Crashworthiness Evaluation of Composite Aircraft Structures

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S. Raju – WSU

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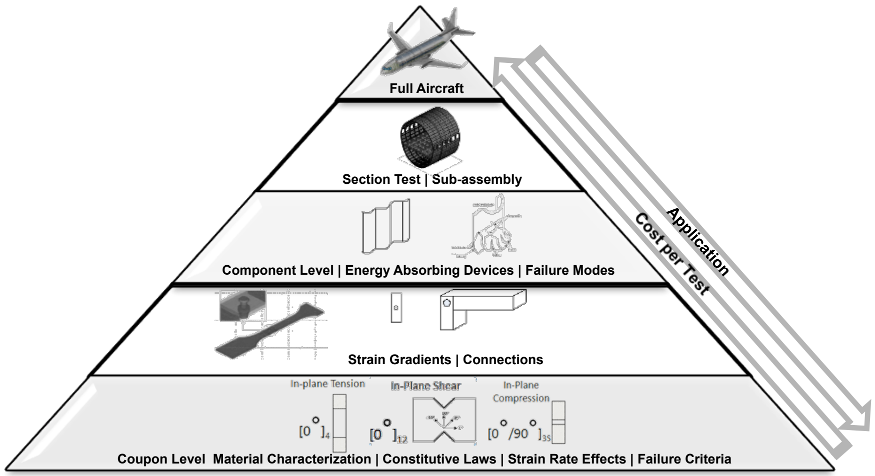
Crashworthiness of Aerospace Composite Structures

- Motivation and Key Issues
  - The introduction of composite airframes warrants an assessment to evaluate that their crashworthiness dynamic structural response provides an equivalent or improved level of safety compared to conventional metallic structures. This assessment includes the evaluation of the survivable volume, retention of items of mass, deceleration loads experienced by the occupants, and occupant emergency egress paths.
- Objective
  - In order to design, evaluate, and optimize the crashworthiness behavior of composite structures it is necessary to develop experimental and numerical methods and predictable computational tools.
- Approach
  - The advances in computational tools combined with coupon/component level testing allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures
  - A building block approach is used to assess the crashworthiness dynamic structural response of composite airframes
  - Research programs are conducted at different levels of the building block
    - High speed test methods are being investigated experimentally and numerically not only for material property generation but also for material model development
    - Numerical tools used to model structural joints are being evaluated



Program Overview

Coupon level

- Dynamic Material Characterization
- Material Models for Simulation
- CMH-17 Round-Robin exercise for Dynamic tensile testing

Element Level

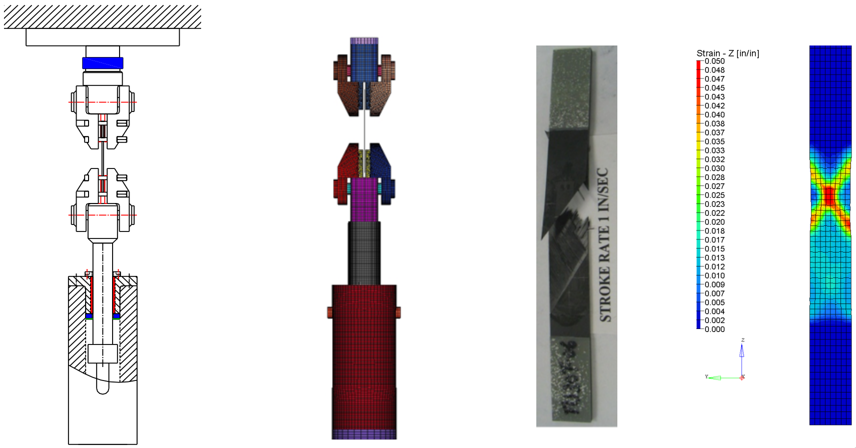
- Guidelines for Modeling Fastener Joints for Crashworthiness Simulations

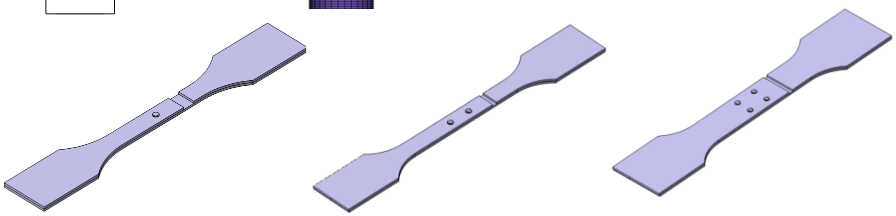
Sub-assembly Level

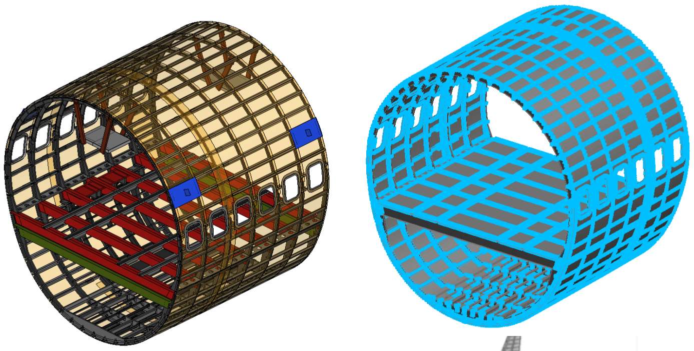
- Drop Simulation 10-ft fuselage section
- Energy Absorbing Capabilities

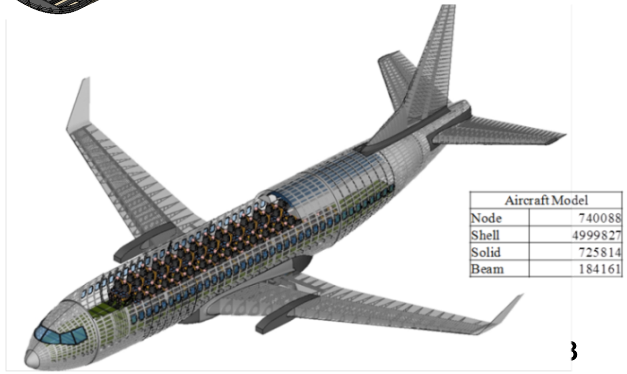
Full-scale Structural Level

- Accident Reconstruction









Aircraft Model	
Node	740088
Shell	4999827
Solid	725814
Beam	184161

Crashworthiness of Aerospace Composite Structures

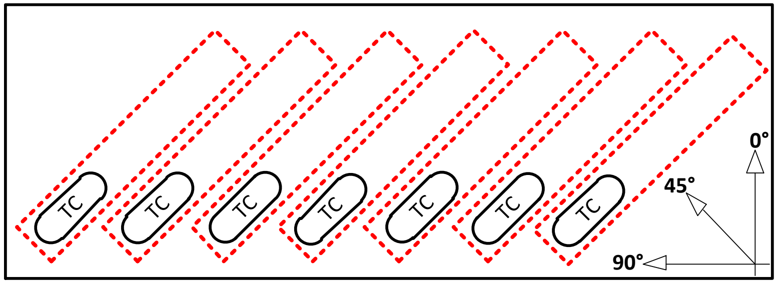
- Principal Investigators & Researchers
  - G. Olivares Ph.D., J.F. Acosta Ph.D.
  - S. Keshavanarayana Ph.D.
  - C. Zinzuwadia, I. Echavarri
- FAA Technical Monitor
  - Allan Abramowitz
- Other FAA Personnel Involved
  - Joseph Pelletiere Ph.D.
- Industry Participation
  - Toray America (S. Tiam)
- Research Institute & University Participation
  - Arizona State University (B. Mobasher, A. Bonakdar), DLR (A. Johnson, M. David), Ohio State University (A. Gilat), Oakridge National Labs (Y. Wang, D. Erdman III, M. Starbuck)

Dynamic Characterization of Round Robin Material

Coupon Level

Dynamic Characterization of Round Robin Material – Coupon Level

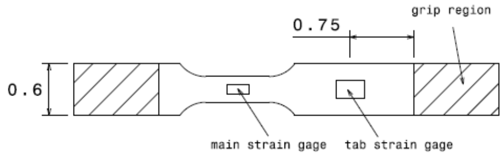
- Characterization of the in-plane dynamic material response in tension of laminated composite materials over a wide range of loading rates to support the crashworthiness building block approach



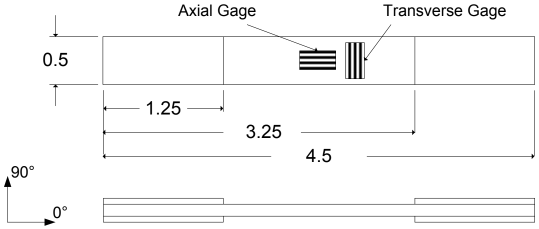
- Primary Objective
  - Evaluate test methods/apparatus and load measurement methods employed by the participating laboratories using an extended tab 2024-T3 aluminum specimen
- Secondary Objective
  - Characterize the strain rate sensitivity of Toray - T700G/2510 Plain Weave carbon/ epoxy material at strain rates ranging between 0.01 to 250 s^{-1}

** Material selection was based on supporting CMH-17 Crashworthiness Group activities*

- Aluminum Specimens
  - Tension coupon per ASTM E 8, accommodated to high strain rate testing



- Composite Specimens
  - Tension coupon per ASTM D 3039, accommodated to high strain rate testing



Group Exercise

Participating Labs/Agencies

- Coordination and Reporting
  - FAA (Program Monitor - A. Abramowitz)
  - NIAR/WSU (G. Olivares, K.S. Raju, J.F. Acosta, M.T. Siddiqui, I. Echavarri)
- Specimen fabrication, fixturing, instrumentation
  - NIAR/WSU
- Material
  - Toray America (S. Tiam)
- Testing
  - Arizona State Uni. (B. Mobasher, A. Bonakdar, Y. Yao)
  - DLR (A. Johnson, M. David)
  - NIAR/WSU
  - Ohio State Uni. (A. Gilat)
  - Oak Ridge National Laboratory (Y. Wang, D. Erdman III, M. Starbuck)

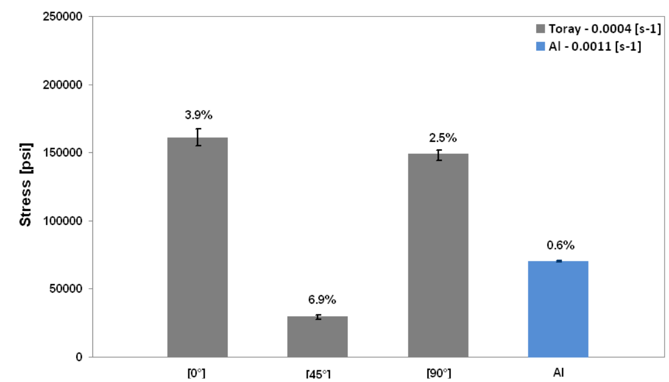
Activities

1. Specimen fabrication
2. Fabrication extra fixtures
3. Test coupons distribution
4. Quasi-static Characterization – NIAR/WSU
5. Dynamic Testing
   - Ohio State University
   - NIAR/WSU
   - DLR
   - Oak Ridge National Laboratory
   - Arizona State University
6. Data submission
7. Data analysis – Apparent Properties
8. Load measurement correction
9. Report

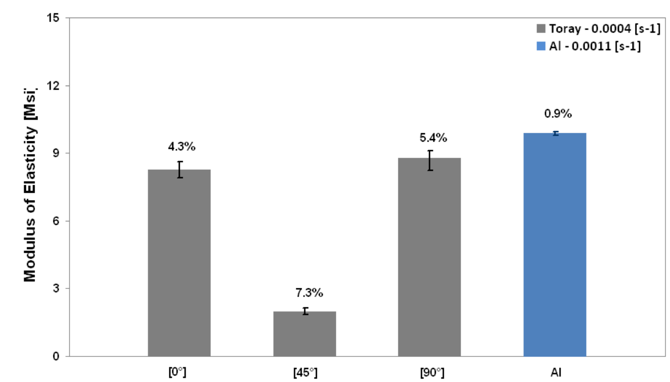
Quasi-static Characterization – Baseline

- Baseline for Strain Rate Effect Evaluation
  - Test Rate
    - Quasi-static (0.05 in/min)
  - Test Method
    - in-plane tension (ASTM D 3039 and ASTM E 8)
  - Load Frame
    - 22 kip Servo-hydraulic MTS
  - Load Measurement
    - Strain gage based load cell (5.5 kip)
  - Strain Measurement
    - Strain gage
    - Signal conditioner Vishay 2210
  - Coefficient of Variation
    - Based on three (3) samples for reference only

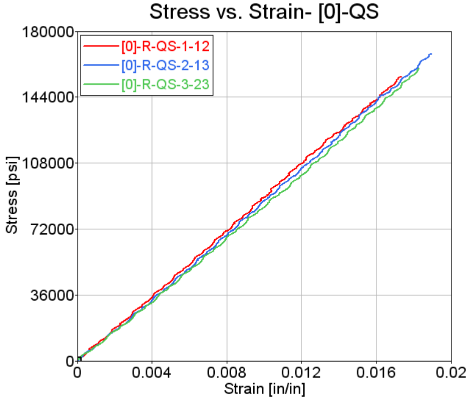
Tensile Failure Strength



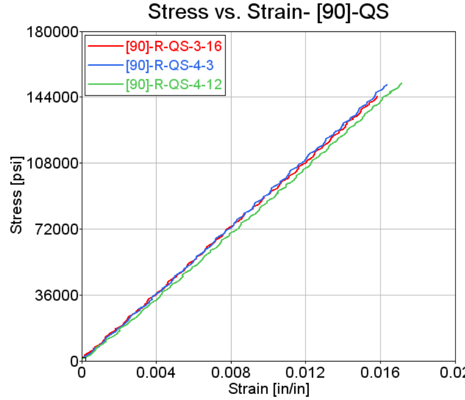
Modulus of Elasticity - Tension



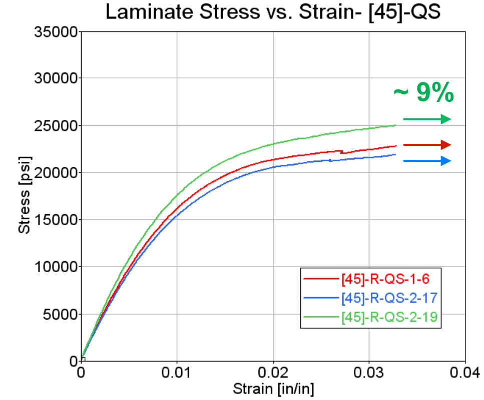
Stress vs. Strain- [0]-QS



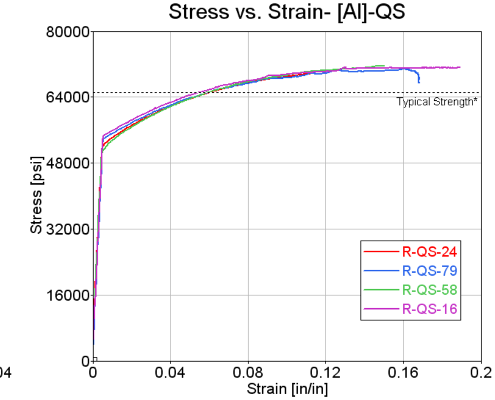
Stress vs. Strain- [90]-QS



Laminate Stress vs. Strain- [45]-QS



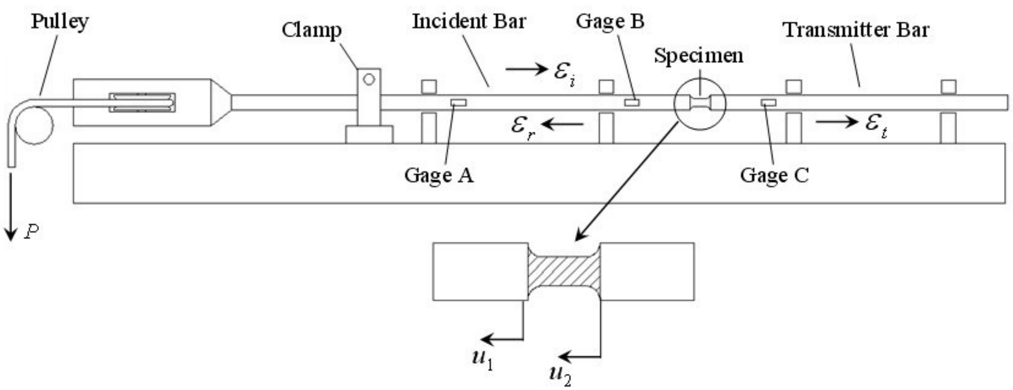
Stress vs. Strain- [Al]-QS



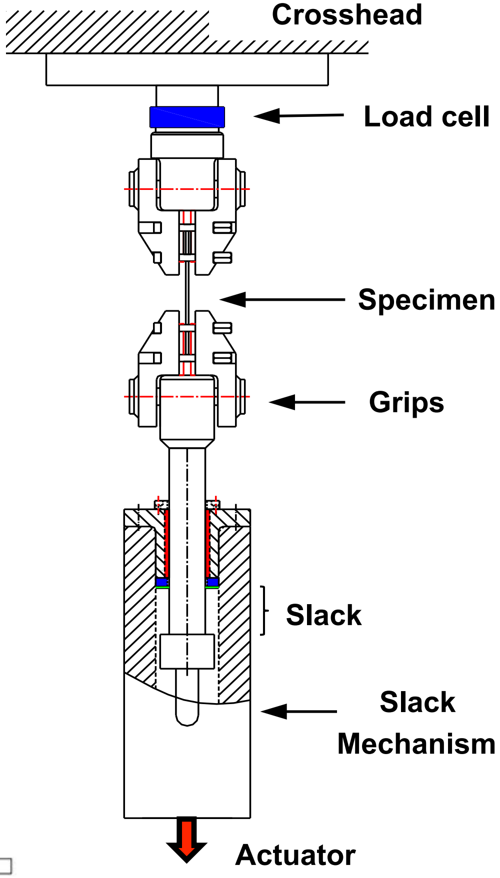
Dynamic Characterization

- Same detailed test procedure provided to all laboratories
  - Four (4) stroke rates
  - Three (3) composite material orientations
  - Limited test specimens (3) per test condition
- Servo-hydraulic Machine
  - Slack inducer
  - Accelerate actuator prior specimen loading
- Tensile Split Hopkinson Pressure Bar

MATERIAL SYSTEM		NOMINAL STRAIN RATE [1/s]			
		0.01	1	100	250
2024-T3 Aluminum		×3	×3	×3	×3
T O R A Y T700/2510	$[0]_4$	×3	×3	×3	×3
	$[90]_4$	×3	×3	×3	×3
	$[\pm 45]_4$	×3	×3	×3	×3

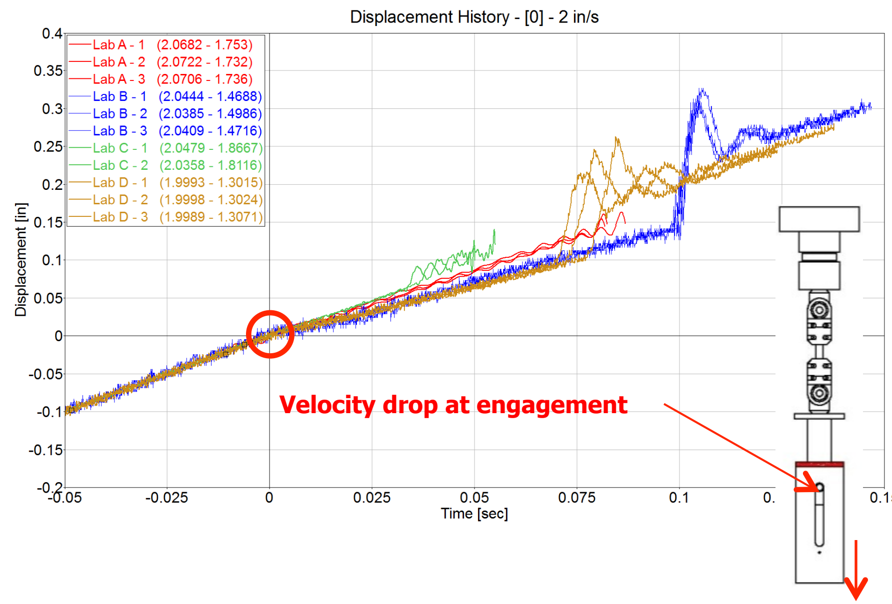


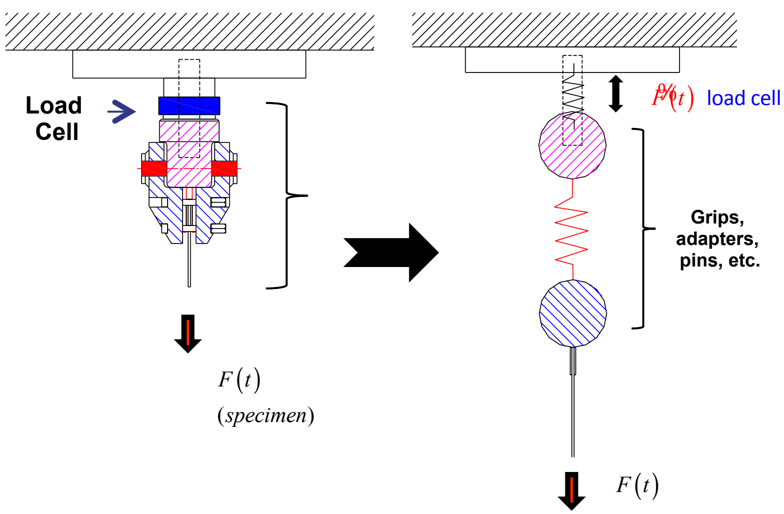
Test Video 75 in/s

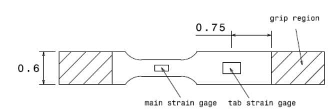


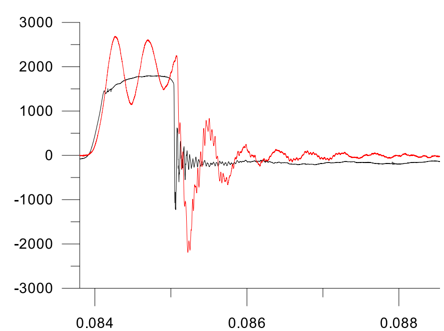
Dynamic Tension Testing Challenges

- Velocity Drop
  - Servo Machines and Slack inducer devices
  - Practical approach – Use sacrificial specimens
  - Can calibrate the controller for the desire rate by testing one specimen of similar stiffness prior to testing the material
- Force signal modulation
  - Load cell characteristics
  - Presence of masses between load cell and specimen
  - Wave propagation & reflections









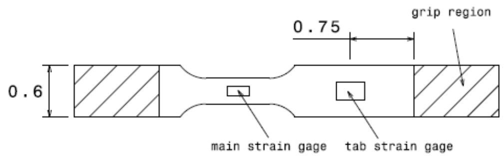
Extended tab **Aluminum Specimen**

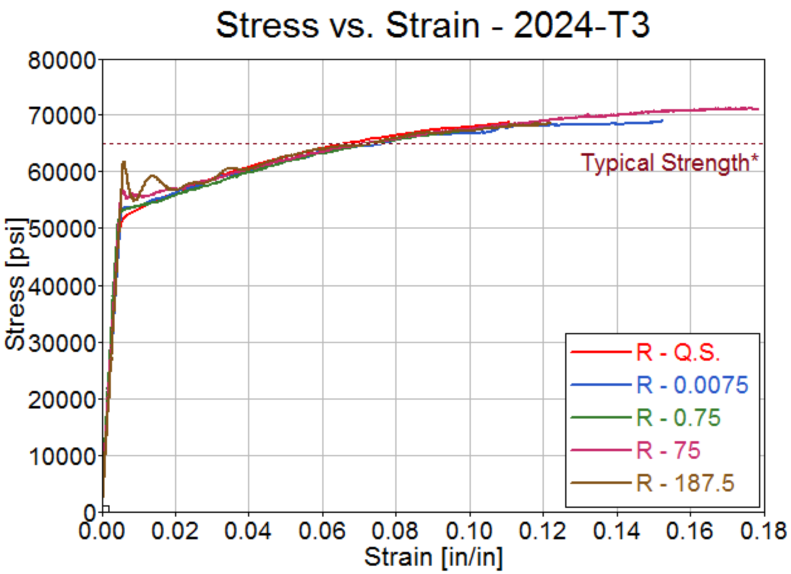
TRANSFER FUNCTION

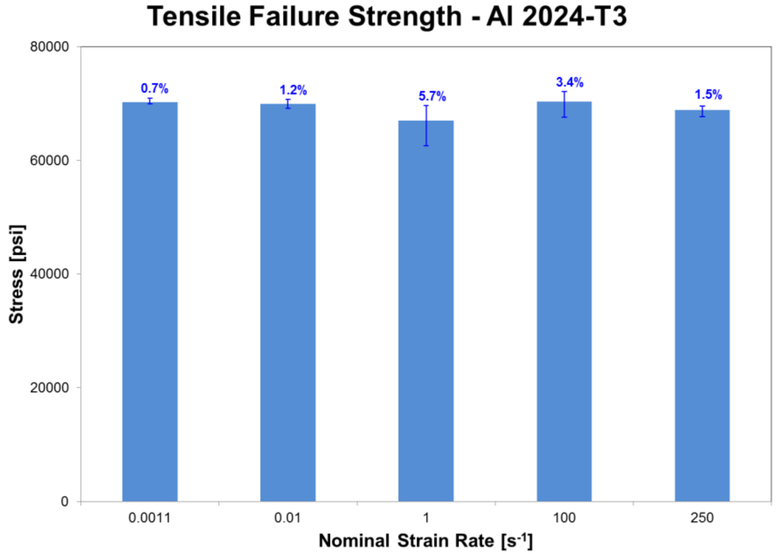
Correct test data for **Composite Specimens**

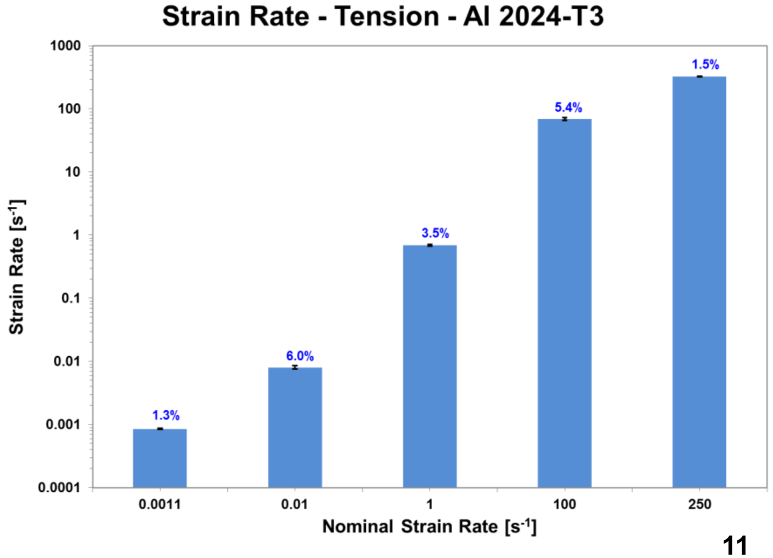
Aluminum Dynamic Characterization Lab A

- Control material for load sensor evaluation
- Tab strain gage used for load measurement
- Used to generate a system characteristic transfer function
- Coefficient of Variation based on three (3) samples



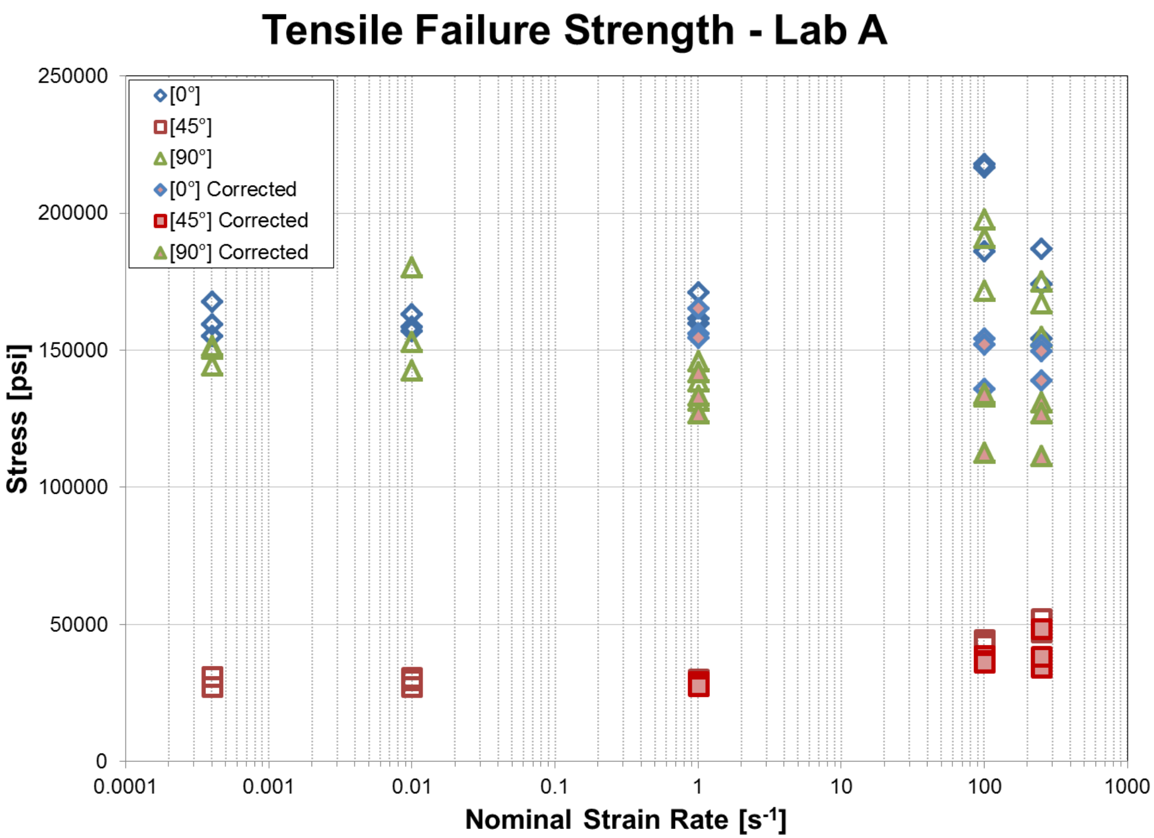






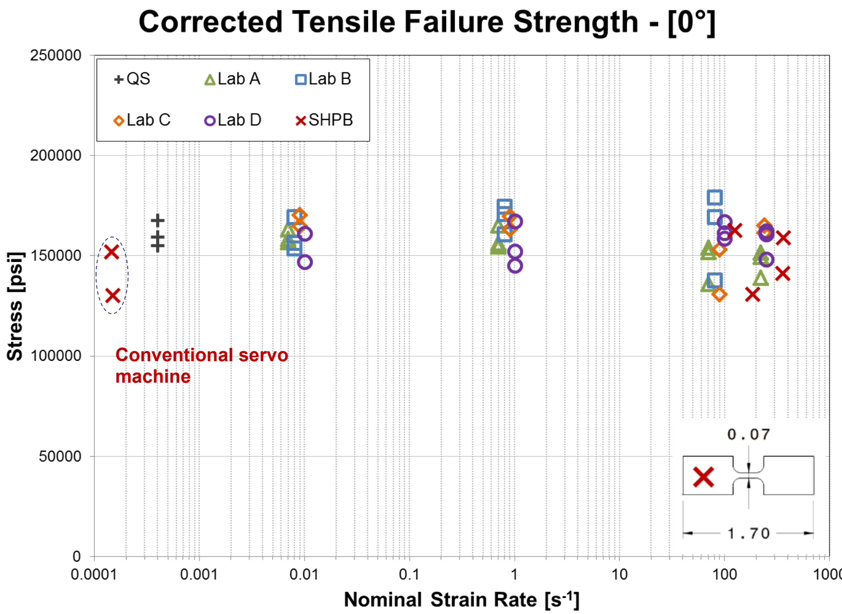
Composite Dynamic Characterization Lab A

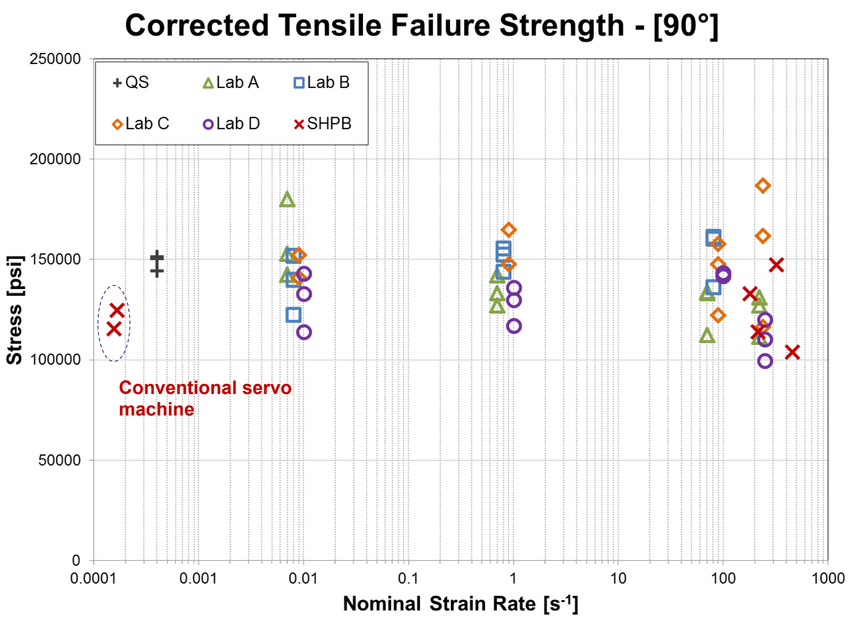
- Example from one of the participating laboratories
- Apparent properties are estimated based on load measurements before correction for signal modulation
- Load measurements corrected for signal modulation

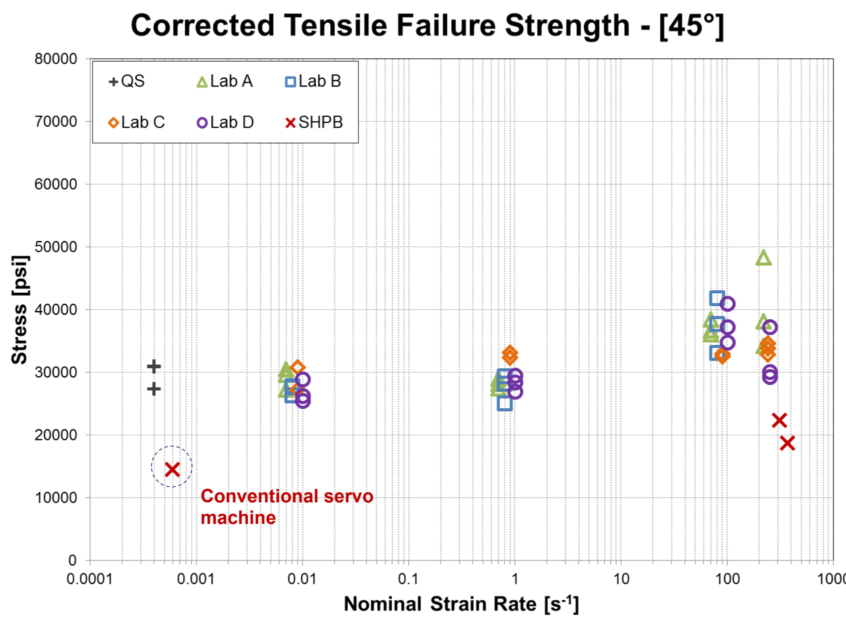


Comparison across Laboratories

- $[0°]_4$
- $[90°]_4$
- $[45°/-45°]_S$
- Load measurement corrected for signal modulation
- Address variability associated to different laboratories generating same material properties
- Reduced strength for SHPB specimens







Conclusions – Dynamic Characterization of Round Robin Material

- Recently completed
- Results to be presented in the American Society for Composites conference – ASC 2014
- Path for High Speed Test Method Development using Servo-Machines
  - Baselines were generated for estimating the effect of strain rates as high as 250 s-1
  - Test procedure and test protocol can be used as guidelines for dynamic tension testing
  - Address repeatability of experiments within each laboratory
  - Address the variability associated to different laboratories generating equivalent material properties
  - Load correction methodology aids the use of servo-machines to generate dynamic material properties
- Material Properties for Simulation
  - Apparent tensile failure strength was corrected for load signal modulation
  - After load correction, the material response of composite specimens in the principal directions [0°] and [90°] does not show significant sensitivity to the evaluated strain rate across laboratories
  - However, the response of the off-axis orientation [±45°] shows some sensitivity to high strain rates
  - The research was limited to tensile testing
  - Strain measurement using Digital Image Correlation methods show to be a reliable tool
  - Larger deformations for equivalent load levels with less sensitivity to material discontinuities
  - Material models for simulation may improve failure detection and better account for damage progression

Modeling Fastener Joints for Crashworthiness Simulations

Element Level

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Modeling Fastener Joints for Crashworthiness Simulations – Element Level

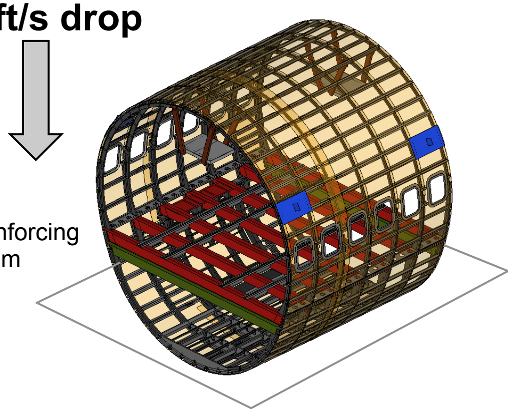
- Motivation and Key Issues
  - Simulation models are used to focus research
  - Metal and Composite Structures use fasteners as of one the primary joining entities to facilitate slip resistance and load transfer
  - 10-ft Fuselage Section Model has 22,012 fasteners. Energy dissipated through fastener joints up to 43 % of total energy for no cargo configurations
- Objective
  - Simplified FE bolt modeling techniques are evaluated to understand its limitations and advantages when used for Crashworthiness (Dynamic Loading, High Strain Rates)
- Approach
  - Fasteners idealized to minimize computational effort
  - Idealizations necessary in simulations involving large structures
  - Compromise between global response or capturing localized effects

Cargo Door

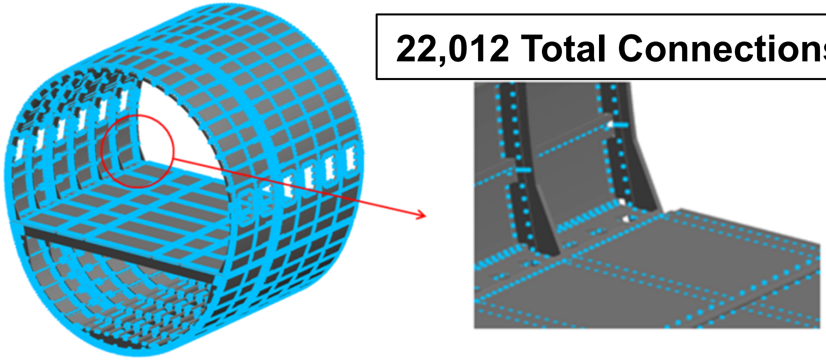
Reinforcing Beam

FAA Test setup

30 ft/s drop



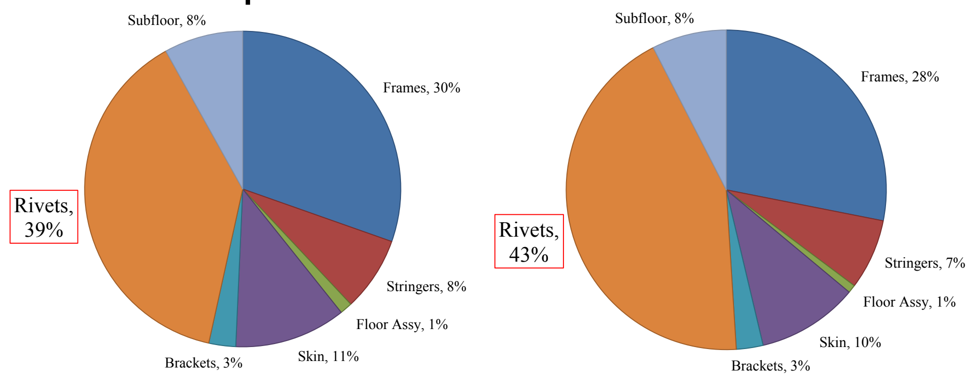
NIAR FE Model



22,012 Total Connections

Energy Balance

Max Compression **Residual**



Joints – Experimental Characterization

Material Characterization

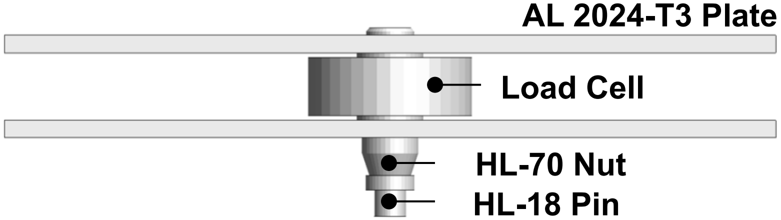
- Tensile Testing Aluminum 2024-T3 Clad

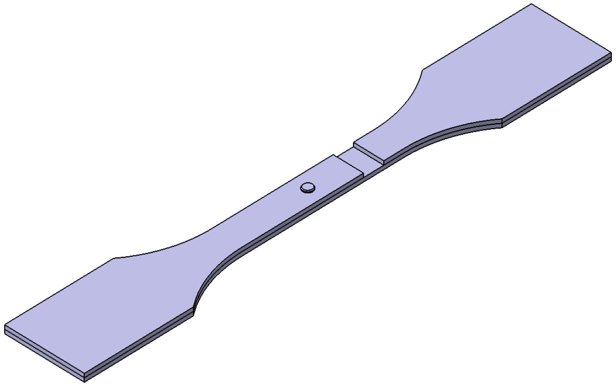
Preload Characterization

- Quantify clamping force generated by Hi-Lok fasteners

Joint – Load Transfer Testing

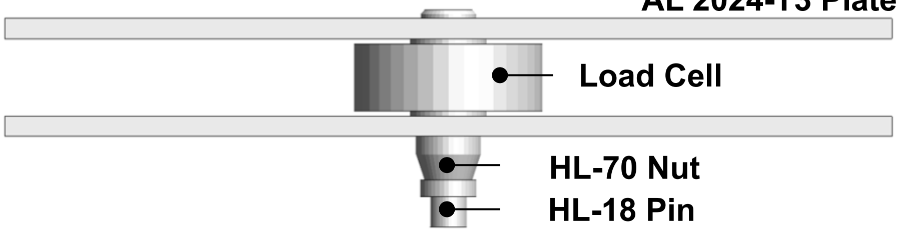
- Testing Single Shear Fastener Joint Specimen to quantify Load Transfer

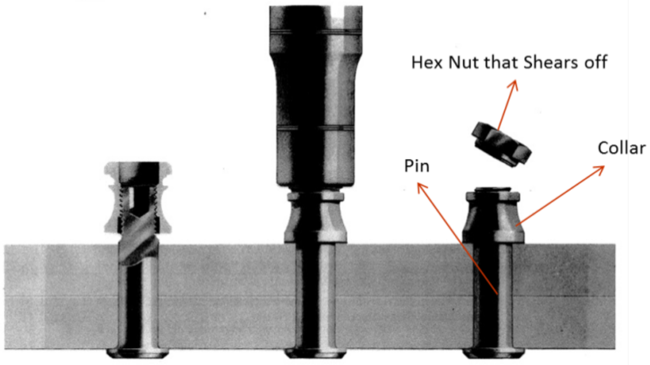


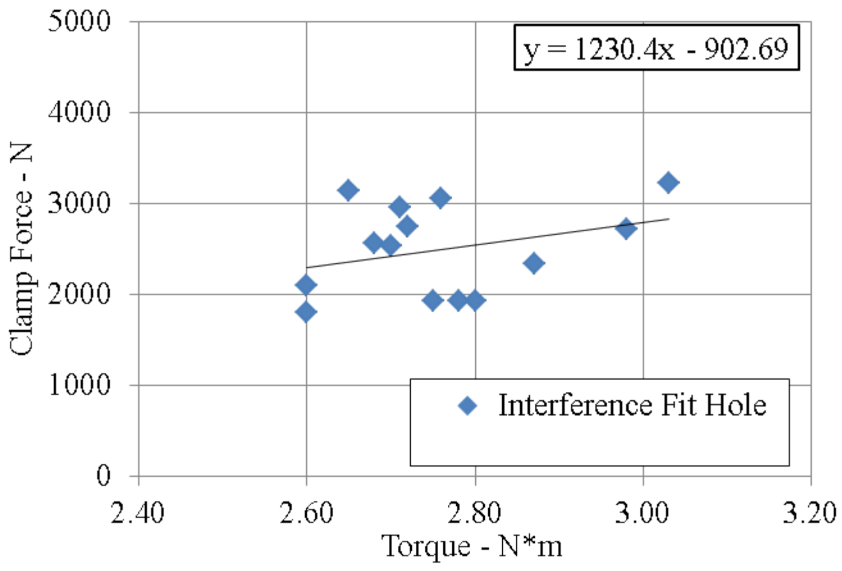


Joints – Preload Measurement

- Quantify clamping force generated by Hi-Lok fasteners for simulation
  - Designed with a predefined range of preload
  - Contains Hex Nut that shears off once preload is within range
- Clamping Force
  - Calibrated Load Cell in Compression
  - 5 Kip Calibrated Load Cell
  - Set Gain on Signal Conditioner based on performance of Load Cell
  - Generated a Voltage versus Load curve
- Two Sets of Hole Diameter tested
  - Interference Fit Hole
  - Clearance Fit Hole

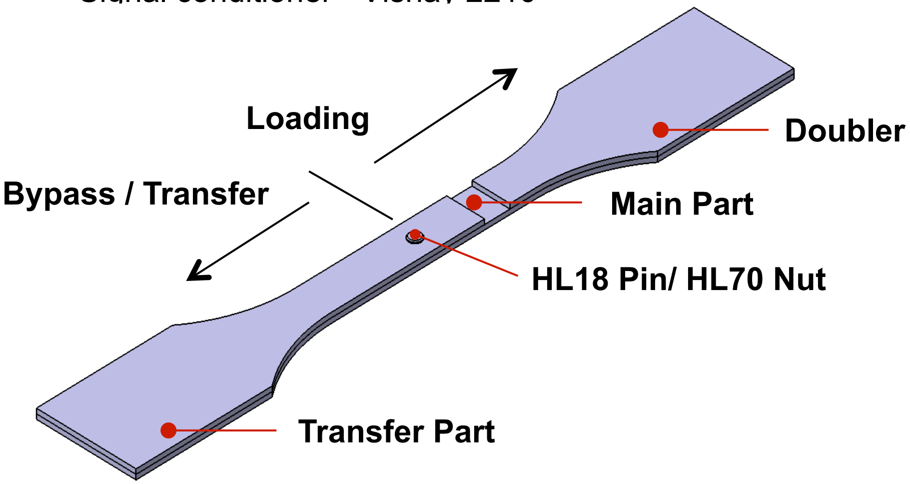


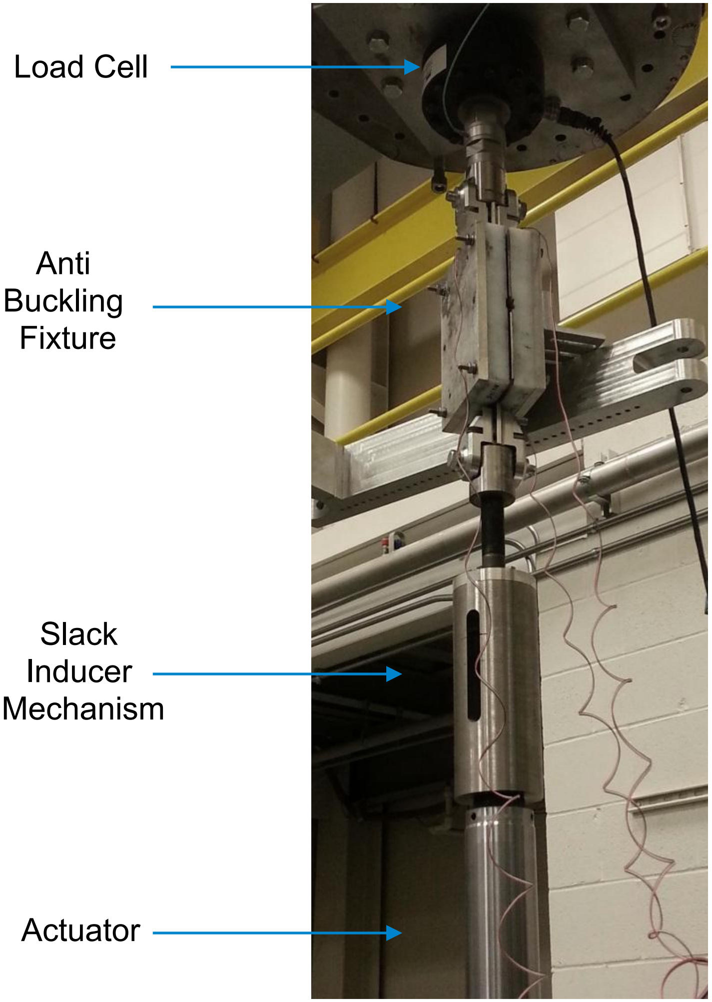




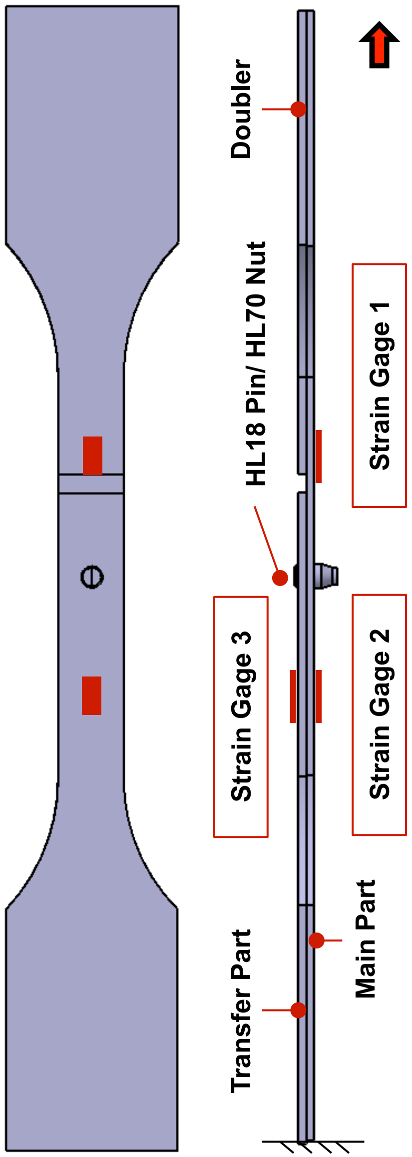
Joints – Load Transfer Testing

- Dog bone specimen joined with one fastener used to understand the load transfer mechanics
- Test method – In-plane tension
- Test apparatus
  - MTS High Stroke Rate Servo-hydraulic
  - Slack Inducer Mechanism
  - Dynamic load up to 5 kip
- Test rate
  - Quasi-Static (0.05 in/min) – Completed
  - Low to Medium Rate (1 to 20 in/s) – Ongoing
- Load measurement
  - Quasi-Static – Strain gage based load cell (22kip)
- Strain measurement
  - 3 Axial train gages - CEA-06-250UN-120
  - Signal conditioner - Vishay 2210

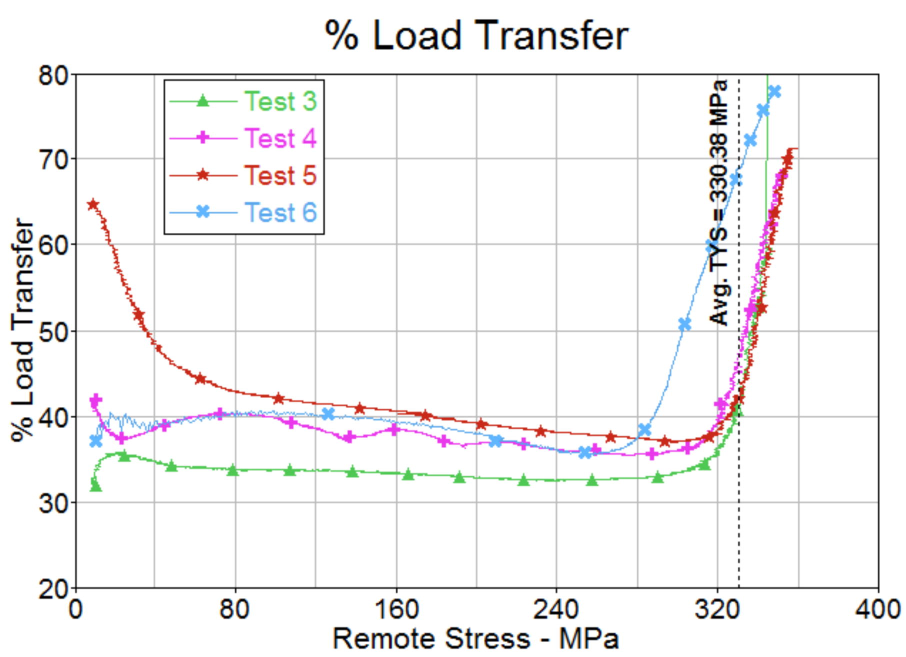


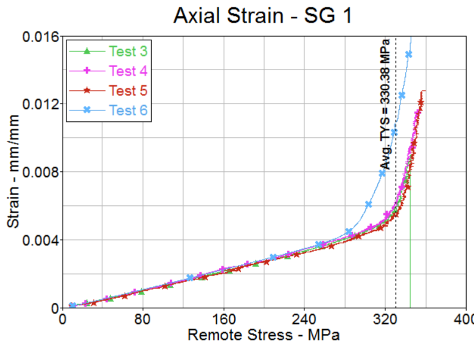


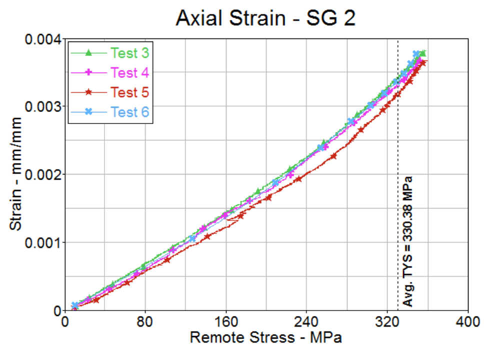
Joints – Load Transfer Testing

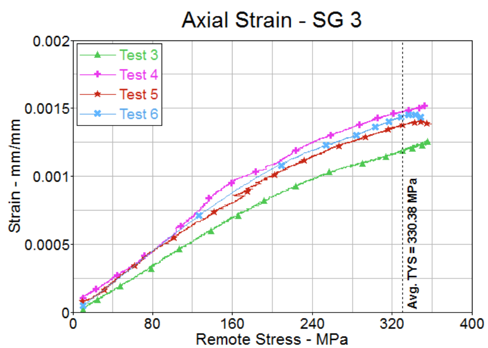


$$\% \; Load \; Transfer = [1 - (SG2/SG1)] \times 100\%$$





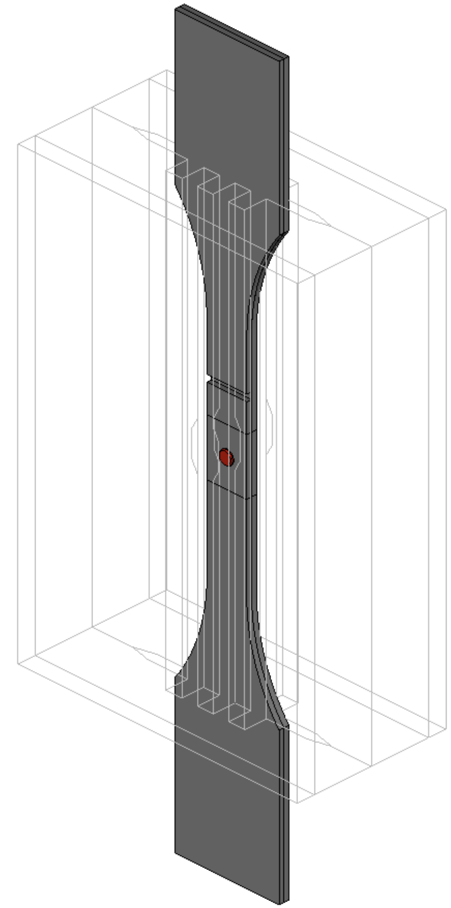




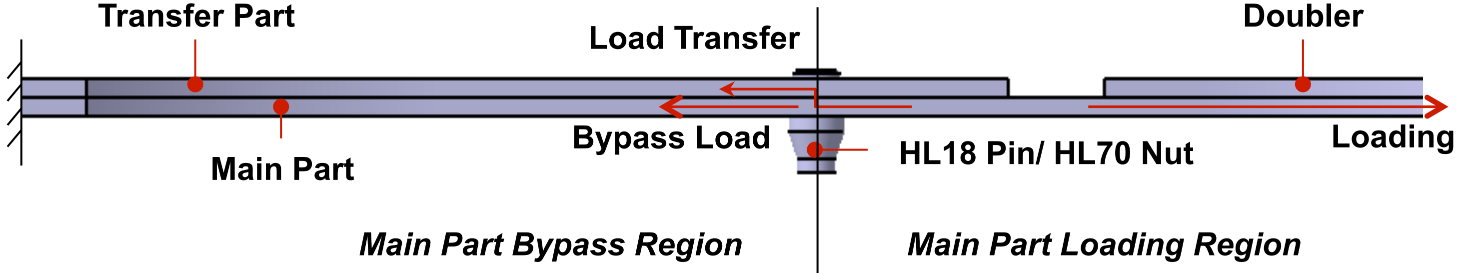
Modeling Fastener Joints for Crashworthiness Simulations

- A **numerical model** of the test was assembled using solid 3D elements and a fine mesh
  - Dog bone specimen joined with one fastener
  - Anti-buckling fixture

- Different **Simplified Bolt Modeling Techniques** were subjected to the same boundary and loading conditions and compared to the test results

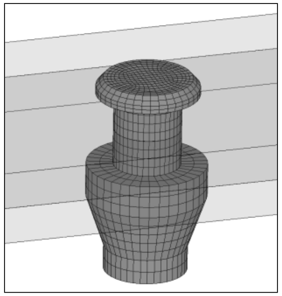


$$\% \; \textit{Load Transfer} = [1 - (SG2/SG1)] \times 100\%$$

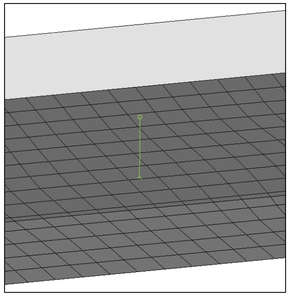


Joints – Available Simulation Techniques

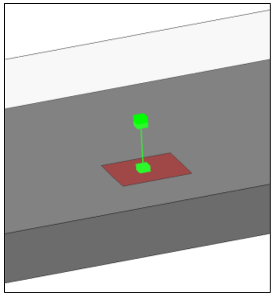
- Several studies have been conducted in the past to understand simplified modeling techniques for crashworthiness
- The techniques have been summarized in the following slides
- Note that several variations exist to the techniques listed in the table below which have been compared in the papers listed in references
- The **techniques highlighted** have been further analyzed and compared to the load transfer study



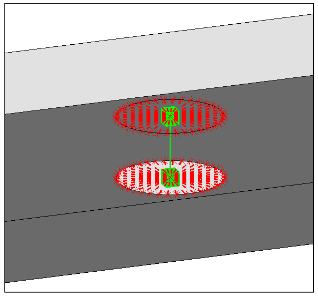
Solid



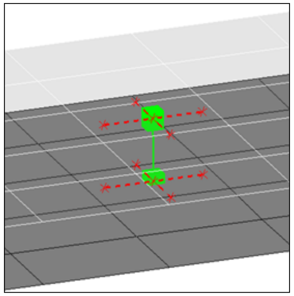
Spotweld Beam



Elastic Patch



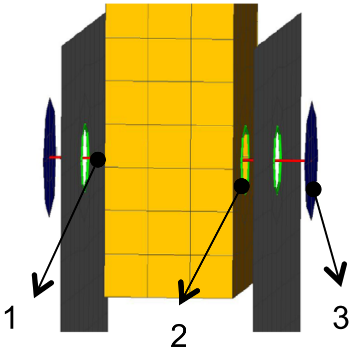
Spider Connection

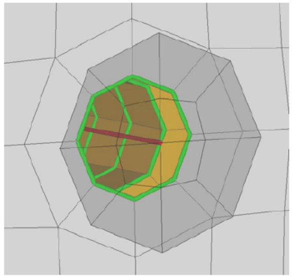


Beam with Rigid Links (no hole)

Simplified Bolt Modeling – LS DYNA

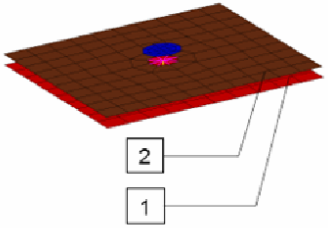
- Other Complex Bolt Modeling Techniques developed by LS DYNA users

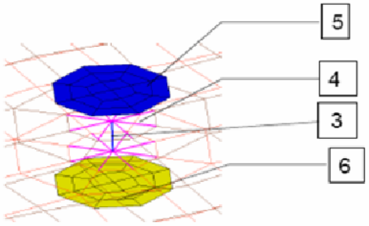




Component	Description
1	Elfrom 9, Spotweld Beams
2	Null beams for Contact
3	Shell Elements for Bolt Head and Nut

- **Sonnenschein, U. "Modelling of bolts under dynamic loads."** ***LS-Dyna Anwenderforum, Bamberg*** **(2008)**
- This modeling technique combines the advantage of the beam with spider connection and the solid modeling technique
- Null beams are modeled around the holes for contact and the bolt shank is modeled with type 9 spotweld-beam elements
- Shell elements are used to model bolt head and nut



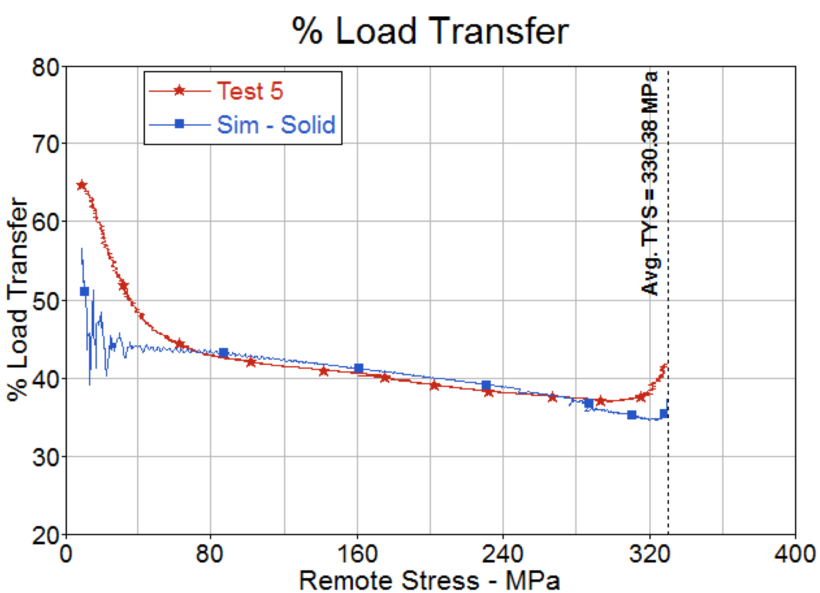


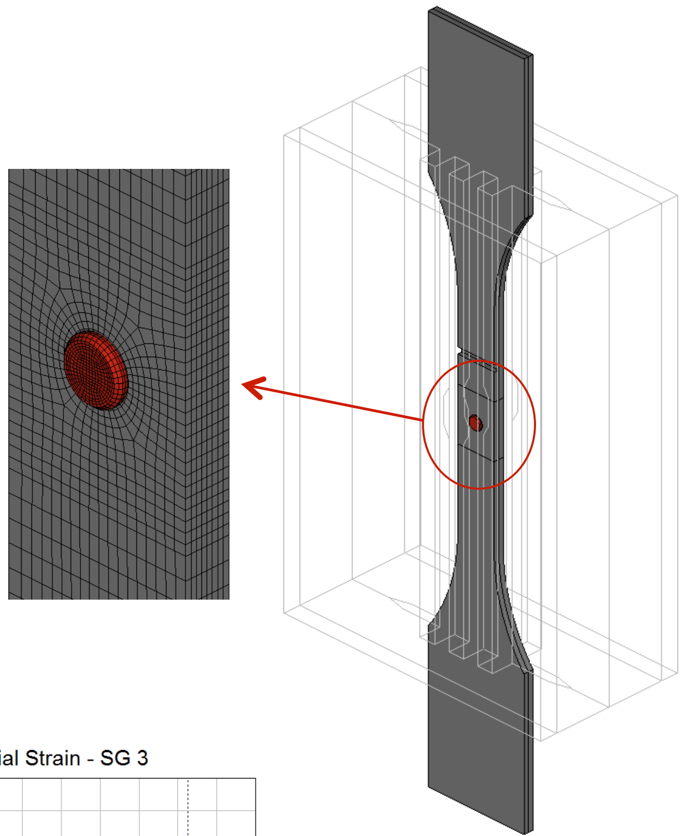
Component	Material	Element Type/ Thickness
1	MAT 24	SHELL, ELFORM 16, 5mm
2		SHELL, ELFORM 16, 5mm
3	MAT 100	BEAM, ELFORM 9, 12mm
4	SDMAT6	CONTACT SPRING
5	MAT20 (CON1=0 CON2=7)	SHELL, ELFORM 2, 5mm
6	MAT20 (CON1=0 CON2=7)	SHELL, ELFORM 2, 5mm

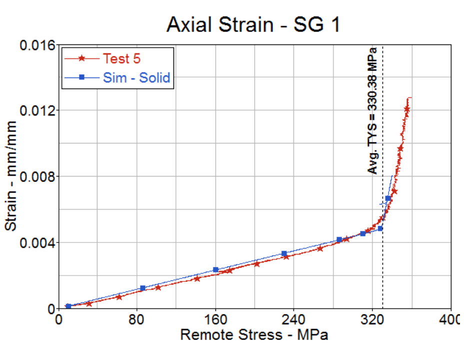
- **Narkhede, Shailesh, et al. "Bolted Joint Representation in LS-DYNA® to Model Bolt Pre-Stress and Bolt Failure Characteristics in Crash Simulations."** ***11th International LS-DYNA® Users Conference*****. (2010)**
- Bolt shank is modeled with a beam element at the center of the hole
- Beam element is connected to the periphery of bolt hole using contact springs
- Shell element patches representing bolt head and nut are modeled as rigid and constrained with XTRA nodeing
- Beam model is advantageous if failure forces for bolted joint are known under different conditions

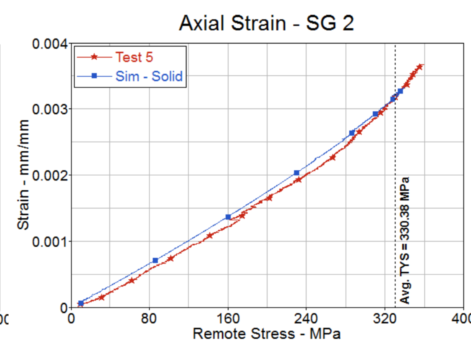
Modeling Fastener Joints – 3D Detailed Model

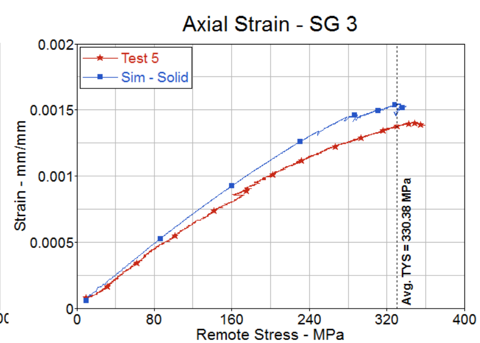
- A Solid 3D Model was developed and Validated against Test Data







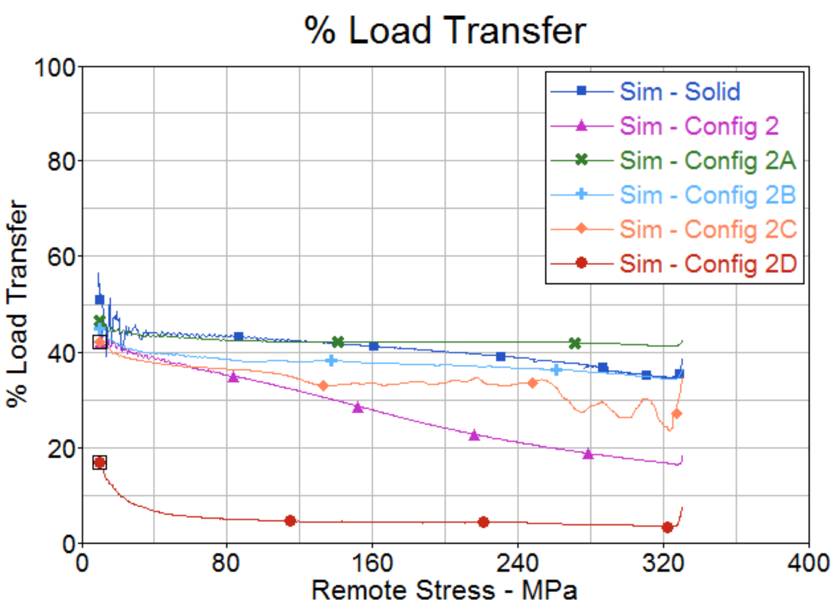


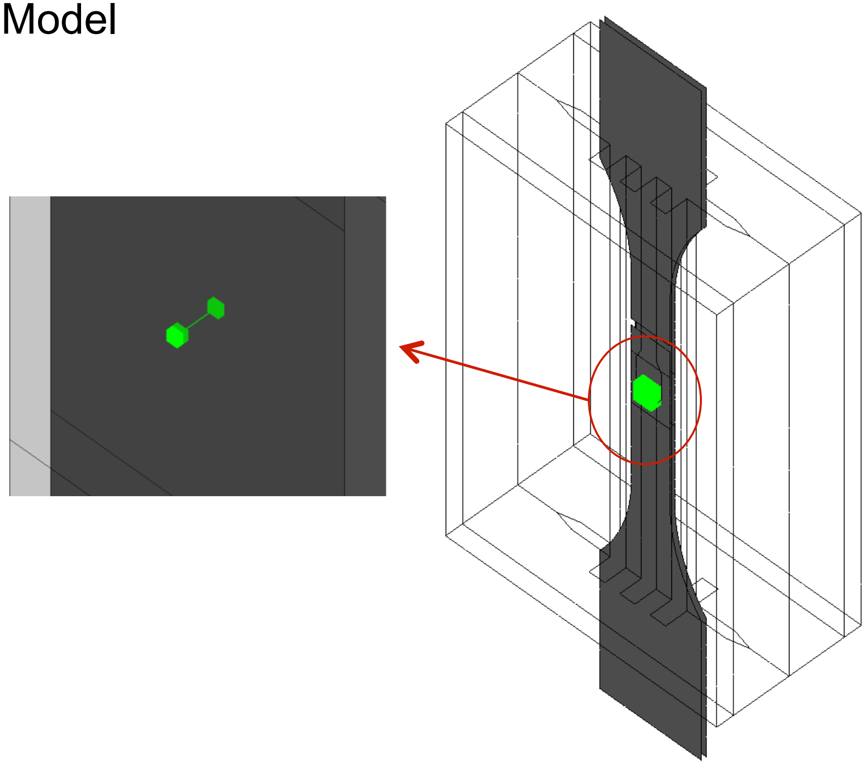


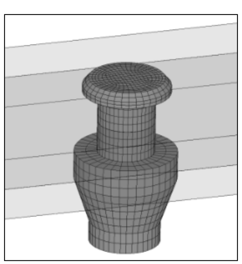
Nodes	Solid Elements	Min Elem Size
28766	21980	0.206 mm

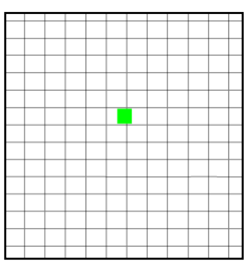
Modeling Fastener Joints – Simplified Model

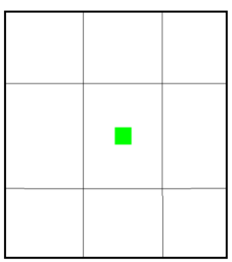
- Shell element model
- Mesh Independent Spotweld Beam Bolt Model

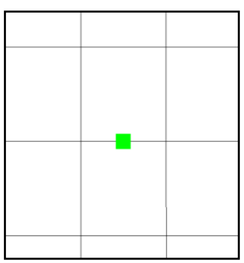


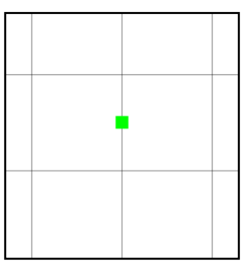


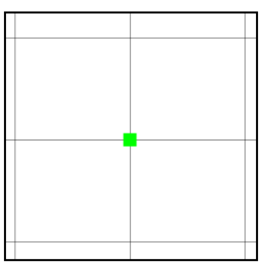

Solid


Config 2


Config 2A

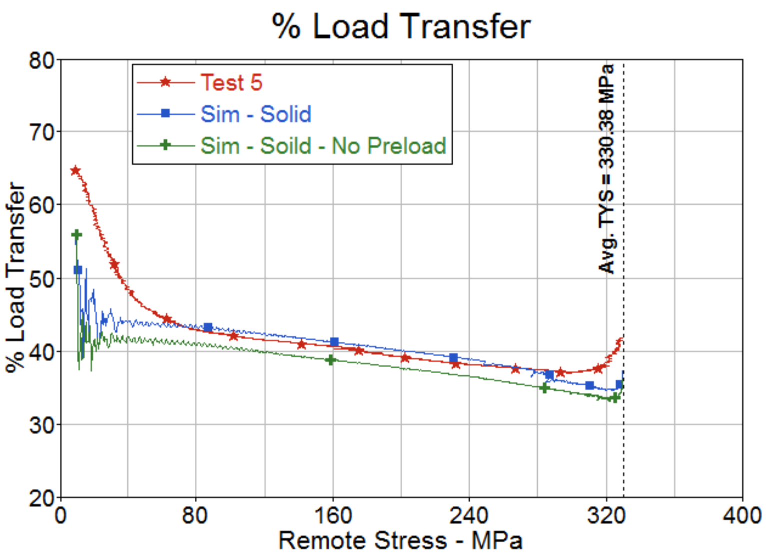

Config 2B

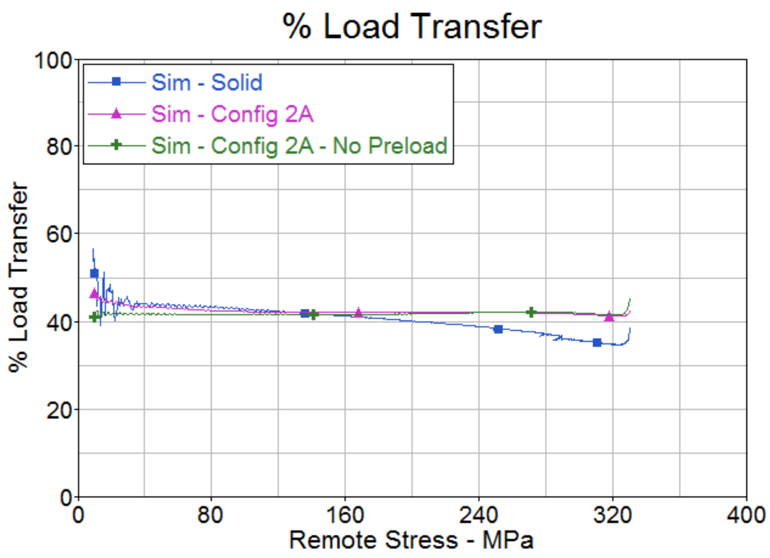

Config 2C


Config 2D

Modeling Fastener Joints – Effect of Preload

- Effect of preload on the Load Transfer Results
- Preload application method in LS DYNA
  - Solid Bolt Model - *INITIAL_STRESS_SECTION
  - Beam Bolt Model - *INITIAL_AXIAL_FORCE_BEAM





For Solid Model With No Preload the following was observed

- Approx. 2.5% Drop in Load Transfer
- Computational Cost Saving – 0%

For Beam Model With No Preload the following was observed

- Approx. 0% Drop in Load Transfer
- Computational Cost Saving – 38.5%

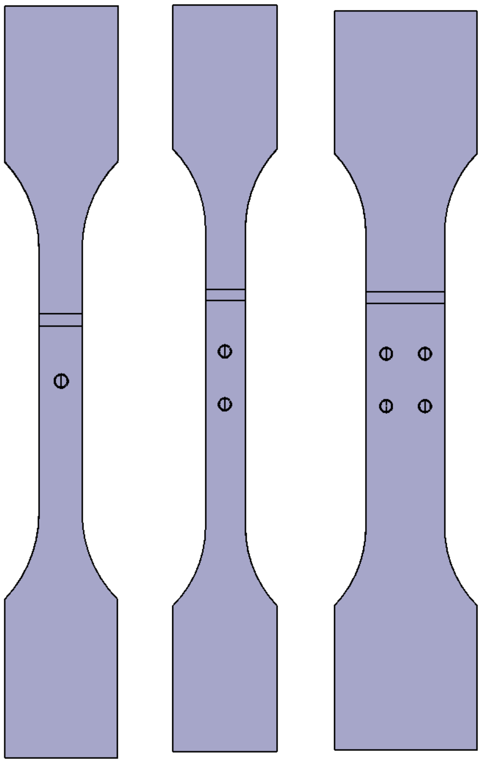
Modeling Fastener Joints – Observations

- Solid Model
  - Shows good correlation to Test Data
- Simplified Techniques
  - Rigid Body Element (RBE) – Load Transfer shows good correlation to Solid Model
  - Mesh Independent Spotweld Beam – Some configurations show good correlation of Load transfer to Solid Model while others deviate. The location of the beam model with respect to element is difficult to control in large models where parts are meshed independently
  - Mesh Independent Spotweld Beam with Patch - Some configurations show good correlation of Load transfer to Solid Model while others deviate
  - RBE with No Hole – Load transfer for all configurations do not correlate well with Solid Model
  - Note that although the load transfer may agree with the solid model, for some of the simplified techniques the absence of fastener hole means that Stress Concentrations around hole are not present. This alters the stress distribution and profile of the joint and will also affect the failure mode
  - It was also noted that Simplified techniques failed at different locations (not necessarily in the vicinity of the hole) and at a later time (since no hole allows more load to be transferred)
- Preload
  - Solid Model – Shows 2.5% Drop in load transfer with no preload
  - Beam Model – Shows no drop in load transfer

Ongoing and Future Work

- Coupon Level – Dynamic Material Characterization
  - Complete generation of material properties required for simulation at the ply level
  - Future work should include shear and compression; develop shear and compression test methods

- Element Level – Joint Modeling
  - Ongoing evaluation
    - Failure modes using these techniques
    - Stress profile of simplified techniques in the vicinity of joint
  - Analyze the effect of dynamic loading and the behavior of simplified techniques under such loading
    - Characterize the dynamic response of the single joint specimens
    - multiple joints specimens over representative loading rates
  - Extend work to composites joints



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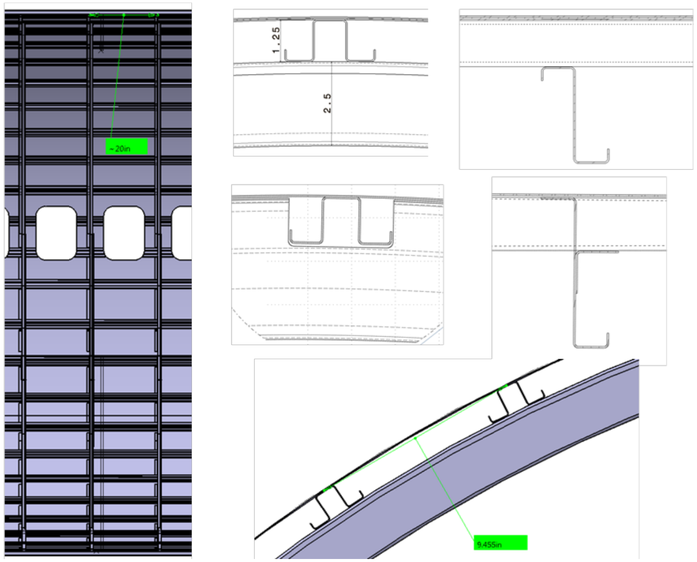
Ongoing and Future Work

- Full Scale Structural Evaluation
  - Accident Reconstruction
    - Validate the full aircraft model response with the data available from the Turkish Airlines Flight that crashed during landing to Amsterdam Schiphol Airport, Netherlands, on February 25th, 2009
  - Structural Evaluation - Ongoing
    - Modification of NIAR's generic Narrow Body Model to represent the actual geometry to be completed by July 2014
    - Areas that need to be addressed
      - Interface between the engine
      - Wing structure
      - Exit doors structure
      - Supporting structure for the landing gear system
  - Passenger Safety Evaluation
    - Meeting with FAA, EASA, and Dutch Authorities after legal issues are clear



Questions and comments are strongly encouraged.

Thank you.

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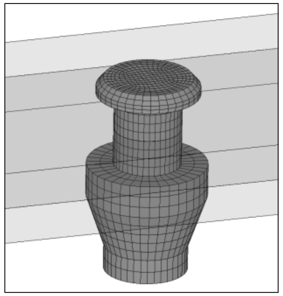
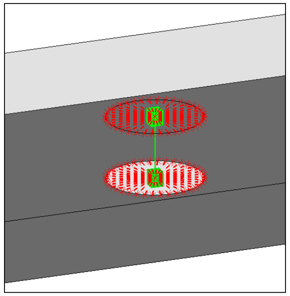
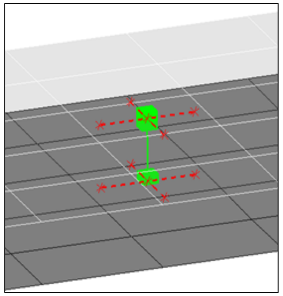
Appendix - Bolt Modeling Techniques



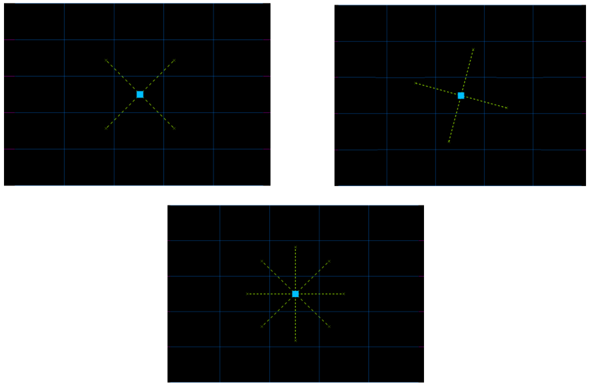
- 3D Solid Elements
- Most accurate FE representation
- Accurately captures bearing stresses and stress around fastener hole

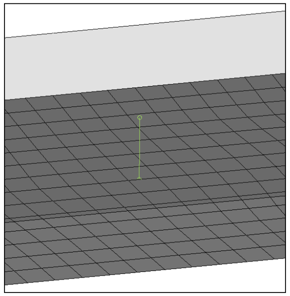


- Bolt shank modeled with beam element and connected to hole using rigid links
- Fastener hole is modeled, therefore meshing of large assemblies will be complicated
- Cannot capture bearing stress since forces are distributed circumferentially around the hole

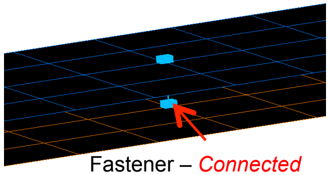


- Bolt shank modeled with beam element and rigid links used to distribute the forces
- Fastener hole not modeled
- Several variations as shown below are possible with this technique

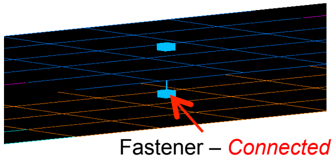




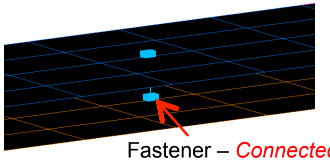
- Type 9 spotweld beam connection to represent the bolt
- Fastener hole not modeled
- Results vary due to both mesh size and location of weld relative to center of contact segment (LS DYNA Keyword Manual). Some variations shown below



Fastener – *Connected on edge of four elements*



Fastener – *Connected at Element Center*



Fastener – *Connected between 2 elements on center of edge*

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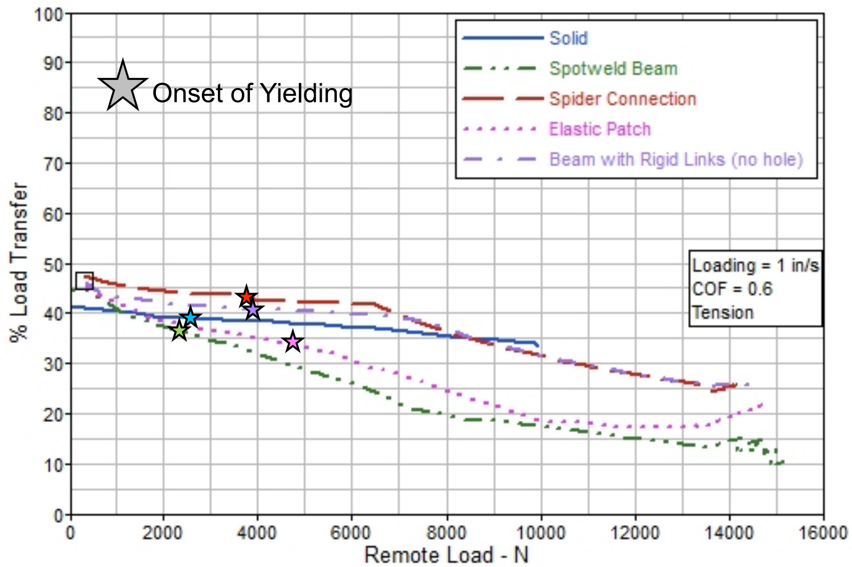
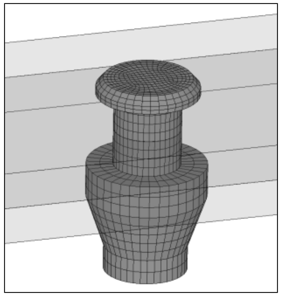
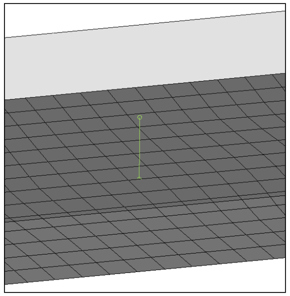
Bolt Modeling Techniques

% LOAD TRANSFER EVALUATION

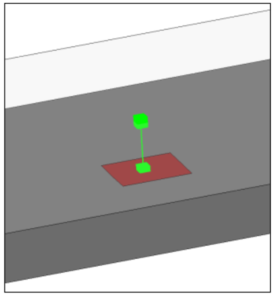




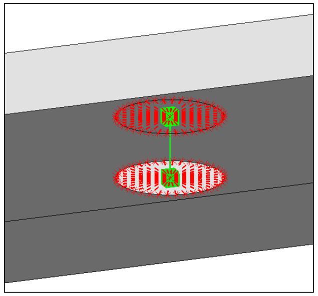
Solid



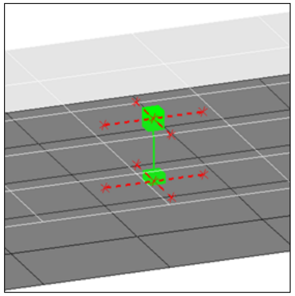
Spotweld Beam



Elastic Patch



Spider Connection



Beam with Rigid Links (no hole)