Boeing Composite Airframe Damage Tolerance and Service Experience

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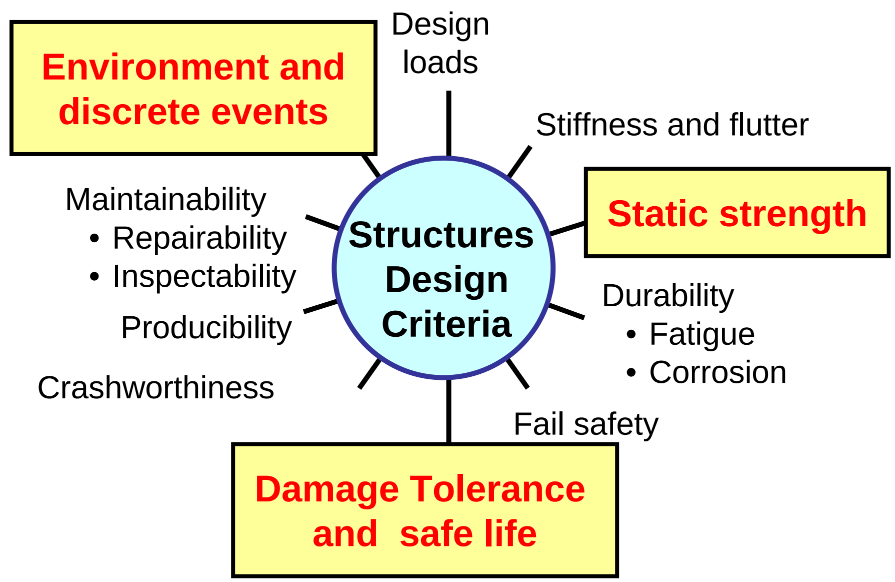
Boeing Commercial Airplanes
787 Program

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



Sample Damage Tolerance Criteria-Impact

Threat	Criteria	Requirement	Notes
Small Tool Drop	48 in-lbs normal to surface.	No visible damage No non-visible damage growth for 3 DSOs Accounted for in Ultimate Design Allowables	1" diameter-hemispherical impactor
Large Tool Drop (BVID)-general acreage (FAR 25.305, AC20-107A)	Up to 1200 in-lbs or a defined dent depth cut-off (considering relaxation) based on level of visibility as related to the inspection method.	Barely visible damage which may not be found during HMV No damage growth for 3 DSOs with LEF Capable of Ultimate strength	1" diameter-hemispherical impactor
Large Tool Drop (BVID)-repeat impact threat areas (FAR 25.305, AC20-107A)	Consider higher than 1200 in-lbs Consider multiple, superimposed impacts Consider clustered impacts	Barely visible damage which may not be found during HMV No damage growth for 3 DSOs with LEF Capable of Ultimate strength	1" diameter-hemispherical impactor
Visible Impact Damage (VID) (Damage Tolerance FAR 25-571b)	No energy cut-off	Visible Damage with a high probability to be found during HMV No damage growth for 2 times the planned inspection interval with LEF Capable of residual Limit strength	1" to 4" diameter hemispherical impactor

Barely Visible Impact Damage Defined

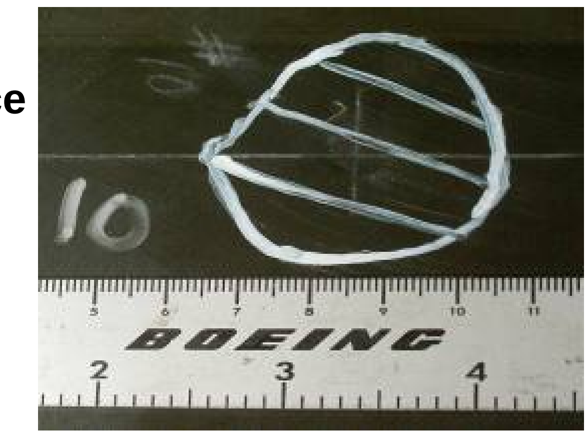
- **BVID**

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

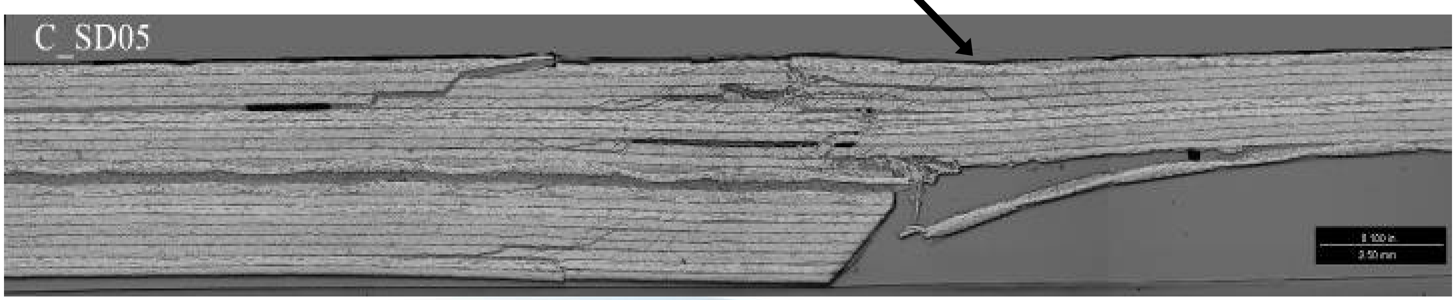
- **Typical dent depth – 0.01 to 0.02 inches (OML)**
- **Dent depth relaxation must be accounted for**

Barely Visible Impact Damage

- **Small damages which may not to 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



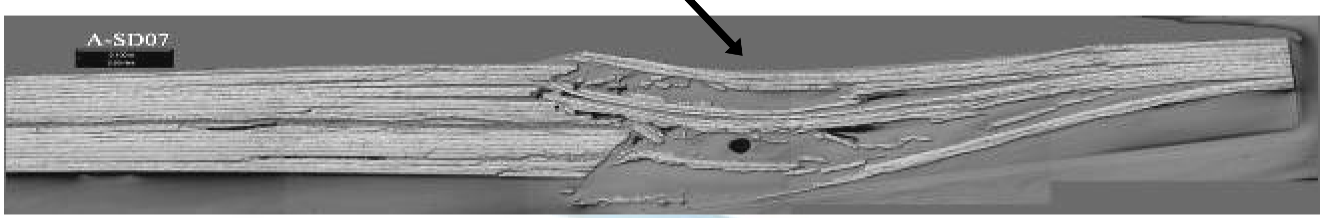
Criteria Requirements for Visible Damage

- **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.**

Impact Location



Wing Skin Visible Impact Damage

OML Impact, 1" Diameter impactor

Impact Energy: Greater than 8000 in-lbs

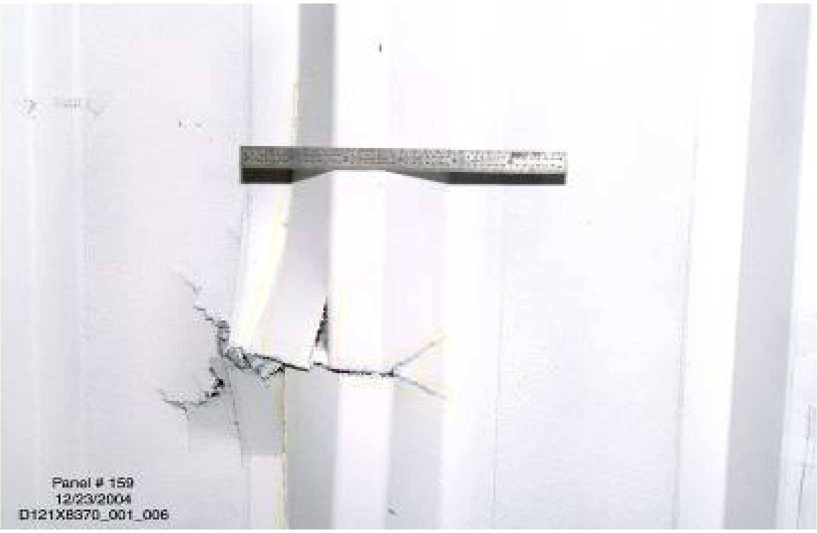
Residual Limit Load

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

Threat	Criteria	Requirement
Runway Debris	0.50-inch dia spherical object @ tangential tire speed.	Ultimate design strength and no detrimental damage growth during DSO, including effect of environment
Ground Hail ~ Non-Removable Structure	Up to 500 in-lb impact with simulated hail ball.	Ultimate design strength, no moisture intrusion and no detrimental damage growth during DSO.
In-flight Hail	Simulated hail ball up to a specified airspeed.	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.
"Failsafety"	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.	Analysis, supported by component tests, shall demonstrate that the airframe will sustain required residual strength loadings without failure.

Sample Damage Tolerance Criteria-Impact

Threat	Criteria	Requirement
Bird Impacts	Continued safe flight and landing following impact of a 4-lb bird (8lb for empennage) at Vc @ sea level, or 0.85 Vc @ 8000 feet.	Bird impact tests on test articles or components representative of A/C design. Where relevant data exists, compliance by analysis may be utilized.
Delamination or Disbonding of Bonded Interfaces	1) Demonstrate that damage to a bondline, due to manufacturing, environment, or accident, does not propagate to a residual strength condition of less than limit load, (or) 2) Be designed with arrestment features such that limit load strength is maintained with a complete disbond between adjacent arrestment features.	Residual strength demonstrated after cyclic load testing for two inspection intervals during which detection of the disbond or fracture is determined to likely occur
Accidental Damage ~ Breaching of Pressurized Fuselage ~ *Threats from Rotating Machinery*	The airplane should be able to complete a flight during which damage occurs due to uncontained: - Fan blade impact or engine failure. - Failure of rotating machinery.	Analyses, supported by large component testing, shall demonstrate ability to predict containment of dynamically imposed penetration damage to the pressurized fuselage.
Accidental Damage ~ Breaching of Pressurized Fuselage ~ *Sudden Decompression*	Structure, inside or outside of a pressurized fuselage compartment, whose failure could interfere with continued safe flight and landing, must withstand sudden release of pressure through an opening in any compartment resulting from: - An opening, without regard to a specific cause, up to 20.0 sq. ft - Opening due to probable airplane or equipment failures.	Compliance with these requirements is to be by analysis, supported by testing.

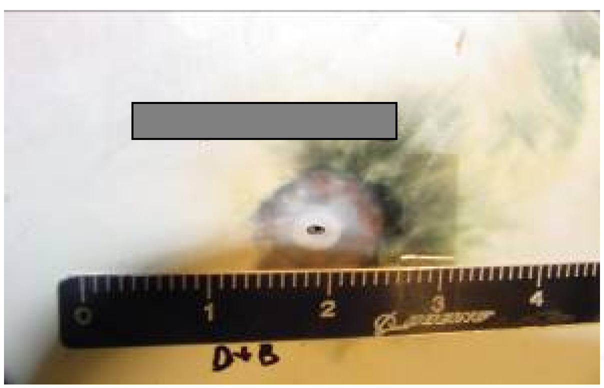
Sample Damage Tolerance Criteria-Lightning Strike

Threat	Criteria	Requirement
High Energy Strike	Strike level in accordance with zoning diagram	No penetration of fuel tank No sparking or hot spotting in fuel tank Protection of systems from lightning attachment Continued safe flight and landing loads per AC25-571-1c para 8.c.(1) and (2)
Nominal Lightning strike	Approximately 50th percentile strike energy level	Structural repair not required Sealing/restoration of protection may be necessary at some point
Dispatch Lightning strike	Approximately 80th to 90th percentile strike energy level	Visually detectable damage Immediate structural repair not required Intermediate inspections may be required Permanent repair may be required after deferral period

Example –Lightning Strike

- 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

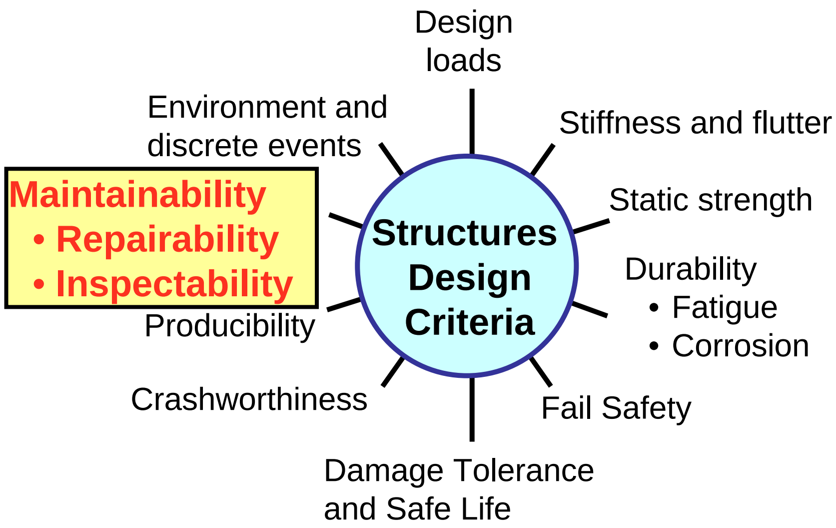
787 composite panel; nominal strike causes superficial damage only. This damage would be expected to be within ADL and the airplane would be dispatched with deferred structural repair



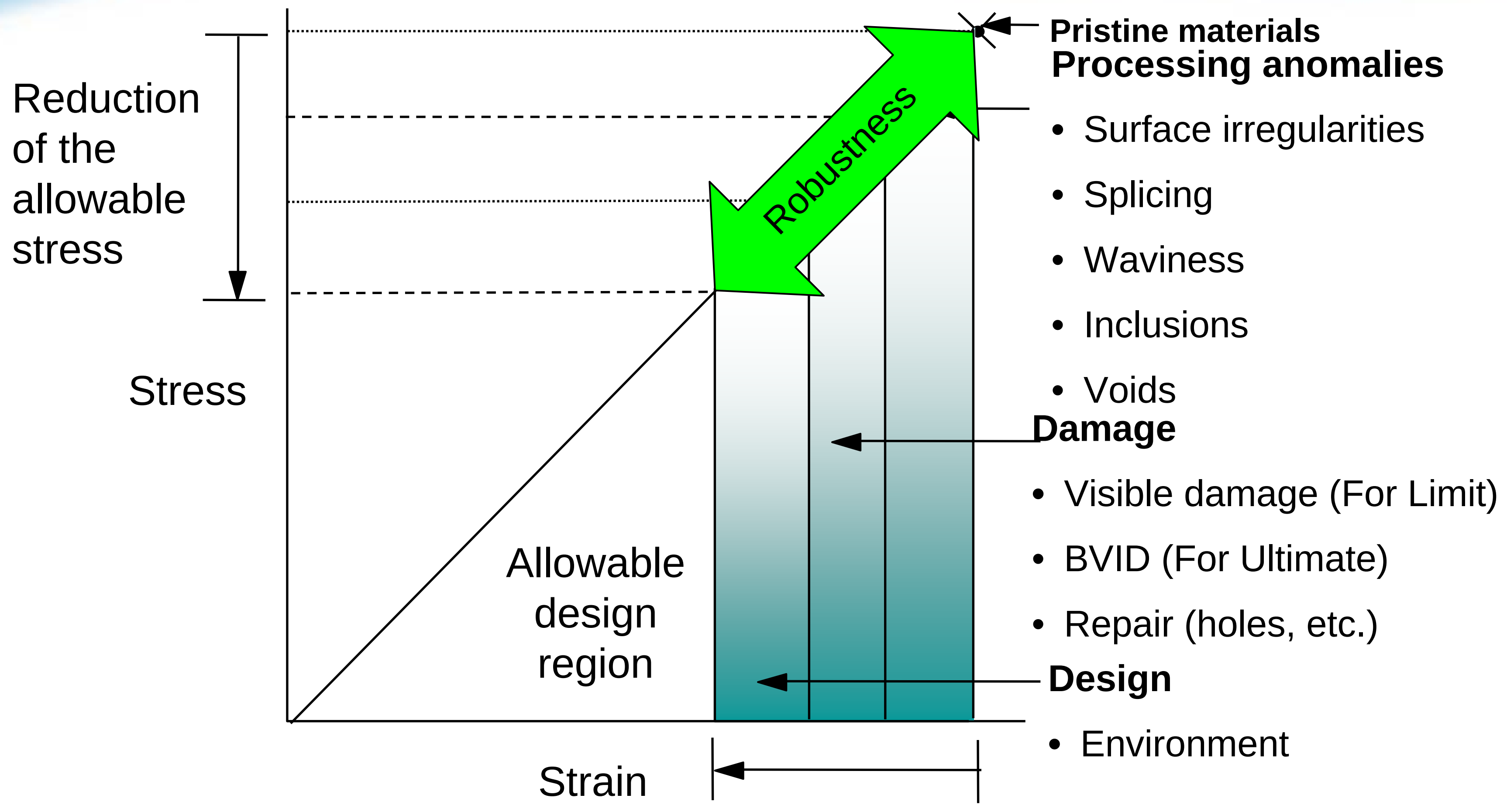
Aluminum panel; nominal strike punctures through a similar gage aluminum panel. Immediate structural repair required to dispatch the airplane. Operational schedule impacted

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**



Composite Design Criteria provide for structural robustness



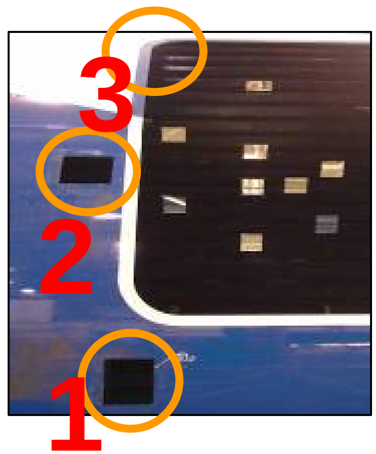
Structural Design Criteria support Maintainability

- **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.**

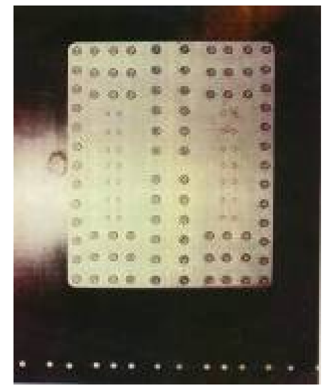
Repairable by Design

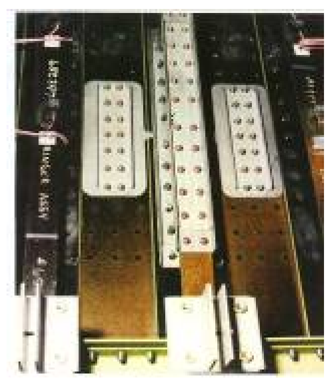
Flush Bolted

Flush Bonded



External Bolted

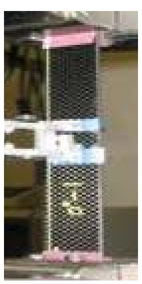




Repairs Validated by Structural Test

- 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

Material Specimens



Elements

Assemblies

Components

Airplanes

Static Test
Fatigue Test
Ground & Flight Tests

Increasing Levels of Complexity

Outline

- Boeing Design Criteria for Damage Tolerant CFRP Primary Structures and the relationship to Maintainability
- **CFRP Structures Service Experience**

Service History

- 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.

Boeing/NASA ACEE 737 Composite Horizontal Stabilizer Program

- **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**

BOEING

Horizontal Stabilizer Description

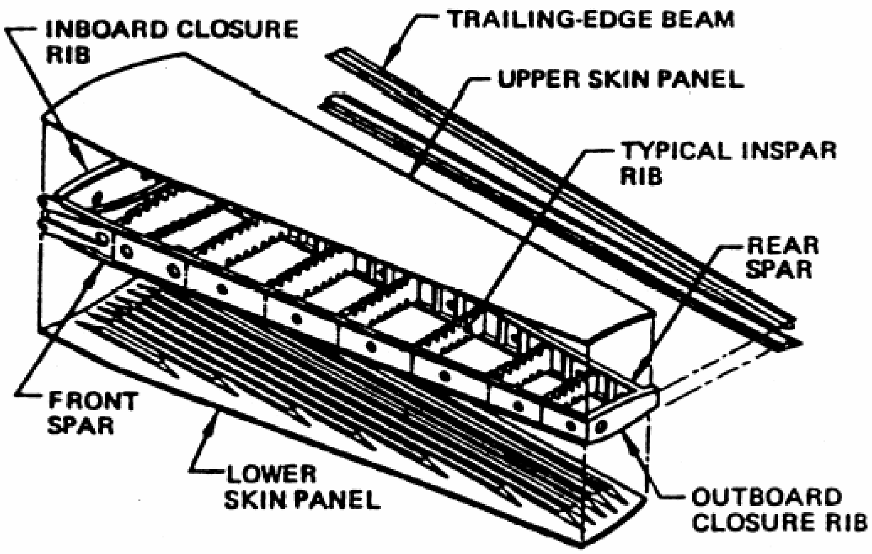
The structural arrangement was designed such that maximum commonality was achieved with the 737 metal configuration

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**

Shipset / Production Line #	Entry into Service	Airline	Status as of March 31, 2006 (except as noted)
1 / 1003	2 May 1984	A	In service (60024 hours, 44712 flights)
2 /1012	21 March 1984	A	In service (61372 hours, 46380 flights, as of May 31, 2006)
3 / 1025	11 May 1984	B	Damaged beyond repair 1990; partial teardown completed in 1991 (17300 hours, 19300 flights)
4 / 1036	17 July 1984	B & C	Stabilizers removed from service 2002 (approx. 39000 hours, 55000 flights); partial teardown of R/H unit at Boeing
5 / 1042	14 August 1984	B & D	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

737 Horizontal Stabilizer In-Service Experience

- **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**

777 In-Service Experience-CFRP Floor Beams

- No reported in-service repairs of composite floor beams*
- Fatigue cracking and corrosion in aluminum floor beams is fairly common and costly

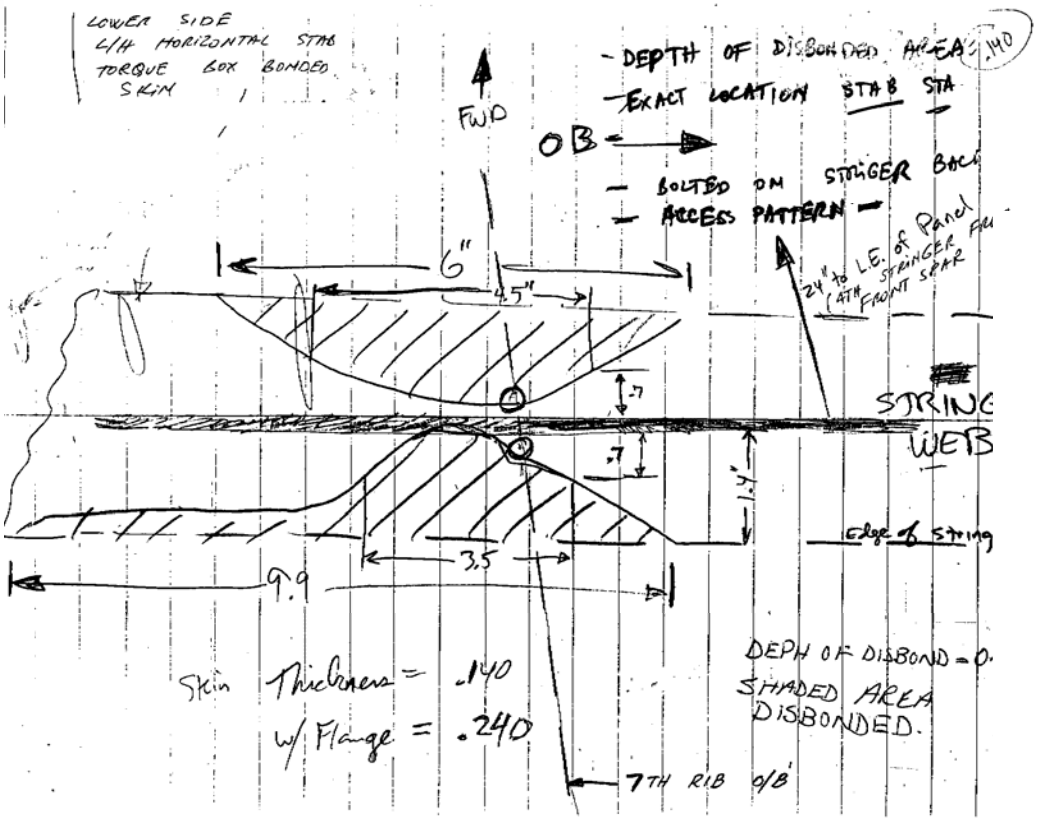
* 500 aircraft in service

777 In-Service Experience-CFRP Empennage

- 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

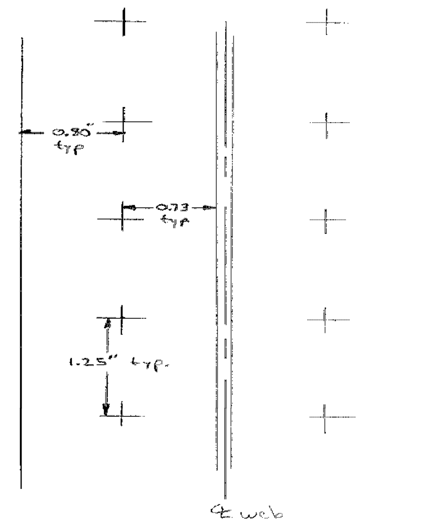
777 In-Service Experience-Details

Empennage Stringer Disbond - Engine Thrown Debris



AOG Damage Description

Straight-forward, effective repair

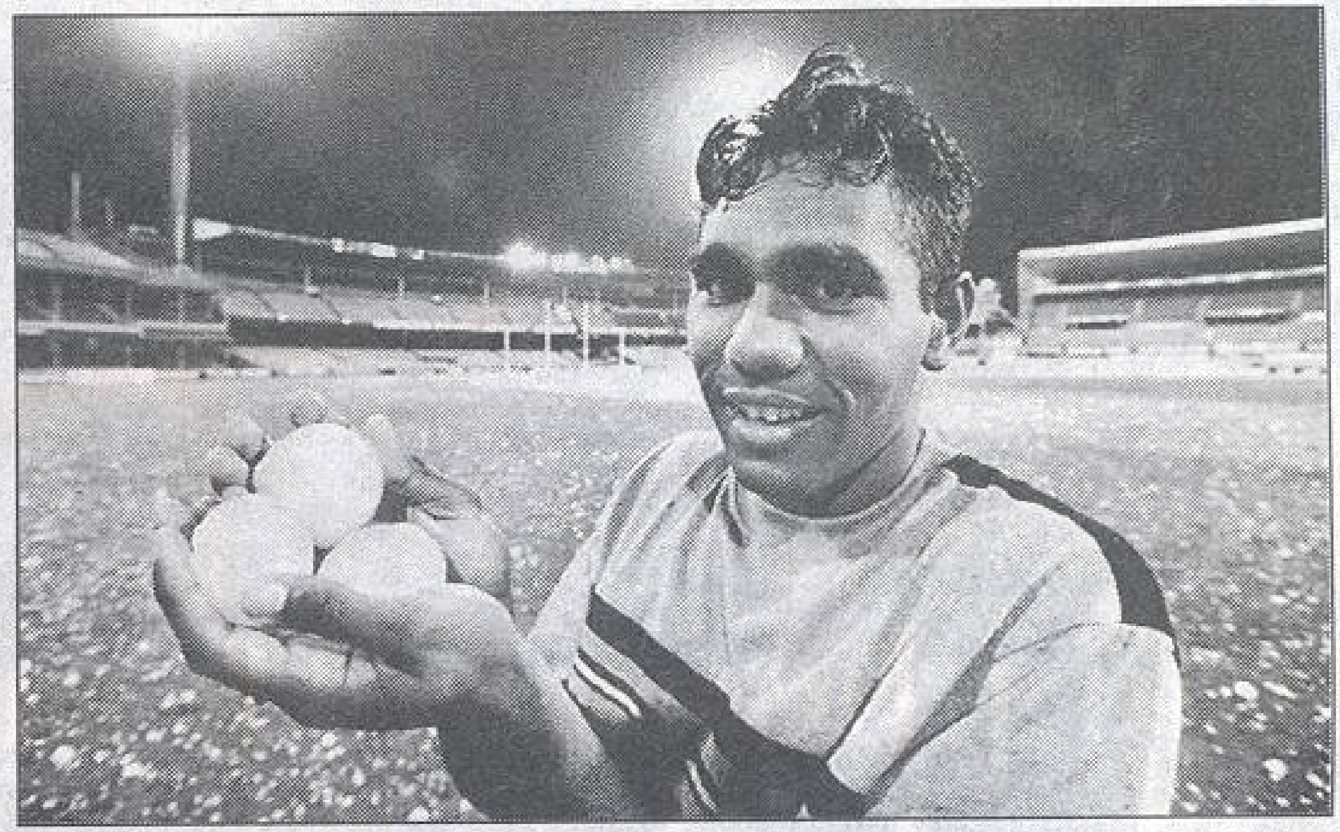


1/4" dia. fasteners

Extend fastener pattern 4" (approx 3 fast.) beyond any disbonded area

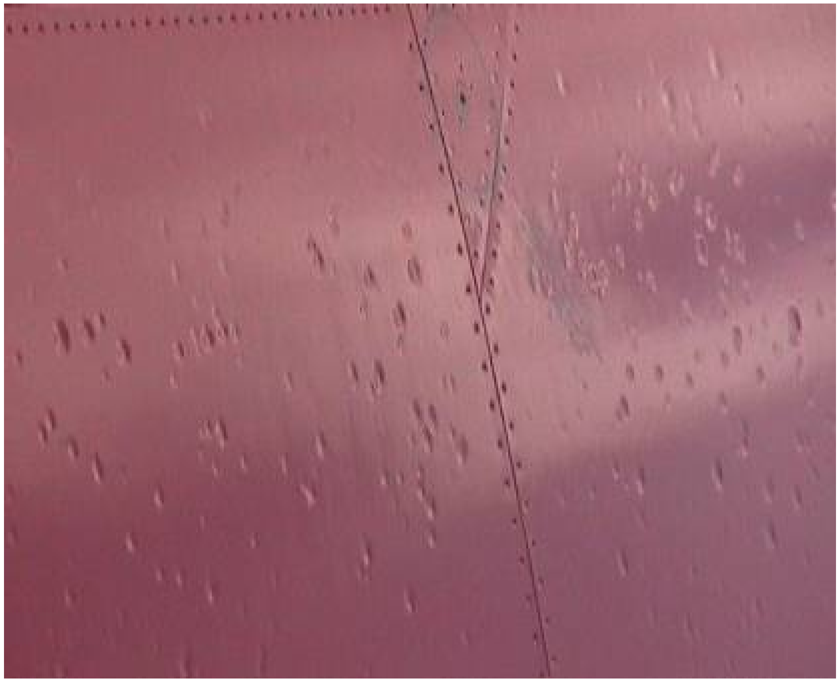
777 In-Service Experience
Sydney Hailstorm

Downed . . . a seagull, above, injured by hailstones at Bondi. Below, Fred Campbell shows why the Swans' SCG training was doomed.



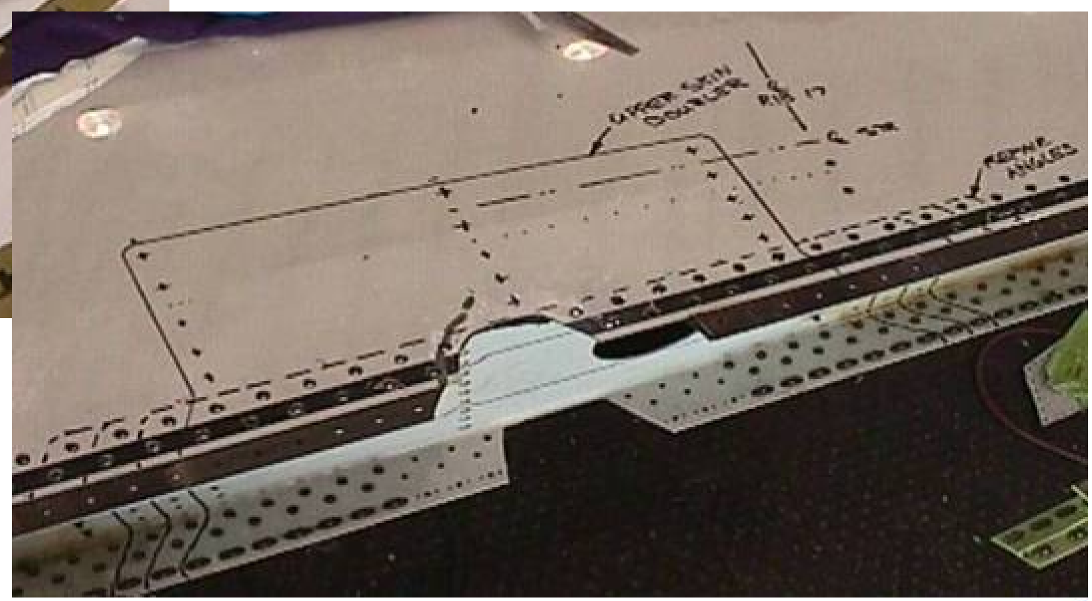
777 In-Service Experience
Sydney Hailstorm

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



777 In-Service Experience-Details

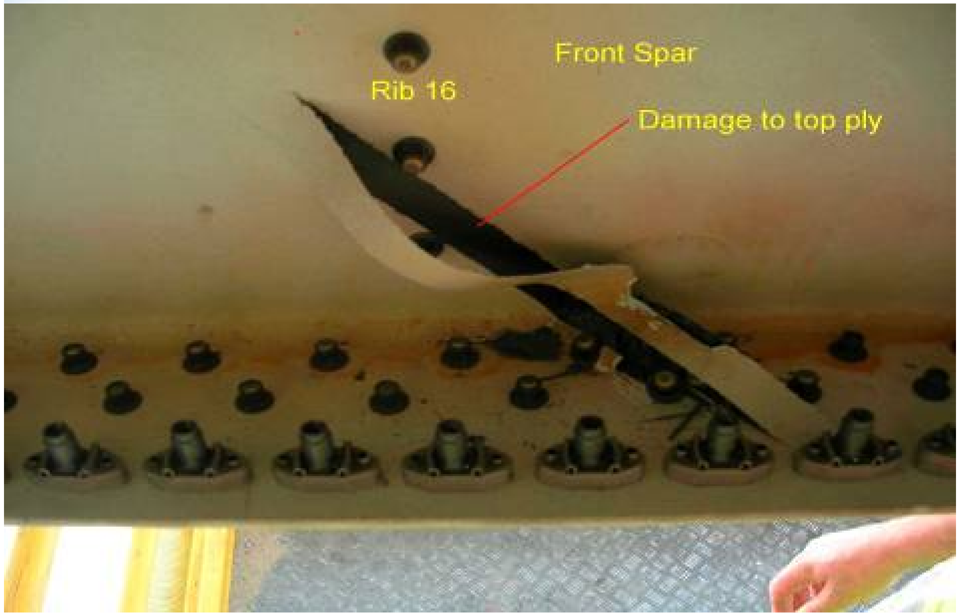
Skin/Spar Damage—Ground Handling Equipment Impact

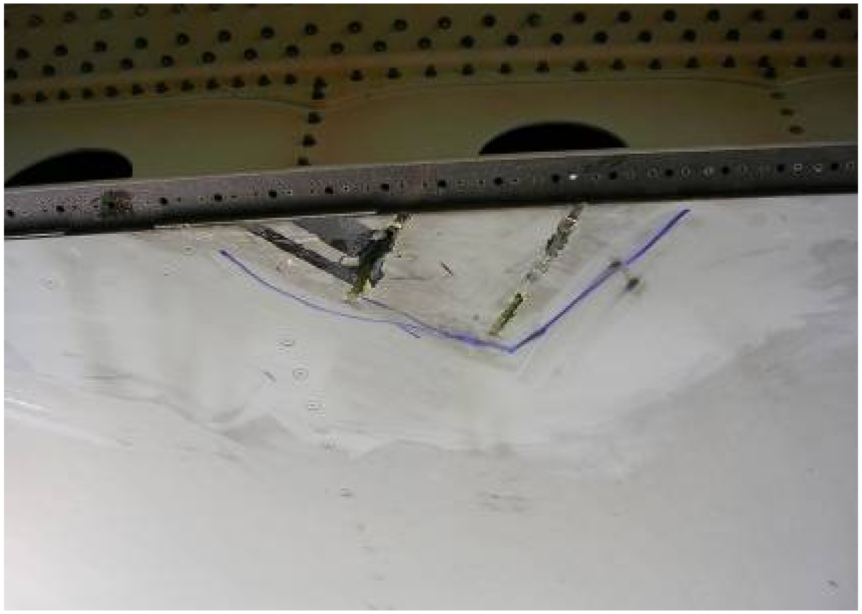


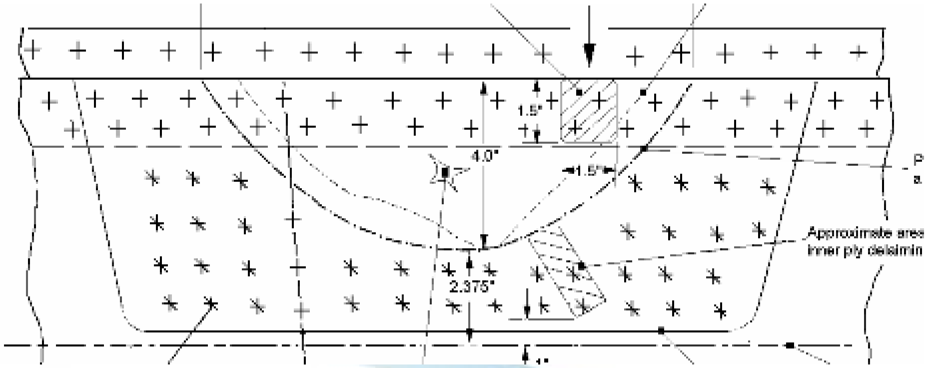
Conventional Bolted Repair

777 In-Service Experience-Details

- **Ground Equipment Impact**







Summary

- 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