A Contribution to Full-Scale High Fidelity Aircraft Progressive Dynamic Damage Modeling for Certification by Analysis

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CRASH LAB

CRashworthiness for Aerospace Structures and Hybrids Lab

Analytical Methods in Aircraft Certification Workshop, Blacksburg Aug. 10-11, 2016

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Assessment of full plane crashworthiness is prohibitively costly and a data collection challenge

- In 1984, a full-scale experiment was conducted by FAA and NASA
- An engine was sheared off during landing and the fire engulfed the entire plane

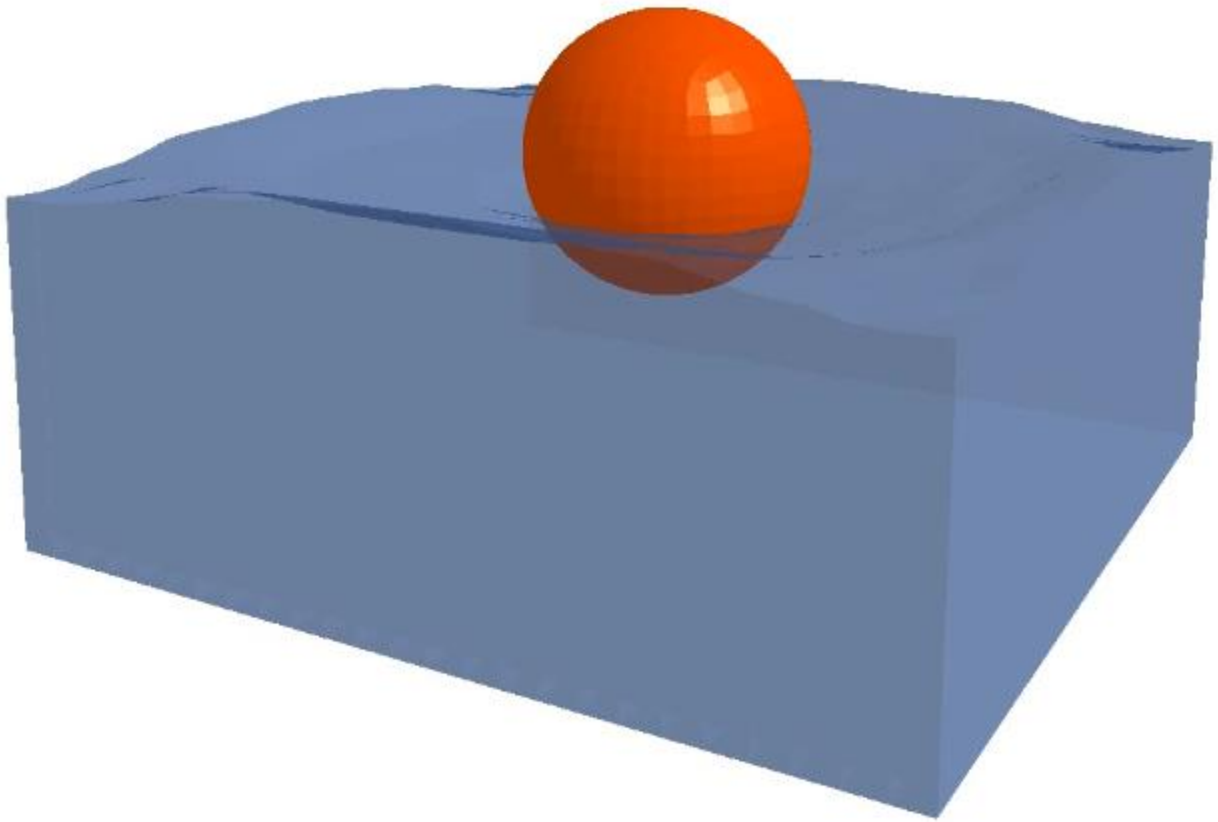
NASA, *NASA Armstrong fact sheet: Controlled Impact Demonstration*, 2015, Available: http://www.nasa.gov/centers/armstrong/news/FactSheets/FS-003-dfrc.html

- Another test was conducted by a team of multiple organizations in 2012
- The plane used to simulate a crash landing scenario to assess crashworthiness

Discovery Channel, *Curiosity: The Plane Crash 2012*, [Online]. Accessed Date: 2015-10 06, Available: https://curiosity.com/paths/a-historic-crash-curiosity-plane-crash-discovery/?ref=ptv#a-historic-crash-curiosity-plane-crash-discovery.

Full-scale crash methodology is systematically developed

- Computational Theory
  - Fluid-structure interaction (FSI)
  - Material definition
- Section-Drop Test
  - Drop test model
  - Validation against experiment
  - Rigid ground vs. soil
- Full-Scale Plane Crash
  - Aircraft model
  - Rigid ground vs. Soil
  - Results and discussion
- Conclusion



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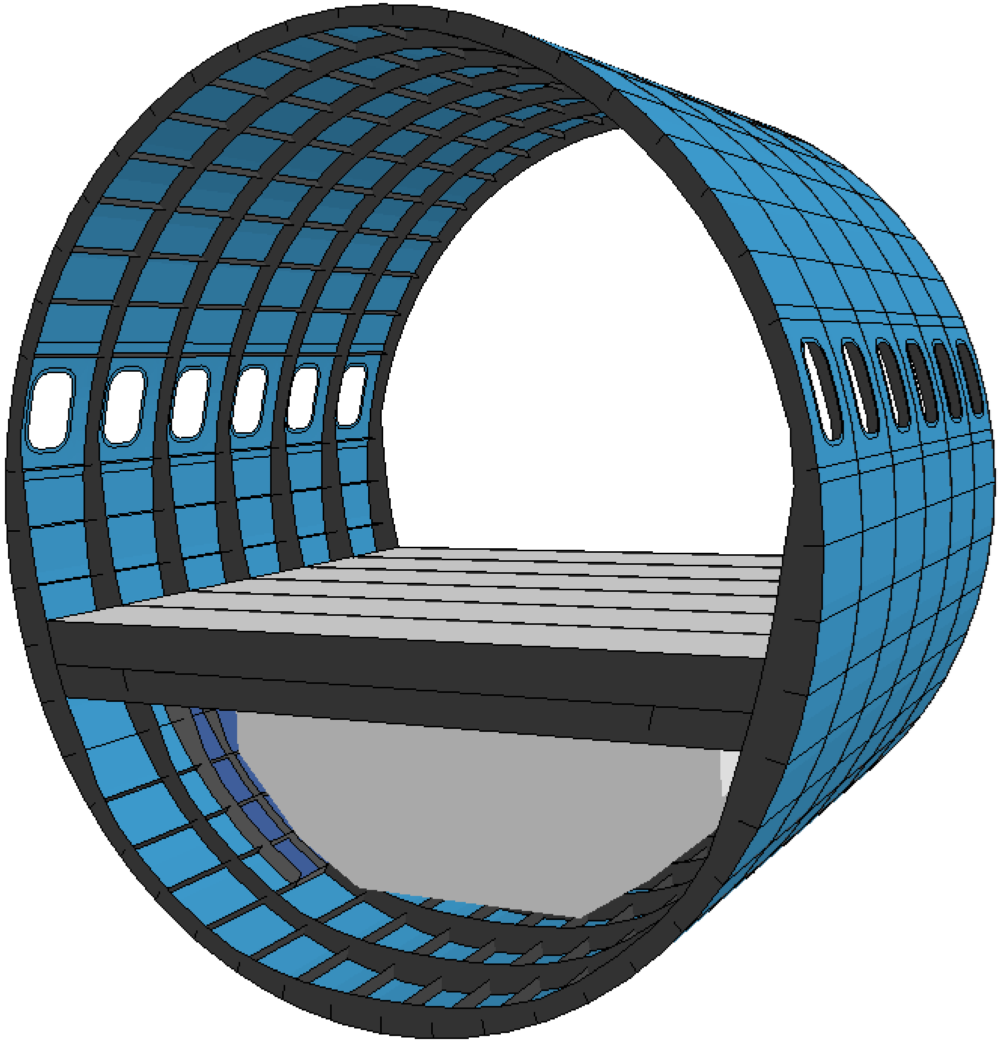

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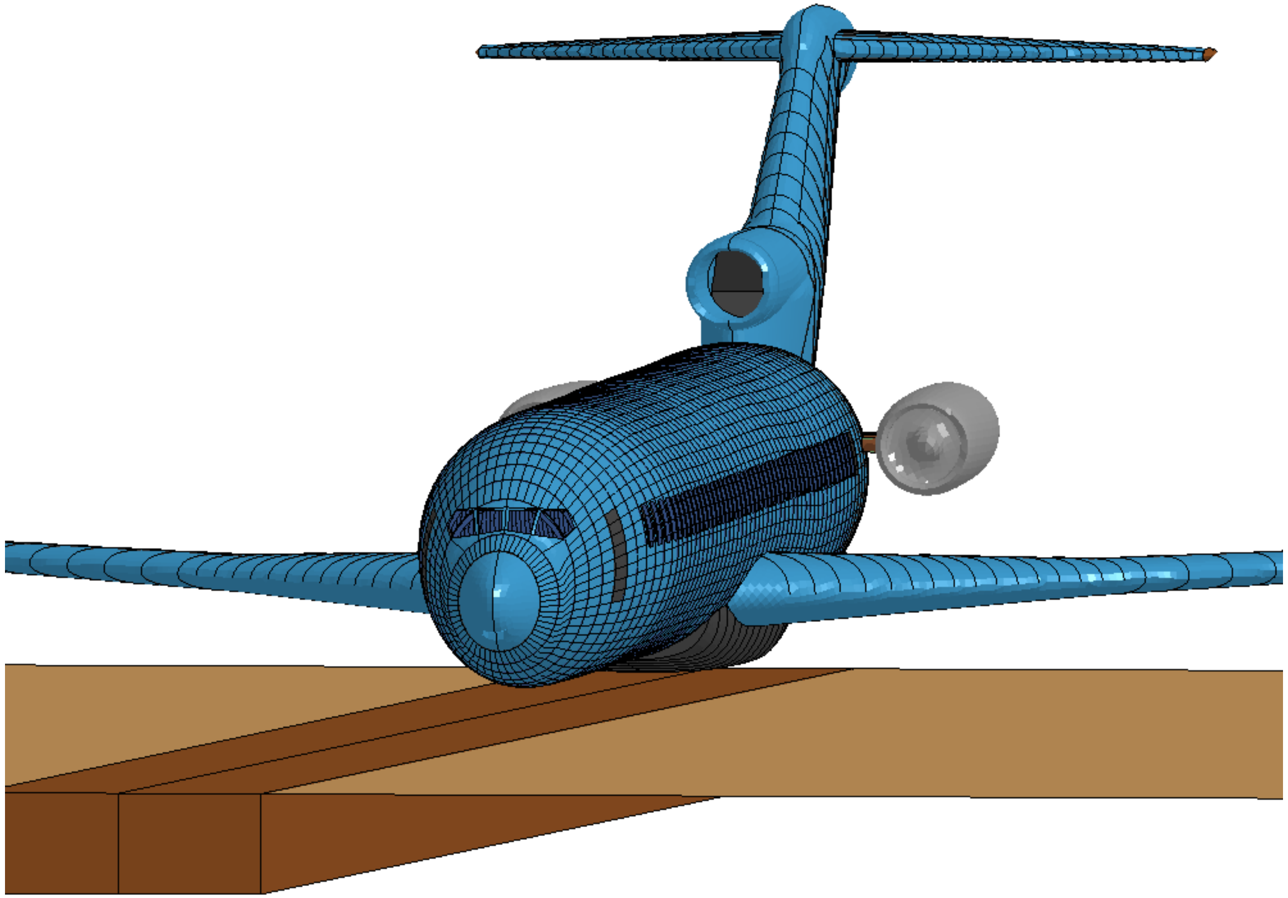
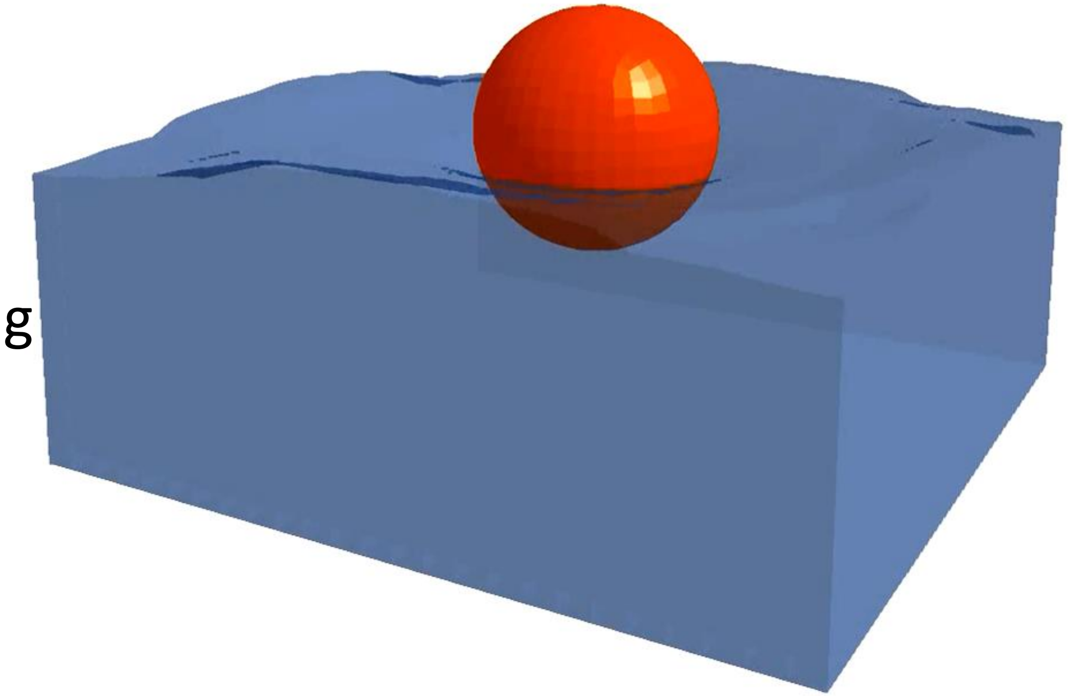


Fluid Solid Interaction

- The comprehensive bi-material interaction was represented by Coupled Lagrangian-Eulerian (CLE) formulation
- Example shown on the right is hollow metal ball dropping into a tank of water
- CLE is able to capture large deformations of slushing water
- This methodology was extended to model the deformable ground (soil)



A CLE formulation was used to mitigate mesh distortion of soil model

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- To numerically predict a fluid-structure interaction, a multi-disciplinary approach was required
- Impact on soil is difficult to simulate with conventional FEA schemes due to mesh distortion and domain separation during interaction
- Coupled methods offer numerically stable solutions due to periodic rezoning of the Lagrangian domain onto an ambient Eulerian mesh

Mass Balance:

$$\left.\frac{\partial \rho}{\partial t}\right|_{ref} + (v_m - \hat{v}) \cdot grad(\rho) = -\rho \nabla \cdot v$$

Momentum Balance:

$$\rho\left(\left.\frac{\partial v}{\partial t}\right|_{ref} + ((v_m - \hat{v}) \cdot grad)v\right) = \nabla \cdot \sigma + \rho \vec{f}$$

ρ = density
v = velocity
σ = stress tensor
f = body force

Model comparison with a section-drop test was conducted for verification and validation purposes

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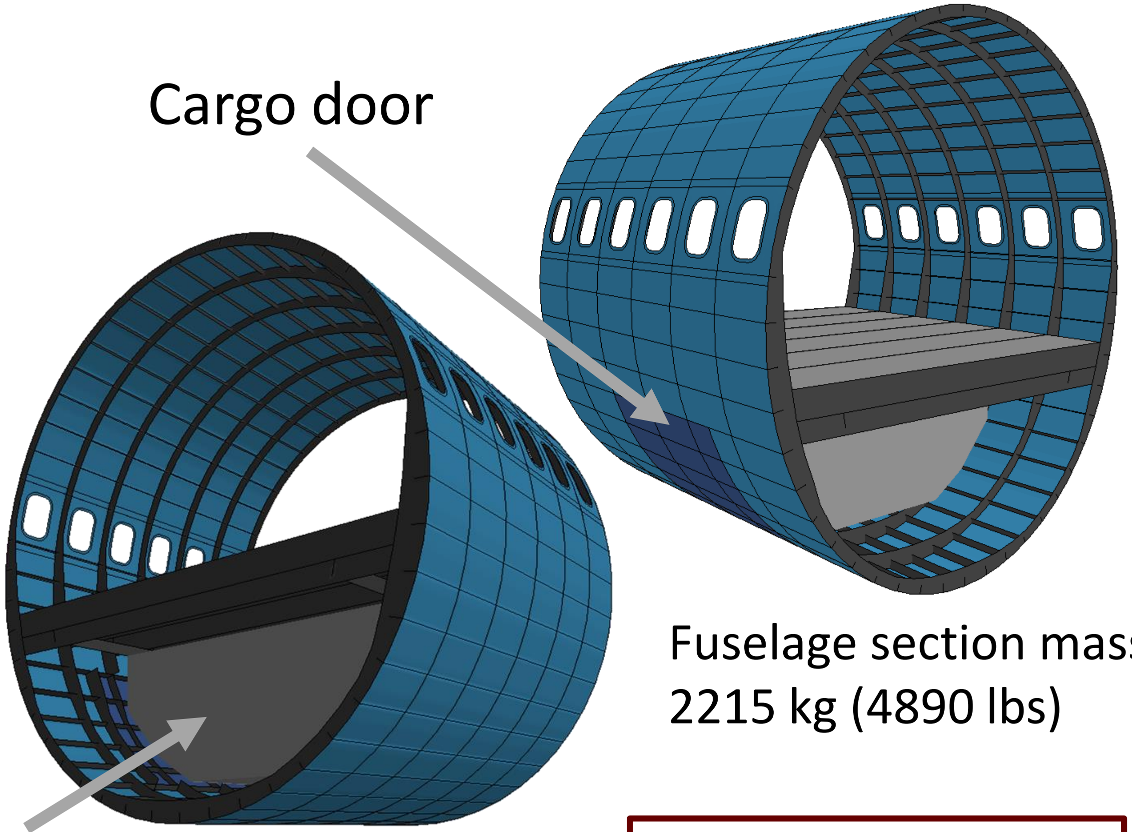
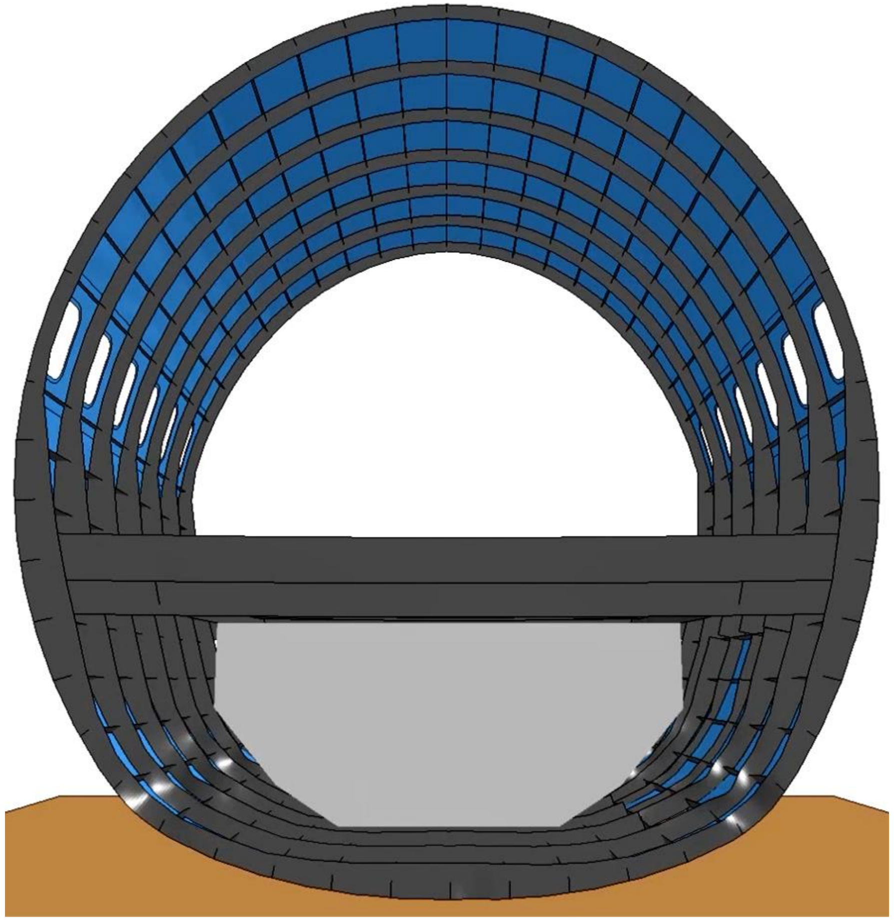
- A section drop test was used as a stepping stone
- Forward section model of a fuselage was created
- One of the currently available experiments is a B-737 section drop test conducted by FAA
- Free fall from 10 ft above the impact surface (9.1 m/s impact speed)



Mesh study was conducted for further verification of the computational model



Rear view section impact on rigid ground

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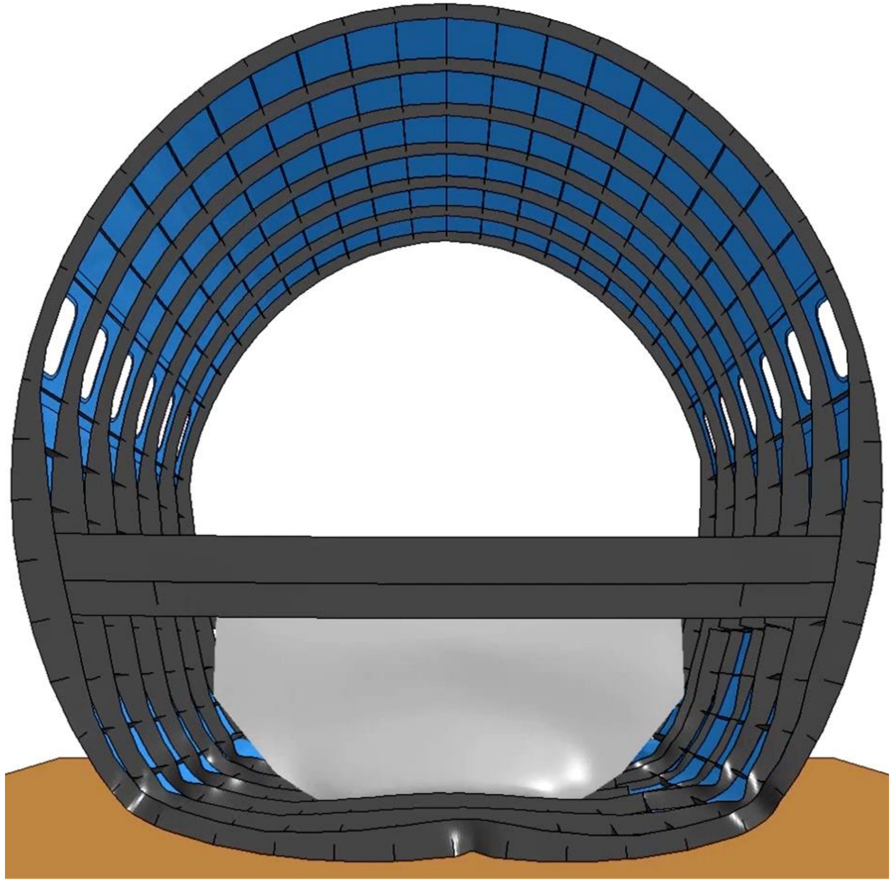

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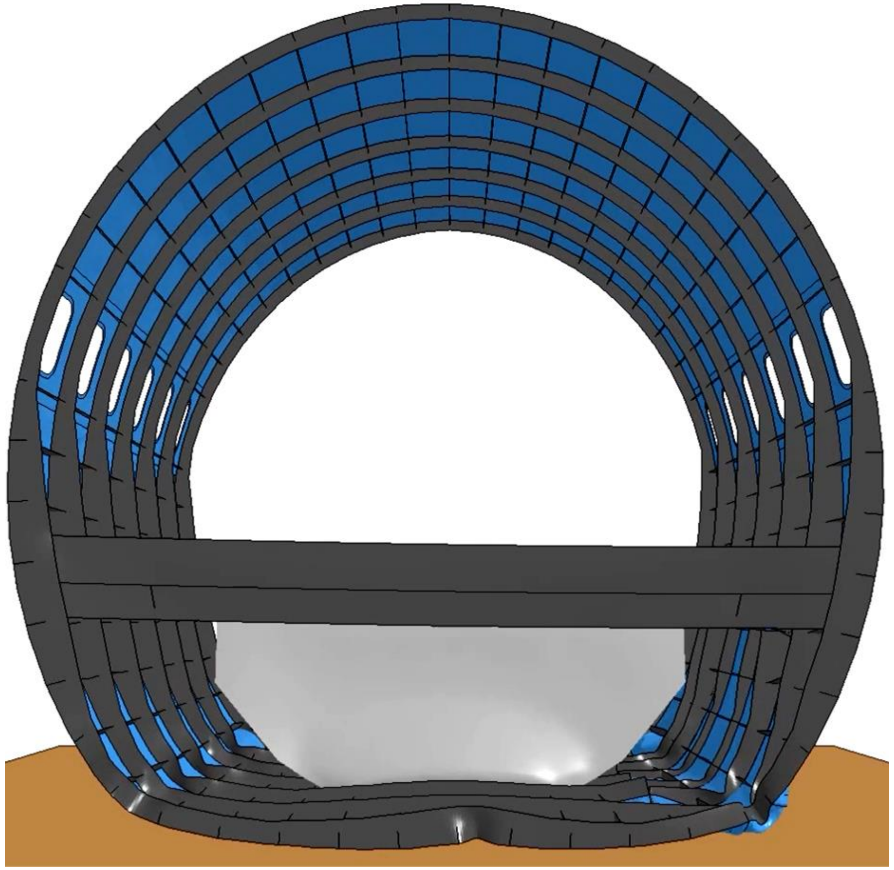

Rear view section impact on rigid ground

Mesh study was conducted for computational model verification for further investigation

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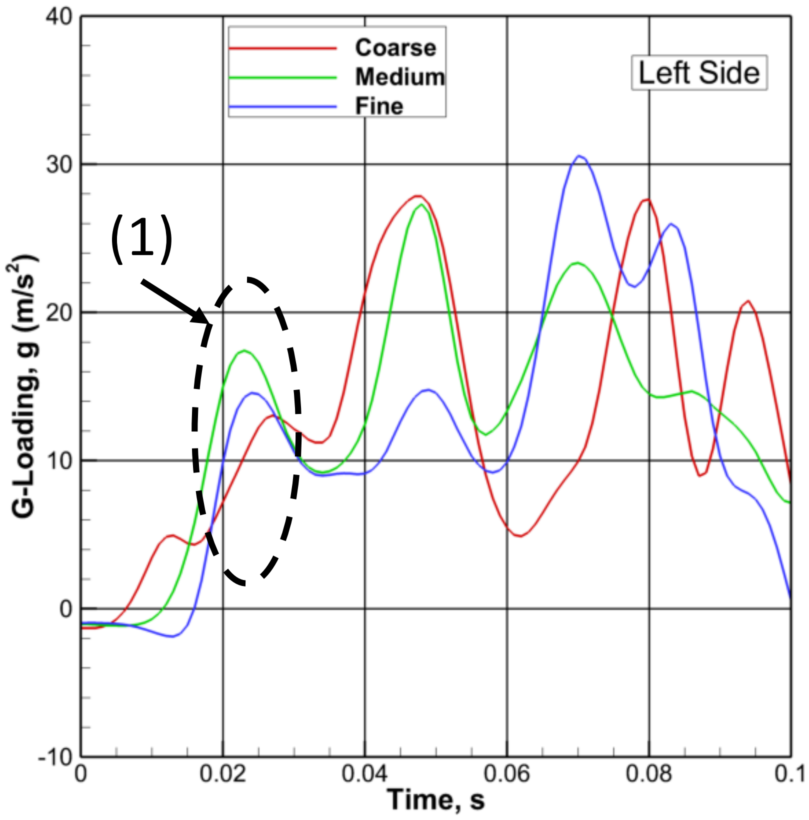
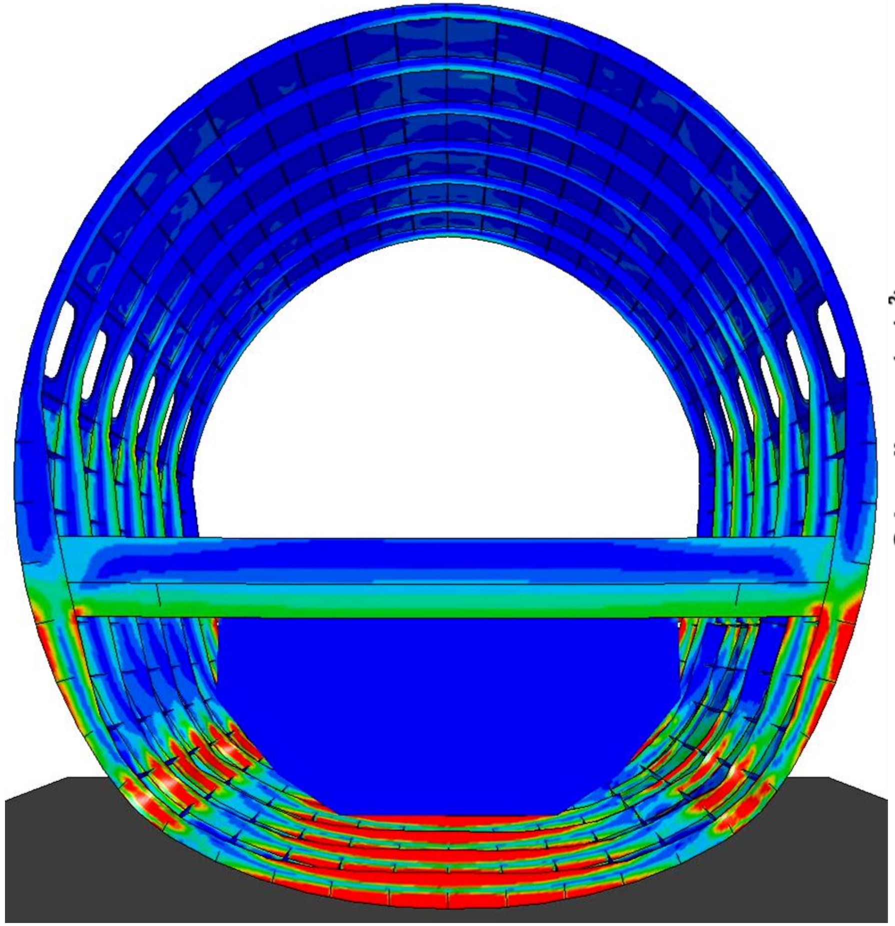


(a) Left side of passenger floor (normal section)



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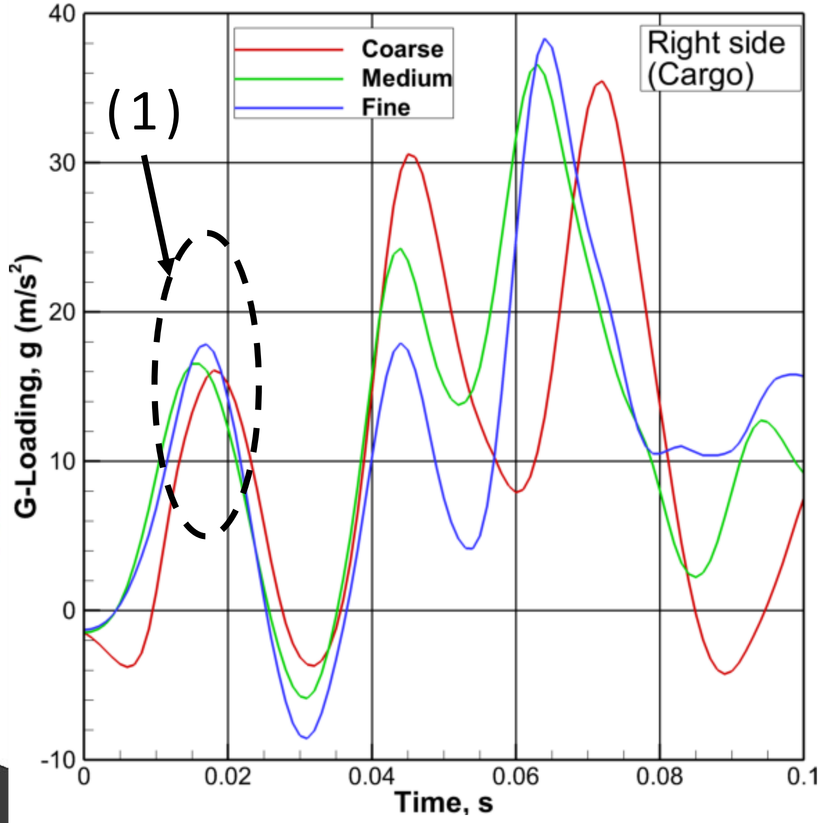

(b) Right side of passenger floor (Cargo door section)

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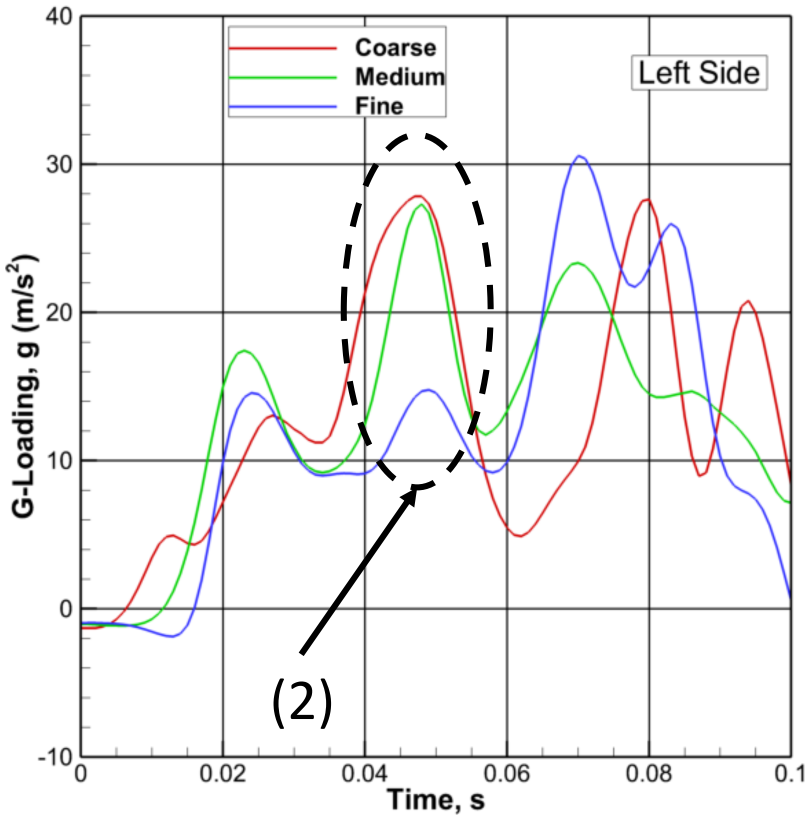

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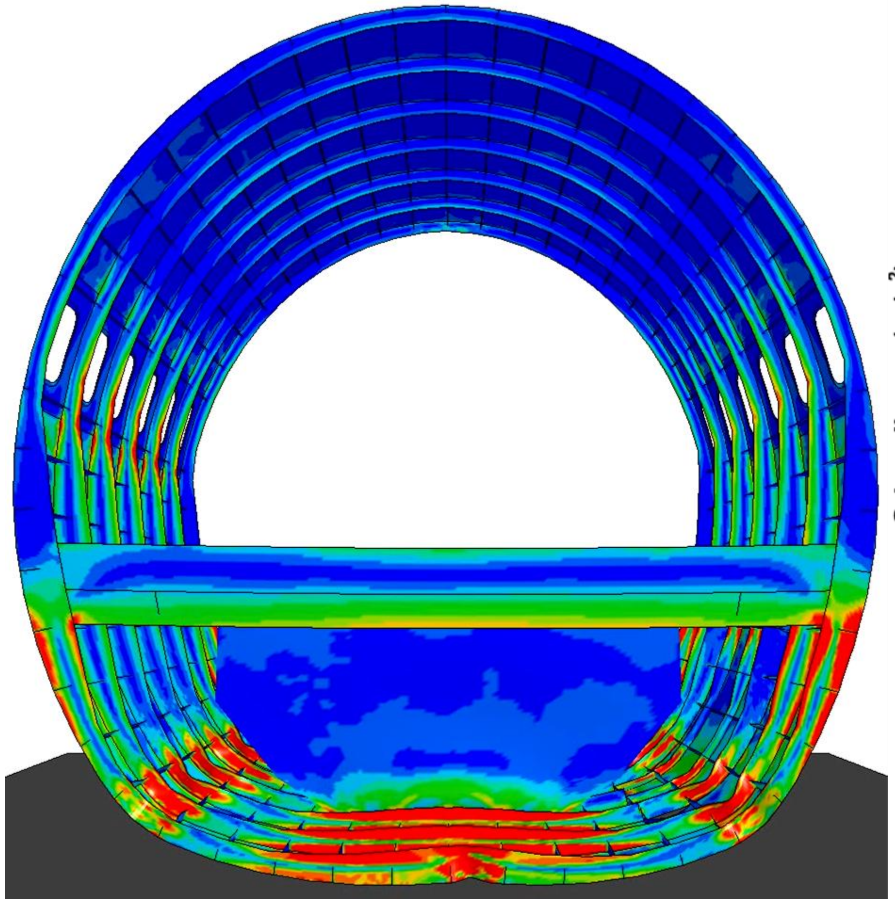
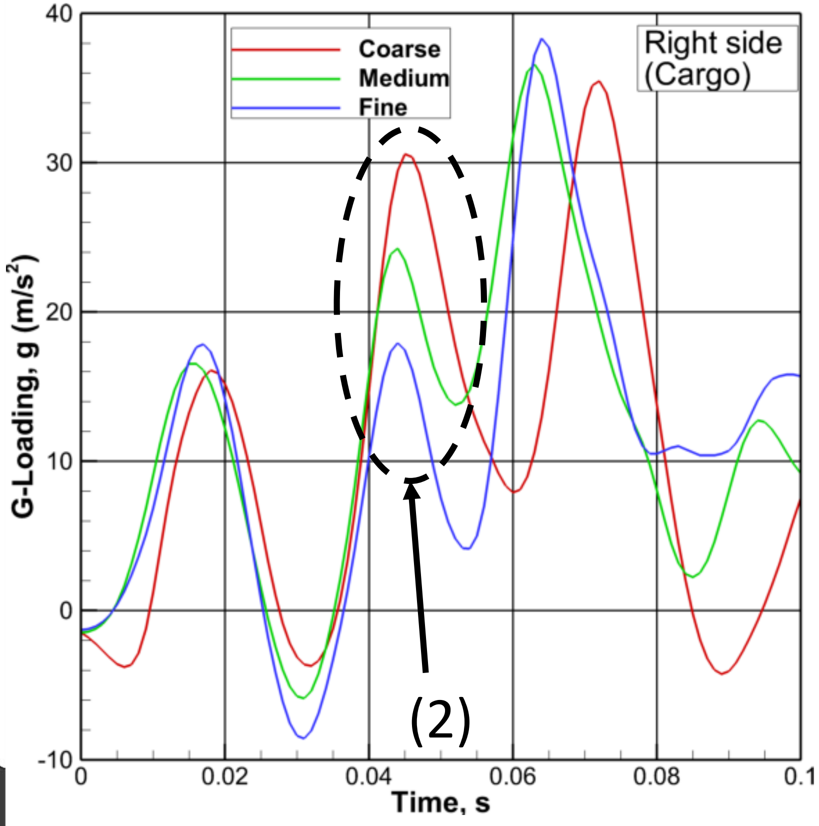


Rear view section impact on rigid ground



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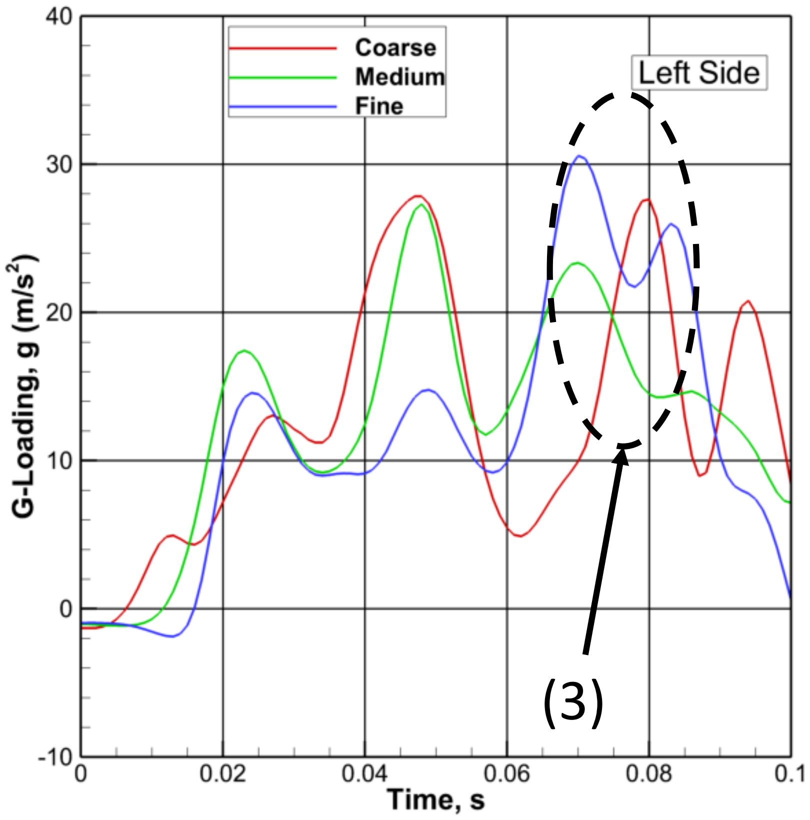

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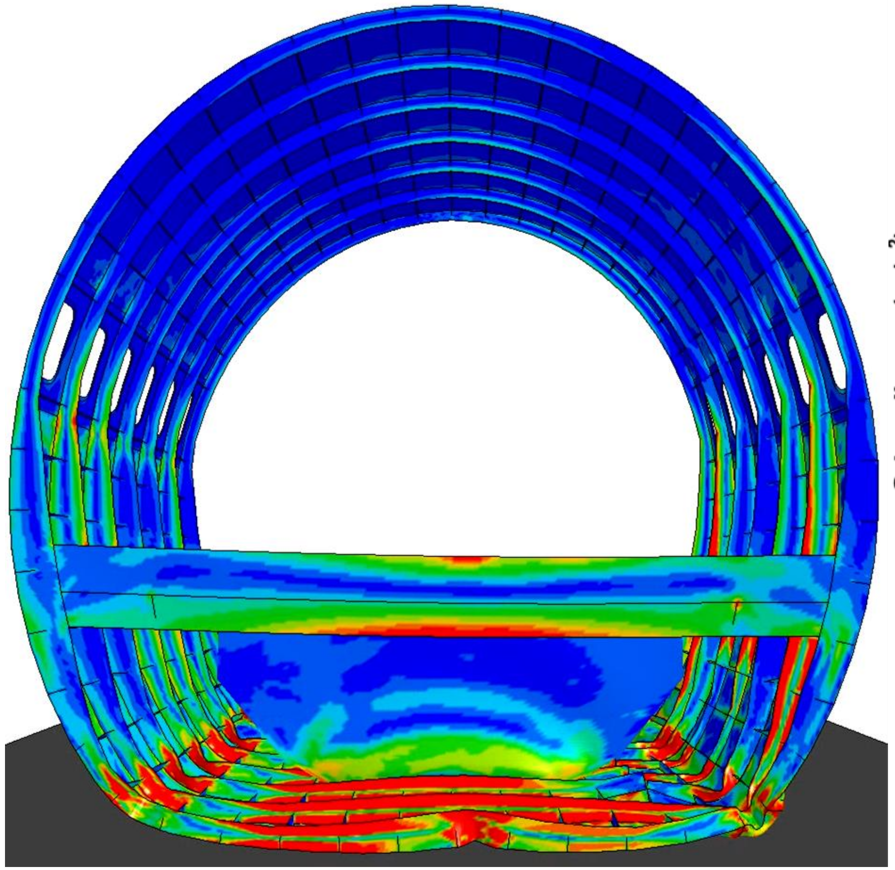

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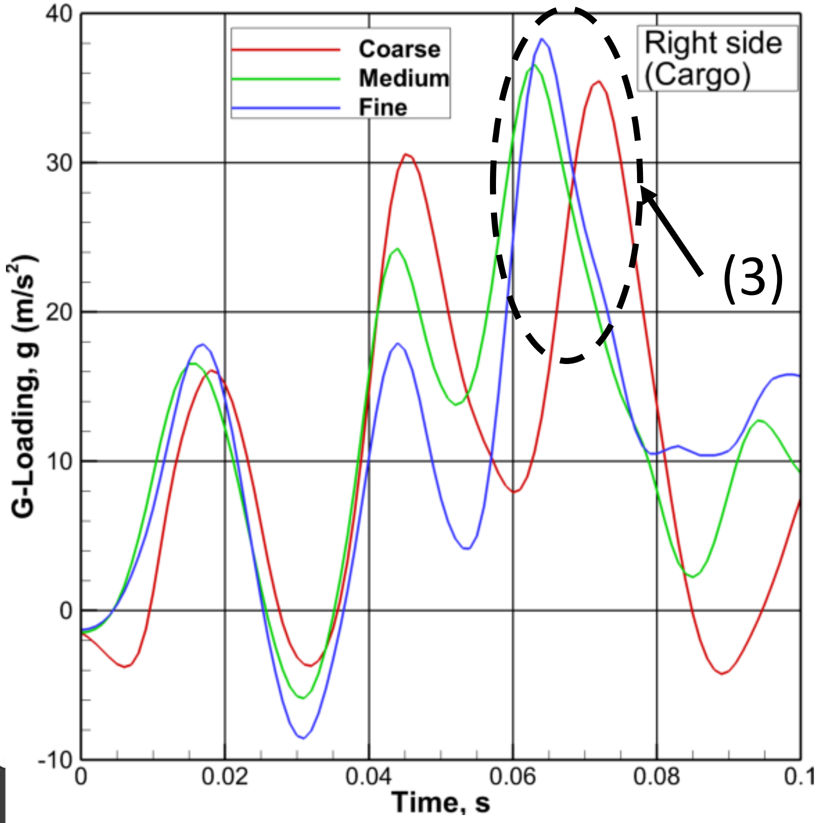
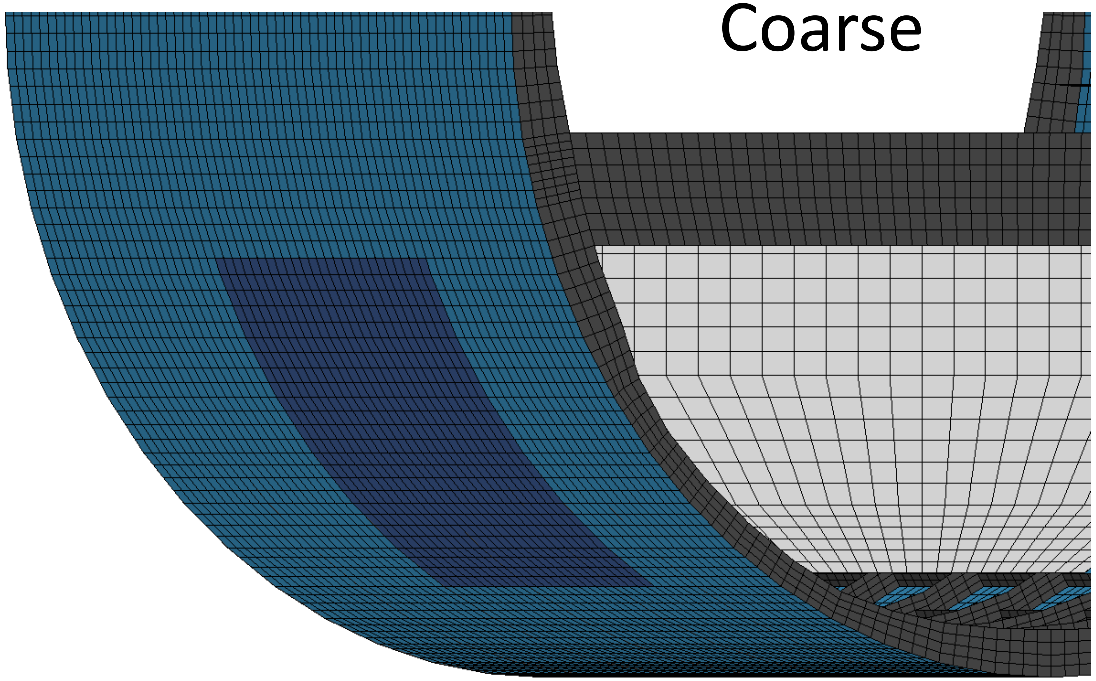
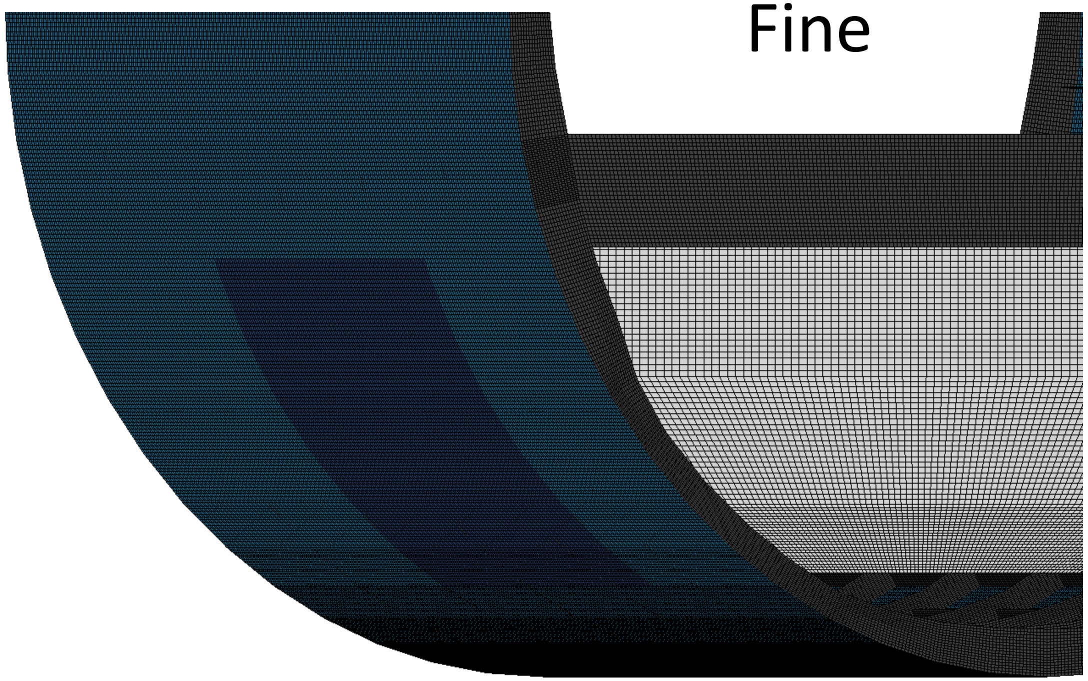


(b) Right side of passenger floor (Cargo door section)

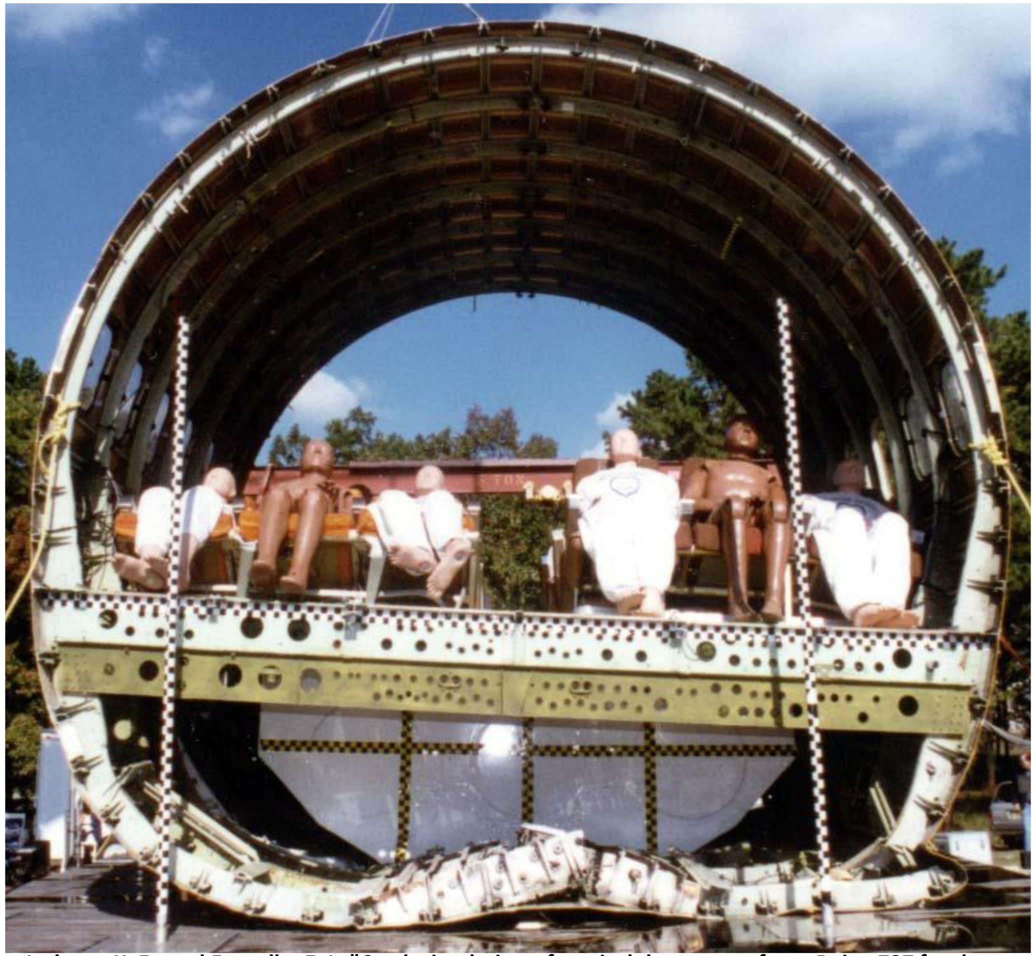
Mesh study was conducted for further verification of the computational model (cont'd)





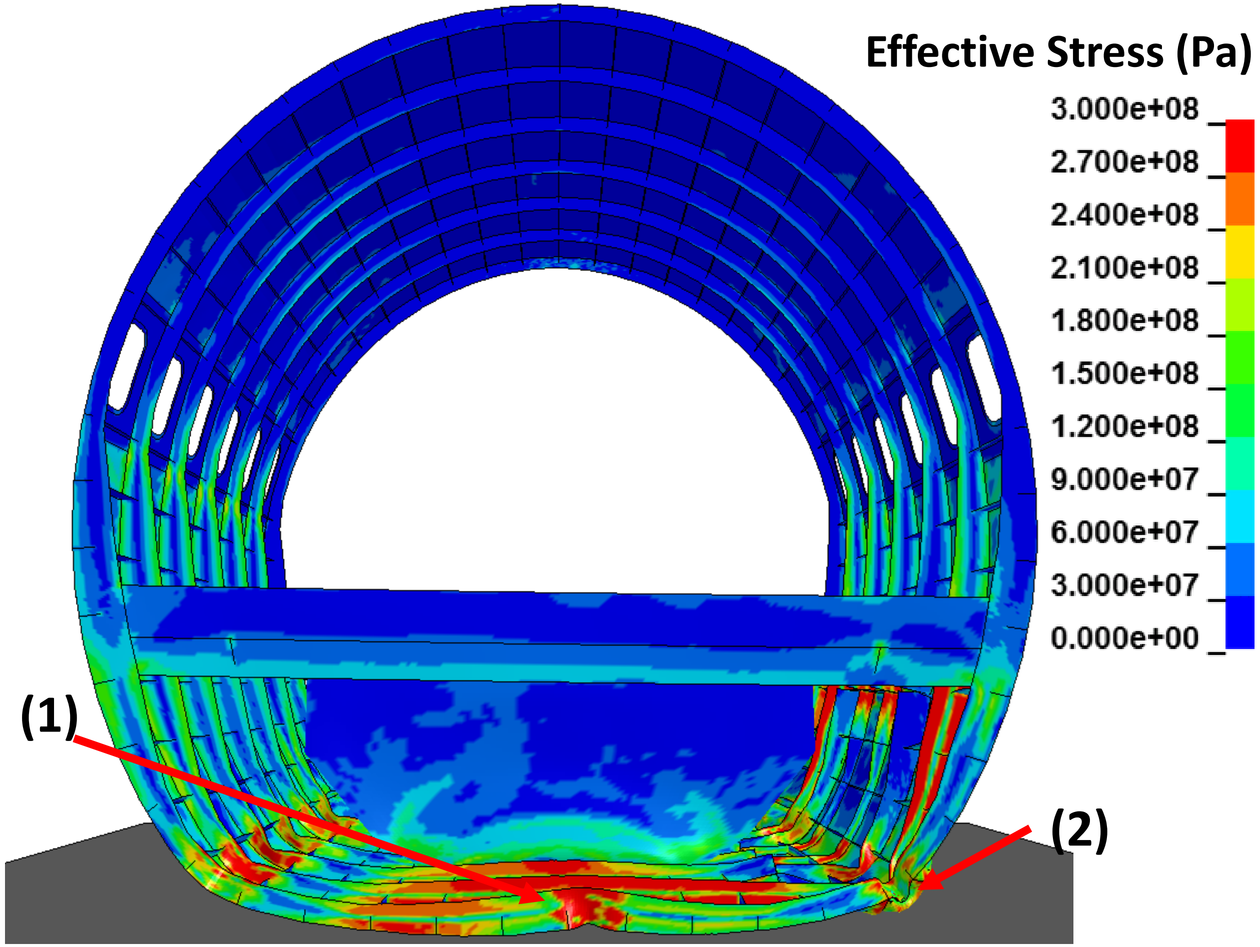
	Coarse	Mid	Fine
# of Element	34,967	142,193	572,455
Time (sec)	768	2,885	25,147

The peak magnitudes of G-loading are highly similar between the experiment and simulation



Jackson, K. E., and Fasnella, E. L. "Crash simulation of vertical drop tests of two Boing 737 fuselage sections." U.S.DOT and FAA DOT/FAA/AR-02/62, 2002, pp. 96

(a) Post-impact picture of section drop experiment



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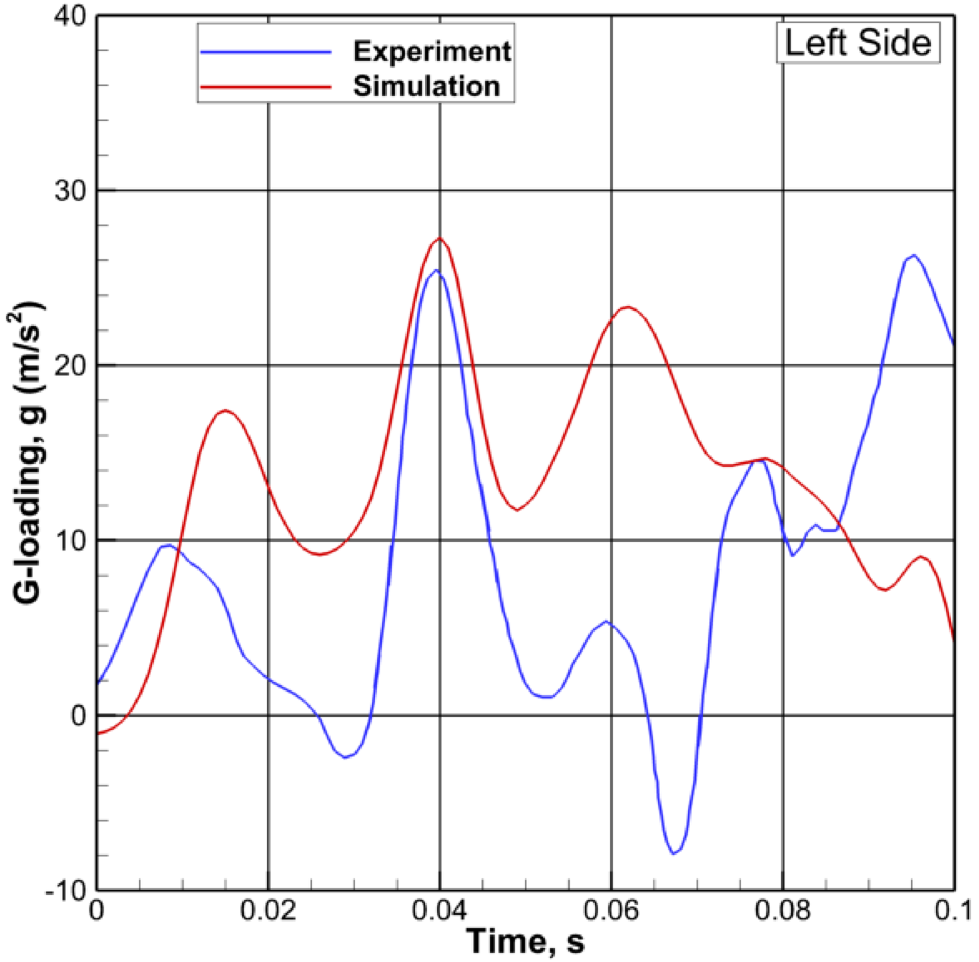
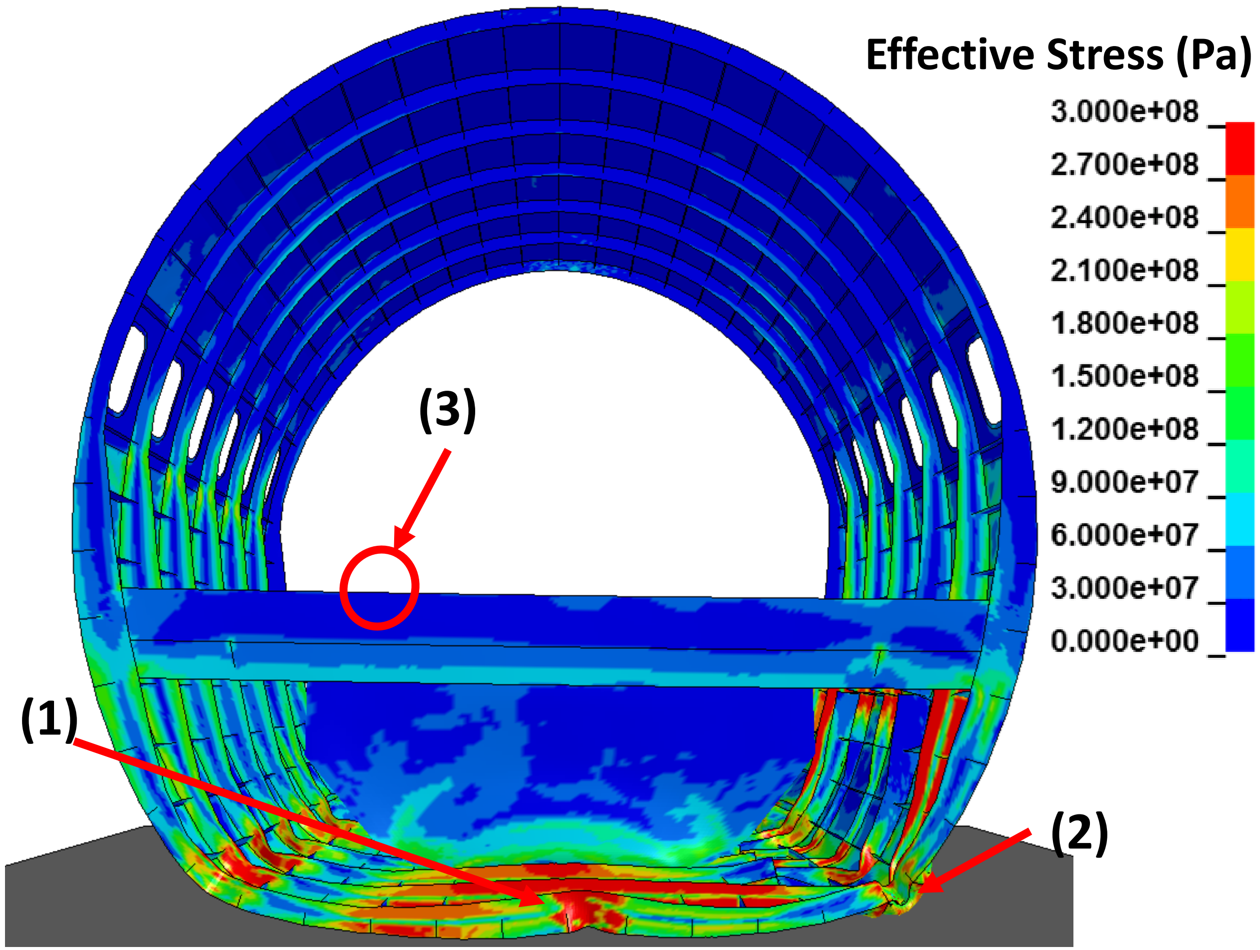


Left side passenger floor (normal section-(3))



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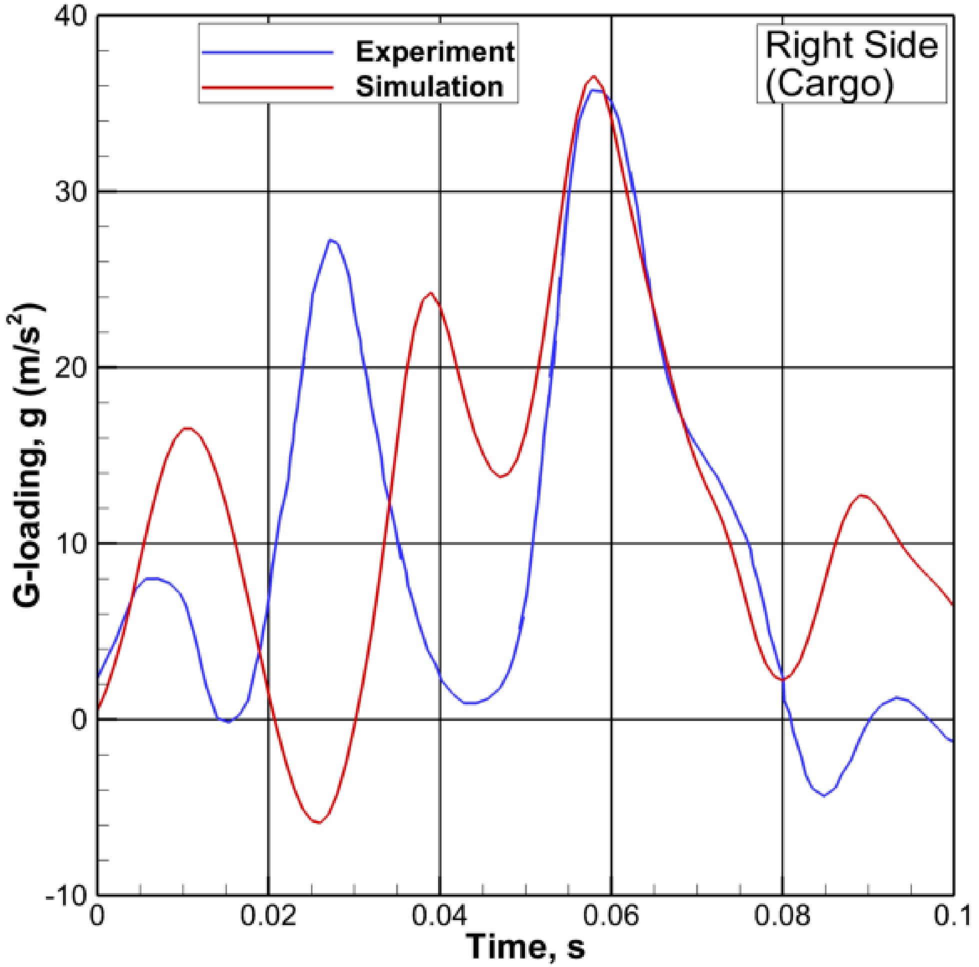

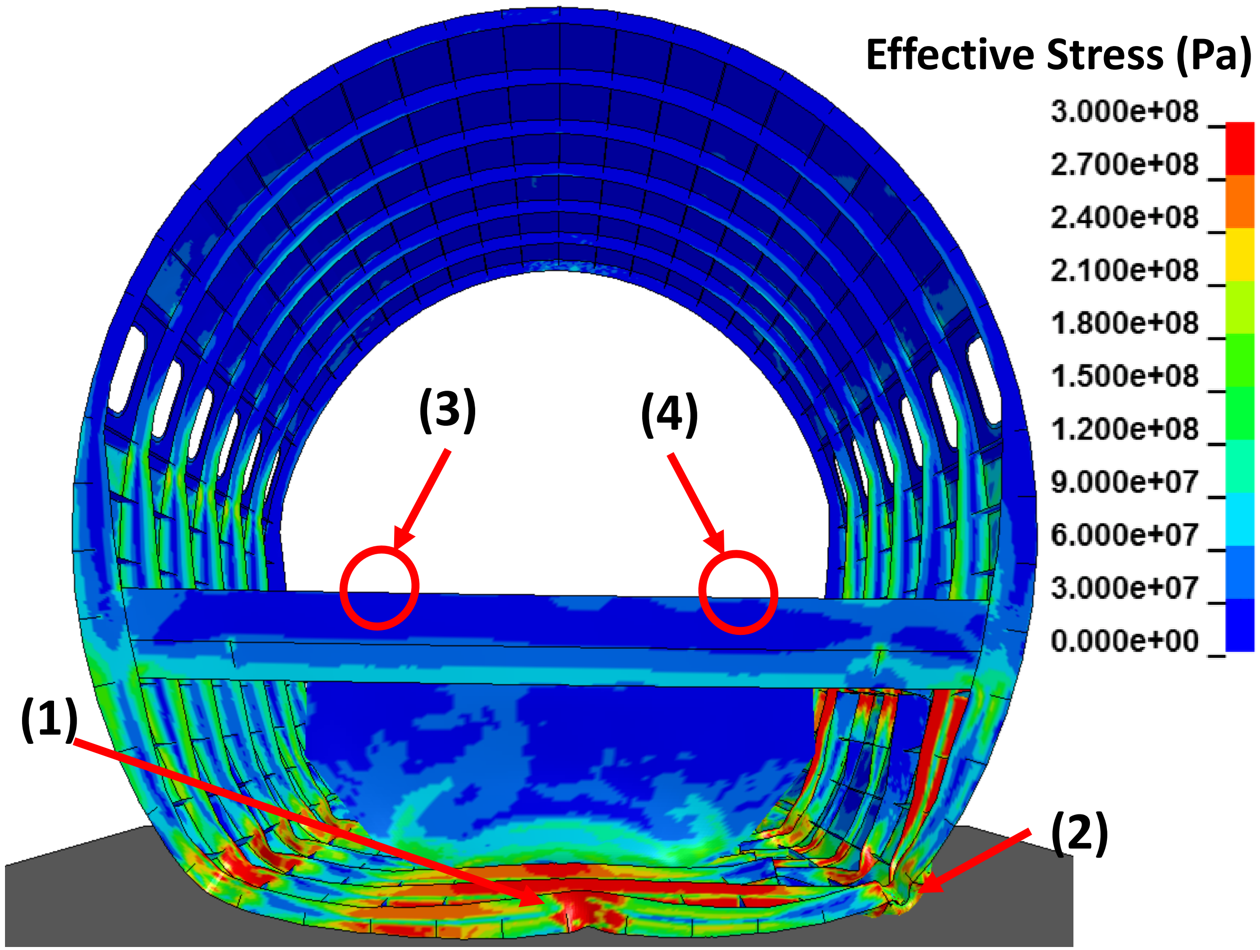

Right side passenger floor (Cargo door section-(4))

10% reduction in G-loading across the peaks was observed when impacted onto soil

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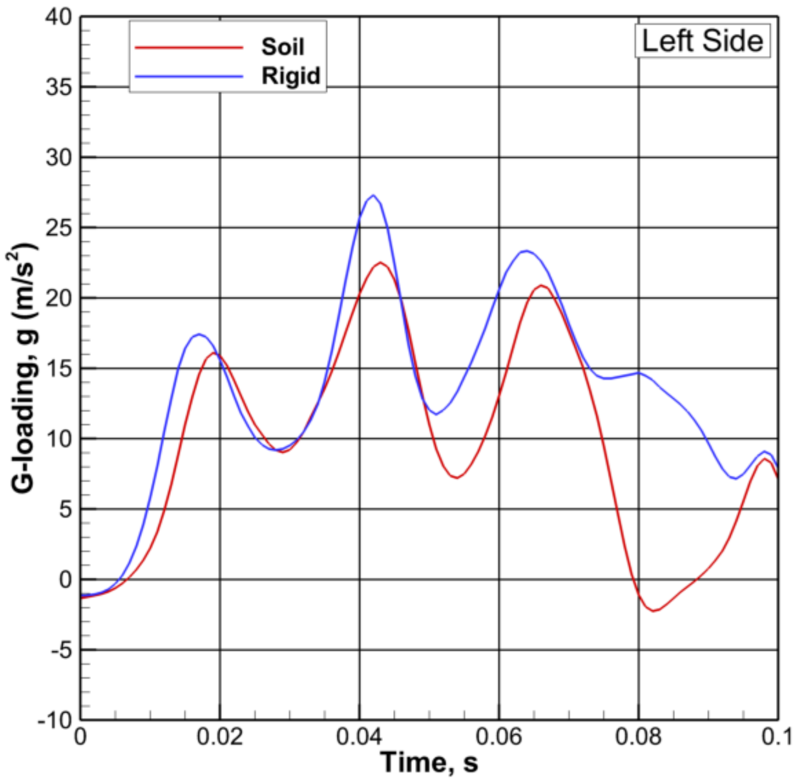
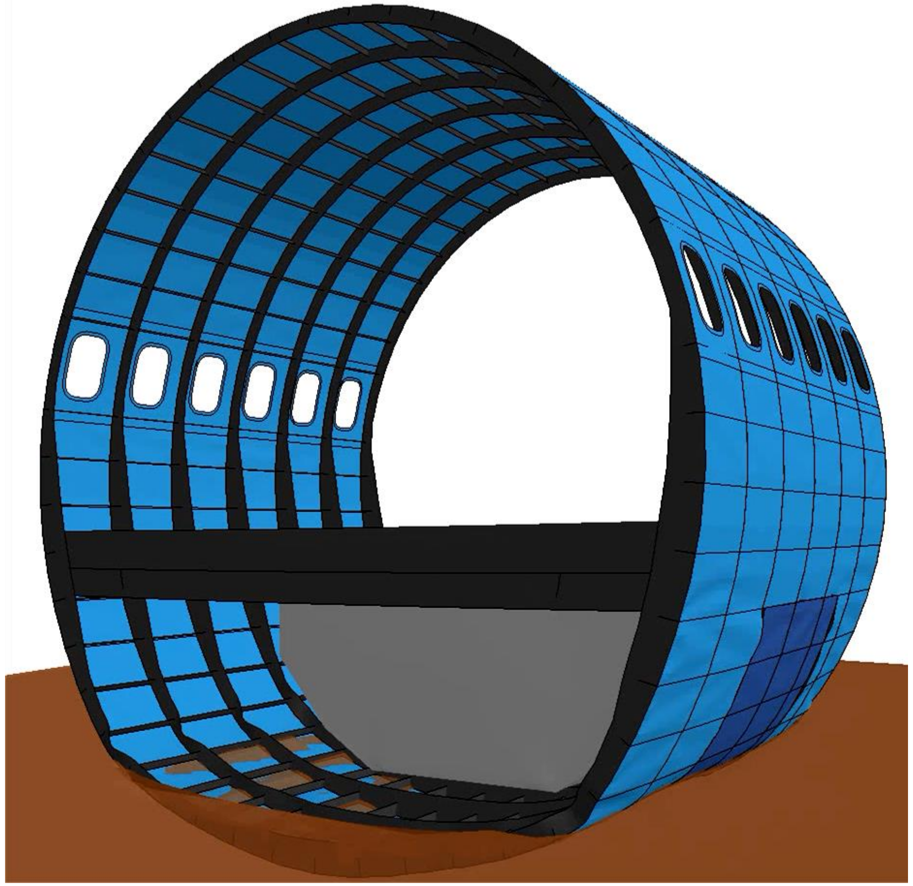
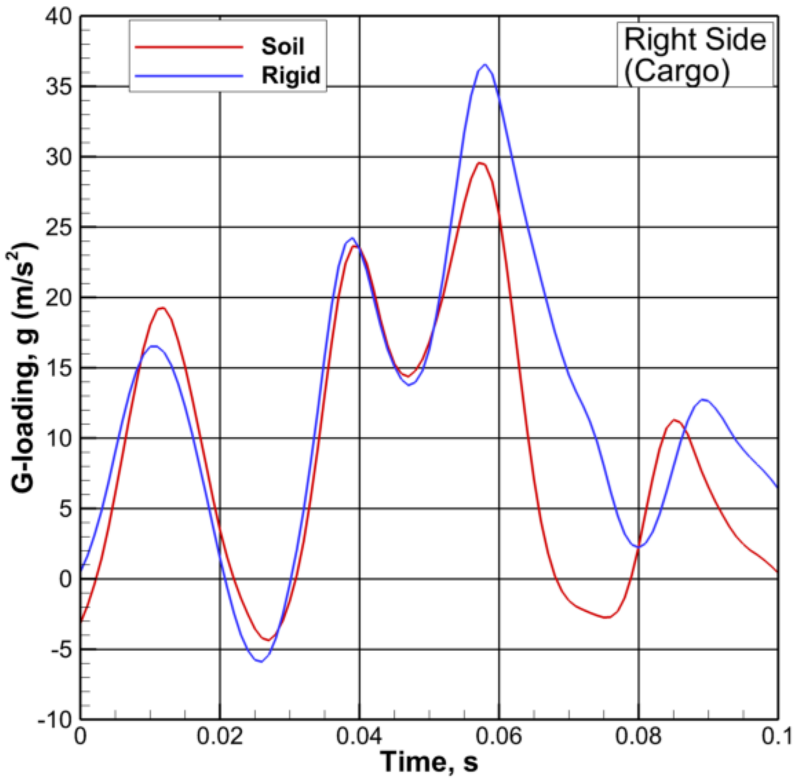


(a) Left side of passenger floor (Clean section)

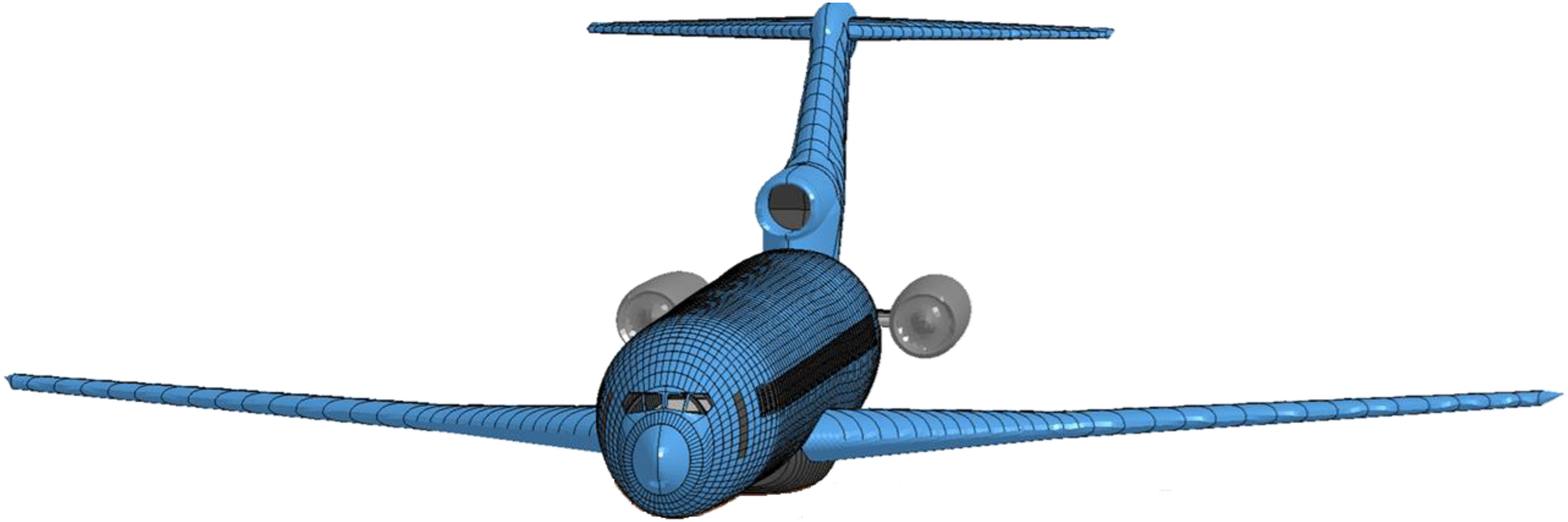


Rear view, impact onto soil

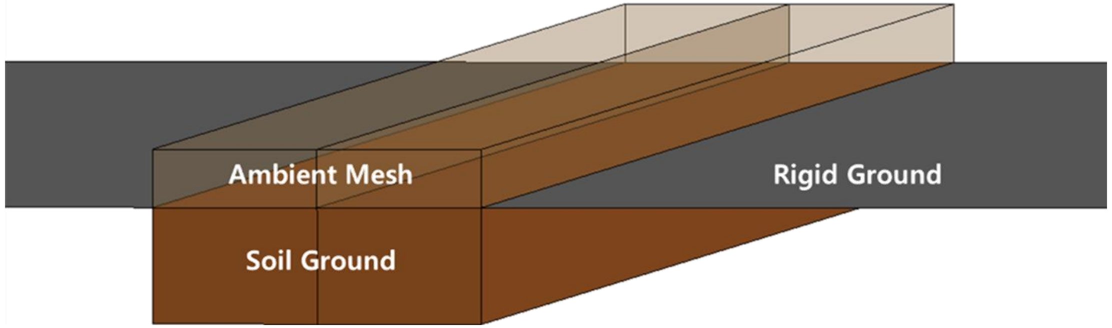


(b) Right side of passenger floor (Cargo door section)

The presented methodology was extended to a full-scale B727 plane crash simulation



- 2^{o} nose down, 10 m/s rate of descent, and 68 m/s horizontal flight velocity
- Half symmetric model was used
- Overall weight was 44,330 kg including fuel
- Several components were modeled as rigid



Rigid ground was implemented for the baseline crash landing simulation

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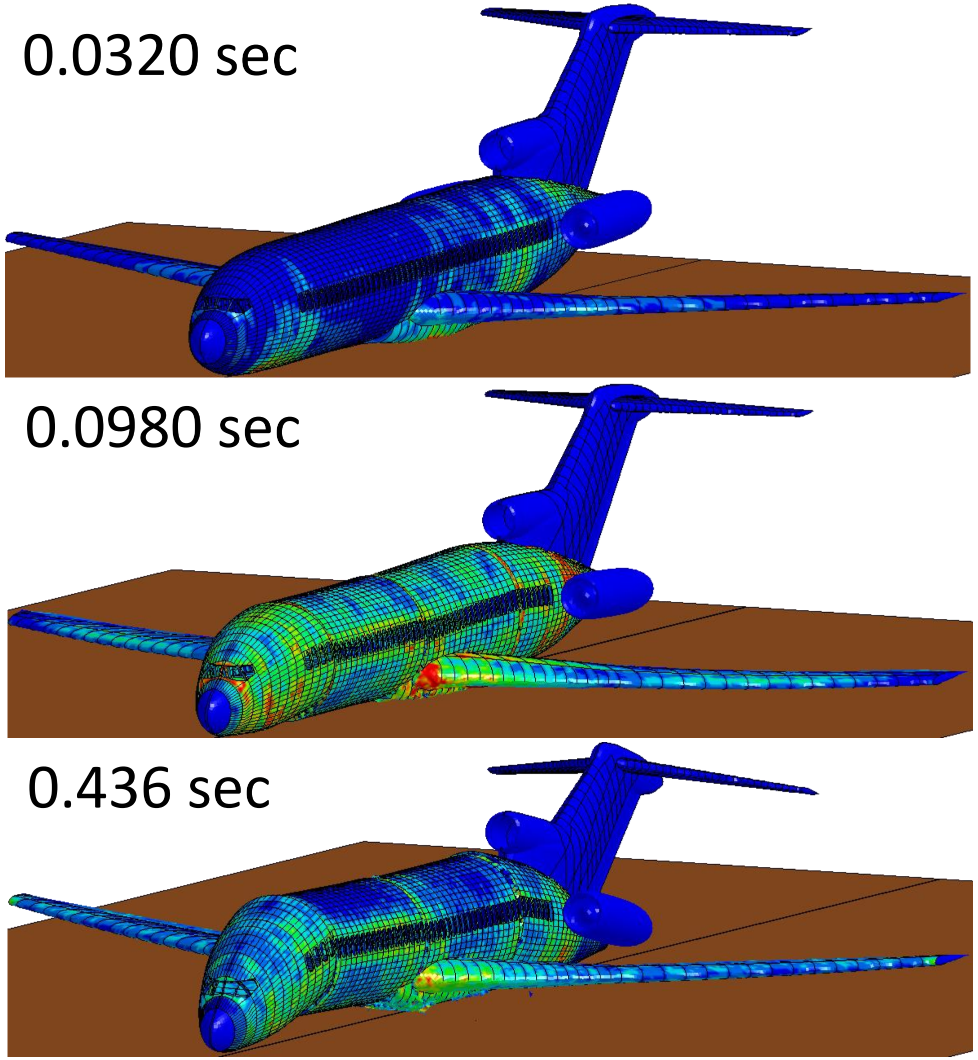
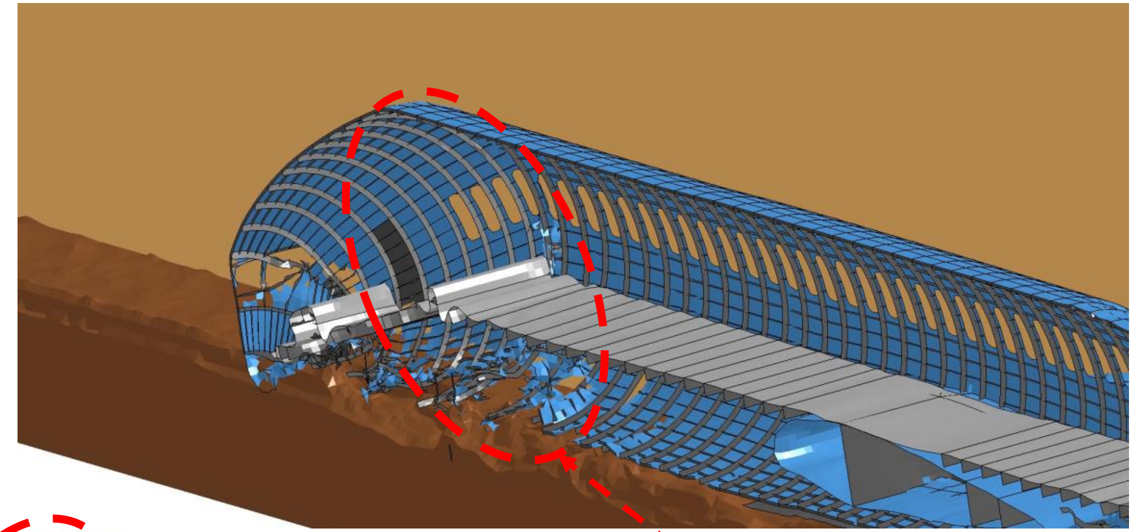
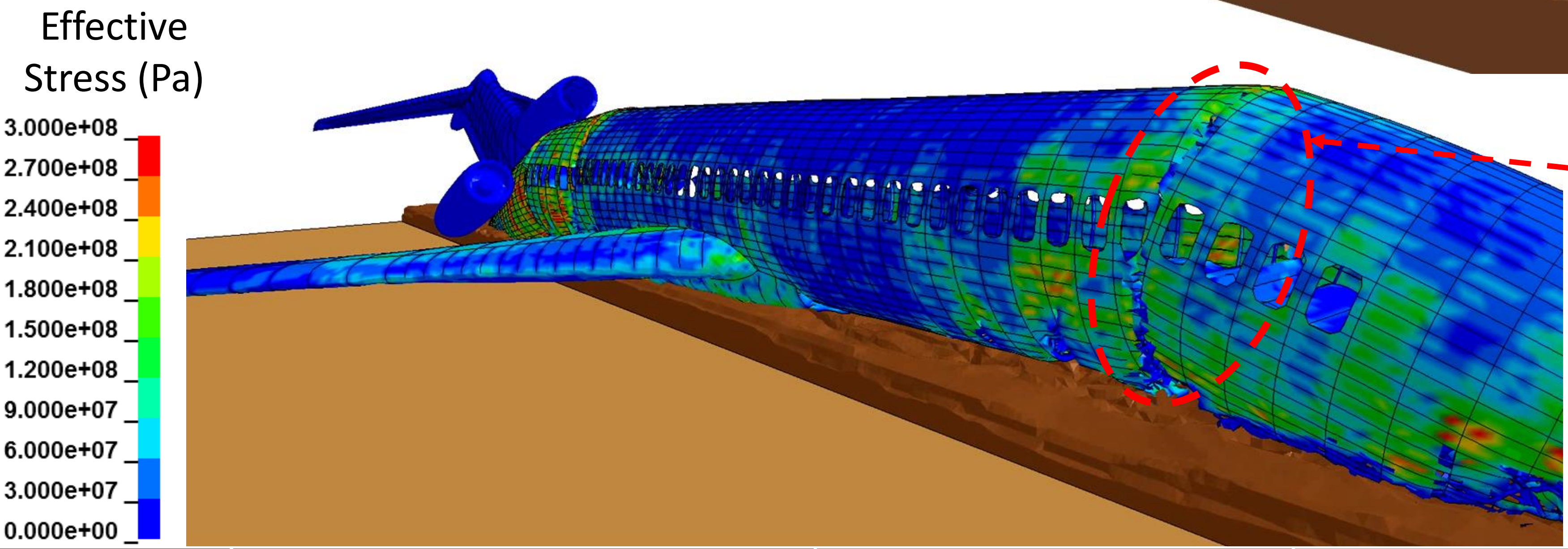


- The initial contact occurred at the belly of the fuselage, closely followed by the forward fuselage section
- The shock loading travels around the fuselage along the airframe and failure is initiated just behind the cockpit
- The empennage suffers from large deformation due to the weight of the stabilizers and engine

Deformable ground was implemented to capture nonlinear failure mechanics of crash landing on soil

- More rapid and larger deformation is caused by ground deformation
- Aft fuselage section also dug into the ground, causing secondary separation on empennage





Forward Fuselage Separation

High fidelity crashworthiness assessment requires a multidisciplinary approach

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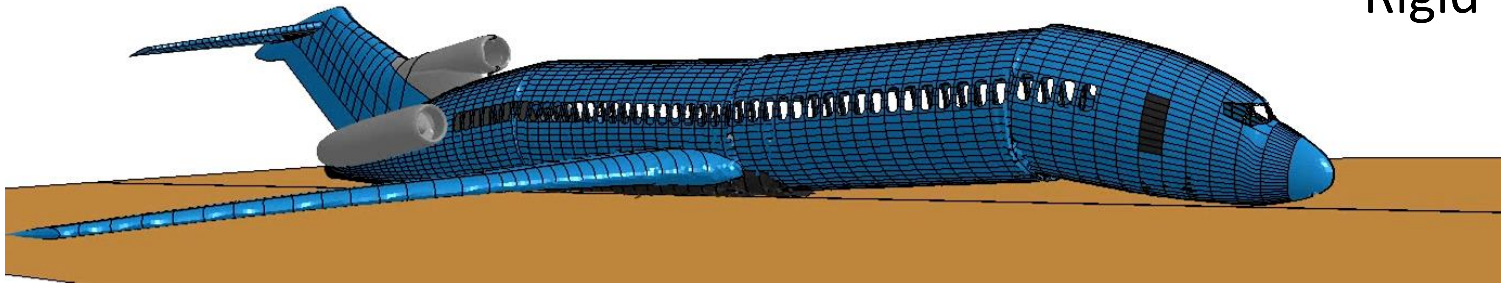
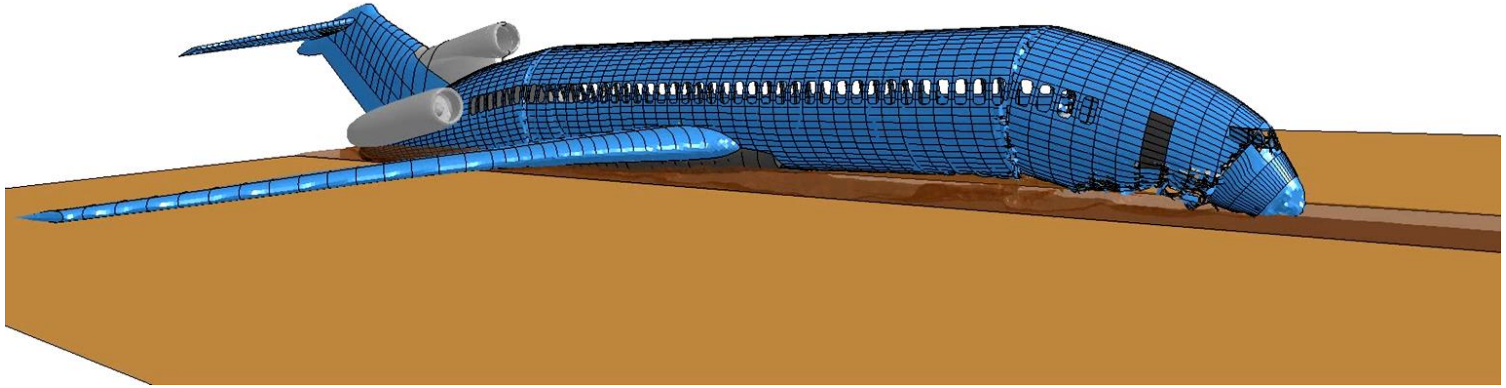
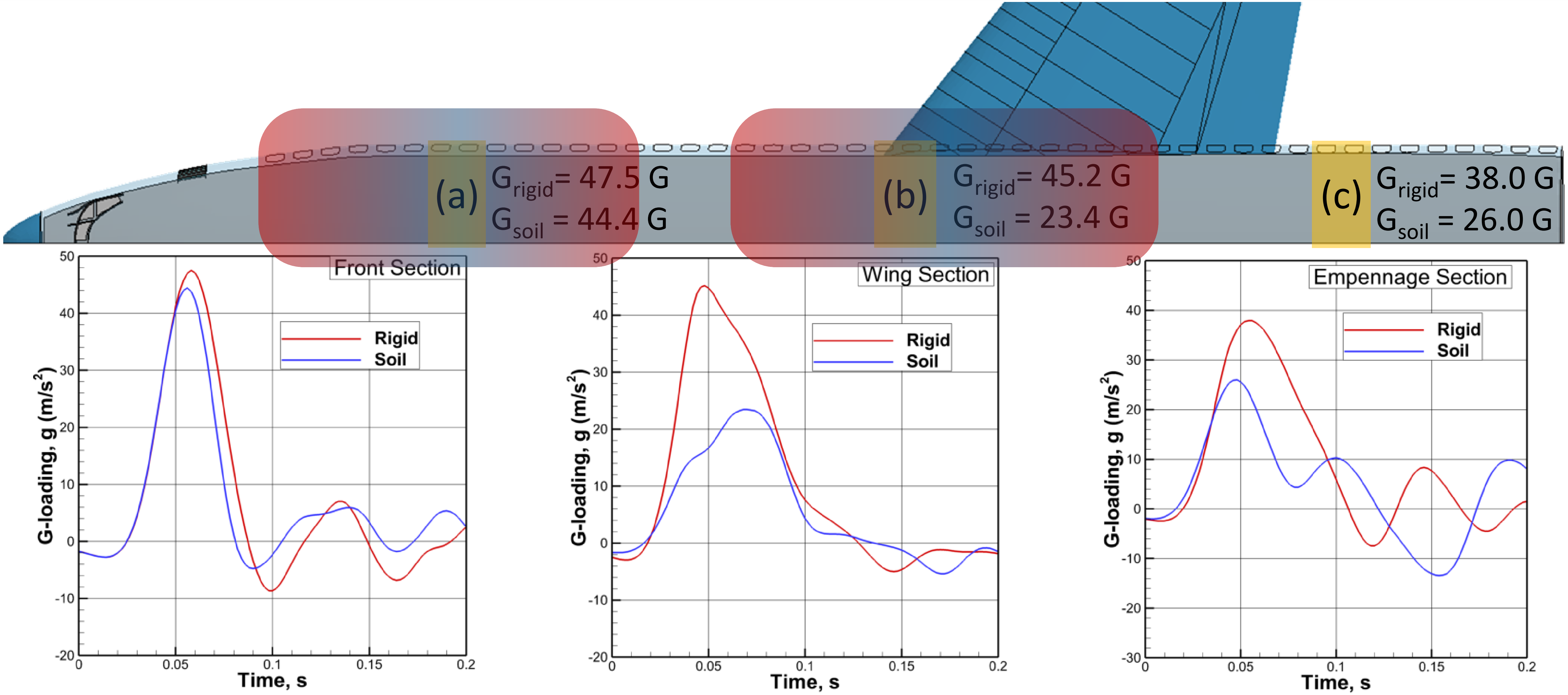
- The major damage along the fuselage was captured in the simulation
- However, the ground conditions changed the results
    - Soil modeling does not impose mid-fuselage separation
    - Because of the deformation of soil model, the airplane suffered larger magnitude of friction which cause the empennage separation





Significant G-loading reduction was observed when the aircraft crashed on soil



Simulating deformable ground is necessary to accurately represent crash landing dynamics

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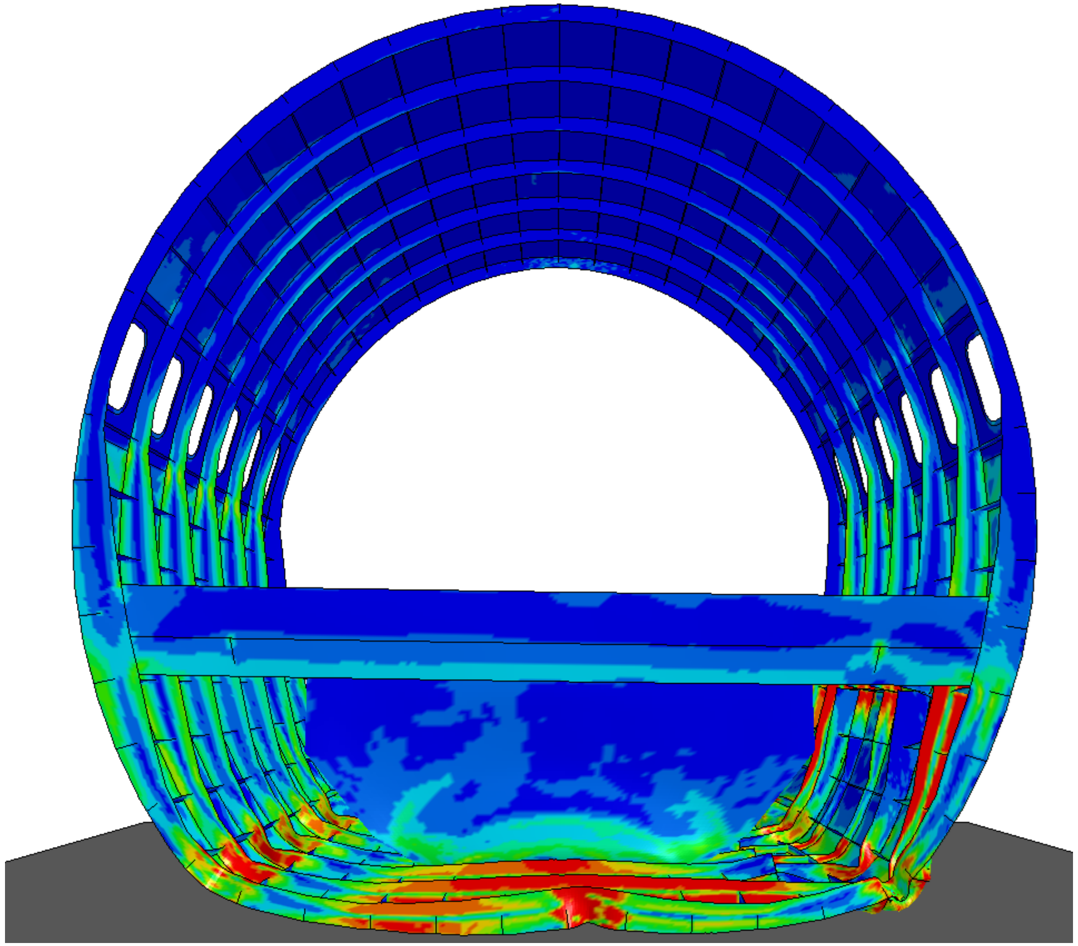
- Section-Drop Test
  - Successful validation
  - Rigid vs. Soil comparison
- Full-Scale Plane Crash
  - Compared against experiment
  - Explored impact surfaces
    - Rigid
    - Soil



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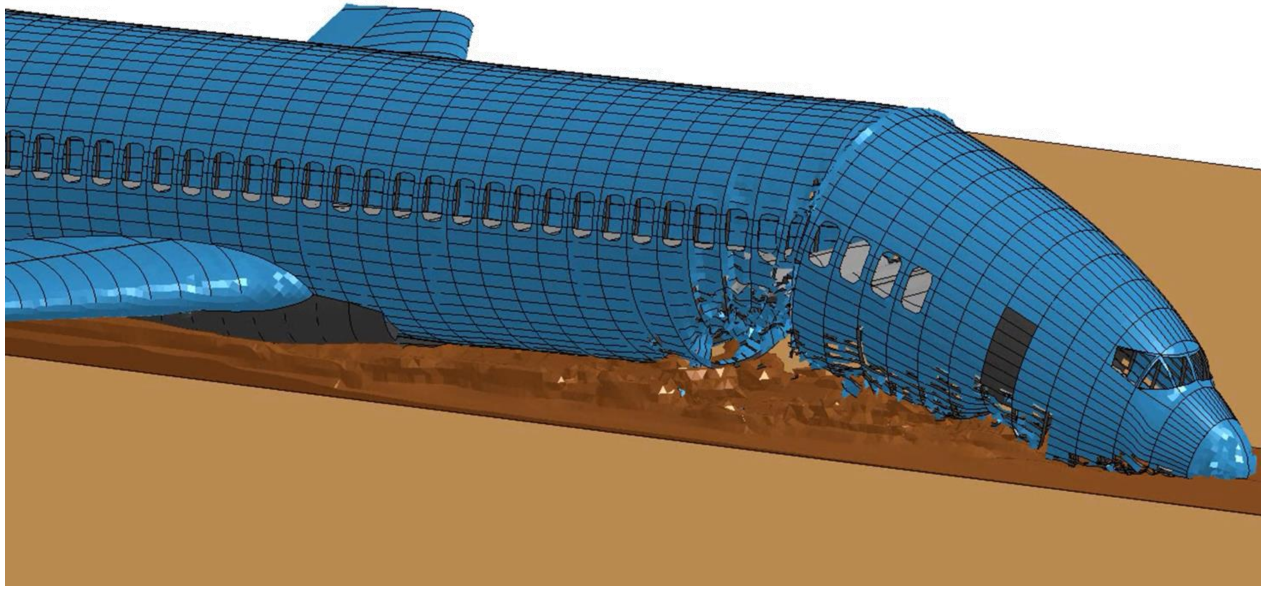

Contributions

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- A certification section drop test was simulated and successfully validated
- The building block methodology combined with FSI was able to simulate an aircraft crash scenario on deformable ground with reasonably high accuracy
- Importance of realistic ground model for high fidelity crash landing was emphasized
- Future work will include the investigation of updated methodology, varying impact surfaces, as well as other impact scenarios to envelope the range and accuracy of the current analysis method proposed to be used for aircraft certification

Fact Sheet

What are the **limitations** of this M&S methodology?

- The primary limitation is the required computational time
  - The entire airplane and deformable ground must be modeled to assess the dynamic response of the entire structure
  - Highly deformable ground, such as soil, requires a computationally expensive element formulation in order to remain stable within a large domain to capture the dynamics
  - Parallel processing does not scale the computational performance linearly, increasing the number of CPUs has diminishing returns in reducing computation time

Fact Sheet

Any issues that you found in building/running your model?

- Public domain aircraft specifications are limited
  - Full computational model had to be somewhat defeatured to reduce computational expense
  - Some aircraft features are based on the engineering estimate
- For deformable ground, the computational cost becomes prohibitively expensive when investigating mesh dependency

Fact Sheet

Any other issues that can contribute to the certification by analysis efforts?

- Collaborations
- Involvement of modelers in tests, and test specialists in simulations
- Availability of key information and data
- Improved HPC facilities
- Availability of multiprocessing licenses to academia for reasonable cost
- Ongoing oversight by FAA on certification by analysis efforts
- Open challenges and opportunities for involvement
- Continued targeted FAA workshops and communications