Crashworthiness by Analysis – Verifying FEM Capabilities by Accident Reconstruction

Chandresh Zinzuwadia, Gerardo Olivaes Ph.D. | Computational Mechanics NIAR | The Eighth Triennial International Fire & Cabin Safety Research Conference
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Agenda

- Physics Based Simulation Method: Building Block Approach
- Accident Overview
- Project Scope
- CAD-FEA Process
- 10-ft Fuselage Section Validation
- Full Scale Preliminary Simulation
- Conclusions and Recommendations
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.

Applications
- Boeing 787 crashworthiness requirement (Special condition 25-362-SC)
- Airbus A350 crashworthiness requirement (Special condition 25-537-SC)
- AC 20-146 Aircraft Seat Certification
  - Demonstrating compliance to standard test requirements for changes to a baseline seat design
  - Establishing the critical seat installation/configuration in preparation for dynamic testing
- ARAC
  - Transport airplane ditching and crashworthiness requirements
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
    - Predictable modeling

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Verifying FEM Capabilities by Accident Reconstruction

- How do we evaluate Full-scale models at the top of the building block approach?
  - With confidence in element, coupon, component and sub-assembly models
  - Comparison to Test Data
    - Fortunately extensive documentation of Turkish Airline Flight 1951 crash by Dutch Authorities
    - Considered survivable crash (only 9 fatalities out of 128 occupants)

- What are we dealing with?
  - Simulation time-step is dictated by minimum element length
  - Model with around 10 million elements – Typical minimum element length for crash analysis is 3mm
  - Computing Resources
  - Model Stability due to large deformations

Minimum element length = 3mm
Aircraft length = 39500 mm
ACCIDENT OVERVIEW

Turkish Airline Flight 1951 on Final Approach to Schiphol Airport
Accident Summary

- **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
- **Final Known Aircraft orientation:** 22 deg Pitch, 10 deg roll to the left
- **Final Known Aircraft Speed:** Approx 107 knots
- **Total Passengers:** 128 Passengers + 7 crew
- **Injury Evaluation:** 9 Fatalities, 120 Injuries (Minor to Serious)
- **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 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 auto throttle and increased thrust but it was too late
  - The aircraft stalled at 350 FT and speed of 105 knots

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

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Damage to Aircraft

- Observed Damage
  - Traveled approximately 100 m from first impact
  - Horizontal Stabilizer separated and flipped
  - Fuselage breaks into 3 pieces
  - Engines detach and fly away

- Why this Accident is interesting?
  - No fire
  - Doors and escape route accessible – Egress
  - Survivable volume maintained
  - Most items of mass retained
  - Fits the definition of survivable accident (FAA)

- Areas this allows to explore
  - Defining requirements for Seats
  - Defining crashworthiness requirements
  - Exploring FEM capabilities (CBA / Special Conditions)
  - Exploring injury criteria

- Accident Documentation
  - Extensive documentation available
  - This complements FEM

Source: Crashed during approach, Boeing 737-800, near Amsterdam Schiphol Airport, 25 February 2009. The Dutch Safety Board
Doc: Rapport_TA_ENG_web.pdf
Project Scope and Tasks

Scope - Prediction of overall failure modes and demonstration of critical parameters such as survivable volume and egress paths

Tasks

- **Full Aircraft CAD – Similar to B737-800**
  - Challenge
  - Solution
    - Actual drawings not available from OEM
    - Books, Online Resources, Repair Manuals
    - Validation study

- **Full Aircraft FEM**
  - Challenge
    - Model critical assumptions
    - Connections
    - Material Application
  - Solution
    - Document Assumptions and its likely impact on results
    - Create an organized process for FEM assembly

- **150 m of Soil FEM**
  - Challenge
    - What will LS-DYNA be able to handle
    - Material properties of soil at crash site not available
  - Solutions
    - Extensive study of FEM techniques for Soil
    - Extensive literature review for material data

- **Crash Boundary Conditions**
  - Challenge
    - Last data point at Aircraft altitude of 80 ft
  - Solution
    - Extensive study of available data
    - Expert opinions
CAD-FEA Model Example

- Constructed using manuals and information in public database

Model Assumptions
- Avionics, wires and systems not modeled
- Lightning holes simplified or assumed
- Fastener points and locations based on repair guidelines (REF)
- Thickness of some parts not available so created based on geometric scaling
- Some access panels and cutouts not modeled
- Interiors not modeled
FE Modeling Process

- Inspect CAD Model
- Mesh Parts
- Mesh Quality Check

- Check Mesh Quality
- Renumber using Table 1 (slide 3)

- Document Part ID’s and Mesh Quality

- Parts connected using beam elements
- Eigenvalue analysis
- Natural Frequencies and mode shapes to review connections

- Assemble individual section to create the full aircraft model
- Wing to Fuselage

- Extract material information from CAD
- Obtain material cards from material database
- Apply to over 2500 sub assemblies

- Other steps include
  - Mass distribution
  - Weight and CG Balance

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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

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<th>Quality Parameter</th>
<th>Allowable Min./Max.</th>
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<td>Max. Aspect Ratio</td>
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<td>Min. Quad Angle</td>
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<td>Min. Jacobian</td>
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**Solid (3D)Mesh**
- Min. Side Length                   | 5 mm
- Max. Aspect Ratio                  | 5
- Tet Collapse                        | 0.3
- Max. Warp Angle                    | 15 deg
- Min. Jacobian                      | 0.5

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

- Intersections and Penetrations need to be fixed
- Not desirable mesh transition
  - Desirable mesh
  - Not desirable mesh (triangular elements around hole)
  - BAD element connectivity
  - Element Normals need fixing
  - Element Normals fixed
Enable multiple people to work on the model
Avoid clashes when assembling model
Independent editing of sections
Ease of documentation and tracking
More manageable amount of work

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<th>Nodes</th>
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<th>Sections</th>
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<th>Others eg. Constraints</th>
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FEA Modeling – Connections and Implicit Check

- Connection Points were derived by research and by following guidelines in FAA Advisory Circular for Repair (AC 43.13-1B)
- Parts were connected using Beam elements (Type 9) in LS DYNA. These are known as 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.
- Implicit Eigenvalue analysis on connected sections to study natural frequencies, mode shapes and connectivity of parts
- Helps characterize basic dynamic behavior and how structure will respond to dynamic loading
FEA Modeling – Materials

- **NIAR COMPMECH Material Database**
  - 1800 Materials from MMPDS
    - Steel
    - Aluminum
    - Titanium
  - Each material has information for
    - Direction – L or LT
    - Basis – A, B, S or Typical
    - Thickness – The ranges provided in MMPDS
  - LS DYNA MAT Cards extracted from information
    - MAT 24
    - MAT 82
    - MAT 224
  - Each MAT Card is Validated against
    - MMPDS Properties
    - Test data – IF AVAILABLE
Full Aircraft FEA Model – 10M Elements
Preliminary Numerical Model Stability Checks

30 ft/s
Comparison to FAA 10-FT Aircraft Section Drop Test

**FEA MODEL VALIDATION**
FAA Vertical Drop Test

- 737-100 Fuselage Drop test
- 30 ft/s
- 10-ft section extracted
- Front cargo bay door included
- Full cargo in Cargo bay
- Extra floor beam for boundary condition
- Two different Overhead bins
- Two different Seat models (UOP and Weber)
- ATD’s and Mannequins placed in seats
- Steel-plates and Camera systems added to fuselage

Simulation Setup

- 10-ft section extracted
- Extra beams added to replicate boundary condition
- Fully filled cargo modeled
- Overhead bins and attachment modeled
- Camera mounts and steel plates for drop added
- Seats, ATD and Mannequin accounted for using added mass
- Camera accounted for using added mass
- Dropped on rigid surface

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Test Simulation Correlation - Results

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

TEST

SIMULATION

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Test Simulation Correlation – Results

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SOIL MODEL STUDIES
Sample Soil Model Validation

Acceleration Response TEST vs. Sim

Penetration [in] - Sim
Comparison of the Soil Materials
Initial Run for Accident Reconstruction

FULL SCALE MODEL VALIDATION
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 airport (EHAM)
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
Preliminary Results
Preliminary Results

- Initial runs show promising results
- Current run only up to 700 ms
- Areas that need more work
  - Engine failure
  - Soil and Landing gear interaction
  - Tail section failure
  - Stability of model for running up to 3 seconds
  - Re-evaluate boundary conditions
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.
- Preliminary analysis results look promising in terms of overall deformations and damage.
- Continue understanding boundary conditions to improve correlation to actual event.
- 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.
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
- FEA models can help accident investigators understand different damage characteristics resulting from various accidents for better understanding of the event

**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
Acknowledgments

- **Principal Investigators & Researchers**
  - **PI’s:** G. Olivares Ph.D., J. Acosta Ph.D., S. Keshavanarayana Ph.D.
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  - Gijsbert Vogelaar - Dutch Safety Board
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