A Modeling approach for Crashworthiness Evaluation of an Aircraft Fuselage Section with Conformable Auxiliary Fuel Tank

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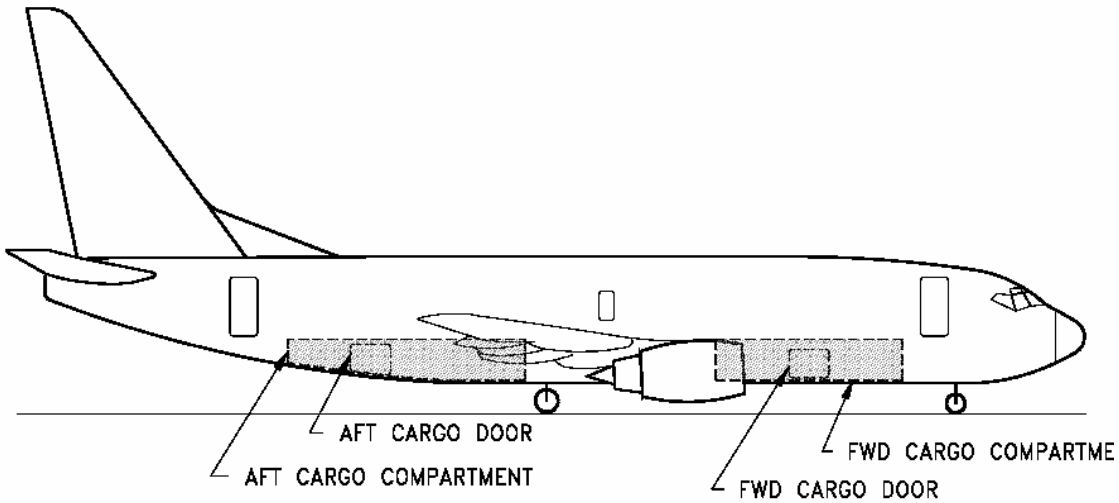
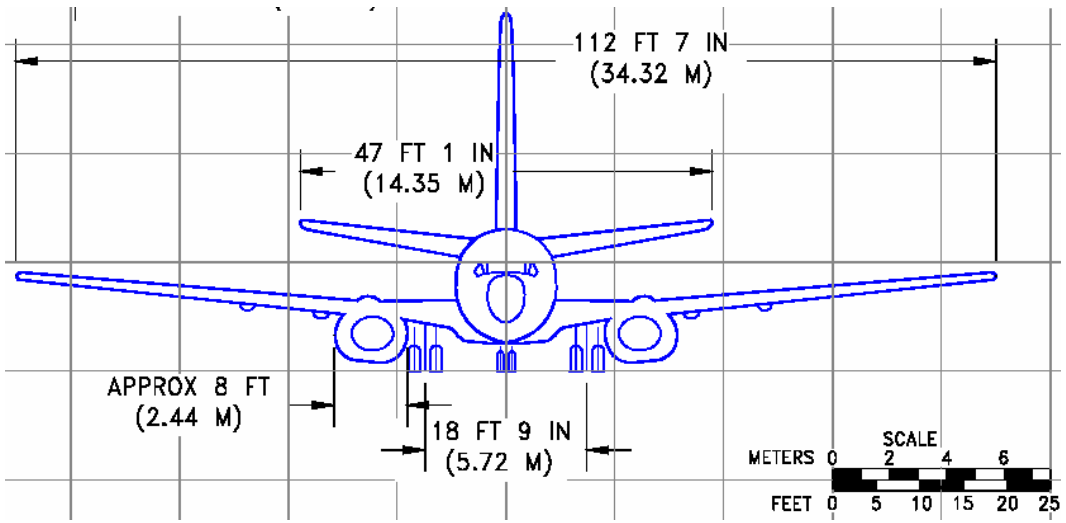
Objectives

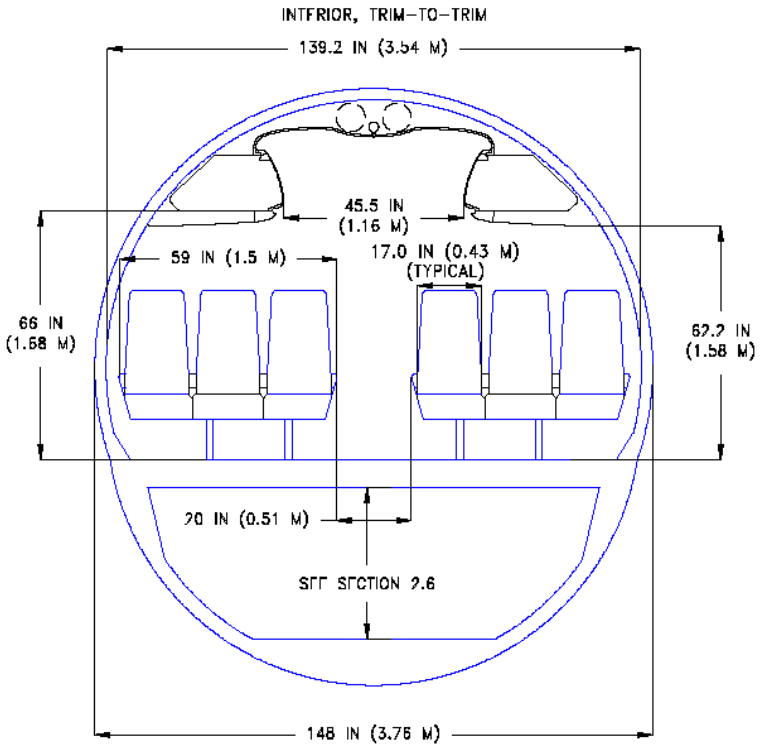
- Develop a detailed nonlinear finite element (FE) model of an aircraft fuselage section subjected to a drop test
- Study the effect of the conformable auxiliary fuel tank
- Study the effect of the cargo door
- Demonstrate the potential of analysis tools and computer simulations
- Conduct scaled model test and utilize scaling laws

Experimental Program (FAATC)

Boeing-737-200

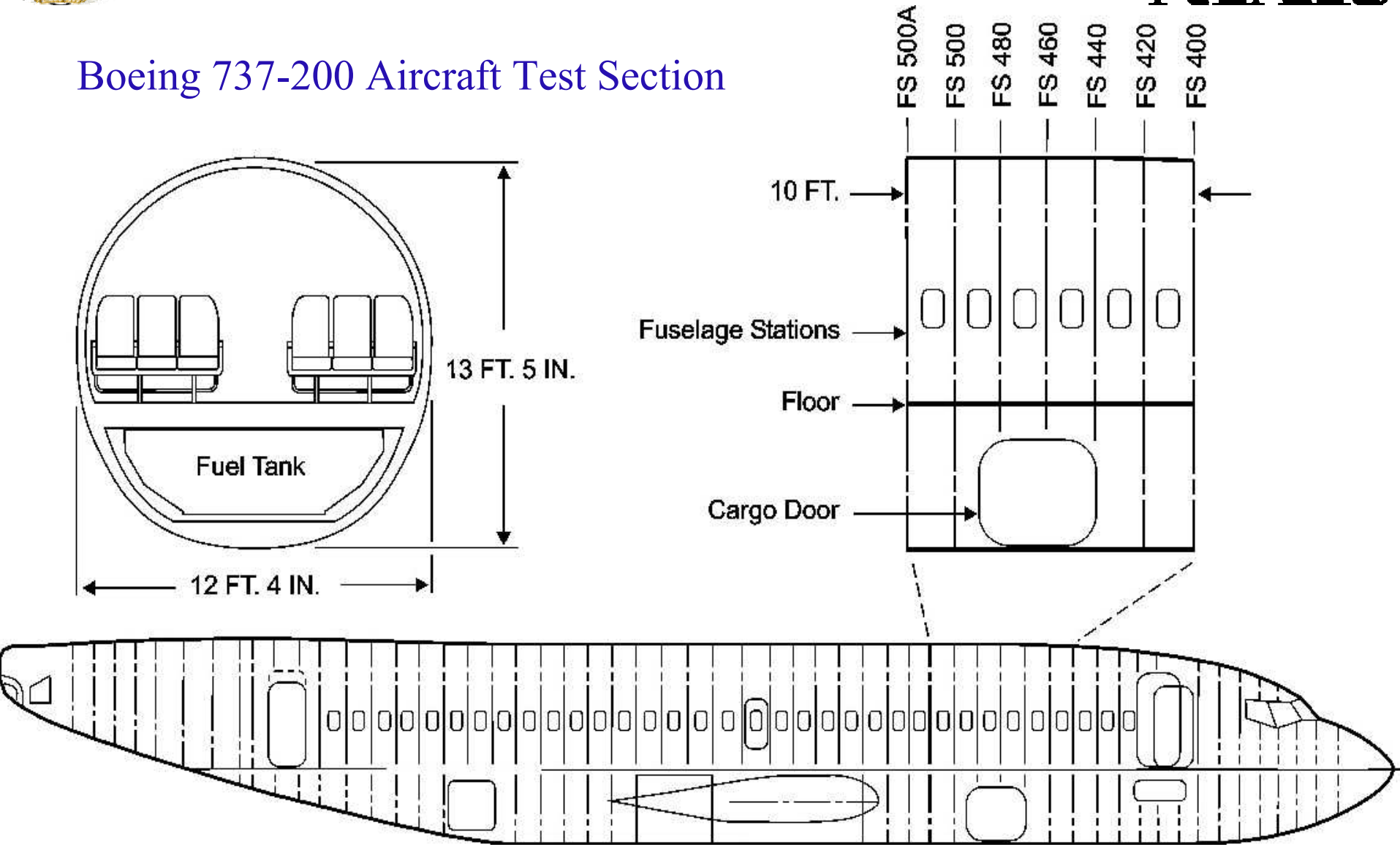




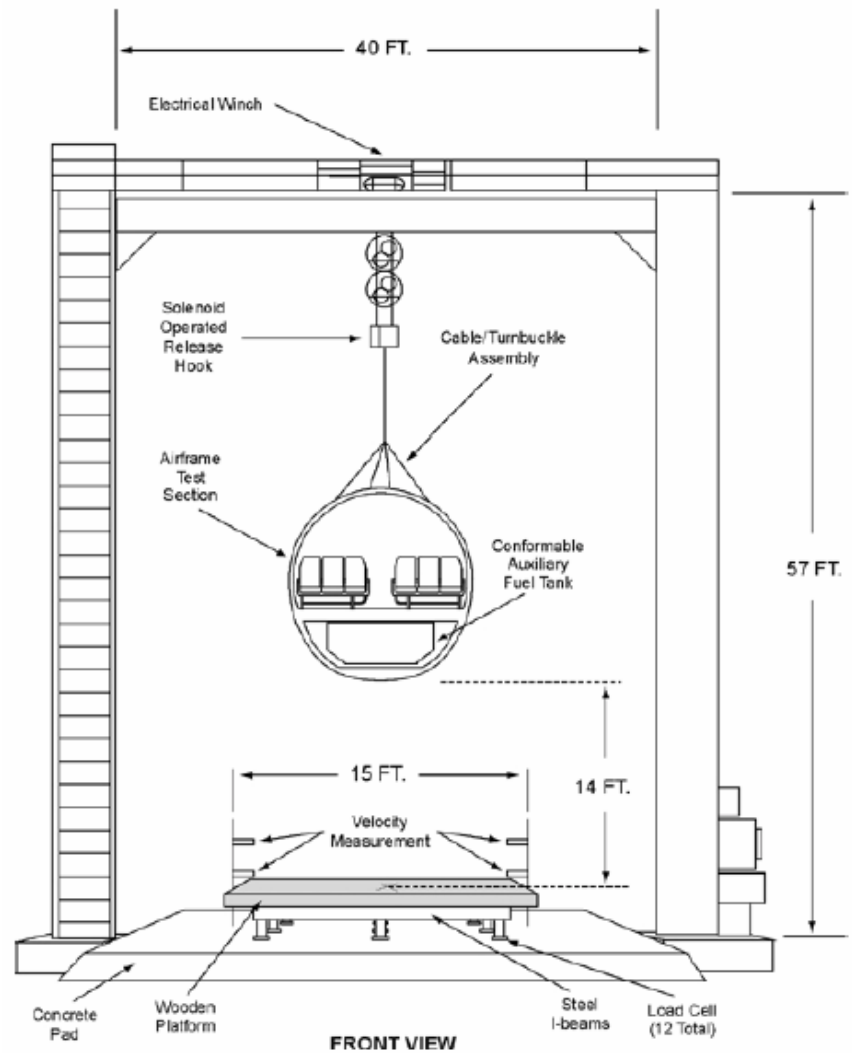


Airframe Test Section

Boeing 737-200 Aircraft Test Section

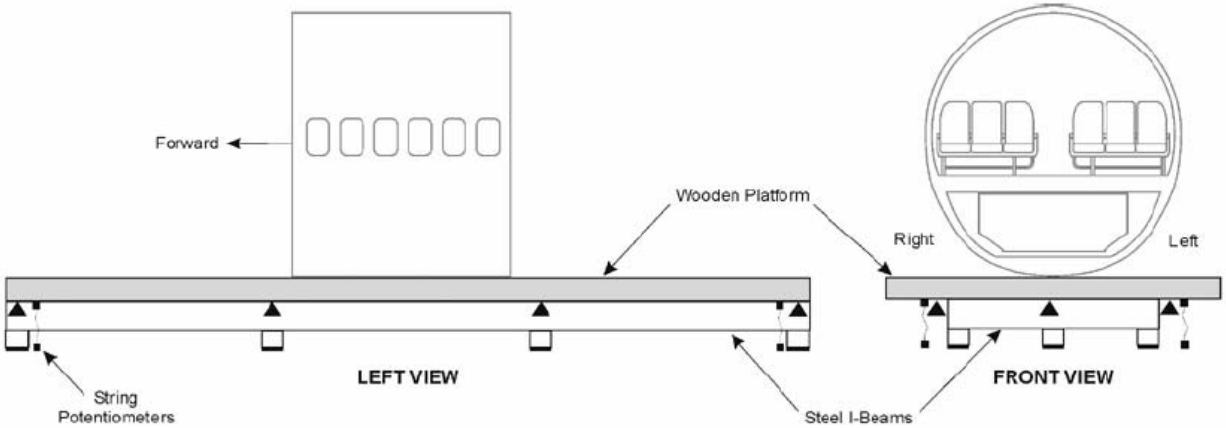


Dynamic Drop Test Facility (Hughes Technical Center)

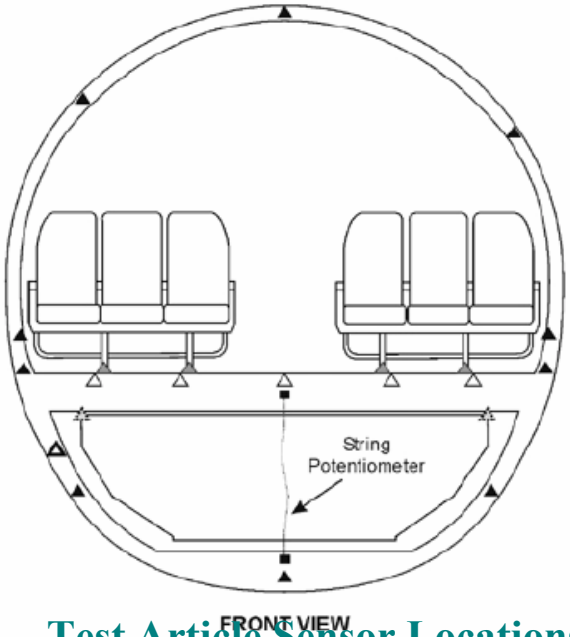


Dynamic Drop Test Facility Diagram

Drop Test Platform



Drop Test Platform Frontal and Side Views



Test Article Sensor Locations

Test Conditions:

Height=14ft
Velocity=30ft/s
Acceleration=25g (FAA Part 25)
Total Weight=8,780lb
Passengers=6triple occupant (170lb.each)
Cargo=3,740lb Conformable Auxiliary fuel tank

Test Article Weight

Item	weight (lb)	Quantity	Total (lb)
ATD	170	6	1020
Mannequin	161	12	1932
Cameras	22	4	88
UOP Seat	80	3	240
Weber Aircraft Seat	68	3	204
Fuel Tank (empty)	370	1	370
Fuel (water)	8.342/gal	404 gal.	3370
Fuselage	1317	1	1317
Camera mounting plate	45	1	45
Data Acquisition System and mount	36	1	36
Miscellaneous	158	1	158
Total			8780

- Test Article Total Weight includes an onboard Conformable Auxiliary Fuel Tank

Impact Results

Pre-Impact Condition

Post Test Results	Right Side	Left Side
Maximum Deformation (in)	10.7	21.7
Peak Acceleration (g)	37	26

ATD No.	Location	Lumbar Load (lb)	Accelerometer Data	
			G_{peak} (g)	Pulse Duration (ms)
1	FS 427 LS	1804	17.4	49
2	FS 426 LS	906	17.3	48
3	FS 462 LS	1734	34	32
4	FS 462 LS	1269	21	55
5	FS 497 LS	1247	27	61
6	FS 498 LS	961	17	18

Right Front Quarter View

Post-Impact Condition

Left Front Quarter View

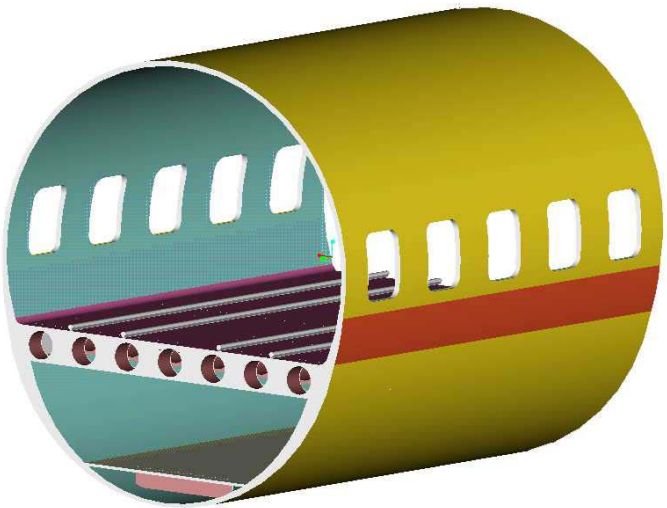
Motivation for Development of Scale Model and Computer Simulation Method

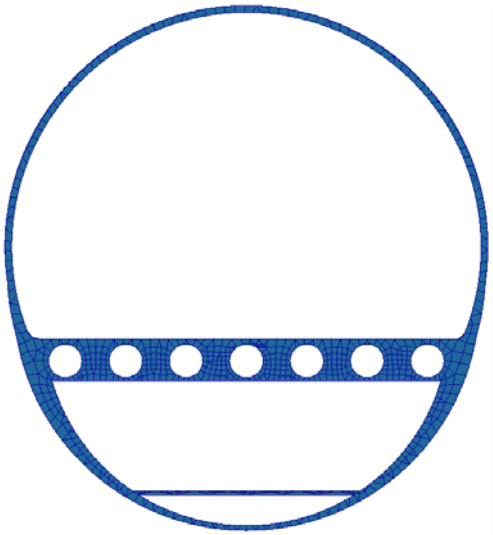
- Validated Scaled/computer model translates to:
  - Easier setups
  - Shorter flow time
  - Simplifies certification tasks
  - Reduces the cost
  - Does not destroy an entire fuselage
  - Effective product development tool
  - Produces less scatter data
  - Appropriate for identifying critical impact location and parameters
  - Reduce the variation between each test
  - May eventually be used as a “certification tool”

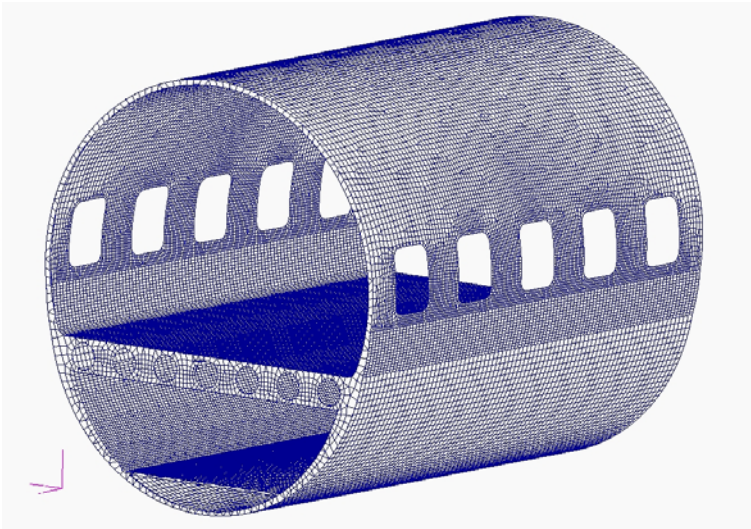
Computer Simulation vs. Full-scale Test

- Requires careful control of the governing physics
  - Only as good as the input data (Garbage in/garbage out!)
  - Need to be evaluated with test data
  - Initially may take longer than a test
  - Provides insight into “WHY” a system performed as it did
  - Provides direction for how to redesign a “problem” configuration
  - Parametric studies provide valuable information on the design and reduce development time

Fuselage Finite Element Modeling







Solid Model

Fuselage Cross section

FE Model

From the Meshed Model → LS-DYNA 3-D FEM Model

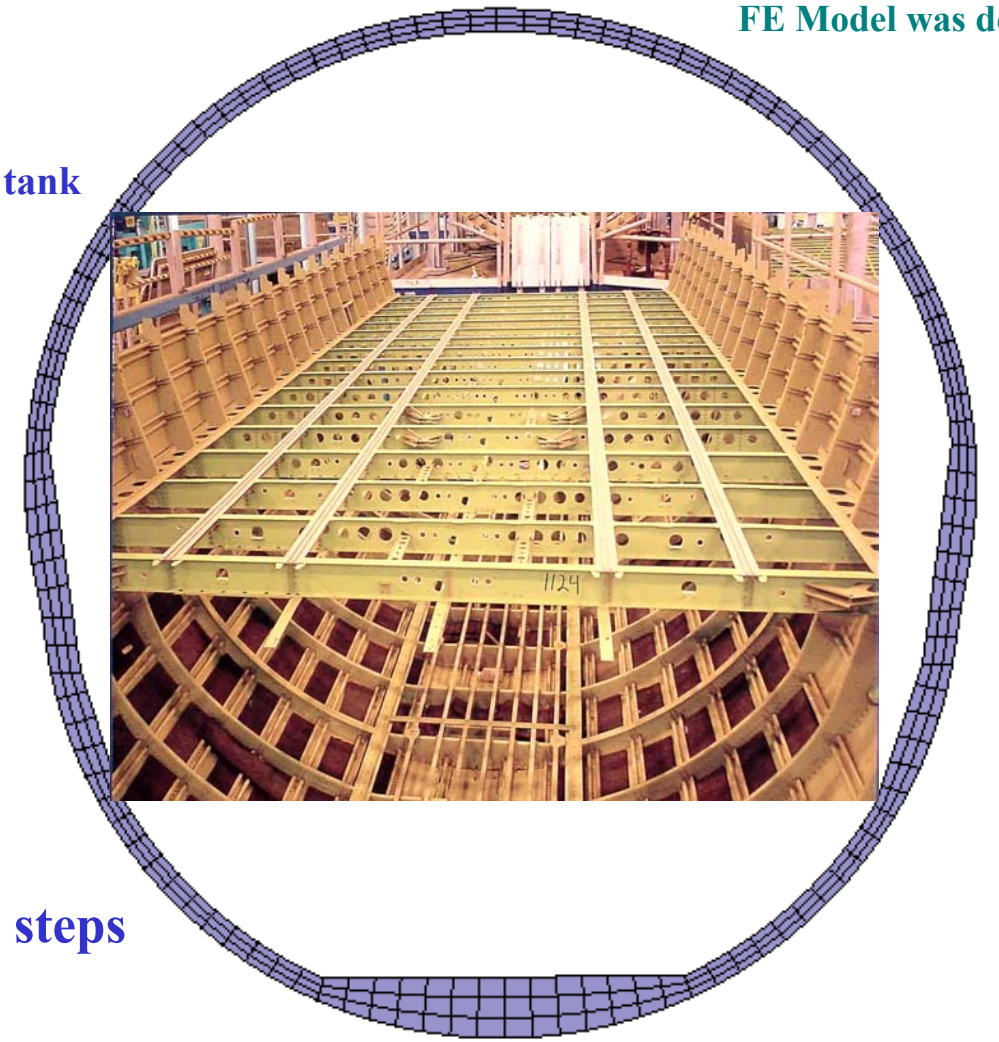
Fuselage Finite Element Modeling

LS-DYNAuserinput
Time= 0

FE Model includes:

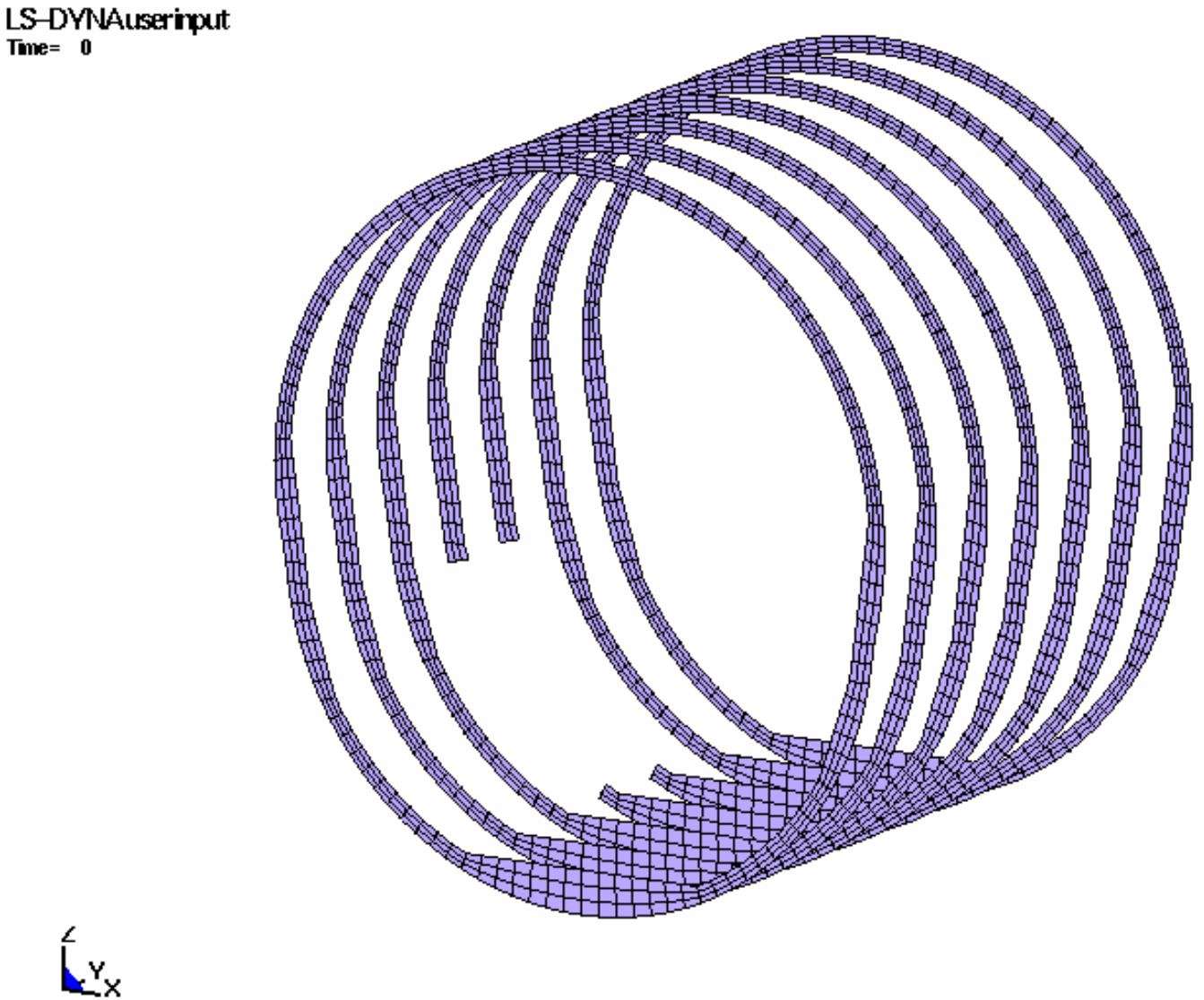
- Fuselage skin
- Cargo door
- Conformable Auxiliary fuel tank
- Ribs
- Windows cut out
- Spar webs
- Spar caps
- Cargo floor
- Passenger floor
- Seat Tracks

With some reasonable approximations, FE Model was design as follow:

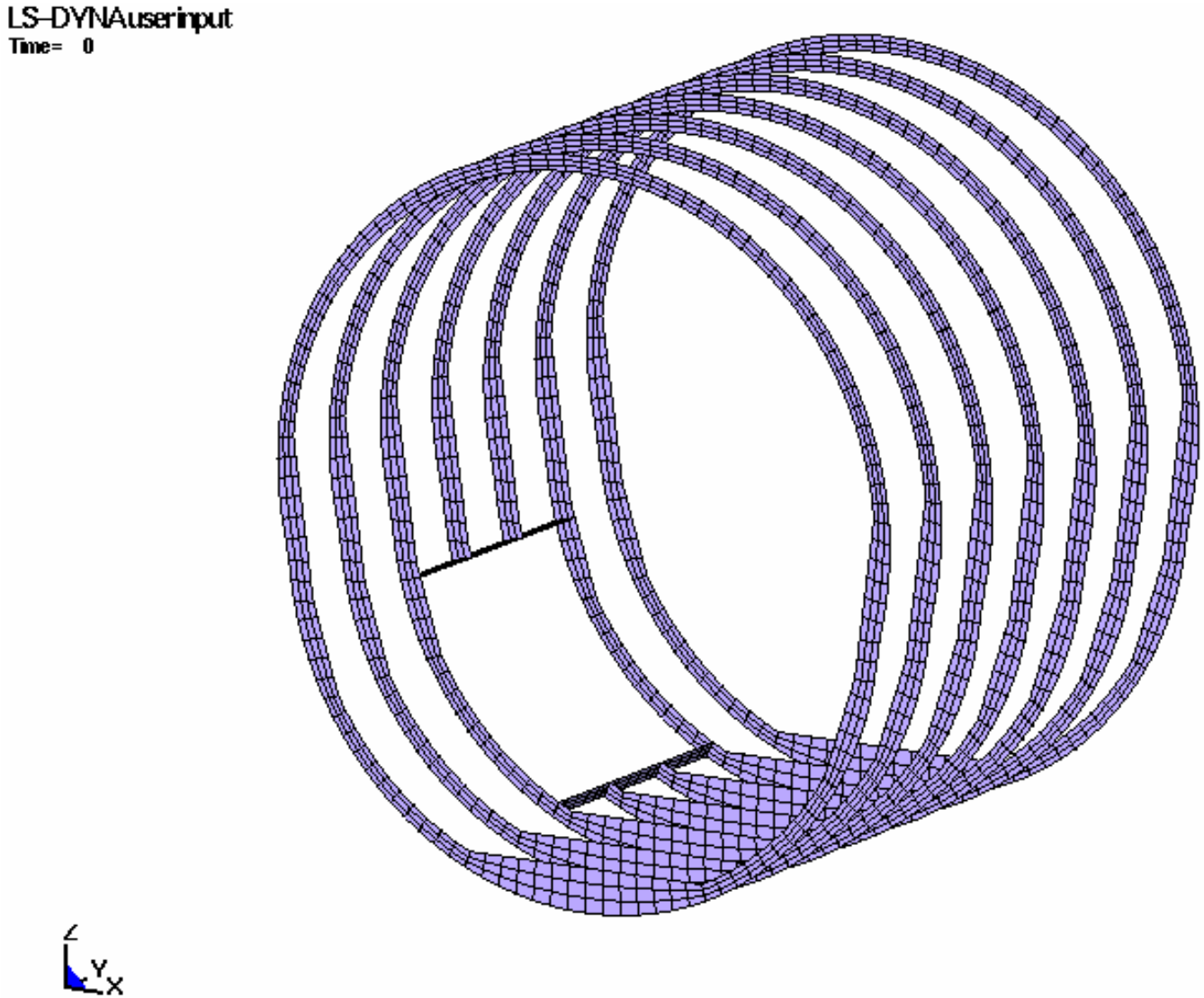


➢ **Shown as pictorial steps**

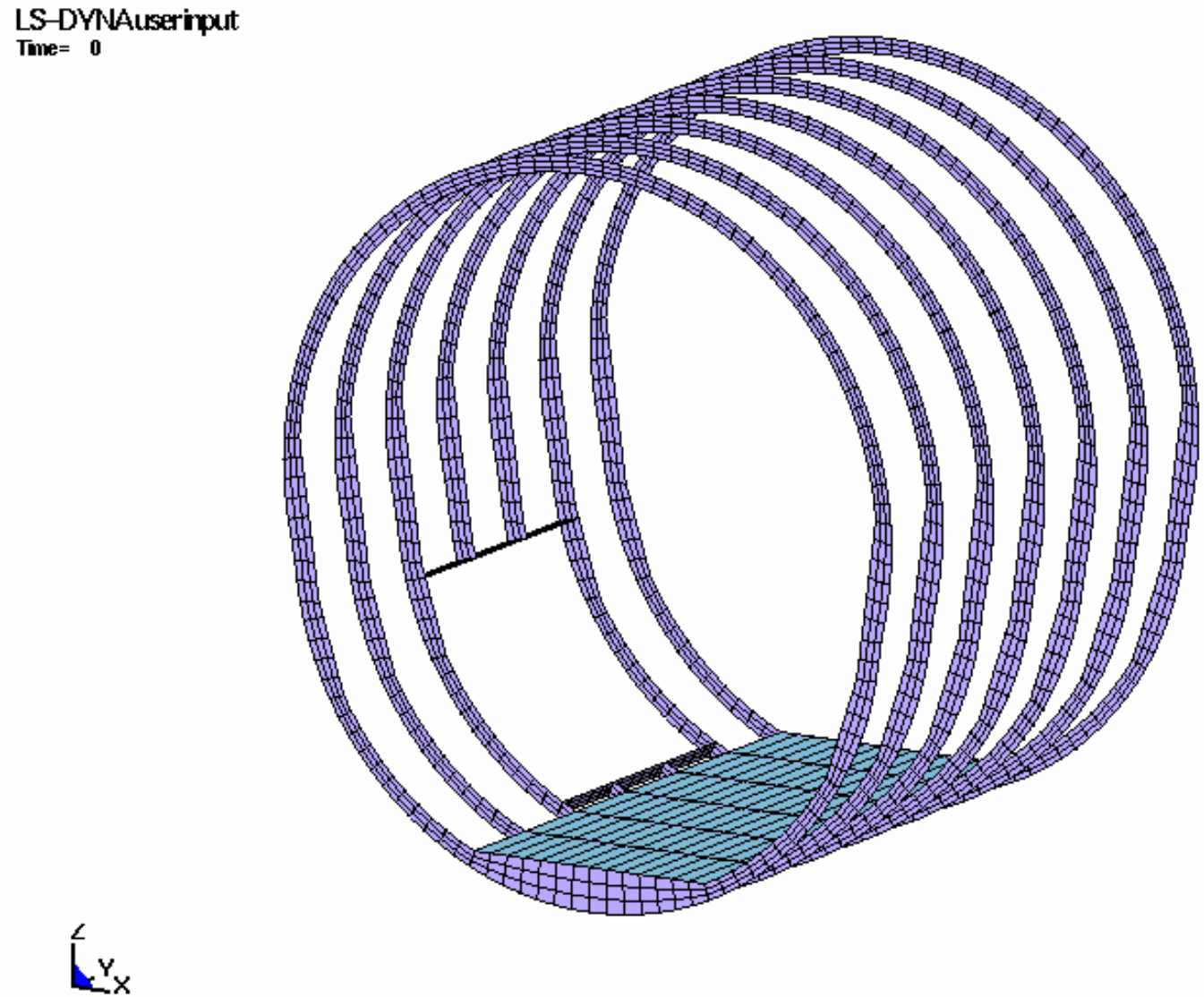
Fuselage Ribs



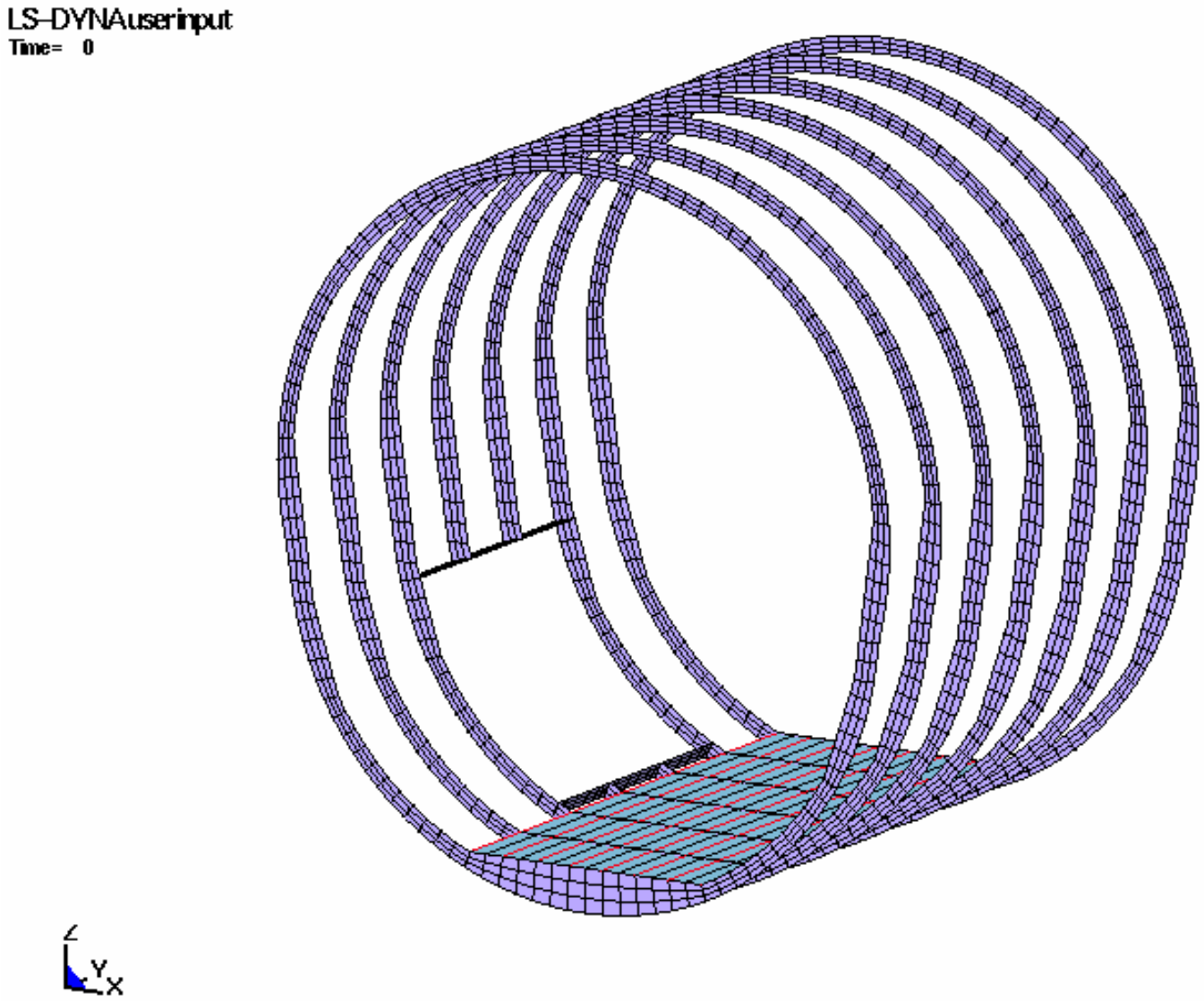
Cargo Door Frame



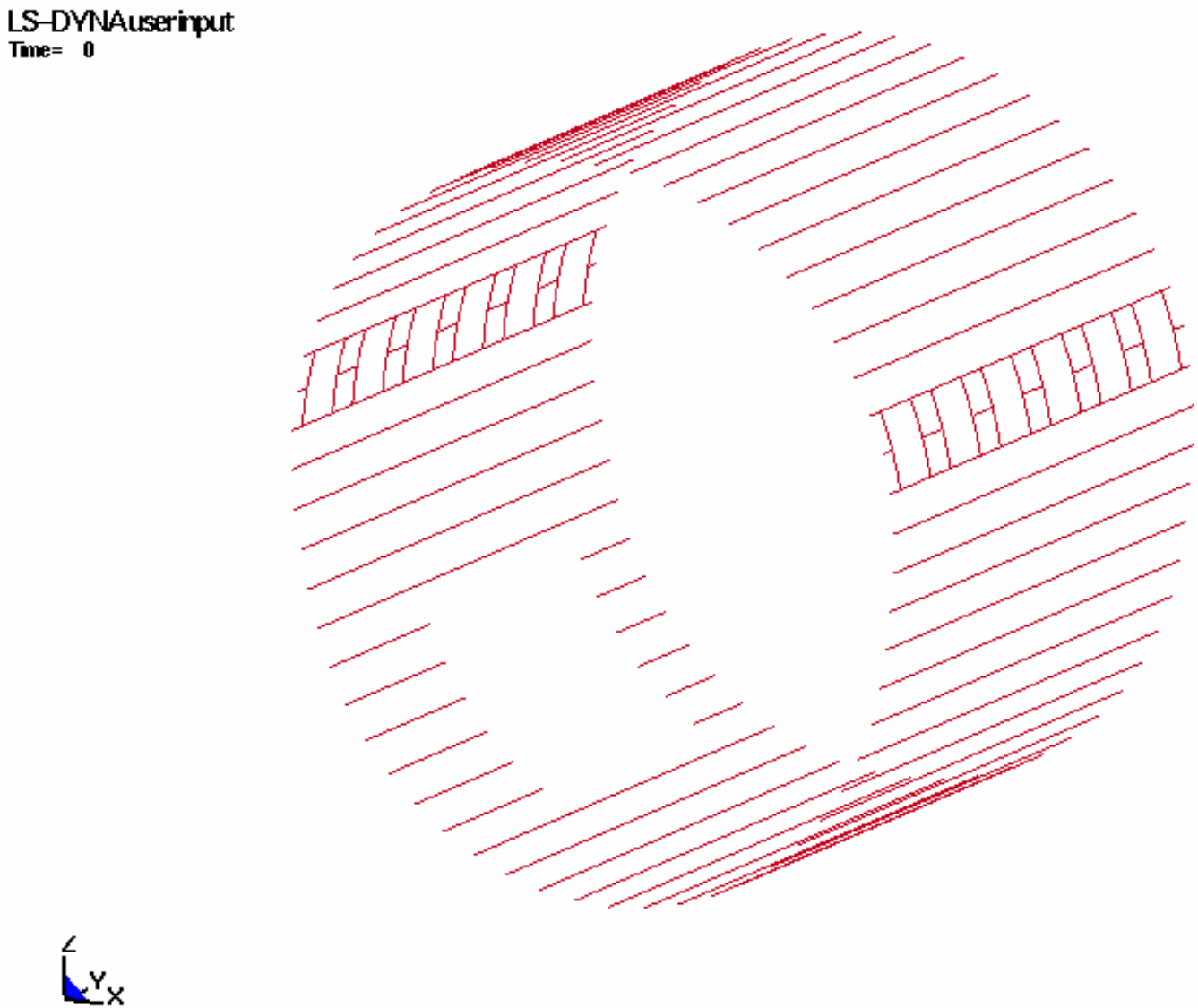
Cargo Floor



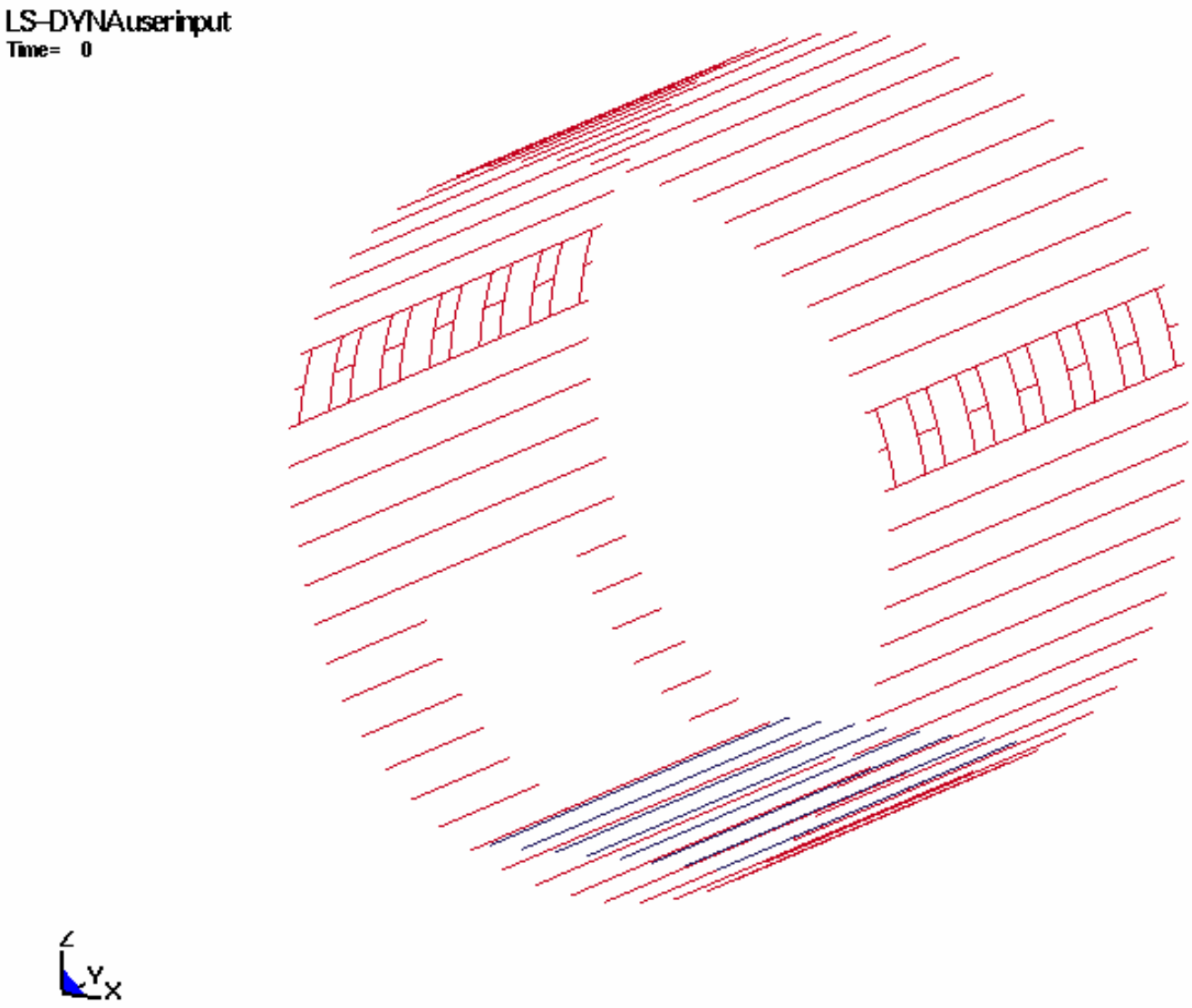
Cargo Floor Beams



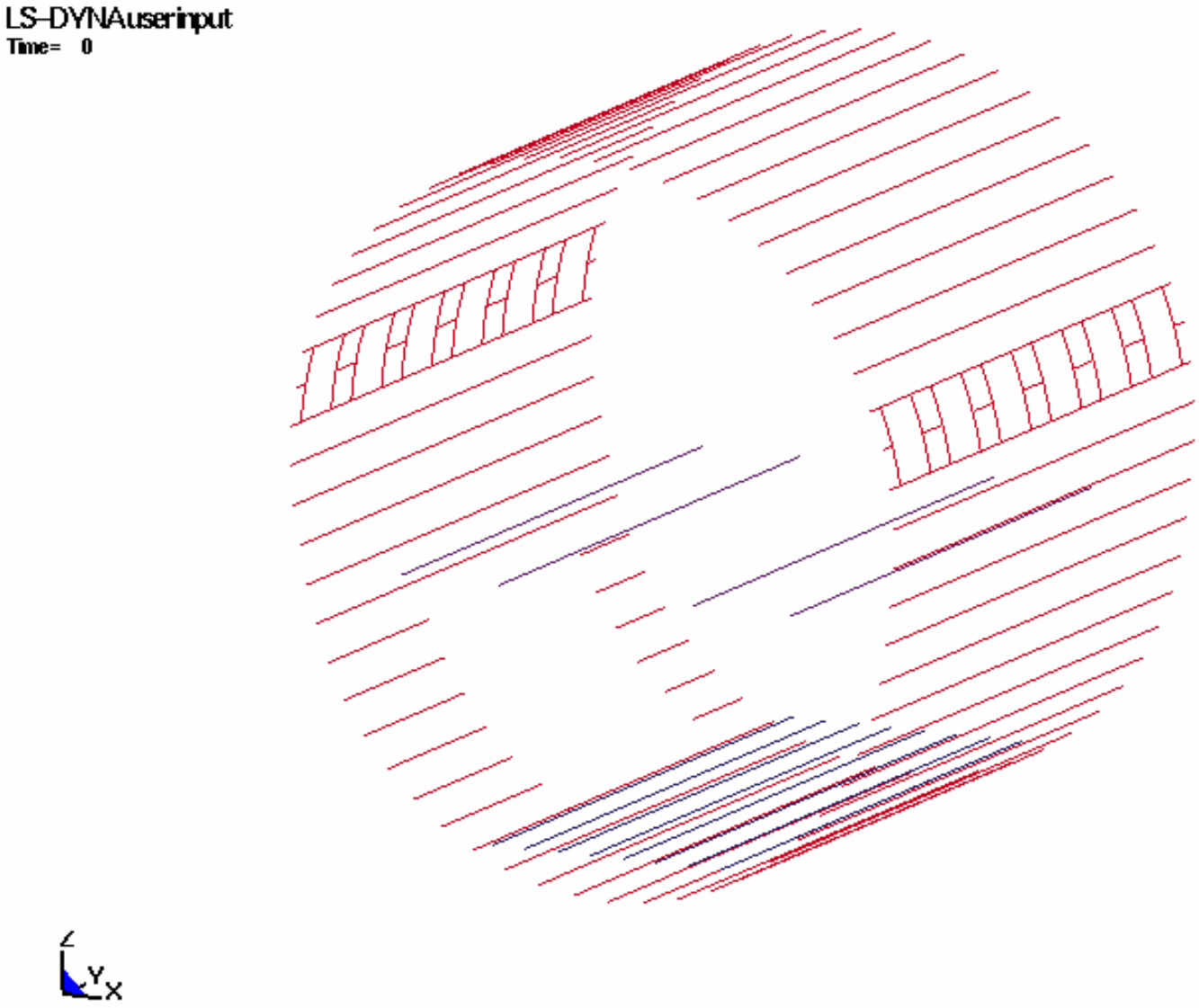
Fuselage Longitudinal Stringers and Window Stiffeners



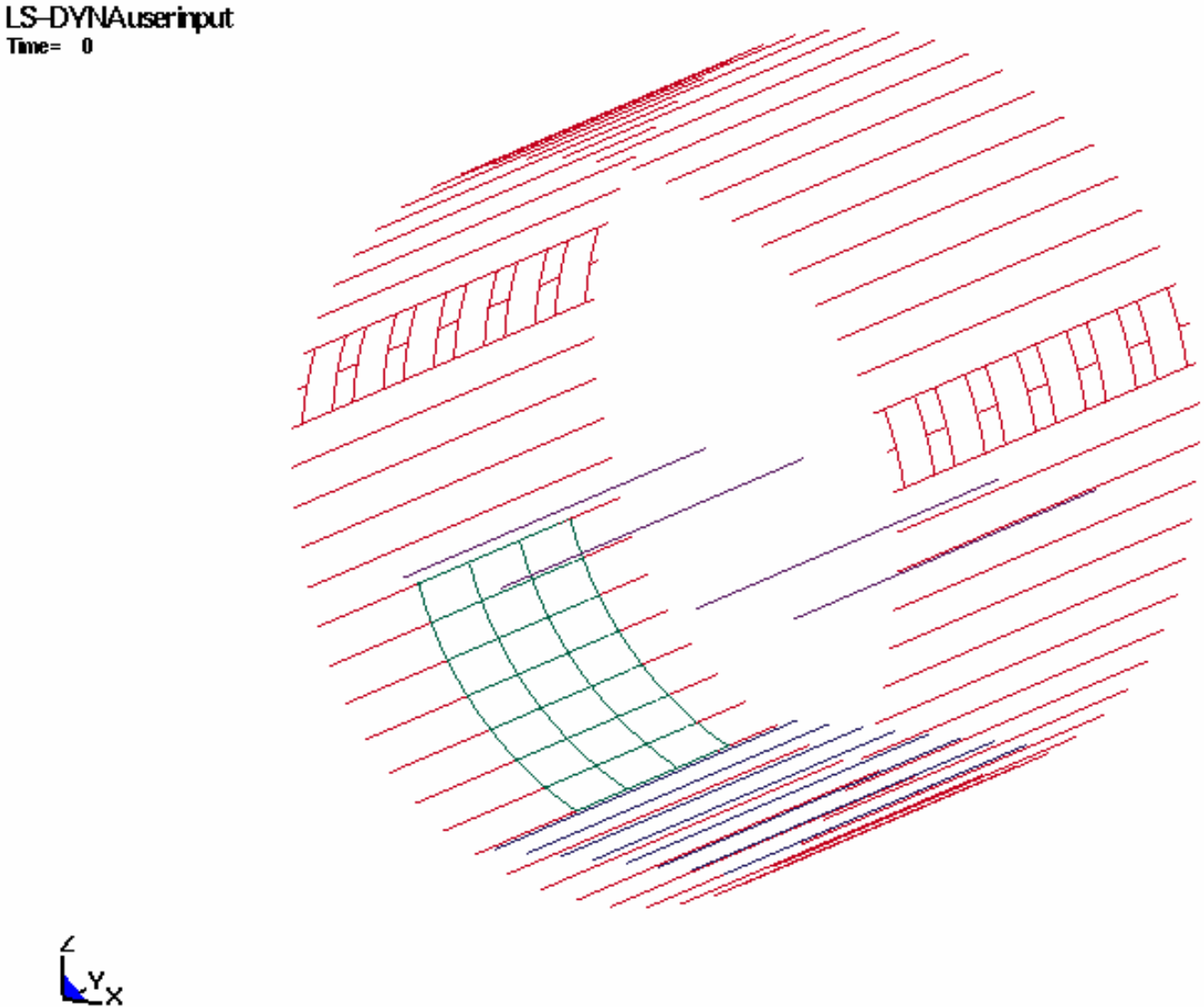
Cargo Floor Beams



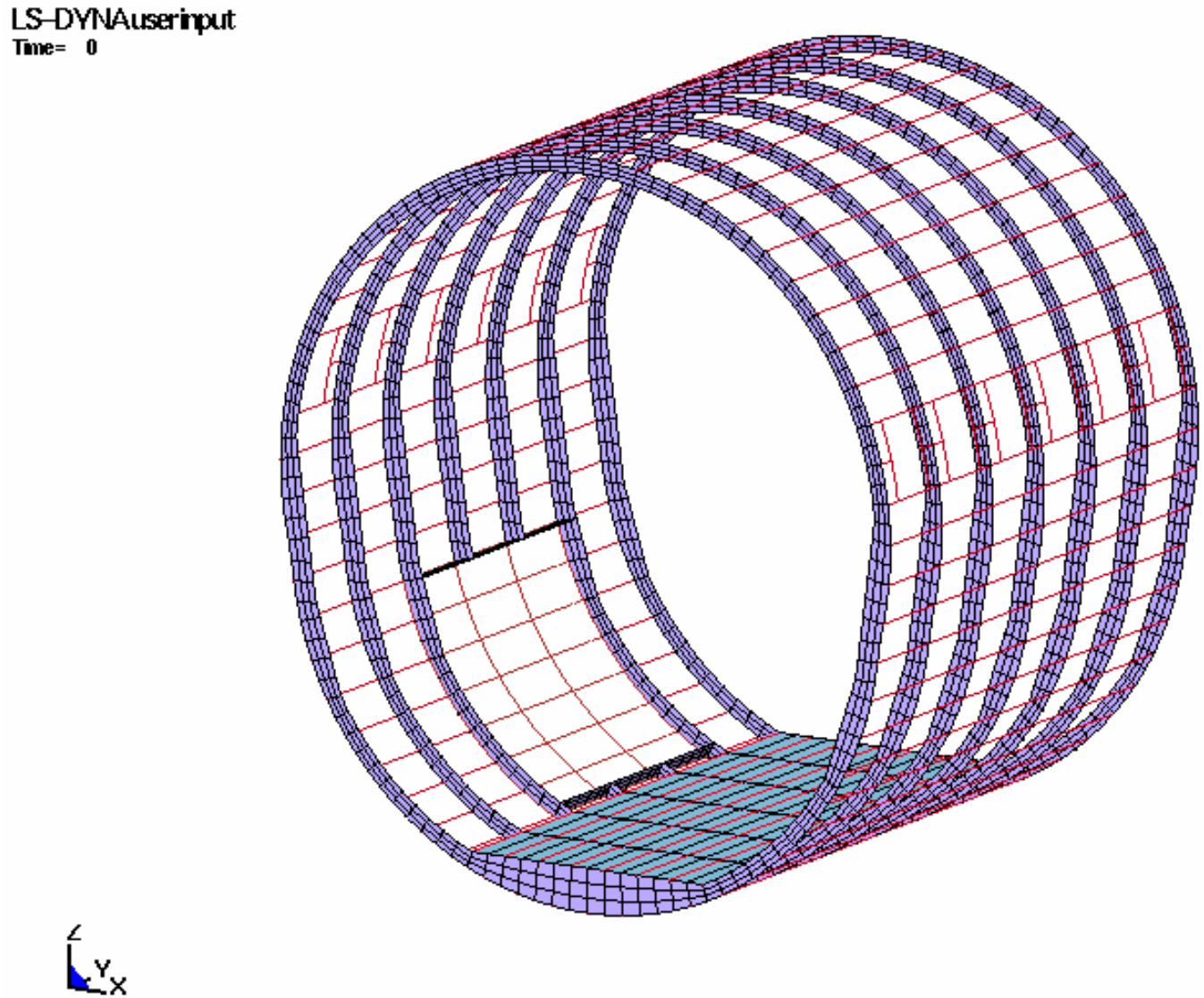
Passenger Floor Longitudinal Beams



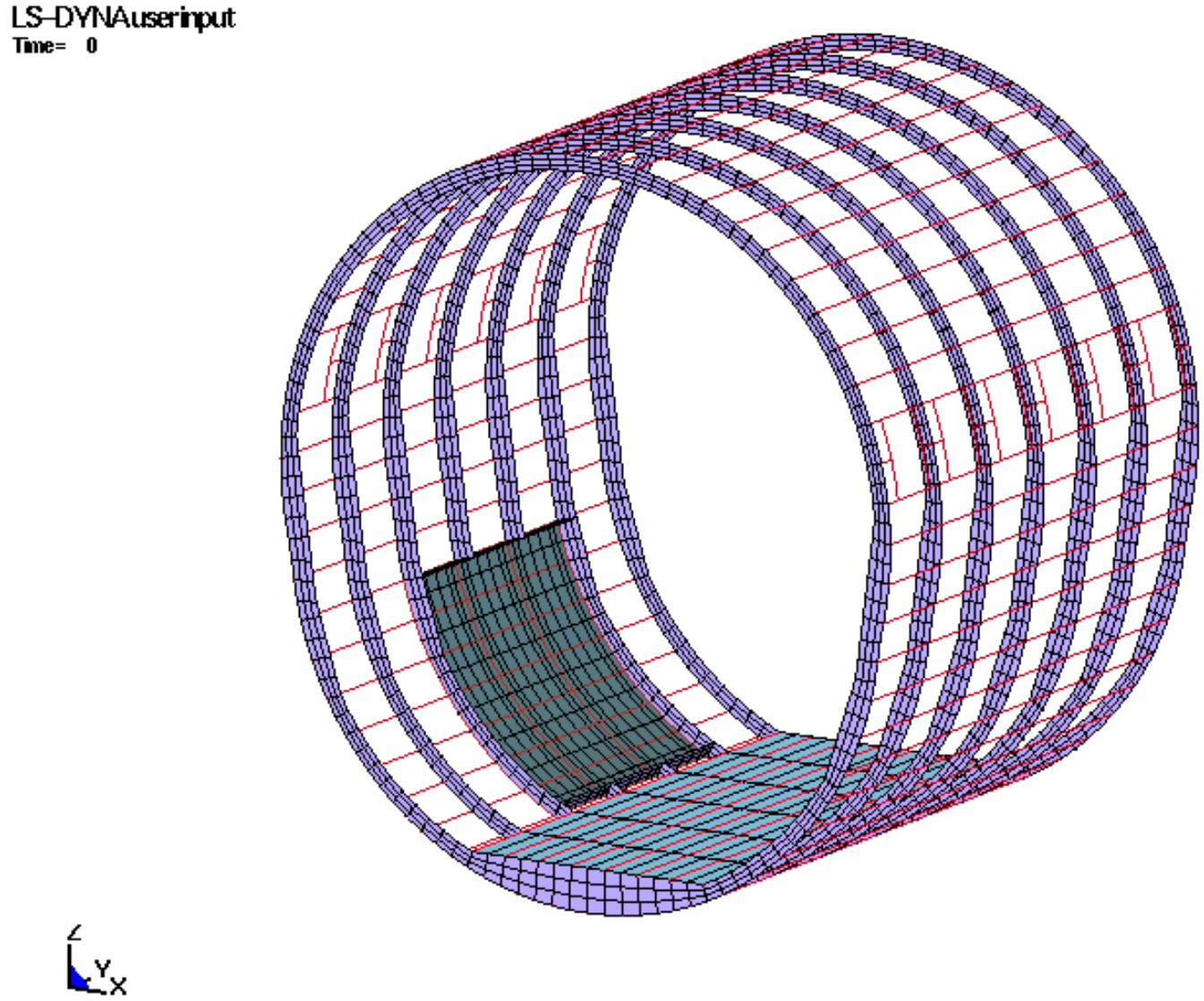
Cargo Door Stiffeners



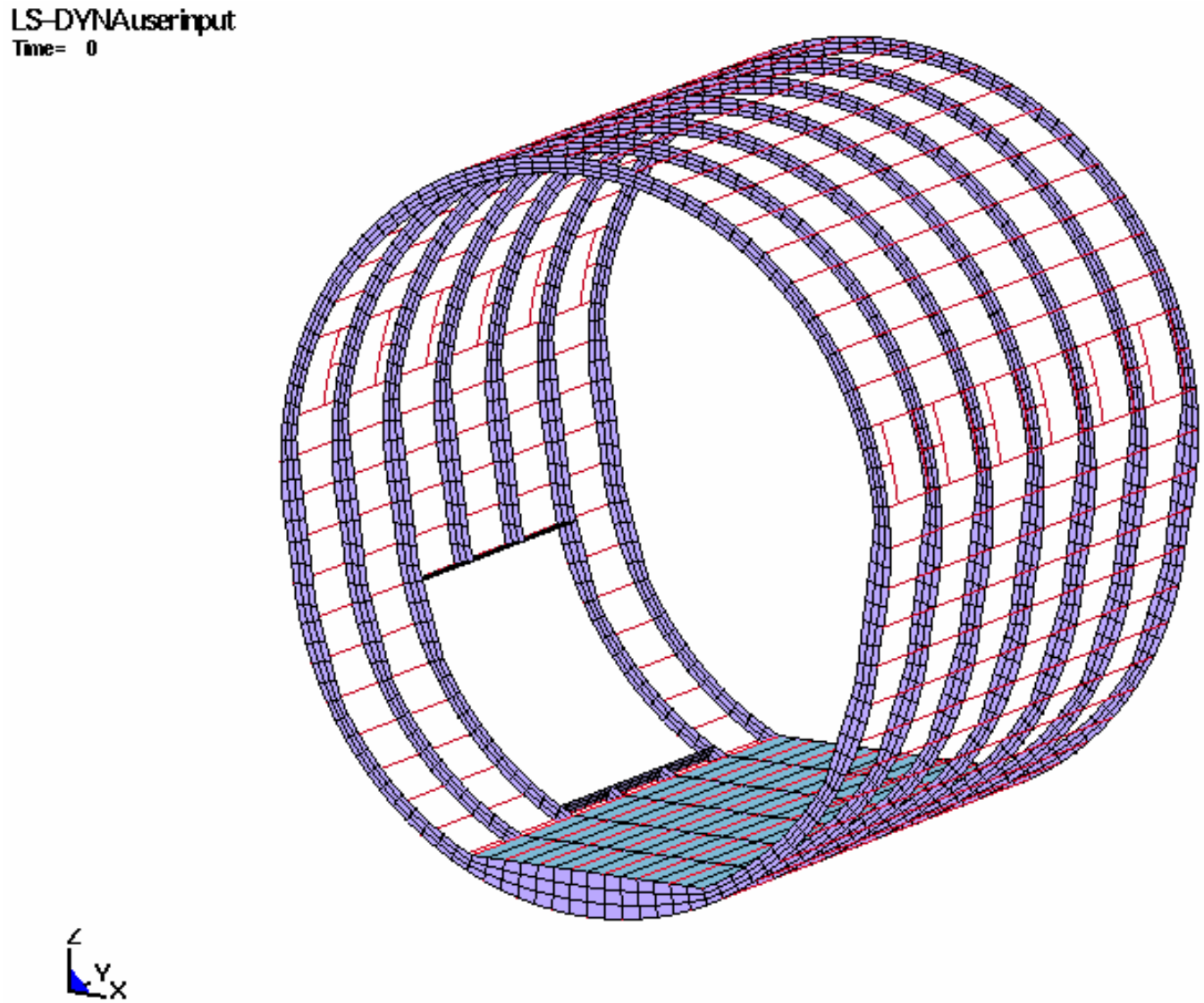
Fuselage Finite Element Modeling



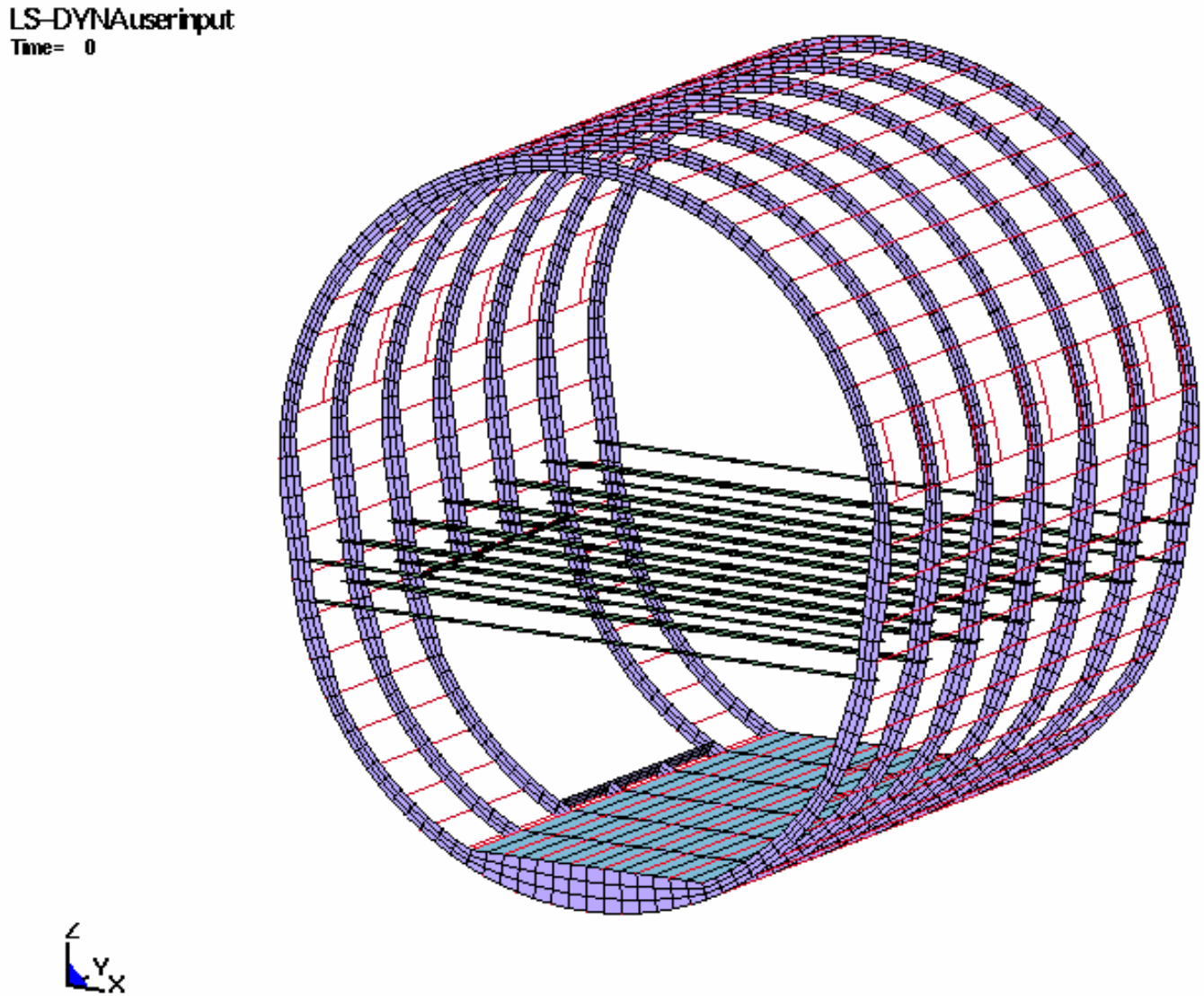
Highly Stiffened Cargo Door



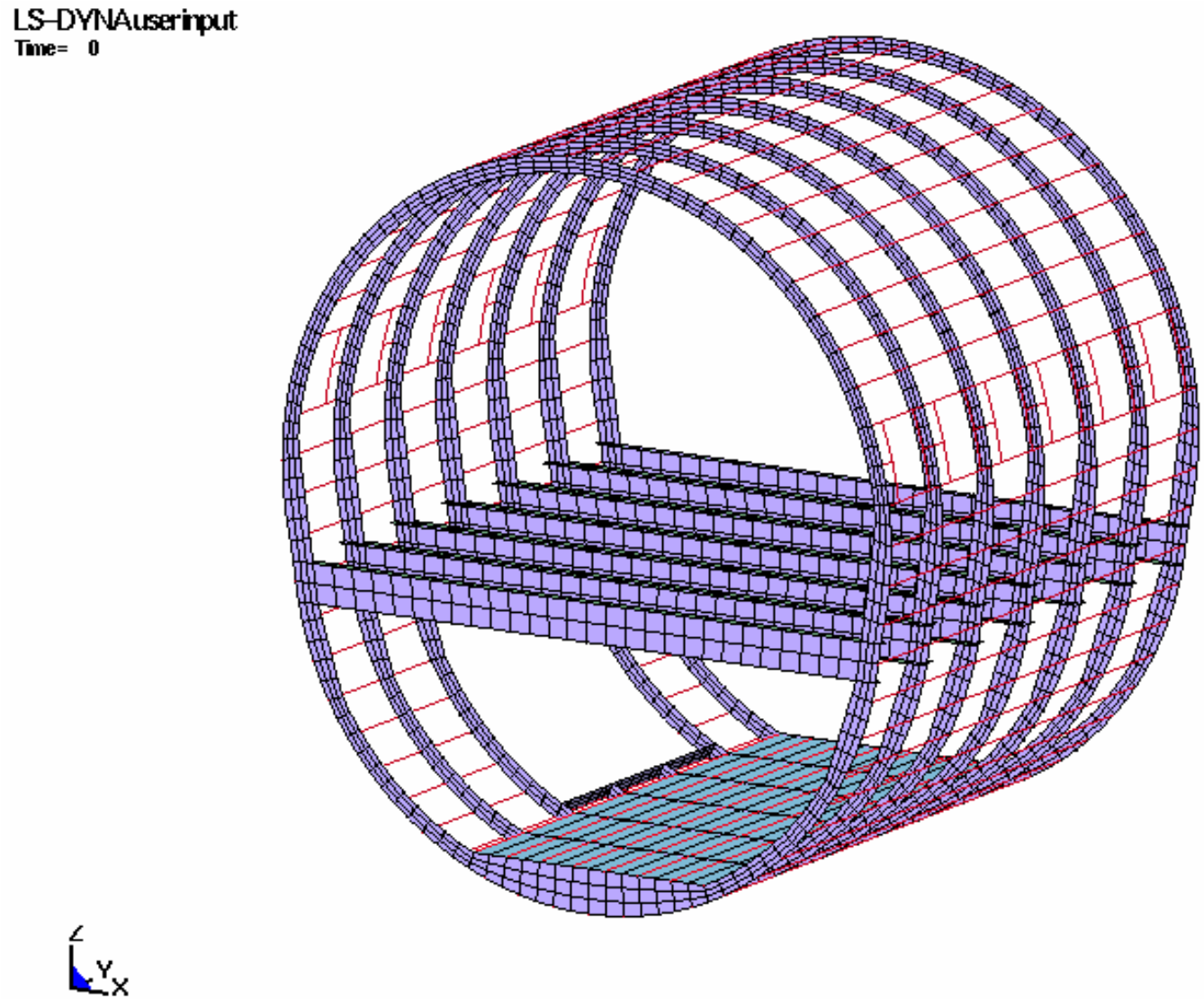
Fuselage Finite Element Modeling



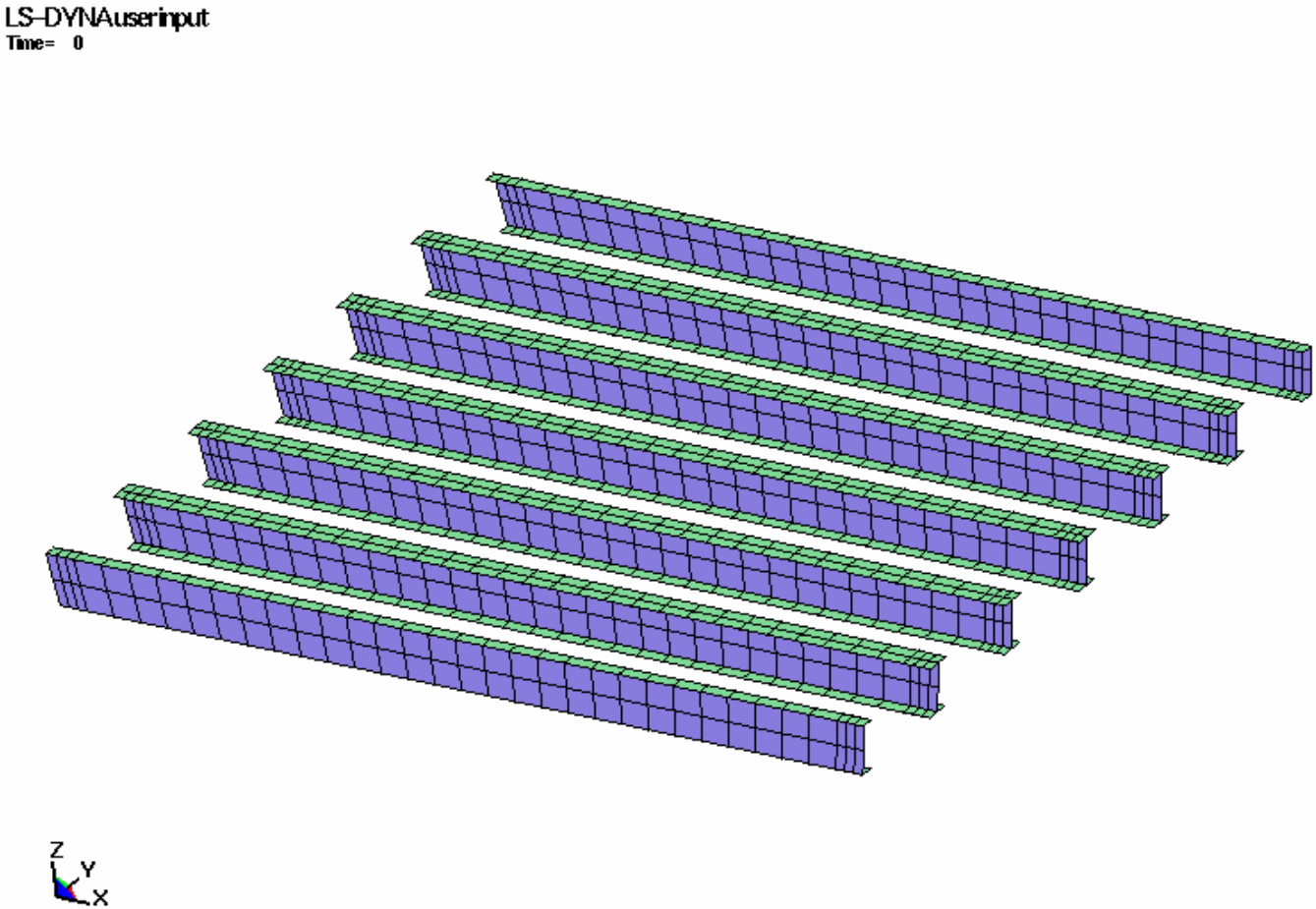
Spar Caps



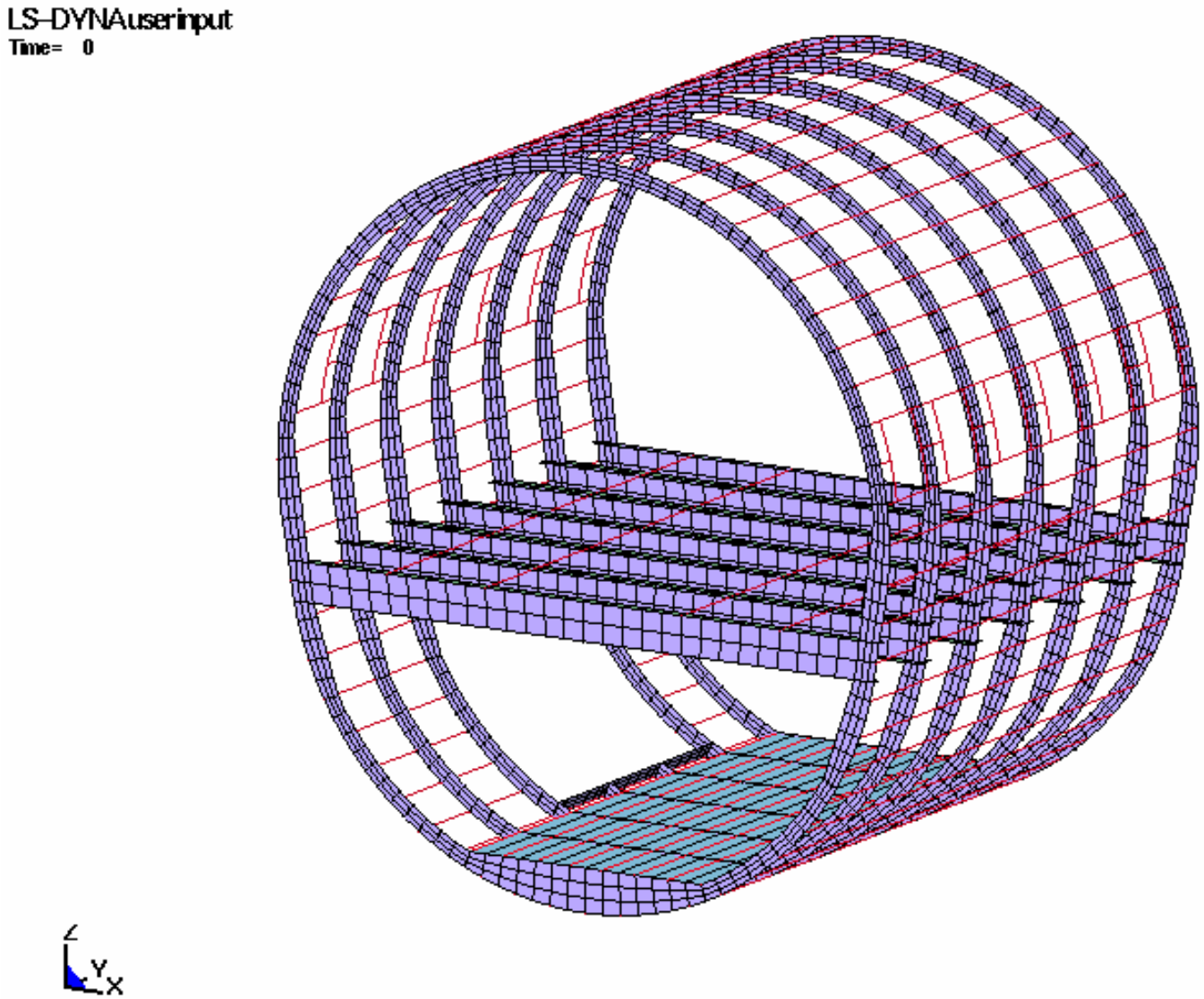
Spar Webs



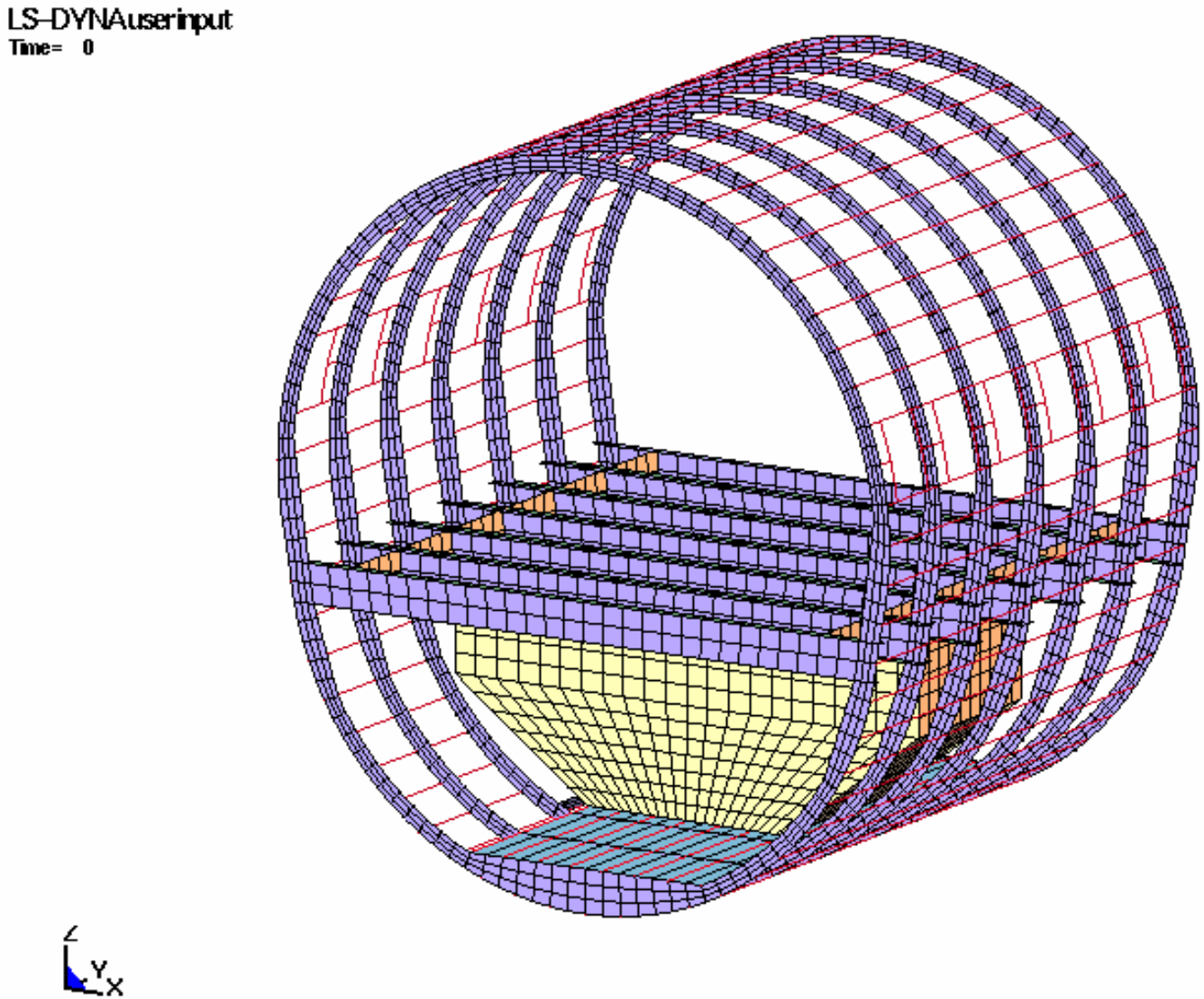
Passenger Floor Beams



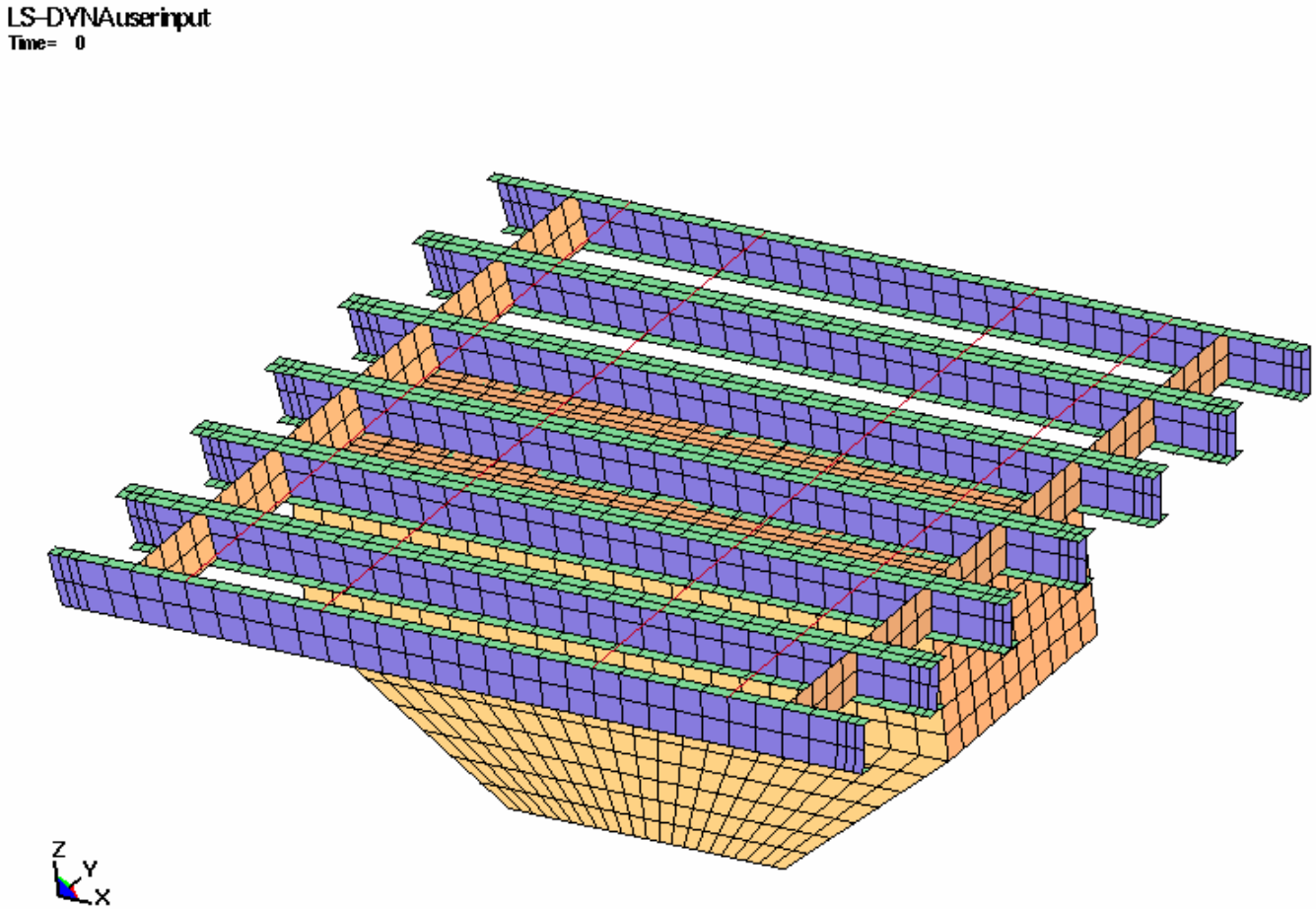
Seat Rails



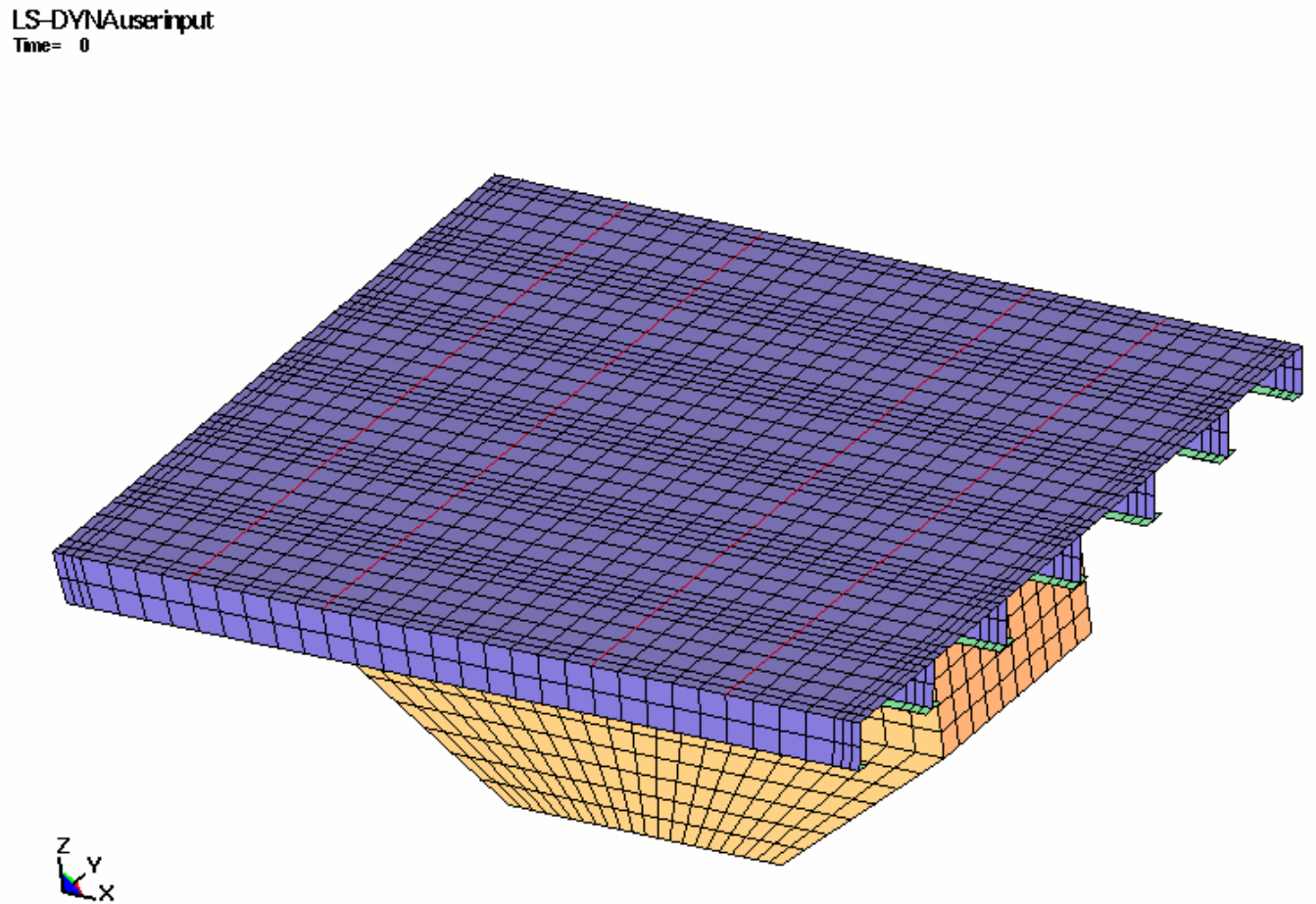
Fuel Tank



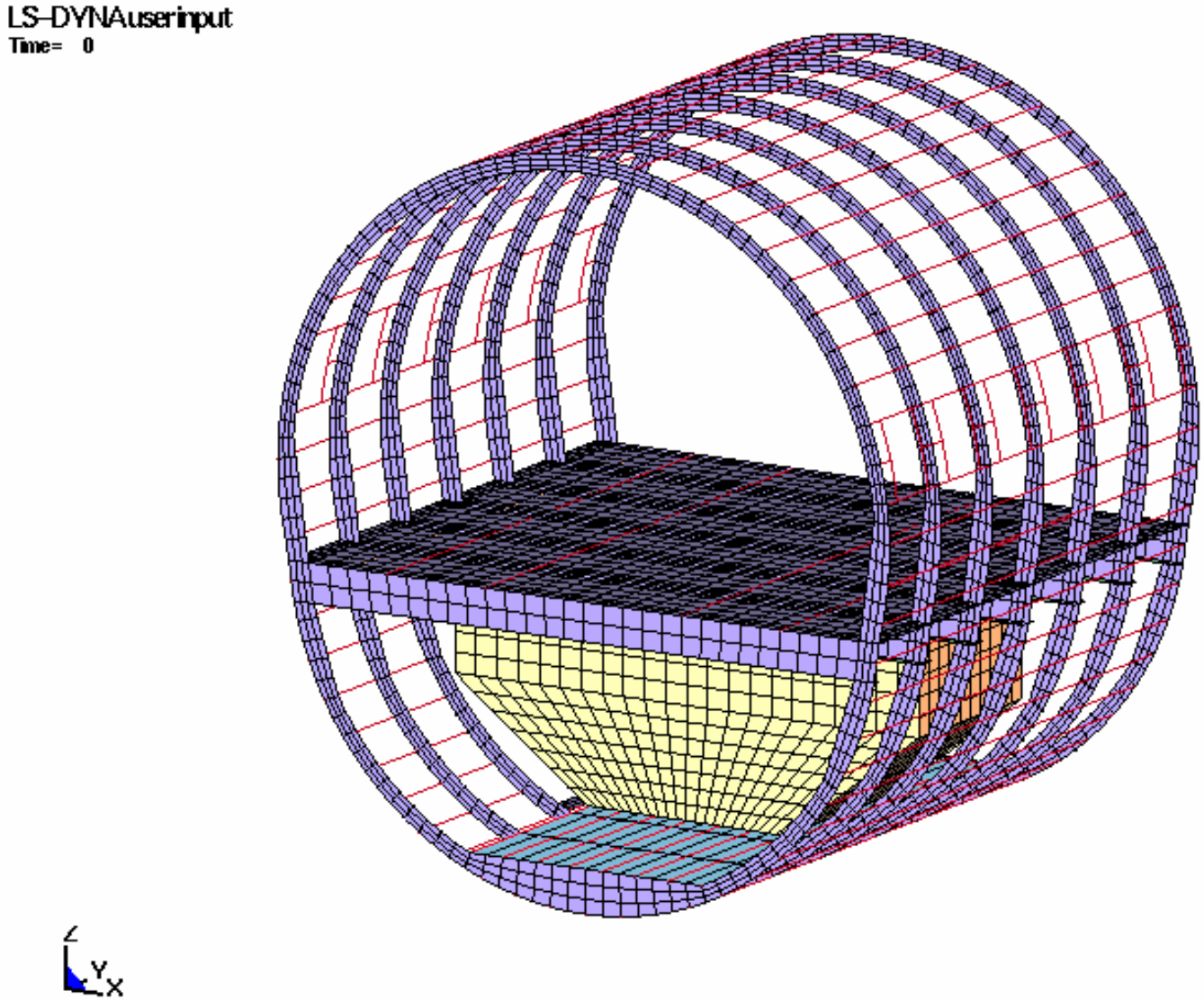
Fuel Tank/ Fuel Tank Rails



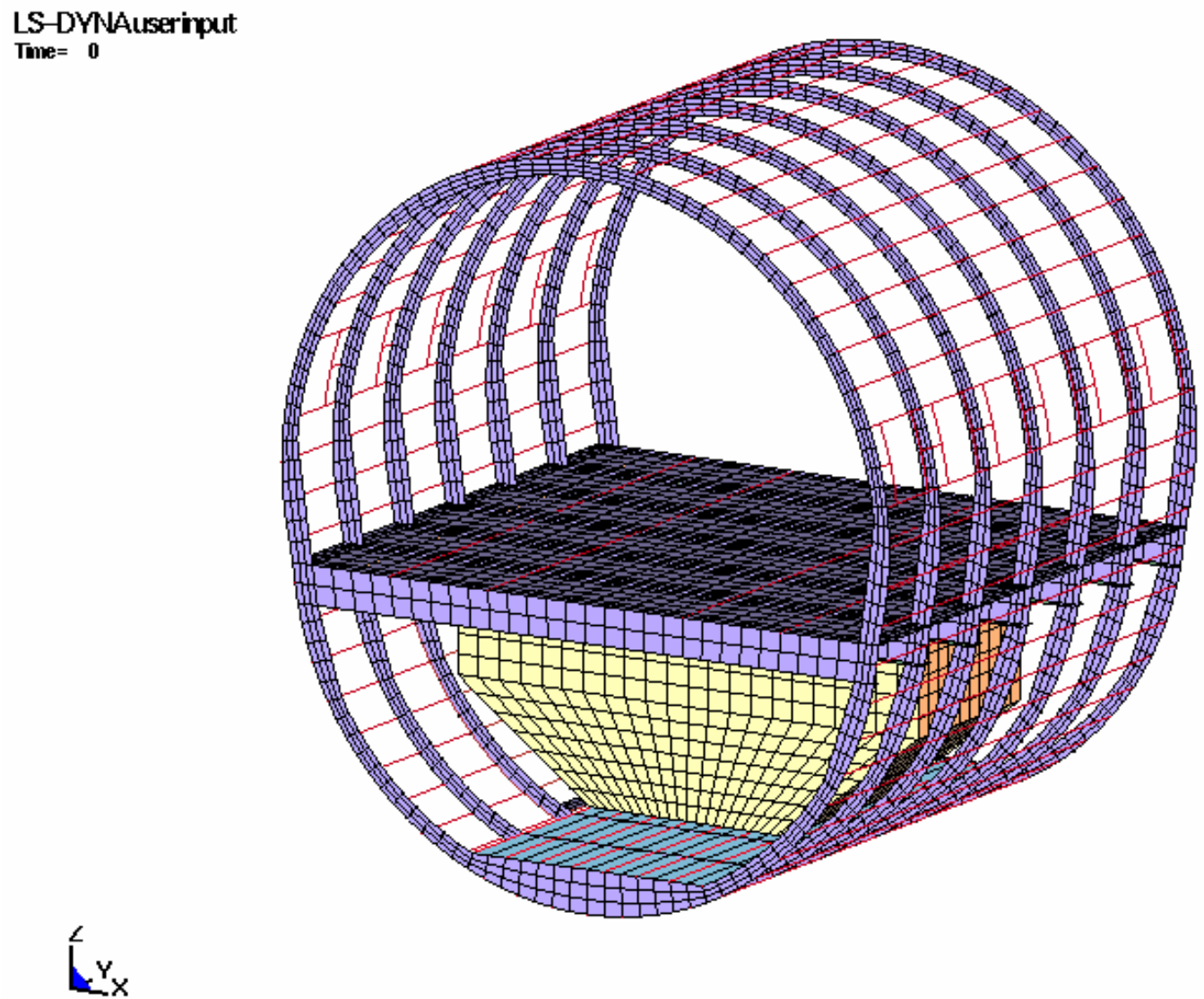
Passenger Floor



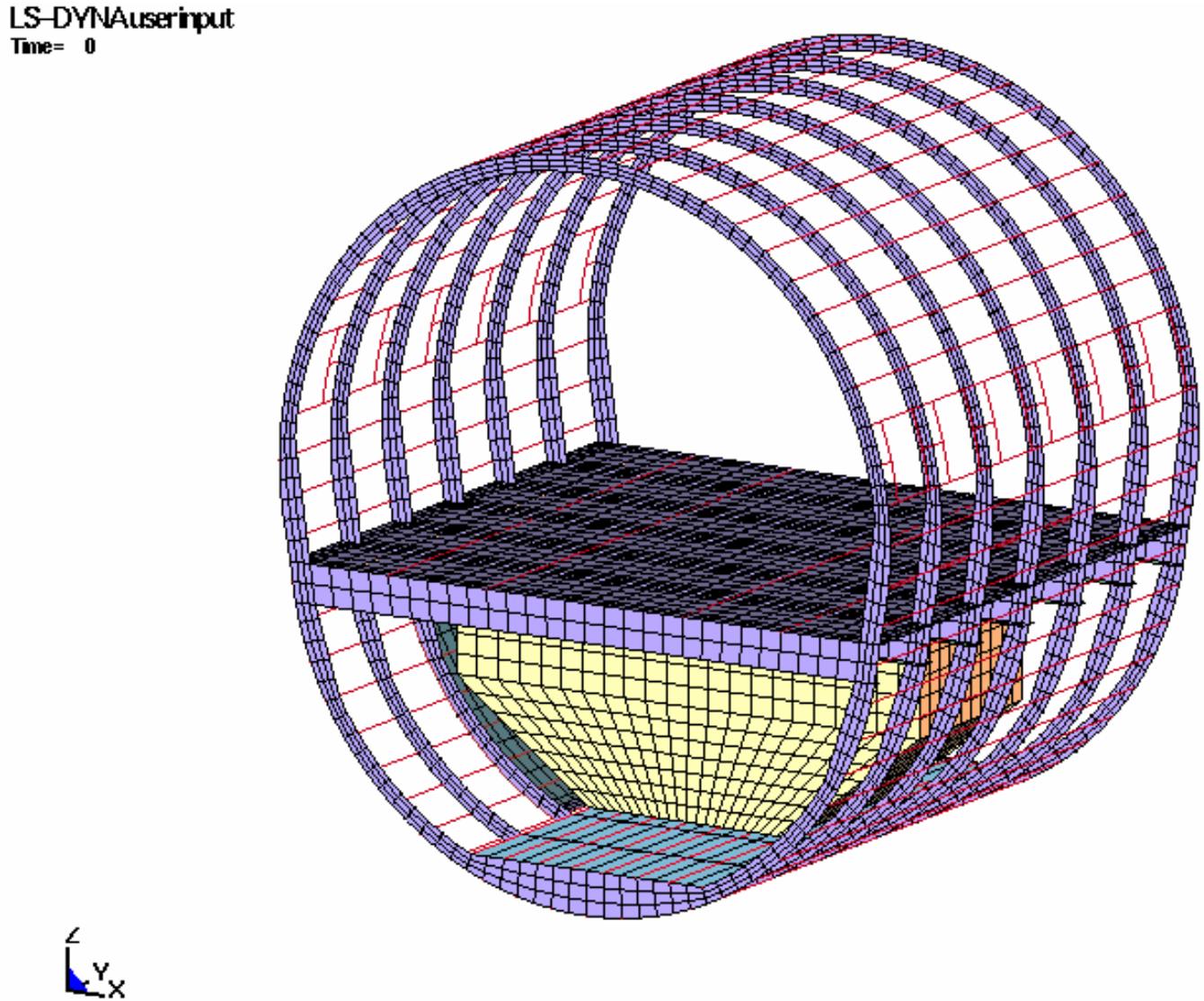
Passenger Floor



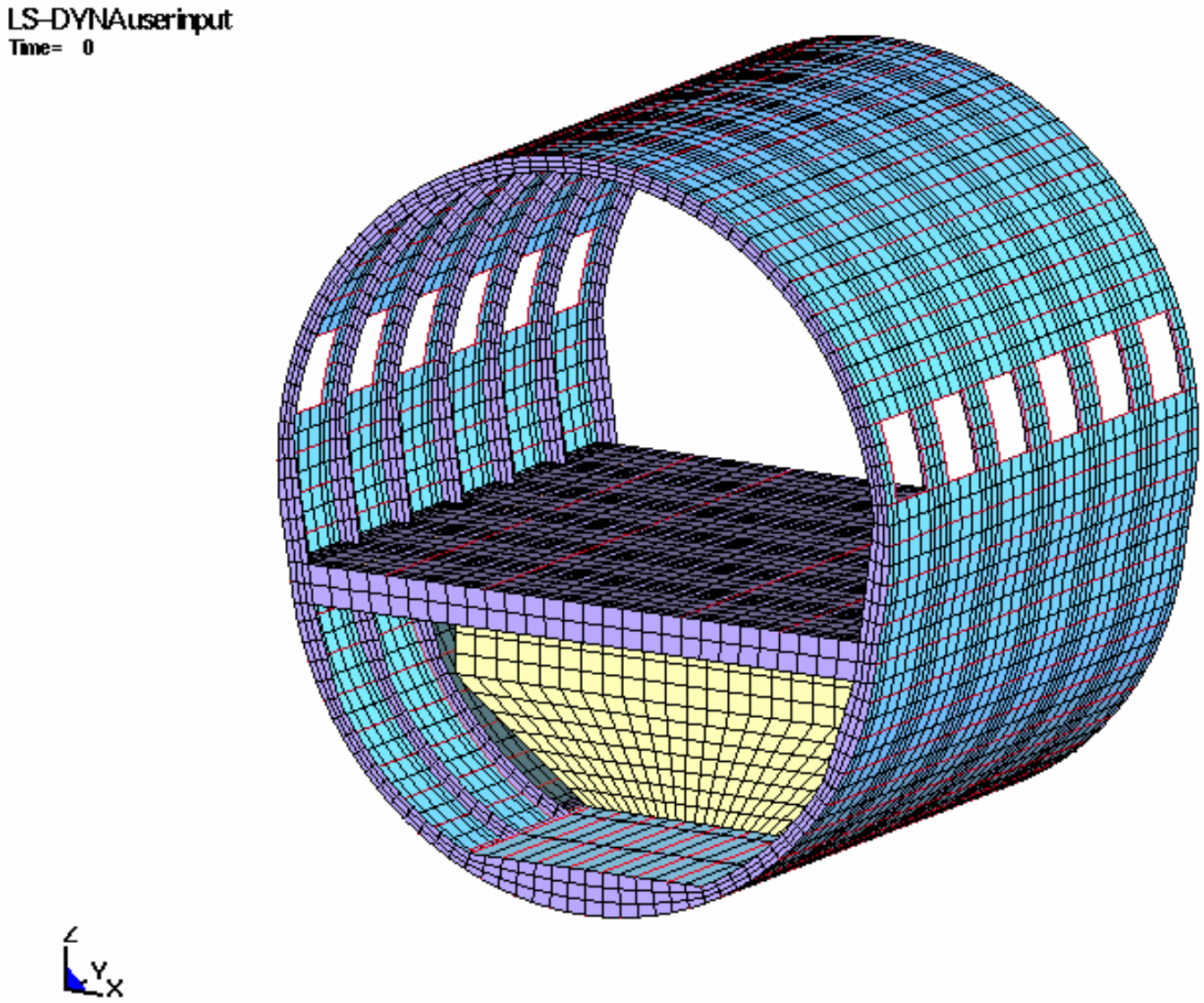
Cargo Door Beams Attached



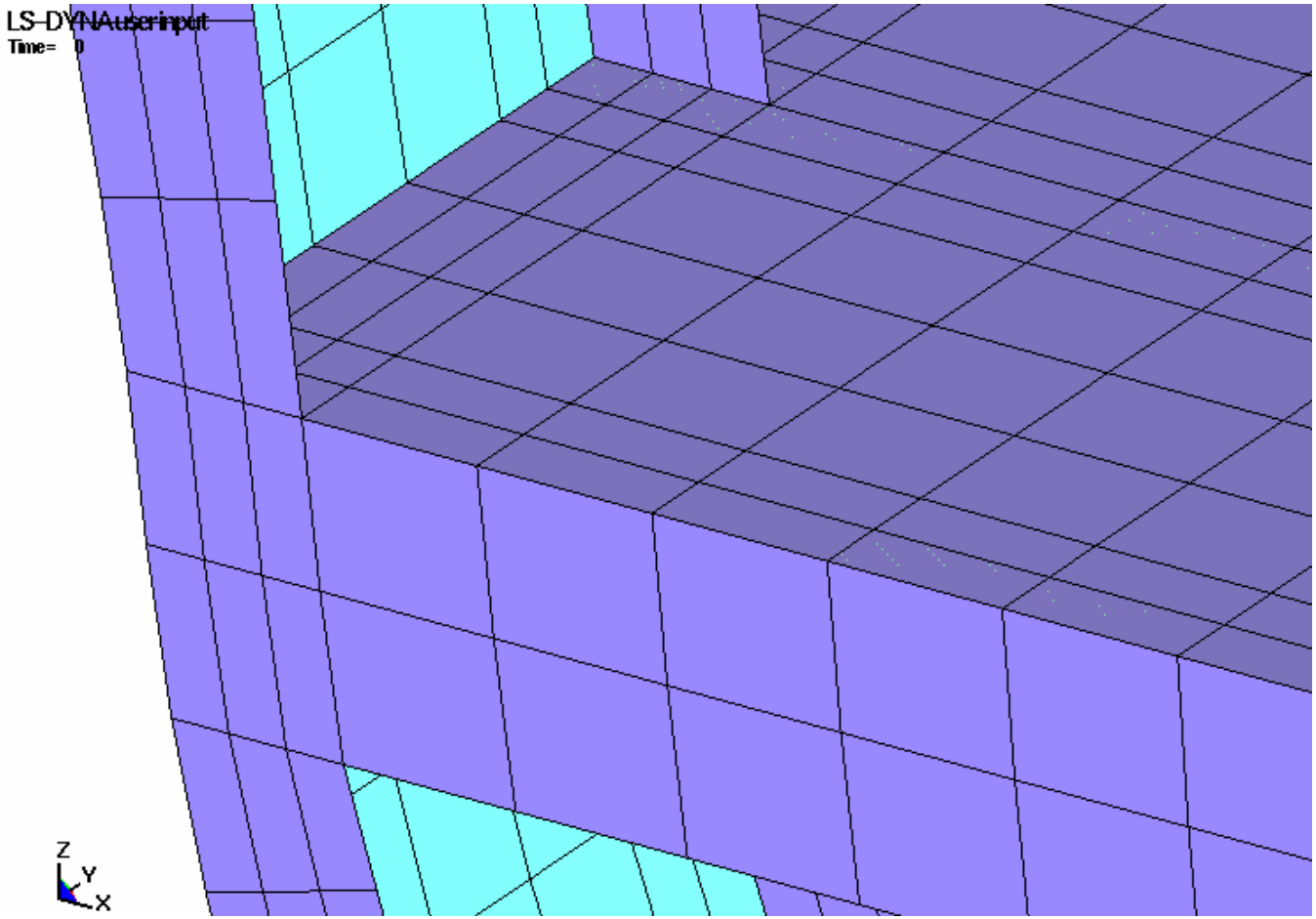
Cargo Door Attached



Complete Model



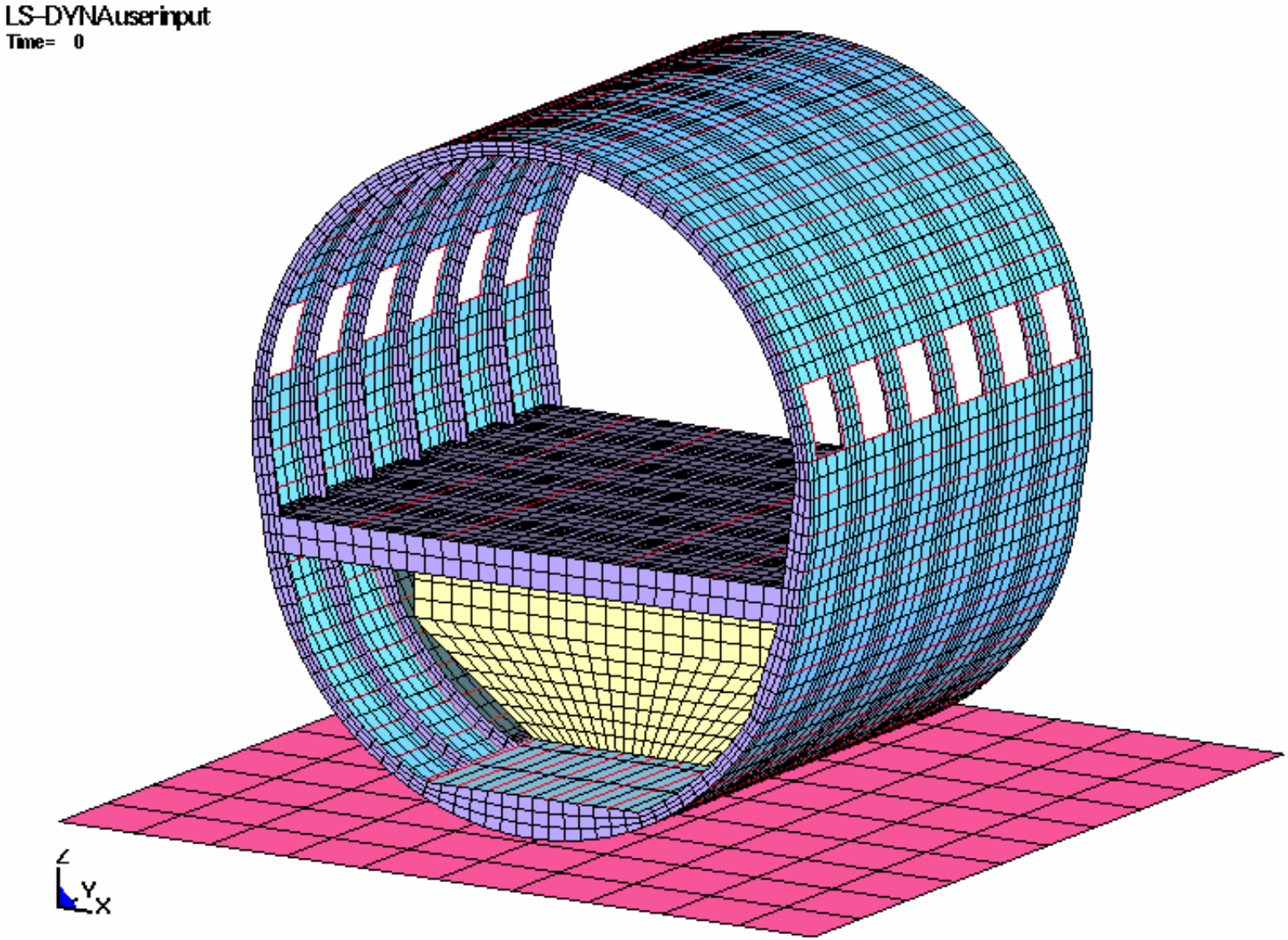
Element Connection Close-up (Passenger Floor)



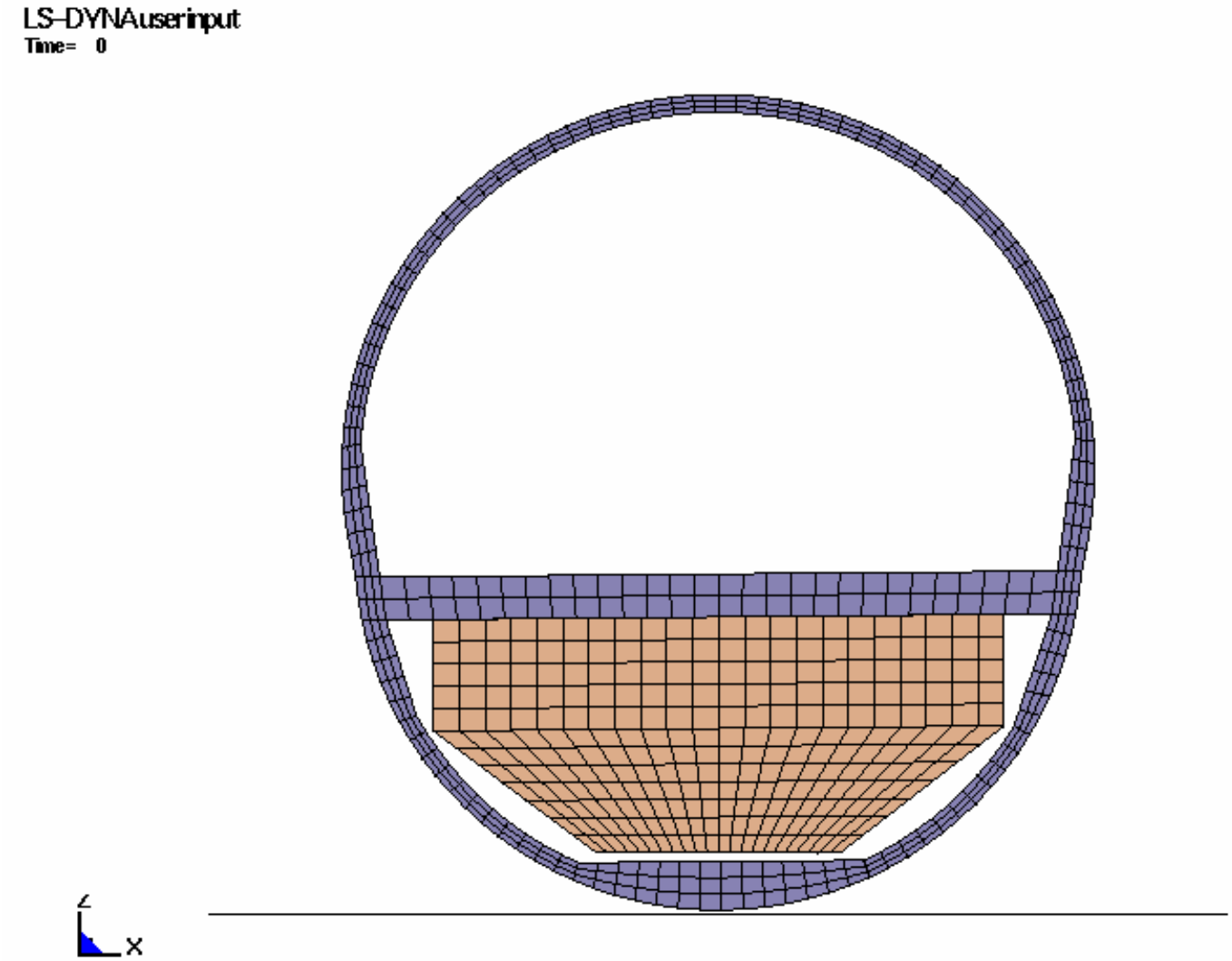
No spot Weld in this Structure

(To insure the uniform load transformation by all the elements)

Complete Model with Ground Impact



Fuselage Cross Section



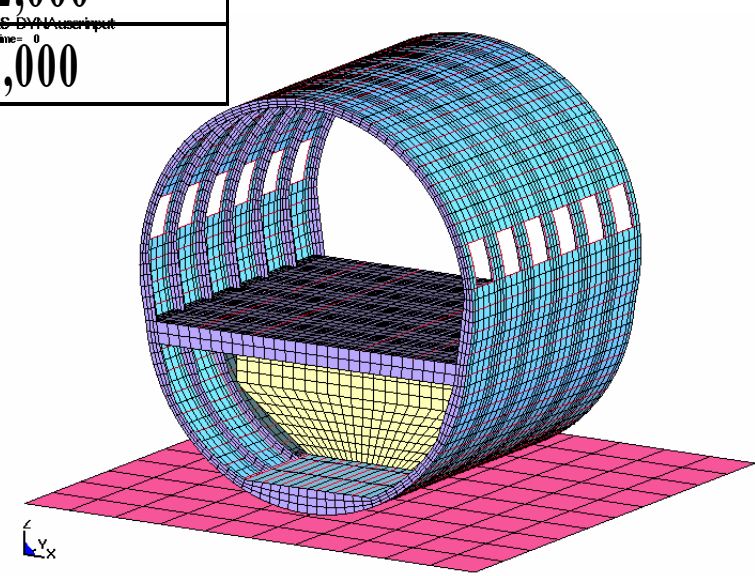
Model's Constitutive Properties

Material	Mass Density (lb/in^3)	Young's Modulus (psi)	Poisson's Ratio	Yield Stress (psi)
Aluminum-2024-T3	0.1	10500000	0.33	50000
Aluminum-7075-T6	0.102	10400000	0.33	73200
American Black Walnut	0.0199	1600000	0.37	7600
Galvanized Steal	0.284	29700000	0.32	141000

Homogeneous Material Properties

Element Formulation	Element Type	Number of Elements
Belytschko-Tsay	Isometric Quad 4 Shell	12,000
Hughes-Liu	Bar	4,000

Element Properties



FE Analysis Code: LS-DYNA 3D

Element Types

- Beam elements → Hughes-Liu
  - The rigid body rotations do not generate strains, allowing for the strain treatment of finite strains that occur in many practical applications
  - Robustness and the computational efficiency
  - Compatibility, the element is based on a degenerated brick element formulation
  - It includes finite transverse shear strains; it does not make assumption of no transverse shear strain
  - It takes great care for calculating accurate bandings

Element Types (Cont.)

- Shell elements → Belytschko-Tsay

It is Ideal for thin shell elements to capture large Lagrangian deformations

Computationally efficient Alternative to the Hughes-Liu Shell Element

For a shell element with 4 through-the-thickness integration points:

- **The Blytschko-Lin_Tsay shell element requires 725 mathematical operation**
- **The Hughes-Liu requires 35,367 mathematical operations.**

For its mathematical efficiency is chosen here the Shell Element Formulation

Test Article Weight

Item	weight (lb)	Quantity	Total (lb)	FEA Model (lb)
ATD	170	6	1020	1020
Mannequin	161	12	1932	1932
Cameras	22	4	88	88
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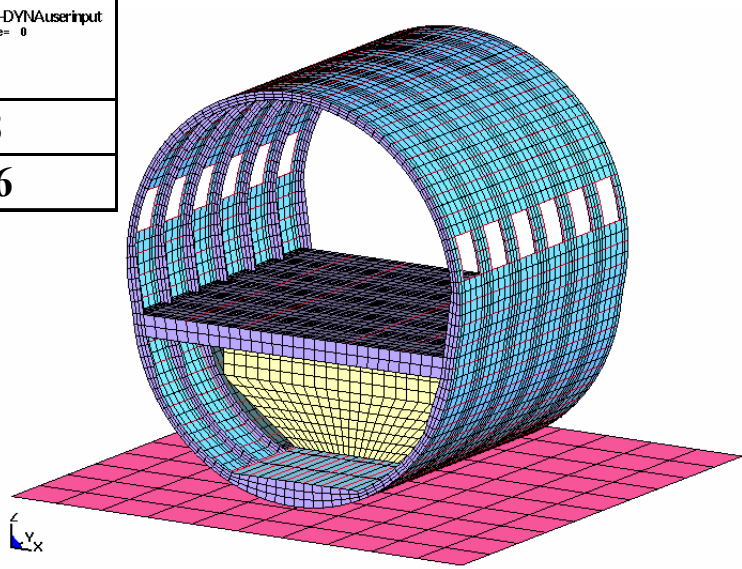

Test Conditions:

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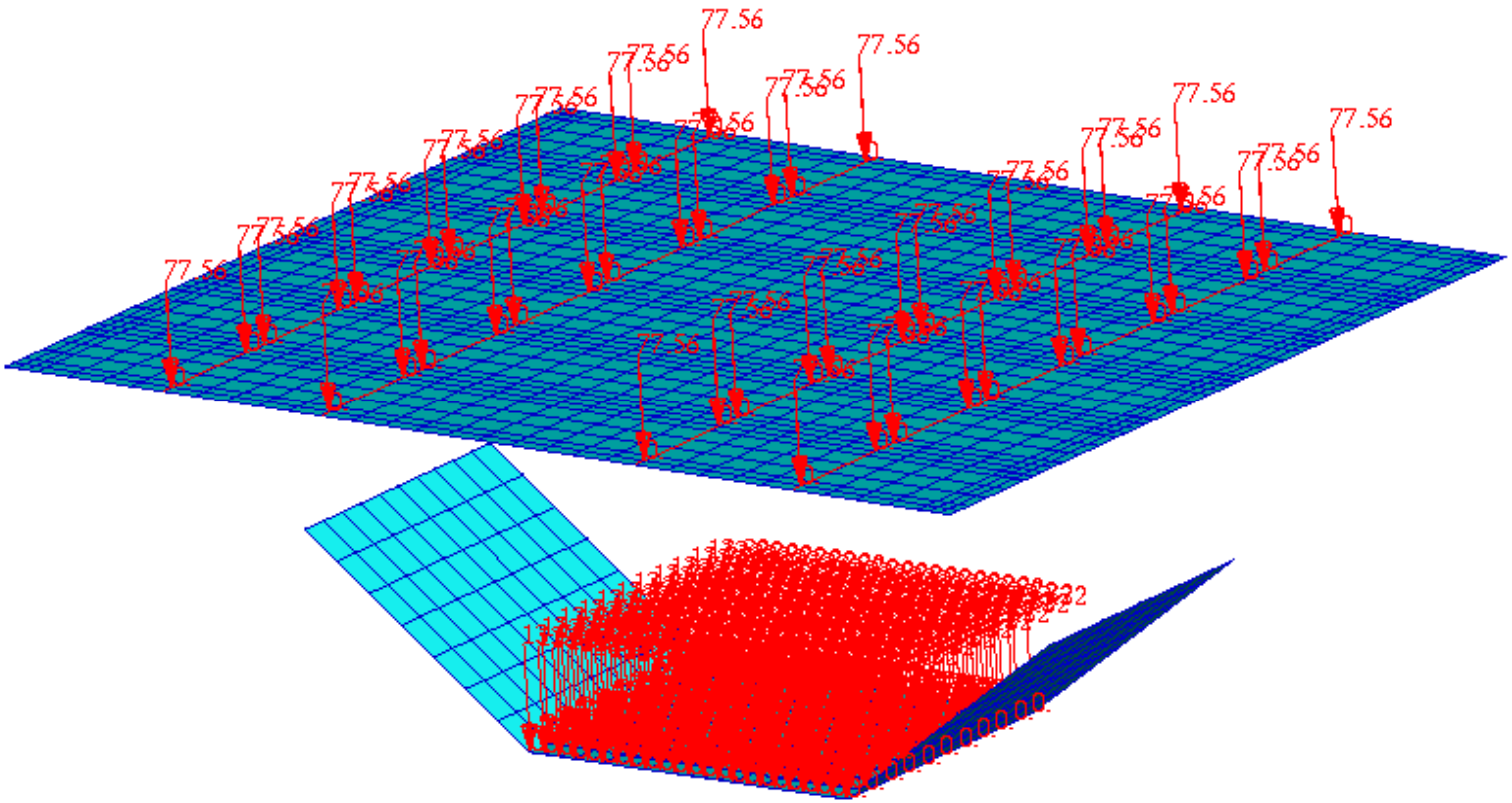
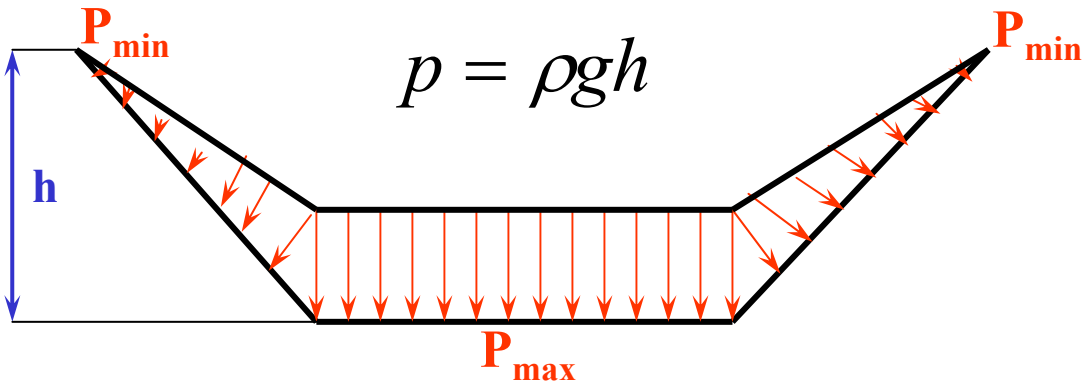
Velocity=360in/s
Total Weight=8,780lb
Passengers=6triple occupant (170lb.each)
Cargo=3,740lb Conformable Auxiliary fuel tank

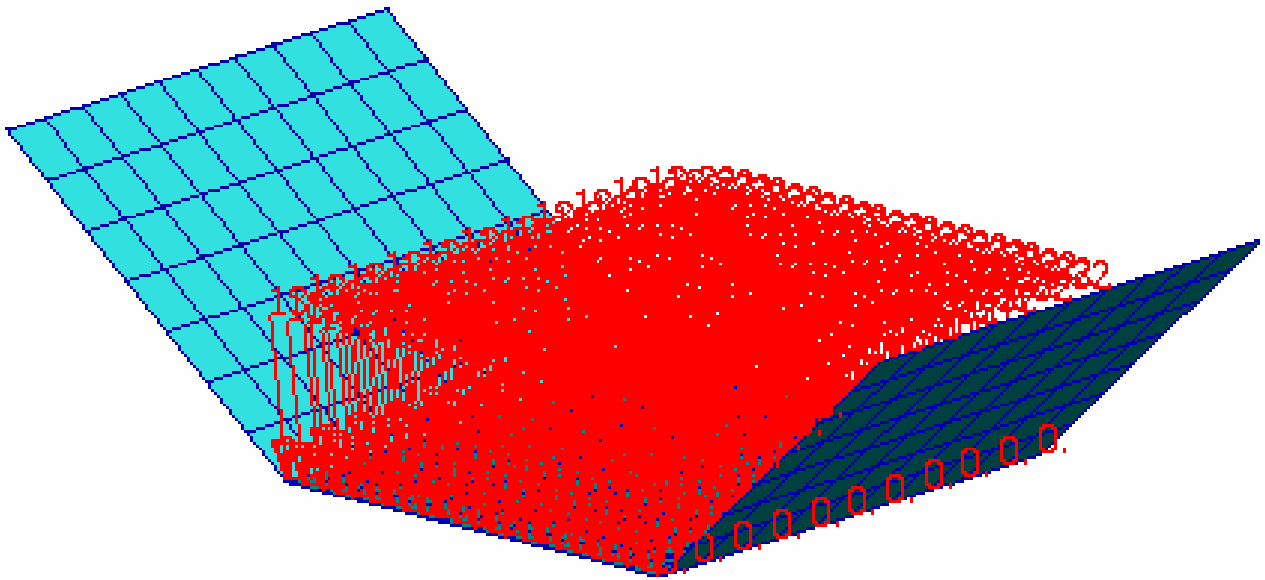
Force and Boundary Conditions

•Nodal Loads in the form of concentrated mass distribution at the location of each seat legs on the fuselage floor seat track

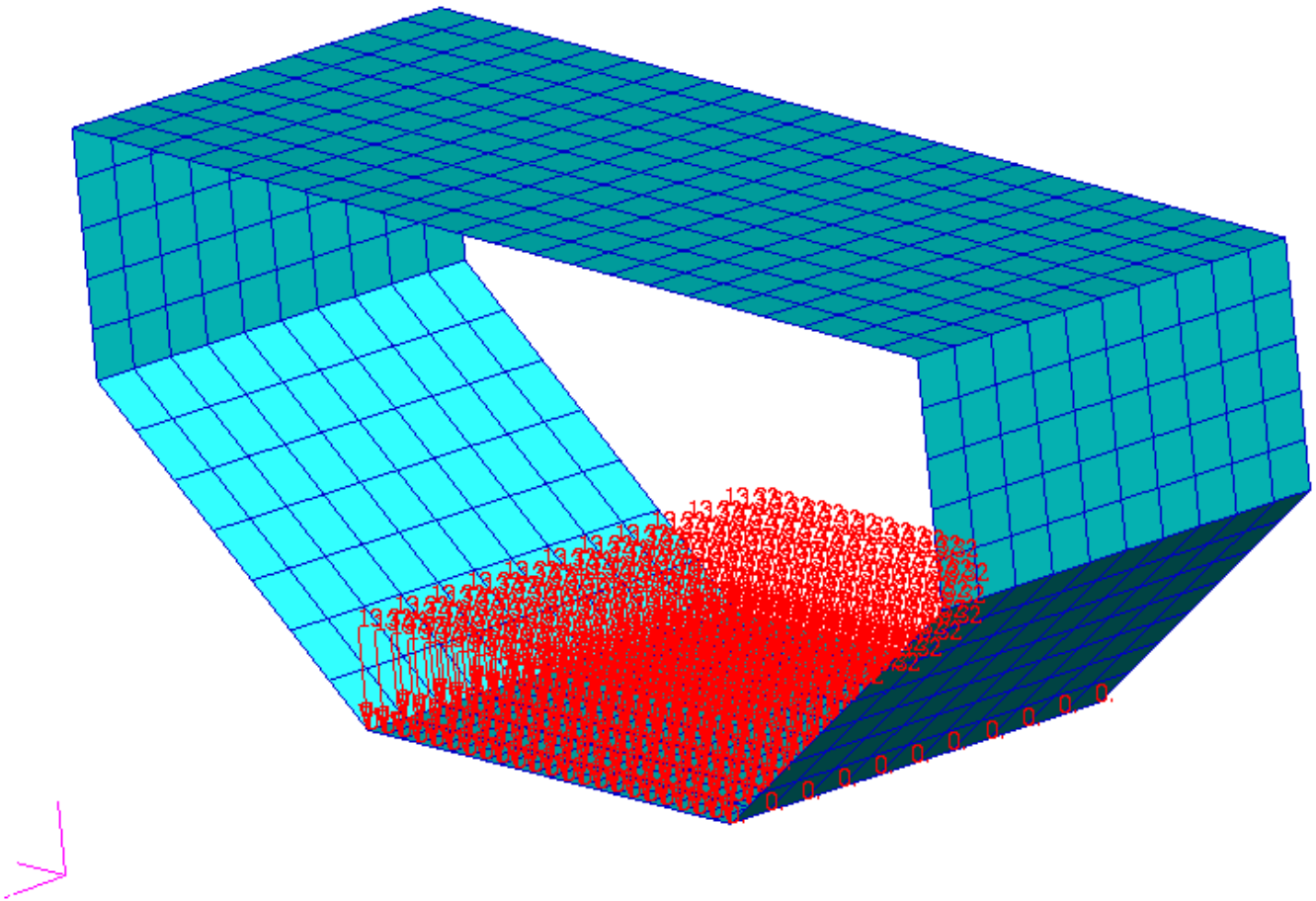


Force and Boundary Conditions (Cont.)

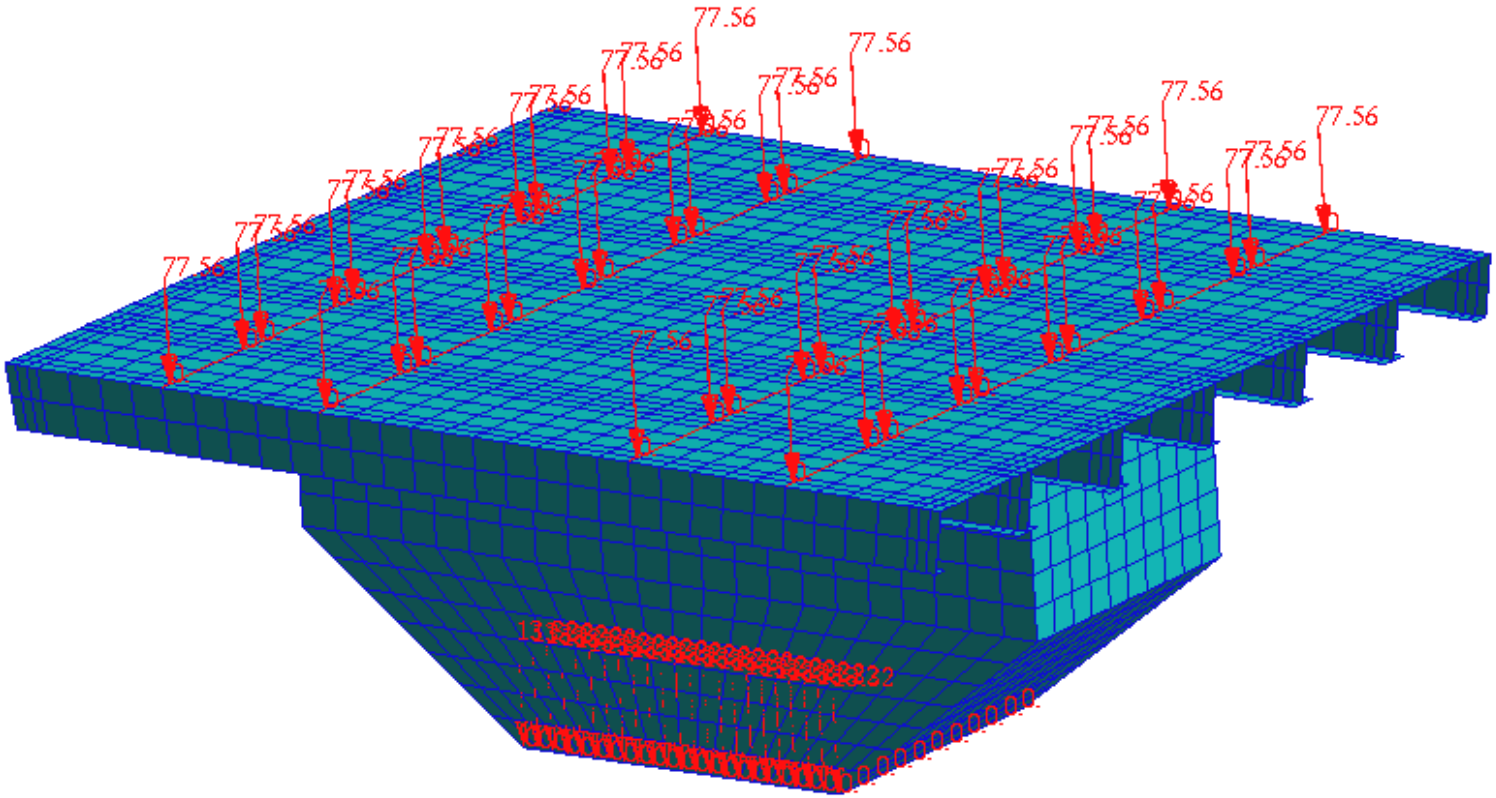




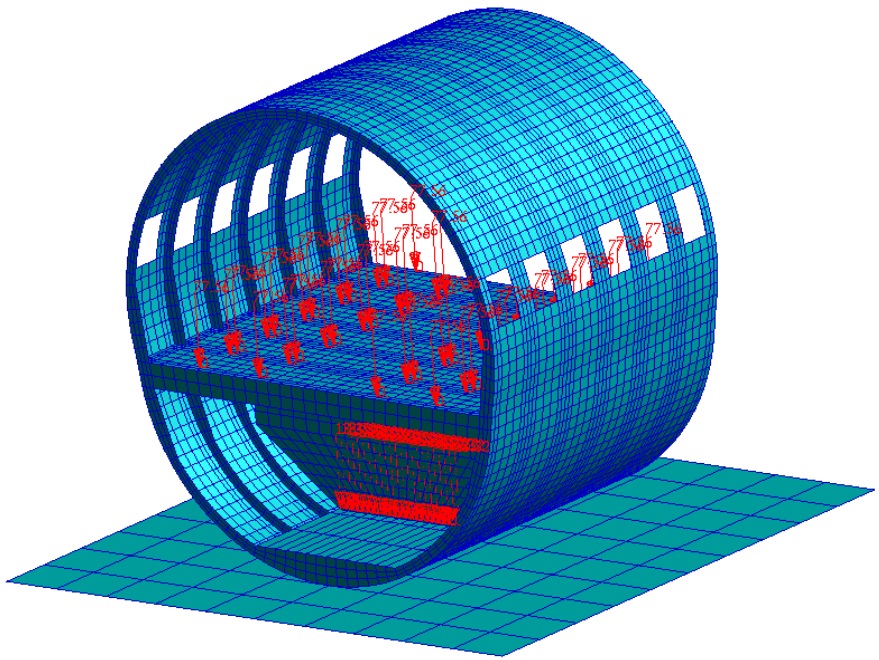
Force and Boundary Conditions (Cont.)



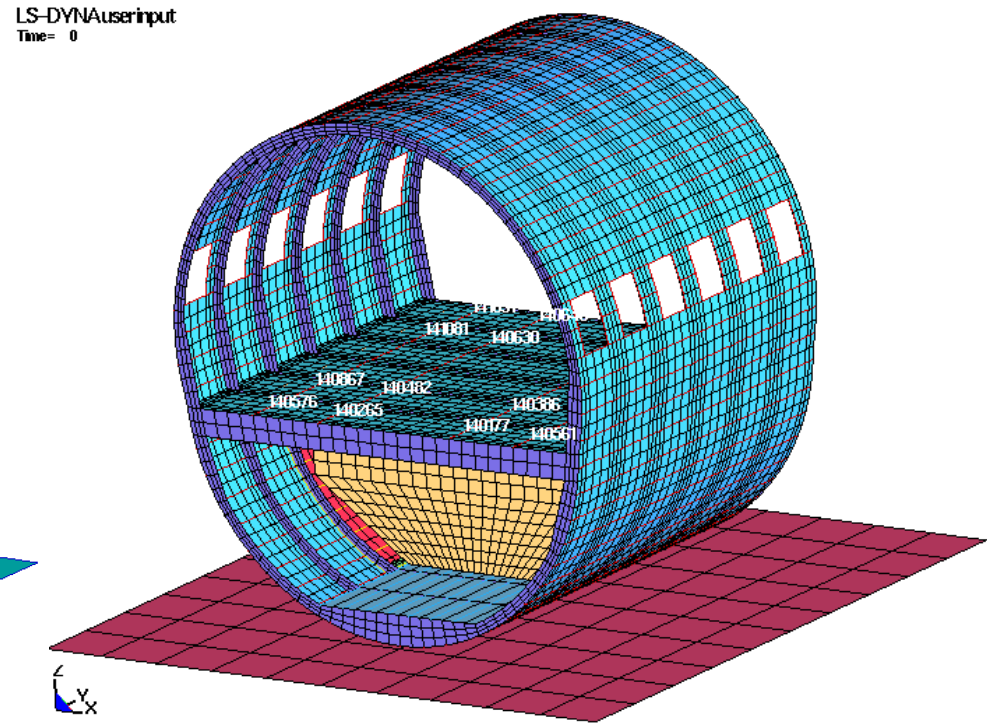
Force and Boundary Conditions (Cont.)



FE Model

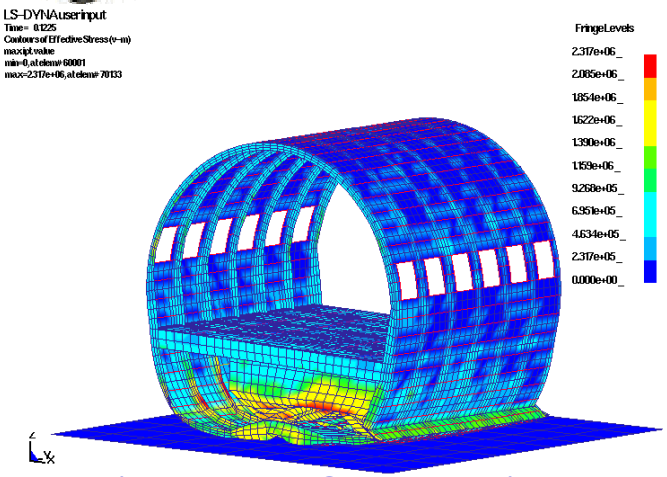


PATRAN FE MODEL

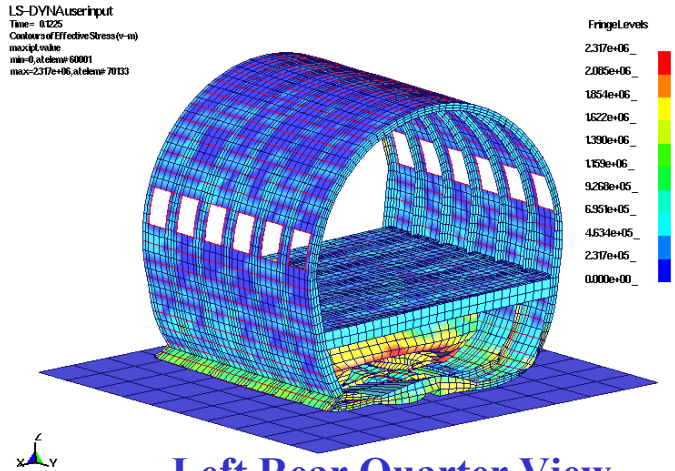


LS-DYNA 3-D MODEL

Von Misses Stresses

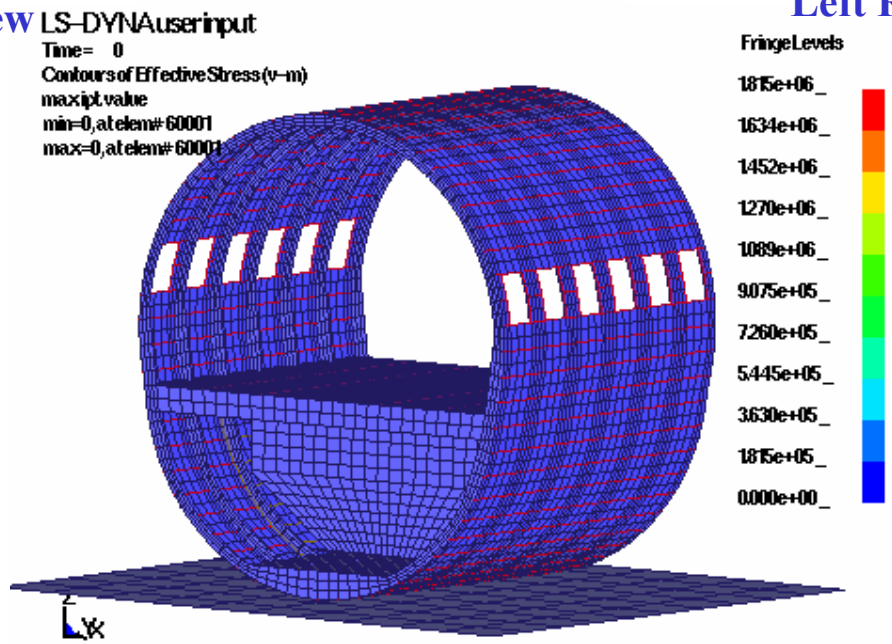


Right Front Quarter View



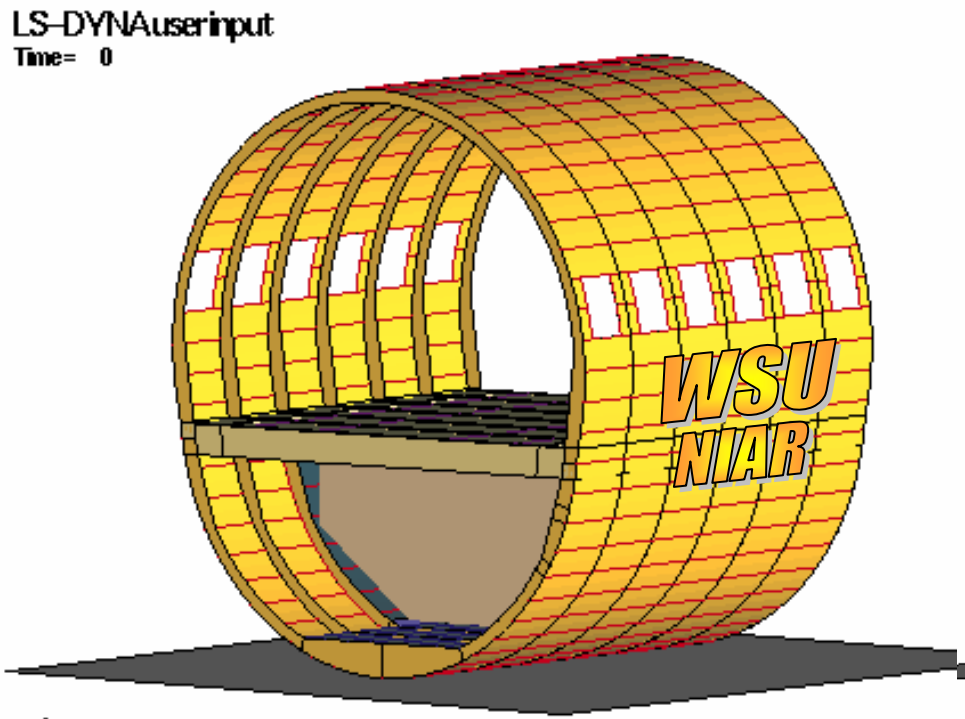
Left Rear Quarter View

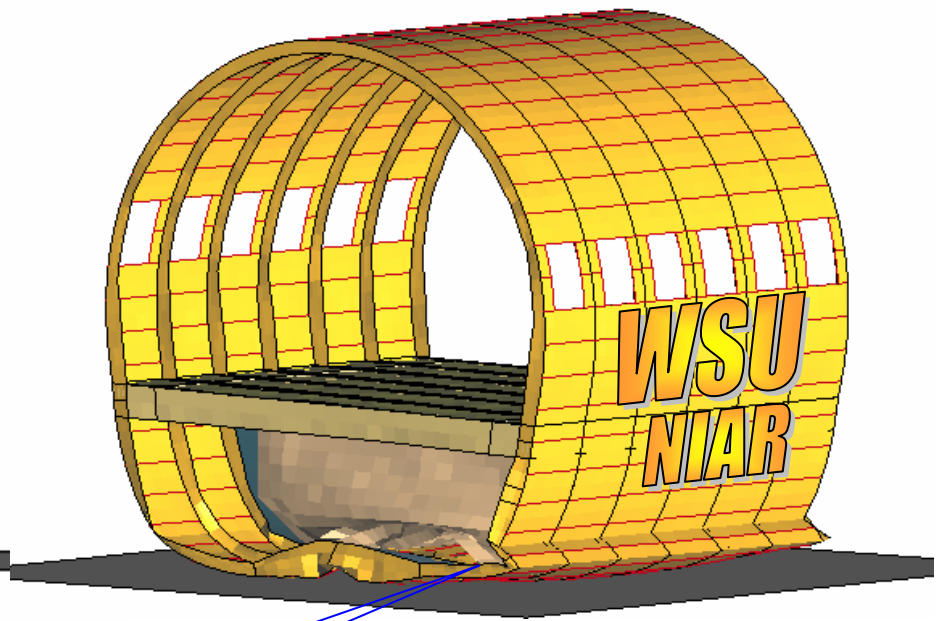
Simulation



Results From Fuselage Drop Simulation

Maximum Deformations at Relax stage (Equilibrium)



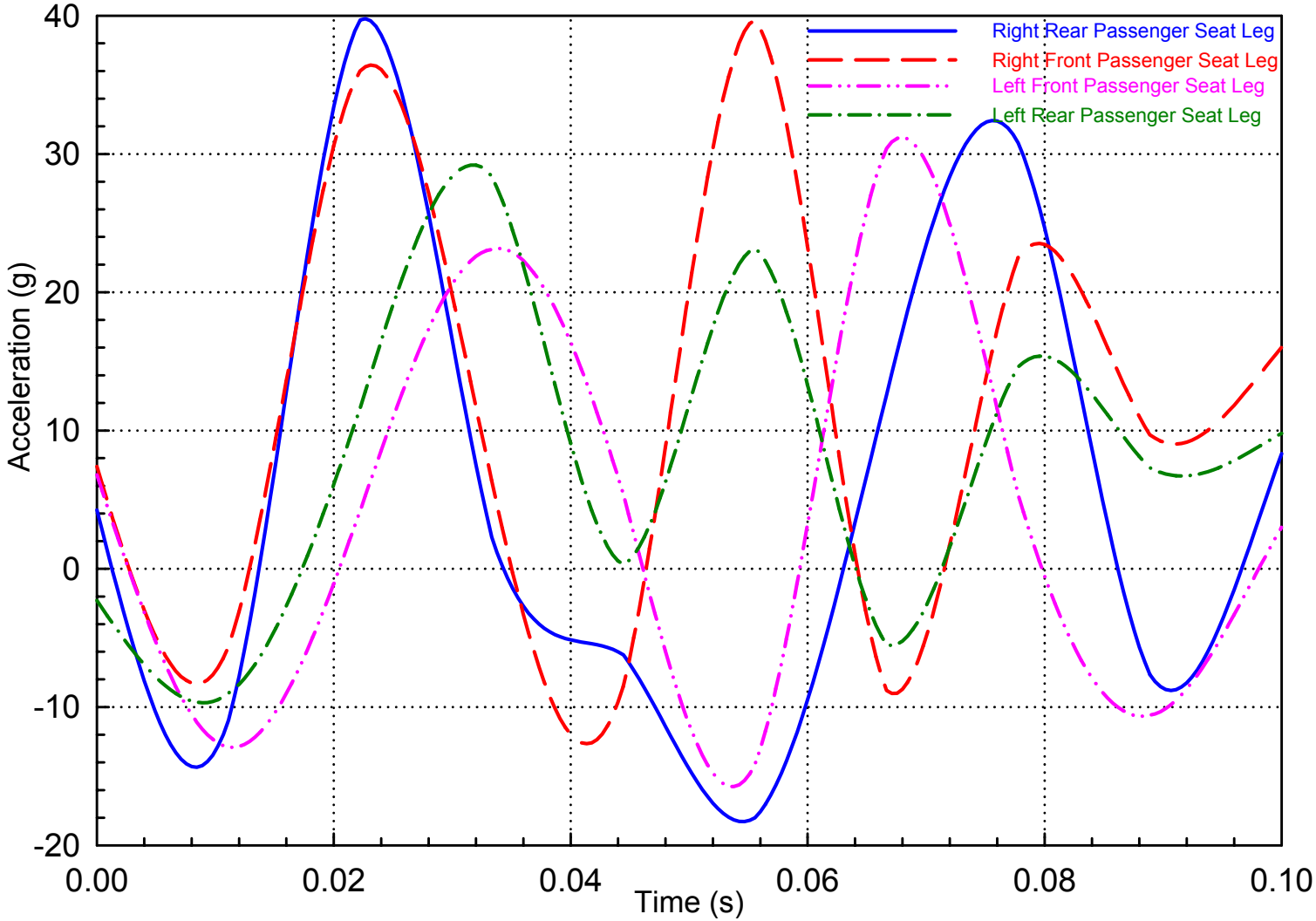


Pre-Deformed Structure

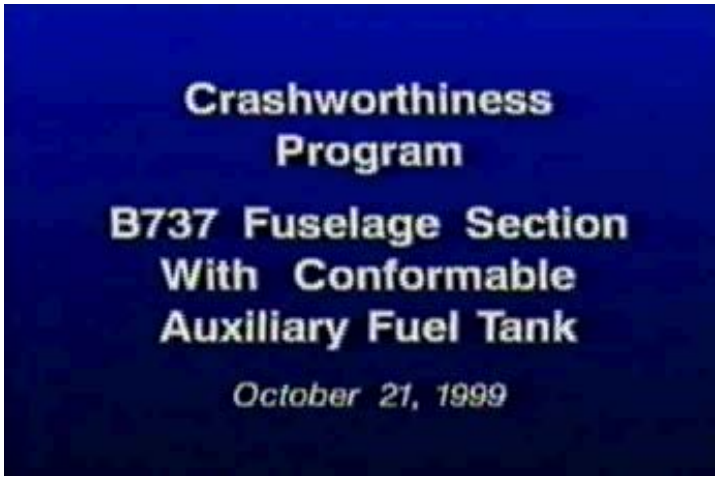
Right Front Quarter View

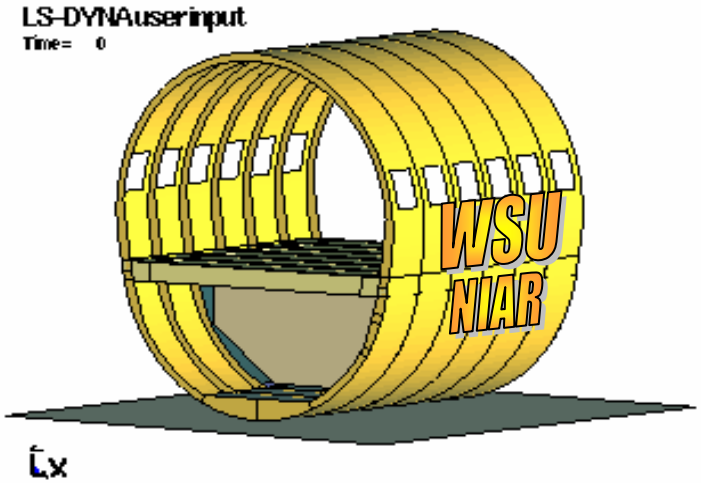
Plastic Hinge

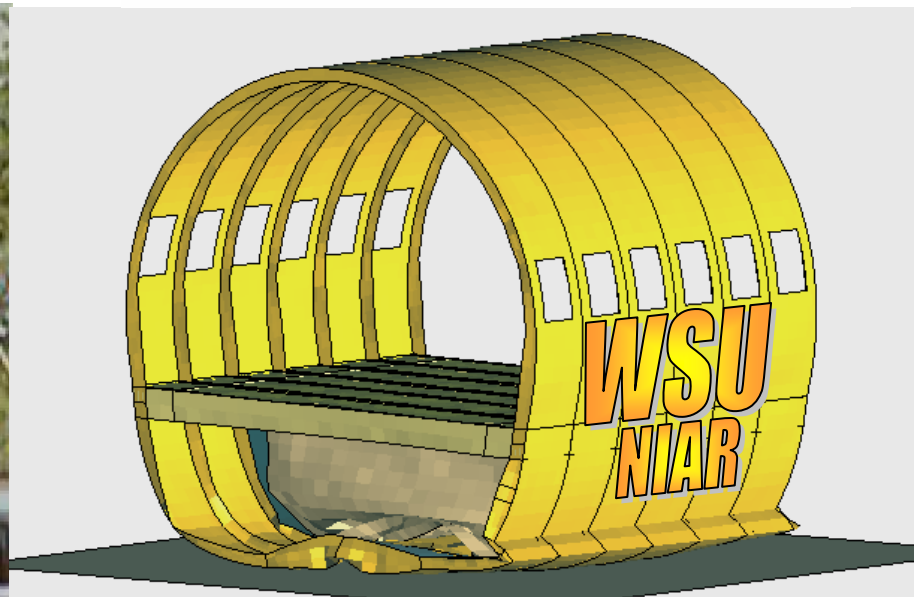
Acceleration Profile for right and Left side Fuselage at Impact



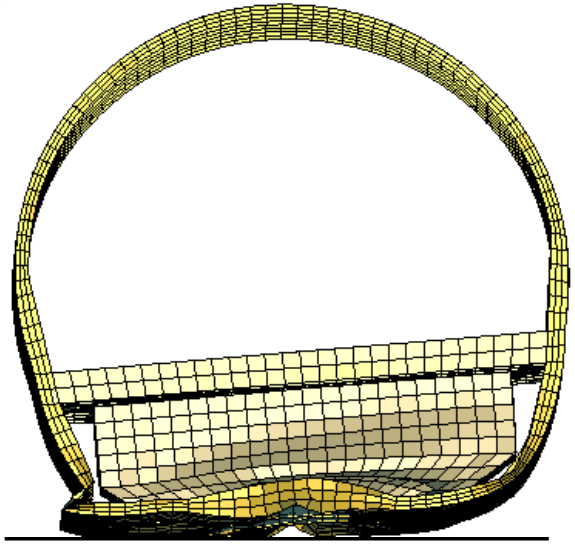
Simulation Analysis and Validations



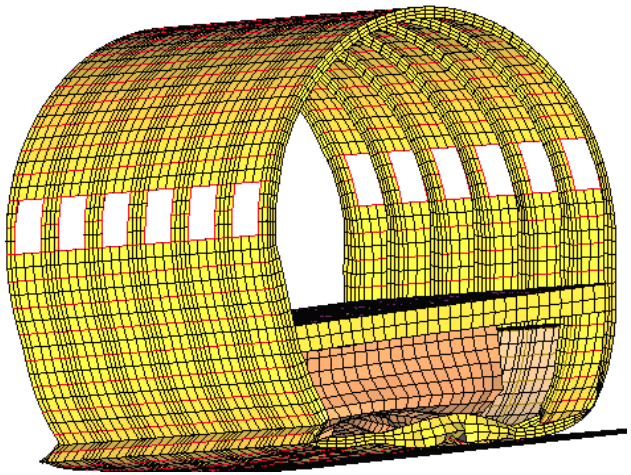




Results and Validation



Rear View

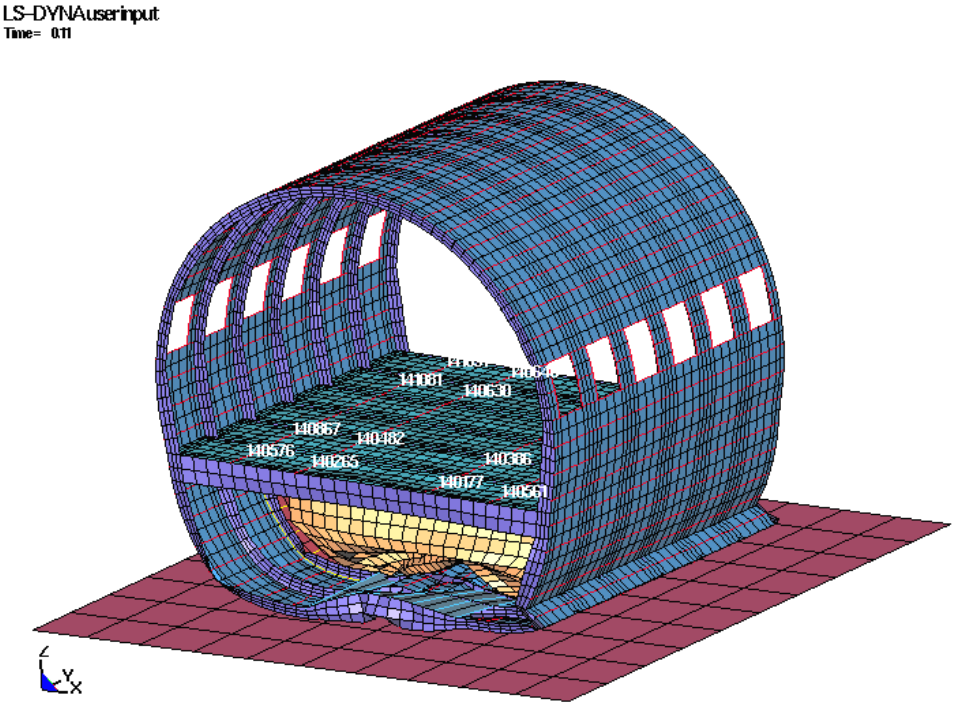


Simulation

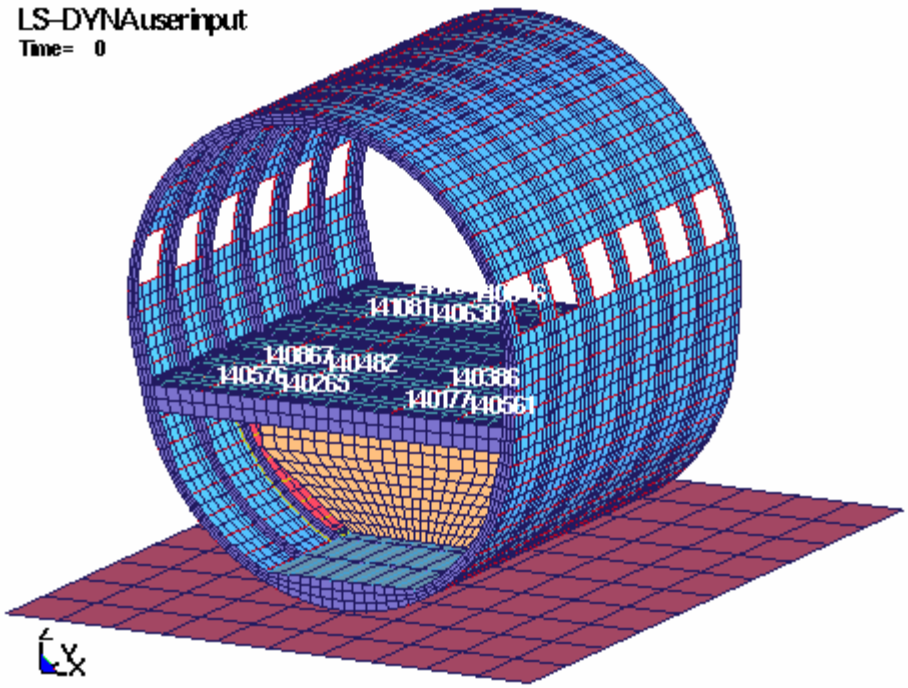
Experiment

Left Rear Quarter View

Results

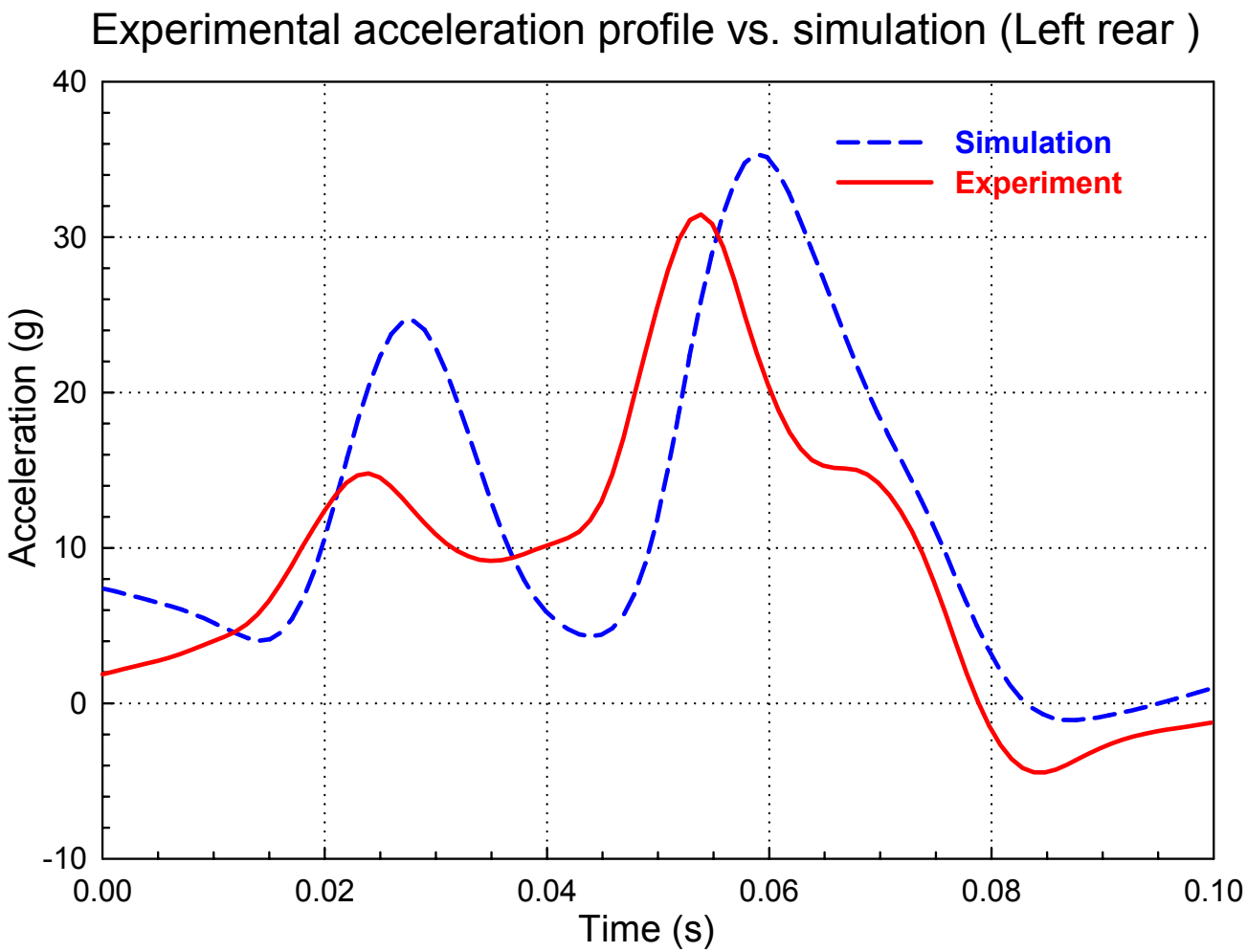


Post Crash Test Deformations at Relax stage (Equilibrium)

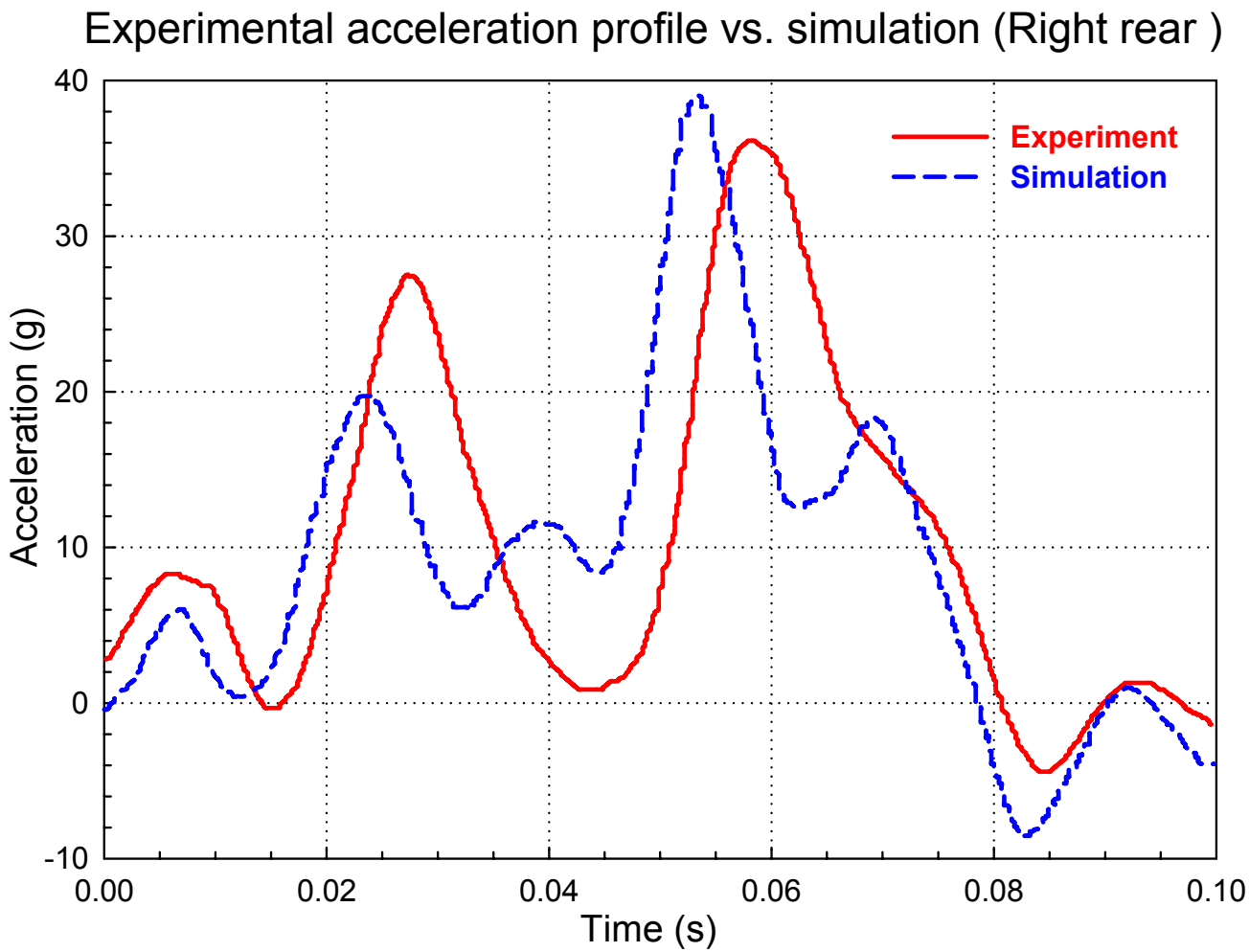


Pre-Deform Fuselage Structure

Validation

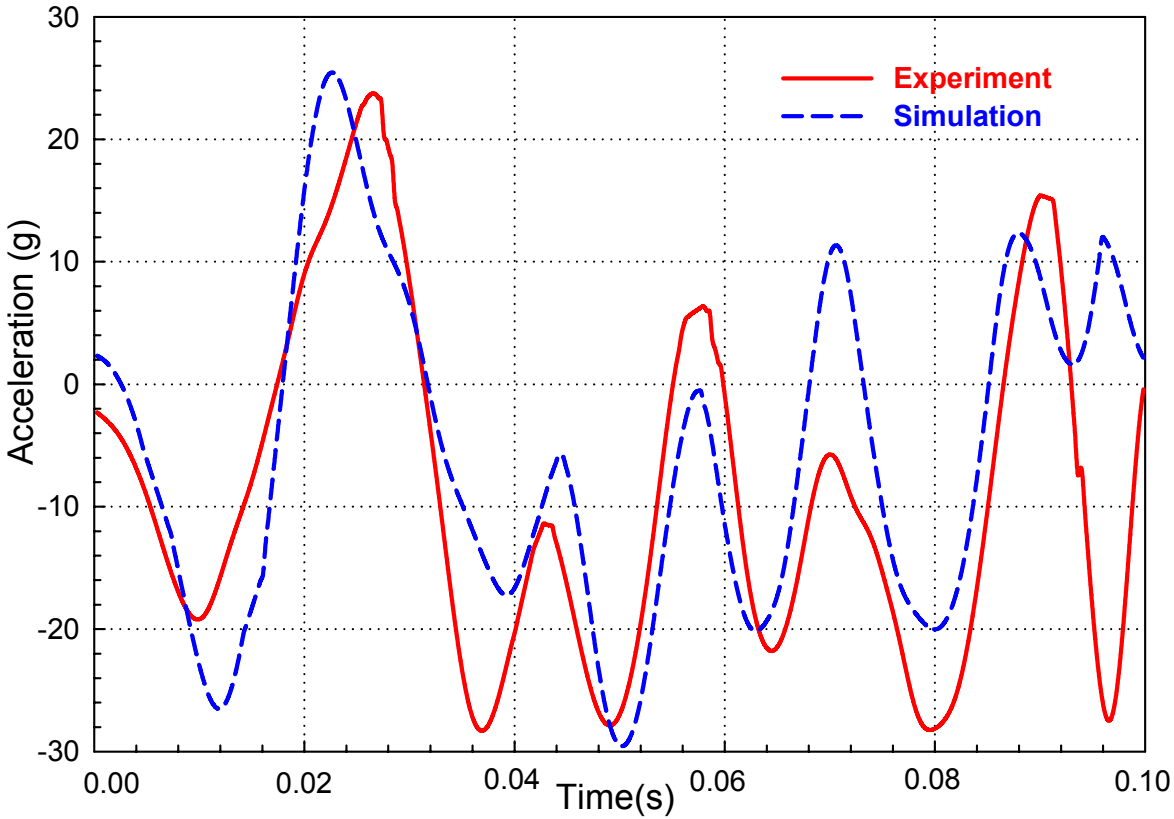

Experimental acceleration profile vs. simulation (Left rear)
Simulation
Experiment
Acceleration (g)
Time (s)
40
30
20
10
0
-10
0.00
0.02
0.04
0.06
0.08
0.10

Validation (Cont.)



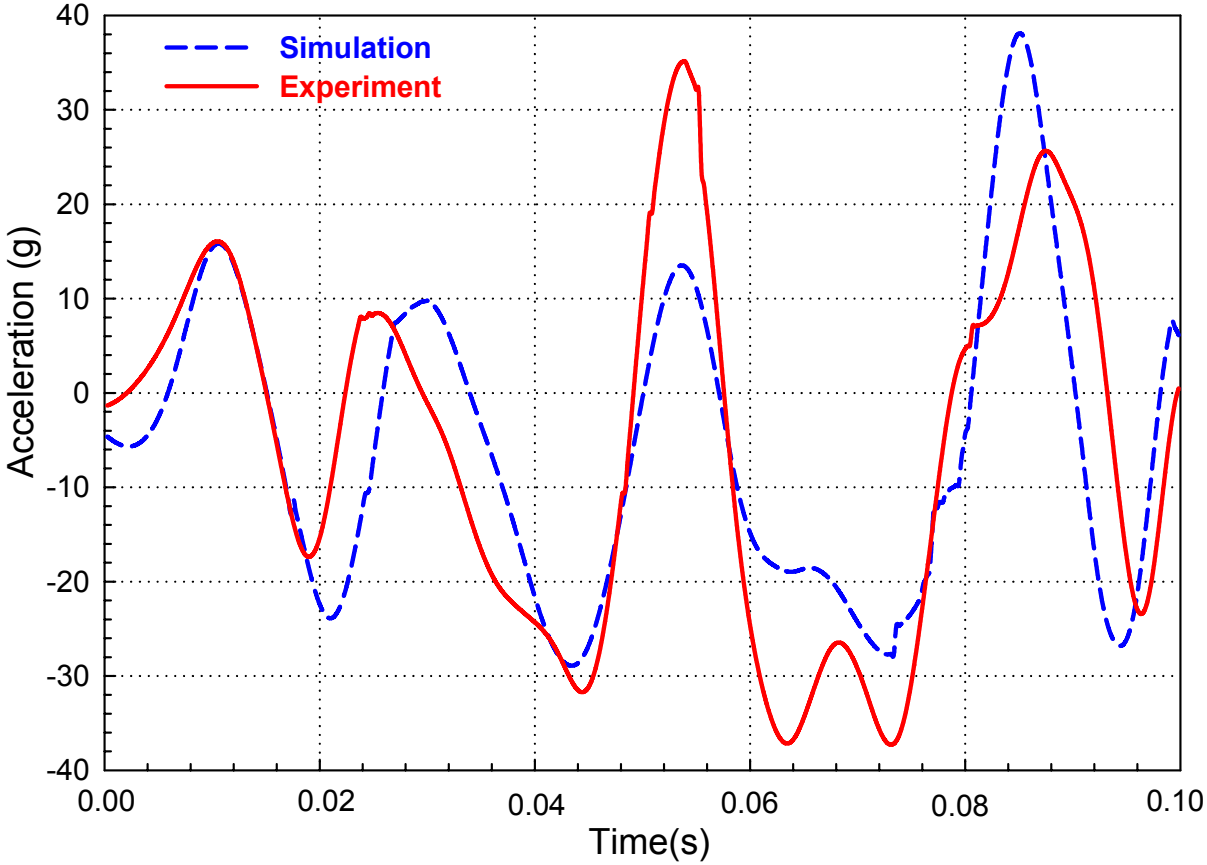
Validation (Cont.)

Left front fuselage acceleration profile simulation Comparing to that of experimental.



Validation (Cont.)

Right front fuselage simulation acceleration profile compare to that of experimental

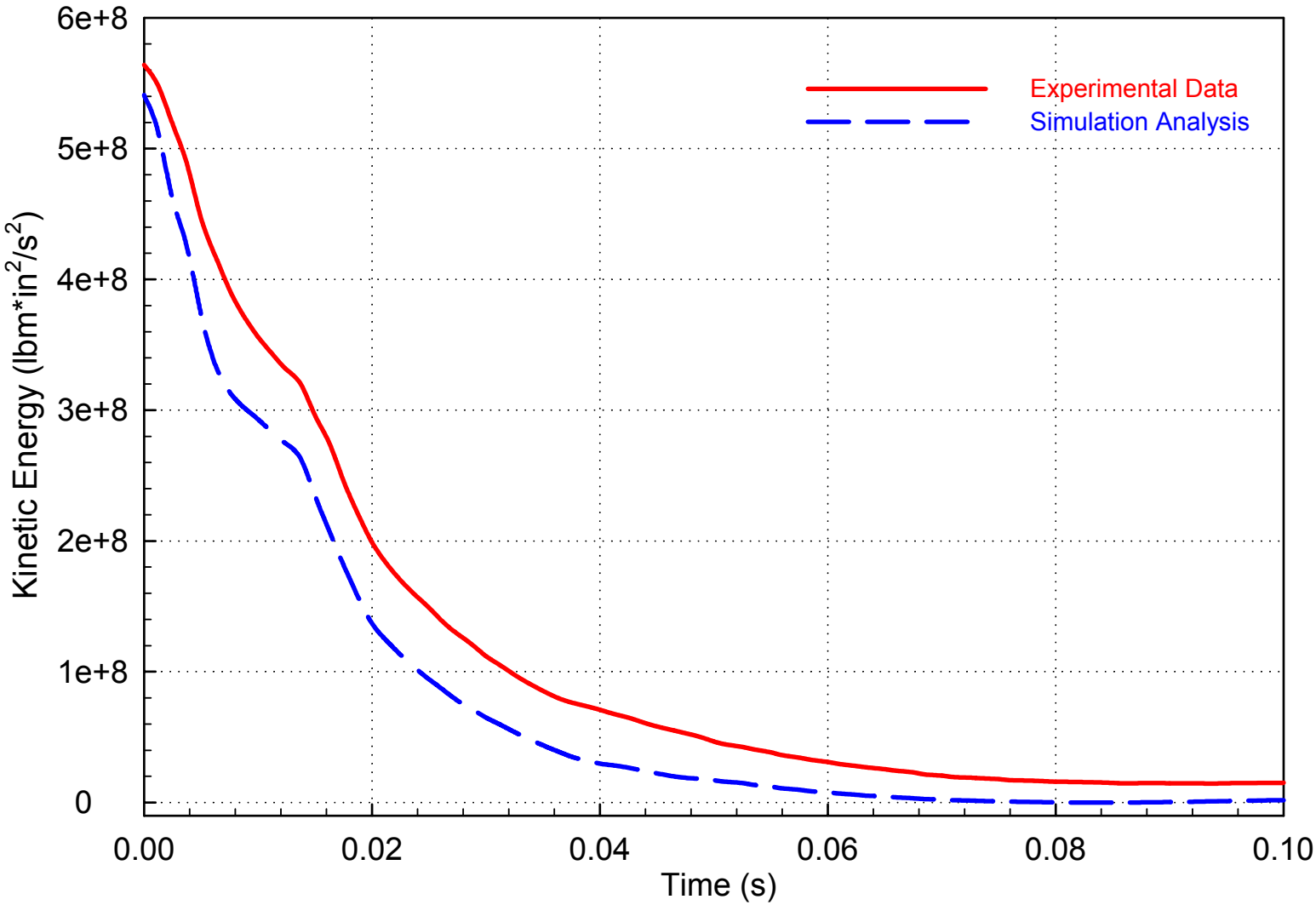


Summary of Acceleration Results for Right and Left Side Passenger Floor

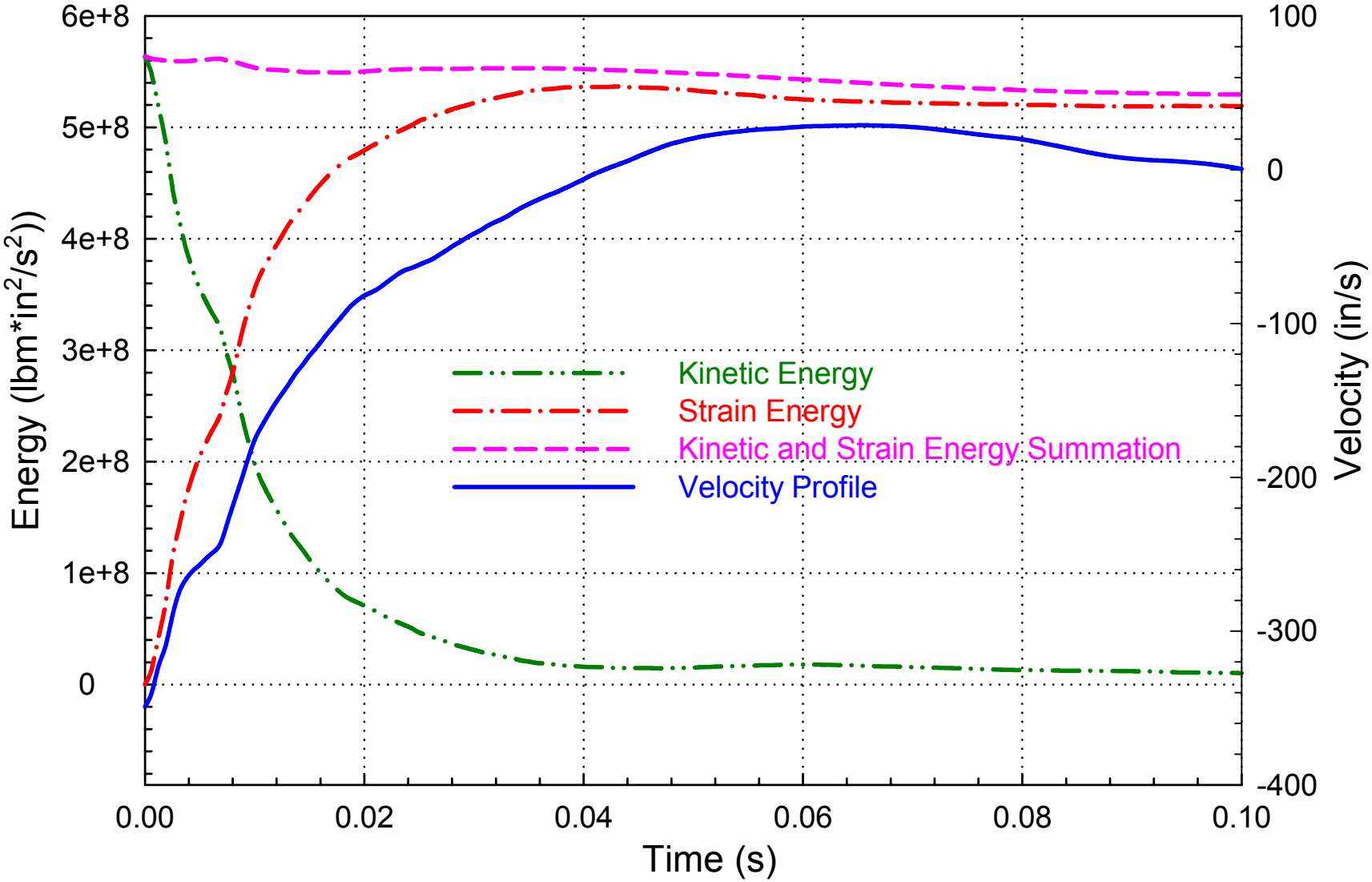
Location	Average Pulse Acceleration						Correlations (%)
	(Experiment)			(Simulation)			
	G_{peak} (g)	Pulse Duration (ms)	Peak Time (ms)	G_{peak} (g)	Pulse Duration (ms)	Peak Time (ms)	
FS 438 (right front seat)	35	10	59	38	9	56	8.6
FS 472 (right rear seat)	37	9	66	39	9	57	5.4
FS 400 (left front seat)	25	10	59	27	10	60	8
FS 504 (left rear seat)	32	10	63	35	10	54	9.4

- The relative high peak acceleration on the right passenger floor is due to the presence of rigid cargo door located on the right side of fuselage
- The relative higher peak acceleration on the aft passenger floor is due to the rearward location of fuel tank

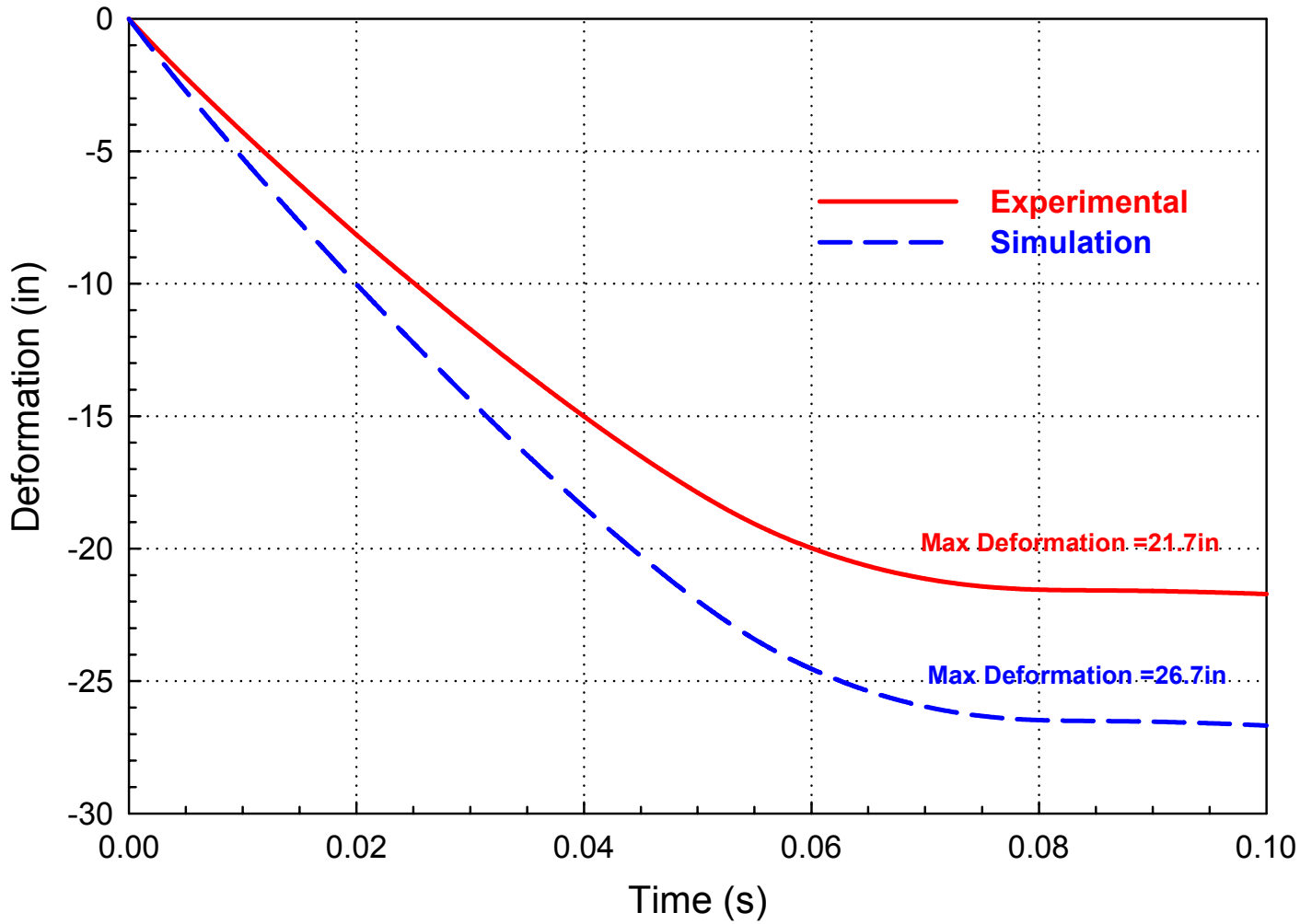
Kinetic Energy



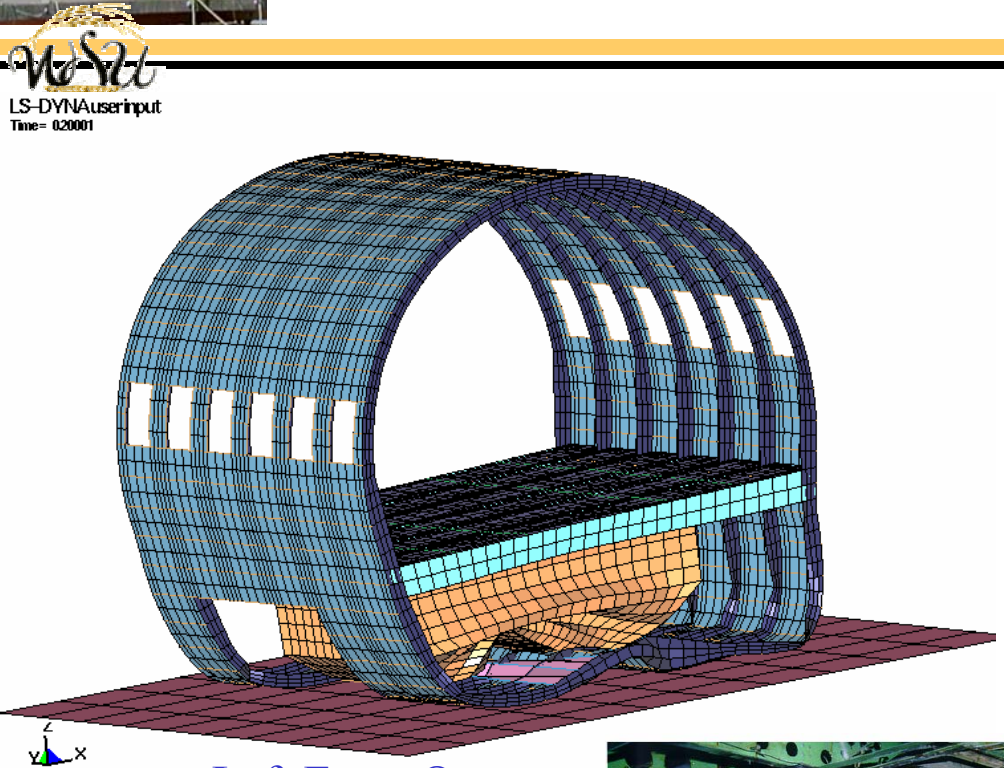
Variation of Kinetic, Strain & Total Energy



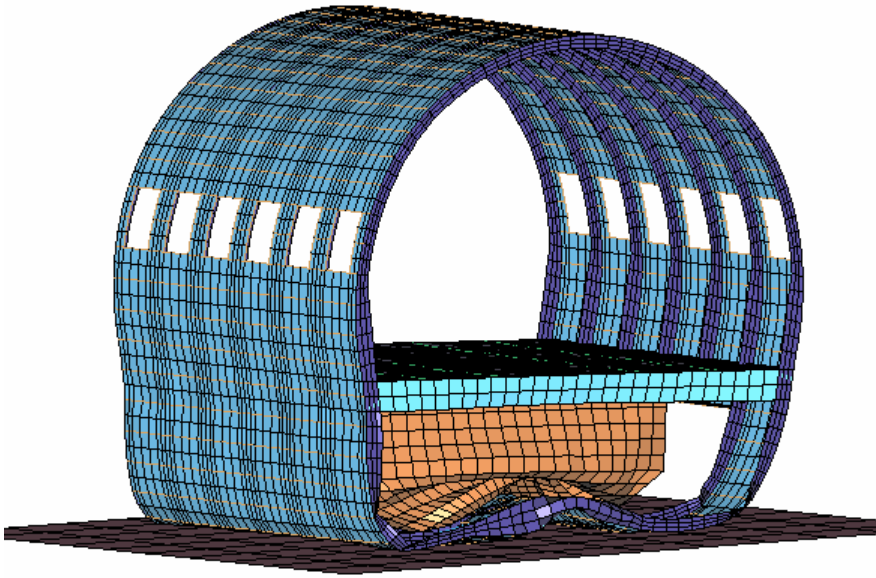
Maximum Global Deformations



Effect of Cargo Door

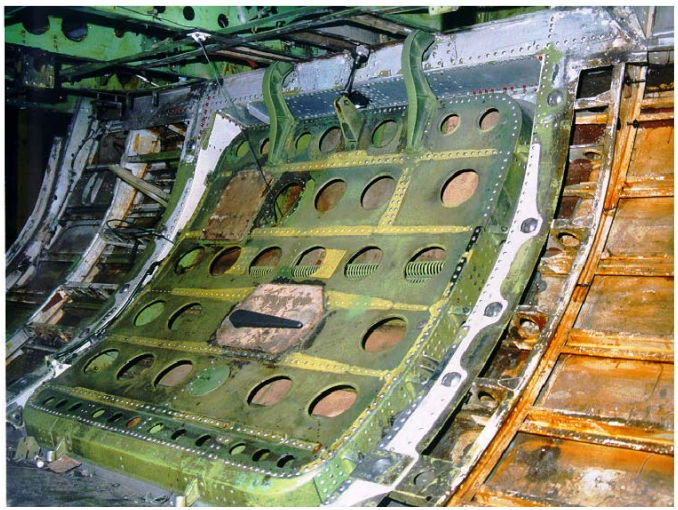


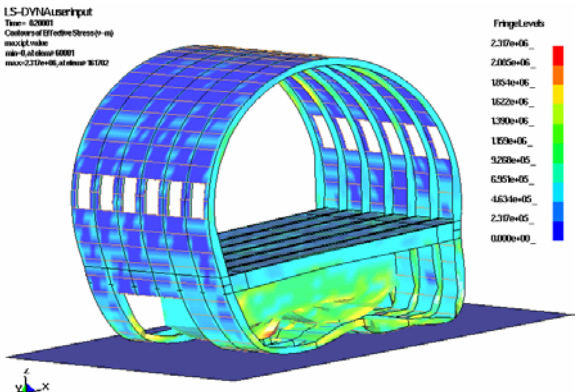
Left Front Quarter View



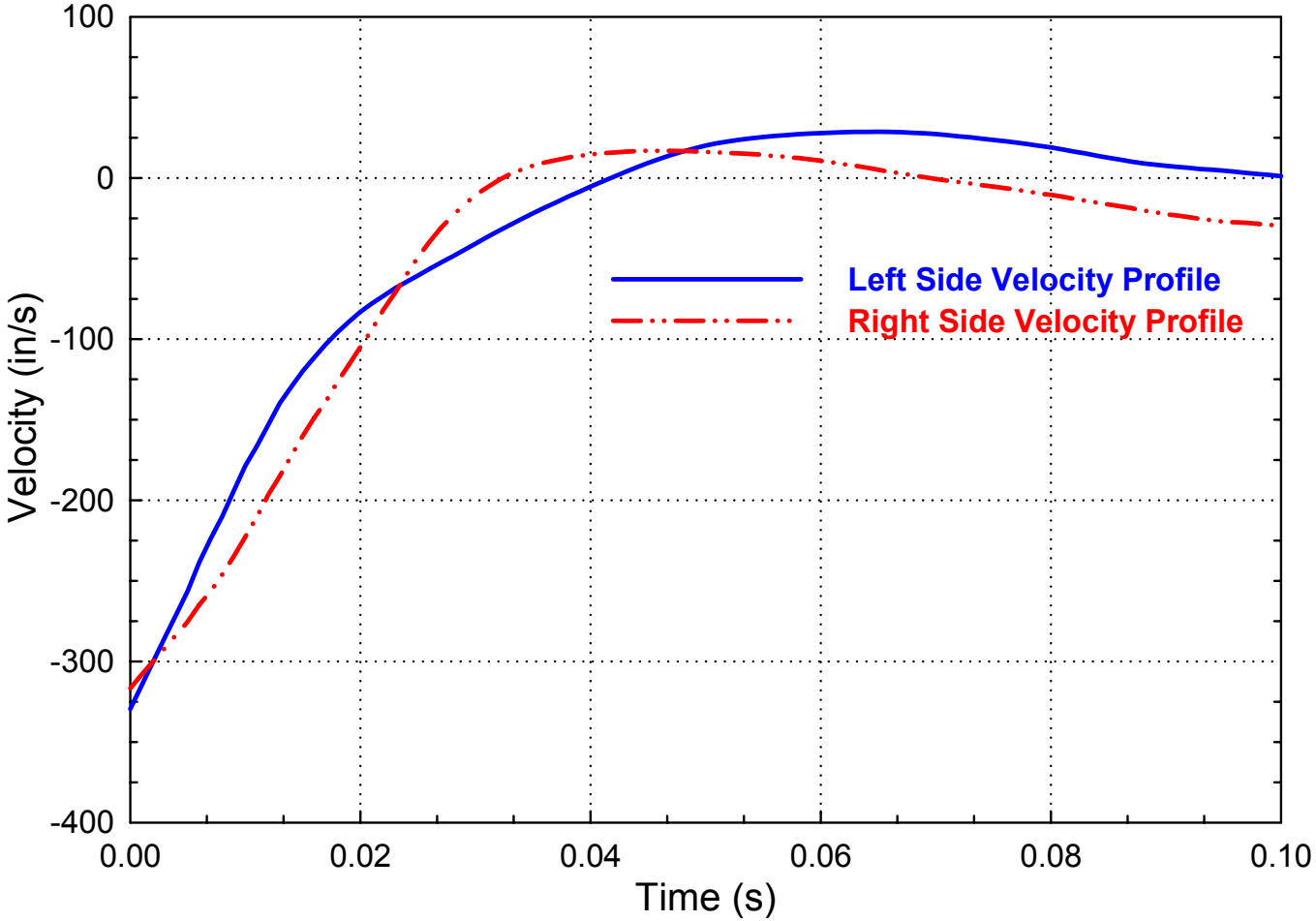
Left Rear Quarter View

Rigid Cargo Door Right Panel





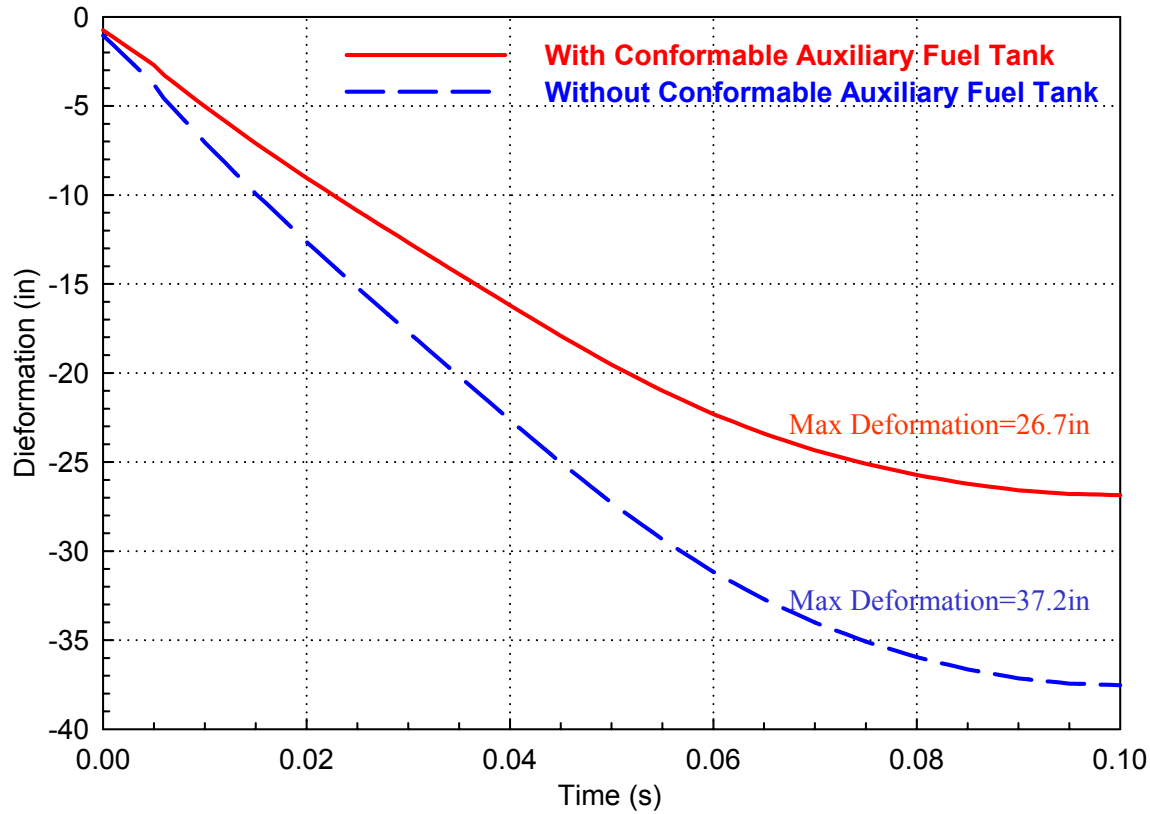
Velocity Profile Comparison of Right and Left Side Fuselage

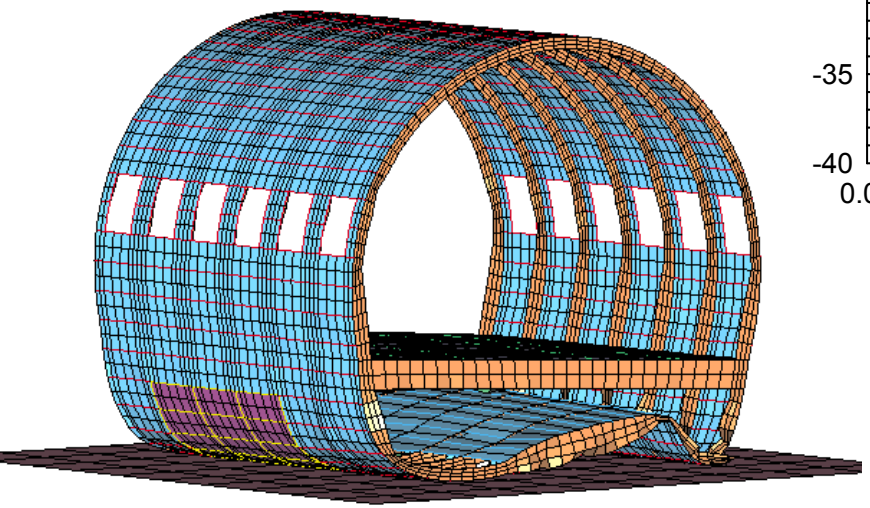


- Right Side Floor Velocity Goes to Zero Sooner than the Left Side Due to Presence of Stiff Cargo Door and Frame

Comparison of Deformations With and Without Conformable Auxiliary Fuel Tank On Board

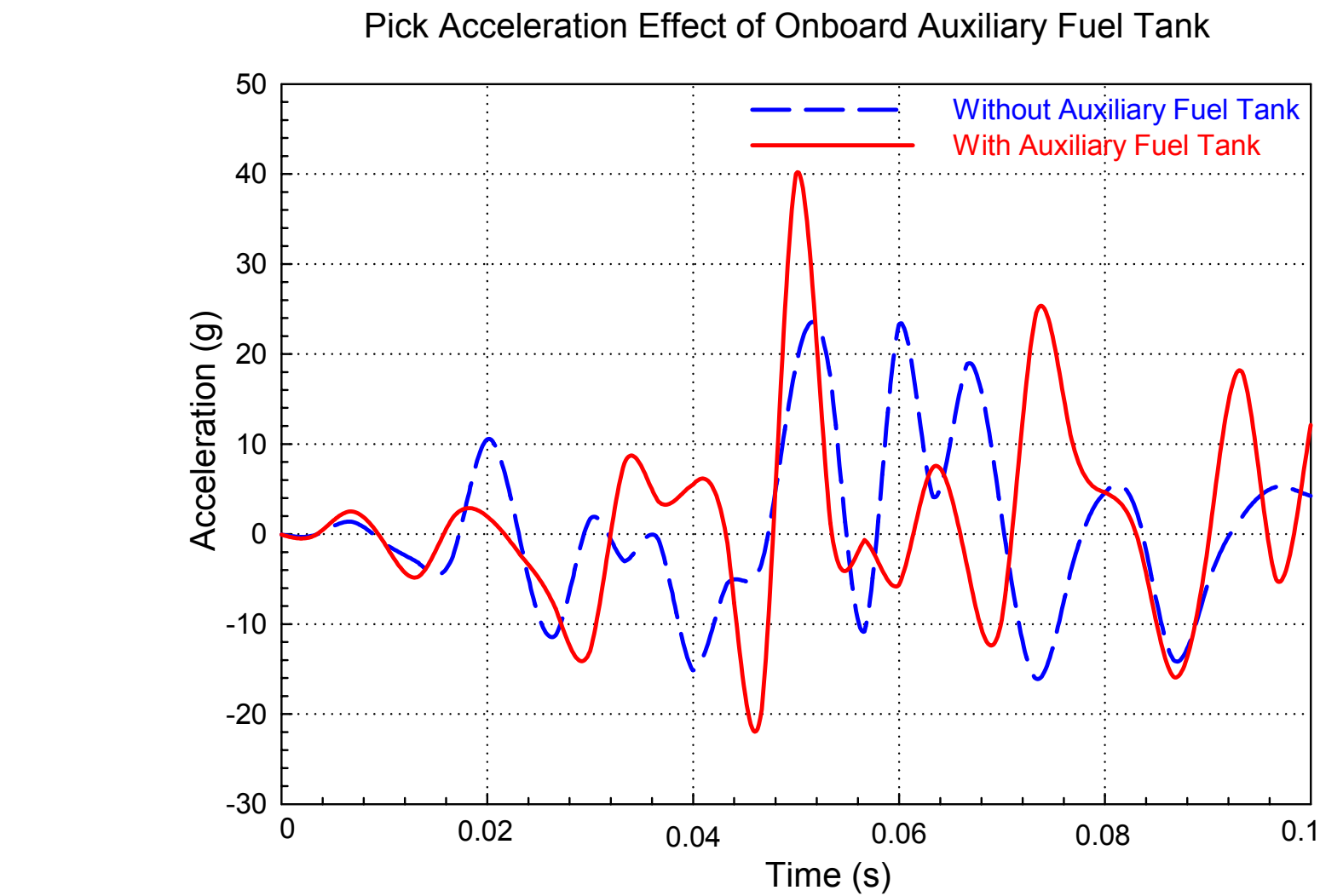
Maximum Deformation (in)	
With Fuel Tank	26.7
Without Fuel Tank	37.2





Maximum Deformation Without on board Conformable Auxiliary Fuel Tank

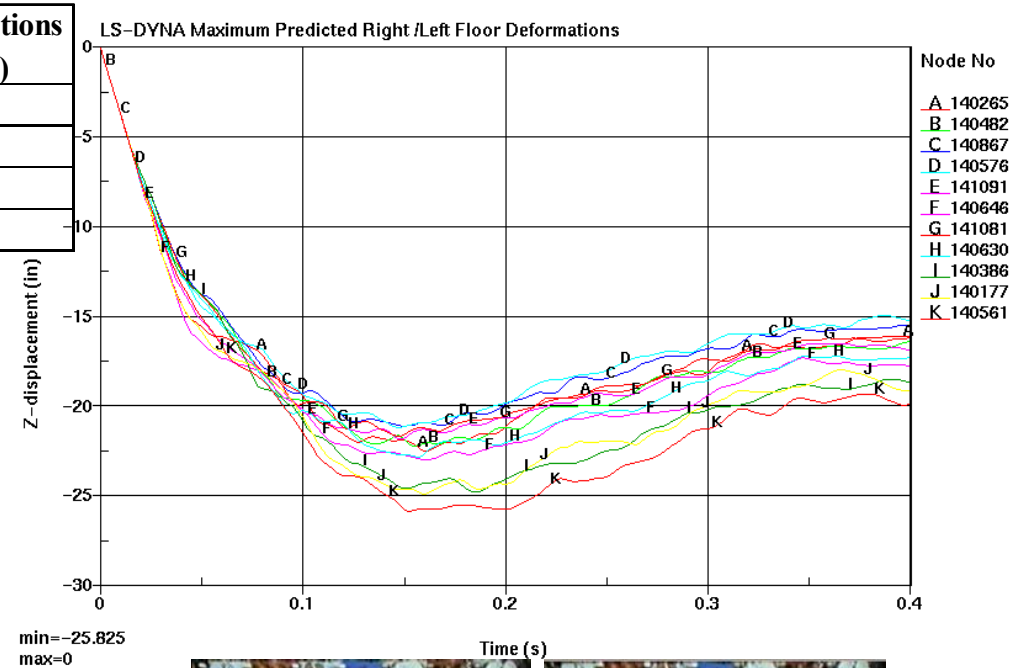
Effect of Rigid Auxiliary Fuel Tank on the Peak Acceleration

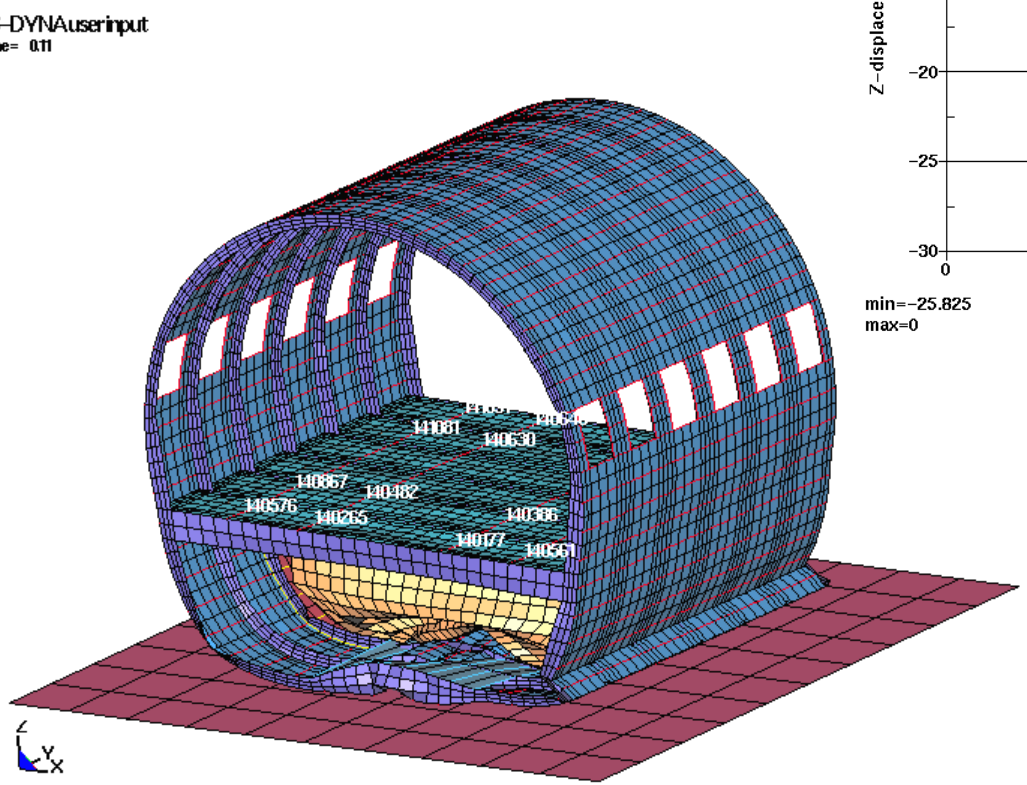


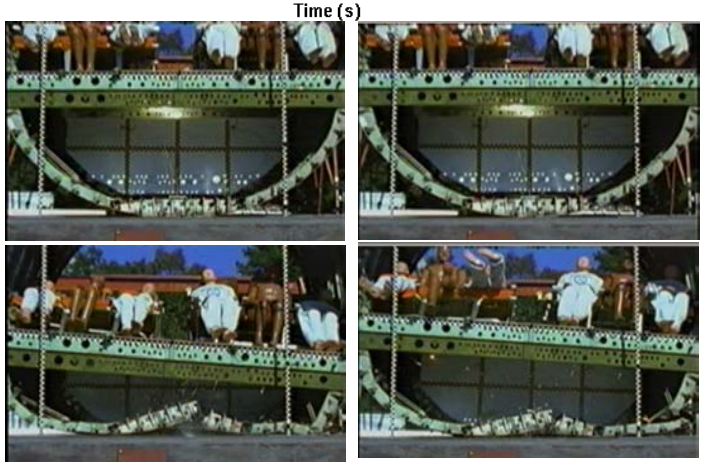
Role of Structural Stiffness in Peak Acceleration

The Effect of Spring Back

Location	Maximum Deformation		Correlations
	(Experiment)	(Simulation)	(%)
FS 400 (right front seat)	10.7	12.2	14
FS 438 (right rear seat)	10.5	11.6	11
FS 472 (left front seat)	21.7	26.8	19
FS 504 (left rear seat)	20.7	23.4	13

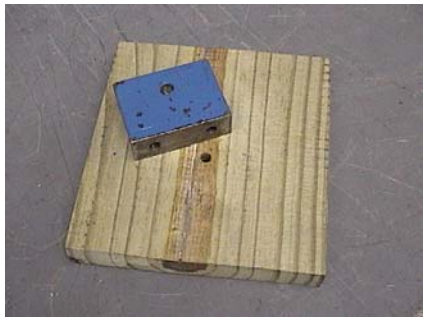




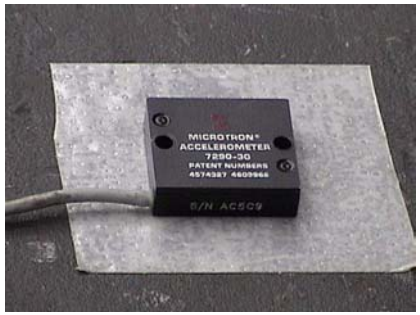


Post Crash Spring Back Effect

1/20th-Scaled Experimental Impact Test (NIAR)



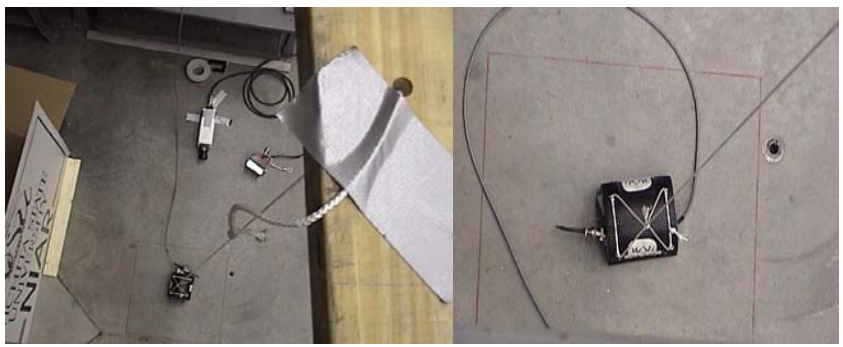
Adding 1.1 lb Weight



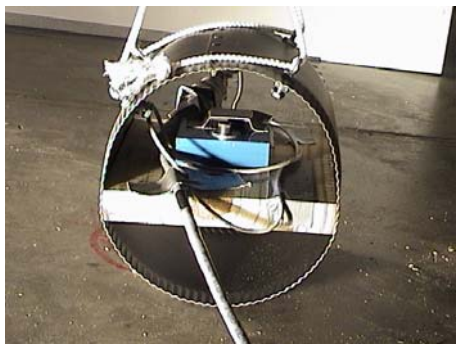
Micron Accelerometer

Accelerometer Positioning

14ft Drop Height

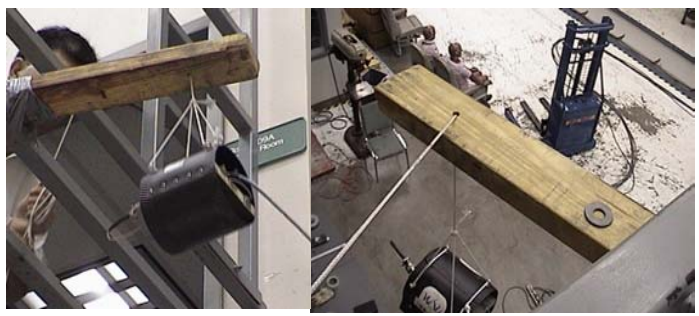


Impact Position Marking



Instrumented Model

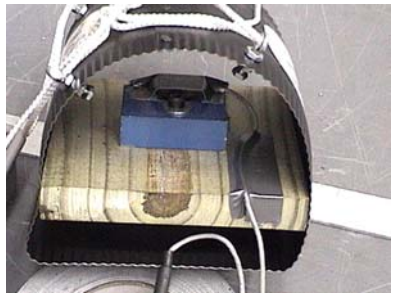
Drop Position



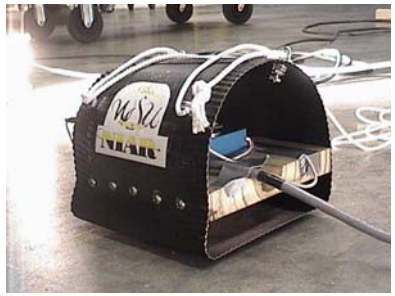
Releasing the Cable

1/20th-Scaled Experimental Impact Test (NIAR)

Data Acquisitions System

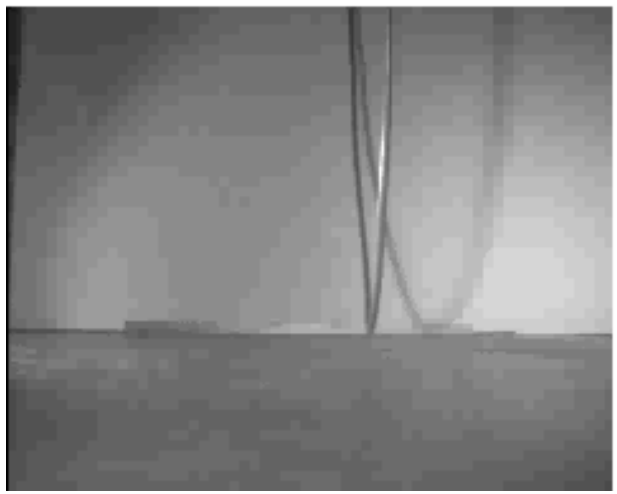


Post Impact Front View

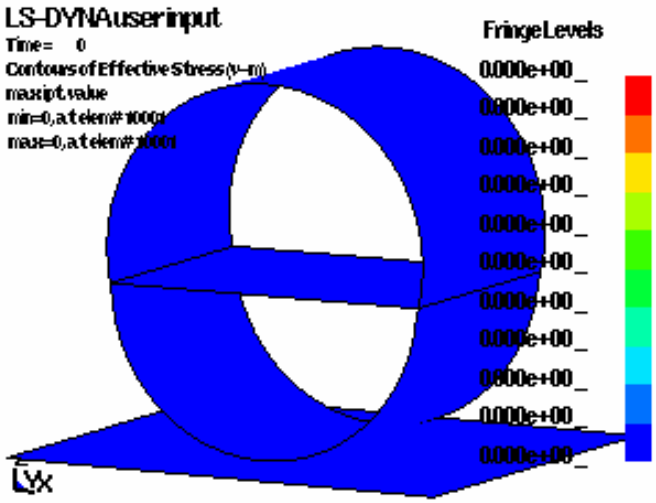


Front Left Quarter View

Scaled to 1/20th of actual size
Weight: 1.1 pounds
Drop height: 14 ft.
Velocity: 26 ft/sec
Acceleration: 28.9 g (Saturated)

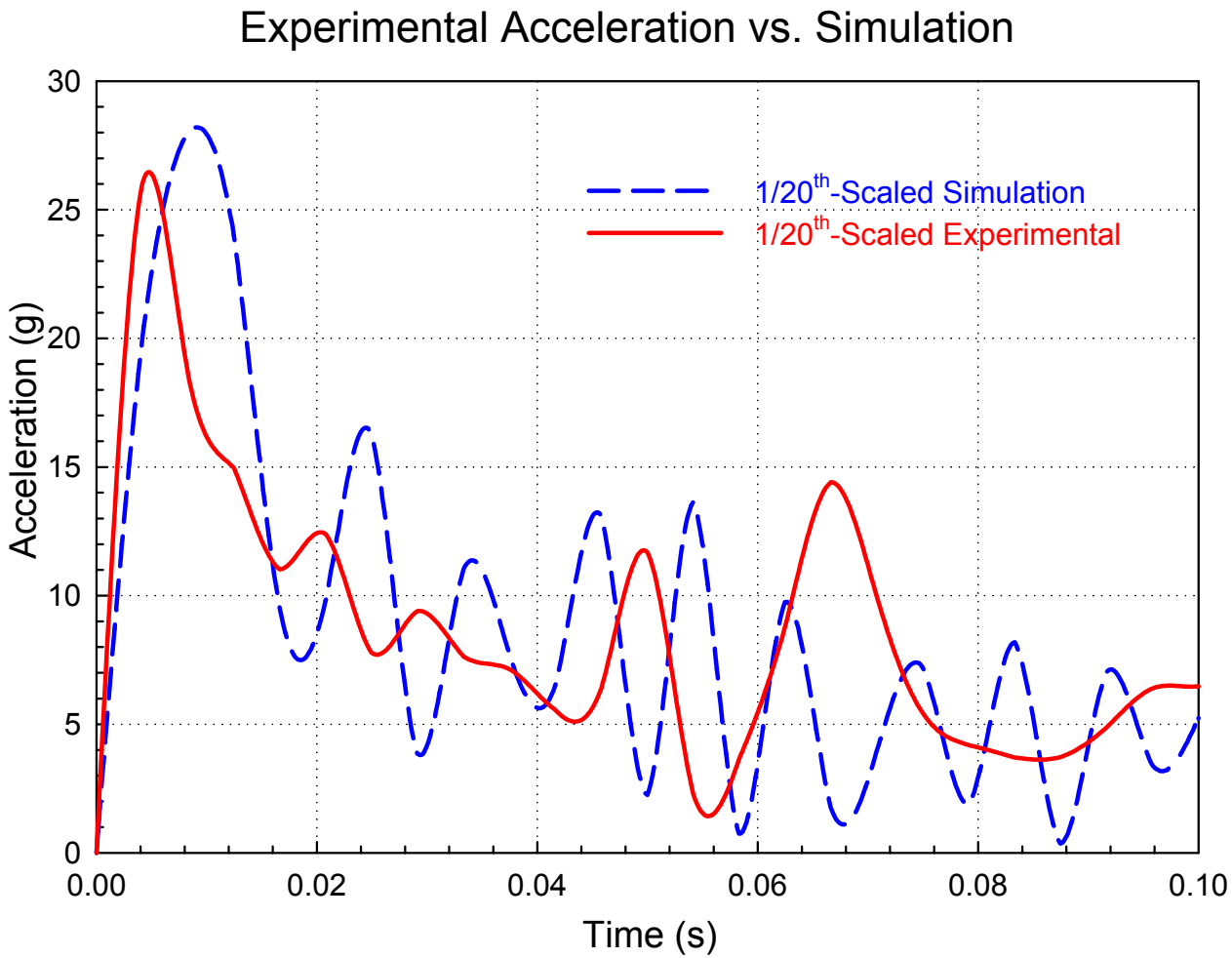


Experimental

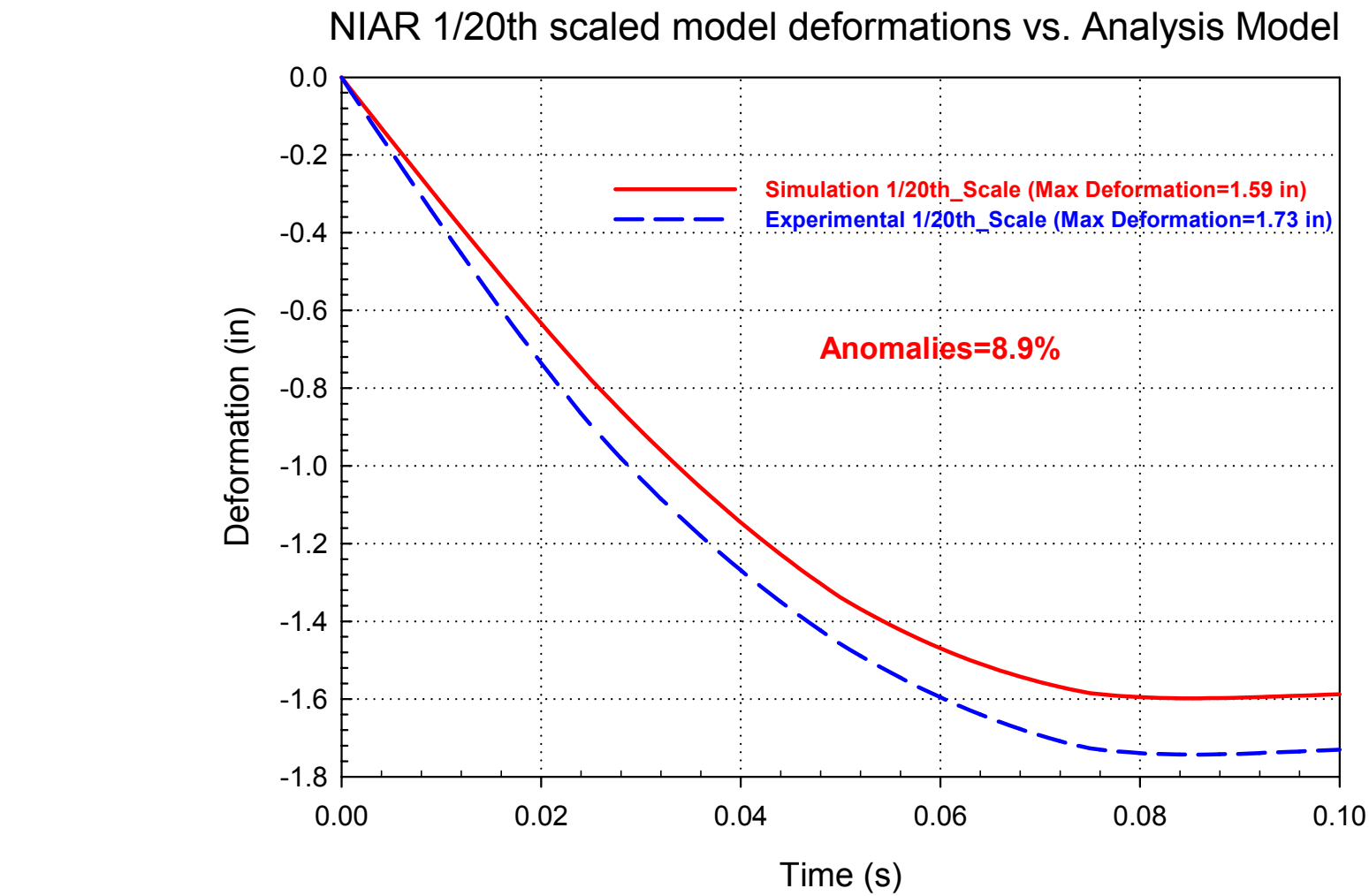


Simulation

1/20th Scaled Acceleration



1/20th Scaled Deformation



Scaling Laws

1. Geometric scaling:

$$\frac{L_m}{L_f} = \lambda$$

$$\frac{V_m}{V_f} = \left(\frac{L_m}{L_f}\right)^3$$

2. Mass scaling:

$$Weight = \rho * V$$

$$\frac{W_m}{W_f} = \frac{\rho_m}{\rho_f} * \frac{V_m}{V_f} = \lambda^3$$

3. Force Per Length scaling:

$$\frac{Force}{Length} = \frac{\lambda^3}{\lambda} = \lambda^2$$

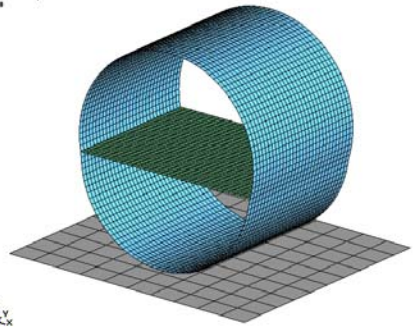
4. Energy scaling:

$$PE_f = M_f g\left(h + \delta_f\right)$$

$$PE_m = M_m g\left(h + \delta_m\right)$$

$$\frac{PE_m}{PE_f} = \frac{M_m}{M_f} * \frac{g}{g} * \frac{\left(h + \delta_m\right)}{\left(h + \delta_f\right)}$$

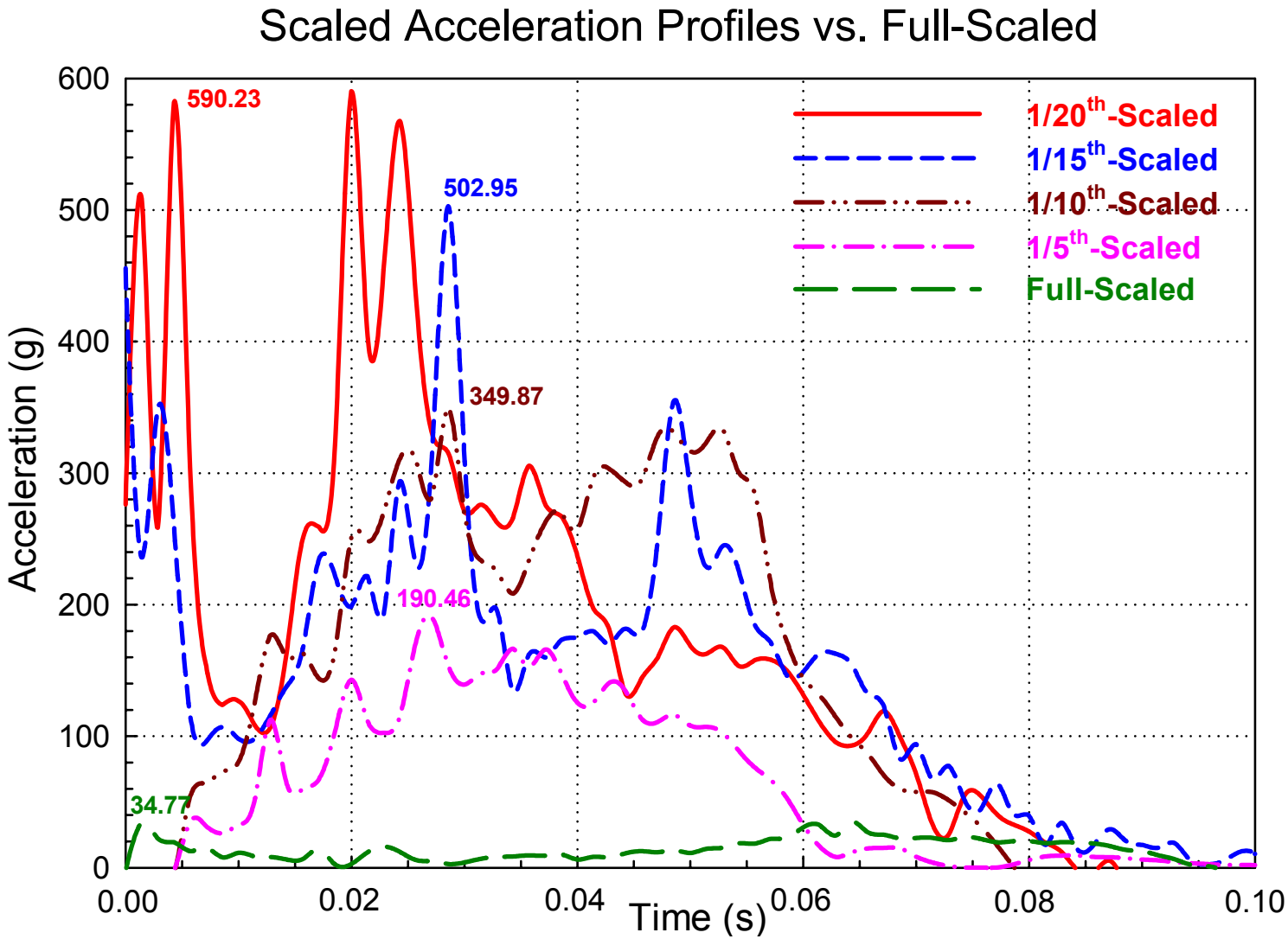
Scaling (Cont.)



- **Scaling Parameters Based on Geometry, Mass and the Energy scaling:**

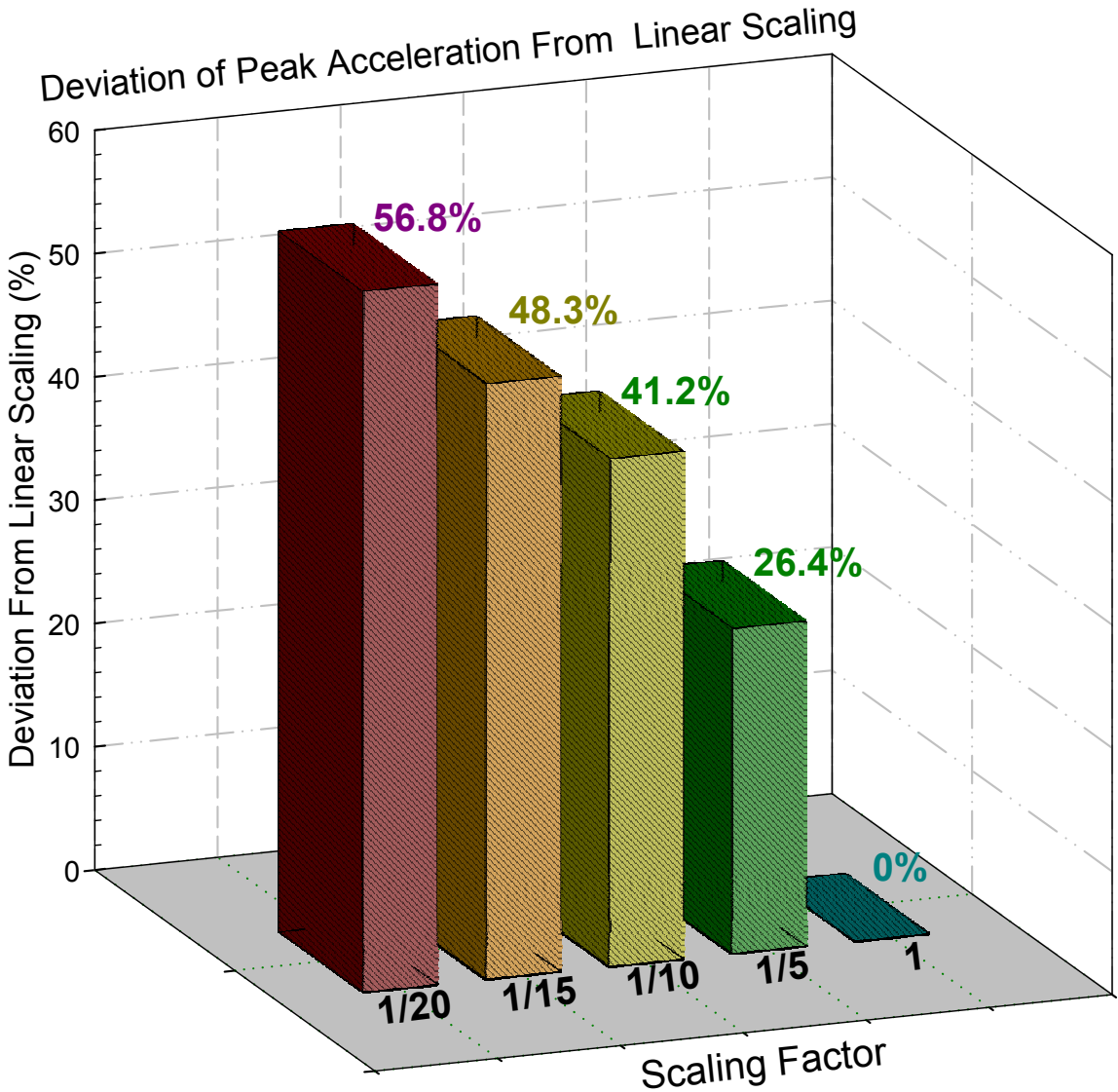
Parameter	Full-Scale	1/5th Scale	1/10th Scale	1/15th Scale	1/20th Scale	Scale Factor
	λ=1	λ=1/5	λ=1/10	λ=1/15	λ=1/20	
Diameter	155 (in)	31 (in)	15.5 (in)	10.3 (in)	7.8 (in)	λ
Length	120 (in)	24 (in)	12 (in)	8 (in)	6 (in)	λ
Impact Velocity	360 (in/s)	360 (in/s)	360 (in/s)	360 (in/s)	360 (in/s)	1
Fuselage Weight (With Auxiliary Fuel Tank)	8,780 (lb)	70.2 (lb)	8.78 (lb)	2.6 (lb)	1.1 (lb)	λ^3
Fuselage Weight	1370 (lb)	10.96 (lb)	1.37 (lb)	0.41 (lb)	0.17 (lb)	λ^3
Floor Loading per Fuselage Length	115.8 (lb/in)	4.63 (lb/in)	1.16 (lb/in)	0.51 (lb/in)	0.29 (lb/in)	λ^2
Average Subfloor Crush Stress	24.13 (psi)	24.13 (psi)	24.13 (psi)	24.13 (psi)	24.13 (psi)	1
Pulse Duration	100 (ms)	20 (ms)	10 ms)	6.67 (ms)	5 (ms)	λ
Floor Level Acceleration	25 (g)	125 (g)	250 (g)	375 (g)	500 (g)	$1/\lambda$
Maximum Predicted Crashing Distance	25.8 (in)	5.16 (in)	2.58 (in)	1.72 (in)	1.29 (in)	λ
Drop Height	168 (in)	168 (in)	168 (in)	168 (in)	168 (in)	1

The Size Effects

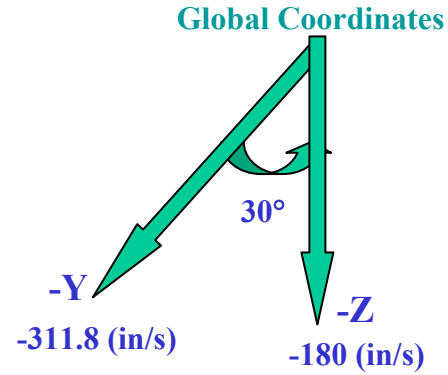


Deviation From Linear Scaling

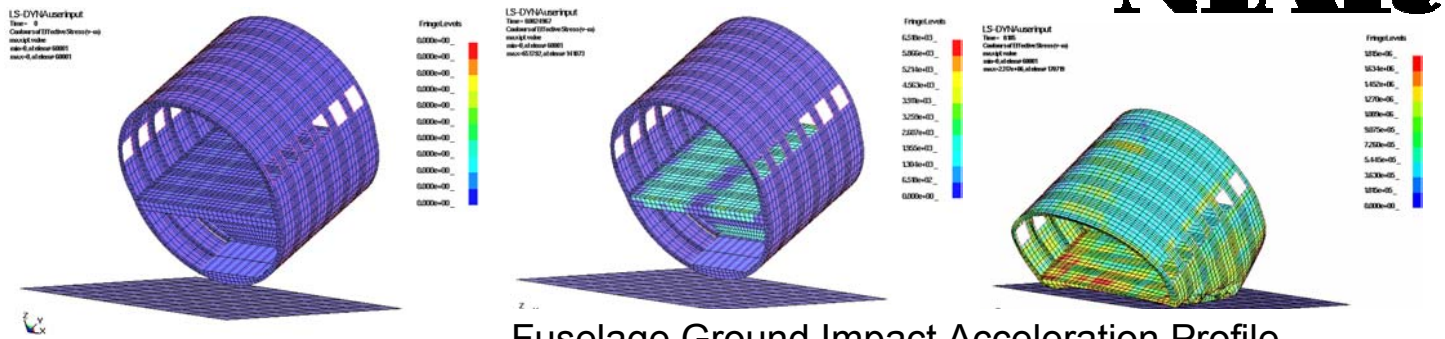
- Although Scaled models are great tools to make an fairly close approximation of the actual full-scale models, However, one should always take extreme caution keeping the scaling factor (correction factor) in mind



Simulating Test-1 Condition

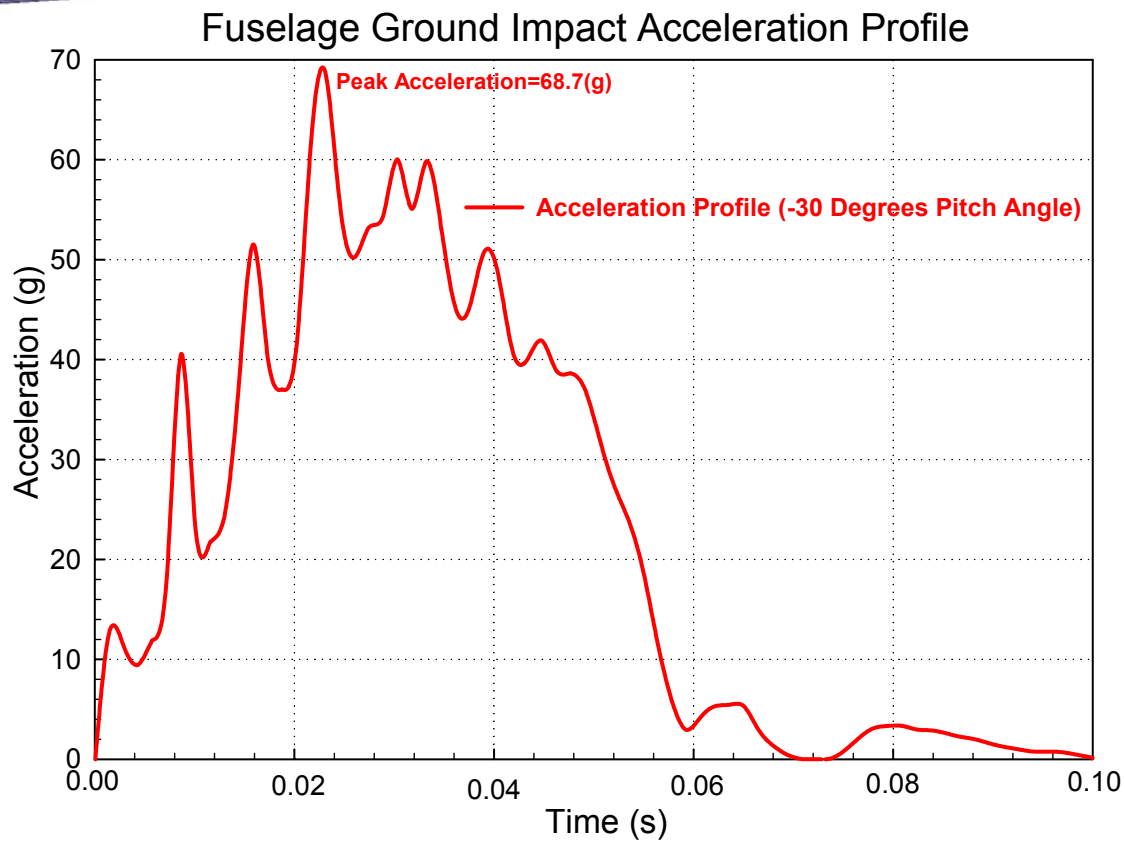


Velocity Vectors



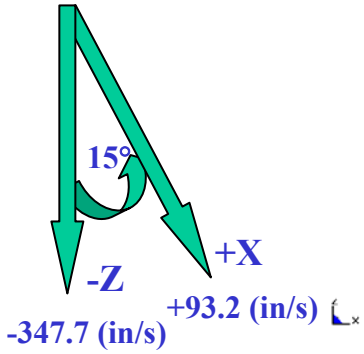
Transbrasil Boeing 737-4Y0 Incident

Nose Landing Gear Failure

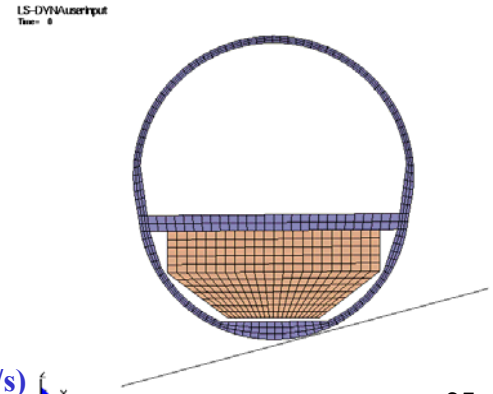


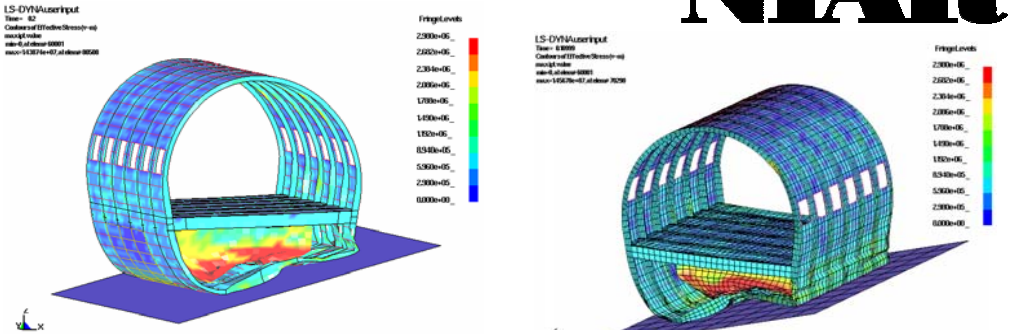
Simulating Test-2 Condition

Global Coordinates



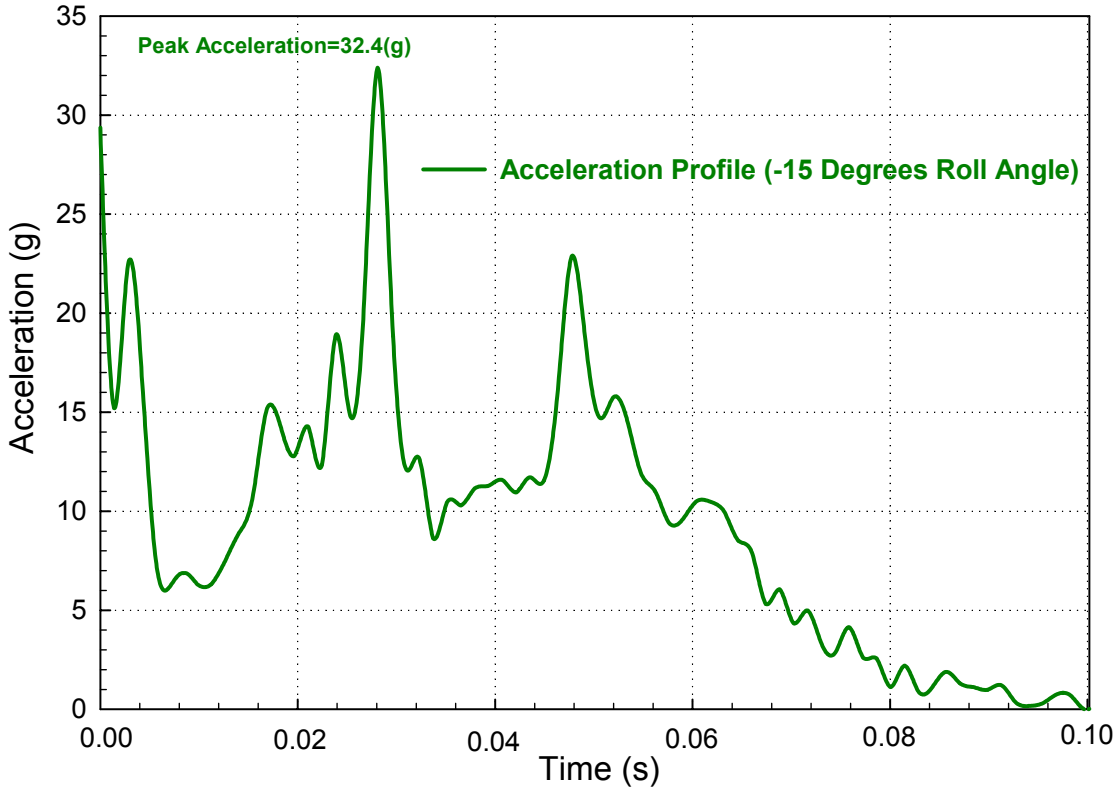
Velocity Vectors



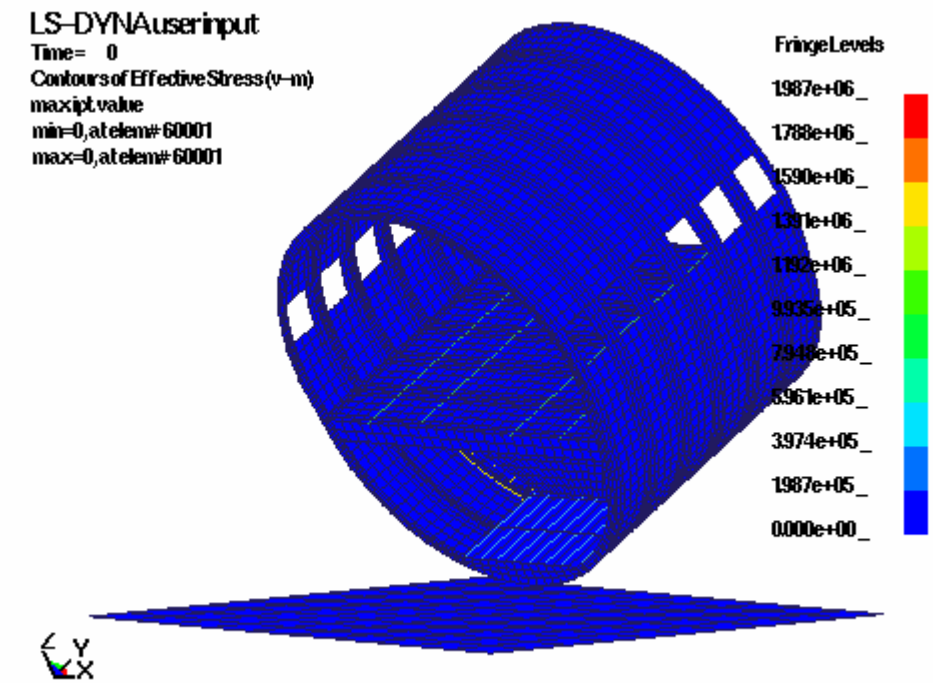


Left Landing Gear Failure

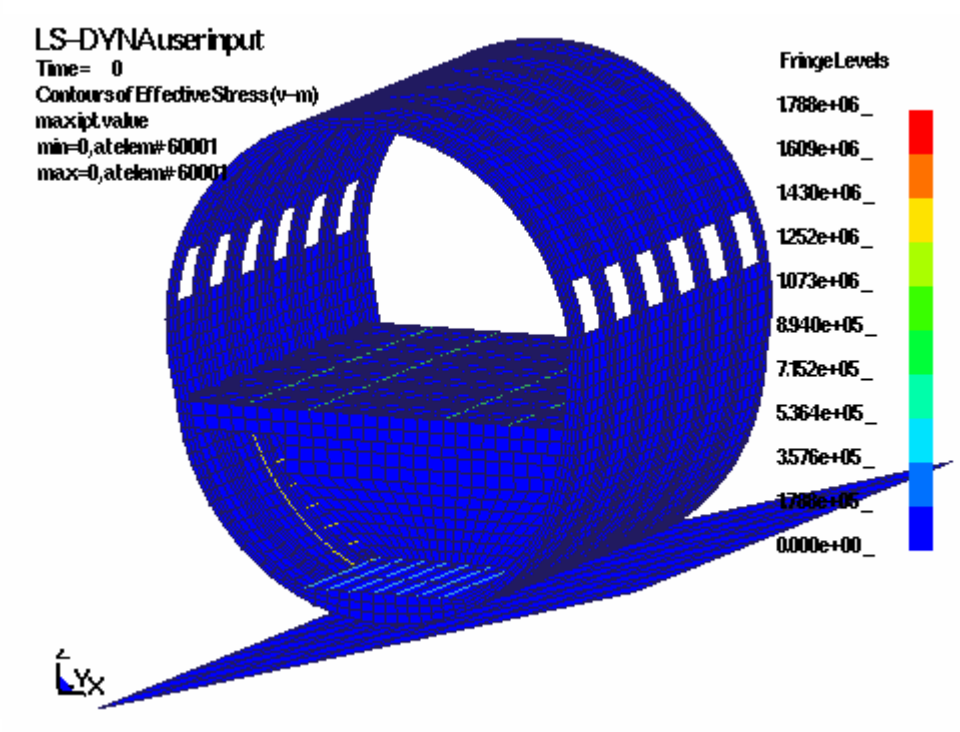
Fuselage Ground Impact Acceleration Profile



Simulating Test 1 &2 Conditions

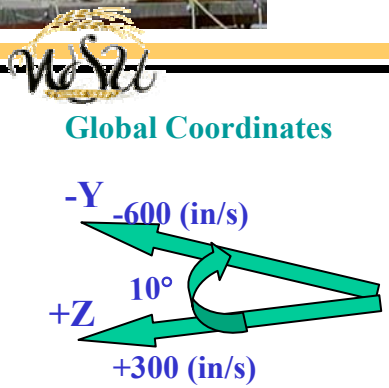


Test-I Condition

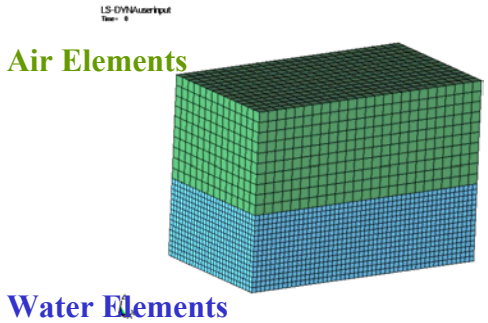


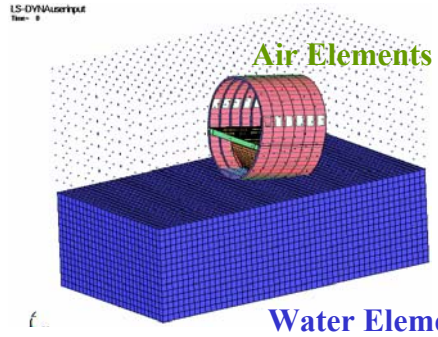
Test-II Condition

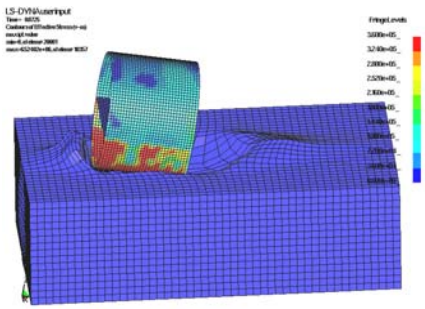
Aircraft Water Impact Simulation



Velocity Vectors

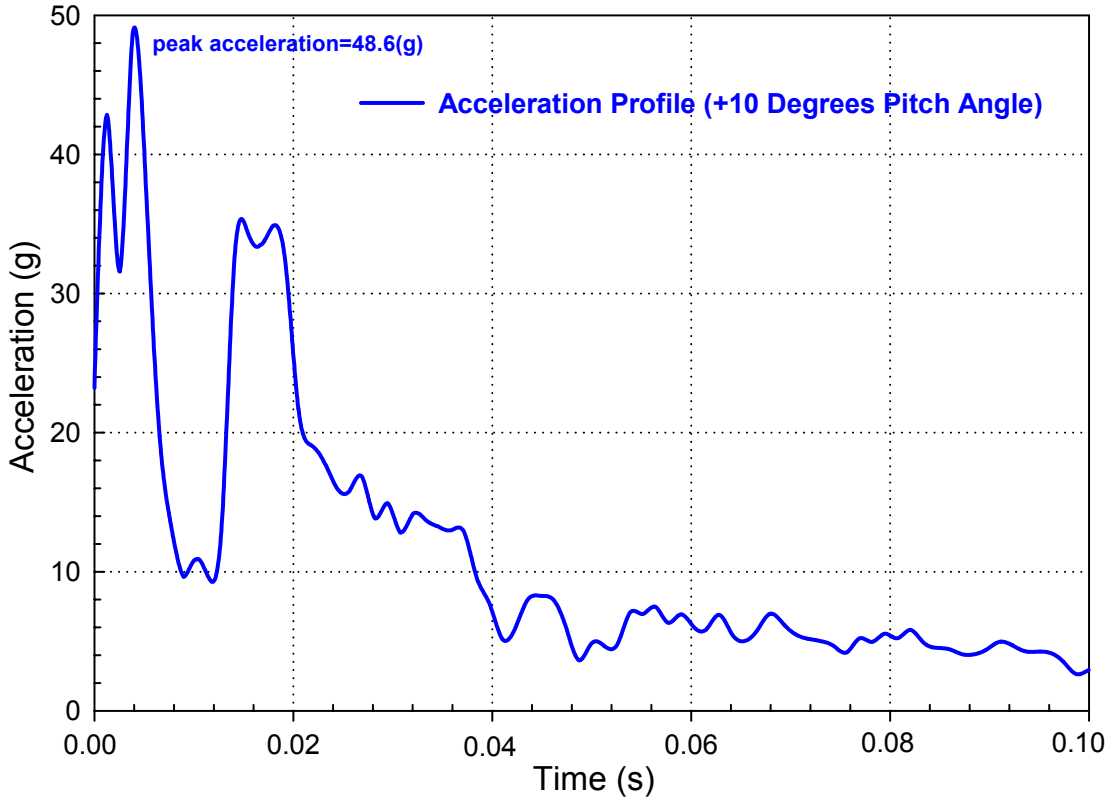






Aircraft Water Impact

Fuselage Water Impact Acceleration Profile



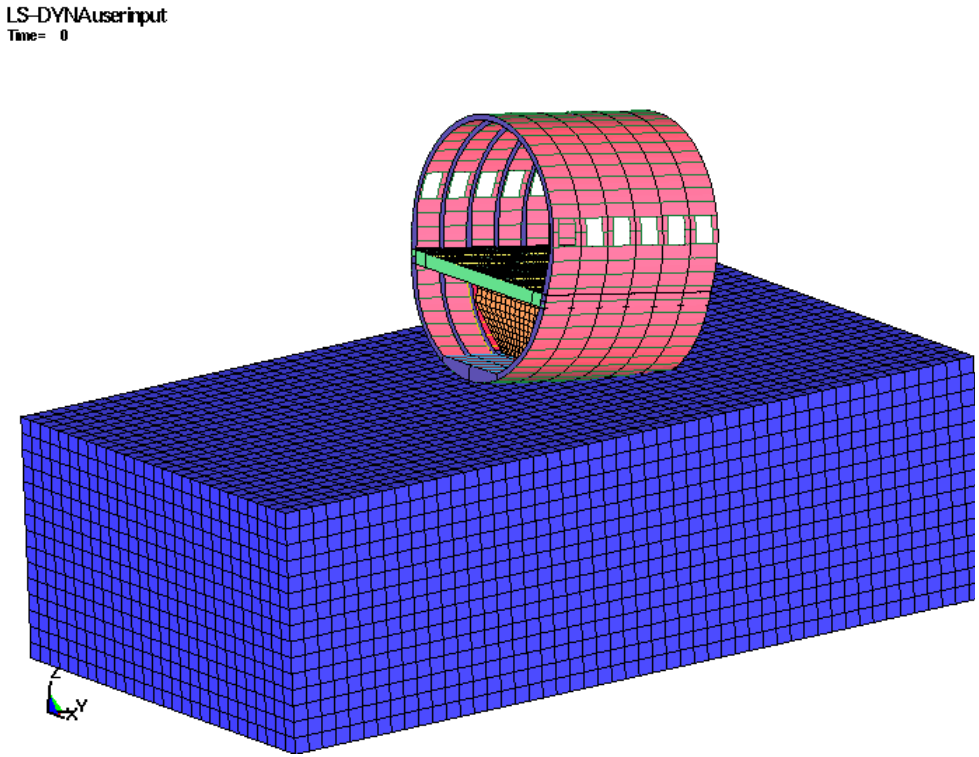
Euler-Lagrange Element Formulation

➢ALE (Arbitrary Lagrangian-Eulerian)

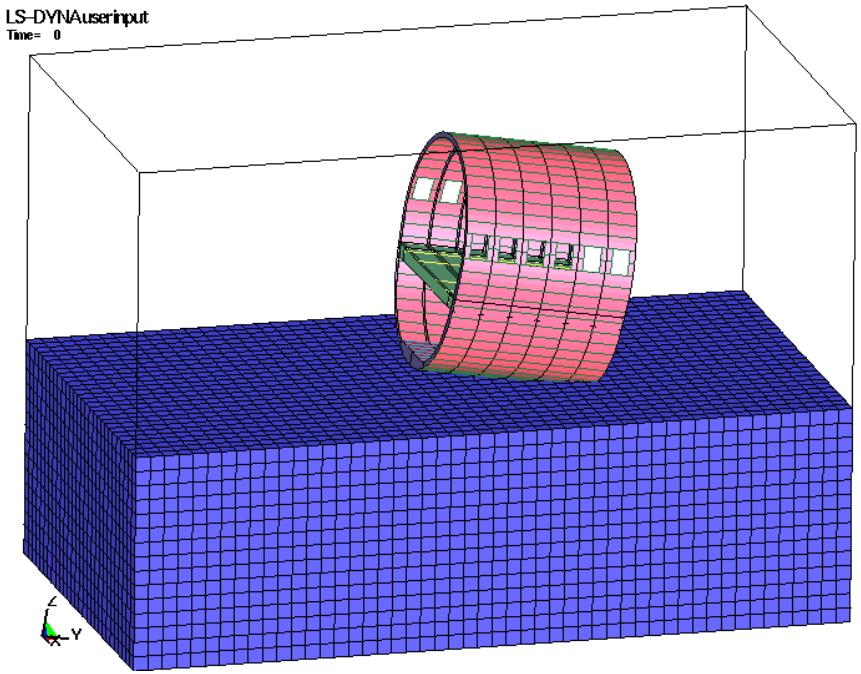
- ➢Stopping the calculation when mesh is distorted
- ➢Smoothing the mesh
- ➢Remapping the solution from the distorted mesh to the smooth mesh

Element Formulation	Element Type	Number of Elements
Belytschko-Tsay	Isometric Quad 4 Shell	12,000
Hughes-Liu	Bar	4,000
Belytschko-Tsay	Isometric Hexahedron Solid	3,500 (air)
Belytschko-Tsay	Isometric Hexahedron Solid	21,000 (water)

Aircraft Water Impact Simulation

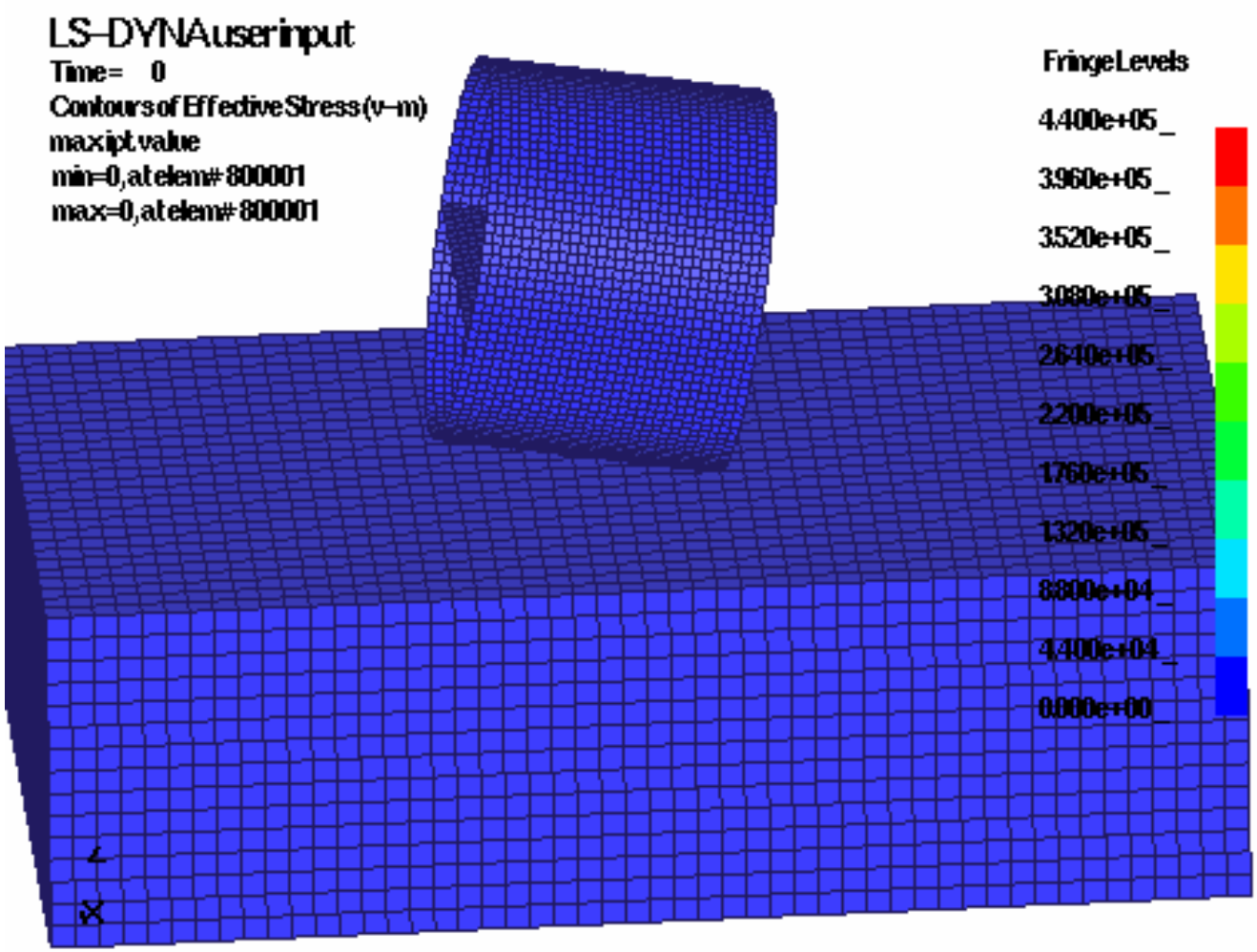


Fuselage Shown In Only Water Mesh

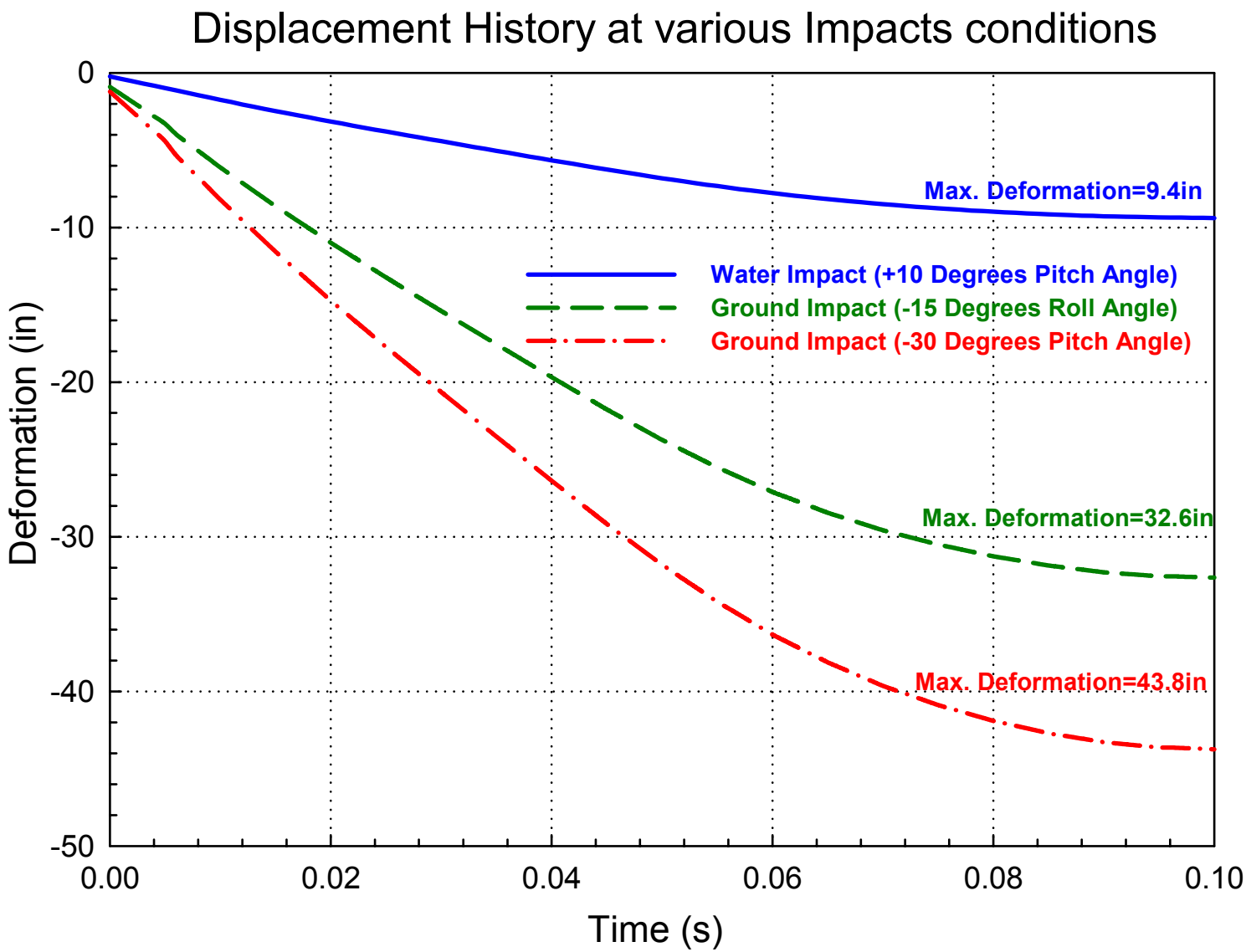


Fuselage Shown In Air and Water Mesh

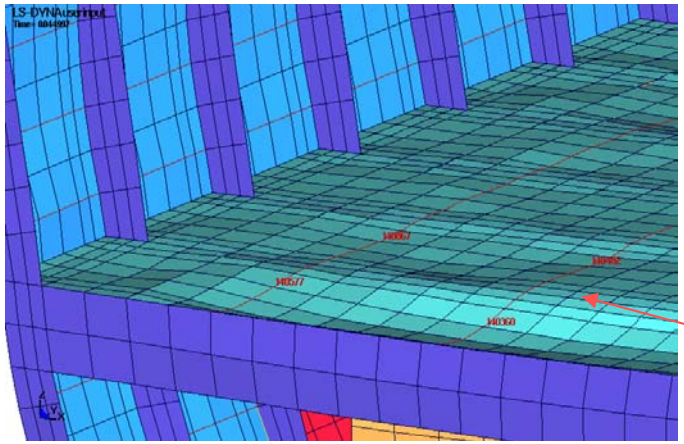
Aircraft Water Impact Simulation

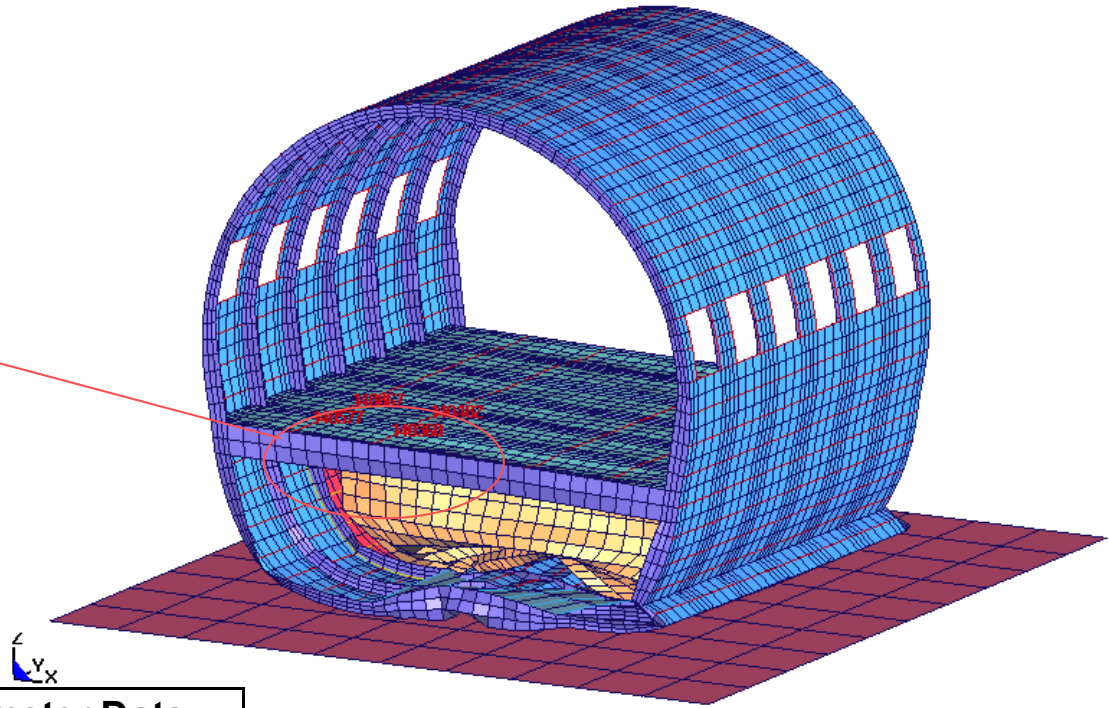


Deformation Profile Comparison



Expanding the Future Research

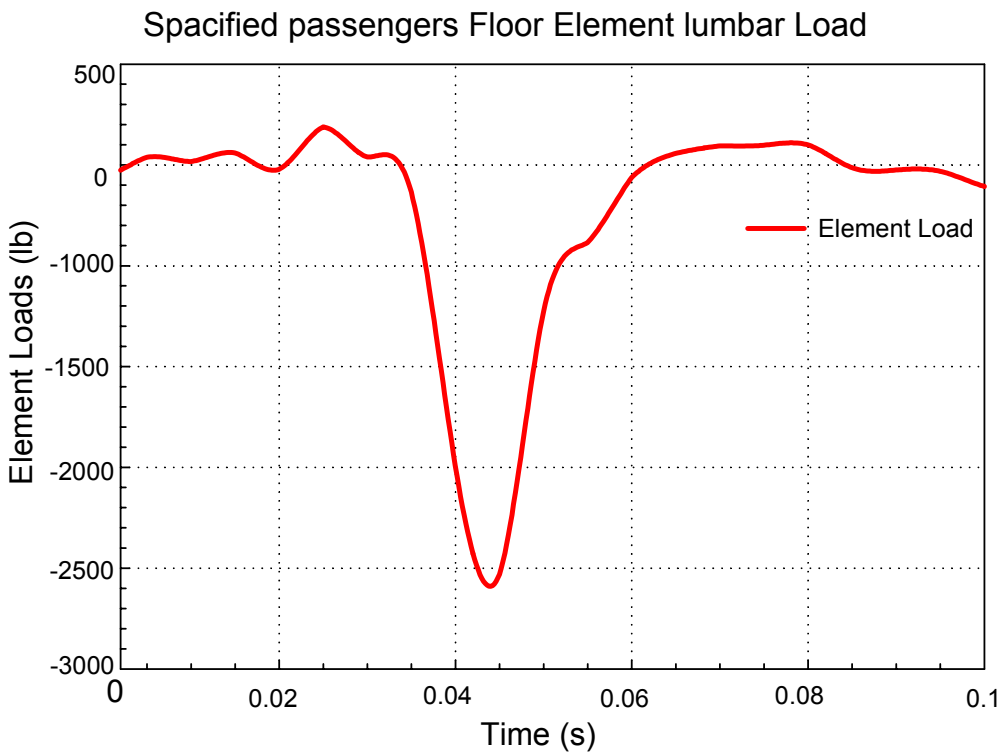


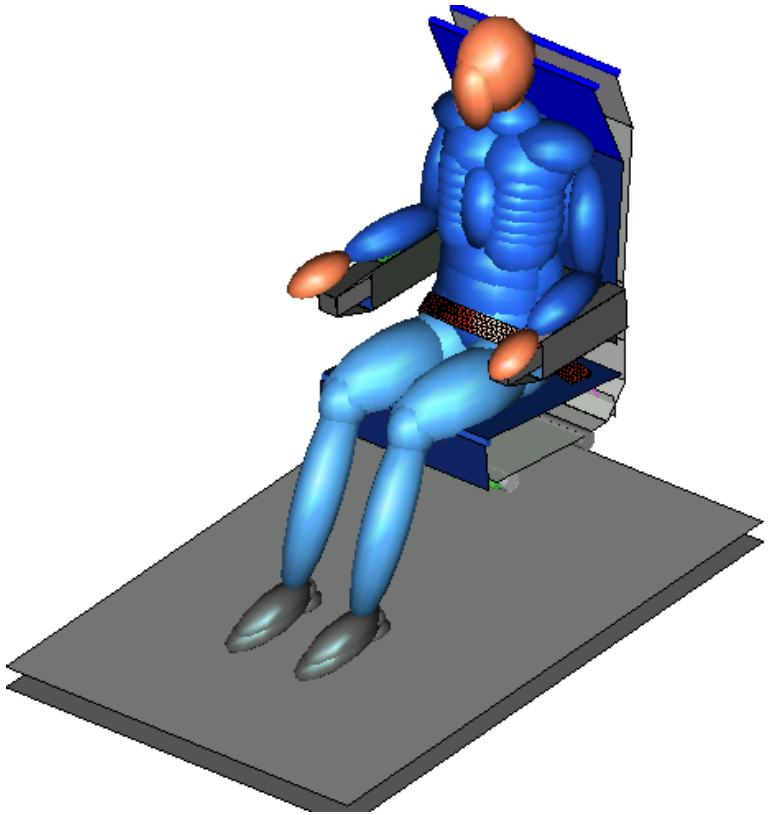


ATD No.	Location	Lumbar Load (lb)	Accelerometer Data	
			G_{peak} (g)	Pulse Duration (ms)
1	FS 427 LS	1804	17.4	49
2	FS 426 LS	906	17.3	48
3	FS 462 LS	1734	34	32
4	FS 462 LS	1269	21	55
5	FS 497 LS	1247	27	61
6	FS 498 LS	961	17	18

Examine the dynamic responses as well as potential injuries to the occupants

MADYMO ATD Model





Estimate the Passenger Lumbar Load, located on each Seat

Using Hybrid II ATD model instead of Mass Elements

Concluding Remarks

- A detailed nonlinear FE model of a transport aircraft fuselage section with auxiliary fuel tank was developed

- The model showed reasonable correlation when compared with the results from the drop test conducted at FAATC

- The nearly rigid fuel tank increases the structural stiffness and therefore increases the peak acceleration response (by 39 percent)

- Clearly, the structural stiffness presents a negative effect on the passenger's safety

- The cargo door on one side increases the stiffness and creates a necking effect

- Scale modeling test can provide insight in the initial stage of a design

Concluding Remarks

- While designing the future aircraft structures, great emphasis should be made to include the higher energy absorbing material in the fuselage floor's substructures, particularly since more of today's carriers are inclined to use the rigid conformable cargo containers locating in the passengers cargo area.

- Although the full scale aircraft fuselage testing could never be entirely ruled out for the purpose of validation, the computer simulation model in this study shows the potential of modeling techniques as a tool
  - for locating critical impact locations and deformations
  - for effective product development
  - for reducing design time, cost and scatter of data
  - that may eventually be used as a "certification tool"

A Modeling Approach for Crashworthiness Evaluation of an Aircraft Fuselage Section with Conformable Auxiliary Fuel Tank

NIAR

Thank You