Composite Aircraft Crashworthiness - Certification by Analysis

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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.
Crashworthiness - Certification by Analysis

• Principal Investigators & Researchers
  – **PI:** G. Olivares Ph.D.
  – **Researchers NIAR-WSU:** S. Keshavanarayana Ph.D., Chandresh Zinzuwadia, Luis Gomez, Nilesh Dhole, Hoa Ly, Armando Barriga, Akhil Bhasin, Aswini Kona
  – 8 Students [Graduate and Undergraduate ]

• FAA Technical Monitor
  – Allan Abramowitz

• Other FAA Personnel Involved
  – Joseph Pelletiere Ph.D.

• Industry\Government Participation
  – ARAC Transport Airplane Crashworthiness and Ditching Working Group [FAA, EASA, Transport Canada, NASA, Aircraft OEMs (Boeing, Embraer, Bombardier, Cessna, Mitsubishi, Gulfstream, Airbus), DLR]
  – KART – Spirit, Textron Aviation, Bombardier/Learjet
  – Gerard Elstak and Gerard Schakelaar – Dutch Politie
  – Hiromitsu Miyaki, Japan Aerospace Exploration Agency, JAXA
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 *0.562 |
- **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 |

[Images of phases I to IV]
CBA: Composite Structures Crashworthiness

**Traditional Approach**
- **Experimental**

**Based on Testing**
- **Test Data to Create Numerical Models**
- **Non Predictable Modeling**

**Airframe Crashworthiness**
- **CBA**

**Predictable Modeling**
- **Virtual Testing**

**Define Crashworthiness Requirements**
- FAR 23, 25, and 27

**Airframe Energy Dissipation Requirements**
- Per FAR 23, 25, and Aircraft Weights (MTOW)

**Loading Rates**
- **Baseline Fuselage Model**
- **Modeling Study Fuselage**
- **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**

**Test Data to Create Numerical Models**

**Non Predictable Modeling**

**Identification**

**Virtual Testing**
NIAR Crash Dynamics Laboratory

Support ARAC for business jet size aircraft configurations

Fuselage Section Drop Tests

- Support the development of airframe level crash requirements for business jet airplanes
- Two tests were conducted:
  - Composites (Hawker 4000)
  - Metallic (Cessna Citation 650)
- Impact velocity 30 ft/s
- Instrumented Reaction Floor
- Hardware
  - Digital Image Correlation
  - Strain-gages
  - Load Cells
  - High Speed Videos
# Metallic Airframe Test Article

## General Characteristics

- **Seating**: 2+7/9
- **External Length**: 55 ft 6 in
- **External tail Height**: 16 ft 10 in
- **Wing Span**: 53 ft 6 in
- **Empty Weight**: 11670 lb (5293 kg)
- **Gross Weight**: 22000 lb (9979 kg)
- **Cruise Speed**: 554 mph (875 kmph)
- **Range**: 2345 mi (3774 km)
- **Service Ceiling**: 51000 ft

## Performance

<table>
<thead>
<tr>
<th>Power</th>
<th>2 × Garrett TFE731-3B-100S Turbofans 3,650 lbf (16.2 kN) thrust each</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise Speed</td>
<td>554 mph (875 kmph)</td>
</tr>
<tr>
<td>Range</td>
<td>2345 mi (3774 km)</td>
</tr>
<tr>
<td>Service Ceiling</td>
<td>51000 ft</td>
</tr>
</tbody>
</table>

## Interior

<table>
<thead>
<tr>
<th>Cabin Height</th>
<th>5 ft 8 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Length</td>
<td>18 ft 7 in</td>
</tr>
<tr>
<td>Cabin Width</td>
<td>5 ft 6 in</td>
</tr>
<tr>
<td>Cabin Volume</td>
<td>762 ft³</td>
</tr>
</tbody>
</table>
Metallic Test Section – Specifications

- Complete Fuselage Available
- Tentative Test Article Dimensions
  - Length: ≈9 ft
  - Diameter: ≈6 ft
- Tentative Test Article Configuration:
  - One Exit Door Opening (Right Side)
  - Seven Window Openings:
    - 3 Right Side
    - 4 Left Side
- Floor Structure with Seat tracks
- Seat Track Width: 15” (wall mounted)
- No wing box structure
- No upper panels/PSUs
- This article could not be used to support the ARAC program since during the accelerometer instrumentation process we found subfloor modifications to the structure
- The fuselage section was dropped to evaluate the Release and DIC system
- If funding is available an additional test is planned with a Bombardier Metallic Fuselage:
  - NIAR purchased the fuselage and seats
  - Testing Q4 2019 or Q1 2020 depending on funding and test facility availability
## Composite Airframe Test Article

### General Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating</td>
<td>2+8/12</td>
</tr>
<tr>
<td>External Length</td>
<td>69 ft 6 in</td>
</tr>
<tr>
<td>External tail Height</td>
<td>19 ft 9 in</td>
</tr>
<tr>
<td>Wing Span</td>
<td>61 ft 9 in</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>23500 lb (10659 kg)</td>
</tr>
<tr>
<td>Gross Weight</td>
<td>26000 lb (11793 kg)</td>
</tr>
</tbody>
</table>

### Interior

<table>
<thead>
<tr>
<th>Interior</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Height</td>
<td>6 ft</td>
</tr>
<tr>
<td>Cabin Length</td>
<td>25 ft</td>
</tr>
<tr>
<td>Cabin Width</td>
<td>6 ft 6 in</td>
</tr>
<tr>
<td>Cabin Volume</td>
<td>762 ft³</td>
</tr>
</tbody>
</table>

### Performance

<table>
<thead>
<tr>
<th>Performance</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2 × Pratt &amp; Whitney Canada PW308A turbofan 6,900 lbf/ ISA + 22 °C () each</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>Mach 0.84</td>
</tr>
<tr>
<td>Range</td>
<td>6075 km</td>
</tr>
<tr>
<td>Service Ceiling</td>
<td>45000 ft</td>
</tr>
</tbody>
</table>
Composite Test Section- Aircraft Location
Composite Airframe Drop Test – H4000

- **Dimensions:**
  - Length: ≈8 ft 2in
  - Diameter: ≈7 ft

- **One Exit Door Opening (Right Side)**

- **Seven Window Openings:**
  - 3 Right Side
  - 4 Left Side

- **Floor Structure with Seat tracks**

- **Seat Track Width:** 8’ ¾’’

- No wing box structure

- No upper panels/PSUs

- **Total Weight:** 1553 lbs.

- **4 Occupants:**
  - 2 Seats: HII and FAA HII
  - 2 Seats: Ballast Weights representative of seats and occupants
Drop Test Instrumentation

- DTS Slice Pro Data Acquisition System, 108 channels
  - 72 channels will be used for the ATDs (32 sensors)
  - H4000 barrel section (40 sensors)
- Endevco 7264C accelerometers with measuring capability of 2000 g’s vertical and 500 g’s on the lateral axis will be used. 4 triaxial accelerometers will be used for the seat track corners. 8 biaxial accelerometers will be used on the seat tracks and 4 biaxial accelerometers will be used at the top center of the barrel section. The accelerometer data will be filtered using the SAE J211 CFC60 filter.
- Six S-VIT AOS Tech. AG High Resolution Color (900 x 700 pixel) – 1000 fps
- 360 HD camera system - 4 GO-PROs
- Two pairs of high speed cameras will be used to perform digital image correlation (DIC) analysis in the fuselage: A pair of monochrome Photron SA-Z 16 Gig RAM high speed cameras and a pair of color Photron SA-Z 16 Gig RAM high speed cameras. Both camera sets are capable to record 20,000 fps at a full resolution of 1024 x 1024 pixels.
- Four Strain Gages EP-08-250BF-350
- HII and FAA HIII ATDs
HSV RWD Side and Center View

NIAR Drop Test – Hawker 4000
Evaluation Criteria

NIAR Drop Test – Hawker 4000

- Maintain Survivable Volume
  - Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)
  - Avoid Occupant to Interior Structure Contacts during impact
- Maintain Deceleration Loads to Occupants
  - Injury Criteria Limits per 14 CFR 25.562:
    - 1500 lbf, HIC 1000, Shoulder Strap Loads
- Retention Items of Mass
  - No items of mass such as overhead bins
  - Occupants and Seat Structures supported throughout the crash event (14 CFR 25.562)
- Maintain Egress Paths
  - Maintain Aisle Distance (Min 12-15 inches per 14 CFR 25.815 and 25.807(d)(4))
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight
Lumbar Load – HII vs. FAA HIII
NIAR Drop Test – Hawker 4000

Lumbar Loads: 2500 lbs for both the HII and FAA HIII
Structural Failures Fuselage Structure
NDT Test Results – Post-Impact Inspection

Equipment: Olympus BondMaster 600
CBA Modeling Methodology

• **Internal NIAR-KART R&D Full Scale Modeling**

  • **Phase I:** Composite Best Modeling Practices: – 3 months
    - H4000 Fuselage Drop Test: Conduct Damage Evaluation Inspection Techniques:
      - NDE: [ Eddy current (EC) method, Ultrasonic (US) method, Radioscopy (X), and/or Thermography ]
      - CTSCAN Damage Areas H4000 Fuselage Drop Test to identify failure modes.

  • **Phase II:** Coupon and Component Level Testing program to improve predictions of composite structure failure mechanisms – 6 months

  • **Phase III:** Update Global H4000 FEA Model and Validate with Drop Test Data – 3 months

  • **Phase IV:** Vertical Impact Velocity Survivability Study
Kinematics Comparison
NIAR Drop Test – Hawker 4000
FEA Model Validation

NIAR Drop Test – Hawker 4000

Note: The seat used for analysis is a representative business jet seat but not the actual model used for testing.
FE Model Structural Failure Mechanisms

NIAR Drop Test – Hawker 4000

Debonded regions (b/w keel beams)
# Parametric Study: Velocity Profiles

Hawker 4000 Drop Test Analysis

<table>
<thead>
<tr>
<th>Velocity Parametric Study</th>
<th>Case ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case - 1</td>
<td>10 ft/s</td>
<td></td>
</tr>
<tr>
<td>Case - 2</td>
<td>15 ft/s</td>
<td></td>
</tr>
<tr>
<td>Case - 3</td>
<td>20 ft/s</td>
<td></td>
</tr>
<tr>
<td>Case - 4</td>
<td>25 ft/s</td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>30 ft/s</td>
<td></td>
</tr>
</tbody>
</table>
Lumbar Load Response – Hybrid III ATD

Parametric Study: Velocity Configurations

Hybrid III ATD

HIII FAA 50th ATD

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Non-Integrated vs. Integrated Safety

NIAR Drop Test – Hawker 4000
Conclusions

• A building block methodology has been developed to evaluate the crashworthiness response of metallic and composite airframes subjected to Emergency Landing Conditions

• Findings from this research have supported the ARAC Transport Airplane Crashworthiness and Ditching Working Group, SAE Seat Committee and CMH17 Working Group

• Not all aircraft configurations certified under 14 CFR 25 are capable of providing the same level of safety to passengers for a vertical $\Delta V$ of 30ft/s. Subfloor configurations with reduced crushable space (14 CFR 25 Business Jets) have shown survivability capabilities up to 18 ft./sec (for metallic, composite or hybrid airframe configurations)

<table>
<thead>
<tr>
<th>Test I</th>
<th>PART 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Peak (s)</td>
<td>0.08</td>
</tr>
<tr>
<td>Peak - Acceleration Pulse (g’s)</td>
<td>14</td>
</tr>
<tr>
<td>Peak - Z Acceleration (g’s)</td>
<td>12.1</td>
</tr>
<tr>
<td>Peak - Z Velocity (ft/s)</td>
<td>31.2</td>
</tr>
<tr>
<td>Peak - Z Displacement (inch)</td>
<td>30.3</td>
</tr>
</tbody>
</table>
Conclusions (cont)

- The 14 CFR 25.562 dynamic seat requirements for business jets dynamic certified seats should be defined taking into consideration the reduced crushable subfloor space and reduced maximum vertical $\Delta V$ airframe/seat capabilities [compared to larger aircraft certified under 14 CFR 25 with 30 inches or more of crushable subfloor space]

- The use of simulation to support the development and certification process will enable the introduction of an integrated safety approach to aerospace crashworthiness, where the restrain system, seat and airframe can be optimized concurrently to improve the occupant survivability rates.

- The introduction of integrated safety will have a big impact in General Aviation and eVTOL Urban Air applications.

- Crashworthiness design needs to be implemented from the conceptual design stage of the vehicle, since the crashworthiness optimization of the various structural elements cannot be implemented once the design has been driven only by airworthiness requirements.
NIAR Aerospace Integrated Safety Center

Experimental and Computational Capabilities

- November 2019
- State of the art aerospace crashworthiness research from coupon level to full scale testing
- Experimental Capabilities:
  - Coupon Level Testing:
    - Quasi and High Strain Rate Capabilities
  - Component Level Tests:
    - Head Component Level Tester
      - Monitors, Seatbacks, monuments
    - sUAS Ground Collision Certification
  - Seats:
    - Seat Backs EA
    - Seat Cushions
    - Actuators
    - Airbag Drop Towers
  - Full Scale:
    - Crash Dynamics Sled
    - Static Seat Testing
    - Fuselage Drop Test Facility
  - Dummy Calibration Facility
- Computational Capabilities:
  - Virtual Engineering Lab
    - Seat Development and CBA
    - Airframe Development and CBA
  - Virtual Flight Testing Lab
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 and composite structures
  – Provide R&D material to the ARAC Transport Airplane Crashworthiness and Ditching Working Group, FAA CBA Workshops, SAE Seat Committee and CMH 17.

• Future needs
  – Address the effects of defects (damage/repair) on the dynamic response of crashworthy composite seat and airframe structures
  – Urban Air Transport Emergency Landing - Crashworthiness Certification Requirements and Protocols
  – General Aviation Crashworthiness Design Strategies – Composites Crashworthy Structures
  – Integrated Safety Concepts and Technology Demonstrators for GA and eVTOL Vehicles
  – Training of Industry and FAA personnel on the use of numerical tools to support the development and certification process