Boeing Composite Airframe Damage Tolerance and Service Experience

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Boeing Commercial Airplanes
787 Program
Outline

- Boeing Design Criteria for Damage Tolerant CFRP Primary Structures and the relationship to Maintainability
- CFRP Structures Service Experience
Key Design Criteria for Primary CFRP Structure which effect Maintainability

- Static strength as related to BVID (Barely Visible Impact Damage)

- Damage tolerance as related to VID (Visible Impact Damage)

- Environment and events as related to Lightning strike, Moisture, Temperature, Runway debris, Tool damage, Rapid decompression, Engine blade loss, Rotor burst, Hail, Bird impact, Tire and wheel threats
<table>
<thead>
<tr>
<th>Threat</th>
<th>Criteria</th>
<th>Requirement</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Tool Drop</td>
<td>48 in-lbs normal to surface.</td>
<td>No visible damage</td>
<td>1” diameter-hemispherical impactor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No non-visible damage growth for 3 DSOs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accounted for in Ultimate Design Allowables</td>
<td></td>
</tr>
<tr>
<td>Large Tool Drop (BVID)-general acreage</td>
<td>Up to 1200 in-lbs or a defined dent depth cut-off (considering relaxation)</td>
<td>Barely visible damage which may not be found during HMV</td>
<td>1” diameter-hemispherical impactor</td>
</tr>
<tr>
<td>(FAR 25.305, AC20-107A)</td>
<td>based on level of visibility as related to the inspection method.</td>
<td>No damage growth for 3 DSOs with LEF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capable of Ultimate strength</td>
<td></td>
</tr>
<tr>
<td>Large Tool Drop (BVID)-repeat impact threat</td>
<td>Consider higher than 1200 in-lbs</td>
<td>Barely visible damage which may not be found during HMV</td>
<td>1” diameter-hemispherical impactor</td>
</tr>
<tr>
<td>areas (FAR 25.305, AC20-107A)</td>
<td>Consider multiple, superimposed impacts</td>
<td>No damage growth for 3 DSOs with LEF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Consider clustered impacts</td>
<td>Capable of Ultimate strength</td>
<td></td>
</tr>
<tr>
<td>Visible Impact Damage (VID) (Damage Tolerance</td>
<td>No energy cut-off</td>
<td>Visible Damage with a high probability to be found during HMV</td>
<td>1” to 4” diameter hemispherical hemispherical impactor</td>
</tr>
<tr>
<td>FAR 25-571b)</td>
<td></td>
<td>No damage growth for 2 times the planned inspection interval with LEF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capable of residual Limit strength</td>
<td></td>
</tr>
</tbody>
</table>
Barely Visible Impact Damage Defined

BVID

Small damages which may not be found during heavy maintenance general visual inspections using typical lighting conditions from a distance of five (5) feet

- Typical dent depth – 0.01 to 0.02 inches (OML)
- Dent depth relaxation must be accounted for
Barely Visible Impact Damage

- Small damages which may not be found during heavy maintenance general visual inspections using typical lighting conditions from a distance of five (5) feet

  - Ultimate design strength required
  - No detrimental damage growth during Design Service Objective with LEF
  - Validated by testing

BVID Impact Location
Criteria Requirements for Visible Damage

Airframe must support design limit loads without failure.

No detrimental damage growth during fatigue cycling representative of the structure’s inspection interval.
  - One missed inspection is assumed (two interval requirement)
  - Validated by testing

Airframe must be able to support residual strength loads until the damage is found and repaired.
  - Damage state contains both visibly detectable and associated non-visibly detectable damage.

[Image of impact location]
Wing Skin Visible Impact Damage

OML Impact, 1” Diameter impactor
Impact Energy: Greater than 8000 in-lbs

Residual Limit Load
No Growth for a missed inspection interval
Fuselage Skin Visible Impact Damage

OML VID Impact

Inside damage associated with OML VID

Residual Limit Load
No Growth for a missed inspection interval
Sample Damage Tolerance Criteria-Impact

<table>
<thead>
<tr>
<th>Threat</th>
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<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway Debris</td>
<td>0.50-inch dia spherical object @ tangential tire speed.</td>
<td>Ultimate design strength and no detrimental damage growth during DSO, including effect of environment</td>
</tr>
<tr>
<td>Ground Hail ~ Non-Removable Structure</td>
<td>Up to 500 in-lb impact with simulated hail ball.</td>
<td>Ultimate design strength, no moisture intrusion and no detrimental damage growth during DSO.</td>
</tr>
<tr>
<td>In-flight Hail</td>
<td>Simulated hail ball up to a specified airspeed.</td>
<td>Ultimate design strength, no moisture intrusion and no detrimental damage growth during DSO for smaller size simulated hail ball. Limit residual strength for larger size simulated hail ball. Hail ball sizes and velocities based on statistical data.</td>
</tr>
<tr>
<td>“Failsafety”</td>
<td>The airframe shall be capable of completing a flight during which complete failure of a structural segment, such as a frame or stiffener, with associated skin or web, occurs due to an undefined source.</td>
<td>Analysis, supported by component tests, shall demonstrate that the airframe will sustain required residual strength loadings without failure.</td>
</tr>
</tbody>
</table>
Analyses, supported by large component testing, shall demonstrate ability to predict containment of dynamically imposed penetration damage to the pressurized fuselage.

Compliance with these requirements is to be by analysis, supported by testing.
# Sample Damage Tolerance Criteria - Lightning Strike

<table>
<thead>
<tr>
<th>Threat</th>
<th>Criteria</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy Strike</td>
<td>Strike level in accordance with zoning diagram</td>
<td>No penetration of fuel tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No sparking or hot spotting in fuel tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Protection of systems from lightning attachment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continued safe flight and landing loads per AC25-571-1c para 8.c.(1) and (2)</td>
</tr>
<tr>
<td>Nominal Lightning strike</td>
<td>Approximately 50&lt;sup&gt;th&lt;/sup&gt; percentile strike energy level</td>
<td>Structural repair not required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sealing/restoration of protection may be necessary at some point</td>
</tr>
<tr>
<td>Dispatch Lightning strike</td>
<td>Approximately 80&lt;sup&gt;th&lt;/sup&gt; to 90&lt;sup&gt;th&lt;/sup&gt; percentile strike energy level</td>
<td>Visually detectable damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Immediate structural repair not required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intermediate inspections may be required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Permanent repair may be required after deferral period</td>
</tr>
</tbody>
</table>
CFRP structures must meet same lightning strike regulatory requirements as Aluminum structures.

Additionally, 787 structures are designed, by requirement, to resist economic levels of lightning strike.

787 composite panel; nominal strike causes superficial damage only. This damage would be expected to be within ADL and the airplane would be dispatched with deferred structural repair.

Aluminum panel; nominal strike punctures through a similar gage aluminum panel. Immediate structural repair required to dispatch the airplane. Operational schedule impacted.
Maintainability by Design

- Utilization of in-service history to define and document appropriate ADLs validated by test.
- All structure is required to have a viable repair plan as part of the product definition data.
- Viable repair plans will contain a suite of repairs including low/medium temp. wet lay-up and bolted repairs.
- All structure is required to be repairable using a minimalized list of standard techniques and materials.

Maintainability
- Repairability
- Inspectability

Structures Design Criteria
- Design loads
- Stiffness and flutter
- Static strength
- Durability
  - Fatigue
  - Corrosion
- Fail Safety
- Damage Tolerance and Safe Life
- Crashworthiness
- Productivity
- Environment and discrete events
Composite Design Criteria provide for structural robustness.

- Processing anomalies
  - Surface irregularities
  - Splicing
  - Waviness
  - Inclusions
  - Voids

- Damage
  - Visible damage (For Limit)
  - BVID (For Ultimate)
  - Repair (holes, etc.)

- Design
  - Environment

- Allowable design region

- Robustness

- Reduction of the allowable stress

- Stress

- Strain
ADLs will be based on visible damage detection parameters—i.e. length, width and depth

Visual inspection techniques as for current aluminum airplanes

Instrumented Non Destructive Test (NDT) will not be required for damages within published ADLs

No new NDT techniques or equipment planned—inspections based on current 777 techniques and equipment modified to account for 787 structural configurations

Instrumented NDT may be required for damages which exceed published ADLs

Methods validated by probability of detection studies and application on test articles.
Repairable by Design

Flush Bolted

Flush Bonded

External Bolted
Numerous test articles ranging from coupons to components have (or will have) repairs of the types planned for the SRM (including bolted, bonded, QCR, etc.) installed on them and will be tested.

Tests include (but are not limited to): static and fatigue (with and without BVID, with and without environment), Tension, Compression and Combined Loads
Outline

- Boeing Design Criteria for Damage Tolerant CFRP Primary Structures and the relationship to Maintainability
- CFRP Structures Service Experience
Hundreds of CFRP and GFRP components have been in-service on Boeing aircraft since the late 50’s-including both honeycomb and solid laminate designs.

Majority of components have an acceptable service record.

Large CFRP primary structures (737 NASA ACEE stabilizers-5 shipsets, 757/767 rudder/elevator, 777 empennage, flaps, rudder/elevator-500+ shipsets, ) have had an outstanding service history to date.
As part of the ACEE program, Boeing redesigned, manufactured, certified, & deployed five shipsets of 737-200 horizontal stabilizers using graphite-epoxy composites.

Boeing 737 Composite Stabilizer Program Objectives:
- Achieve a 20% weight reduction with respect to the existing metal structure
- Manufacture at least 40% (by weight) of the components from composite materials
- Demonstrate cost competitiveness of the structure
- Obtain FAA certification for the structure
- Evaluate the structure in service
Horizontal Stabilizer Description

The structural arrangement was designed such that maximum commonality was achieved with the 737 metal configuration.

**MATERIAL**
- NARMCO T300/5208

**STRUCTURAL ARRANGEMENT**
- Stiffened Skin Structural Box arrangement with I-section stiffener panels: the entire skin/stiffener combination was co-cured to ensure high bond reliability.
- Bolted Titanium spar lugs: this concept used two titanium plates bonded and bolted externally to a pre-cured graphite-epoxy chord.
- Honeycomb ribs were used because of the simplicity of the concept in terms of tooling, fabrication and cost.
### 737 Fleet Status

#### Five Shipsets were manufactured and certified in August 1982

<table>
<thead>
<tr>
<th>Shipset / Production Line #</th>
<th>Entry into Service</th>
<th>Airline</th>
<th>Status as of March 31, 2006 (except as noted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 / 1003</td>
<td>2 May 1984</td>
<td>A</td>
<td>In service (60024 hours, 44712 flights)</td>
</tr>
<tr>
<td>2 / 1012</td>
<td>21 March 1984</td>
<td>A</td>
<td>In service (61372 hours, 46380 flights, as of May 31, 2006)</td>
</tr>
<tr>
<td>4 / 1036</td>
<td>17 July 1984</td>
<td>B &amp; C</td>
<td>Stabilizers removed from service 2002 (approx. 39000 hours, 55000 flights); partial teardown of R/H unit at Boeing</td>
</tr>
<tr>
<td>5 / 1042</td>
<td>14 August 1984</td>
<td>B &amp; D</td>
<td>Stabilizers removed from service 2002 (approx. 52000 hours, 48000 flights); teardown of L/H unit at Boeing; teardown of R/H unit at NIAR, Wichita State</td>
</tr>
</tbody>
</table>
Four reported service-induced damage incidents

- 2 De-icer impact damages on upper surface panels. Impacts were relatively minor. Damage limited to the skin, not affecting the stiffener elements.
  - Repair accomplished on site, in-situ using a low temperature, wet layup repair.

- Fan blade penetration of lower skin. Penetration missed the stiffener elements. Damage was limited to a small area of the skin panel.
  - Repair accomplished on site, in-situ using a low temperature, wet layup repair.

- Impact indications found on the lower leading edge panel forward of the front spar. Visible damage to the front spar web and upper and lower chord radii.
  - Bolted repair using titanium reinforcements

All units returned to service
No reported in-service repairs of composite floor beams*

Fatigue cracking and corrosion in aluminum floor beams is fairly common and costly

* 500 aircraft in service
5 reported service-induced damage incidents associated with the main torque boxes

- FOD damage due to engine run-up
  - Area of skin/stringer disbond repaired with blind fasteners

- Tip damage due to impact while taxiing
  - No damage to CFRP primary structural components

- Hailstorm damage
  - No damage to main torque box structure

- Damage due to impact with maintenance stand
  - Damage to front spar, main torque box skins, aux spar and leading edges
  - Bolted titanium sheet metal repair on front spar, skin, other parts replaced

- Damage due to impact with service truck
  - Damage to front spar and main torque box skin
  - Bolted titanium sheet metal repair on front spar and skin
Empennage Stringer Disbond - Engine Thrown Debris

AOG Damage Description

Straight-forward, effective repair
Downed... a seagull, above, injured by hailstones at Bondi. Below, Fred Campbell shows why the Swans’ SCG training was doomed.
2.5” to 3.0” hail dented the fixed 5 ply honeycomb structure shown here but did no damage to the CFRP main torque box.
Skin/Spar Damage—Ground Handling Equipment Impact

Conventional Bolted Repair
777 In-Service Experience-Details

- Ground Equipment Impact
In-service experience with primary composite structure has been excellent.

Visual based inspection program validated. In-service NDT techniques validated.

Damage occurrences are at or below those for equivalent metal structure.

Repair techniques have proven to be effective and efficiently applied.