Crashworthiness - Certification by Analysis

Gerardo Olivares Ph.D., NIAR-WSU

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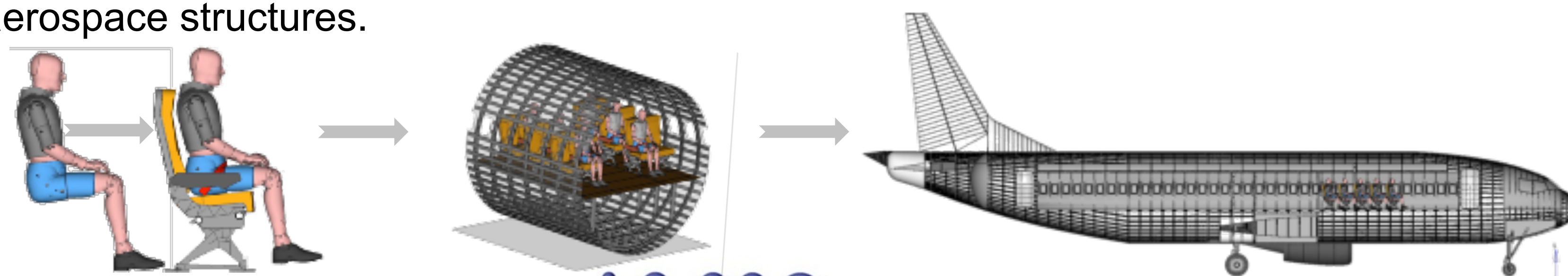
Crashworthiness - Certification by Analysis

- 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 an evaluation methodology (experimental and numerical) and predictable computational tools.
- Approach
  - The advances in computational tools combined with the building block approach allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures.



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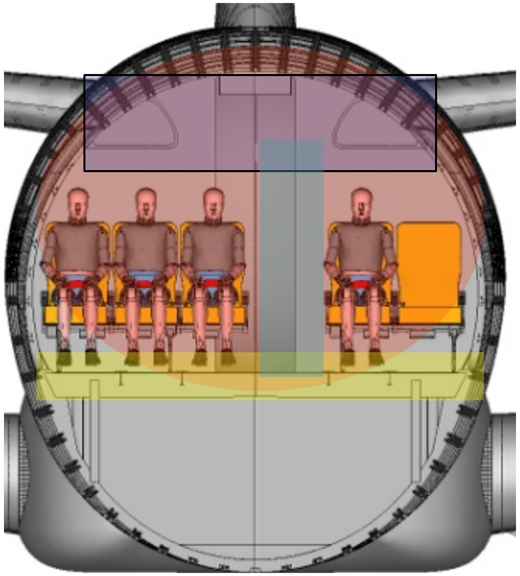
Crashworthiness - Certification by Analysis

- **Principal Investigators & Researchers**
  - **PI's:** G. Olivares Ph.D. , J. Acosta Ph.D, S. Keshavanarayana Ph.D.
  - **Researchers NIAR:** Chandresh Zinzuwadia , Adrian Gomez , Nilesh Dhole
  - Hiromitsu Miyaki , Japan Aerospace Exploration Agency, JAXA
  - **8 Graduate and Undergraduate Students:** Nathaniel Baum, Miguel Correa, Hoa Ly, Armando Barriga, Ranjeethkumar Jalapuram, Vikar Mohammad, Rohit Madikeri and Sameer Naukudkar.
- **FAA Technical Monitor**
  - Allan Abramowitz
- **Other FAA Personnel Involved**
  - Joseph Pelletiere Ph.D.
- **Industry\Government Participation**
  - Gerard Elstak and Gerard Schakelaar - Politie
  - Gijsbert Vogelaar - Dutch Safety Board
  - Willem Doeland - EASA

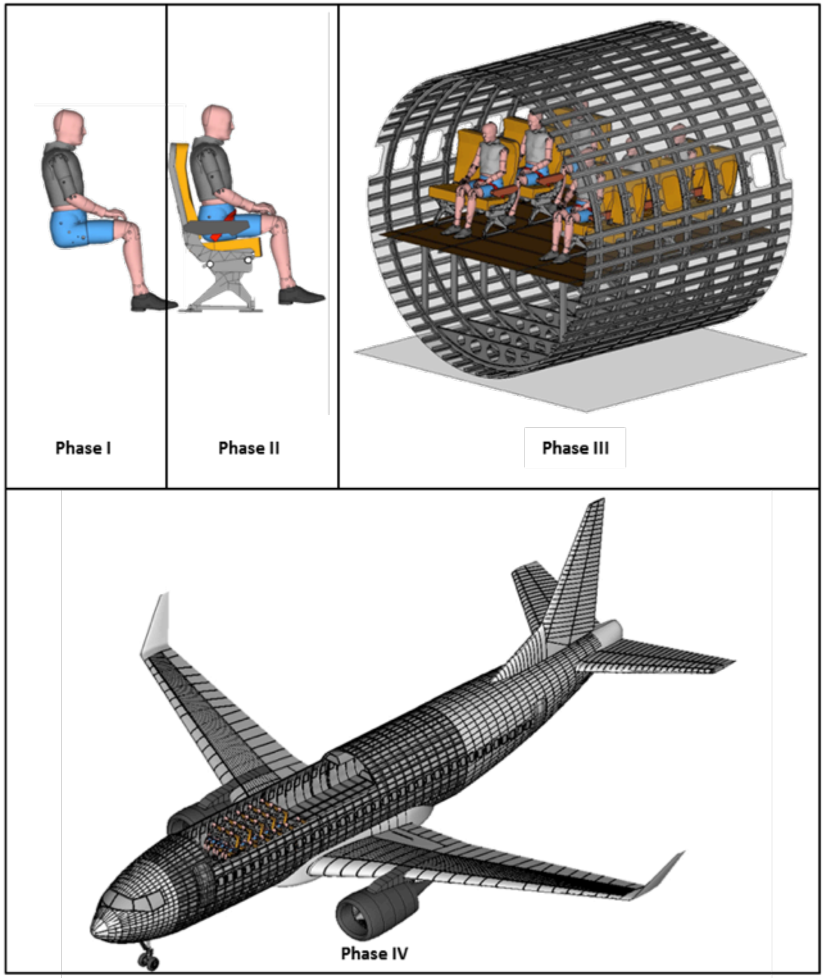
Aerospace Structural Crashworthiness

- **Crashworthiness performance of composite structures to be equivalent or better than traditional metallic structures**
- **Crashworthiness design requirements**:
  - Maintain survivable volume
  - Maintain deceleration loads to occupants
  - Retention items of mass
  - Maintain egress paths



- **Currently there are two approaches that can be applied to analyze this special condition:**
  - **Method I: Large Scale Test Article Approach**
    - **Experimental:**
      - Large Scale Test Articles (Barrel Sections)
      - Component Level Testing of Energy Absorbing Devices
    - **Simulation** follows testing – Numerical models are **"tuned"** to match large test article/EA sub-assemblies results. Computational models are only predictable for the specific configurations that were tested during the experimental phase. For example if there are changes to the loading conditions (i.e. impact location, velocity, ..etc.) and/or to the geometry, **the model may or may not predict** the crashworthiness behavior of the structure.
  - **Method II:** Building Block Approach
    - **Experimental and Simulation**
      - Coupon Level to Full Scale
    - **Simulation**: Predictable modeling

Crashworthiness CBA R&D Phases



- **Phase 0:** Define Occupant Injury Limits | **FAR** *.562 | ✓
- **Phase I:** Develop and validate occupant ATD numerical models **| SAE ARP** 5765 **|** ✓
- **Phase II**: Define Modeling and Certification by Analysis Processes of Aerospace Seat Structures and Installations **|AC** 20-146**|SAE ARP** 5765 | Aircraft OEMS and Seat Suppliers Modeling and CBA Standards | ✓
- **Phase III:** Define Crashworthiness Building Block Approach for Aircraft Structures **|CMH-17| ARAC** Transport Airplane Crashworthiness and Ditching Working Group| Aircraft OEMS Methods| ✓
- **Phase IV:** Define Structural CBA Methodology **|CMH-17| ARAC** Transport Airplane Crashworthiness and Ditching Working Group|

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Building Block Approach R&D

BENCHMARKING

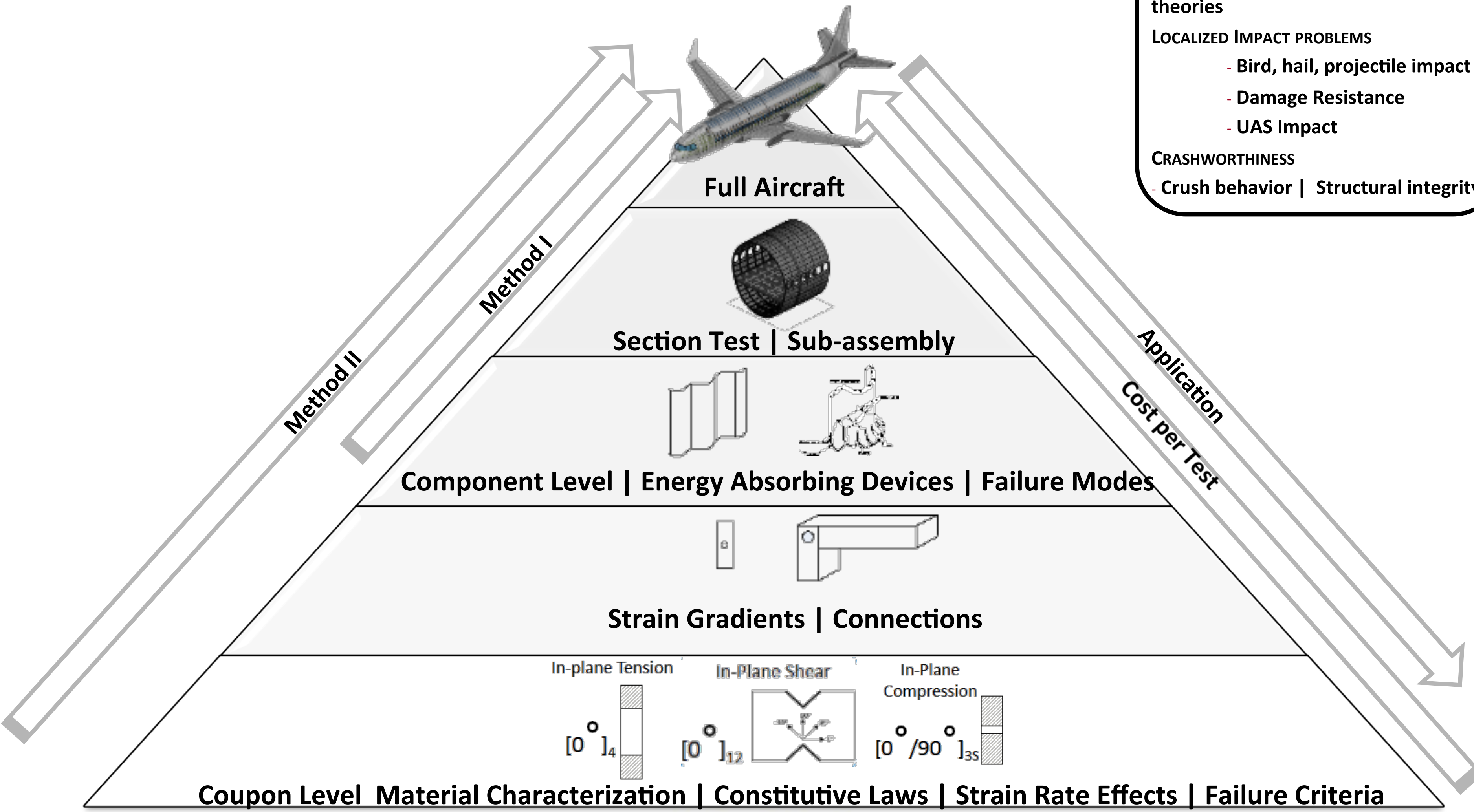
- Constitutive models | Failure theories

LOCALIZED IMPACT PROBLEMS

- Bird, hail, projectile impact
- Damage Resistance
- UAS Impact

CRASHWORTHINESS

- Crush behavior | Structural integrity



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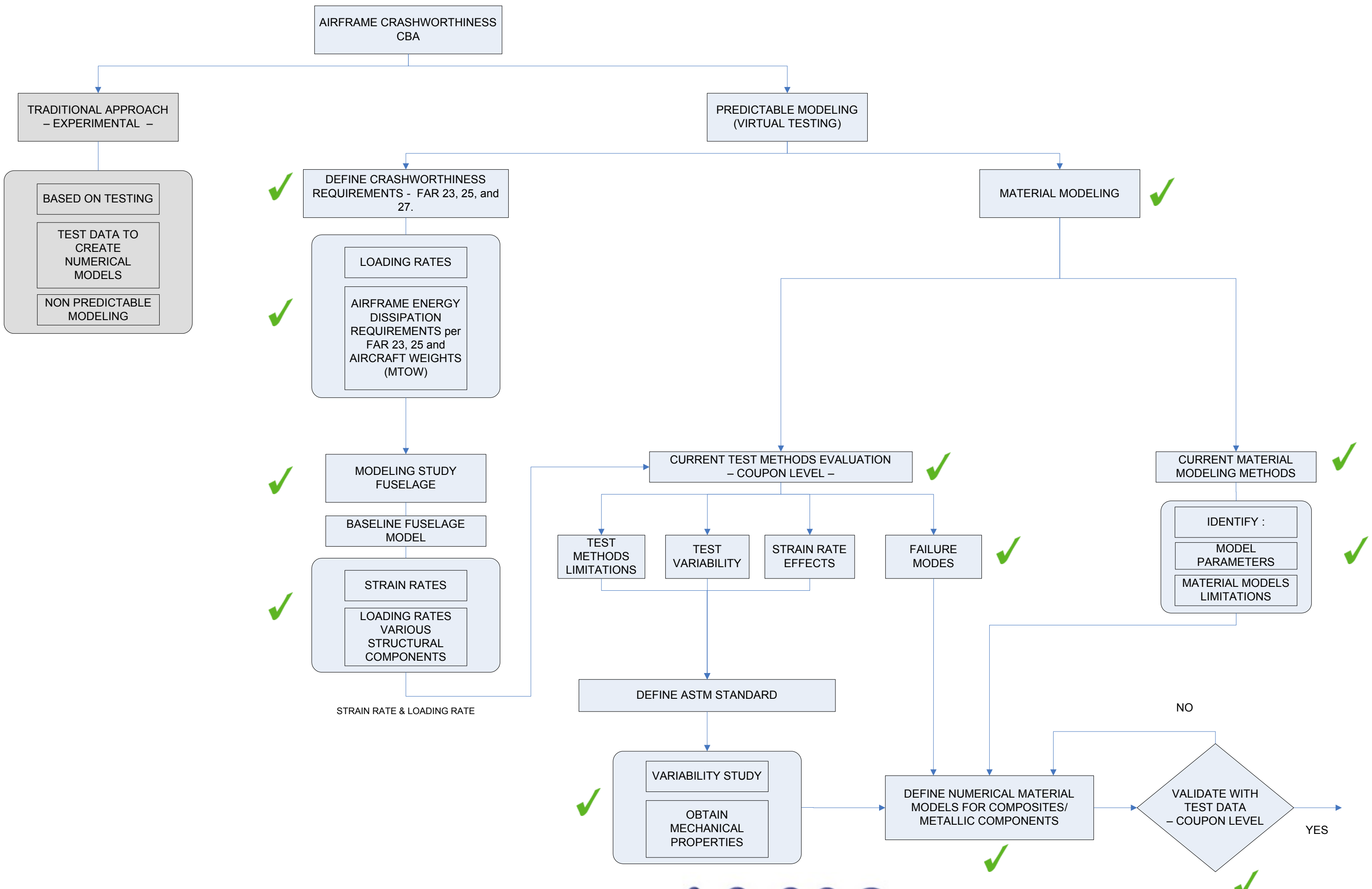
CBA: Composite Structures Crashworthiness



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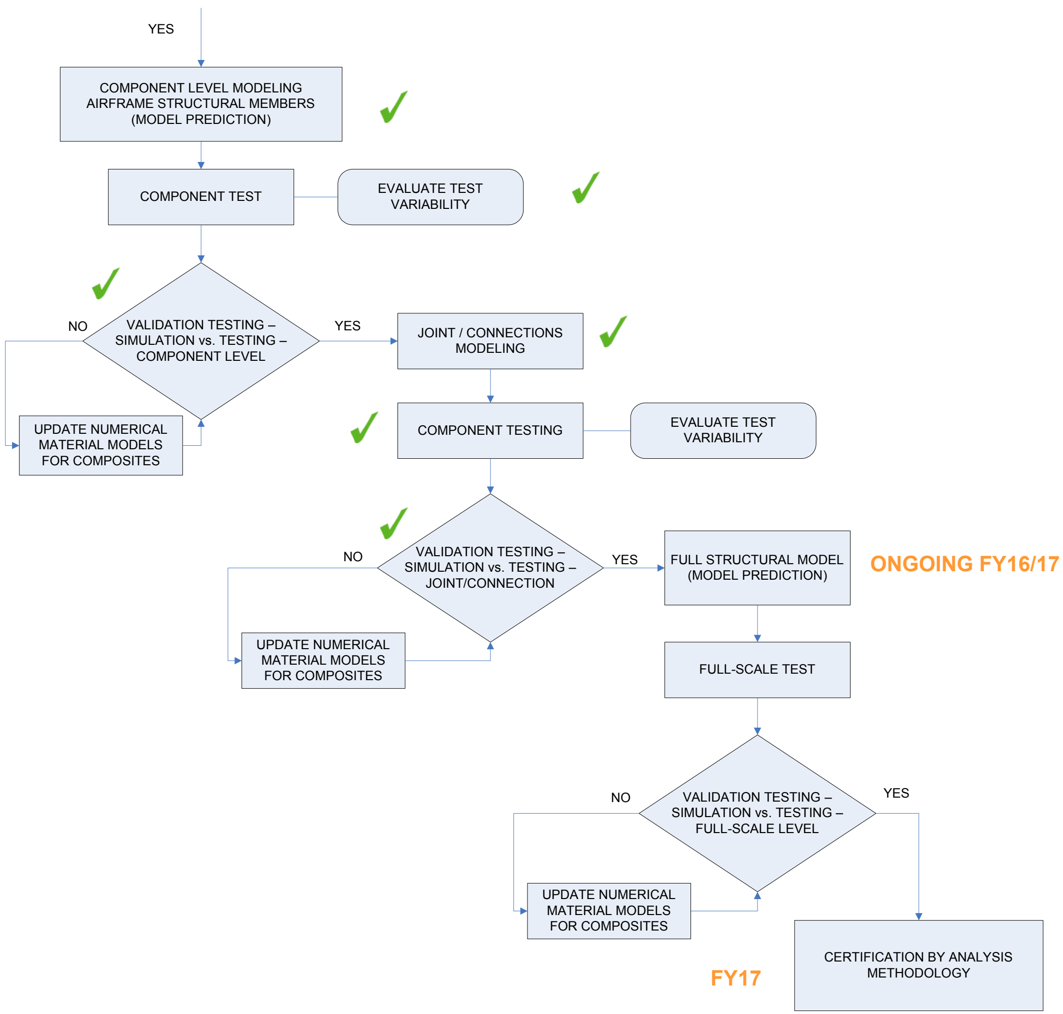
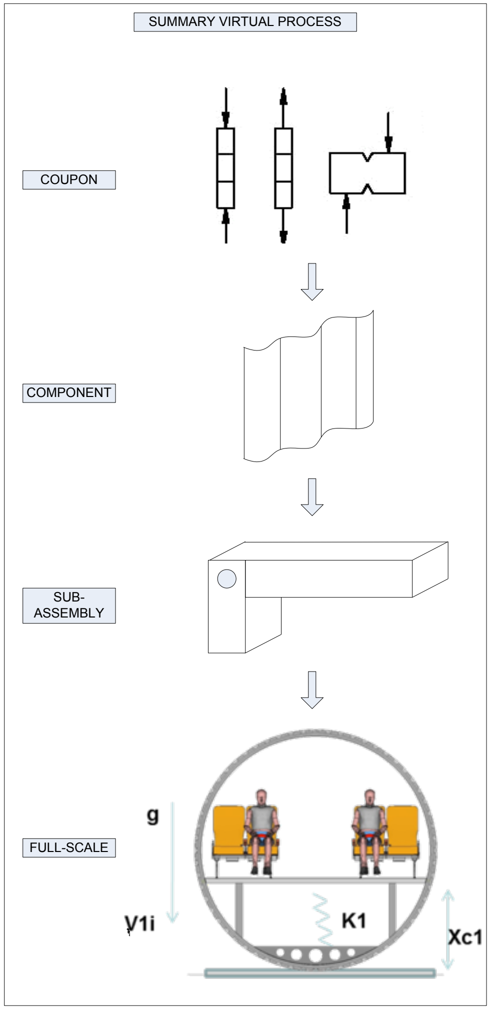
CBA Composite Structures Crashworthiness





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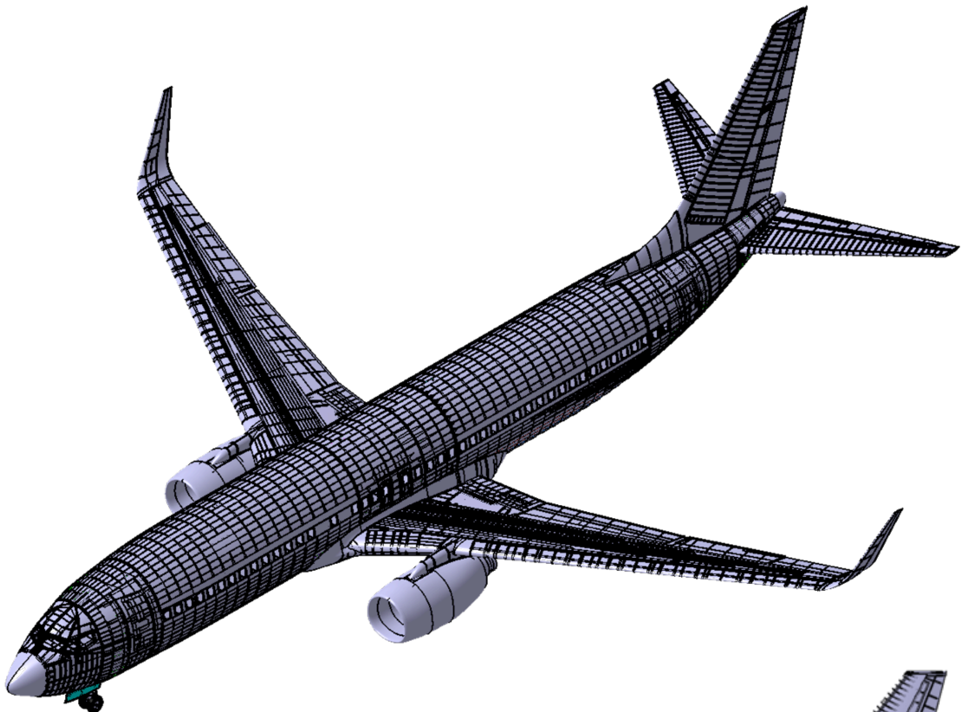
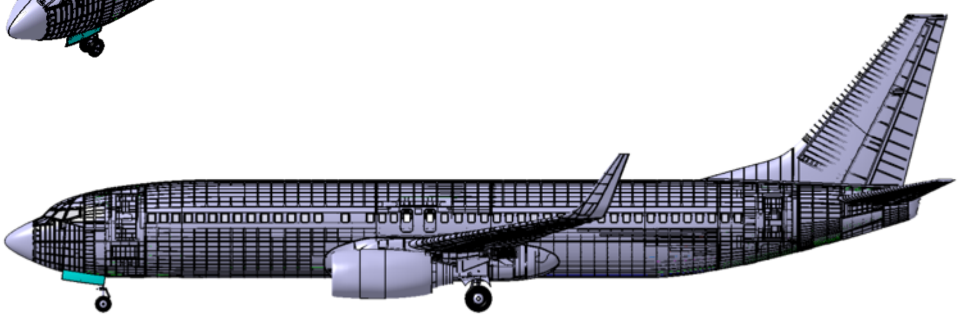
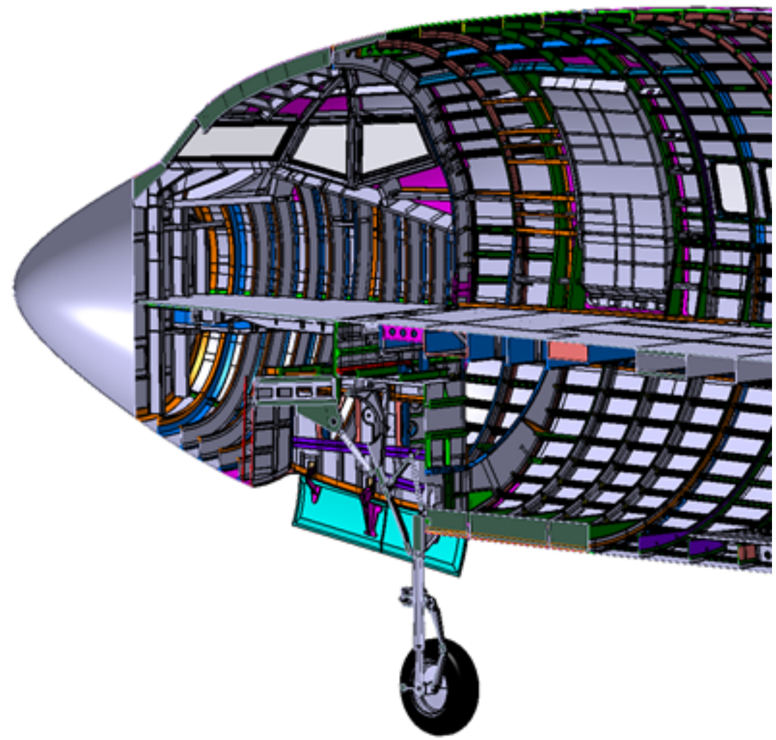
Full Scale Aircraft - CAD Model Definition

- 10,000+ Engineering Hours [2 FTE, and 4 Students]
- 2500 Sub-Assemblies
- Representative Narrow Body Aircraft Model







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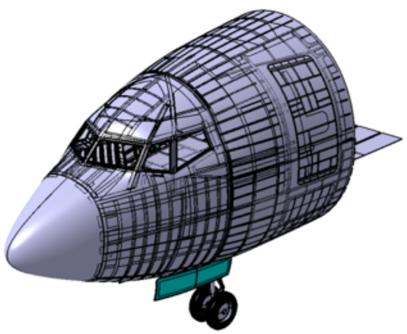
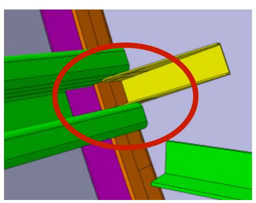
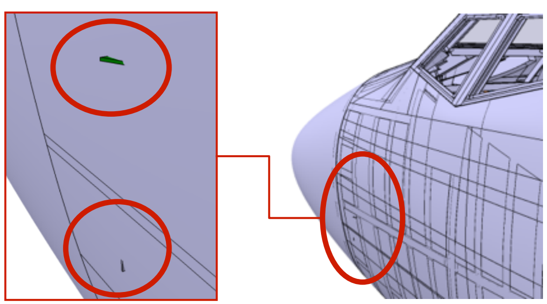
FEA Modeling - Discretization Process

Geometry Cleanup

- Inspect CAD model for
  - Penetration
  - Intersections
- Document and Request corrections

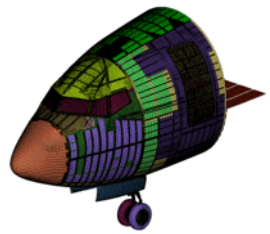


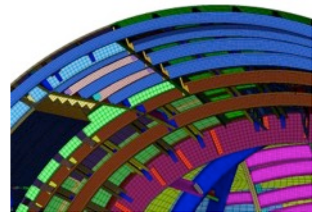




Meshing

- Consistent Element Sizes
- Mesh Flow
- Minimize number of Trias < 5%
- Mesh Quality Criteria for Crash Analysis



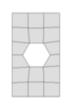


Shell (2D)Mesh

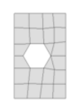
Quality Parameter	Allowable Min./Max.
Min.Side Length	5 mm
Max.Aspect Ratio	5
Min. Quad Angle	45 deg
Max. Quad Angle	140 deg
Min. Tri Angle	30 deg
Max. Tri Angle	120 deg
Max Warp Angle	15 deg
Min. Jacobian	0.7

Solid (3D)Mesh

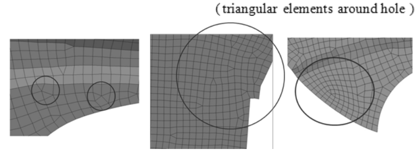
Quality Parameter	Allowable Min./Max.
Min.Side Length	5 mm
Max.Aspect Ratio	5
Tet Collapse	0.3
Max Warp Angle	15 deg
Min. Jacobian	0.5



Desirable mesh



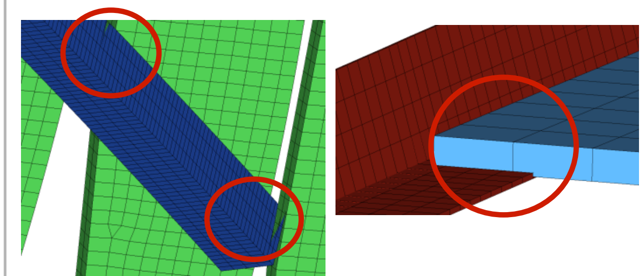
Not desirable mesh (triangular elements around hole)



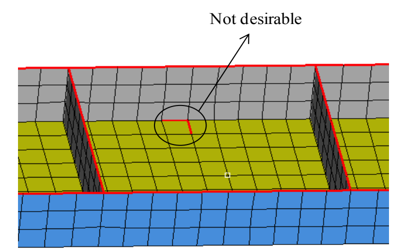
NOT desirable mesh transition

Quality Check

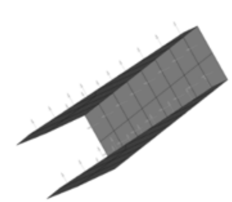
- Check Normals
- Check Penetrations
- Check Intersections
- Check Edges and Element Connectivity
- Check for Duplicates



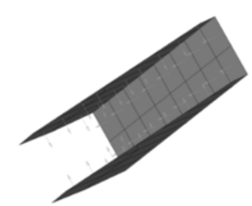
Intersections and Penetrations need to be fixed



Bad element connectivity



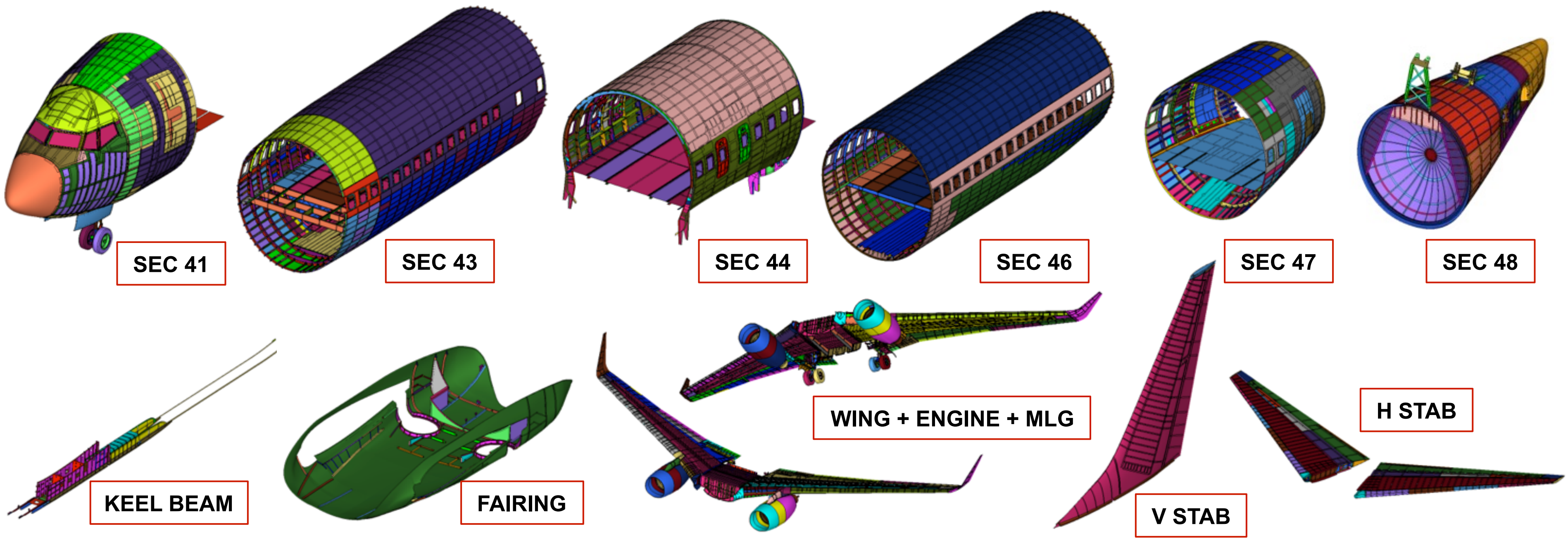
Element Normals need fixing



Element Normals fixed

FEA Modeling - Modular FEA Model Approach

	Numbering Ranges					
Include Sections	Nodes	Elements	Parts	Sections	Sets	Others eg. Constraints
FUSELAGE	**1 - 16,000,000**	**1 - 16,000,000**				
SEC 41 + NLG	1 - 2,499,999	1 - 2,499,999	410000 - 419999	410000 - 419999	410000 - 419999	410000 - 419999
SEC 43	2,500,000 - 4,999,999	2,500,000 - 4,999,999	430000 - 439999	430000 - 439999	430000 - 439999	430000 - 439999
SEC 44	5,000,000 - 7,499,999	5,000,000 - 7,499,999	440000 - 449999	440000 - 449999	440000 - 449999	440000 - 449999
SEC 46	7,500,000 - 9,999,999	7,500,000 - 9,999,999	460000 - 469999	460000 - 469999	460000 - 469999	460000 - 469999
SEC 47	10,000,000 - 12,499,999	10,000,000 - 12,499,999	470000 - 479999	470000 - 479999	470000 - 479999	470000 - 479999
SEC 48	12,500,000 - 14,999,999	12,500,000 - 14,999,999	480000 - 489999	480000 - 489999	480000 - 489999	480000 - 489999
KEEL BEAM	15,000,000 - 15,499,999	15,000,000 - 15,499,999	400000 - 409999	400000 - 409999	400000 - 409999	400000 - 409999
WING-BODY FAIRING	15,500,000 - 16,000,000	15,500,000 - 16,000,000	450000 - 459999	450000 - 459999	450000 - 459999	450000 - 459999
WING	**17,000,000 - 20,500,000**	**17,000,000 - 20,500,000**				
Wing + Engine + MLG	17,000,000 - 20,500,000	17,000,000 - 20,500,000	500000 - 529999	500000 - 529999	500000 - 529999	500000 - 529999
VERTICAL STAB	21,000,000 - 21,999,999	21,000,000 - 21,999,999	700000 - 709999	700000 - 709999	700000 - 709999	700000 - 709999
HORIZONTAL STAB	22,000,000 - 22,999,999	22,000,000 - 22,999,999	800000 - 809999	800000 - 809999	800000 - 809999	800000 - 809999



FEA Modeling - Model Documentation

No	Component Name	ID	Geometry	CAD RELEASE DATE: No. of Parts	Revision	Date Received	Thickness(mm)	Normal's check	Duplicate elements	Connectivity
	DoorEdgeFrameSTA440_Doubler2	430037					1.016	YES	NONE	YES
	DoorEdgeFrameSTA440_InnerFailSafe3	430038					1.016	YES	NONE	YES
	DoorEdgeFrameSTA440_Splice11	430036					2.286	YES	NONE	YES
	DoorEdgeFrameSTA492.4_7050-T7451	430039					1.6	YES	NONE	YES

MESH QUALITY CHECK	Min Length	% Failure	Max Length	% Failure	Aspect ratio	% Failure	Warpage	% Failure	Jacobian	%Failure	Max Quad	% Failure	Min Quad	% Failure	Max Trias	% Failure	Min Trias	% Failure	No. of Quads	No. of Trias
	5		30		5		15		Shl - 0.7, Sol - 0.5		140		45		120		30			
DoorEdgeFrameSTA440_Doubler2	6.066986	0	16.7	0	2.246449	0	0.000001	0	0.74353	0	122.418	0	50.88	0	76.64	0	41.35894	0	2213	4
DoorEdgeFrameSTA440_InnerFailSafe3	8.510385	0	12.15	0	1.254705	0	0.237056	0	0.998495	0	90.1459	0	89.85	0	NA	0	NA	0	738	0
DoorEdgeFrameSTA440_Splice11	6.930739	0	12.45	0	1.788022	0	1.914195	0	0.901114	0	102.5779	0	78.36	0	NA	0	NA	0	273	0
DoorEdgeFrameSTA492.4_7050-T7451	5.879037	0	16.87	0	2.219162	0	0.457715	0	0.730229	0	132.5299	0	49.45	0	77.31	0	41.52555	0	3179	7

- Model Parameters Documentation:
  - Part ID and Image
  - CAD Revision
  - Mesh Quality
  - Materials
  - Tracks FE modeling status
  - Tracks revisions
  - …etc.

No	Component Name	ID	Geometry	CAD RELEASE DATE: No. of Parts	Revision	Date Received	Material	Thickness(in)
	DoorEdgeFrameSTA440_Doubler2	430037					7075-T62_CladSheet	0.04000
	DoorEdgeFrameSTA440_InnerFailSafe3	430038					2024-T3511_Extru	0.04000
	DoorEdgeFrameSTA440_Splice11	430036					7075-T62_CladSheet	0.09000
	DoorEdgeFrameSTA492.4_7050-T7451	430039					7050-T7451_Plate	0.06299

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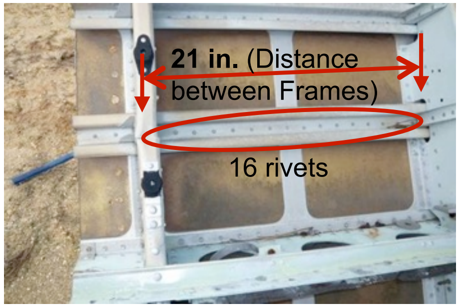
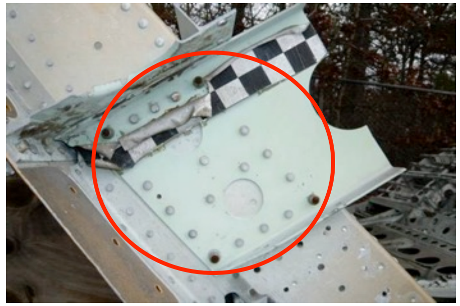
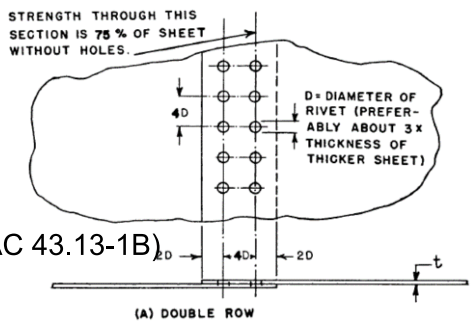
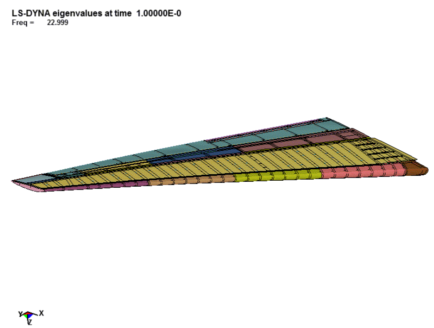
FEA Modeling - Connections





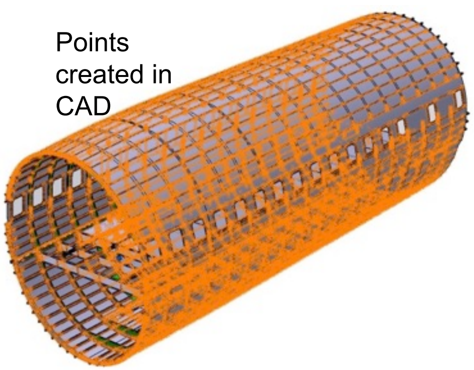


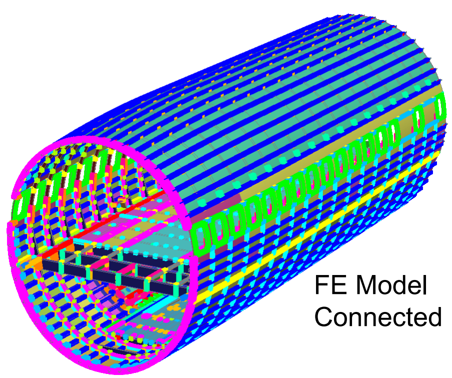
(AC 43.13-1B)



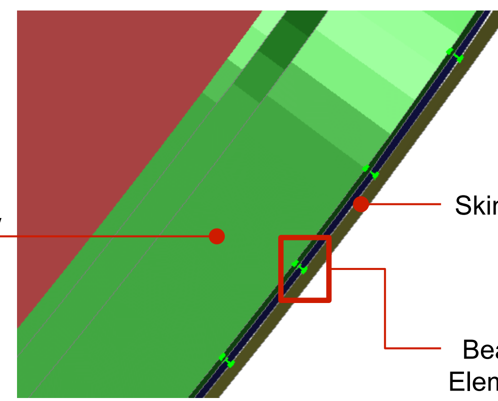
- Connection Points were derived by reverse engineering and FAA Advisory Circular for Repair (AC 43.13-1B) guidelines.
- Parts were connected using Beam elements (Type 9) in LS DYNA [Mesh-Independent Spot-weld Beams]. Based on our joint modeling R&D this is the most practical solution available in LS DYNA for large structural models.

Points created in CAD





FE Model Connected



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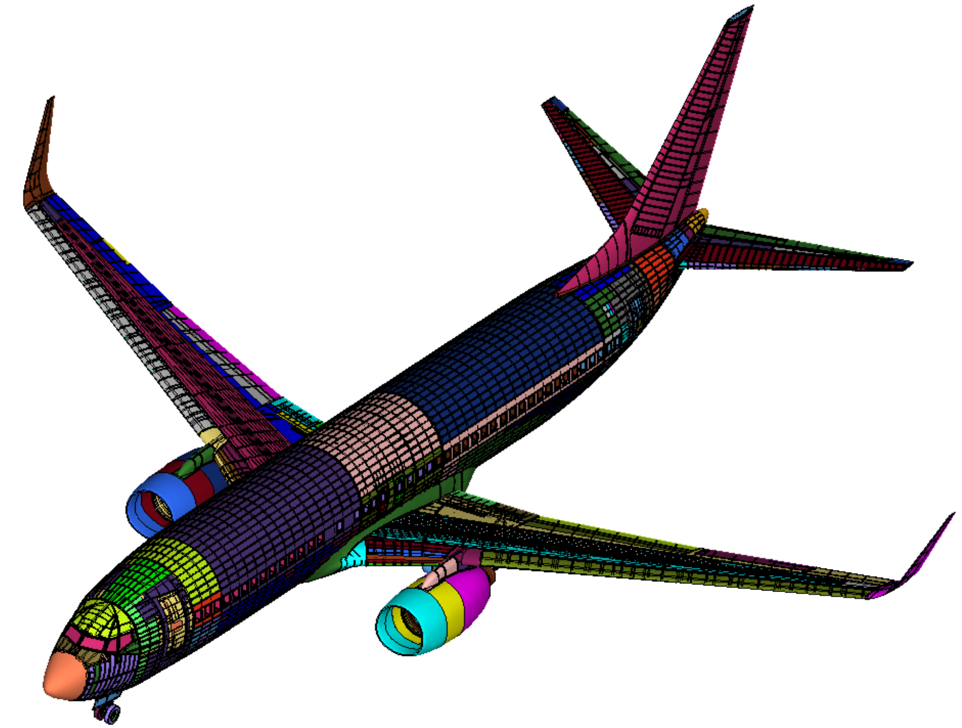
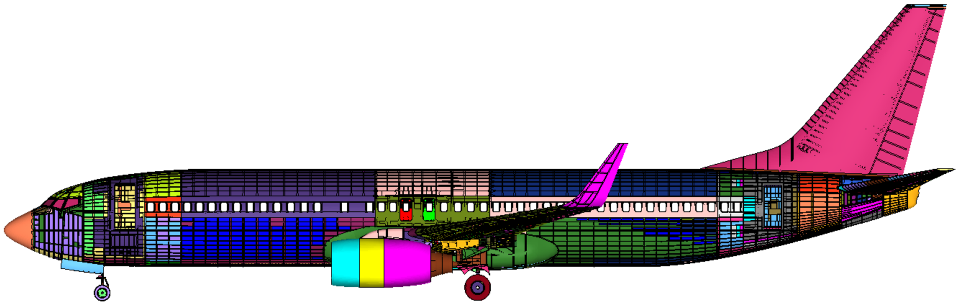
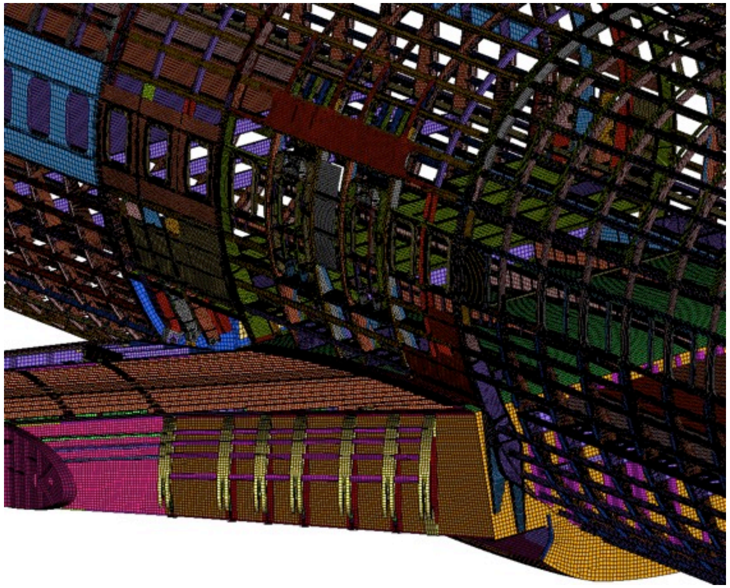
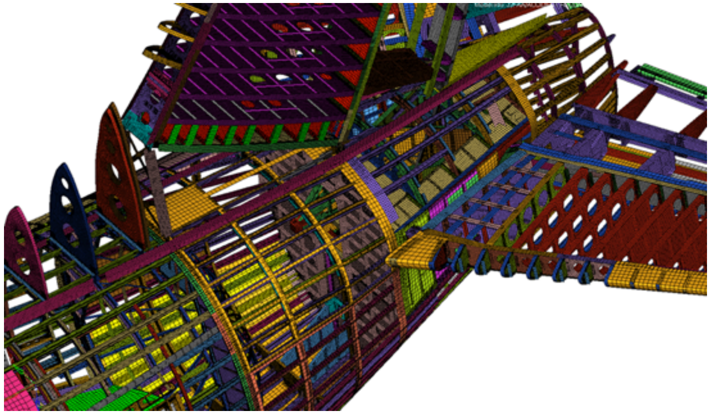
Full Aircraft Mesh – 10M Elements









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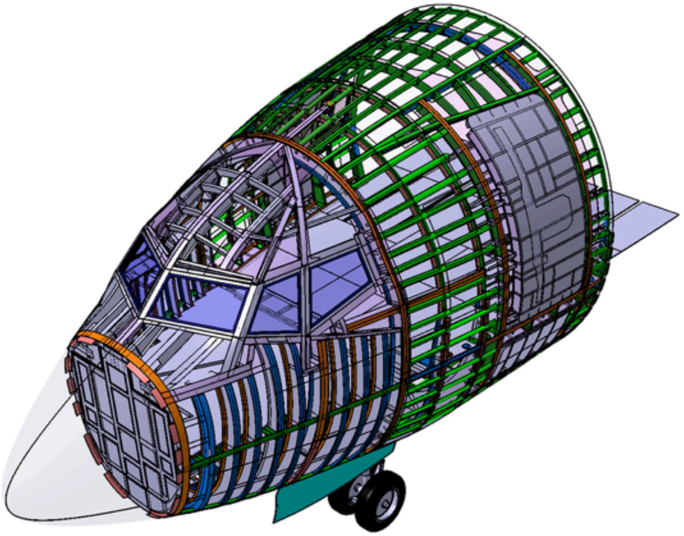
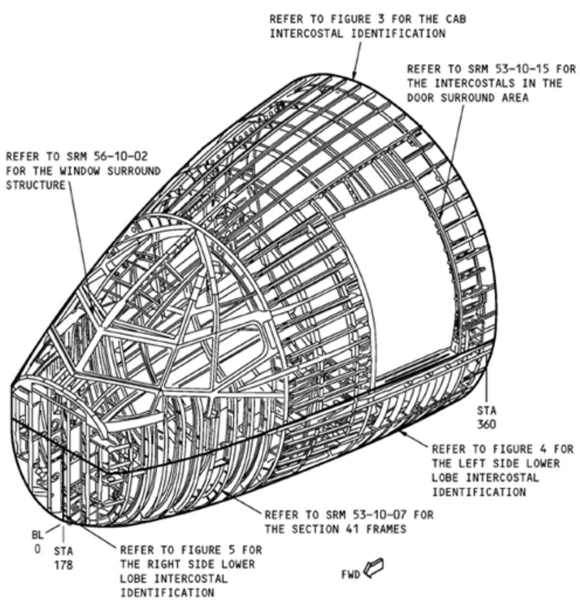
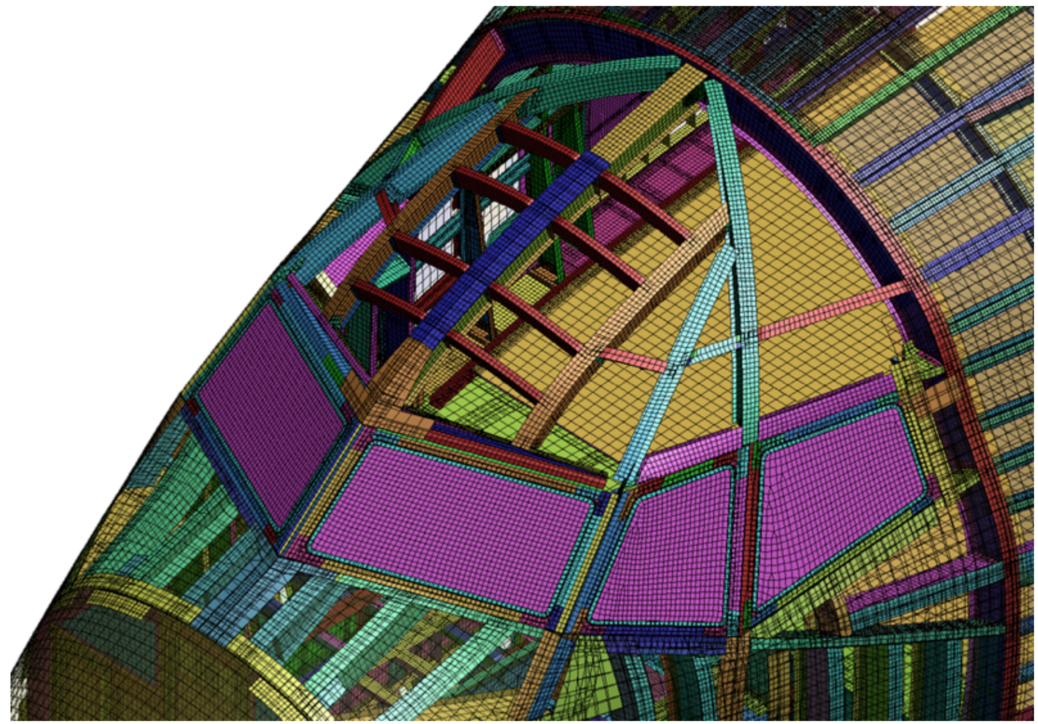
CAD-FEA Model Example – Section 41







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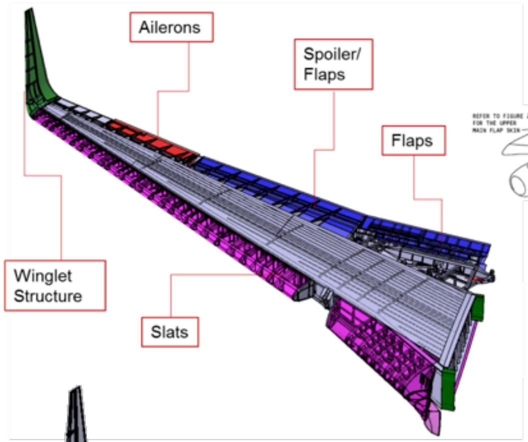
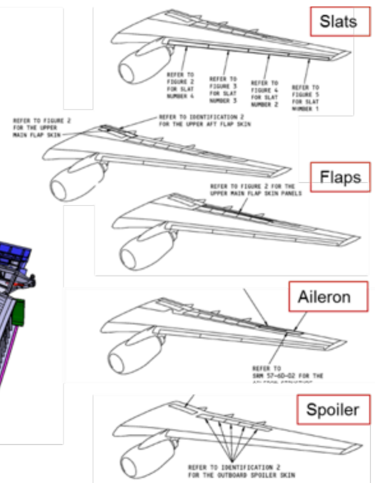
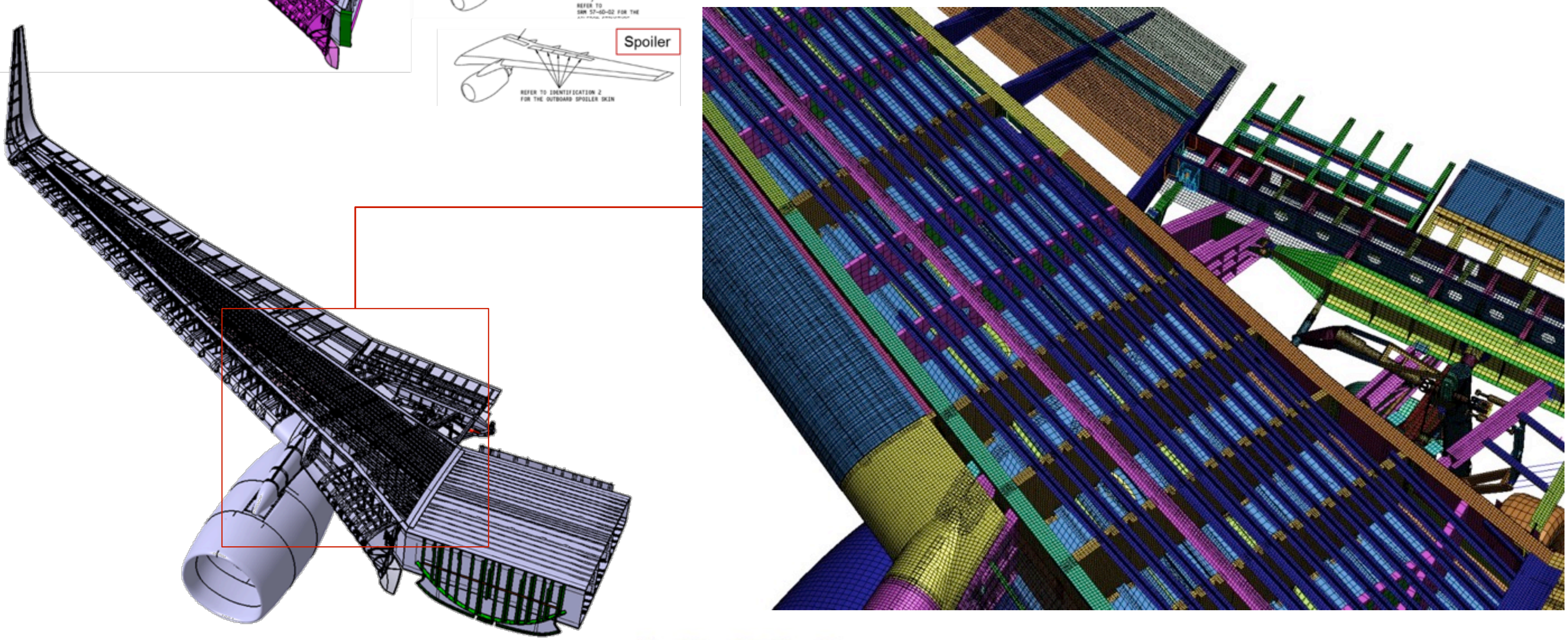
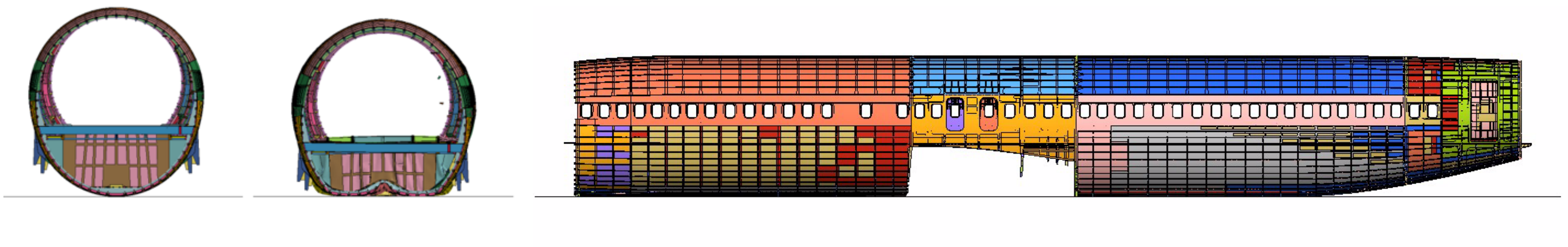
CAD-FEA Model Example - Wing

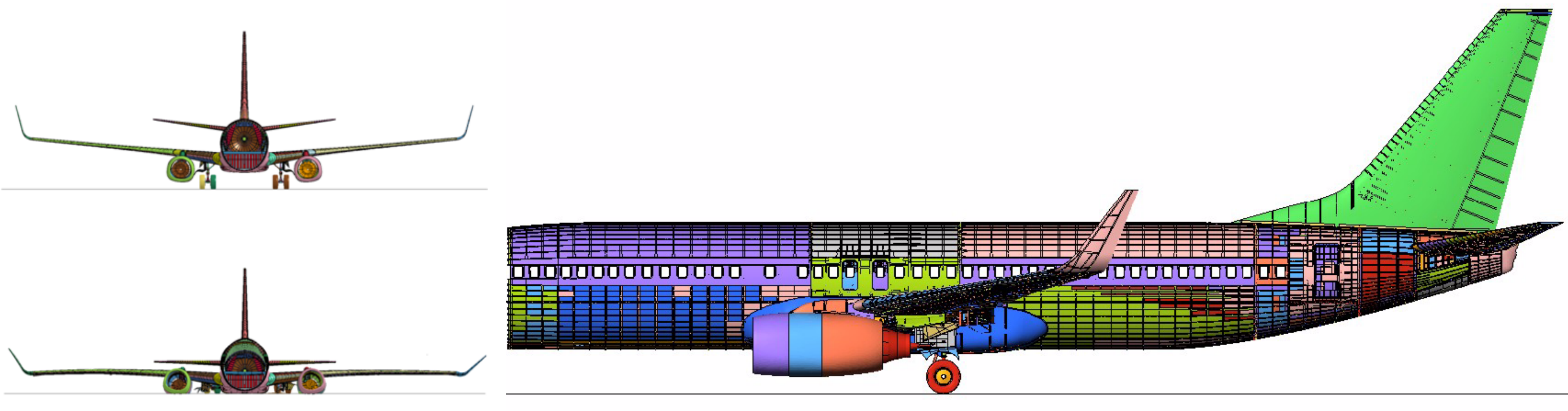






Preliminary FEA Model Evaluation – 30ft\s





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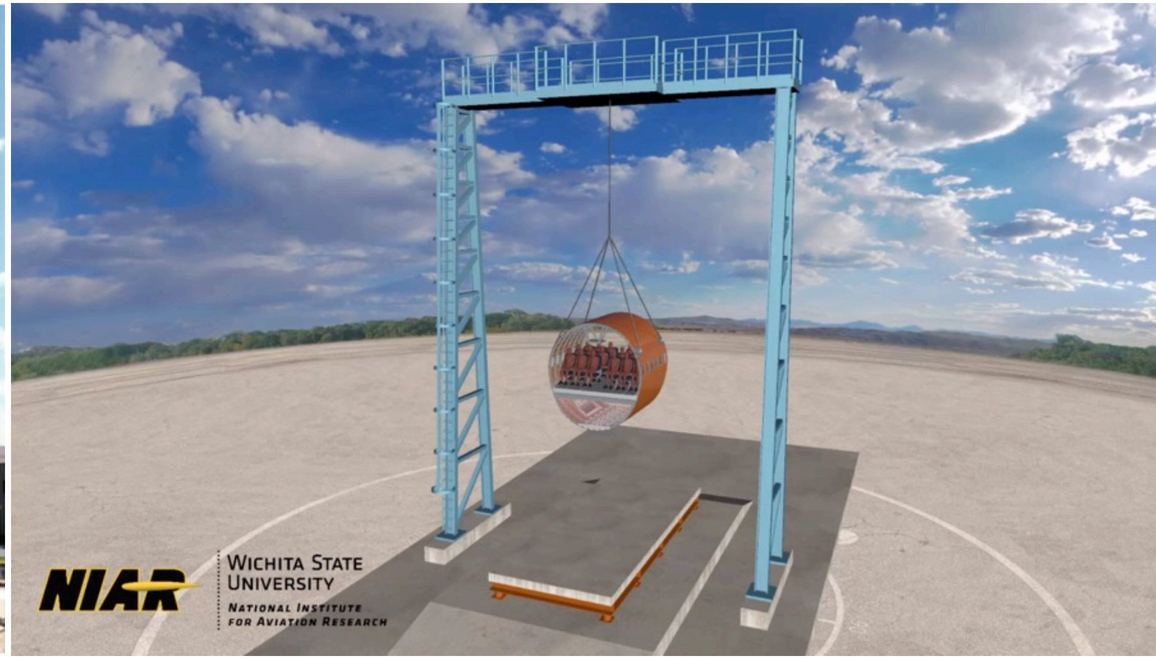
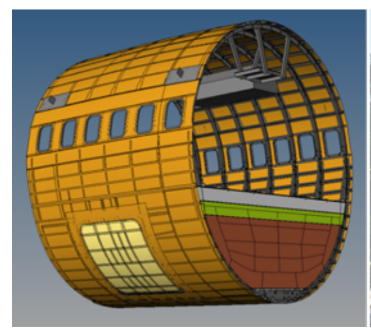
FEA Model Section Validation



FAA 10-FT Drop Test:

- 30 ft/s Drop
- Full Cargo
- 737-100 Aircraft Model



Abramowitz,Allan , Smith,Timothy G. Vu, Dr. Tong and Zvanya, John R. "*Vertical drop test of a narrow-body transport fuselage section with overhead stowage bins*", FAA Report: DOT/FAA/AR-01/100 ,(2002).

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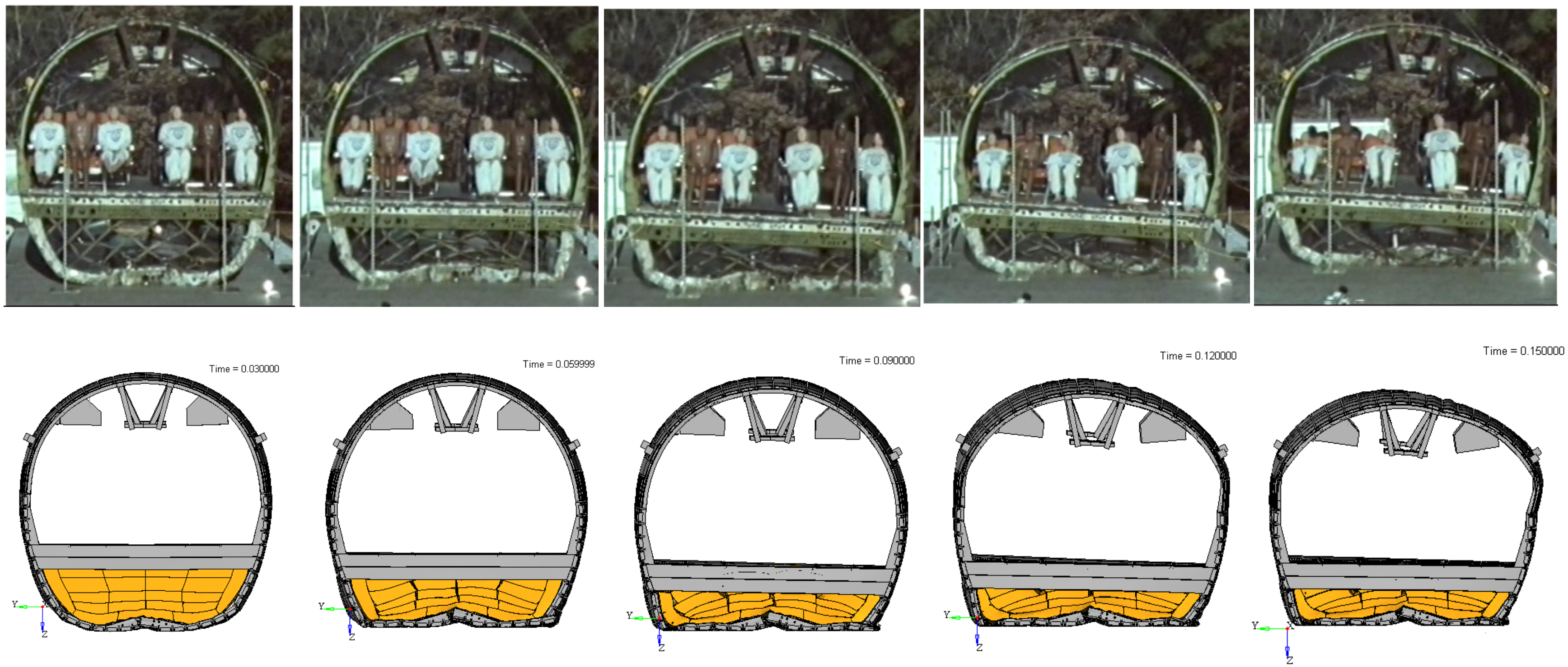
FEA Section Model Validation - Kinematics

T= 0.03 s **T= 0.06 s** **T= 0.09 s** **T= 0.12 s** **T= 0.15 s**



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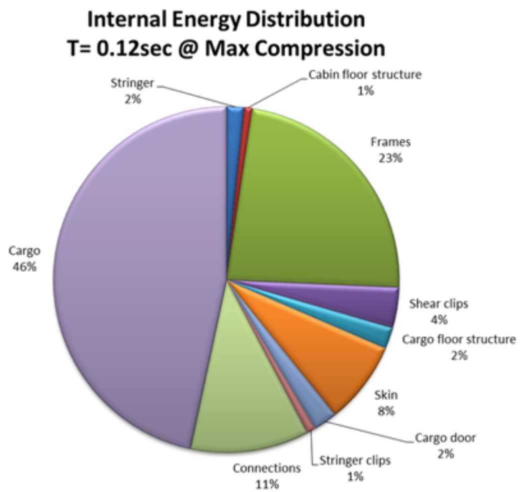
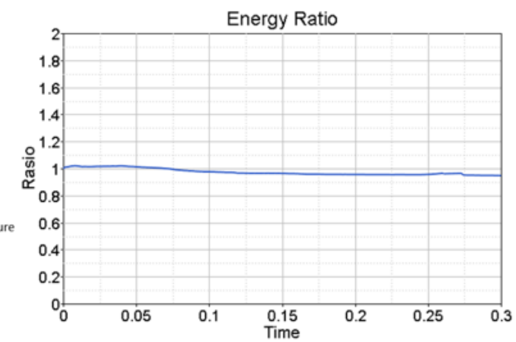
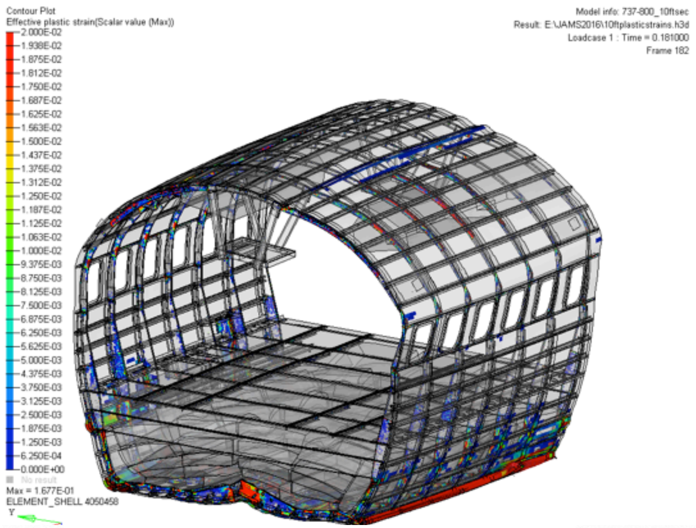
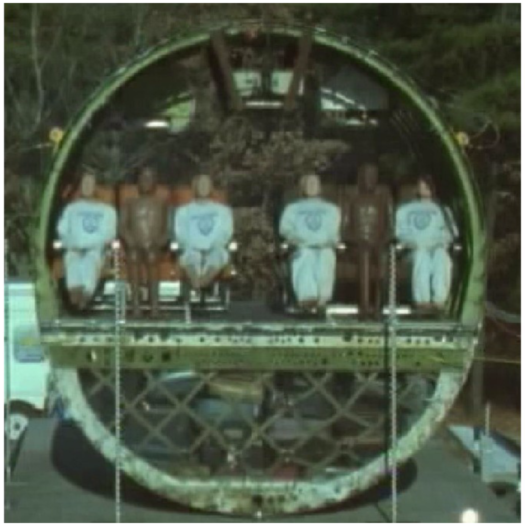
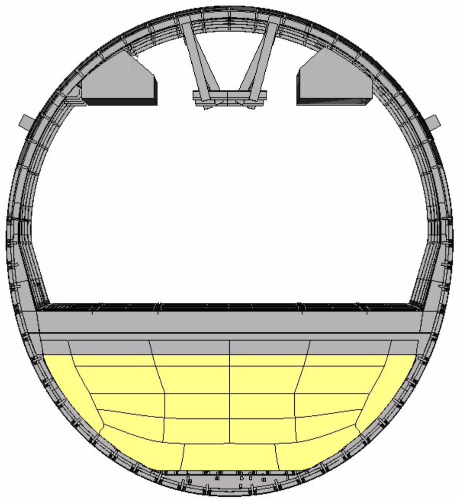
FEA Section Model Validation - Kinematics

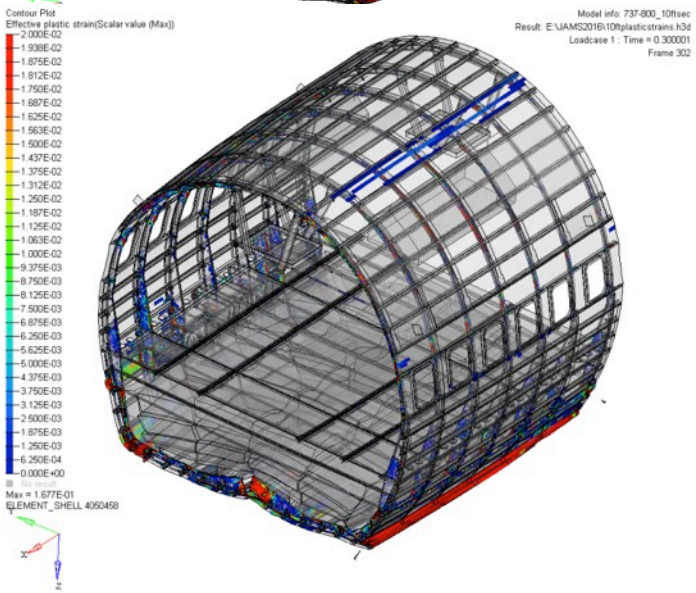












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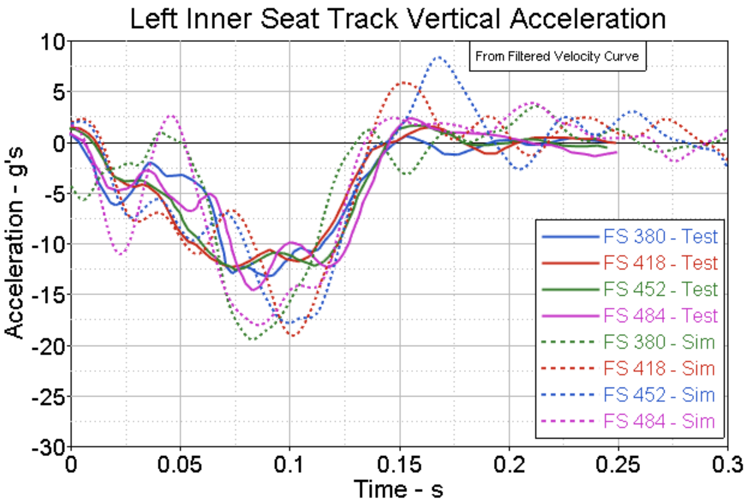
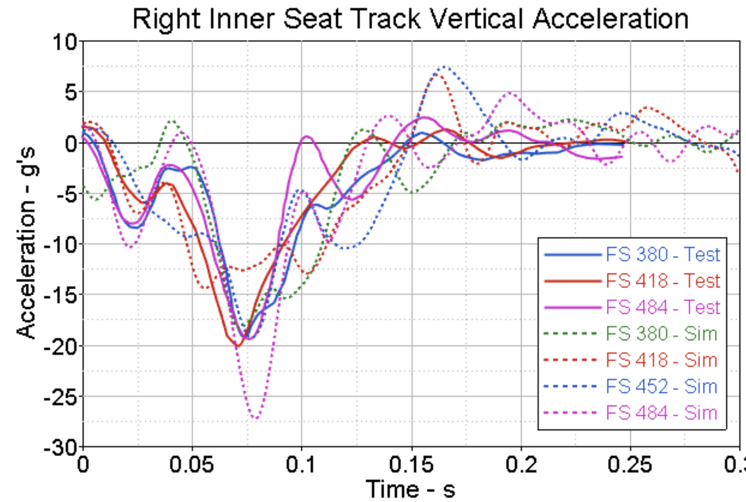
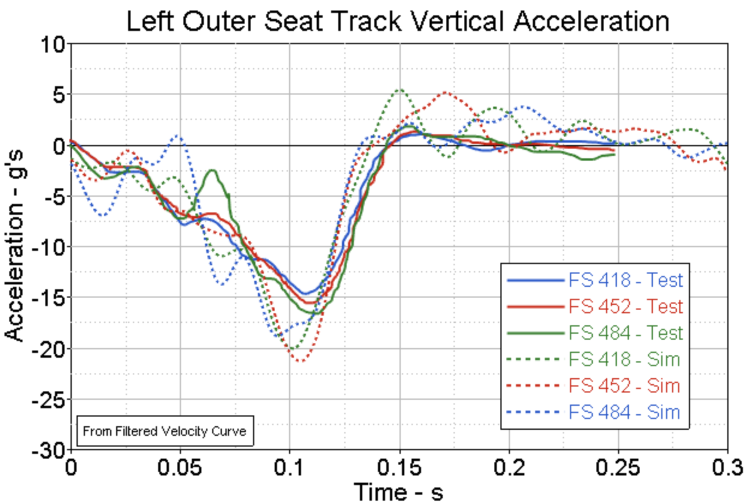
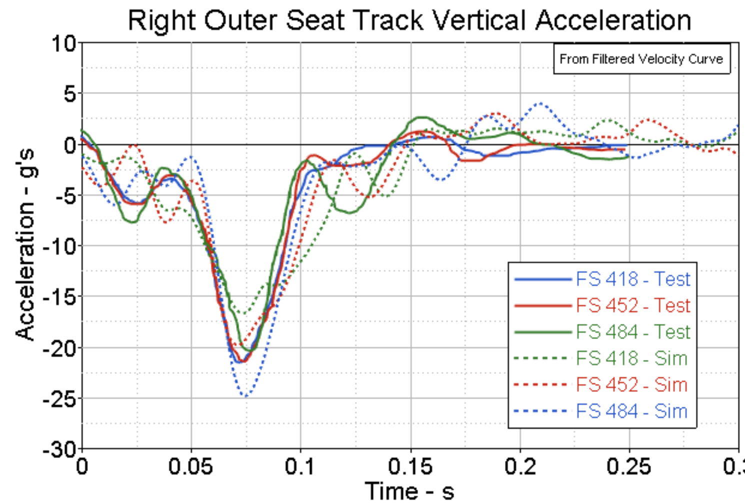
FEA Section Model Validation - Accelerations









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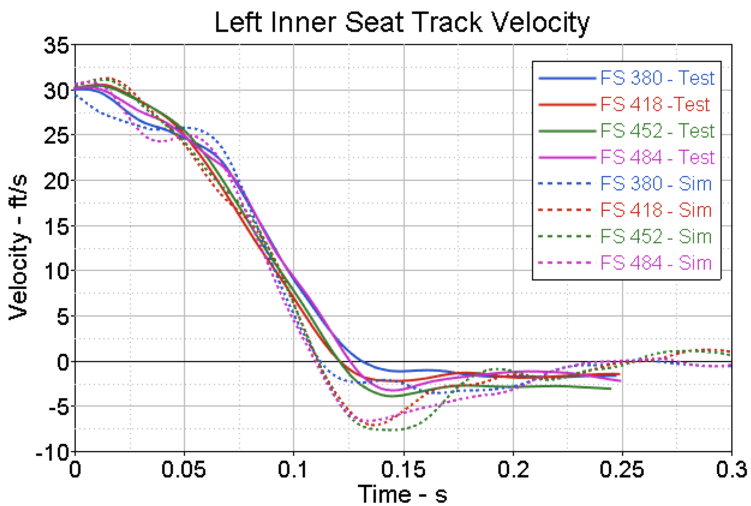
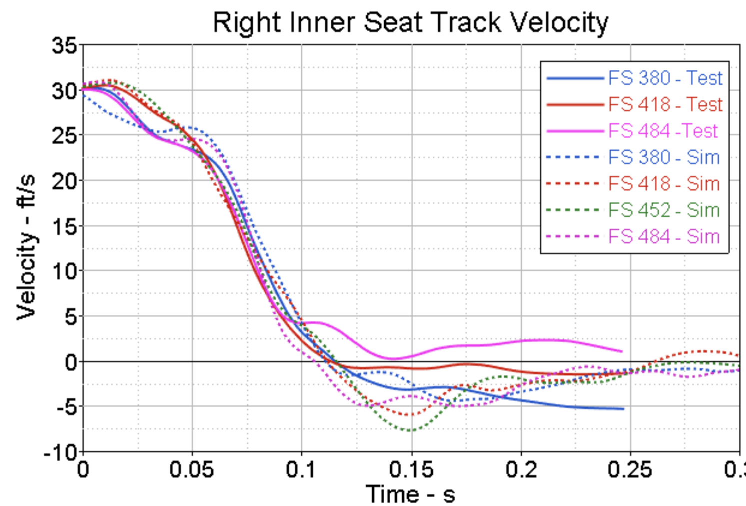
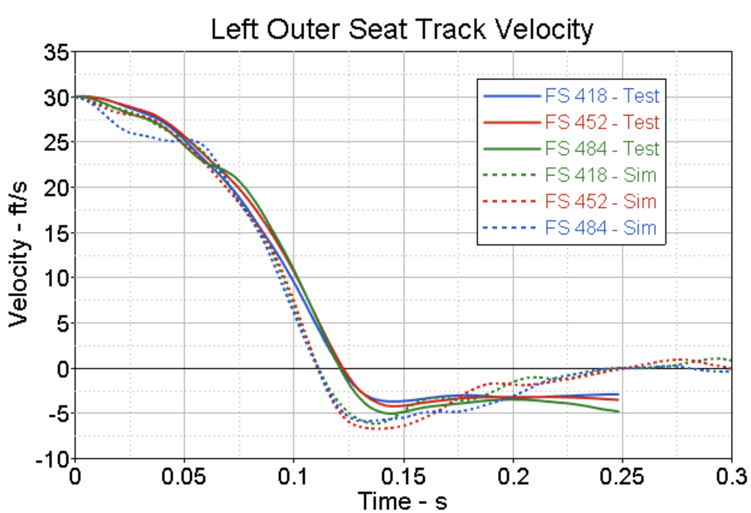
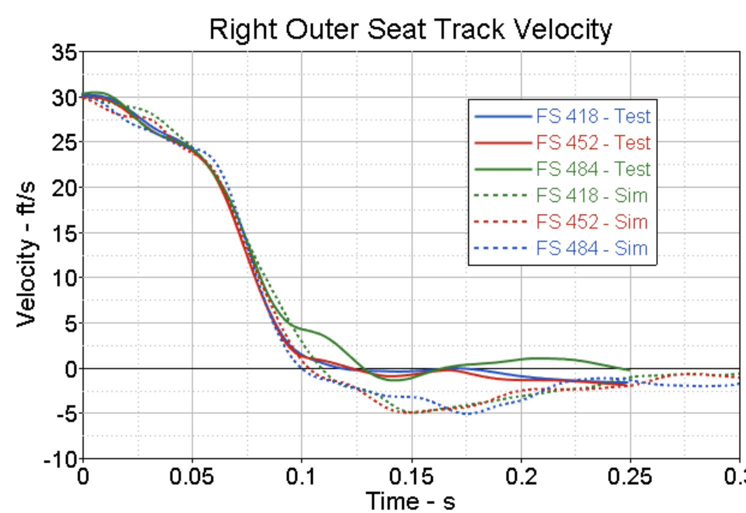
FEA Section Model Validation - Velocities



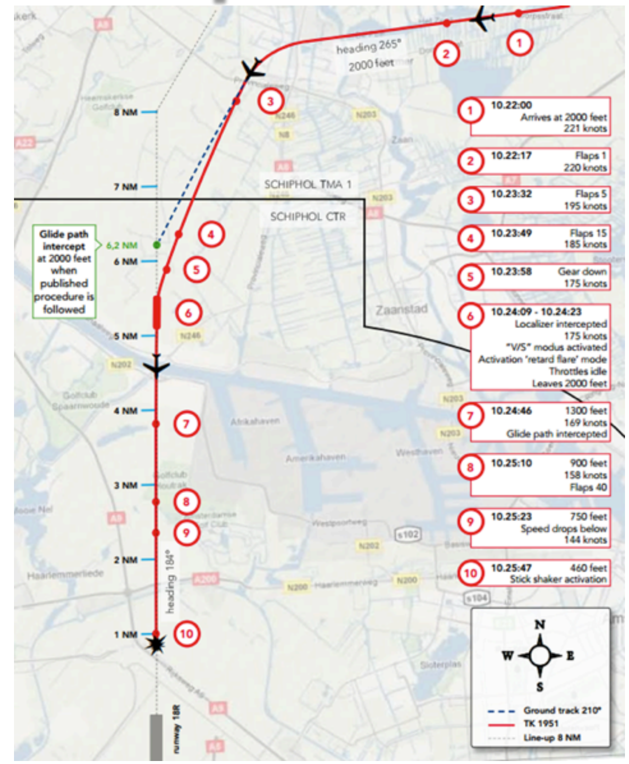






Accident Analysis – Event Description

- Turkish Airlines Flight 1951
- **Flight Route:** Istanbul to Amsterdam
- **Crash Date:** 25 February 2009 at 10.26 hours (local Dutch time)
- **Crash Location:** 1.5km (0.93 miles) from Polderbaan (18R) - Amsterdam Schiphol airport (EHAM)
- **Aircraft Type:** Boeing 737-800
- **Aircraft Orientation:** 22 deg. Pitch, 10 deg. roll to the left
- **Aircraft Speed:** Approx. 107 knots
- 128 Passengers + 7 crew
- **Overview of Crash Event:**
  - Aircraft entered Glide path late (almost one mile closer to runway)
  - Had to set low thrust to intercept path from above
  - Faulty left hand altimeter displayed -8 feet altitude (primary input for autothrottle)
  - Faulty input commanded the autothrottle to “RETARD Flare mode”
    - RETARD flare mode is selection normally applied during final landing phase below 27 feet
  - This reduced thrust to idle at an altitude and airspeed insufficient to reach the runway
  - The right hand altimeter displayed correct altitude
  - At 460 ft altitude, aircraft warned of approaching stall and crew reacted by pushing throttle up to regain airspeed
  - Then captain took over and in response first officer relaxed his push on the throttle
  - Since autopilot was not deactivated, throttle went back to idle (RETARD mode)
  - Captain then deactivated autothrottle and increased thrust but it was too late
  - The aircraft stalled at 350 FT and speed of 105 knots



Data Source: Crashed during approach, Boeing 737-800, near Amsterdam Schiphol Airport, 25 February 2009. The Dutch Safety Board

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High Resolution Panorama Spherical Photography

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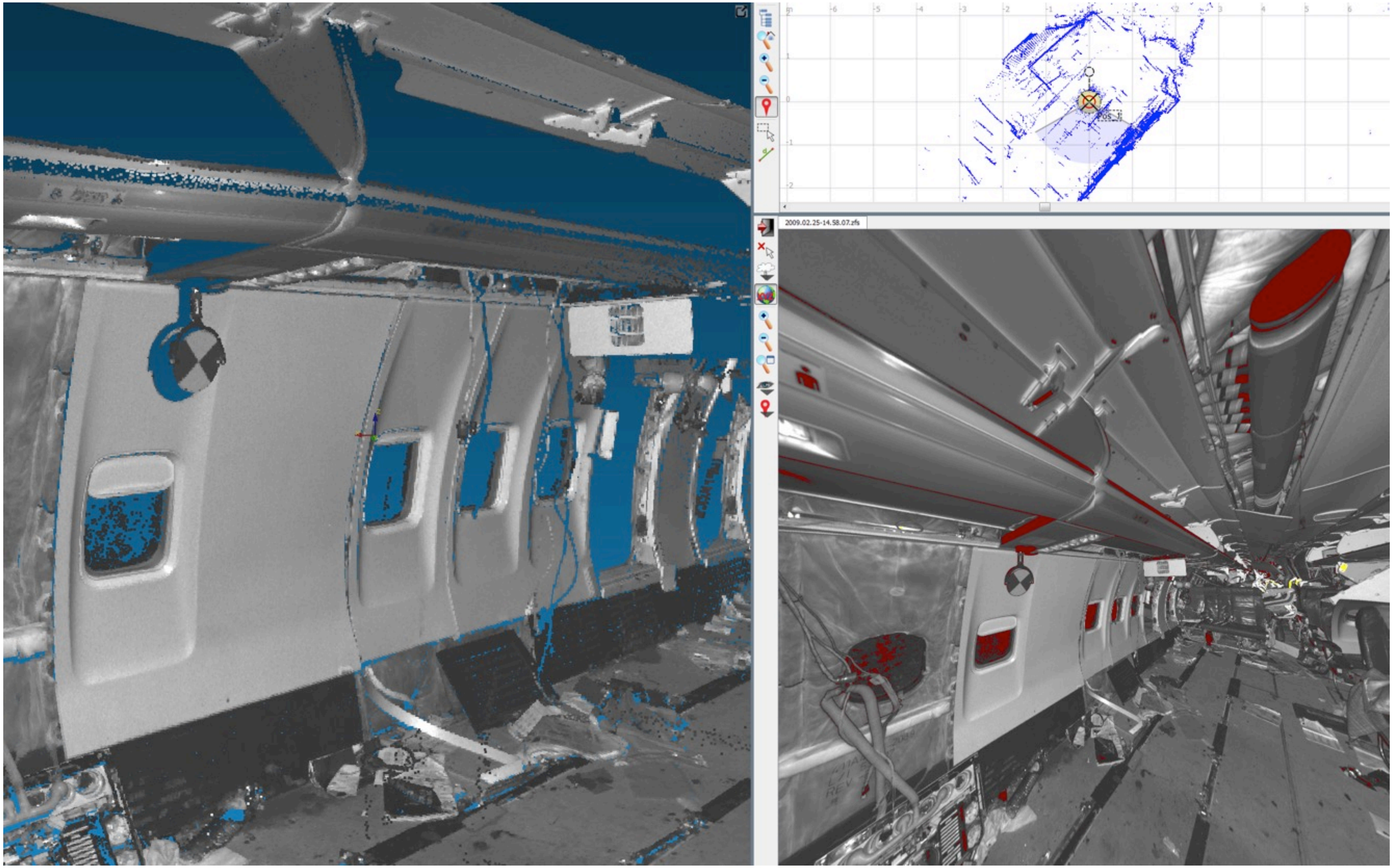
Internal 3D CAD Scan Geometry



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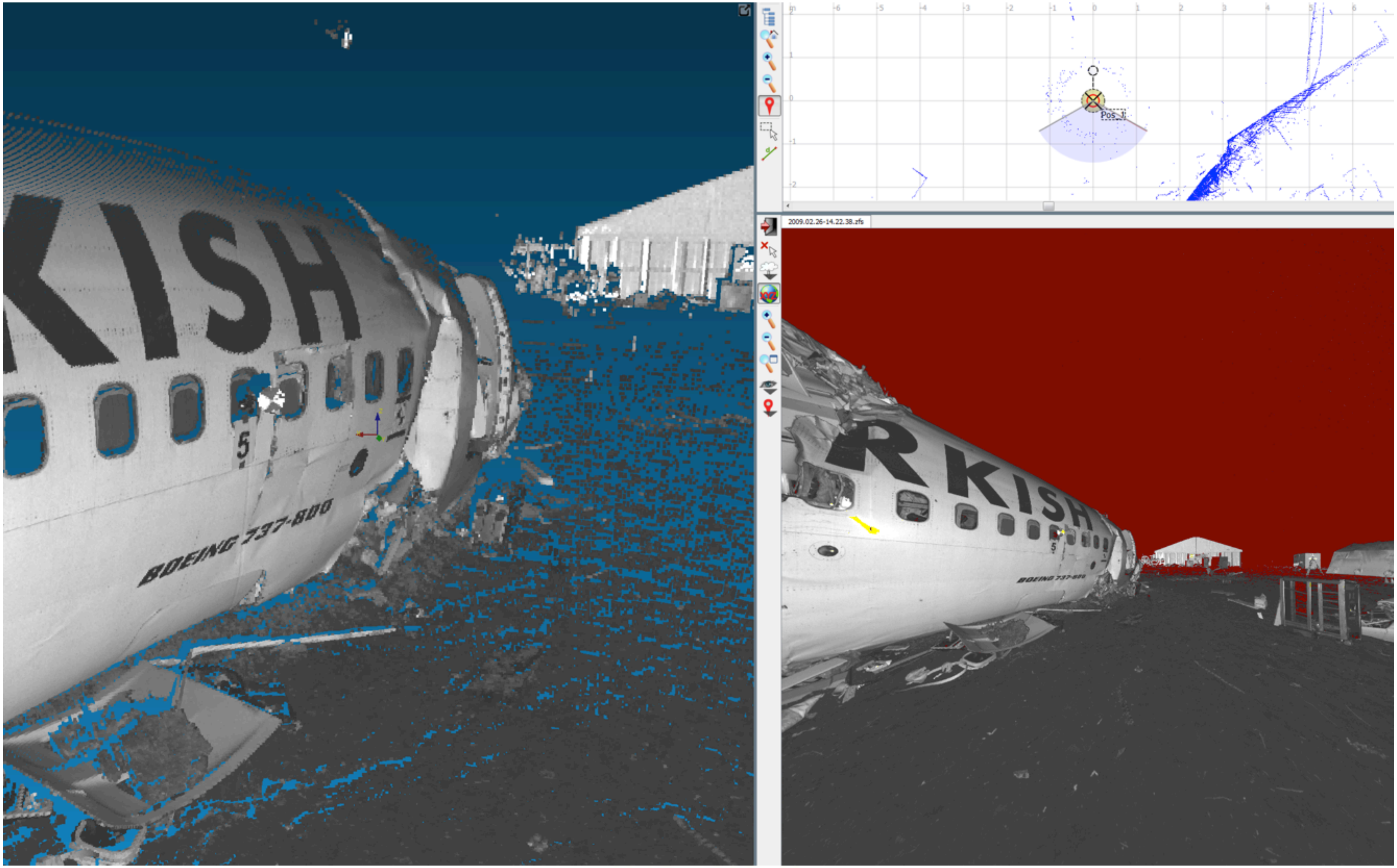
External 3D Scan CAD Geometry



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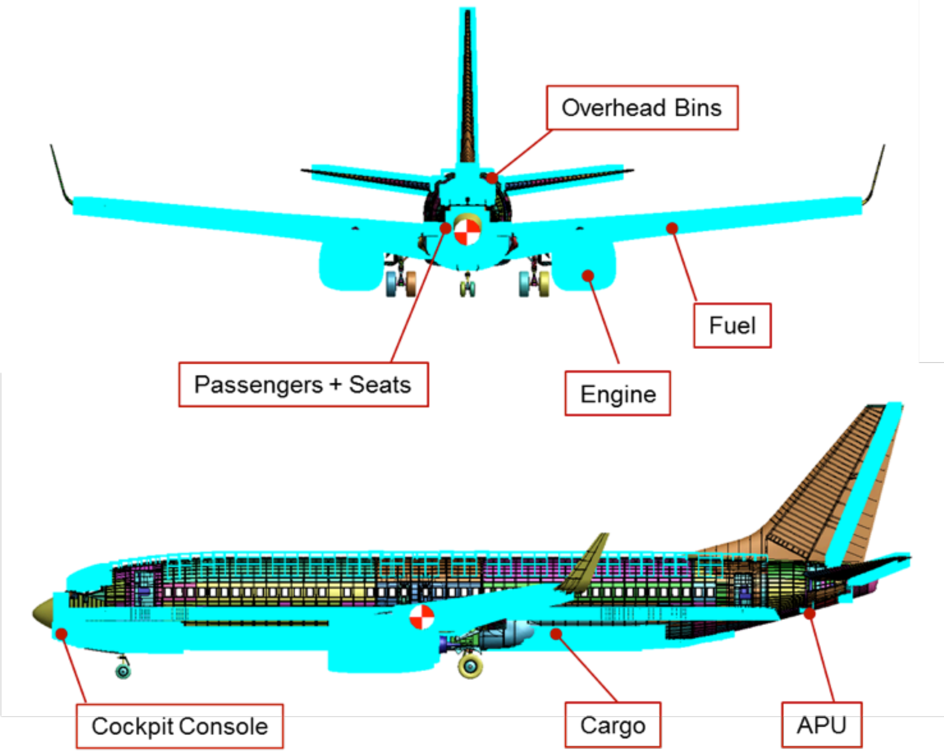
FEA Weight Configuration Crash Analysis

- 737- 800 Empty Weight:
- Total weight baggage according to Loading Message (LDM)]: T=4000 kg
  - Compartment 1: 500 kg
  - Compartment 2:1907 kg
  - Compartment 3: 1819 kg
  - Compartment 4: 174 kg
- Passengers according the Movement message (MVT):
  - 126 pax, 1 infant.
  - Passenger Location Diagram
- Fuel on board after crash
  - Right wing: 1920 kg
  - Left wing: 1810 kg
  - This is the amount of fuel that was removed out of the tanks post crash. The center tank was empty.



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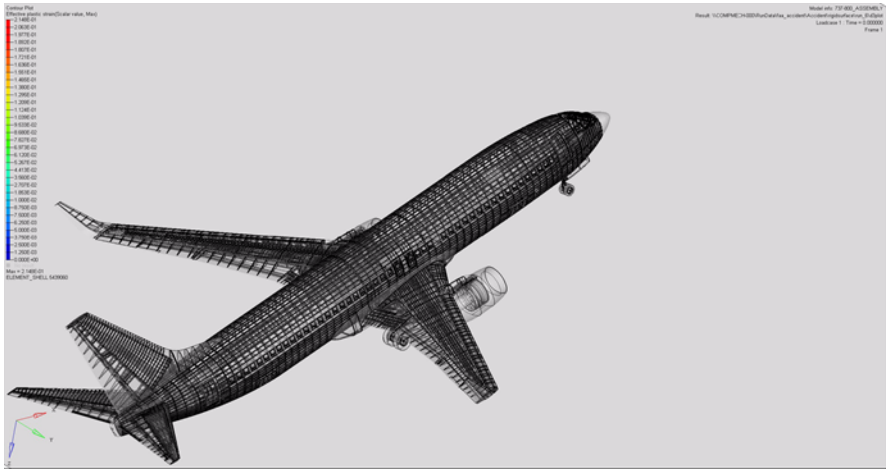
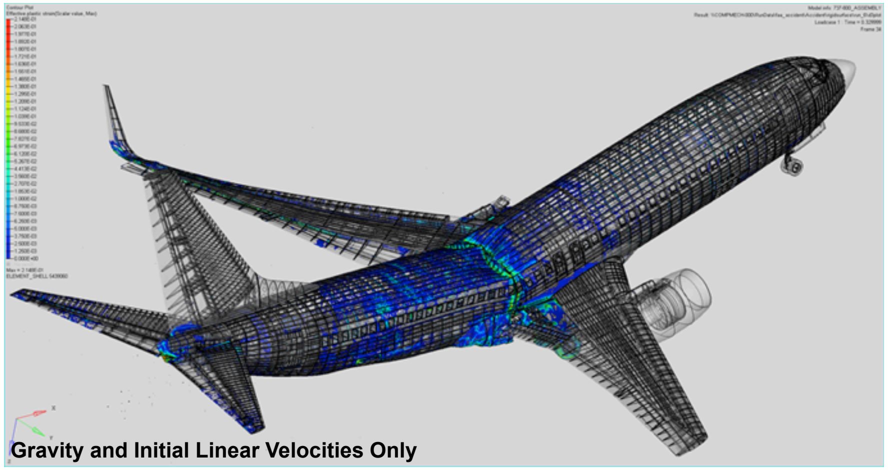
Initial FEA Model Evaluation – Rigid Surface



- Preliminary Evaluation FEA Model Stability
- Identify Issues with Analysis BC:
  - Not taking into account the aerodynamic and propulsion forces will affect the failure locations, and the post impact kinematics



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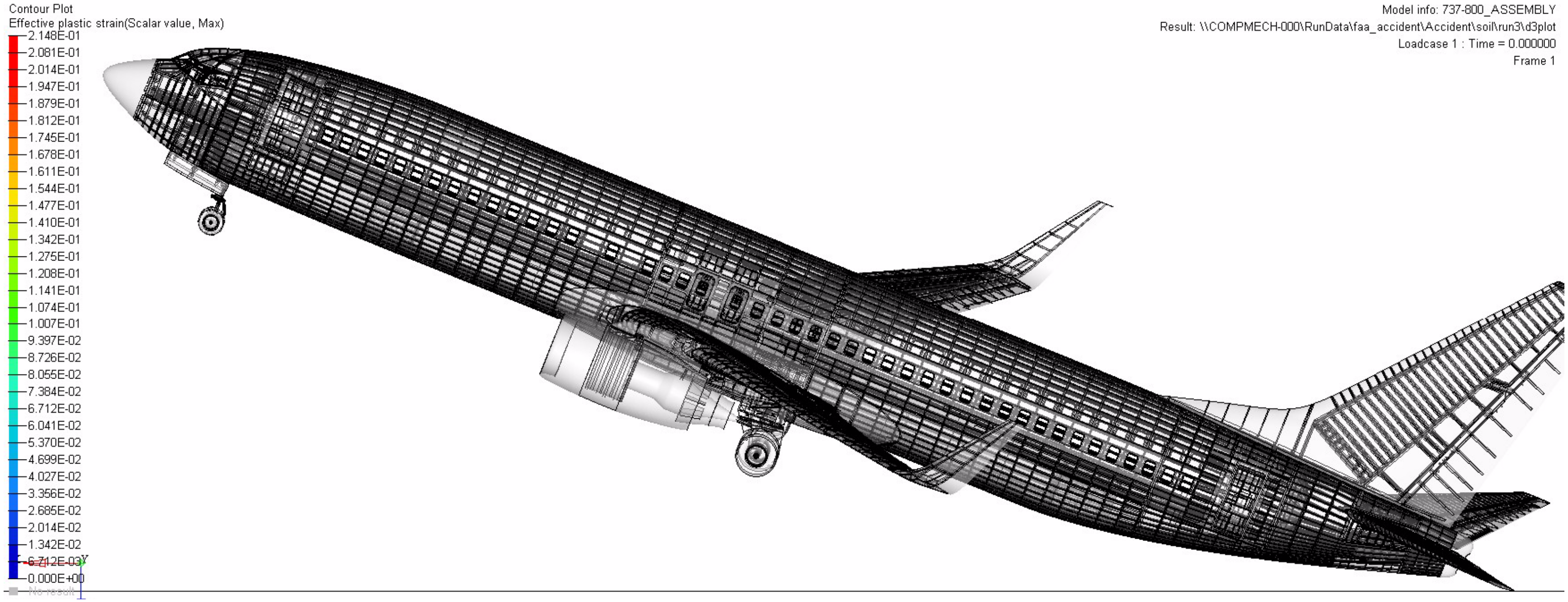
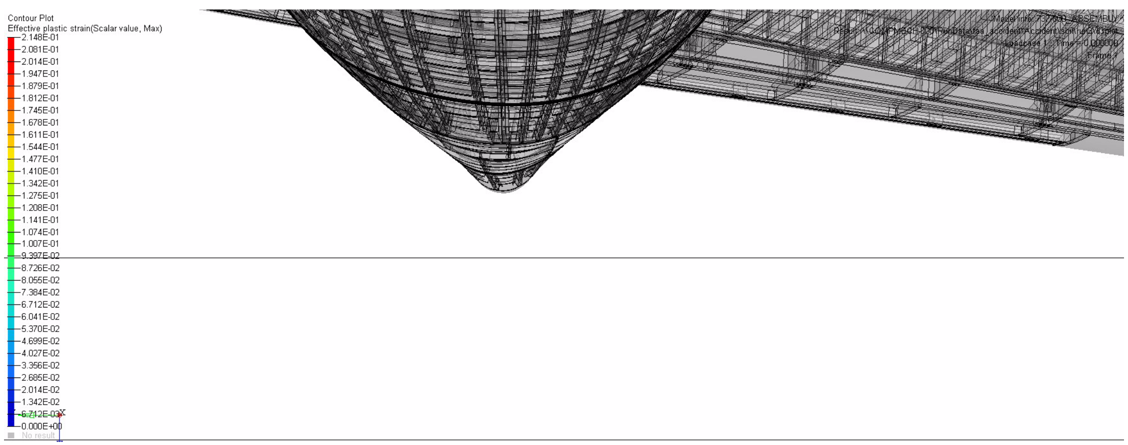
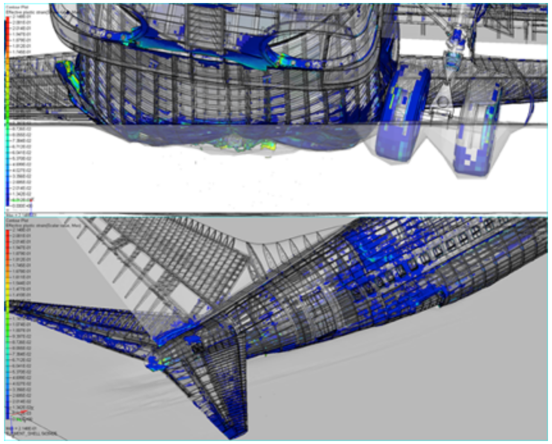
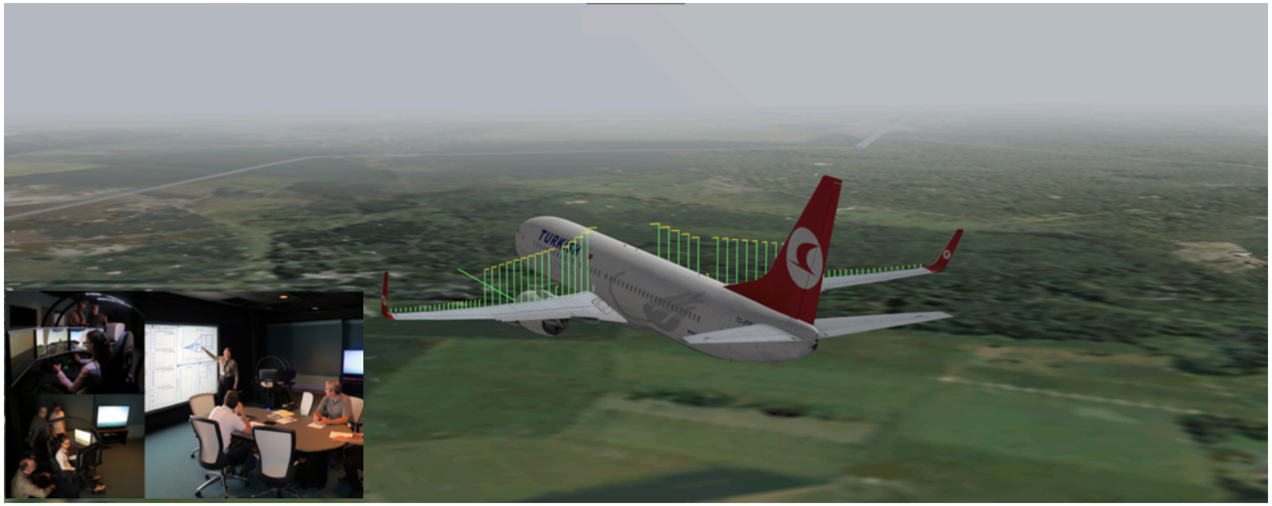
Initial FEA Model Evaluation – Soil Surface



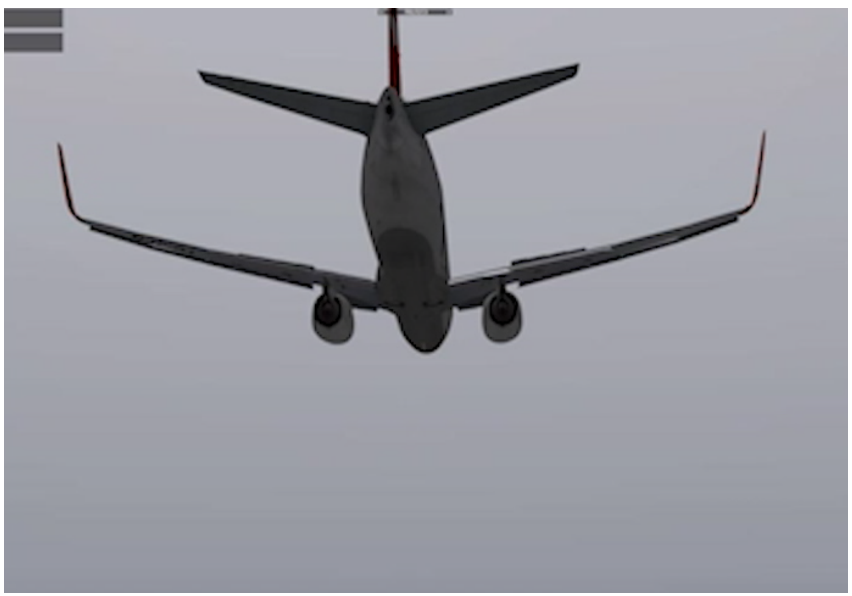


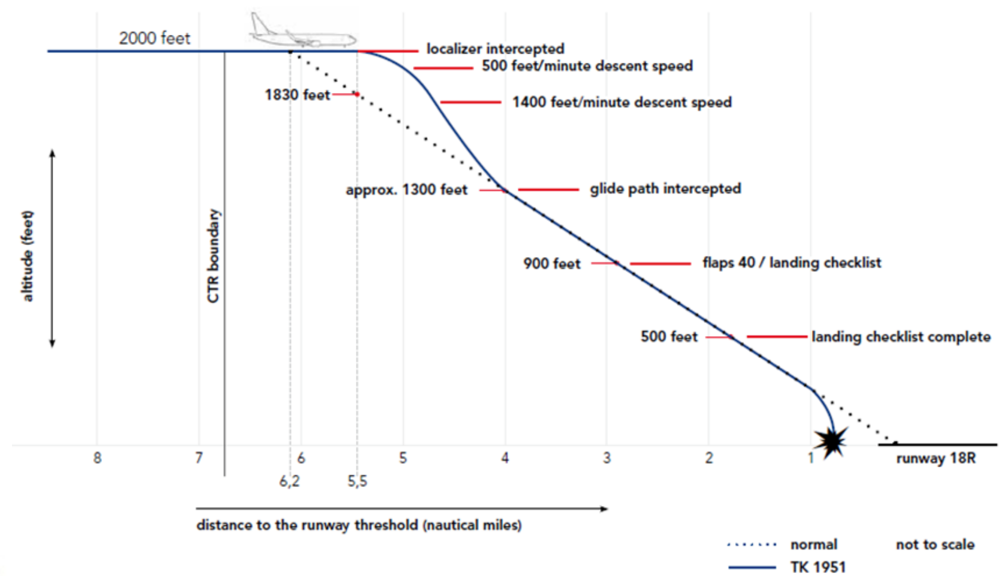


Flight Model Pre-Impact



- **NIAR Virtual Flight Testing Lab**
- **Define Aircraft Boundary Conditions prior to impact:**
  - Linear Velocities
  - Angular Velocities
  - Forces and Moments
- **Crash Location:**
  - 1.5km (0.93 miles) from Polderbaan (18R) - Amsterdam Schiphol





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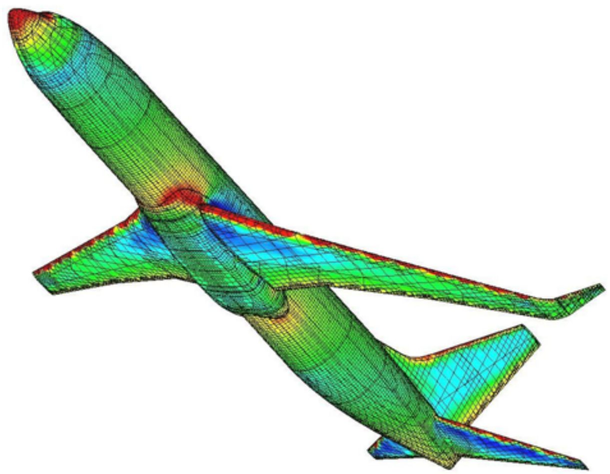
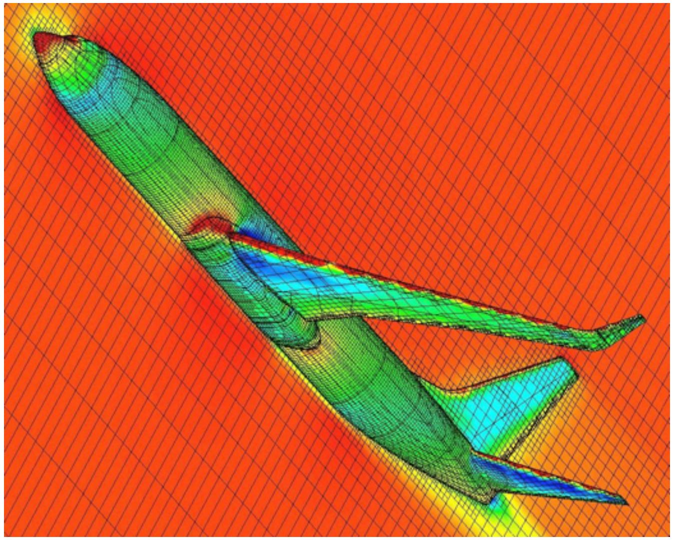
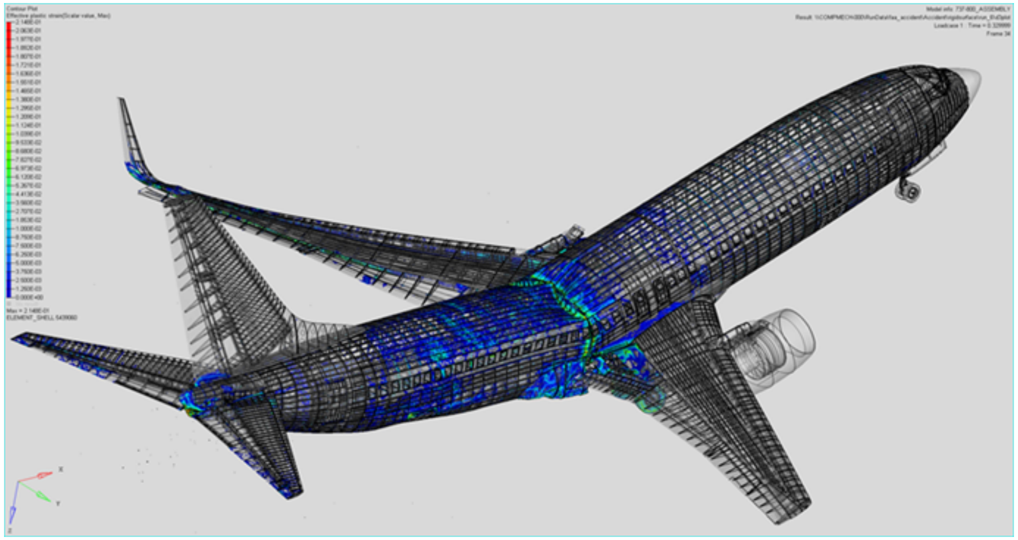
CFD Analysis Pre-Impact & Impact BC's



- Pre-impact Boundary Conditions Definition: Pressure Mapping
- Impact BC's :Pressure Mapping vs. Aircraft Orientation
- CFD Analysis Ongoing





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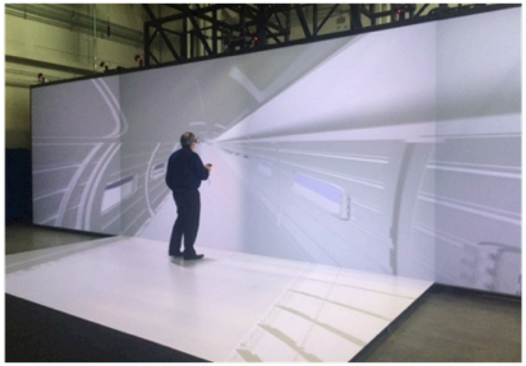
Conclusions and Future Work

- Full aircraft model impact simulations need to address not only the structural component of the analysis but also include aerodynamic, propulsion and control input data to define the proper boundary conditions
- The model is a representative narrow body structure therefore obtaining the exact same failure locations and mechanisms may not be possible
- Ongoing efforts to obtain the accident site soil data
- Present preliminary analysis results at the FAA Cabin Safety Conference in November 2016
- Summarize findings in an interim report to support the ARAC Transport Airplane Crashworthiness and Ditching Working Group
- In parallel we are working in High End Visualization for Accident Data and Simulation Data using NIAR's new CAVE VR Environment
- Working on the definition of a full scale test and simulation program for a part 25 composite and metallic business jet configuration



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Looking Forward

- Benefit to Aviation
  - Provide a methodology and the tools required by industry to maintain or improve the level of safety of new composite aircraft when compared to current metallic aircraft during emergency landing conditions
  - Improve the understanding of the crashworthy behavior of metallic structures
  - Provide R&D material to the ARAC Transport Airplane Crashworthiness and Ditching Working Group
  - The FEA models developed for this program are contributing also to ongoing UAS-Aircraft impact R&D
  - These models may also be used for ditching evaluations
- Future needs
  - Development of a High Strain Rate Testing Standard for material characterization
  - Training of Industry and FAA personnel on the use of numerical tools to support the development and certification process
  - Conduct a baseline business jet size metallic aircraft drop test

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