Crashworthiness of Composites
- Certification by Analysis

2011 Technical Review
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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 coupon/component level testing allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures.
Technical Approach – Airframe Crashworthiness

TRADITIONAL APPROACH – EXPERIMENTAL –

BASED ON TESTING
TEST DATA TO CREATE NUMERICAL MODELS
NON PREDICTABLE MODELING

AIRFRAME CRASHWORTHINESS CBA

DEFINE CRASHWORTHINESS REQUIREMENTS – FAR 23, 25, and 27
LOADING RATES
AIRFRAME ENERGY DISSIPATION REQUIREMENTS per FAR 23, 25 and AIRCRAFT WEIGHTS (MTOW)
MODELING STUDY FUSELAGE
BASELINE FUSELAGE MODEL
STRAIN RATES
LOADING RATES VARIOUS STRUCTURAL COMPONENTS
STRAIN RATE & LOADING RATE

CURRENT TEST METHODS EVALUATION – COUPON LEVEL –
TEST METHODS LIMITATIONS
TEST VARIABILITY
STRAIN RATE EFFECTS
FAILURE MODES

DEFINE ASTM STANDARD
VARIABILITY STUDY
OBTAIN MECHANICAL PROPERTIES
DEFINE NUMERICAL MATERIAL MODELS FOR COMPOSITES/METALLIC COMPONENTS

MATERIAL MODELING
CURRENT MATERIAL MODELING METHODS
IDENTIFY:
MODEL PARAMETERS
MATERIAL MODELS LIMITATIONS

VALIDATE WITH TEST DATA – COUPON LEVEL

2009-2011
2011-2012
Crashworthiness Certification by Analysis

• Principal Investigators & Researchers
  – G. Olivares Ph.D. (PI)
  – S. Keshavanarayana Ph.D.
  – J. Acosta, V. Yadav

• FAA Technical Monitor
  – Allan Abramowitz

• Other FAA Personnel Involved
  – Joseph Pelletiere
  – David Moorcroft - CAMI
  – Rick Deweese - CAMI

• Industry Participation
  – Bombardier/Learjet, Hawker Beechcraft, Spirit Aerosystems, Airbus NA, Cessna, and Boeing
  – Pending definition software developers group
Phase I - Overview Current Activities

- **Phase I:** Airframe Crashworthiness Certification* by Analysis [July 2009 –September 2011]:
  - Evaluation coupon level material testing variability for Composites (Fiberglass, Toray-Carbon Uni, Toray Carbon Fabric) and Metallic Materials (Al 7075-T6)
  - Coupon Level Numerical Material Models Evaluation – Composites and Metallic Materials
  - Coupon Level Mesh Sensitivity Studies
  - High Strain Rate Coupon Level Round Robin Exercise - Experimental
  - Literature review NTSB/FAA aircraft accident and test data
  - Develop and validate energy based analytical methods to define stiffness, crush zone, and deceleration profiles
  - Metallic airframe preliminary crashworthiness evaluation – Design, and analysis of a conventional narrow body airplane barrel section and full aircraft model
  - Setup industry workgroup: Aerospace and Software Suppliers
  - Propose Airframe Crashworthiness Evaluation Methodology

* Note there are no current requirements for airframe crashworthiness, only special conditions with the introduction of composite fuselages (equivalent level of safety to metallic structures).
Coupon Level – Experimental and Computational

• Quantify the high strain rate coupon level mechanical properties test variability for:
  – Toray - T800S/3900-2B Unitape
  – Newport - E-Glass Fabric NB321/7781
  – Toray - T700G-12K-PW/3900-2 (fabric)
  – Orientations: [0°]_N, [0°/90°]_3S, [15°/-15°]_NS, [30°/-30°]_NS, [45°/-45°]_NS
  – Aluminum 7075-T6

• Identify variables and coupon level tests required to define material cards (MAT 54 and MAT 58 in Ls-dyna)

• Evaluation of LS-dyna MAT 54 and MAT 58 coupon level models with quasi-static and high strain rate data.
  – Tension, Shear and Compression
  – Mesh Sensitivity Studies

• Develop detailed FE models of the experimental test equipment

• Identify current limitations of the coupon level experimental test procedures and numerical material models.
  – Round- Robin High Strain Rate Testing Material Characterization – Coupon Level: Due to the lack of a standard high strain rate testing protocol for composite materials at the coupon level, a round-robin exercise will be coordinated between NIAR and four research partners during FY11.
Conclusions Coupon Level

- Current coupon level testing practices do not provide all the data required for crashworthiness simulations:
  - **Strain measurements** (Failure Strain): limited by strain gage measurement capabilities and SG bonding procedures/techniques. Photogrammetry may be able to solve these issues.
  - **Ultimate strength measurements**: limited by “ringing” observed in piezo-electric and piezo-resistive load cells. This issue is more noticeable at higher loading rates.

- In general, higher levels of correlation are observed during the early stages of deformation when the material response is in the elastic region. At the coupon level, LS-DYNA material card MAT-58 captures the non-linearity of the material response observed experimentally by the off-axis orientations without the manipulation of damage evolution parameters.

- The Mat-58 implementation of Hashin failure criterion is observed to overestimate failure for tensile failure modes and to underestimate failure for matrix failure modes. The material model limitation to predict failure may be due to limitations of the material model failure criterion and/or the limitations of the experimental data (strain gage limitations and load data collection at high strain rates).

- A draft report summarizing all the coupon level work will be available for review in May 2011.

- A round robin exercise is underway to study the variability in the material properties characterization for various high strain rate testing facilities. The results of this study may be used in the future as the basis of a standard high strain rate coupon level test protocol.
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

Design Parameters:
- Mass
- Impact Conditions:
  - Impact Velocity: horizontal and vertical components (for survivable accidents)
  - Impact surface: hard, soft soil, water...
  - Aircraft impact attitude (P,R,Y)
- Structural Crashworthiness Parameters (stiffness and crush zone):
  - Subfloor Configuration: Fuel Tanks, Cargo, EA Devices, etc.
  - Aircraft Type: Transport, Business Jet, General Av.
  - Material Selection: Composite, Metallic, and Hybrid (Met. And Com.)
## FAR *.562 Crush Zone Requirements

### Test I

<table>
<thead>
<tr>
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<th>PART 25</th>
<th>PART 23</th>
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<tr>
<td>Time to Peak (s)</td>
<td>0.08</td>
<td>0.05</td>
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<td>Peak - Acceleration Pulse (g's)</td>
<td>14</td>
<td>19</td>
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<td>Peak - Z Acceleration (g's)</td>
<td>12.1</td>
<td>16.4</td>
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<tr>
<td>Peak - Z Velocity (ft/s)</td>
<td>31.2</td>
<td>26.5</td>
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<tr>
<td>Peak - Z Displacement (inch)</td>
<td>30.3</td>
<td>16.2</td>
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</table>

**All dimensions in inches**

![Graphs and diagrams]
NIAR Narrow-Body Transport Aircraft

MTOW 138,000 lb (63,000 kg)
MDLW 121,000 lb (55,000 kg)
MDZFW 110,000 lb (50,000 kg)
MFuelCW 33,000 lb (15,000 kg)
OEW 72,600 lb (33,000 kg)
Pass. Capacity 135 Passengers

All dimensions in inches
### NIAR Narrow-Body Transport Aircraft – FE Assembly

<table>
<thead>
<tr>
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<th>Fuselage Model</th>
<th>Section Model</th>
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<tr>
<td>Nodes</td>
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<td>Shells</td>
<td>3,519,040</td>
<td>334,644</td>
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<td>Solids</td>
<td>157,452</td>
<td>0</td>
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<tr>
<td>Fasteners</td>
<td>181,341</td>
<td>20,247</td>
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<tr>
<td>Run Time (300 ms.)</td>
<td>90 hours</td>
<td>9 hours</td>
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<tr>
<td>No. of Cores</td>
<td>32</td>
<td>32</td>
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NIAR Narrow-Body Transport Aircraft – FE Model
Parametric Studies Overview

- Parametric analyses (Narrow Body Transport and Business Jet Aircraft):
  - Parametric Analysis I: Cabin Sub-floor Configurations
  - Parametric Analysis II: Selection of a Representative Test/Analysis Article
  - Parametric Analysis III: Survivable Accident Conditions
**Scope:** Evaluate the crashworthiness response of a typical narrow body transport aircraft structure with various sub-cabin floor configurations (cargo, and no cargo).

**Parameters:**
- Subfloor Configuration: Structural Design and Cargo Configuration (Volume, Stiffness)
- Impact Surface: Soft Soil, Hard Surface, Water
- Impact Conditions: 30 ft/sec

**Analysis:**
- Structural Stiffness Evaluation
- Strain Rates
- Energy Distribution
- Dynamic Force Balance
- Evaluation Survivable Volume
- Cabin Floor Decelerations
- Passenger | Seat Dynamic Evaluation
Parametric Analysis I - Typical Cargo Configurations*

160 in
(406.4 cm)

125 in
(317.5 cm)

60.4 in
(153.4 cm)

64 in
(162.6 cm)

88 in
(223.5 cm)

125 in
(317.5 cm)

60.4 in
(153.4 cm)

64 in
(162.6 cm)

64 in
(162.6 cm)

125 in
(317.5 cm)

96 in
(243.8 cm)
Parametric Analysis I: FEA Model Definition

**7075-T6**
Yield Strength = 70 ksi (482 MPa)
Ultimate Strength = 79.9 ksi (551 MPa)
Percentage Elongation = 8 %
Parts (Frames, Stringers, Floor Beams & Floor Tracks)

**2024-T42**
Yield Strength = 38 ksi (262 MPa)
Ultimate Strength = 61.9 ksi (427 MPa)
Percentage Elongation = 15 %
Parts (Skin, Windows, Fail Safe Strap & Brackets)

Total Weight (Without Cargo) = 4787 lbs
Total Weight (With Cargo) = 8304 lbs
Parametric Analysis I: Structural Stiffness Calculations

<table>
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<tr>
<th>Cargo Configuration</th>
<th>Internal E.</th>
<th>3.6 E6 in lbf</th>
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<tr>
<td>Mass</td>
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<tr>
<td>Stiffness (lbf/in)</td>
<td>X1 (in)</td>
<td>X2 (in)</td>
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<tr>
<td>3750</td>
<td>0</td>
<td>42.5</td>
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<tr>
<td>33557</td>
<td>42.5</td>
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<table>
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<th>No-Cargo Configuration</th>
<th>Internal E.</th>
<th>1.24E6 in lbf</th>
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<tbody>
<tr>
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<tr>
<td>Stiffness (lbf/in)</td>
<td>X1 (in)</td>
<td>X2 (in)</td>
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<tr>
<td>10044</td>
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<td>-2587</td>
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<td>23</td>
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<tr>
<td>5517</td>
<td>23</td>
<td>35</td>
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</table>
Parametric Analysis I - Kinematics
Parametric Analysis I: FE Model Check with Similar Aircraft Type Test Data

FIGURE 36. RIGHT OUTER SEAT TRACK VERTICAL ACCELERATIONS (20 Hz)

Ref: DOT/FAA/AR-01/100: Vertical Drop Test of a Narrow-Body Transport Fuselage Section With Overhead Stowage Bins
Parametric Analysis I – Energy Distribution

Airframe Energy Distribution | No Cargo Configuration | 30 ft/sec
Parametric Analysis I – Energy Distribution

Airframe Energy Distribution - Cargo | 30 ft/s

[Bar chart showing energy distribution across various components of an airframe.]
Parametric Analysis I – I.E. Distribution

Airframe Internal Energy Distribution - TMC
No Stanchions | Cargo | 30 ft/s

Airframe Internal Energy Distribution - TMC
No Stanchions | No Cargo | 30 ft/s
Parametric Analysis I - Strain Rate no-Cargo Configuration
Parametric Analysis I – Passenger Dynamic Evaluation

**Acceleration Pulse Z Component**

- **PART 25 Test I Pulse - Z Component**
- **With Cargo Pulse - Z Component**
- **Without Cargo Pulse - Z Component**

![Graph showing acceleration pulse Z component over time.]

**Simulation Lumbar Z Force Comparison**

- **PART 25 Sled Test**
- **PART 25 Sled Simulation**
- **With Cargo Pulse**
- **Without Cargo Pulse**

![Graph showing simulation lumbar Z force comparison over time.]

- [CECAM](https://www.cecam.org)
- [JAMS](https://www.jams.org)
- [AMTAS](https://www.amtast.or)
**Scope:** The purpose of this parametric study is to identify a representative aircraft structure test section to be used for analytical and experimental certification test articles - ongoing

**Parameters:**
- Full Aircraft, Fuselage, Barrel, and Half Barrel Section

**Conditions:**
- Impact Surface: Hard Surface
- Impact Velocity: 30 ft/sec

Fuselage Section Total Weight = 43733 lbs.
Barrel Section Total Weight = 4850 lbs.
Parametric Analysis II - Kinematics
Parametric Analysis II - Kinematics
Parametric Analysis II - Kinematics
Parametric Analysis II – Cabin Floor Acceleration Profiles

Peak Acceleration Comparison
F/8 Section to Full Aircraft

Right Outer Seat Track Vertical Acceleration

Left Outer Seat Track Vertical Acceleration
Parametric Analysis II – Passenger Dynamic Evaluation

**Simulation Lumbar Z Force Comparison**

- **25.562 Vertical:** 1200 lbf
- **10 ft Section:** 768 lbf
- **Full Aircraft:** 1913 lbf

**Acceleration Pulse Z Component**

- **PART 25 Test I Pulse – Z Component**
- **10 ft Section with Stanchions – Z Component**
- **Full Aircraft Model – Z Component**
Scope: Study impact conditions for survivable aircraft accidents | Literature Review and Computational Models | - ongoing

Parameters:
- Narrow Body Transport and Business Jet Aircraft
- Impact Surface: Soft Soil, Hard Surface, Water
- Impact Conditions: Velocity | Attitude
Parametric Analysis I and II – Conclusions

- The design/configuration of the cabin-subfloor section significantly affects the dynamic response of the airframe and passengers.
- The variability of cargo configurations (shape, stiffness, no-cargo) needs to be addressed in future crashworthiness requirements:
  - Develop structures with stanchions and other structural elements in order to reduce the energy absorbing capabilities of the cargo.
  - And/or develop a “standard worst case geometry/stiffness” cargo configuration to be used in the development and certification processes.
- Using simulation tools we were able to quantify for all the components in the structure the Strain Rate, Loading Rate, Energy Distribution, Accelerations, Dynamic Structural Efficiency, and Structural Deformations throughout the crash event.
- The new detailed numerical aircraft seat and passenger models developed in CBA Phase I provide a predictable tool that can be used to evaluate the passenger’s risk of injury.
- This analysis methodology for metallic structures can be applied to composite structures once composite material failure models are improved.
Looking Forward

- Release coupon level material model evaluation report
- Round Robin exercise – coupon level
- Continue the parametric studies of Narrow-Body Transport and Business Jet configurations
- Develop guidance material to design crashworthy metallic, composite and hybrid structures
- Crashworthiness Forum October 2012:
  - Certification by Analysis Aircraft Interiors
  - Certification by Analysis Aircraft Structures
  - Experimental and Computational Methods
  - Workshops:
    - Modeling Techniques: ATDs, Seats, Airframe, Material Models
    - Coupon, Component Level Testing
    - Sled Testing
End of Presentation.
Thank you.