Crashworthiness Evaluation of Composite Aircraft Structures

2013 Technical Review

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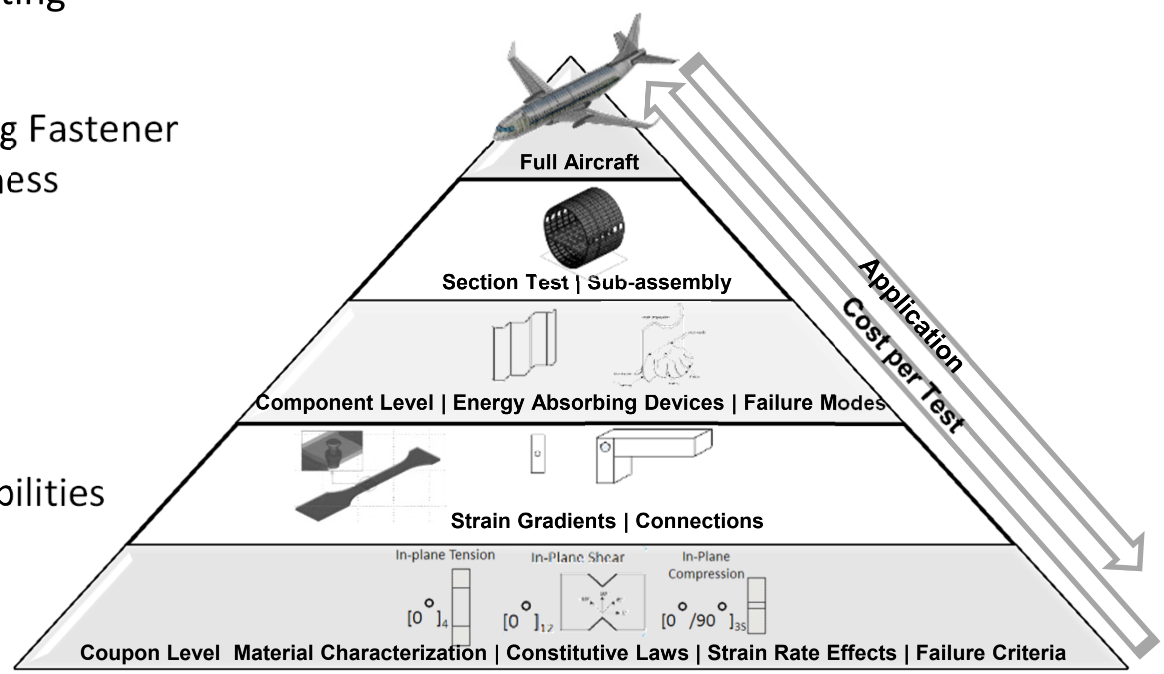
Crashworthiness of Aerospace Composite Structures

- 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 including the evaluation of survivable volume, retention of items of mass, deceleration loads experienced by occupants, and emergency egress paths. Two research programs are conducted at different levels of building block: high speed test methods are being investigated experimentally and numerically not only for material property generation but also for material model development and numerical tools used to model structural joints are being evaluated

Approach

- Building Block Approach
  - Coupon level
    - Material Characterization
    - CMH-17 Round-Robin exercise for Dynamic tensile testing
  - Element level
    - Guidelines for Modeling Fastener Joints for Crashworthiness Simulations
  - Sun-assembly level
    - Drop simulations
    - 10-ft fuselage section
    - Energy absorbing capabilities



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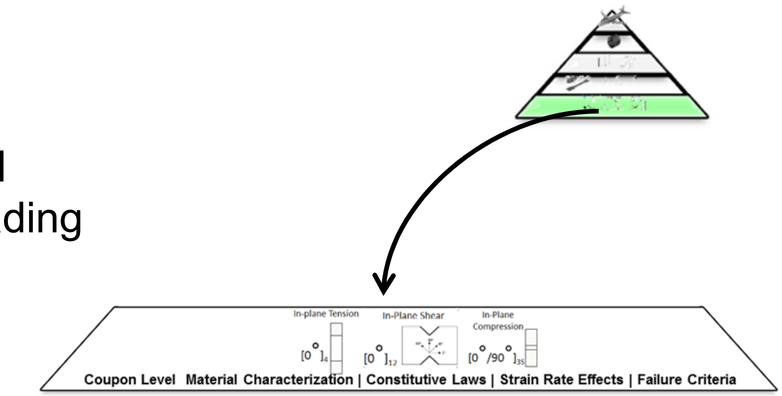
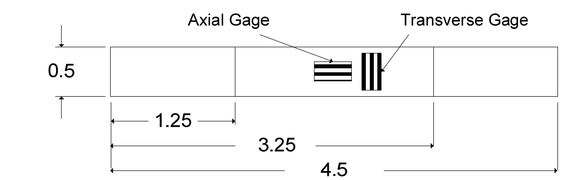
Crashworthiness of Aerospace Composite Structures

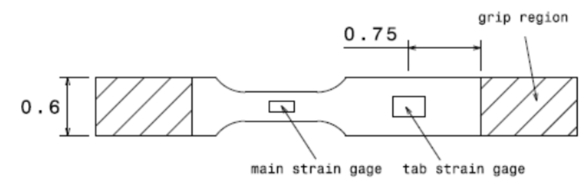
- Principal Investigators & Researchers
  - G. Olivares Ph.D, J.F. Acosta Ph.D
  - S. Keshavanarayana Ph.D
  - C. Zinzuwadia, I. Echavarri
- FAA Technical Monitor
  - Allan Abramowitz
- Other FAA Personnel Involved
  - Joseph Pelletiere Ph.D.
- Industry Participation
  - Toray America (S. Tiam)
- Research Institutes\Universities 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

- Primary Objective
  - Characterization of dynamic in-plane material properties in tension over a wide range of loading rates to support the crashworthiness building block approach
  - 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 (F6273C-07M) material at strain rates ranging between 0.01 to 250 s^{-1}





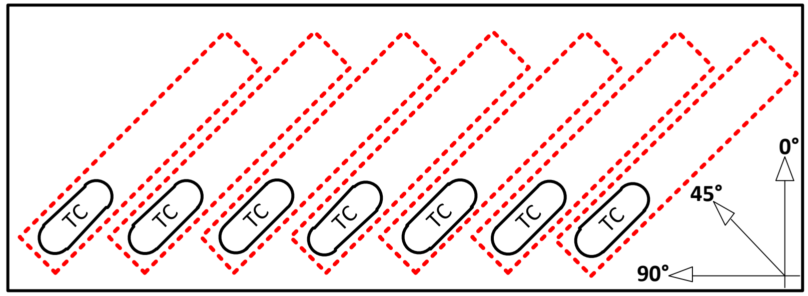


** CMH-17 Material – Fiber and matrix*

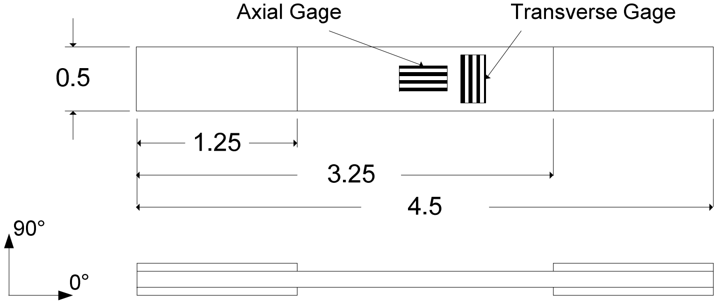
Round Robin Participating Labs

- 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)
  - DLR (A. Johnson, M. David)
  - NIAR/WSU
  - Ohio State Uni. (A. Gilat)
  - Oak Ridge National Laboratory (Y. Wang, D. Erdman III, M. Starbuck)

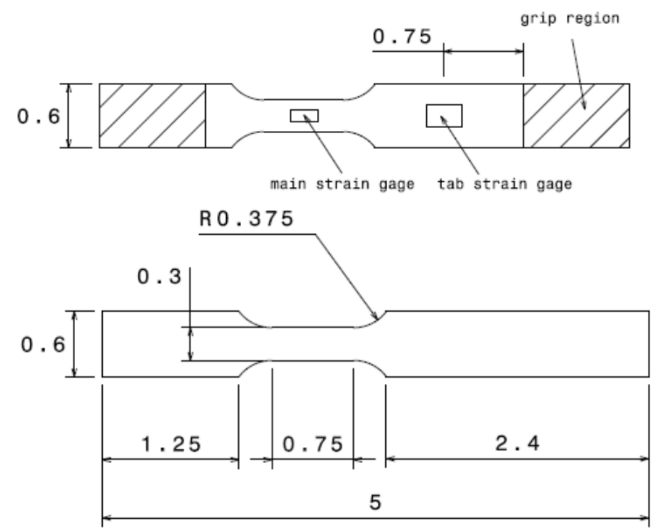
Specimen Preparation



- Composite Specimens
  - Tension testing coupon per ASTM D 3039, but accommodated to high strain rate testing
  - Nominal dimensions**
    - L x W x t = 4.5 in x 0.5 in x t



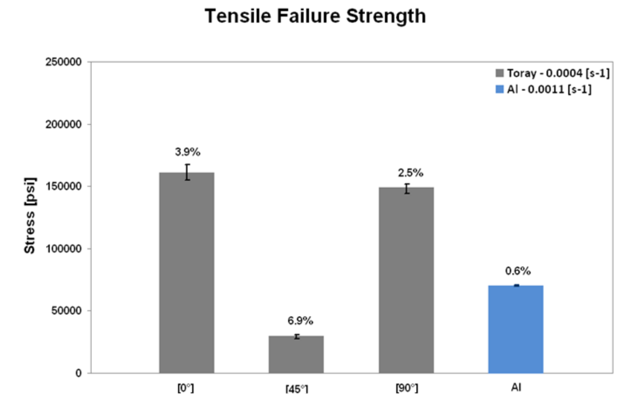
- Aluminum Specimens*
  - Tension testing coupon per ASTM E 8, but accommodated to high strain rate testing
  - Nominal dimensions**
    - L x W x t = 5 in x 0.6 in x 0.09 in

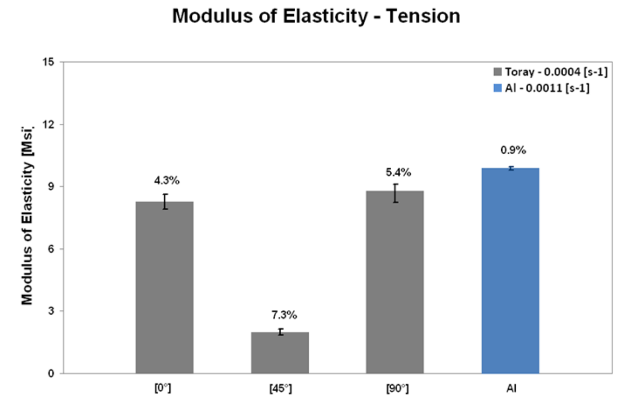


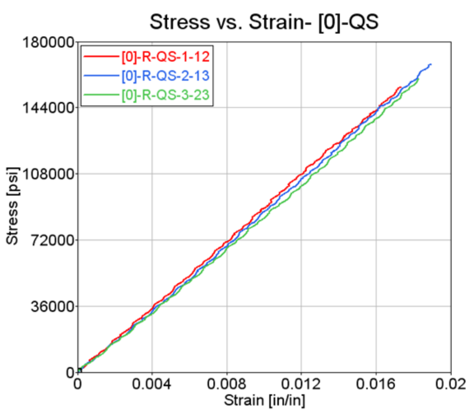
* *Rusinek, A. et al, "Dynamic Behavior of High-strength Sheet Steel in Dynamic Tension: Exp. & Num. Analysis," J. Strain Analysis, 2008.*
** *Dimensions [in]*

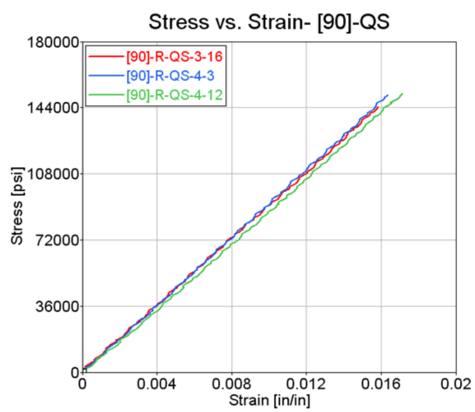
Quasi-static Characterization

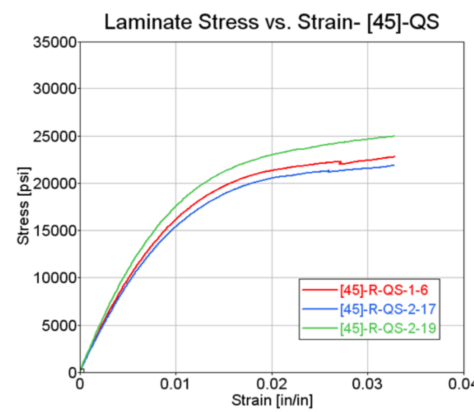
- Test Method – in-plane tension
  - (ASTM D 3039 and ASTM E 8)
- Load Frame – 22 kip Servo-hydraulic MTS
- Test Rate – quasi-static (0.05 in/min)
- Load Measurement – strain gage based load cell (5.5 kip)
- Strain Measurement – strain gage
  – signal conditioner Vishay 2210 (1-5 V)
- Baseline for Strain Rate Effect Evaluation
- Coefficient of Variation – based on three (3) samples for reference only

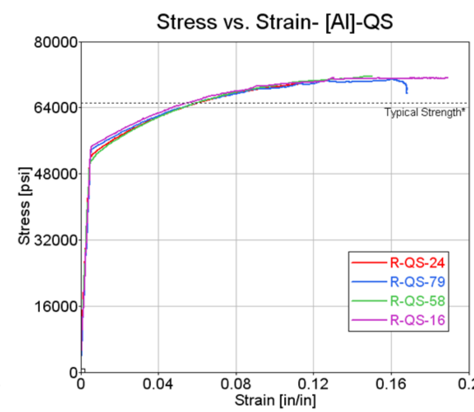












Dynamic Characterization

- Same detailed test procedure provided to all laboratories
- Four (4) stroke rates
- Three (3) composite material orientations
- Limited test specimens (3) per test condition

Material System	Nominal Strain rate (1/s)			
	0.01	1	100	250
2024-T3 Aluminum	×3	×3	×3	×3
TORAY T700/2510 plain weave/epoxy (F6273C-07M)				
$[0]_4$	×3	×3	×3	×3
$[90]_4$	×3	×3	×3	×3
$[\pm45]_4$	×3	×3	×3	×3

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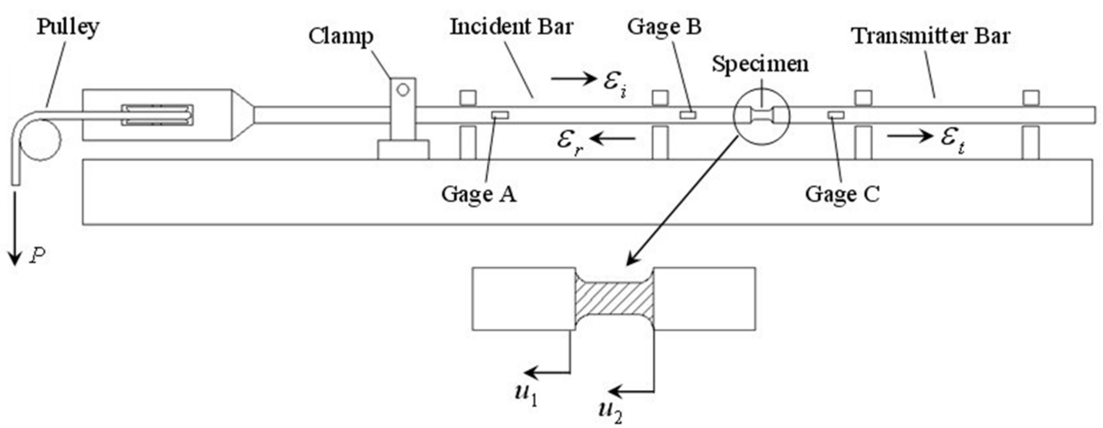
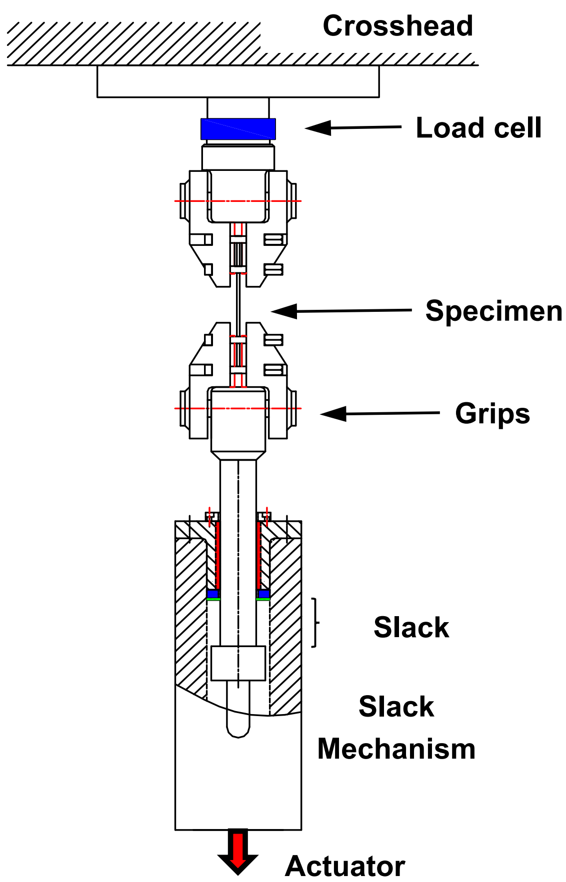
Test Apparatus

- Servo-hydraulic Machine
  - Slack inducer
  - Accelerate actuator prior specimen loading
- Tensile Split Hopkinson Pressure Bar



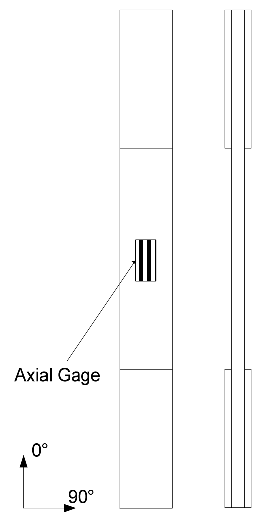


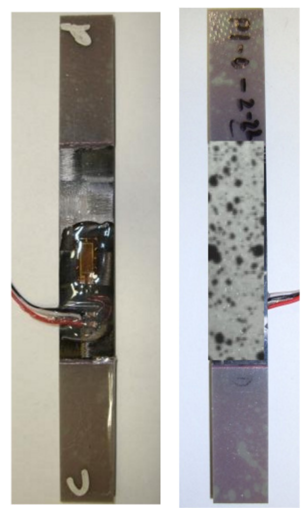
Force and Strain Measurements

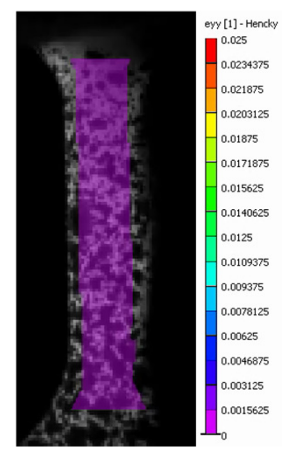
- **Force**
  - Participating labs use their own Load sensors

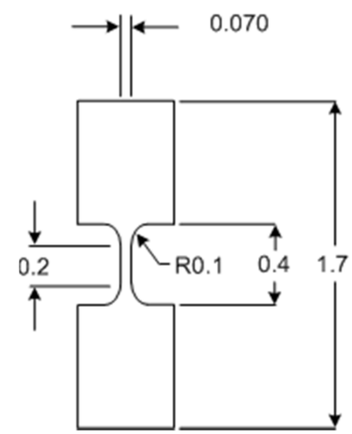
Lab	Load Cell	Capacity (kips)	Natural Frequency (kHz)
A	PCB Piezotronics 206C	± 10.0[A]	~ 40*
B	Kistler 9041A	± 20.2	~ 62*
C	Kistler 9361B	± 13.5	~ 55*
D	Kistler 9051A	± 9.0	~ 28

- **Strain**
  - Strain gage mounted on specimen gage section
  - Photogrammetry – Lab D
    - Aramis









Dimensions [in]

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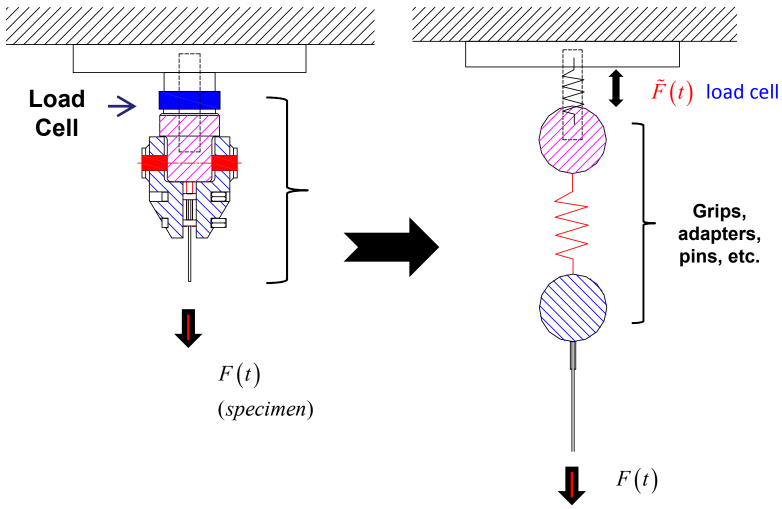
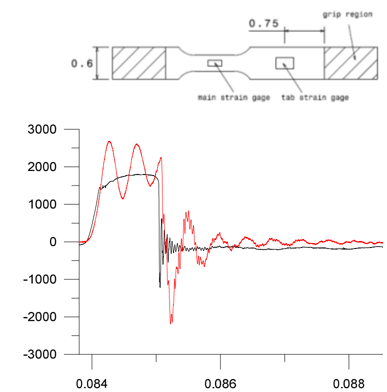
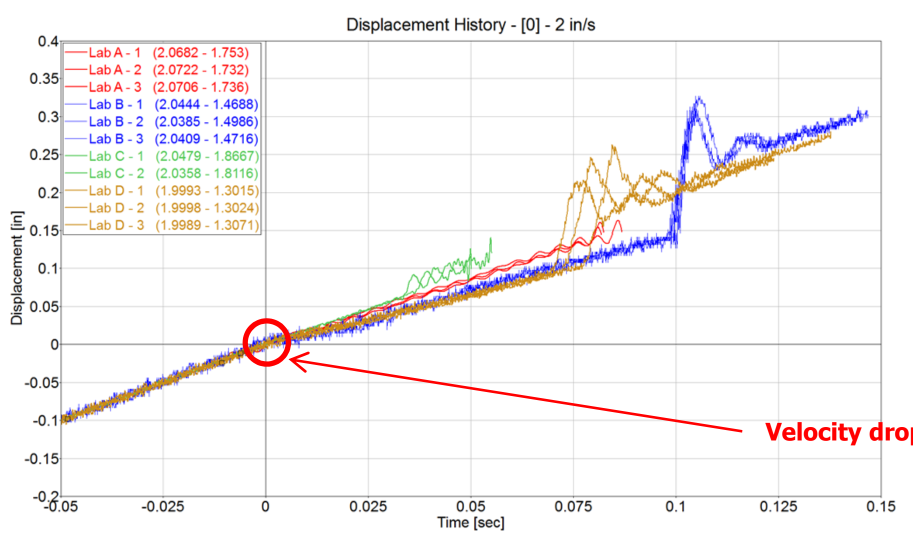
Dynamic Tension Testing Challenges

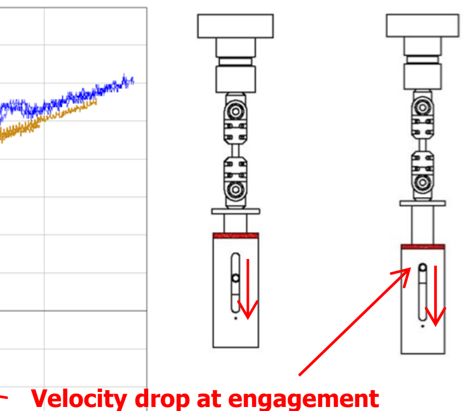
- Force signal modulation
  - Load cell characteristics
  - Presence of masses between load cell and specimen
  - Wave propagation & reflections





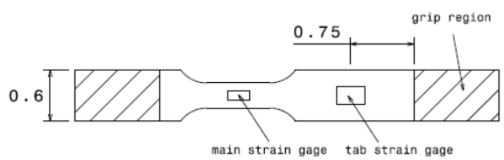
- Velocity Drop

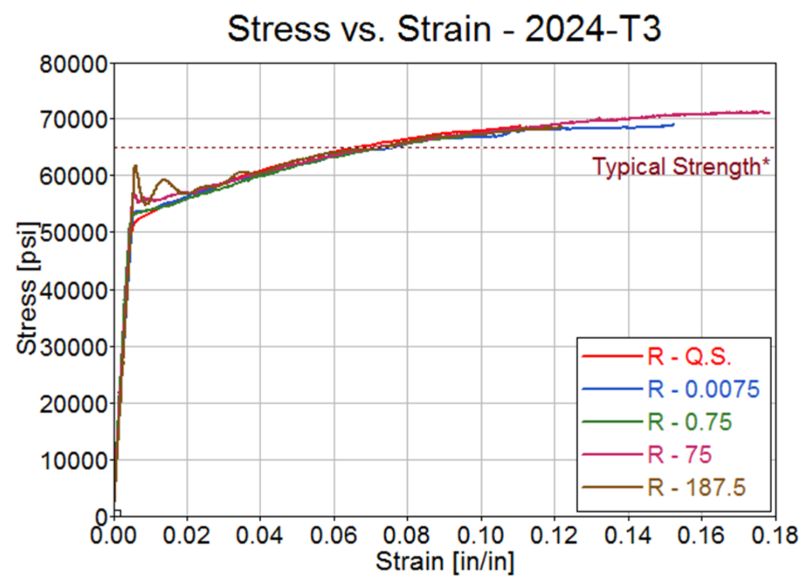


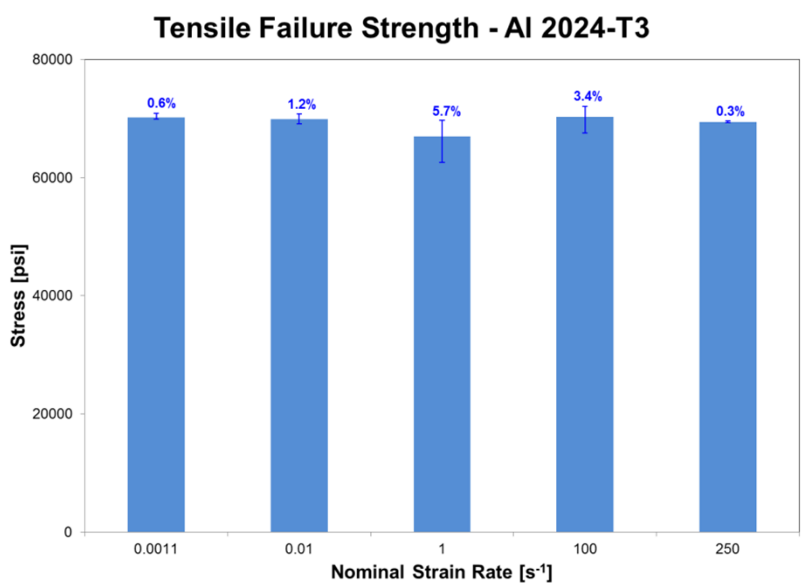


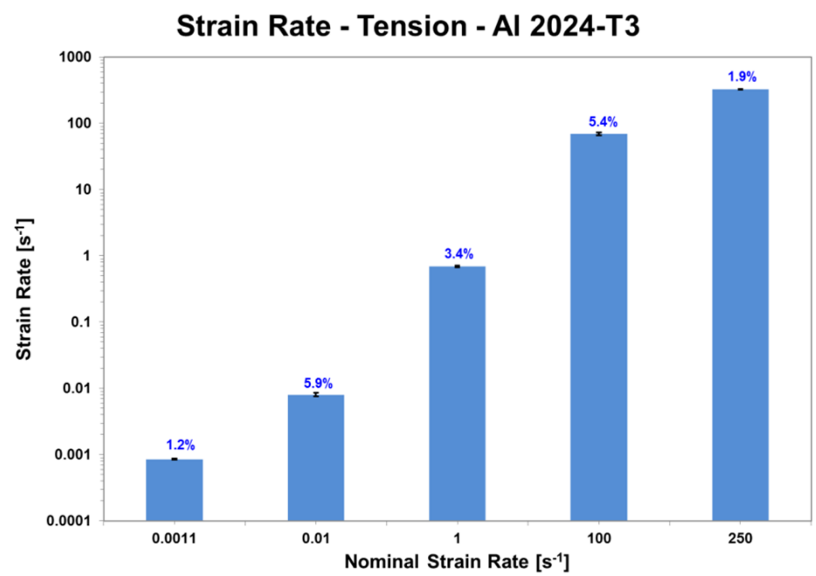
Aluminum Dynamic Characterization – Lab A

- Control material for load sensor evaluation
- Tab strain gage used for load measurement
- Coefficient of Variation based on three (3) samples



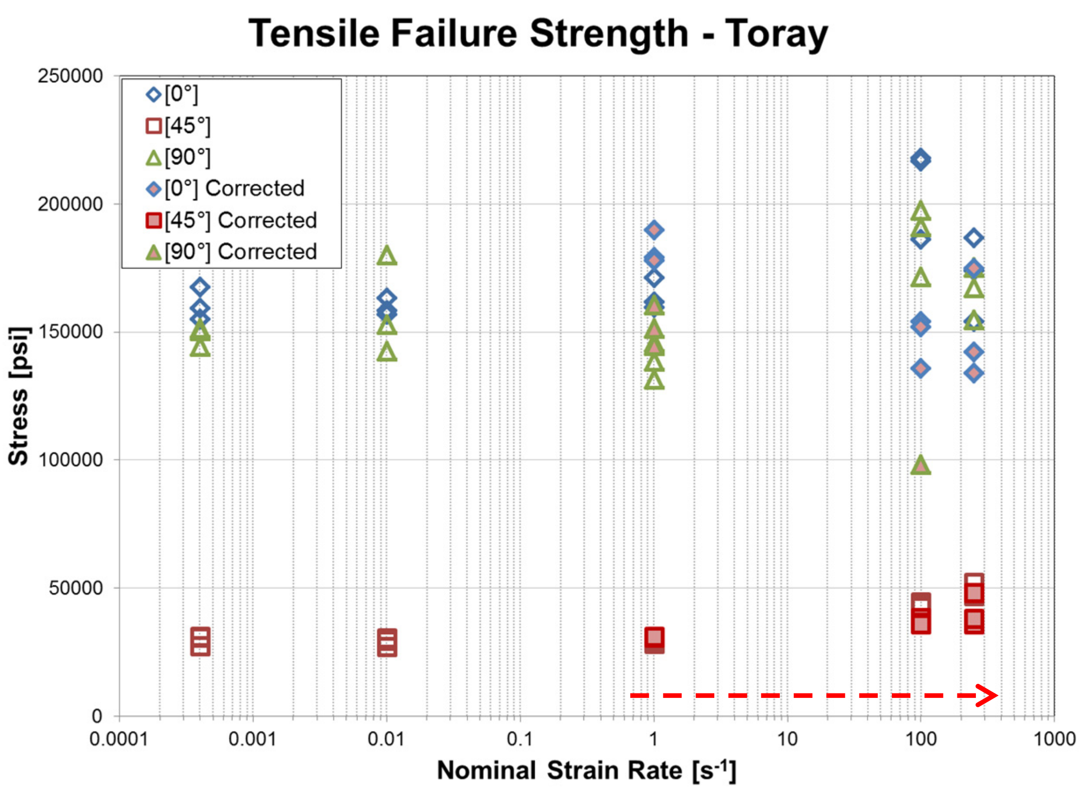






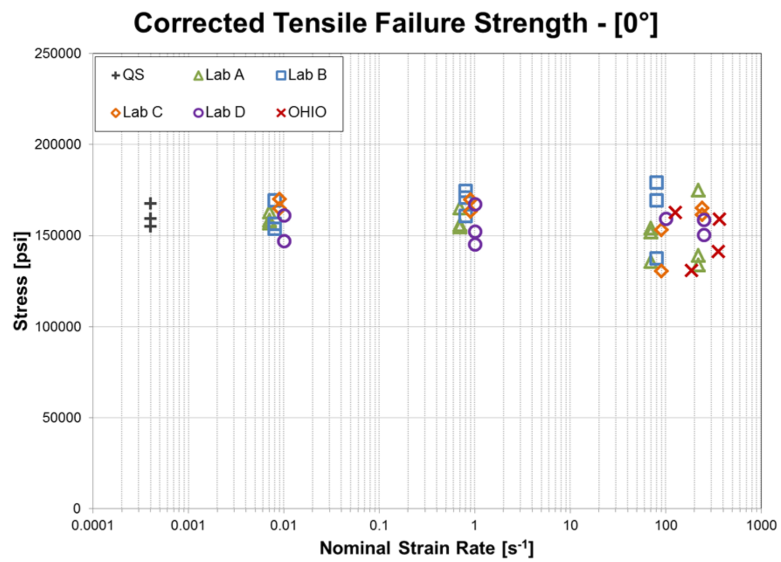
Composite Dynamic Characterization – Lab A

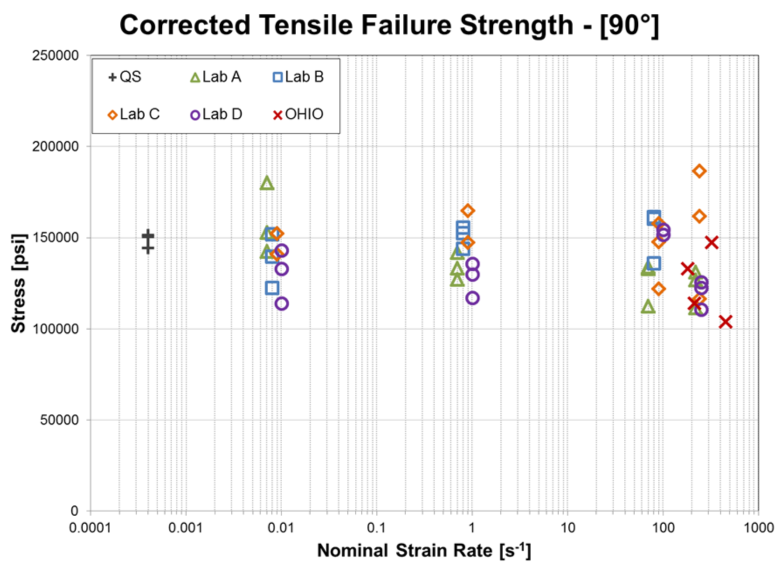
- Apparent properties are estimated based on load measurements before correction for signal modulation
- Load measurements corrected for signal modulation

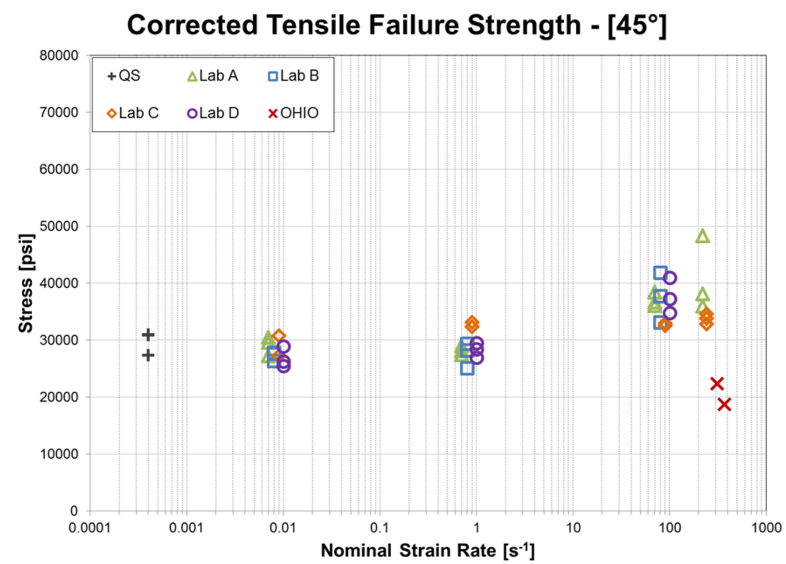


Comparison across Laboratories

- $[0°]_4$
- $[90°]_4$
- $[45°/-45°]_S$
- Load measurements corrected for signal modulation
- Address the variability associated to different laboratories generating same material properties







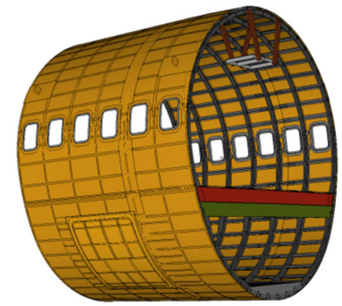
Modeling Fastener Joints for Crashworthiness Simulations

- Structural assemblies use fasteners as primary joining entities to facilitate slip resistance and load transfer

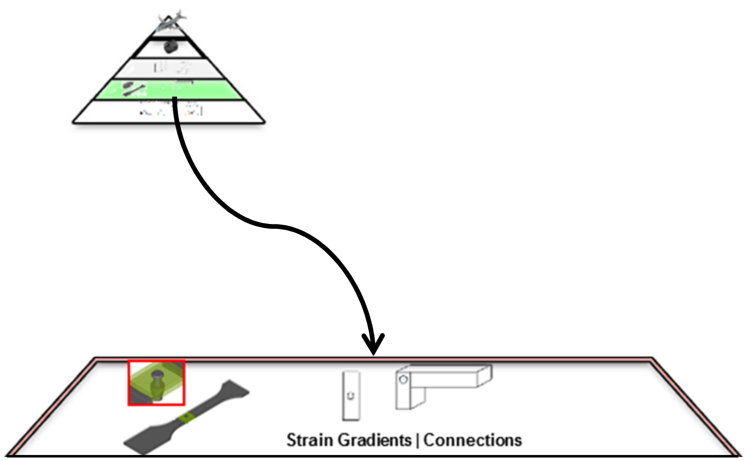
- Energy dissipated through fastener joints in the structure can be up to **43 %** of the total energy for no cargo configurations.

30 ft/s drop

FAA Test setup

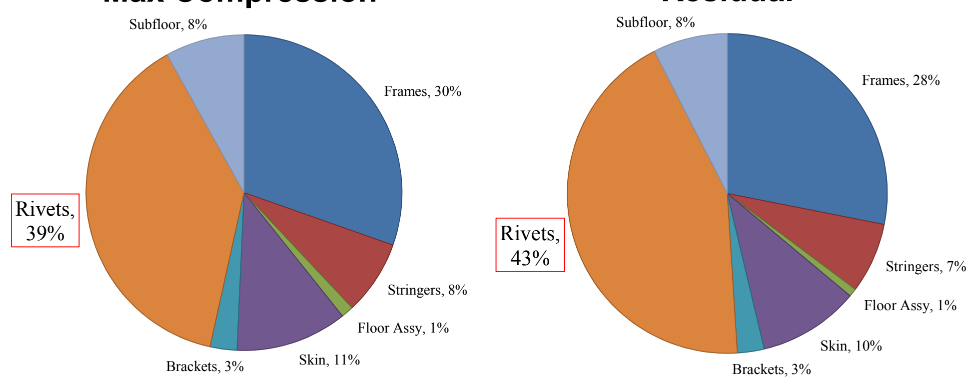


NIAR FE Model



Energy Balance

Max Compression | **Residual**



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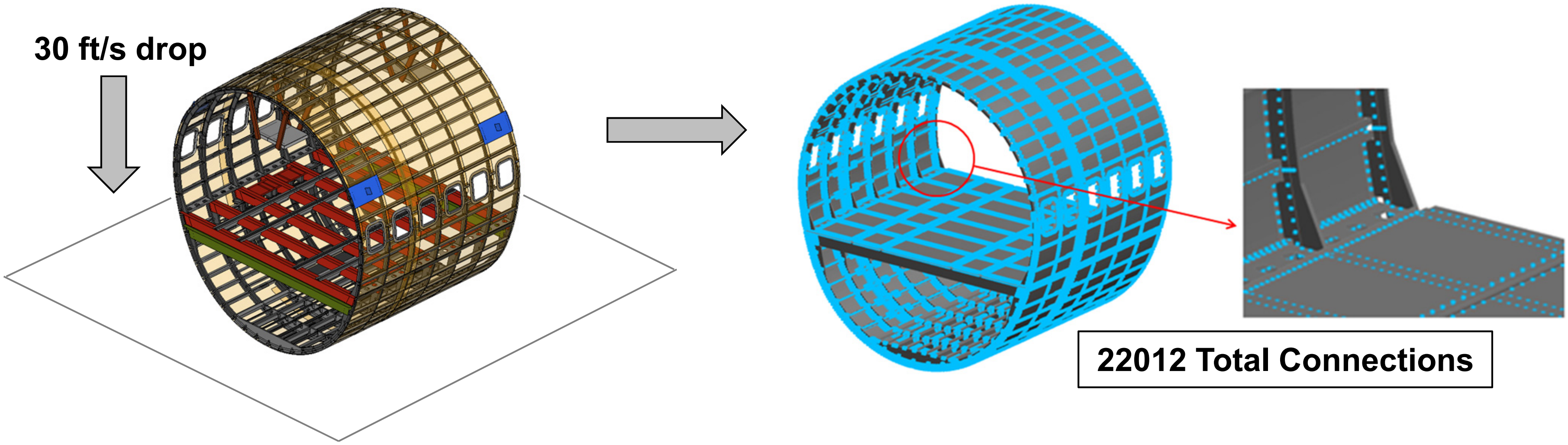
Modeling Fastener Joints for Crashworthiness Simulations



- The 10-ft Fuselage Section Model has **22012 fasteners**.
- Modeling all fasteners accurately with solid elements is not practical for computational efficiency
- Fasteners need to be **idealized** to minimize the computational effort
- Such idealizations are a necessity when dealing with simulations involving **large structures** where a compromise has to be made between studying the global responses whilst capturing localized effects
- Therefore, **Simplified FE bolt modeling techniques** need to be explored to understand its limitations and use.

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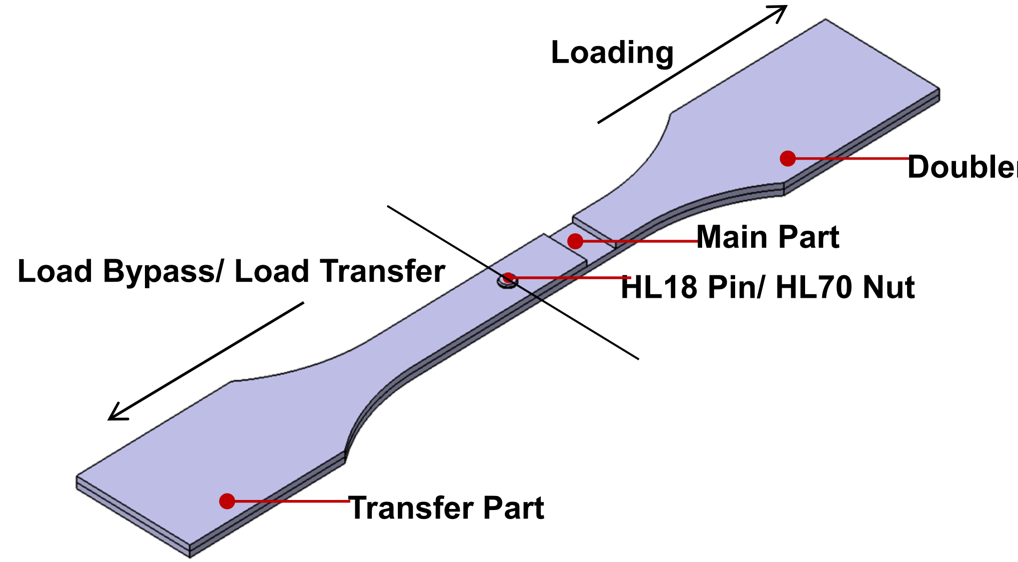
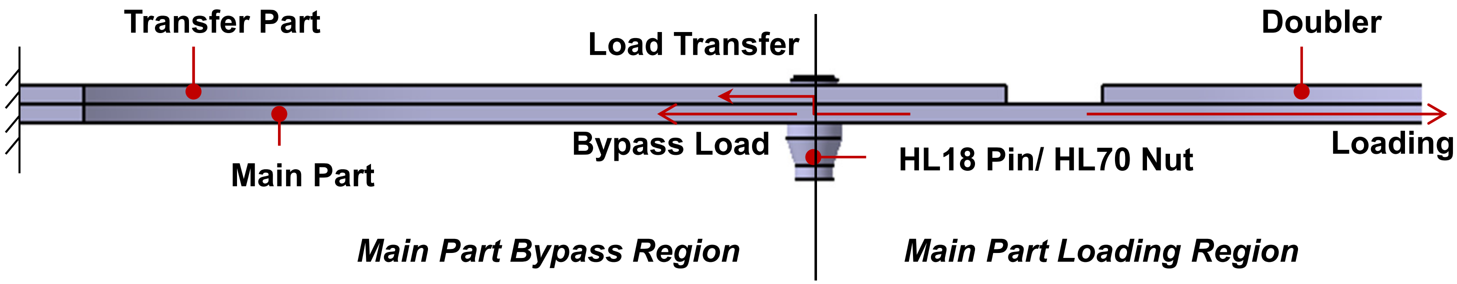
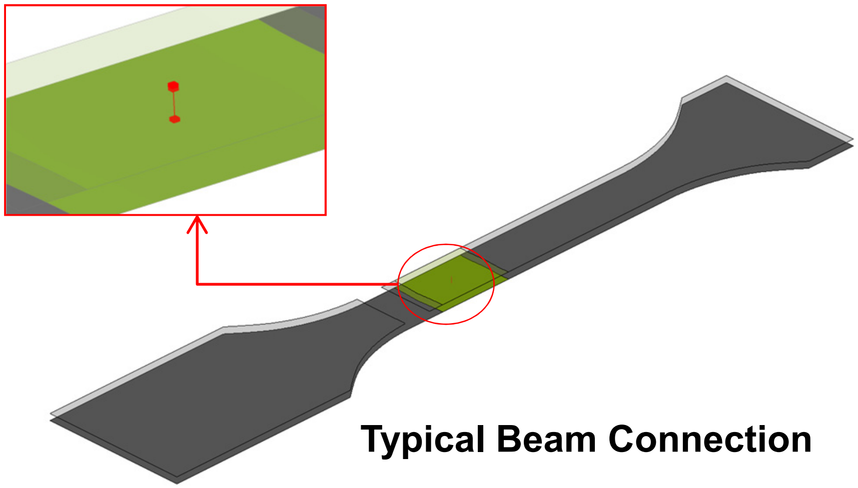
Modeling Fastener Joints for Crashworthiness Simulations

- A dog bone specimen joined with one fastener is used to understand the **load transfer mechanics**, and the effect of **friction and preload** on the load transferred
- A numerical model of the test will be generated using Solid 3D elements and a fine mesh to replicate the test results
- Different **Simplified Bolt Modeling techniques** will be subjected to the same boundary and loading conditions and compared to the test results

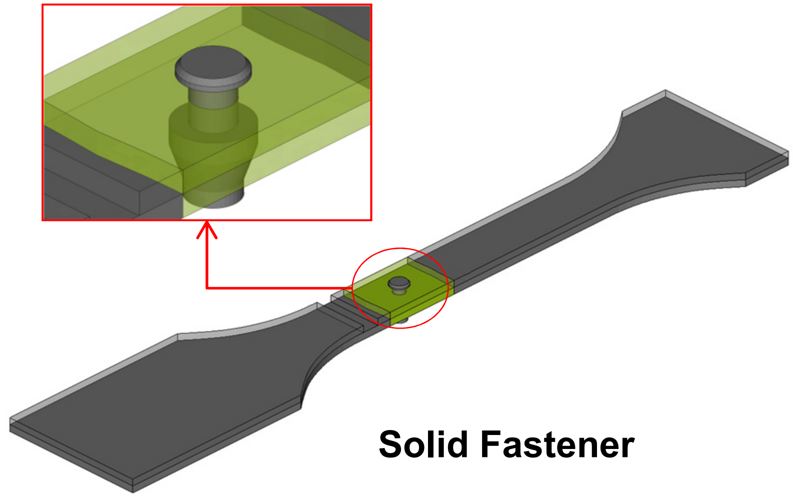




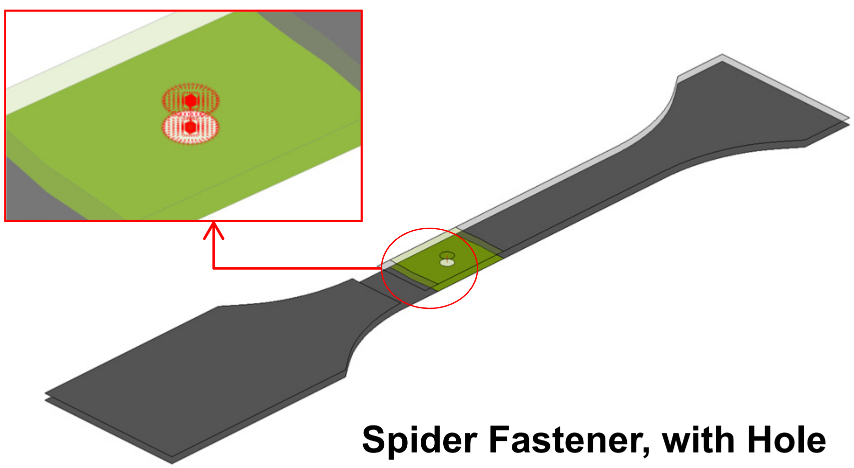
Bolt Modeling Techniques



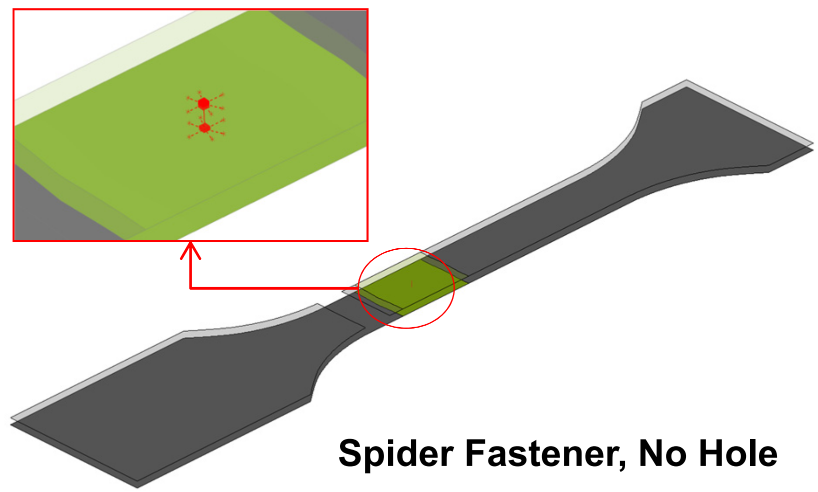
Typical Beam Connection



Solid Fastener



Spider Fastener, with Hole



Spider Fastener, No Hole

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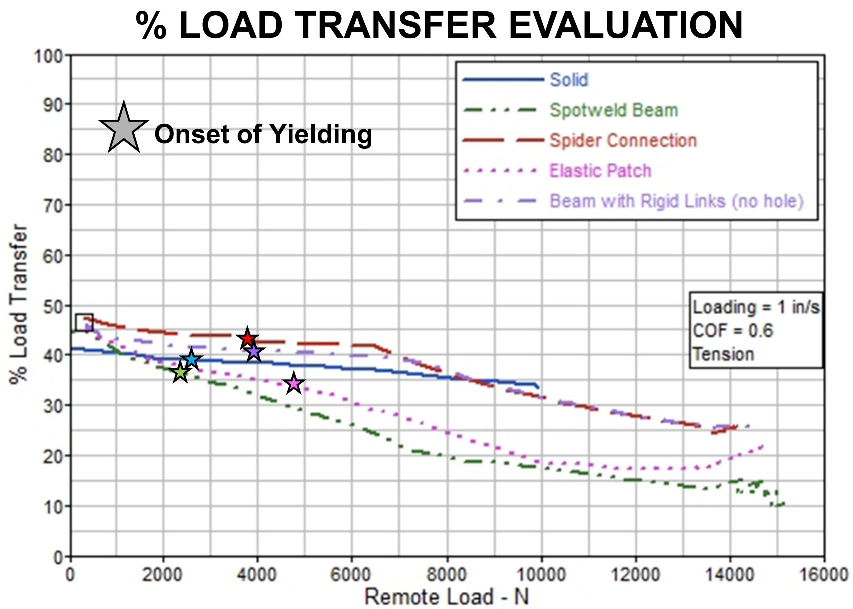
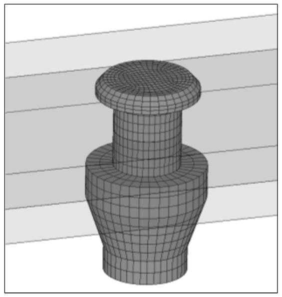
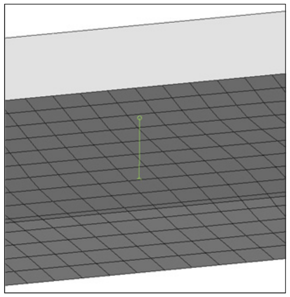
Bolt Modeling Techniques

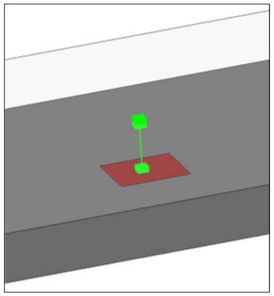




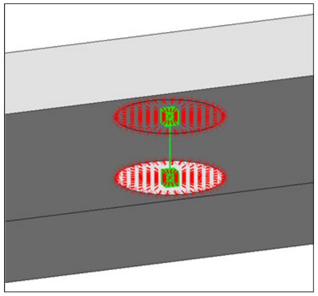
Solid



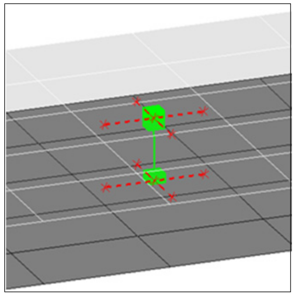
Spotweld Beam



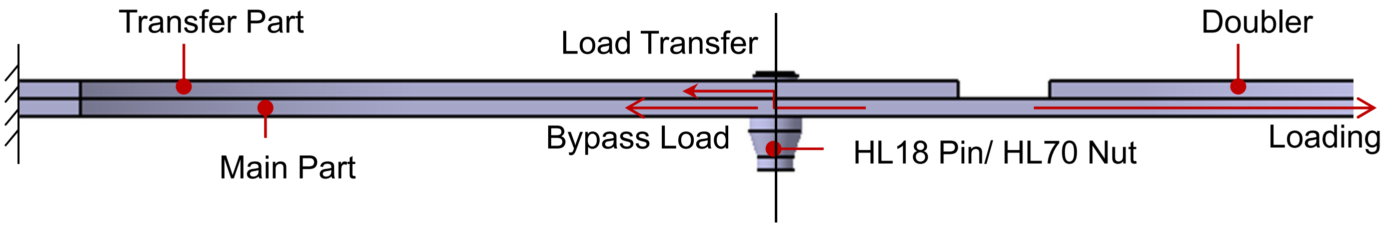
Elastic Patch

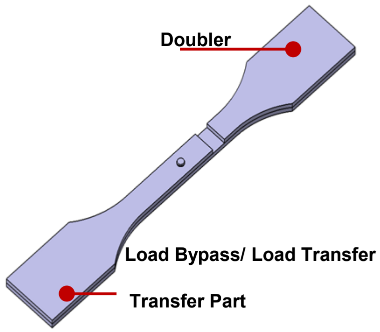


Spider Connection

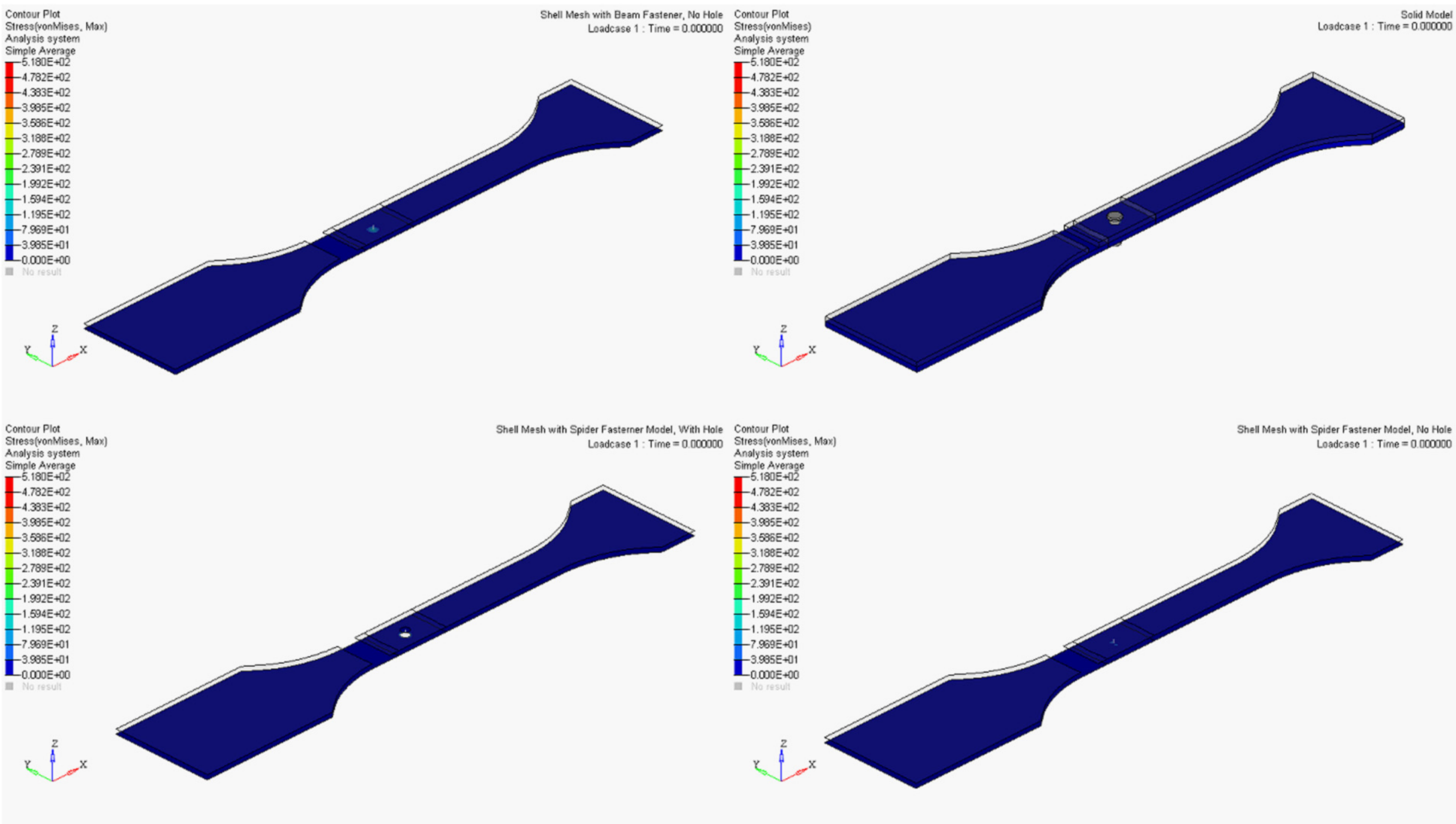


Beam with Rigid Links (no hole)





Bolt Modeling Techniques

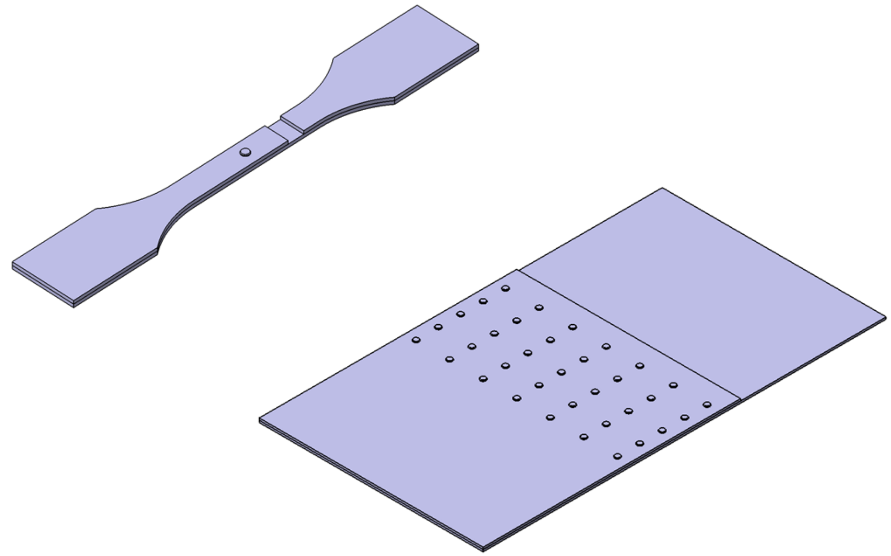


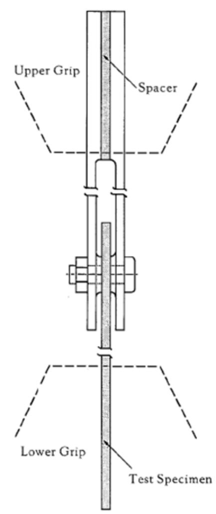
Future Work

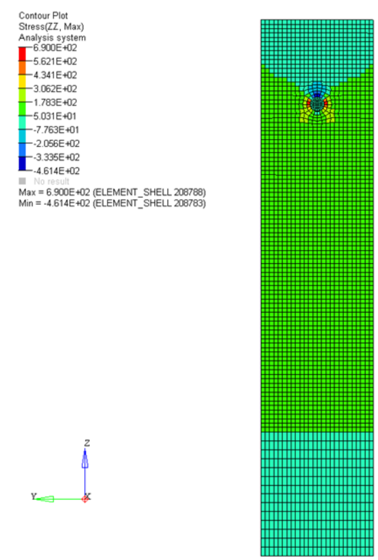
- Analyze Composite joints and joint behavior in Composite materials
  - Composite - Composite Joints
  - Hybrid Joints Metal - Composite
  - Joint types
    - Fastener joints (Preload)
    - Pin-bearing

- Evaluate differences between single fastener joints and multiple fastener joints for both metallic and composite materials

- Understand the differences and performance of simplified bolt modeling techniques when used for a single fastener joint compared to multiple fasteners.







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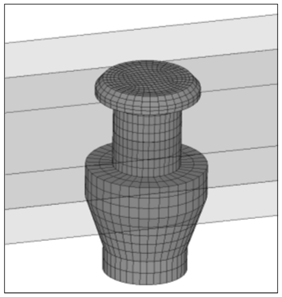
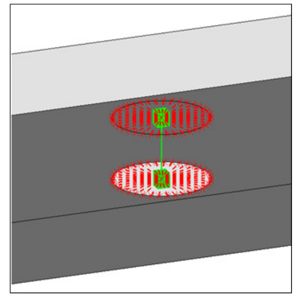
Crashworthiness Evaluation of Composite Aircraft Structures

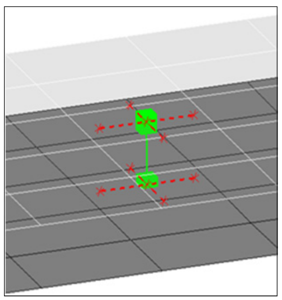
Appendix - Bolt Modeling Techniques



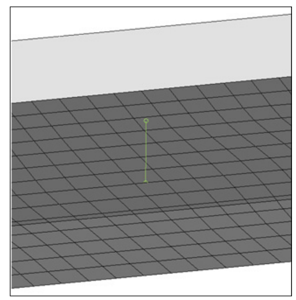
- 3D Solid Elements
- Most accurate FE representation
- Accurately captures bearing stresses and stress around fastener hole



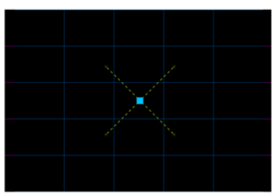
- Bolt shank modeled with beam element and connected to hole using rigid links.
- Fastener hole is modeled, therefore meshing of large assemblies will be complicated
- Cannot capture bearing stress since forces are distributed circumferentially around the hole

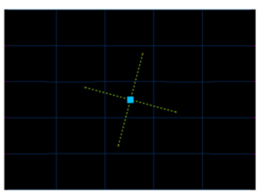


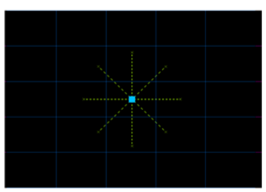
- Bolt Shank modeled with beam element and rigid links used to distribute the forces
- Fastener hole not modeled
- Several variations as shown below are possible with this technique.

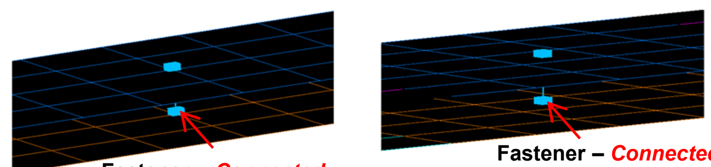


- Type 9 spotweld beam connection to represent the bolt
- Fastener hole not modeled
- Results vary due to both mesh size and location of weld relative to center of contact segment (LS DYNA Keyword Manual). Some variations shown below



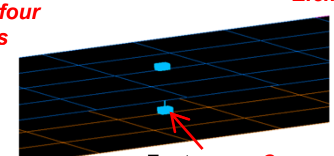






Fastener – ***Connected on edge of four elements***

Fastener – ***Connected at Element Center***



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

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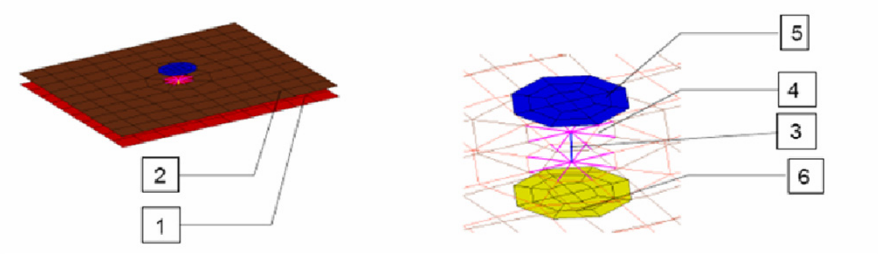
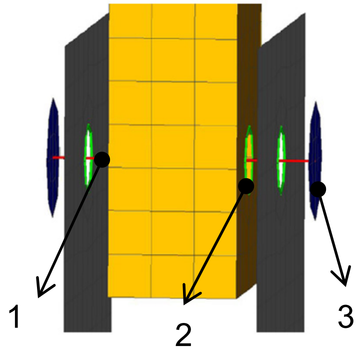
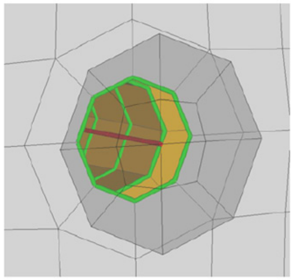


Component	Material	Element Type/ Thickness
1	MAT 24	SHELL, ELFORM 16, 5mm
2		SHELL, ELFORM 16, 5mm
3	MAT 100	BEAM, ELFORM 9, 12mm
4	SDMAT6	CONTACT SPRING
5	MAT20 (CON1=0 CON2=7)	SHELL, ELFORM 2, 5mm
6	MAT20 (CON1=0 CON2=7)	SHELL, ELFORM 2, 5mm

- **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

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