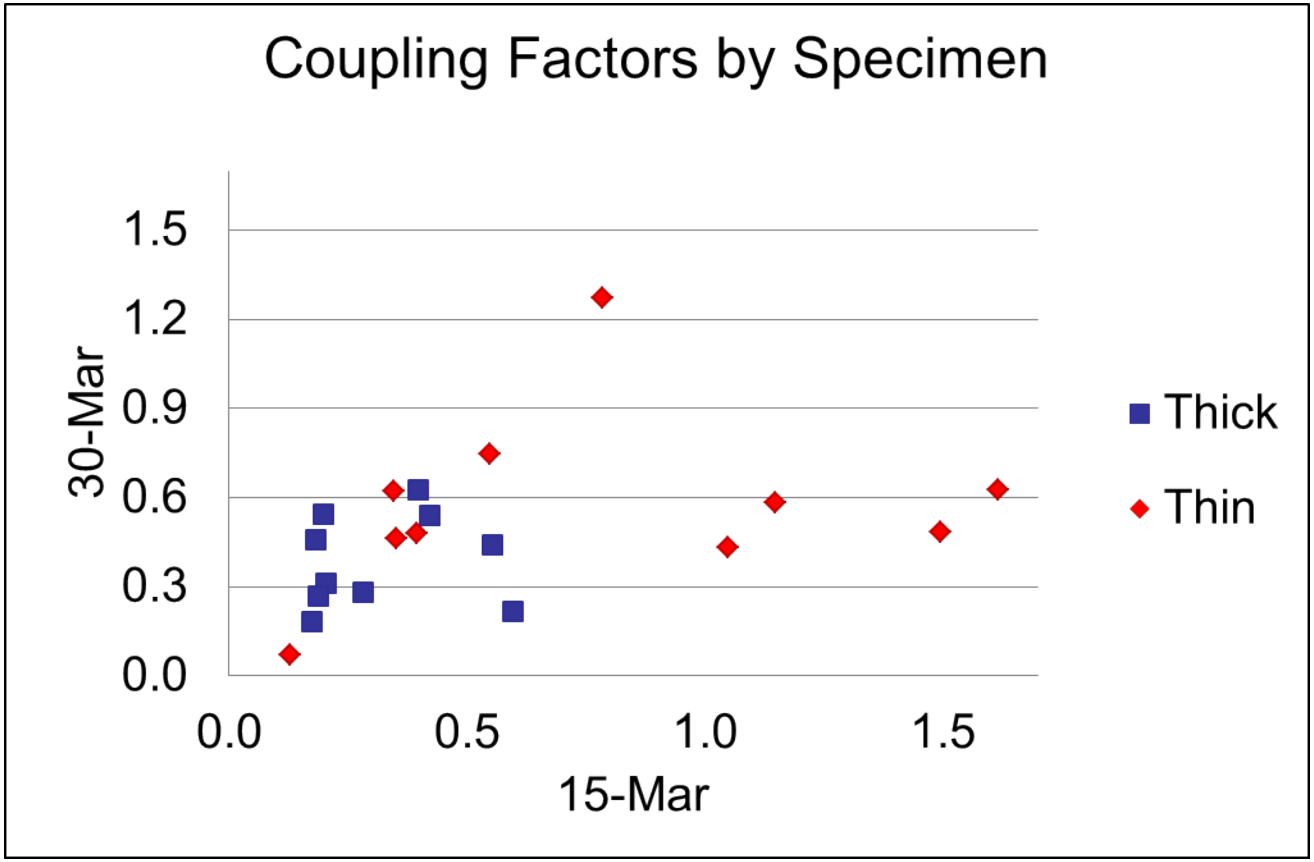
Coupling – Factor Determination

Spec 14 Out of Plane Displacement

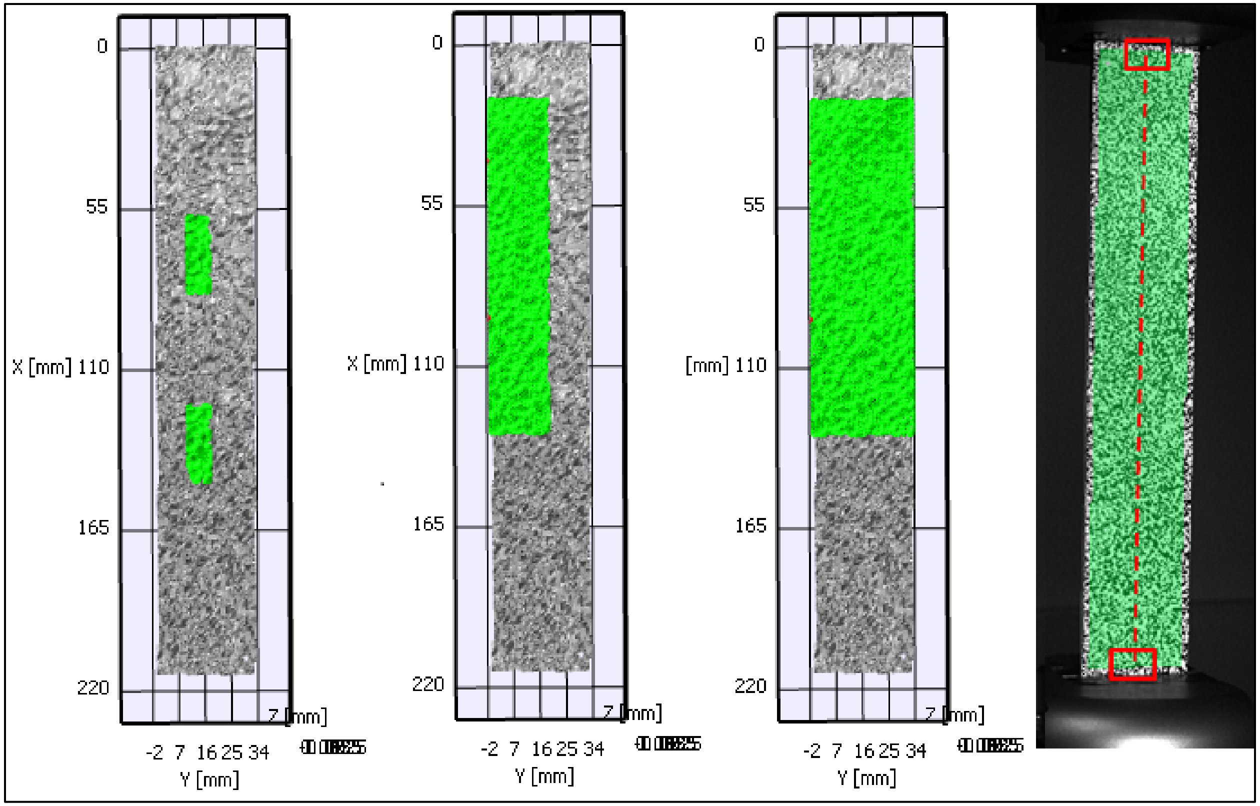


Coupling – Factor Measurement Repeatability

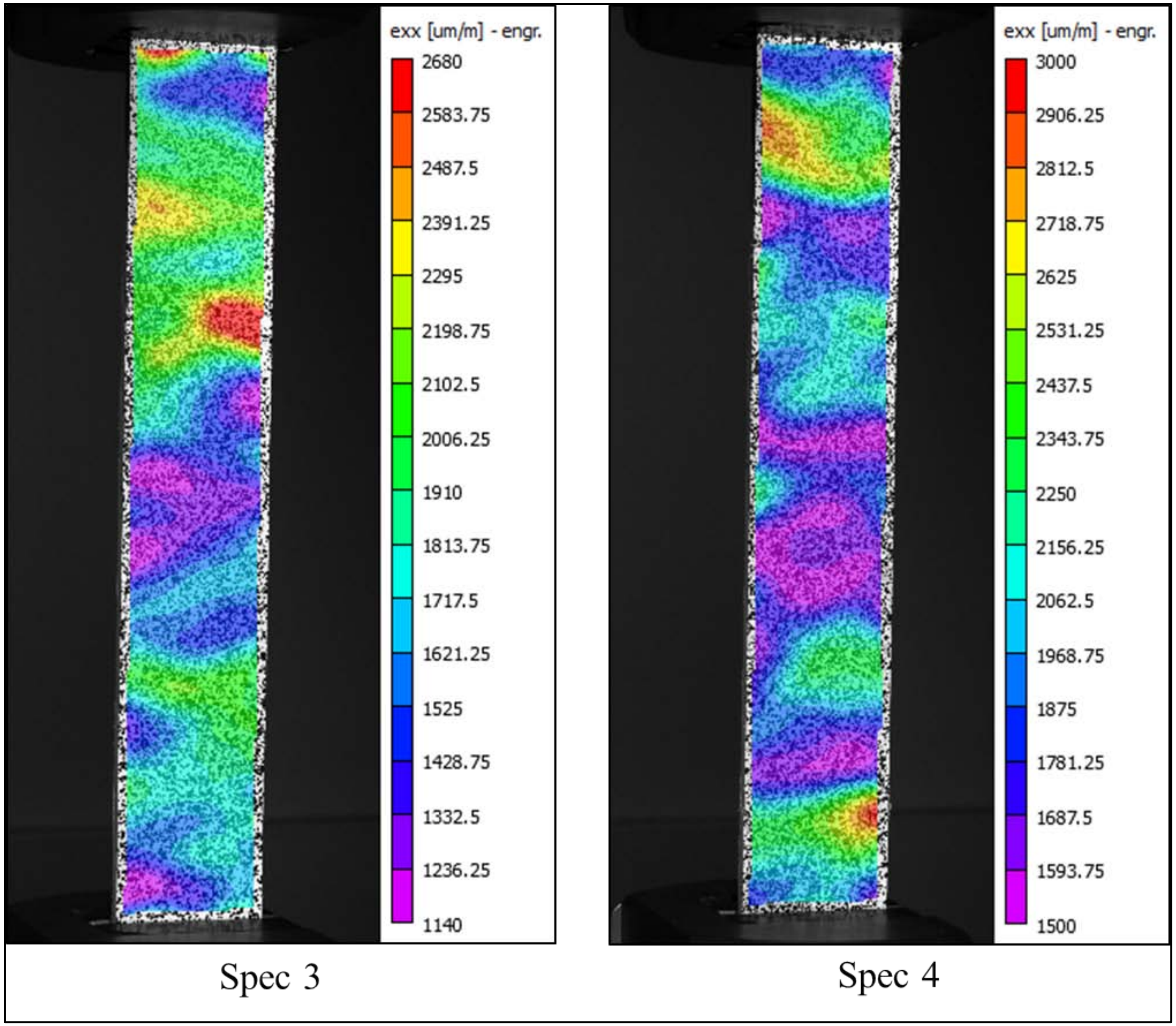


Modulus – Gauge Regions

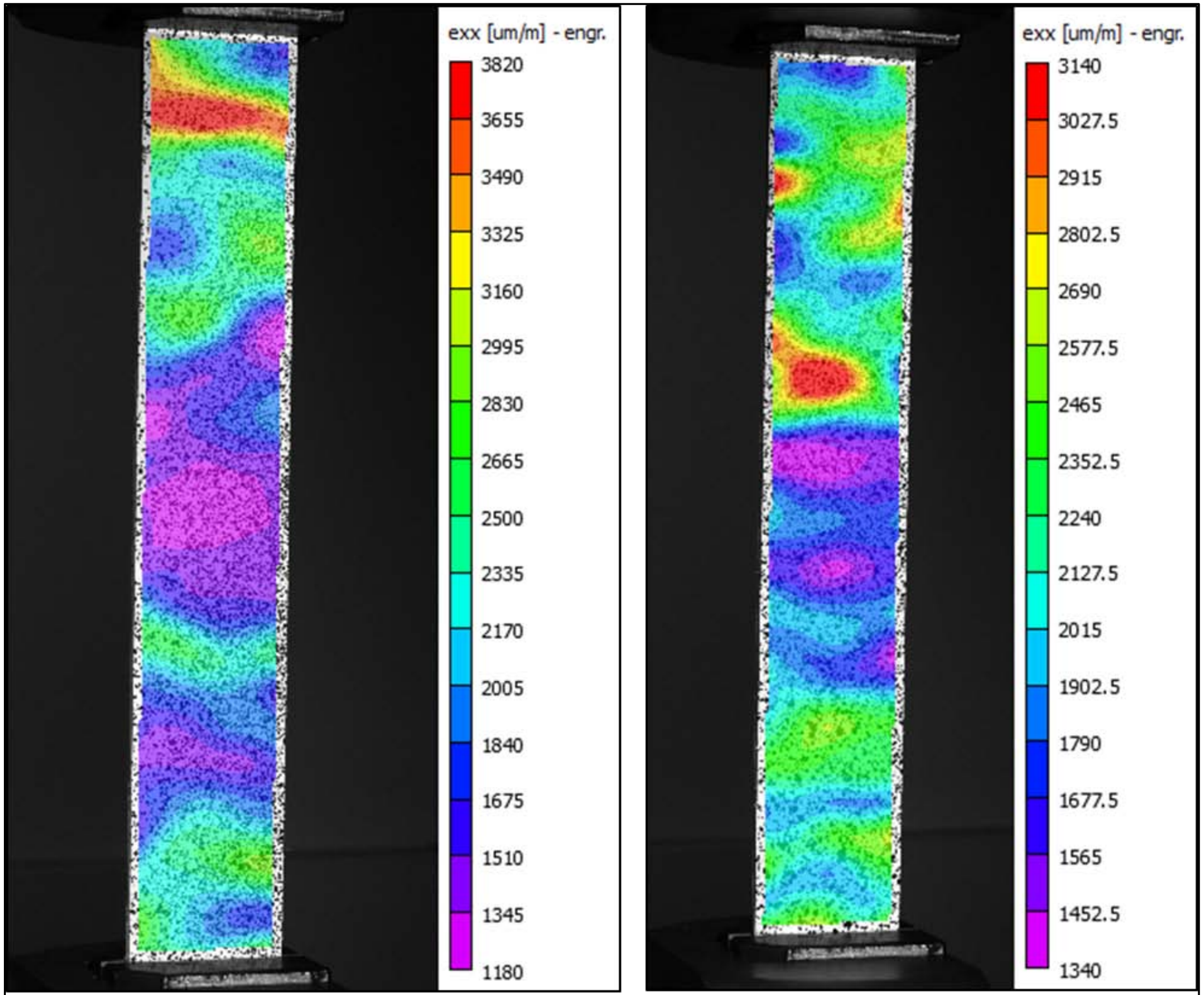
- Average strain over four sizes of gauge regions was measured
  - 0.25 in^2
  - 3.38 in^2
  - 6.75 in^2
  - 13.5 in^2



Modulus – Thick Spec. Contour Plots



Modulus – Thin Spec. Contour Plots



Spec 13

Spec 14

Modulus – Results

Thick	G1	G2	1/4 Surf	1/2 Surf	Ext	Thin	G1	G2	1/4 Surf	1/2 Surf	Ext
Spec 1 S1	7.87	8.06	7.56	7.55	7.09	Spec 11 S1	5.92	6.46	6.19	6.16	6.16
Spec 1 S2	7.16	6.09	7.13	7.11	7.20	Spec 11 S2	7.27	6.41	6.43	6.34	6.24
Spec 2	7.62	6.49	7.15	7.10	6.94	Spec 12	7.02	6.87	6.74	6.67	6.52
Spec 3	7.68	6.68	7.11	7.10	7.28	Spec 13	6.32	7.55	7.18	7.31	6.19
Spec 4	6.72	6.15	6.81	6.91	6.44	Spec 14	7.00	5.03	6.63	6.57	6.12
Spec 5	6.58	6.48	6.18	6.20	6.09	Spec 15	8.47	6.55	6.32	6.30	6.42
Spec 6	6.42	7.33	6.21	6.32	6.47	Spec 17	6.95	6.94	6.60	6.69	6.29
Spec 7	5.14	8.11	6.20	6.17	6.36	Spec 18	4.57	7.40	5.66	5.75	5.79
Spec 8	5.89	7.45	6.60	6.81	6.61	Spec 19	6.60	8.23	6.98	6.97	6.90
Spec 9	6.65	6.67	7.11	6.99	6.67	Spec 20	5.81	8.72	5.74	5.72	6.17

Min	5.14	6.18	6.17	6.09	Min	4.57	5.66	5.72	5.79
Avg	6.86	6.81	6.83	6.71	Avg	6.81	6.45	6.45	6.28
Max	8.11	7.56	7.55	7.28	Max	8.72	7.18	7.31	6.90

St Dev	0.74	0.49	0.46	0.39	St Dev	1.04	0.49	0.50	0.29

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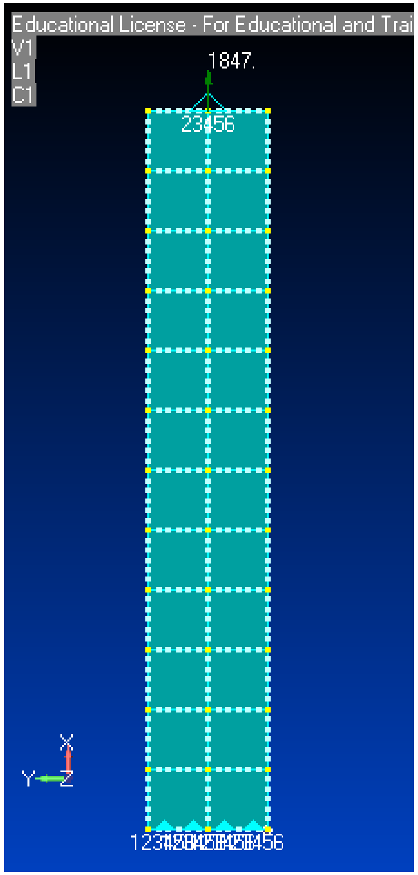
Modeling Approach

- Visual Basic program written to interface with FEMAP API
  - Creates RLVE regions of user specified size
  - Assigns random stacking sequence to each one
  - Meshes model with user defined mesh size
  - Each run takes about 5-7 seconds
  - Model is run a statistically significant number of times



E_{11}	18.1 Msi
E_{22}	1.34 Msi
ν_{12}	.302
G_{13}	0.565 Msi

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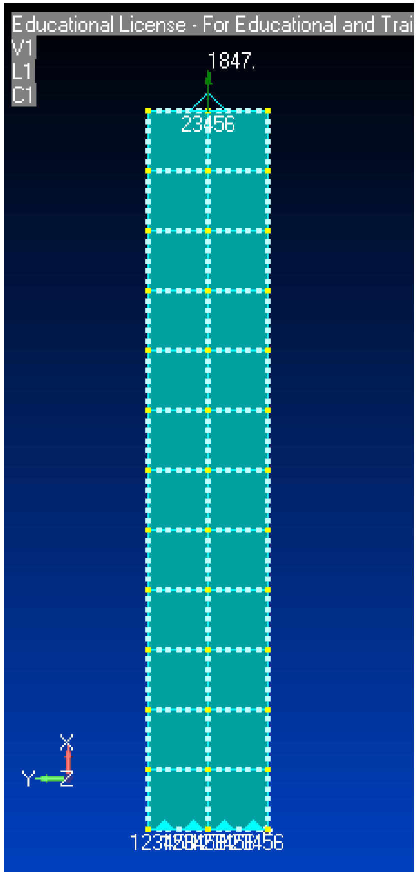

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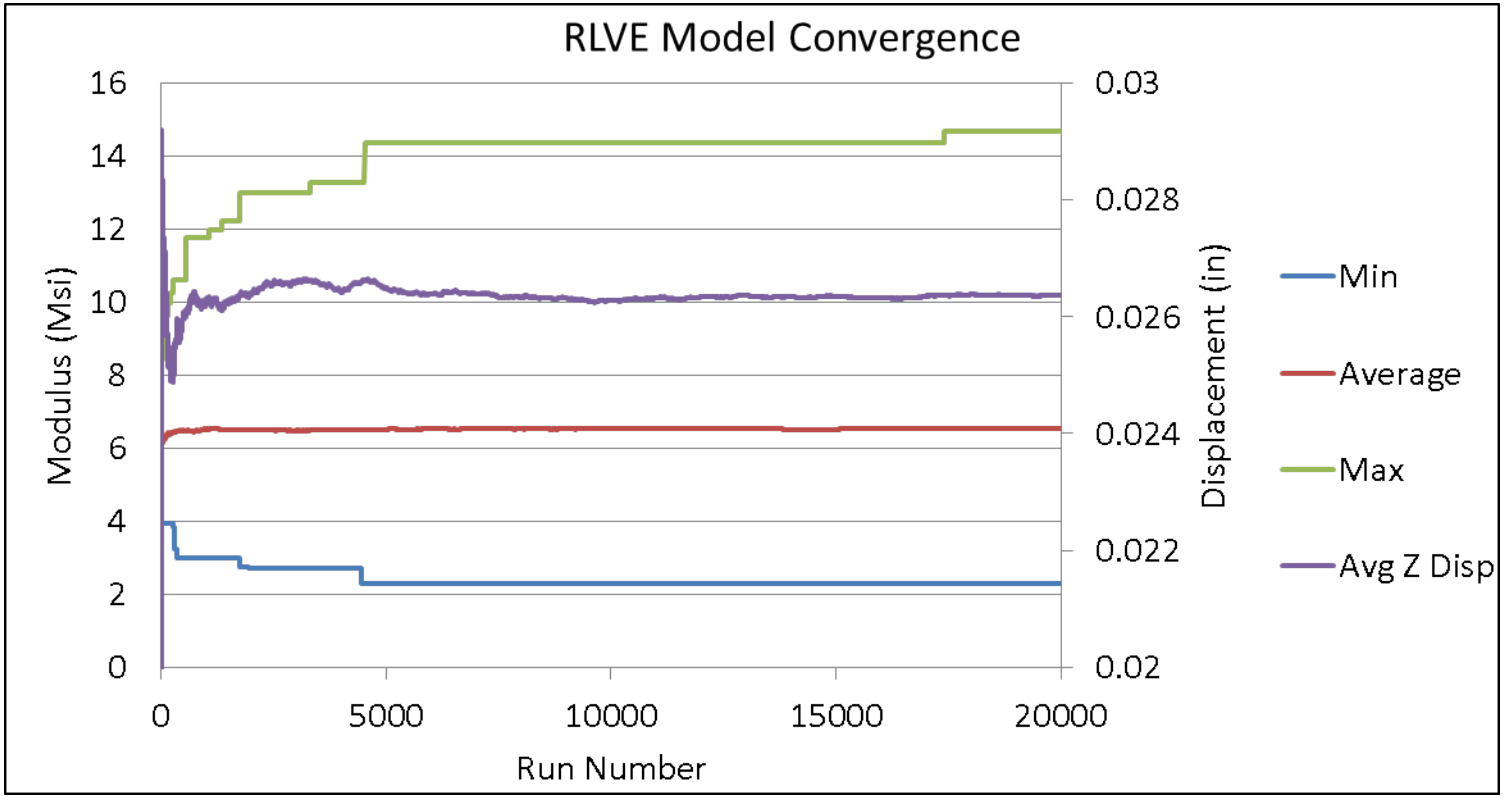
Modeling - Convergence

- Convergence of the predictions was obtained after ~5000 predictions

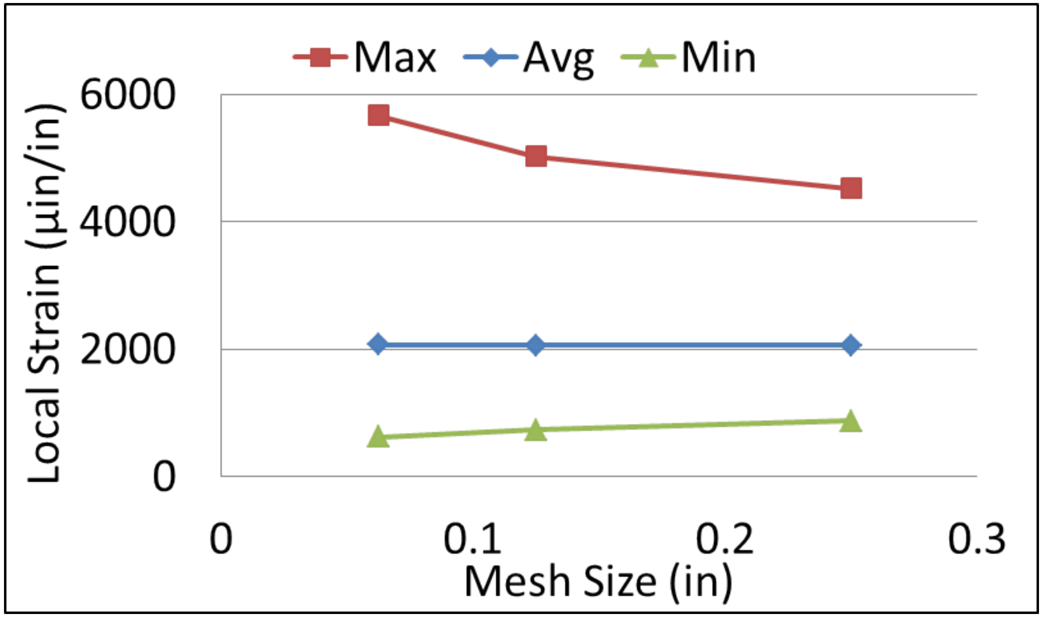


- All modeling configurations run 5000 times

Modeling – Mesh Sizing

- Mesh size
  - Global stiffness and out of plane displacements found to be mesh independent for proper mesh sizes
  - Local strains found to be mesh dependent, diverging as mesh size decreased

	Avg Strain (µin/in)	Max Z Disp (in)
0.0625	2067	0.0599
0.125	2063	0.0598
0.25	2056	0.0595



Modeling – RLVE Sizing

- For this study we chose to choose the RLVE size by comparison of predicted strain variations and out of plane displacements to experiments

Modeling – RLVE Sizing

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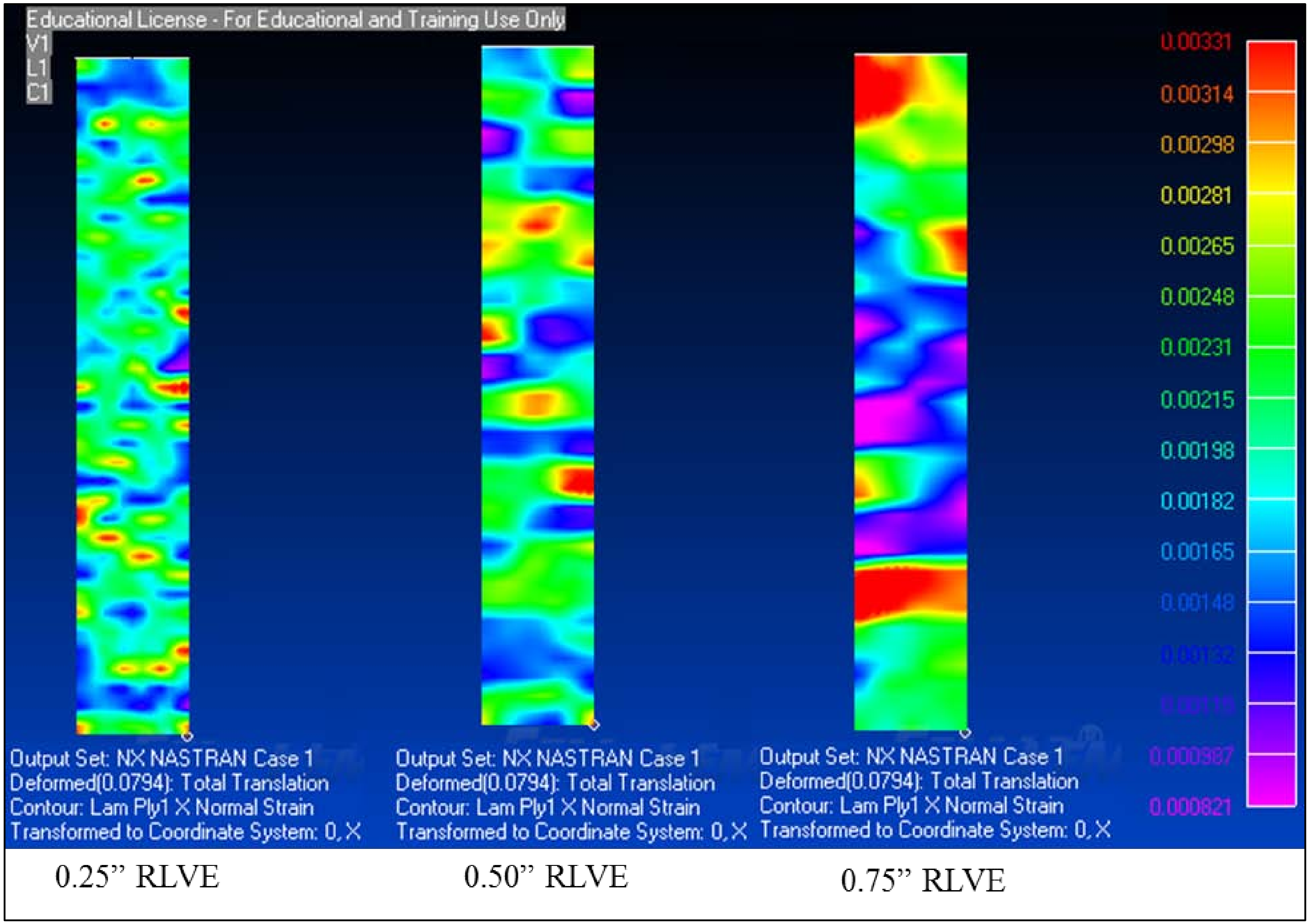
Modeling – Modulus Variation



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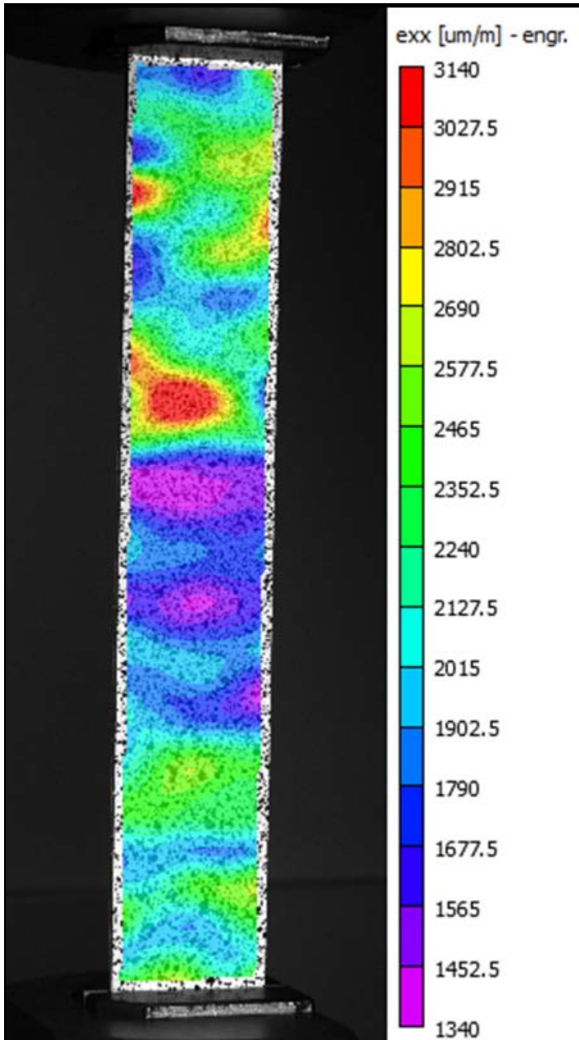
Modeling – Modulus Variation



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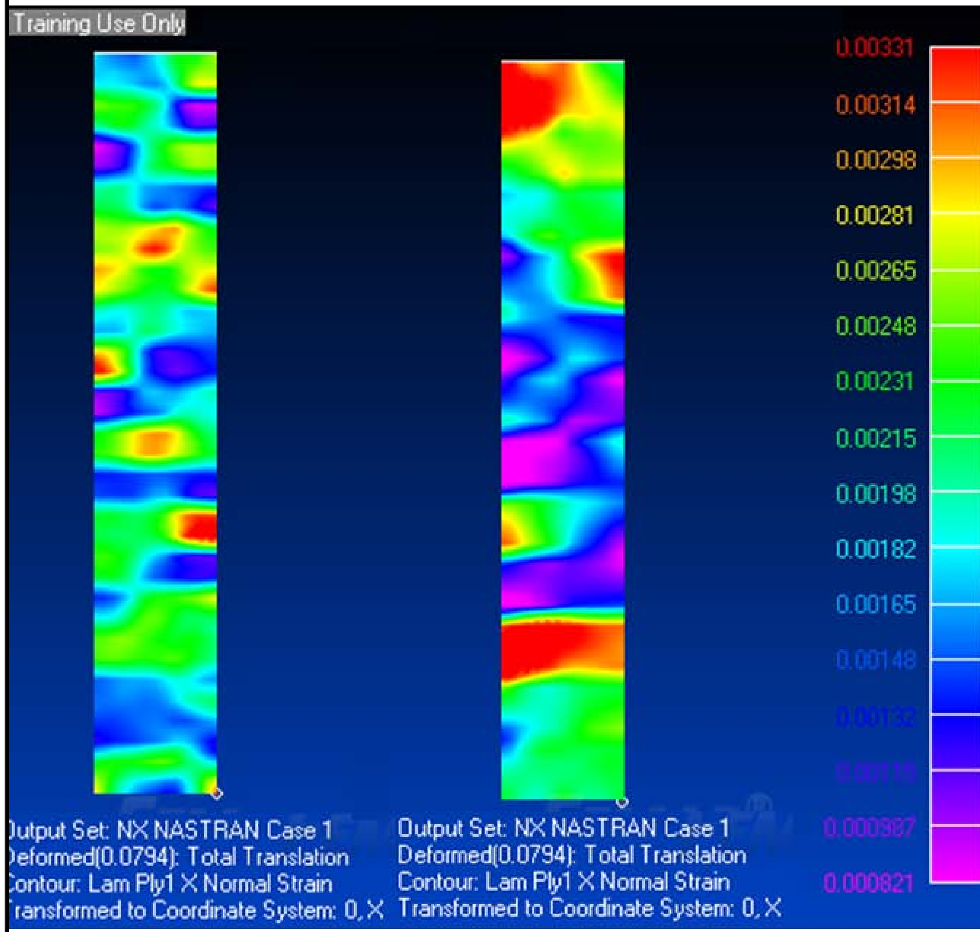


0.50" RLVE

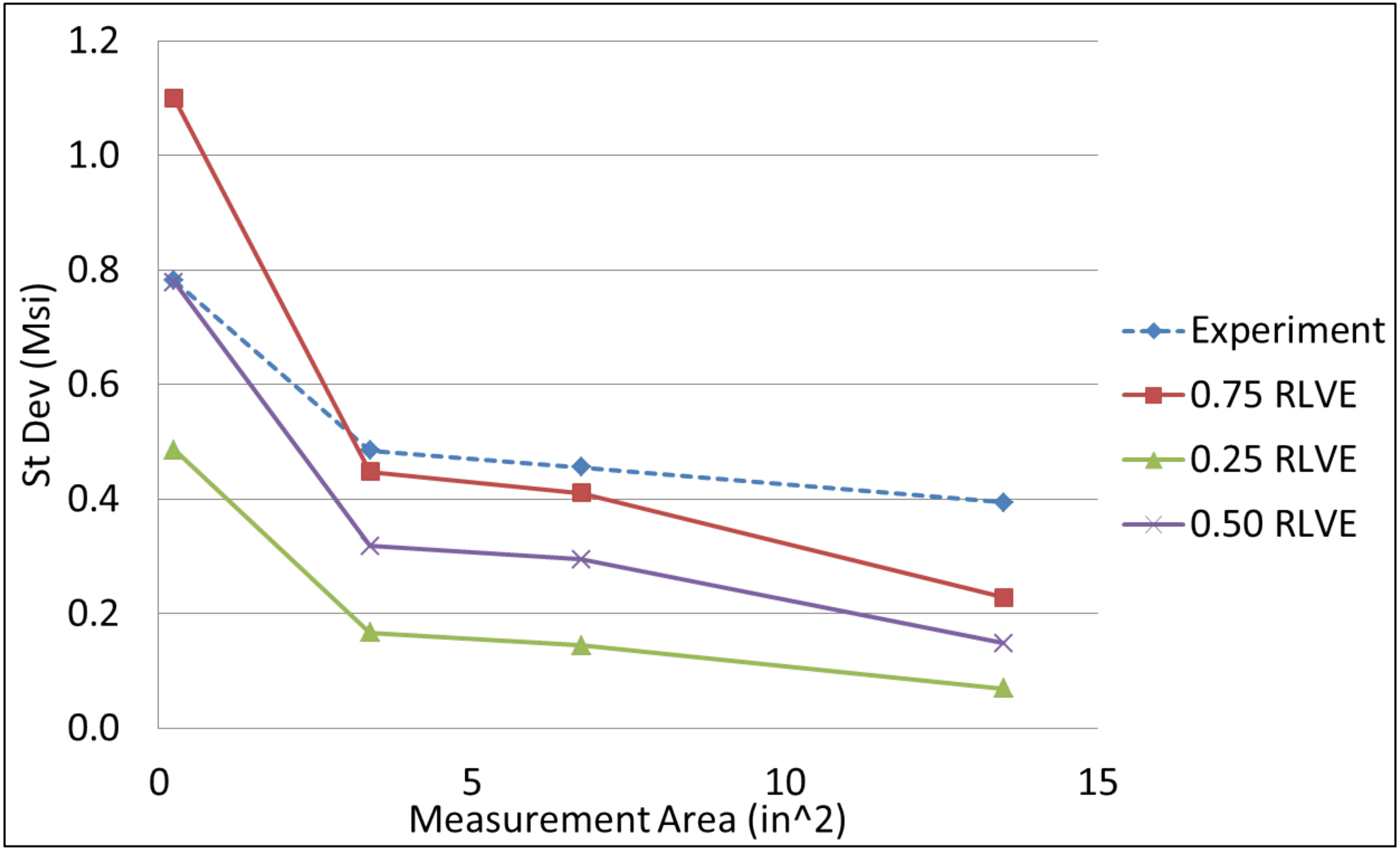
0.75" RLVE

Modeling – Modulus Variation

Thick	0.25" RLVE		0.5" RLVE		0.75" RLVE	
Area	Avg (Msi)	St Dev (Msi)	Avg (Msi)	St Dev (Msi)	Avg (Msi)	St Dev (Msi)
0.25	6.52	0.487	6.554	0.778	6.60	1.10
3.375	6.49	0.167	6.474	0.318	6.45	0.449
6.75	6.49	0.144	6.473	0.295	6.44	0.411
13.5	6.53	0.070	6.500	0.149	6.47	0.228
Error	-2.76%		-3.18%		-3.64%	

Thin	0.25" RLVE		0.5" RLVE		0.75" RLVE	
Area	Avg (Msi)	St Dev (Msi)	Avg (Msi)	St Dev (Msi)	Avg (Msi)	St Dev (Msi)
0.25	6.40	0.602	6.470	1.063	6.53	1.42
3.375	6.37	0.208	6.308	0.408	6.28	0.569
6.75	6.36	0.190	6.306	0.376	6.27	0.530
13.5	6.40	0.108	6.343	0.201	6.29	0.287
Error	1.91%		1.00%		0.21%	

RLVE Sizing – Thick Specimen



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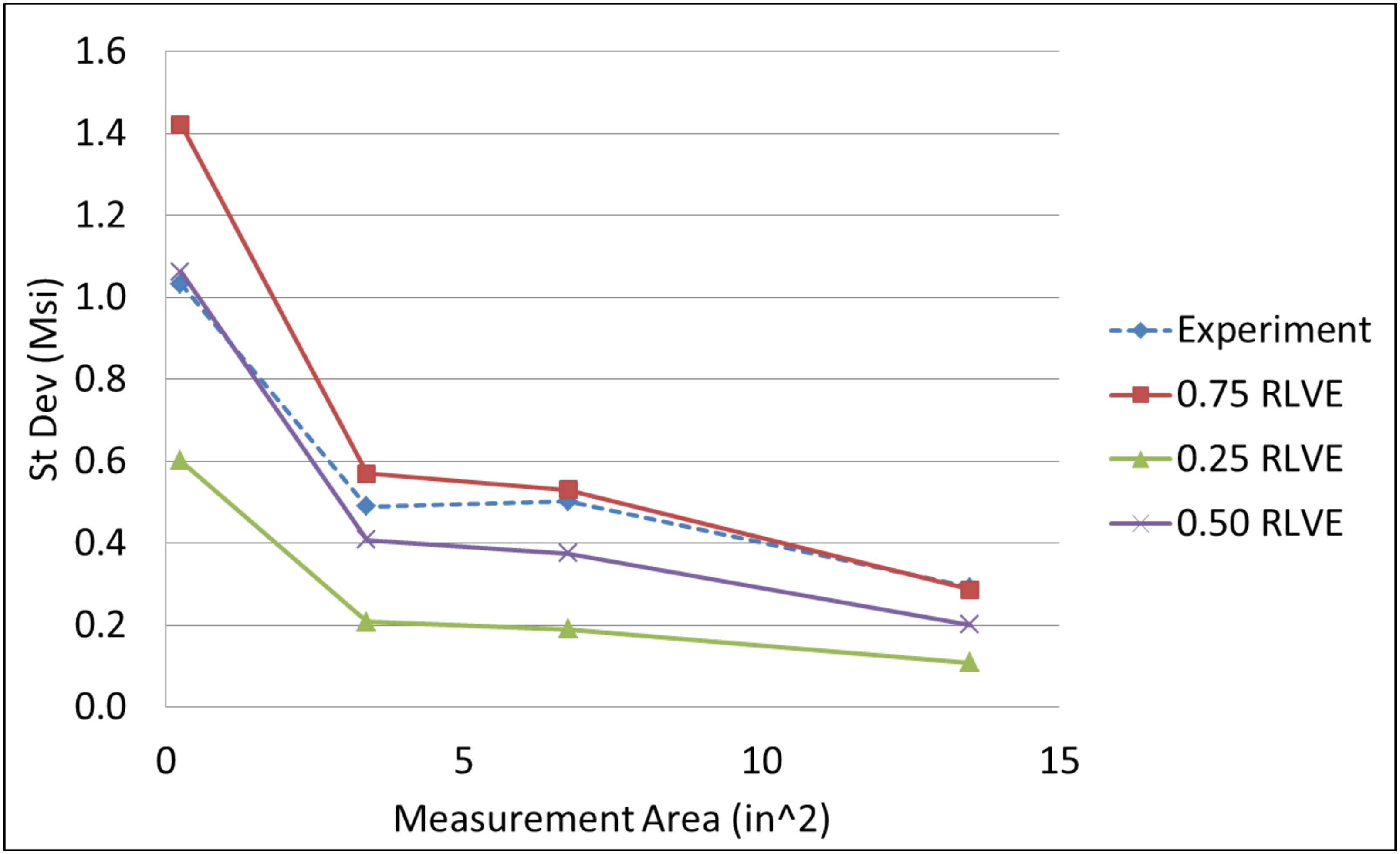
RLVE Sizing – Thin Specimen



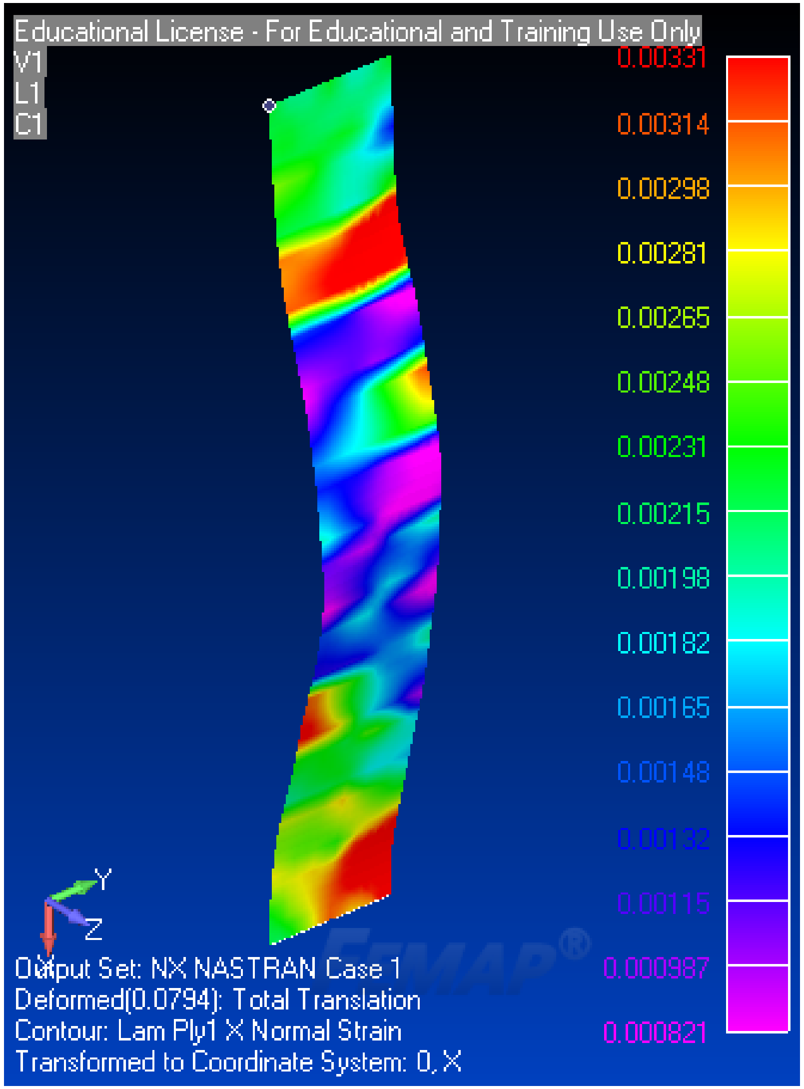
Modeling – RLVE Sizing

- Suggested RLVE size taken to be average of two
  - Independent of thickness
  - 0.76” x 0.76”

	Suggested RLVE Size (in)	
Gauge Area (in^2)	Thick	Thin
0.25	0.50	0.51
3.375	0.82	0.64
6.75	0.85	0.71
13.5	1.27	0.77
Average	0.86	0.66

Modeling – Coupling

- Out of plane displacements are predicted by model



Typical thin model

Modeling – Coupling

- Predicted displacements are of the same order of magnitude as measured

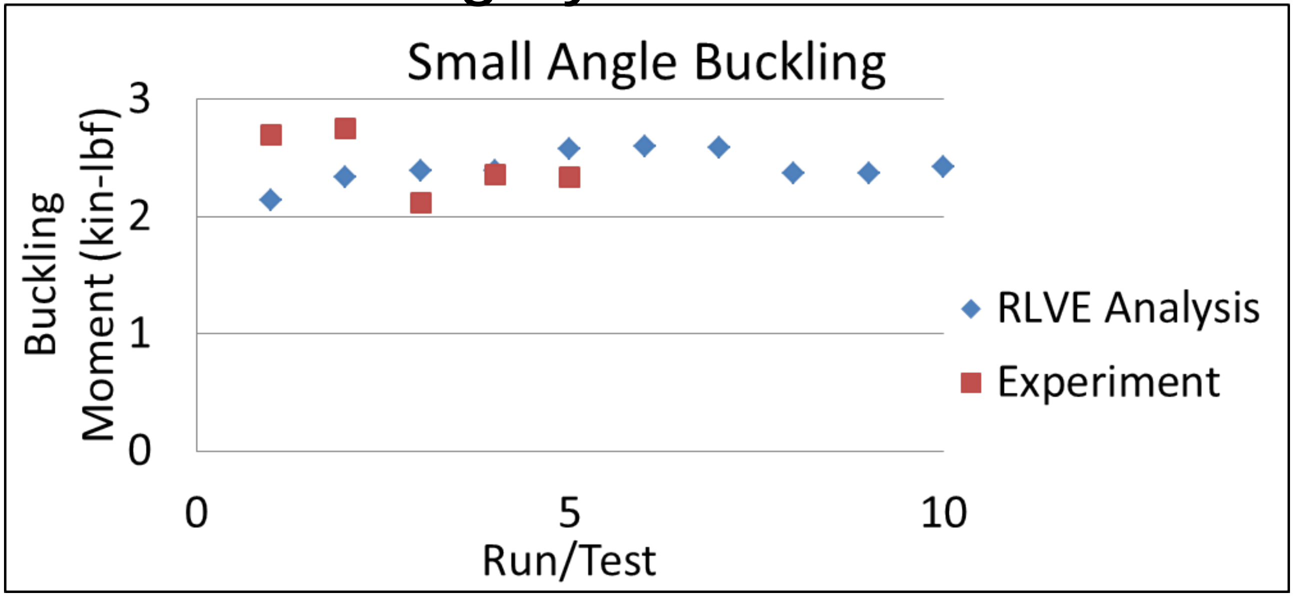
	Thick			Thin		
	0.25" RLVE	0.5" RLVE	0.75" RLVE	0.25" RLVE	0.5" RLVE	0.75" RLVE
Avg (in/Msi)	0.349	0.623	1.014	0.691	1.37	2.08
St Dev (in/Msi)	0.134	0.260	0.411	0.282	0.576	0.881

Conclusions

- RLVE modeling is capable of predicting stiffness variation of HexMC, provided proper RLVE size is chosen
- MBC effects could not be consistently measured, but RLVE modeling did predict coupling between in plane loads and out of plane displacements

Application to Angle Buckling
-Preliminary Results

- Previous work predicted buckling load of angle beams subjected to pure bending
  - JAMS 2012 and AMTAS 2012
- For small angle size previous efforts over predicted buckling by 20 – 25% or more



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Future Work

- Complete analysis of buckling of angle beams
- Area based failure criteria for use with RLVE modeling
- Apply RLVE method to intercostal predictions

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Benefit to Aviation

- Results of this study will ultimately help establish a method to certify DFC aircraft parts by analysis supported by experimental measurements
  - RLVE modeling effort provides insight into the cause of under prediction of buckling loads when isotropic properties are used for modeling

End of Presentation.

Thank you.

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