Sandwich Disbond Certification Overview

Design Criteria and Substantiation for Face Sheet Disbonds

Supported by

Federal Aviation Administration

Wichita State University

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Technical University of Denmark (DTU), Copenhagen, Denmark

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Outline

- Certification Rules and Guidance
- Damage Threat Assessment
- Design Criteria & Inspection
- Substantiation with Analysis and Test
- Engineering Approaches
- Summary, Conclusions, and Discussion Topics

Rules and Regulations – Procedures & Product Types

General Procedures

- Part 21 – Certification Procedures for Products and Parts

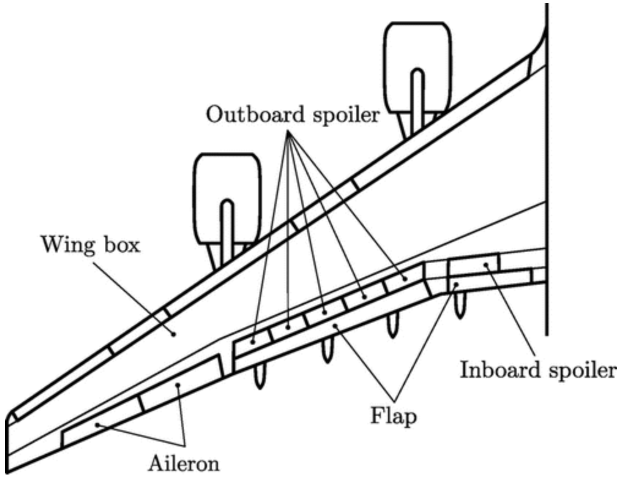
Focus is often on Part 25 aircraft, but rotorcraft and engine nacelles have unique aspects. There are also new applications that use a mix of types (e.g., eVTOL).

Aircraft Types (Airworthiness Standards)

- Part 23: Normal, Utility, Acrobatic, & Commuter Airplanes
- Part 25: Transport Airplanes
- Part 27: Normal Rotorcraft
- Part 29: Transport Rotorcraft

Other Product Types

- Part 33 – Aircraft Engines
- Part 35 – Propellers



Regulatory Guidance

FAA Advisory Circulars (AC)

- AC 20-107B "Composite Aircraft Structure" (harmonized with EASA AMC 20-29)

Main guidance for composites for all types of aircraft and rotorcraft

- AC 29-2C, "Certification of Transport Category Rotorcraft" (see Change 4, Subpart C, AC 29.573, which replaced MG8)

Some rotorcraft-specific aspects but mostly covered by AC 20-107B

FAA Policy Statements (PS)

- PS-AIR-100-14-130-001 "Bonded Repair Size Limits" (BRSL) (harmonized with EASA CM-S-005)

Requires limit load for a failed bonded repairs between constraints, including due to weak bonds.

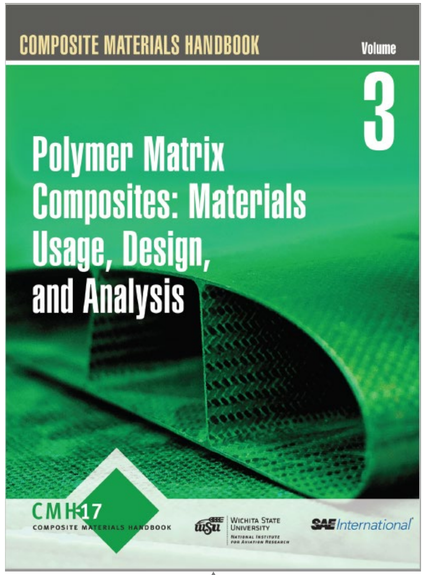
EASA Certification Memorandum (CM)

- CM-S-010 Issue 01 "Composite Materials - The Safe Design and Use of Monocoque Sandwich Structures in Principal Structural Element Applications"

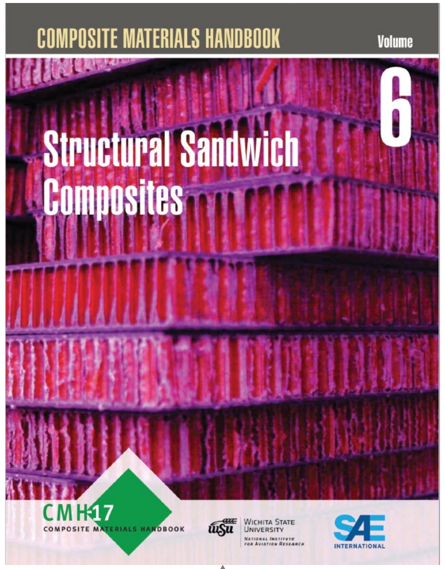
Specific guidance for monocoque sandwich structure, some aspects may also apply to multi-load path.

Other Guidance – CMH-17 Volume 3 Chapters

1. General Information
2. Introduction to Composite Structure Development
3. **Aircraft Structure Certification and Compliance**
4. **Building Block Approach For Composite Structures**
5. Materials and Processes
6. Quality Control of Production Materials and Processes
7. Design of Composites
8. Analysis of Laminates
9. Structural Stability Analyses
10. Design and Analysis of Bonded Joints
11. Design and Analysis of Bolted Joints
12. **Damage Resistance, Durability, and Damage Tolerance**
13. **Defects, Damage, and Inspection**
14. **Supportability, Maintenance, and Repair**
15. Thick-section Composites
16. Crashworthiness and Energy Management
17. Structural Safety Management
18. ...



Main Durability and Damage Tolerance Content (Rev H).



Major updates in-work with specific coverage for sandwich disbond (Rev A)

Categories of Damage and Load Requirements

Categories of Damage (per AC 20-107B)

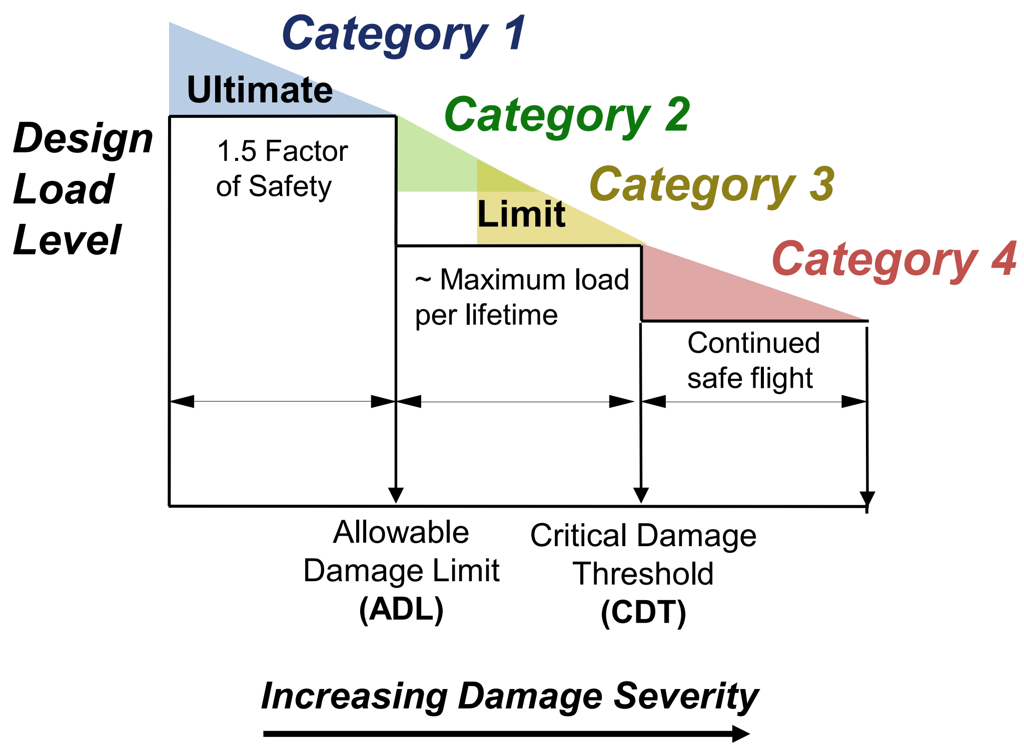
- Categories of Damage depend on damage or defect visibility and the ability to find it during inspection.
  - *Varies depending on configuration, material and inspection type*
- Other considerations (based on Category):
  - *Repeated loads (Cat 1, Cat 2, and limited Cat 3)*
  - *Stiffness and flutter (Cat 1, Cat 2, Cat 3-?, Cat 4 - CSFL)*
  - *Critical vs. typical environment*

Considerations for Sandwich Structure

FOCUS

- Bondlines – sandwich face sheet-to-core interface can be considered a bonded joint, disbonds occur due to damage or processing issues.
- Impact damage threats – relationship between impact variables and resulting damage visibility is complex.
- Economic issues – damage resistance often drives Cat 1 allowable damage limits (ADLs) for fixed and removable primary structure (e.g., for hail damage).

Load Requirements for Categories of Damage*



***Applies to Principal Structural Elements (PSEs) and Critical Structure (per AC 20-107B)**

Categories of Damage and Defects – Definitions

Category	Examples (not inclusive of all damage types)
Category 1: Allowable damage that may go undetected by scheduled or directed field inspection (or allowable mfg defects)	Barely visible impact damage (BVID), scratches, gouges, minor environmental damage, and allowable mfg. defects that retain ultimate load for life
Category 2: Damage detected by scheduled or directed field inspection @ specified intervals (repair scenario)	VID (ranging small to large), deep gouges, mfg. defects/mistakes, major *local* heat or environmental degradation that retain limit load until found
Category 3: Obvious damage detected within a few flights by operations focal (repair scenario)	Damage obvious to operations in a "walk-around" inspection or due to loss of form/fit/function that must retain limit load until found by operations
Category 4: Discrete source damage known by pilot to limit flight maneuvers (repair scenario)	Damage in flight from events that are obvious to pilot (rotor burst, bird-strike, lightning, exploding gear tires, severe in-flight hail)
Category 5: Severe damage created by anomalous ground or flight events (repair scenario)	Damage occurring due to rare service events or to an extent beyond that considered in design, which must be reported by operations for immediate action

Cat 1 and Cat 2 can include sandwich face sheet disbond (with fatigue + GAG pressure loading)*

Cat 3 is "obvious" damage that will be found in a few flights (limited fatigue)

Cat 4 - Cat 5 will typically trigger conditional inspections (no fatigue)

***Weak bonds between arrestment features may fall under Cat 2 depending on criteria and inspection.**

Structural Damage Capability (SDC) & Fail-Safety

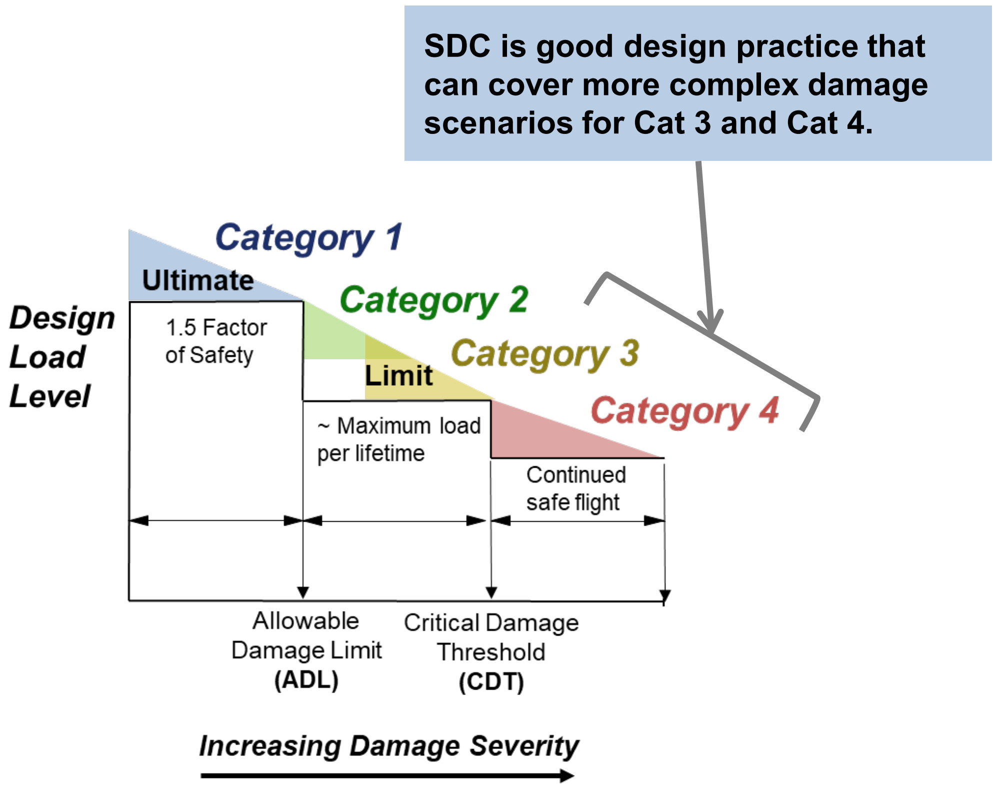
CMH-17 V3 – 12.3.2.5 Structural damage capability (SDC)

- OEM criteria that do not generate additional inspection.
- "...SDC criteria leads to structural configurations that in the event of a certain level of damage, the remaining intact structure is capable of carrying the applicable residual strength loads and can provide arrestment of damage growth before catastrophic failure..."
- "SDC is also used to: **1)** address the complexities and uncertainties of accidental impact damage (size vs. detectability, impactor variables, etc.), **2) ensure that <u>very rare local weak bonds will not cause catastrophic failure</u>**, and **3)** address possible interactions between damage threats."

Considerations for Sandwich Structure

- <u>Bondlines</u> – can use SDC to cover sandwich disbond between arrestment features even if not a regulatory requirement.
  - *e.g., **<u>co-cured sandwich structure</u>** (definition, wet face sheets?—<u>needs discussion!</u>).*
- <u>Impact and other threats</u> – can use SDC to cover complex damage from accidental impact, fluids, water ingression, heat damage, etc.

Structural Damage Capability (SDC) Criteria



Structural Damage Capability (SDC) for Robust Design

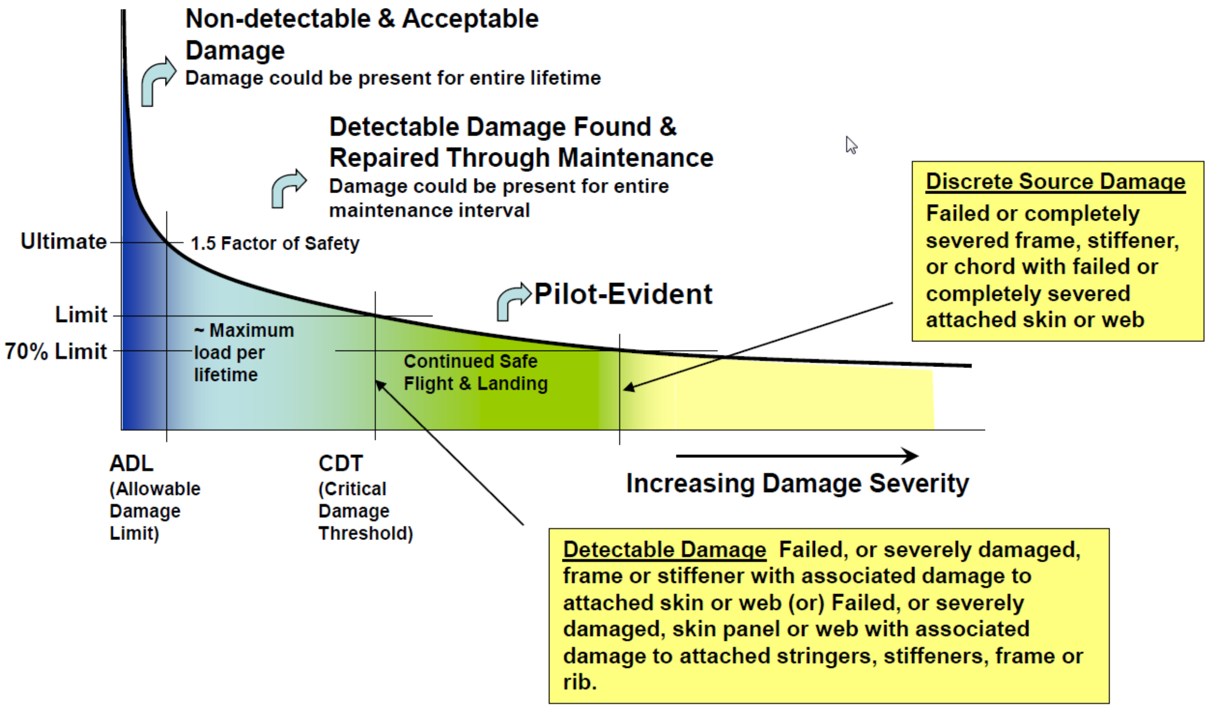
CMH-17 V3 – 12.3.2.6 Relationships among categories...

- "As shown in the figure, **the combination of damage design criteria used results in a <u>near "flat" residual strength curve for severe damage</u> such that a large increase in damage severity beyond the Critical Damage Threshold (CDT)** results in a small reduction in the residual strength capability."
- "In this example, this desired **shape of the residual strength curve is achieved by the application of a Limit Load requirement for "Detectable Damage".**

Sandwich Considerations

- **Criteria for <u>weak bonds</u>** between arrestment features and **<u>SDC</u> criteria** can both be used to drive **robust, fail-safe (<u>multi-load path</u>) sandwich structures**.
- <u>"Monocoque"</u> sandwich structures without design features to break up panels or arrest damage/disbond growth <u>need careful evaluation</u> (see EASA CM-S-010) to avoid "falling off a cliff" at large damage sizes.

SDC criteria will typically lead to designs with <u>multi-load path</u> structure (fail-safety)!



AC 20-107B – Bonding Guidance

27. Structural Bonding: A structural joint created by the process of adhesive bonding, comprising of one or more previously-cured composite or metal parts (referred to as adherends).

c. Structural Bonding. Bonded structures include multiple interfaces (e.g., composite-to-composite, composite-to-metal, or metal-to-metal), where at least one of the interfaces requires additional surface preparation prior to bonding.

29. **Weak Bond:** A bond line with mechanical properties lower than expected, but without any possibility to detect that by normal NDI procedures. Such situation is mainly due to a poor chemical bonding.

(3) 14 CFR § 23.573(a) sets forth requirements for substantiating the primary composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. Although this is a small airplane rule, the same performance standards are normally expected with transport and rotorcraft category aircraft (via special conditions and issue papers).

(a) For any bonded joint, § 23.573(a)(5) states in part: "*the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods—(i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or (ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or (iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.*"

Definitions for structural bonds discussing pre-cured parts and required surface prep.

Defines weak bonds that can't be found with production NDI.

Specifies limit load for disbonds between arrestment (design) features or must do proof testing or have NDI that can find weak bonds.

Note that proof testing is questionable for bonding and does not evaluate all load cases, fatigue loading, or durability.

AC 20-107B – Sandwich Guidance

9. Proof of Structure – Flutter and Other Aeroelastic Instabilities. The aeroelastic evaluations, which includes flutter, control reversal, divergence, and any undue loss of stability and control as a result of structural loading and resulting deformation, are required. Flutter and other aeroelastic instabilities must be avoided through design, quality control, maintenance, and systems interaction.

a. The evaluation of composite structure needs to account for the effects of repeated loading, environmental exposure, and service damage scenarios (e.g., large Category 2, 3 or 4 damage) on critical properties such as stiffness, mass, and damping. Some control surfaces exposed to large damage retain adequate residual strength margins, but the potential loss of stiffness or mass increase (e.g., sandwich panel disbond and/or water ingression) may adversely affect flutter and other aeroelastic characteristics. This is particularly important for control surfaces that are prone to accidental damage and environmental degradation. Other factors such as the weight or stiffness changes due to repair, manufacturing flaws, and multiple layers of paint need to be evaluated. There may also be issues associated with the proximity of high temperature heat sources near structural components (e.g., empennage structure in the path of jet engine exhaust streams or engine bleed air pneumatic system ducting). These effects may be determined by analysis supported by test evidence, or by tests at the coupon, element or subcomponent level.

The only sandwich-specific guidance in the AC addresses <u>stiffness and flutter</u> issues related to sandwich disbond (i.e., limit load residual strength also means being good for flutter).

AC 29-2C, Chg. 4, “Certification of Transport Category Rotorcraft”

(D) The use of composite secondary bonding in manufacturing or maintenance requires strict process and quality controls to achieve the reliability needed to use such technology in critical structures (see AC 21-26). Assuming good process and quality controls, service history has shown that additional damage tolerant design considerations are also needed to ensure the safety of structure with secondary bonds (i.e., random, but an unacceptable number of weak bonds discovered in service). Unless the ultimate strength of each critical bonded joint can be reliably substantiated in production by NDI techniques (or other equivalent, approved techniques), then the limit load capability should be ensured by any or a combination of the following:

(1) Consider isolated disbonds and weak bonds (represented by zero bond strength) in structural elements that use secondary bonding for primary load transfer. The associated disbond size should be up to the limitations provided by redundant design features (i.e., mechanical fasteners or a separate bonding detail). The structure containing such damage should be shown to carry limit load by tests, analyses, or some combination of both. For purposes of test or analysis demonstration, each disbond should be considered separately as a random occurrence (i.e., it is not necessary to demonstrate residual strength with all structural elements disbonded simultaneously).

(2) Each critical bonded joint on each production article should be proof-tested to the critical limit load.

(3) Critical bonded joints that have high static margins of safety (e.g., some rotor blades) may be accepted based on satisfactory service history of like or similar components.

AC 29-2C includes an additional means of compliance, aka “Ultimate Strength Approach”.

Rotorcraft-specific AC is generally consistent with AC 20-107B with limit load for disbonds between redundant design (arrestment) features (i.e., multi-load path).

However, co-cured sandwich structure is not considered bonded structure for the purpose of the AC.

Needs further discussion and standardization!

(11) Cocure. The process of curing several different materials in a single step. Examples include the curing of various compatible resin system pre-pregs, using the same cure cycle, to produce hybrid composite structure or the curing of compatible composite materials and structural adhesives, using the same cure cycle, to produce sandwich structure or skins with integrally molded fittings.

(50) Secondary Bonding. The joining together, by the process of adhesive bonding, of two or more already-cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself. The joining together of one already-cured composite part to an uncured composite part, through the curing of the resin of the uncured part, is also considered for the purposes of this advisory circular to be a secondary bonding operation. (See COCURE).

EASA CM-S-010 Issue 01 – Bonding Requirements*

Co-bonded structure	Components bonded together during cure of one, or more, of the components, but not all components, e.g. bonding to metallic or a pre-cured component.
Co-cured Structure	Structure obtained by a single cure of uncured components
Monocoque	Thin shells which rely entirely upon the skins for the capacity to resist loads (Megson). Note: For the purposes of this CM a sandwich structure forming a shell comprising 2 skins and a core (e.g. fuselage or tail boom) is considered to be the 'thin shell', and thus described as a monocoque.

Specific to "monocoque" sandwich structure in PSE applications but also provides general guidance and approaches for multi-load path sandwich structure.

For example, to be confident regarding likely damage modes resulting from impact threats, it is considered to be appropriate to test throughout the threat impact energy range up to readily detectable damage using a range of appropriate impactor geometries, e.g. including sharp impactors and blunt impactors up to diameters agreed with EASA, e.g. for CS25, a range of impactors up to 4 inches diameter have been accepted, based upon typical protection device geometries carried by ground vehicles. Furthermore, it may be appropriate to consider a range of impactor stiffnesses, e.g. for hail, or ground vehicle rubber bumpers, such that all competing damage modes can be identified. Representative boundary conditions should be used in the substantiation test campaigns.

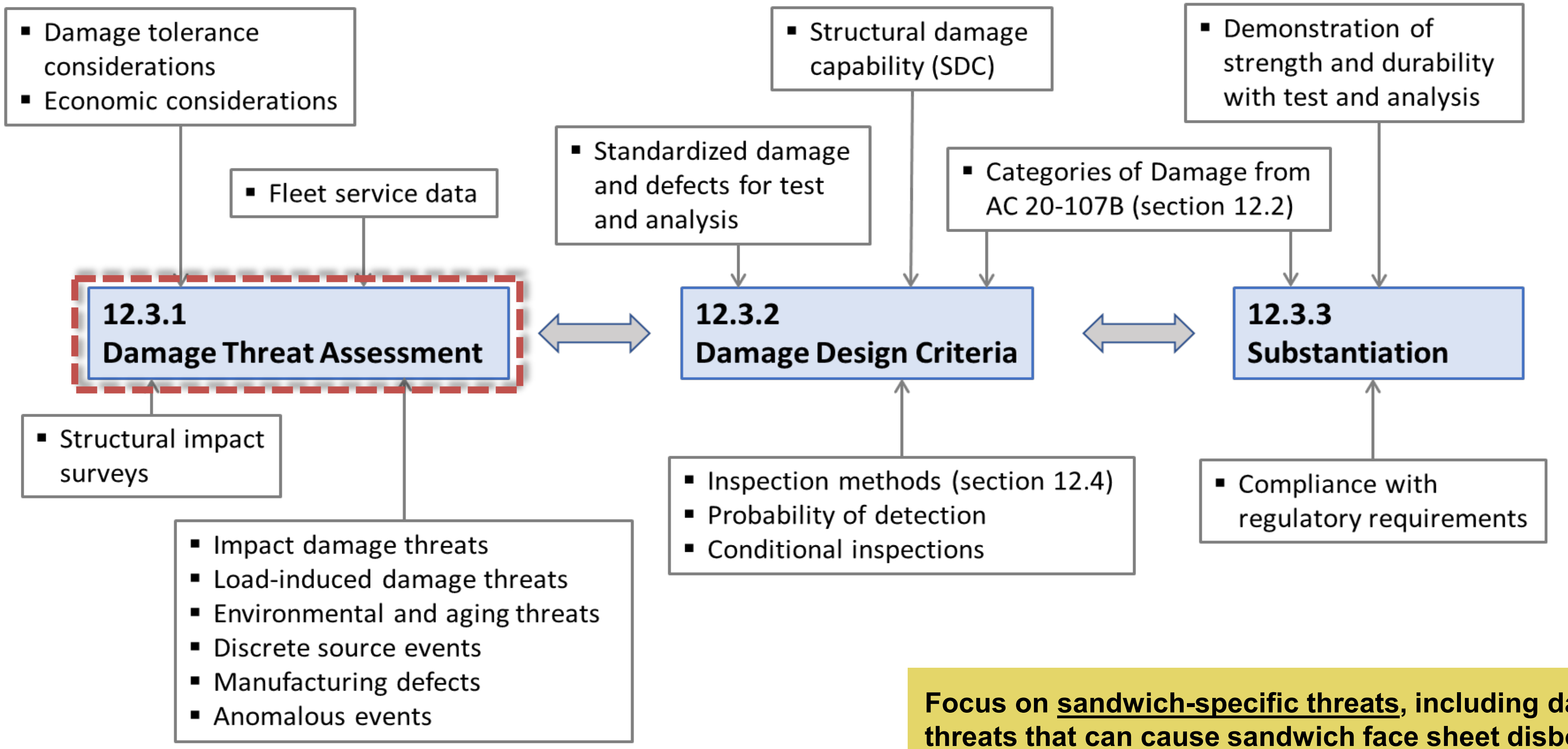
- **Guidance on impact energies and impactor types.**
- **Makes link between GSE and 4" impactors**

Note: In some cases, it may be possible to conservatively bound many damage types, and thus reduce the detailed substantiation workload, by demonstrating a larger structural damage capability. However, this will require demonstration that all likely damage modes have been bounded by the structural damage capability assumption, e.g. a large penetration could be used to address all likely damage modes within the bounds of the penetration.

- **Covers the use of SDC to conservatively bound many damage types**

**See back up slides for additional excerpts from EASA CM-S-010.*

Damage Threat Assessment*



Focus on <u>sandwich-specific threats</u>, including damage threats that can cause sandwich face sheet disbond.

**Ref. CMH-17 V3, 12.3 Design Development and Substantiation*

Damage Threat Assessment (DTA) for Sandwich Structure

CMH-17 V3 – 12.3.1 Damage Threat Assessment

- *"...manufacturing and operational threats can be classified according to four broad areas as identified in AC 20-107B: **manufacturing threats, fatigue damage (FD), environmental deterioration (ED), and accidental damage (AD)**."*

General Considerations

- DTA is used to set impactor sizes and shapes.
- DTA can be used to set energy level cutoffs.
  - *Often used for Cat 1, may not be relevant for many sandwich structures since cutoff energies may produce through-damage.*
  - *For Cat 2, normally increase energy until visible with larger diameter impactors (2-4").*
- Zoning approach is typically used for each component based on specific threats identified.
  - *Can use probability approach to set energy levels by location.*
- Structural impact surveys used to establish link between damage threat, visibility, damage state.

Key sandwich damage threats*:

- Accidental impact (e.g., tool drop, FOD)
- Ground service equipment (GSE), larger impactor diameters for Cat 2/VID
- Hail, in-flight and ground
- Manufacturing defects including weak bonds (if considered a bond!)
- Aging and durability threats
- Moisture ingression (design details)
- Overheating (nacelles, rotorcraft exhaust zones)
- Step loads (no step zones)
- Lightning strike
- Tire rupture (flaps)
- Repair (sandwich panels, main rotor blades), consider BRSL Policy Statement

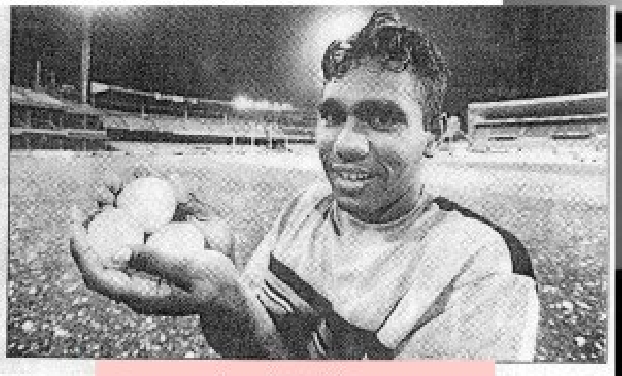
**Also identify which threats trigger Conditional Inspection (found and repaired before further flight, affects design criteria).*

Damage Threats from Ground Service Equipment (GSE)

- Sandwich structure is particularly exposed to GSE (control surfaces, nacelles, winglets.
  - *Typical GSE damage threats include a wide range of impactor geometries, velocities, and energies.*
  - *Diameters of 2-4” have been used for VID (ref. EASA CM-S-010).*
- Helicopters have unique exposure to GSEs (as do business jets, small aircraft, and eVTOL applications).
  - *Large vehicles have limited access near structure.*
  - *High Energy Wide Area Blunt Impact (HEWABI) may be less relevant (maybe Low Energy “LEWABI” instead?)*

Damage Threats from Hail Strike

- Consider both in-flight hail and ground hail.
- Often triggers conditional inspection.
- If damage is evident, need NDI to find extent of damage (can be tap test, e.g., thin face sheets).
- Ground hail threats should also consider economics in terms of damage resistance and allowable damage limits (ADLs) Consider types of structure:
  - *Fixed primary, fixed secondary*
  - *Removable primary, removable secondary*
- CMH-17 V3 – Content
  - *12.3.2 Damage design criteria*
  - *12.5.2.5 Ground hail*



Example of Hail Damage from 1999 Sydney Storm

Dents on Boeing 777 Aft Flap (thin skin metal bonded sandwich)

Dents and Punctures on Boeing 757 Inboard Aft Flap (thin skin of composite sandwich)

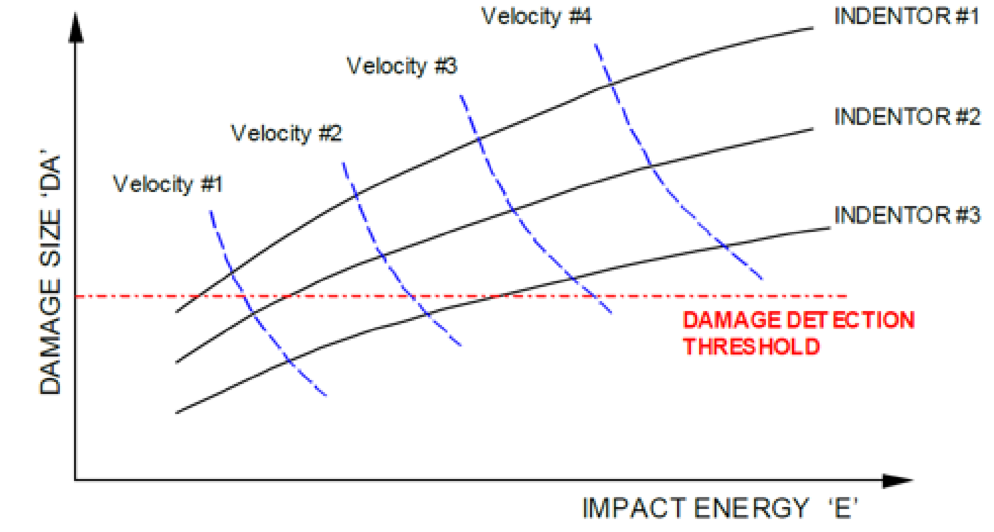
Impact Surveys – Sensitivity to Impact Variables

CMH-17 V3 – 12.5.1.8 Sandwich structure*

- CMH-17 section discusses unique aspects of sandwich impact.
  - ***Springback** – strongly affects visibility*
  - *Face sheet thickness effects*
  - *Core density and thickness effects*
  - *Sensitivity to impactor diameters and shapes*
  - *Interaction of damage modes, e.g., core damage leads to face sheet instability.*
  - *Panel size and boundary conditions*
  - *Panel curvature*
- The figure shows an example of how the results of a sandwich panel impact study can be used to understand relationship of impact variables to damage sizes and detectability.

**Ref. CMH-17 V3, 12.5 Damage Resistance*

Impact Survey Showing Sensitivity of Sandwich to Impact Variables

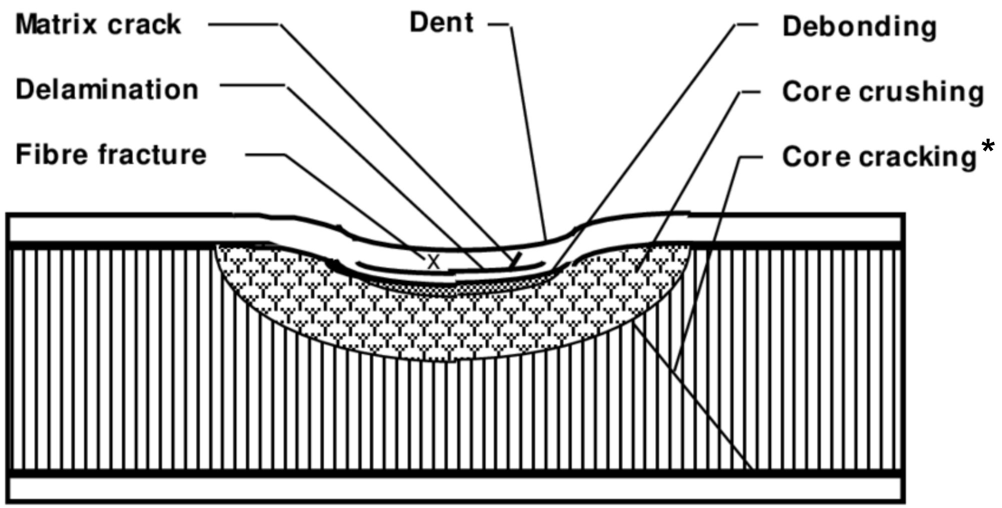


The relationship between impact variables and resulting damage visibility can be more complex for sandwich structures than for solid laminates.

Impact Surveys – Damage and Failure Modes

Sandwich Damage Modes for Impacts

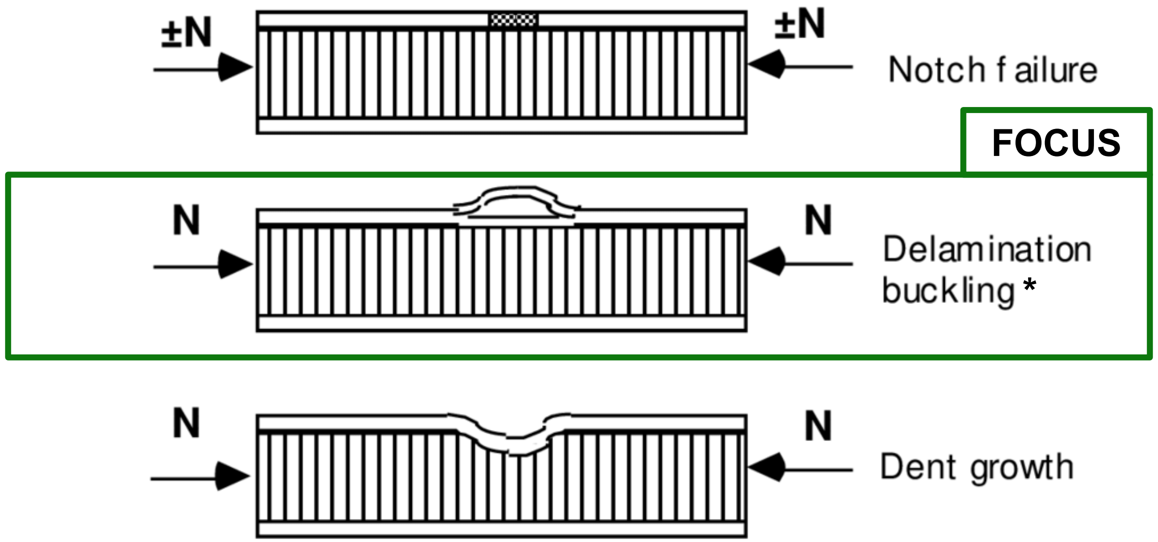
- Impact damage often results in a complex combination of damage modes.
- Important to understand visibility of each damage mode.
  - *Consider both visual inspection and NDI.*
  - *Consider face sheet springback!*
  - *Some core damage types may be difficult to find.*



May also occur as "core shear" (vertical shear plane)

Sandwich Failure Modes from Impact Damage

- Three example failure modes (there are many more).
- Sandwich disbond is associated with face-sheet-to-core interface failure.
  - *Can be a delamination in the face sheet and/or a complete face sheet disbond.*



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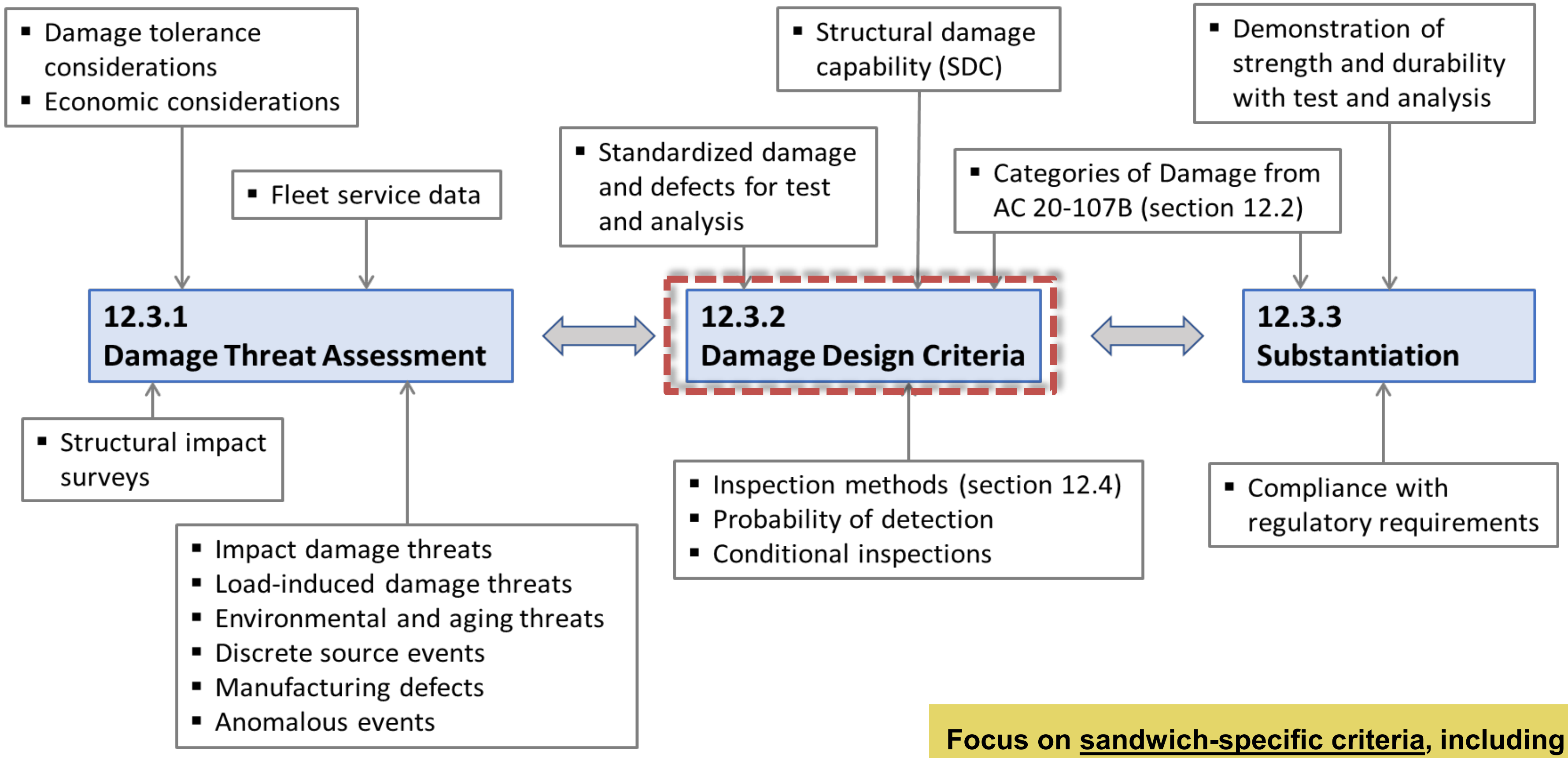
Design Criteria & Inspection*



Focus on <u>sandwich-specific criteria</u>, including criteria for sandwich face sheet disbond.

**Ref. CMH-17 V3, 12.3 Design Development and Substantiation*

Design Criteria for Sandwich Disbond – Size Criteria

Disbond Size Criteria for Accidental Damage

- Selected disbond sizes often cover a range of impact damage threats and resulting damage states based on impact surveys.
  - *May also cover other damage threats (e.g., heat damage, water ingress).*
- Cat 1 vs. Cat 2 based on visibility and ADLs.
  - *Cat 2 if can be found with in-service inspection, otherwise Cat 1.*
  - *Larger damage sizes may be used for Cat 1 to increase ADLs for economic reasons (e.g., hail damage).*
- Disbond no-growth criterion typically used for both Static and Fatigue.

- **Simplified disbond size criteria are often used to cover range of threats.**
- **Typical ~2-6" diameter disbond may be appropriate for Cat 1 or Cat 2 impact damage depending on inspection type and ADLs.**

Disbonds Size Criteria for Weak Bonds & Process Failures

- For weak bonds (undetected in production) – disbond size criteria is set between arrestment features (bonded joint criteria).
- Cat 1 vs. Cat 2 based on what can be found with in-service inspection?
  - *See later slide regarding inspection*
- Alternatively, SDC criteria can be used to drive robust, multi-load path design (and cover Cat 3 and Cat 4).

- **Criteria based on regulatory guidance for bonded joints.**
- **Arrestment features are key (see later slide).**

Note that the weak bond criterion might cover the other Cat 2 disbonds (if so, what is role of ~4" disbond if good between arrestment?)

Design Criteria for Sandwich Disbond – In-Service Inspection

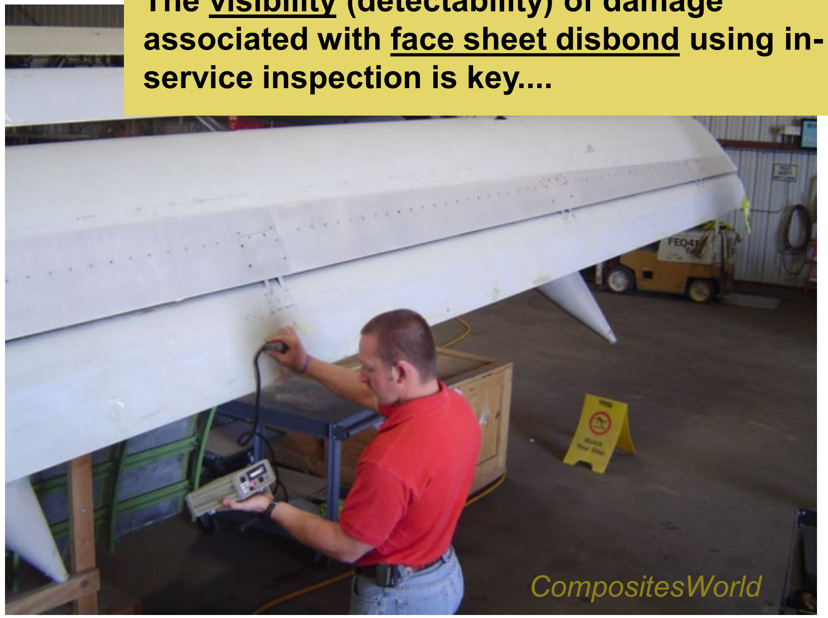
How In-Service Inspection Relates to Disbond Criteria

- Treating sandwich disbonds as Cat 2 damage requires that they can be reliably found during in-service inspection.
  - *If the disbond is caused by impact or other accidental damage, the damage may be visible with GVI or DVI, which in turn would trigger an NDI inspection of the damage area to determine the disbond size.*
- If the accidental damage cannot reliably be found with planned in-service inspection, it must be covered by Cat 1 (or must be found Unplanned Inspection).

How to Address Weak Bonds and Process Failures

- Will weak bonds between arrestment features eventually become visible during in-service inspection? If so, then → Cat 2.
  - *Will pressure or out-of-plane loading make the disbond visible with GVI or DVI?*
  - *Or will disbonds only become detectable with NDI (tap test or A-scan)?*
- If weak bonds cannot be found, must they be assumed to exist between arrestment features and treated as Cat 1? Or?
- Or use SDC criteria in some cases for disbond between arrestment (Limit Load, no fatigue, no associated inspection)?

The visibility (detectability) of damage associated with face sheet disbond using in-service inspection is key....



Types of In-Service Inspection

- GVI - General Visual Inspection
- DVI - Detailed Visual Inspection
- NDI - Non-Destructive Inspection (includes “tap test”)
- Unplanned Inspection – triggered by an event that is obvious to flight or ground crew (hail, tire, bird, etc.)

Design Criteria for Sandwich Disbond – Arrestment

Design Features for Arrestment

- Core ramps
- Frames
- Ribs
- Bolted Joints

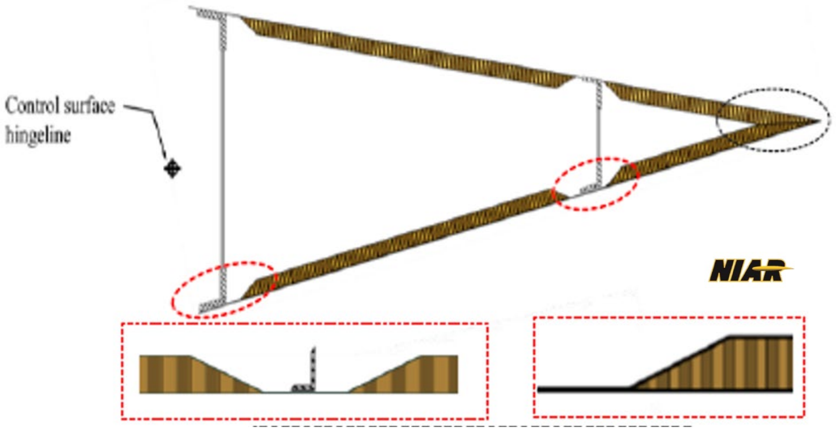
Geometric Features for Arrestment

- Corners, etc.
- Curvature

Other Forms of Arrestment

- Load changes
- Pad-ups, strain reduction

Whatever form of arrestment is used, it must be demonstrated by test and analysis for static and fatigue loading (if Cat 1 or Cat 2).



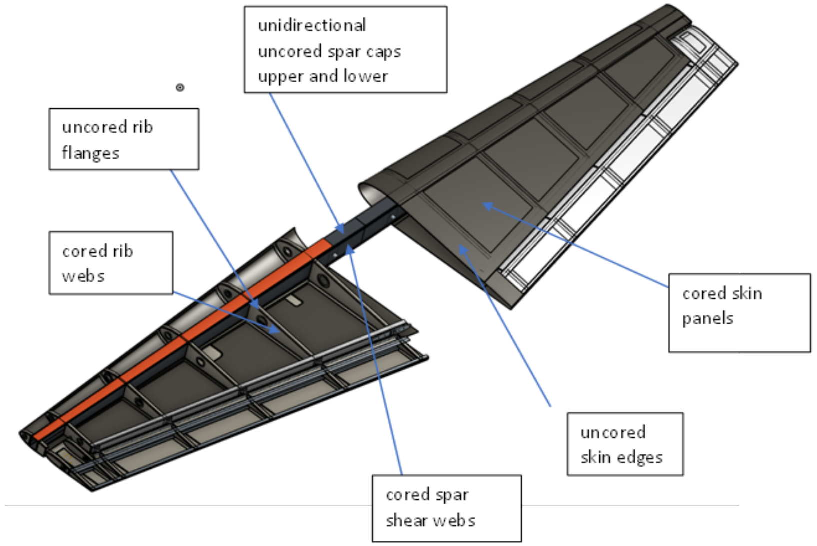


Fig.1.b: EC135 Sub floor group structure

Design Criteria for Sandwich Disbond – Face Sheet Buckling

No Face Sheet Buckling for Static Loads and/or Fatigue Loads

- Can be used to avoid disbond growth for static mechanical loading for non-pressure cases.
  - *No static buckling at Ultimate Load (Cat 1) or Limit Load (Cat 2).*
  - *Can also use Ultimate Load for Cat 2 (conservative).*
- Can be used to avoid disbond growth for fatigue mechanical loading.
  - *No fatigue buckling at operating loads.*
  - *Compare spectrum to constant amplitude no-growth thresholds.*

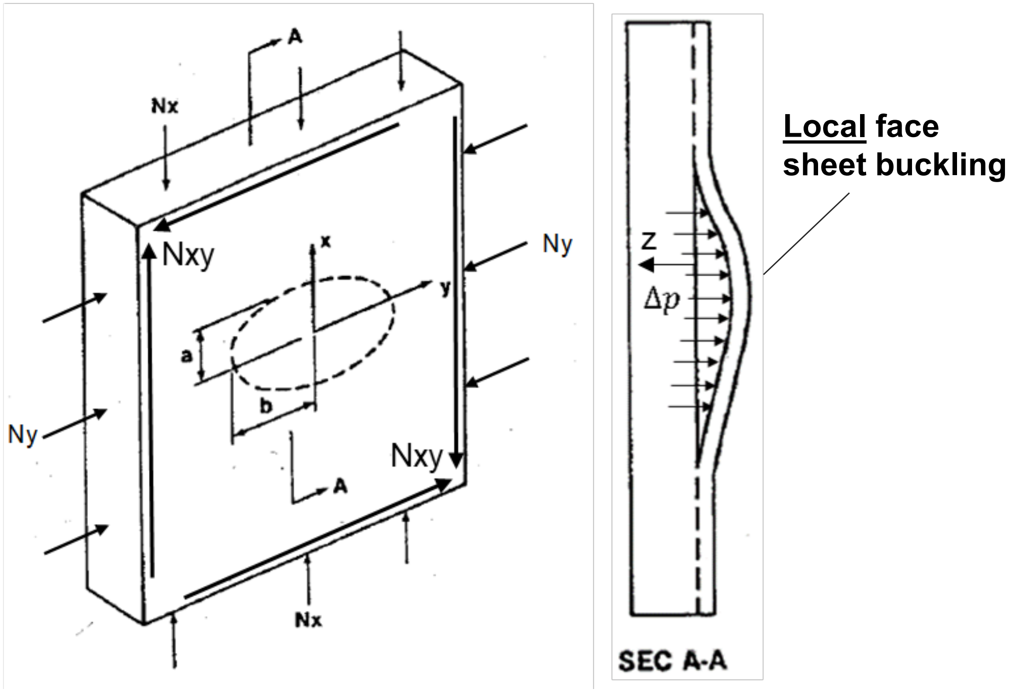
GAG Pressure Cycling Considerations

- Pressure causes out-of-plane displacement (similar to buckling)
- Need to consider combined mechanical + pressure with respect to buckling of face sheet (?)

Face Sheet Thickness Considerations

- “No Buckling” criteria can be overly conservative for larger disbonds of thin face sheets since not enough energy to “drive” disbond growth.

Generalized In-Plane Loads + **Internal Pressure**



Important to understand the relationship of buckling and disbond growth as a function of face sheet thickness.

Other Design Criteria for Sandwich Disbond

Stiffness Loss and Flutter

- Any structure requiring limit load residual strength or higher must also retain adequate stiffness to maintain aero-elastic stability to avoid flutter.
- Flutter is also considered in Cat 4 with respect to CSF&L (per AC25-571-1D)

Secondary Structure

- Parts departing airplane
- Economic considerations

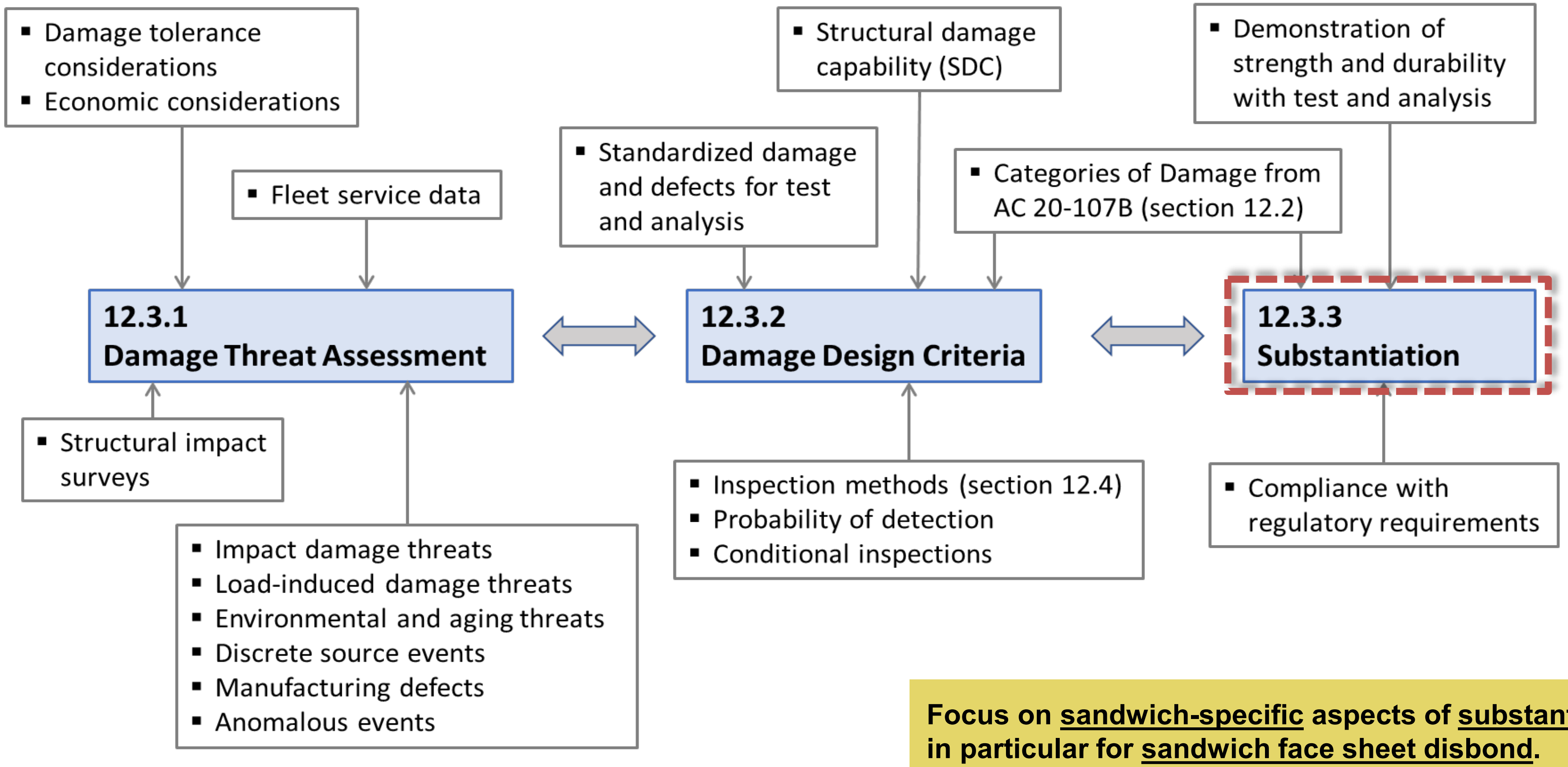
Engines

- Overheating
- Corrosion, erosion
- Fluids

Other Sandwich Design Issues

- Carefully design sandwich structures and associated design details.
- Evaluate design details for potential water ingress.
- Establish design guidelines for minimum core densities, minimum face sheet thicknesses, etc.

Substantiation*



Focus on sandwich-specific aspects of substantiation, in particular for sandwich face sheet disbond.

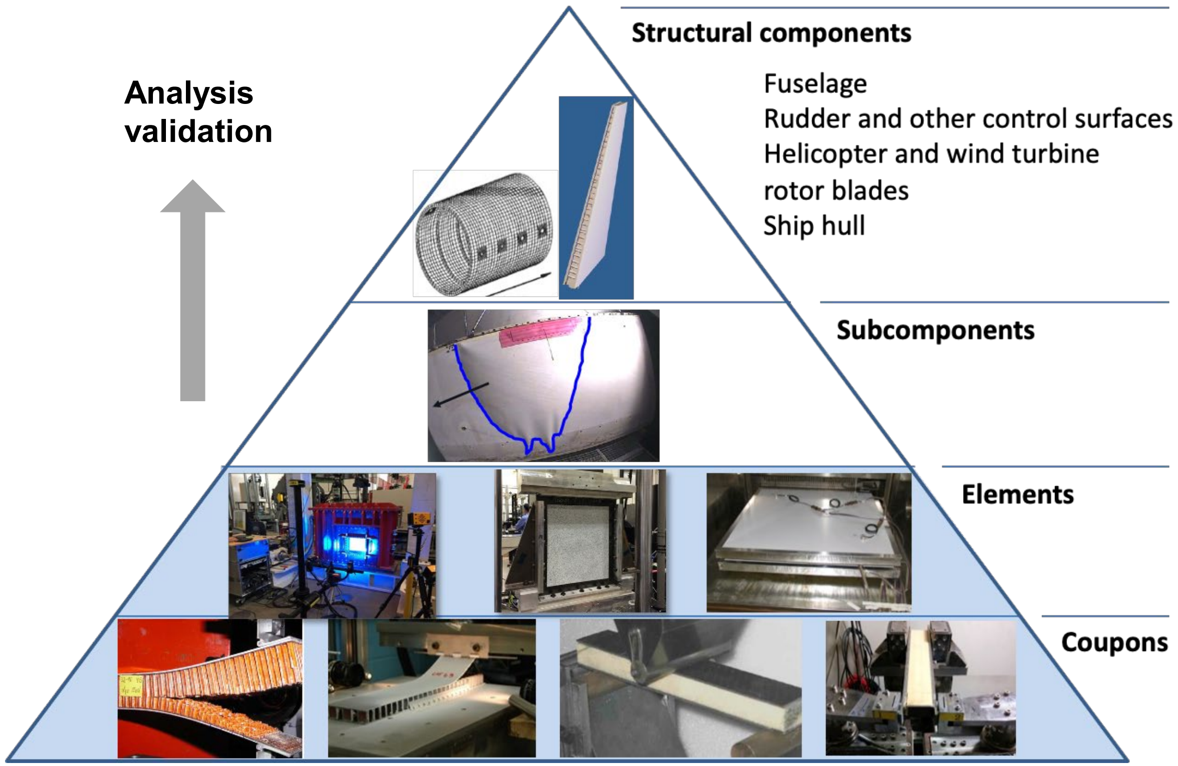
**Ref. CMH-17 V3, 12.3 Design Development and Substantiation*

Substantiation Building Block – Analysis Supported by Test

"Certification by Analysis Supported by Test"

- This is the most common approach but there are many ways to do it.
  - *Traditional building block vs. "top down, bottom-up" vs. hourglass, etc.*
- Lower-level data is often used with simplifying assumptions to evaluate designs during trade studies.
- Higher-level testing validates analysis which is then used to write margins as part of substantiation.
- Full scale component testing is often used mainly to verify load paths and strain levels.

Test-Analysis Building Block for Sandwich Disbond



Courtesy of R. Krueger

Engineering Approaches for Substantiation

See BACK UP slides for additional discussion.

Engineering Problems

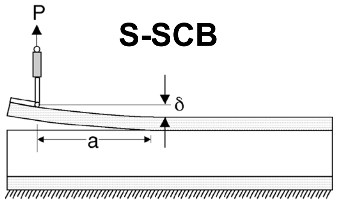
- Engineering problems can have many solutions.
- Engineering problems can be complex, but their solutions don't have to be.
- The best solution for an application represents an appropriate <u>balance between the level of complexity and the required accuracy</u>.

Engineering Approach

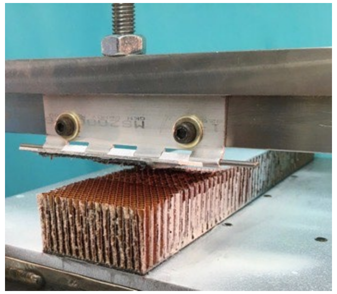
- An engineering approach uses pertinent experience and good engineering judgement to produce <u>practical solutions that meet all design requirements in a cost-effective manner</u>.
  - *Engineering approaches for <u>analysis are reliable and repeatable</u>.*
- An engineering approach generally considers:
  - *The need to reliably meet all safety requirements while considering the performance objectives of the application (not be overly conservative).*
  - *The objectives of all members of the Integrated Product Team (IPT).*

Engineering Approach for Sandwich Disbond Analysis

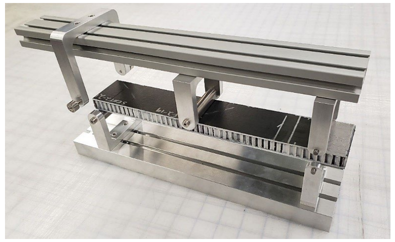
S-SCB



ASTM WK56166



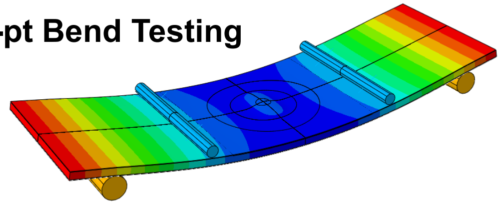
S-MMB

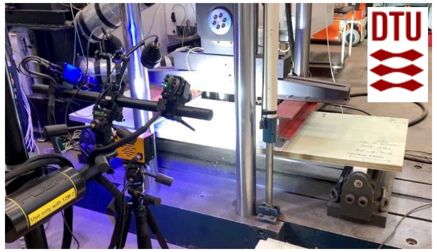


Courtesy of D. Adams (U of Utah)

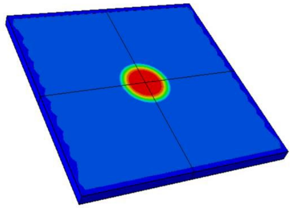
Coupon testing for static and fatigue Gs

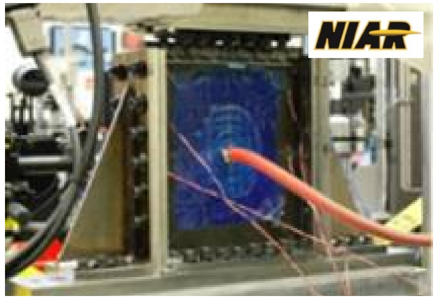
4-pt Bend Testing



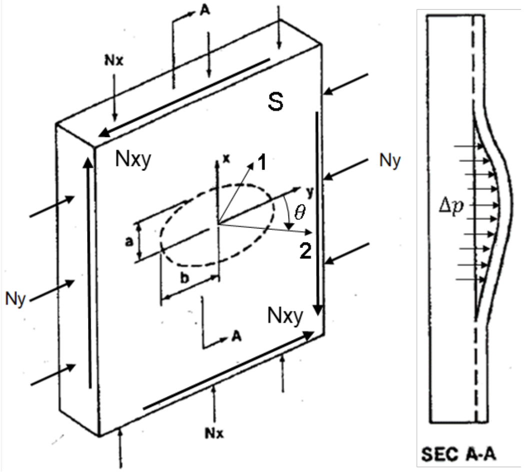


Panel Testing





ESDA Approach



Detailed FEA

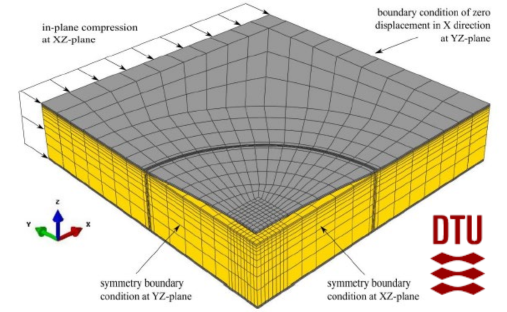
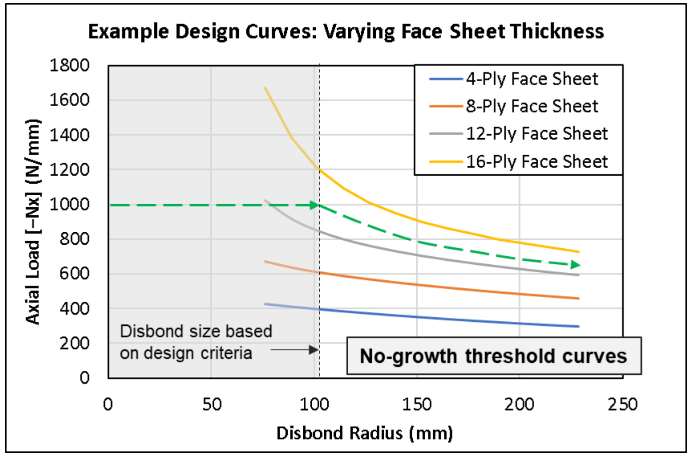


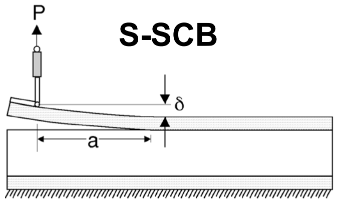
Figure 33: Global model of the disbonded sandwich used for the static parametric study.

<u>End result</u> = repeatable, reliable analysis output (i.e., design curves) validated by test data.

Design Curves

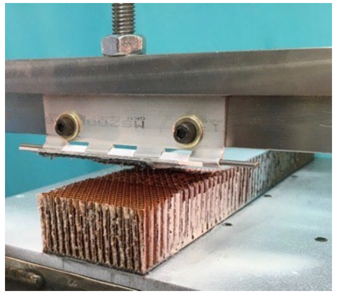


- **<u>Engineering approach</u> incorporates simplifying (conservative) assumptions and other constraints.**
- **Used for <u>design studies and sizing</u> to understand when sandwich disbond becomes critical (goal is to avoid).**



S-SCB

ASTM WK56166



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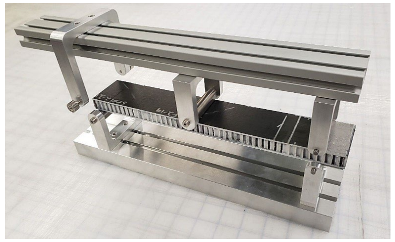
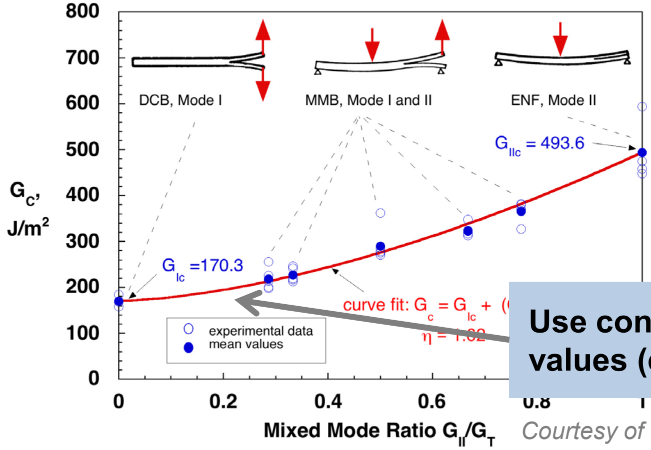


Coupon testing for static and fatigue Gs

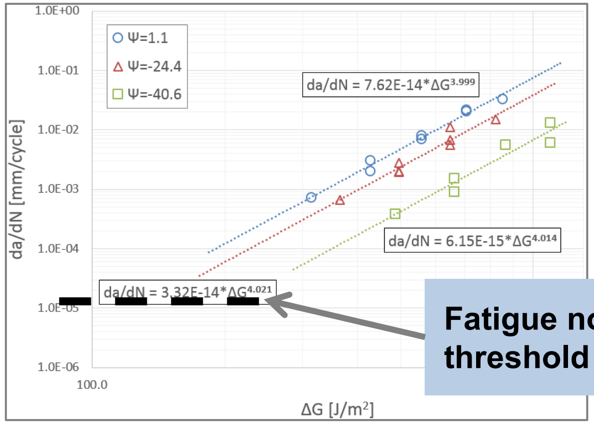
<u>Static</u> Gc (Mixed-Mode)



Use conservative values (e.g., Mode I)

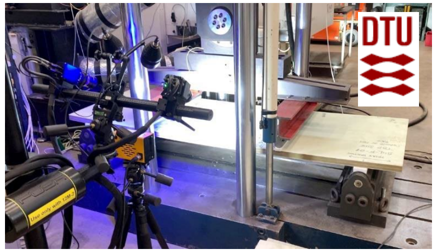
Courtesy of R. Krueger

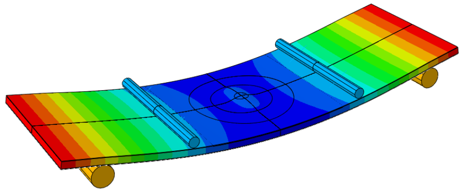
<u>Fatigue</u> G (da/dN)



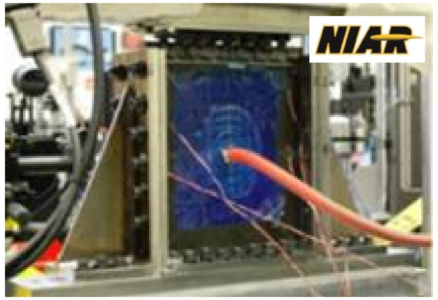
Fatigue no-growth threshold is needed

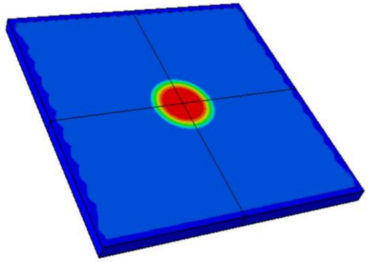
4-pt Bend Testing





Panel Testing



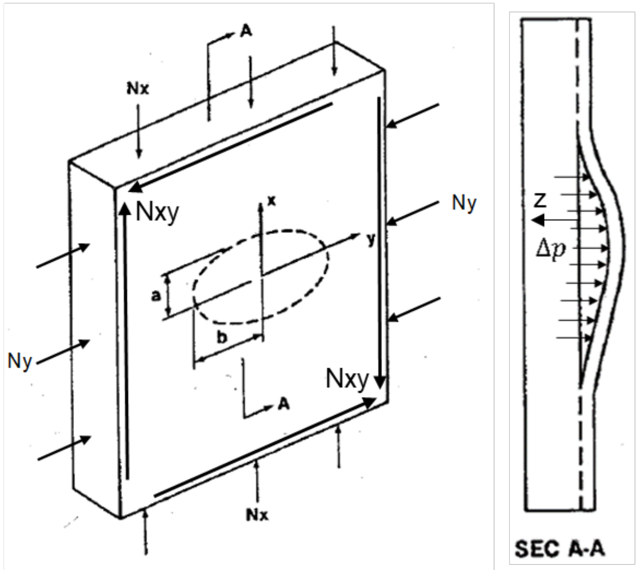


<u>Panel-level testing</u> can be used directly to back out "<u>Effective Gc</u>" values for static and fatigue.

Loading Considerations for Sandwich Disbond

In-Plane Static Mechanical Loading

- Compression and shear drive disbond buckling (and growth).
- Use simplifying assumptions to conservatively envelop critical loads.
  - *Assume peak panel strains exist over entire panel,*
  - *Envelop combined compression and shear.*



In-Plane Fatigue Loading

- Compression and shear drive disbond buckling (and growth).
- Envelop fatigue spectra with constant amplitude cycling to understand thresholds.

GAG Pressure Loading (cyclic)

- Can add to static or fatigue loading
- Differential cavity pressure dependent on altitude and temperature.
- Application specific (transport aircraft vs. rotorcraft).

For combined mechanic and pressure loads, need to consider altitude during critical load cases and during fatigue loading.

Other Out-of-Plane Loading

- Aero pressure loads (add to GAG cavity pressure), Fuel loads? Secondary bending?

Role of Large-Scale Testing for Sandwich Disbond

Large Scale Testing

- Large-scale certification testing is often used mainly to validate load paths and strain levels.
- Top-down, bottom-up approach uses early (e.g., preproduction) large-scale testing to understand scaling effects and critical loading and failure modes.

Sandwich Disbond Considerations

- Sandwich disbond is not typically substantiated at full scale – <u>relies on analysis supported by lower-level testing</u>, uses strains from FEM validated at full scale.
  - *Exceptions might be in cases where component level testing is needed to include complex combined loading and/or structural details (e.g., curvature).*
- Large-scale analysis may look at <u>buckling stability</u> of disbonded face sheets but difficult to implement fracture analysis (e.g., VCCT).

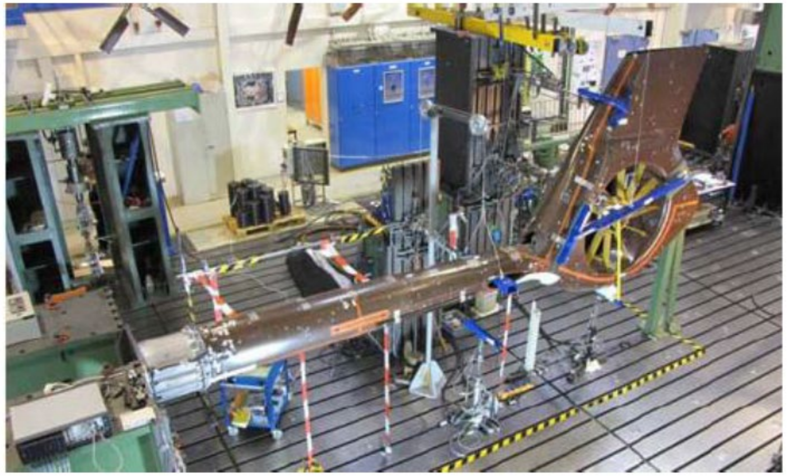


Fig.11: Static test article of tail boom structure *

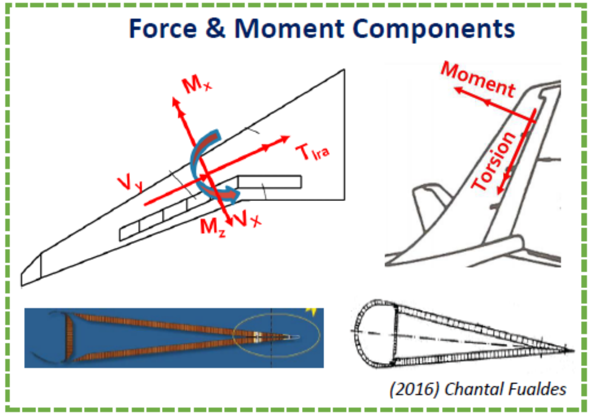
Fig. 10: FEM Model of tail boom structure *

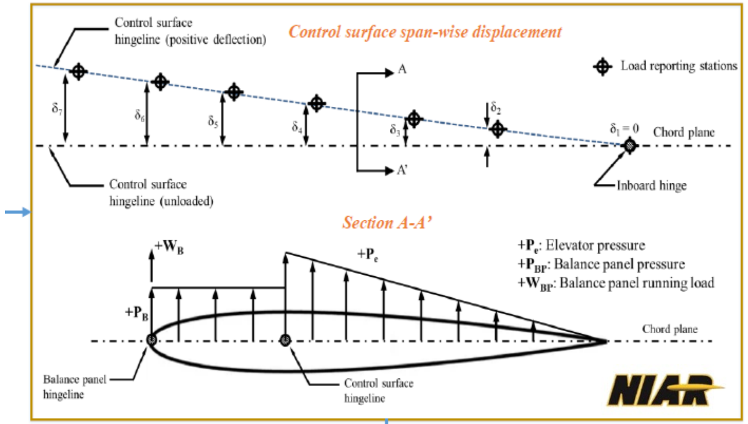
**A. Engleder, D. Strobel, Eurocopter, CMH-17 Meeting 2012 Boston "Common Local Instabilities of Composite Sandwich Structures with Honeycomb Cores."*

Complex Loading and Design Details for Sandwich Disbond

Variable loading

- Realistic <u>combined in-plane load conditions vary</u> over the control surface or other sandwich parts.
- <u>Internal pressure is not always matched</u> with a uniform compression and/or shear for large areas of a control surface box structures.





Shear loading

- Face sheet buckling under shear loading can drive disbond growth, but it is more difficult to analyze.
- <u>Shear-buckled face sheets can still carry shear loads</u> (aggressive analysis for disbond between arrestment?)
- Shear loading may be important for many GA applications where the outboard wings are sandwich construction and are driven by torsion loading.

Loading at Structural Details

- Core ramps, curvature, potted fittings
- Also need to consider loading at arrestment features.

<u>Engineering approaches</u> for complex loading may include <u>conservative simplifying assumptions</u> to envelop the realistic loading on the structure.

<u>How well can real load conditions be addressed</u> by uniform compression loading + internal pressure?

Outline

Summary & Conclusions

Certification

- PSEs and critical structure must meet damage tolerance requirements, typically based on Categories of Damage.
- ACs establish criteria for bonding – relevant to sandwich.
- EASA CM has specific guidance for sandwich structure.
  - *e.g., 4-inch impactor, SDC approach*
- CMH-17 covers Structural Damage Capability (SDC).

Damage & Defect Threats

- Impact damage threats depend on location and geometry.
  - *Can be very different for aircraft vs. helicopters vs. engine.*
  - *Sandwich is highly sensitive to impact variables.*
  - *Structural impact surveys are used to establish link between damage threat, visibility, damage state.*
- Many sandwich defect threats are related to bonding.
  - *Co-bonded vs. Co-cured, potential "weak bonds"*

Design Criteria & Inspection

- Criterial for Cat 1 and Cat 2 cover a wide range of accidental damage and defects.
  - *ADLs often drive criteria for sandwich structure.*
- No-growth criteria are typically used for both Static and Fatigue (includes sandwich disbond).
  - *No buckling criteria can be used for disbonded face sheets.*
- Criteria for weak bonds are key and depend on inspection.
  - *Design criteria for arrestment are important.*

Substantiation & Engineering Approaches

- Building block used for test and analysis substantiation.
- Consider combined GAG pressure + mechanical loading for face sheet disbond no-growth (static and fatigue).
- Engineering approaches for sandwich disbond use conservative assumptions with repeatable, reliable analysis that can be efficiently used in design (i.e., design curves).

Sandwich Disbond Certification – Discussion Topics (1 of 2)

Bonded Structure Criteria

- Consider full disbonded face sheet between arresting features for both wet and precured face sheets?
  - *Co-bonded structure (pre-cured face sheet bonded to core) can be considered a bonded joint susceptible to weak bonds.*
  - *Co-cured structure ("wet" face sheets co-cured to core) may not be considered a bonded joint.*
- Sandwich "monocoque" vs. "semi-monocoque" (multi-load path) – definitions?
  - *Monocoque sandwich structure relies entirely on the shell (face sheets and core) to carry loads (no backup frames, ribs, etc.).*
  - *Semi-monocoque sandwich structure includes backup structure and/or other design features to arrest damage growth and/or carry redistributed load.*
- When do weak bond criteria apply (i.e., assumed disbond between arrestment)?
- When is fatigue "no growth" needed for sandwich disbond?
  - *Only for Cat 1 and Cat 2 impact damage? Or also for weak bonds?*
  - *Does it depend on co-cured vs. co-bonded and monocoque vs. multi-load path?*
  - *Can sandwich disbond be covered as SDC with limit load only requirement, no fatigue, no associated inspection. Still doing Cat 1, 2 and if needed Cat 3 for realistic damage threats.*

Key Questions

- When is sandwich structure a bonded joint?!
- Inspection – Can weak bonds be found in-service?
- Should there be a fatigue requirement for disbond between arrestment? i.e., Cat 2 vs. SDC.
- What requirements or design criteria are needed to drive robust design (multi-load path, fail-safe)

Sandwich Disbond Certification – Discussion Topics (2 of 2)

Risk Discussion

- More risk in co-bonded sandwich due to bond prep required (chemical weak bond)?
  - *Should co-bonded sandwich designs have the capability for limit load with a full disbond between arrestment In the presence of LEWABI?*
- More risk to monocoque sandwich due to lack of residual strength capability due to large damage (LEWABI and similar).
  - *Is monocoque construction for PSEs a valid option?*
- Less risk for co-cured sandwich and/or using semi-monocoque construction?
  - *If the risk for LEWABI (and similar) is still there, does this forces a semi-monocoque approach?*
  - *If there is no LEWABI (and similar) risk, can a monocoque approach be used if using co-cured sandwich? If so, this puts great importance on the accuracy of threat assessment. It must be very well thought out and with proven service experience. This should be discussed…………..*

BACKUP SLIDES

EASA CM-S-010 Issue 01 – Bonding Requirements

Co-bonded structure	Components bonded together during cure of one, or more, of the components, but not all components, e.g. bonding to metallic or a pre-cured component.
Co-cured Structure	Structure obtained by a single cure of uncured components
Monocoque	Thin shells which rely entirely upon the skins for the capacity to resist loads (Megson). Note: For the purposes of this CM a sandwich structure forming a shell comprising 2 skins and a core (e.g. fuselage or tail boom) is considered to be the 'thin shell', and thus described as a monocoque.

Specific to "monocoque" sandwich structure in PSE applications but also provides general guidance and approaches for multi-load path sandwich structure.

Although AMC 20-29 and AC 29 2C MG8 could be interpreted as excluding sandwich structures from the requirements associated with bonded structure, e.g. AC 29 2C MG8 cites sandwich structures as being examples of co-cured structures, this would seem to be inappropriate, particularly when considering PSE sandwich designs as addressed in this CM, because many sandwich structures comprise of metallic and/or pre-cured skins and/or cores. Unless individual elements of the monocoque sandwich shell, e.g. inner skin, outer skin, can be demonstrated to independently satisfy the requirements, then it would seem to be appropriate to address the bonding requirements (e.g. CS23.573(a)5) for such structure. These include the requirements for rigorous process control and for 'design features' intended to prevent catastrophic failure, typically considered to be discrete 'back-up' features or 'arrest' features. However, in the absence of discrete design features intended to avoid catastrophic failure, other mitigating actions may be acceptable subject to agreement with EASA.

"...other mitigating factors may be acceptable...."

EASA CM-S-010 Issue 01 – Impact Energies and Impactor Diameters

For example, to be confident regarding likely damage modes resulting from impact threats, it is considered to be appropriate to test throughout the threat impact energy range up to readily detectable damage using a range of appropriate impactor geometries, e.g. including sharp impactors and blunt impactors up to diameters agreed with EASA, e.g. for CS25, a range of impactors up to 4 inches diameter have been accepted, based upon typical protection device geometries carried by ground vehicles. Furthermore, it may be appropriate to consider a range of impactor stiffnesses, e.g. for hail, or ground vehicle rubber bumpers, such that all competing damage modes can be identified. Representative boundary conditions should be used in the substantiation test campaigns.

Note: In some cases, it may be possible to conservatively bound many damage types, and thus reduce the detailed substantiation workload, by demonstrating a larger structural damage capability. However, this will require demonstration that all likely damage modes have been bounded by the structural damage capability assumption, e.g. a large penetration could be used to address all likely damage modes within the bounds of the penetration.

Link between GSE and 4” impactors

EASA CM-S-010 Issue 01 – Impact Energies and Impactor Diameters

3.1.4.2. Residual strength

As is generally required for composites in the existing regulations, e.g. AMC 20-29, monocoque sandwich structure will be expected to demonstrate UL capability with damages at the limits of detectability resulting from fatigue, environmental degradation, accidental damages, e.g. BVID/DDID, and manufacturing defects, e.g. local disbonds, throughout, and at the end of, the product's life. However, noting that such structure has no alternative load paths available, and may not include discrete design features intended to avoid catastrophic failure, e.g. doublers, stringers etc., it is essential that damage and defects are more thoroughly understood, more so than would be expected for multi-load path structures.

Also, as required for composites, the applicant is to demonstrate that the monocoque sandwich PSEs can sustain no less than LL capability with detectable damage (e.g. Cat 2 per AMC 20-29, VID per AC 29 2C etc.), damage near LL capability with obviously detectable damage (e.g. Cat 3 per AMC 20-29, CVID per rotorcraft application), and 'continued safe flight and landing' with discrete source damage (e.g. Cat 4 per AMC 20-29) for all damage modes, particularly those which could be potentially catastrophic. However, unless the applicant can also demonstrate, to the satisfaction of the Agency, robust experience* using similar materials and processes in similar configurations at similar strain levels and in similar service environments, then any potentially catastrophic damage mode, which may not initially be readily detectable**, should be identified and addressed for growth up to readily detectable levels and/or should be demonstrated to exhibit 'no detrimental damage growth' under repeated loadings for the applicable duration. The intent is to ensure that the damaged structure demonstrates no-growth, or stable slow progressive growth (maintaining a predictable damage mode), i.e. it maintains a safe margin relative to the steep slope on the residual strength curve.

Opens the door to not having arrestment features, just have to have a thorough understanding of damage and defects

Includes "weak bonds"?

AC 29-2C, Chg. 4, “Certification of Transport Category Rotorcraft”

(16) Damage Tolerance. The attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, accidental or discrete source damage.

(17) Damage Tolerant Fail-Safe. The capability of structure remaining after a partial failure to withstand design limit loads without catastrophic failure within an inspection period.

(18) Damage Tolerant Safe Life. Capability of structure with damage present to survive expected repeated loads of variable magnitude without detectable damage growth and to maintain ultimate load capability throughout service life of the rotorcraft.

Rotorcraft-specific definitions

Sandwich Panel ADLs – AIAA Paper Overview

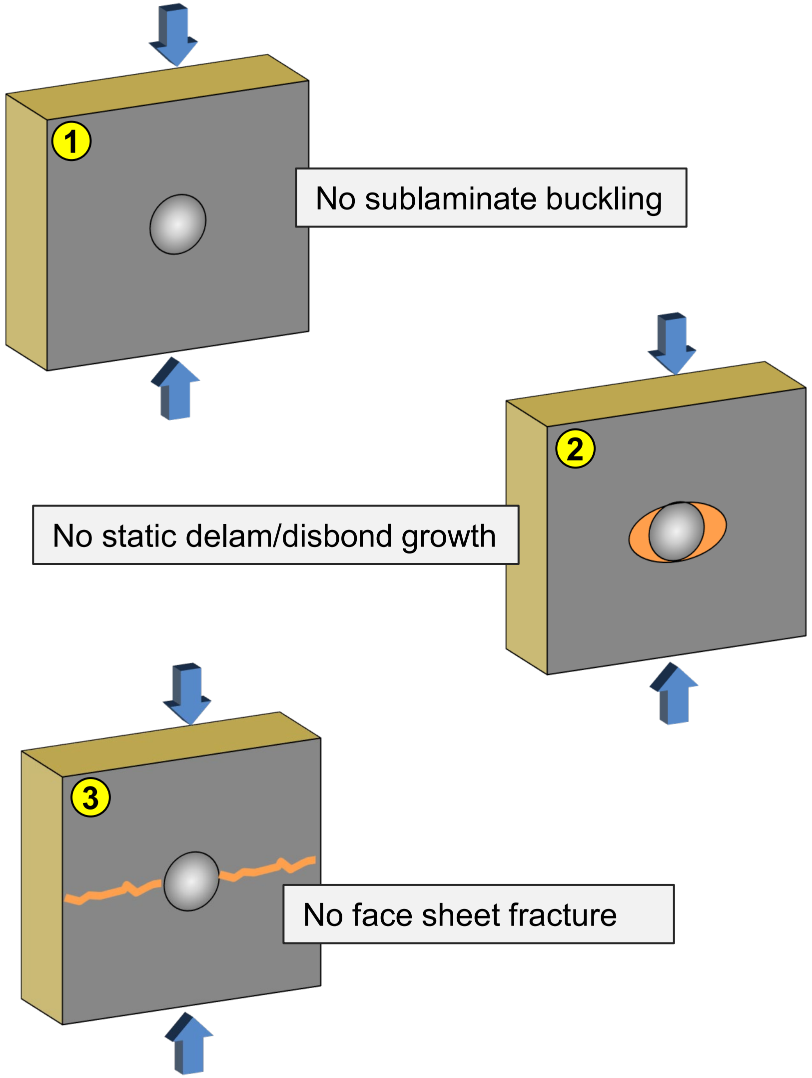
Strength of Impacted Sandwich Panels

- The approach in AIAA 2003-1596 [1]* addressed the strength and fatigue life of sandwich panels with face sheet disbonds.
  - *Analysis was used to set Allowable Damage Limits (ADLs) for Boeing 737s.*
- Face sheet disbond falls within the sublaminate buckling analysis for the "delamination with no dent".

Criteria to Address Three Failure Modes

1. **Fatigue disbond growth**
   - *No face sheet or sublaminate buckling at Operational (fatigue) compression loads.*
2. **Static disbond growth**
   - *No static disbond growth at Ultimate compression load.*
3. **Static strength**
   - *No face sheet fracture at Ultimate compression load (accounting for the stress concentration caused by buckled disbonded region).*

*https://nsecomposites.com/damage-tolerance/damage-assessment-for-composite-sandwich-structure/



What is an Engineering Approach?

Engineering Problems

- Engineering problems can have many solutions.
- Engineering problems can be complex, but their solutions don't have to be.
- The best solution for an application represents an appropriate balance between the level of complexity and the required accuracy.

Engineering Approach

- An engineering approach uses pertinent experience and good engineering judgement to produce practical solutions that meet all design requirements in a cost-effective manner.
  - *Engineering approaches for analysis are reliable and repeatable.*
- An engineering approach generally considers:
  - *The need to reliably meet all safety requirements while considering the performance objectives of the application (not be overly conservative).*
  - *The objectives of all members of the Integrated Product Team (IPT).*

Engineering Approach Options for Structural Analysis

Design Guidelines

- Use design guidelines to avoid known bad design details.
  - *Bad design details may include designs that are prone to failure modes that are difficult to characterize by analysis and/or testing.*
- Guidelines are typically based on in-service experience and “lessons learned”.

Design Criteria

- Use simplified damage or defect criteria to cover complex damage scenarios.
  - *Large notch criterion (e.g., severed skin-stiffener) to cover a range of impact threats.*
- Use criteria to avoid characterization of complex damage growth.
  - *“No Growth” criteria for Category 1 damage/defects (e.g., BVID) under cyclic loading.*
  - *“Onset” criteria for delamination or disbonds under static loading.*

FOCUS

Design Curves

- Use design curves to capture complex behaviors in a simplified manner.
- It is desirable for design curves to be based on theoretical structural responses but consider trends from detailed analysis as well as behavior and failure modes observed in testing.

Design Curve Objectives (1 of 2)

Simplified Analysis

- The use of design curves is typically driven by the need for solutions that are simple, intuitive, reliable, and repeatable.
- Simplified analyses in the form of design curves can be used to meet the design requirements and objectives in a practical and cost-effective manner.

Envelop the Problem

- Sometimes use a “lower bound” approach to envelop behavior observed in testing and/or analysis.
- Supporting detailed analyses are typically performed to understand the sensitivity to key variables.
- Ideally, the design curve envelops the problem while producing a design that is not overly conservative.

Design Curve Objectives (2 of 2)

Reduced Computational Time

- The use of closed-form analysis methods in the form of design curves is often driven by the need to perform rapid analysis of design iterations.
  - *Such design curves can be implemented in the production design environment.*
  - *It is not general practice to use FEA for the analysis of acreage structure.*
- "On a commercial transport jet, the number of primary airframe load conditions investigated could well be over 10,000."*
  - *"The number of actual critical design conditions is about 300-500, involving almost every type of maneuver required by FAR."*
  - *"Additionally, critical internal loads may occur at as many as near 20,000 locations on an average wide-body size jet transport."*
- For preliminary design optimization 100,000 iterations may be run for a single location.

Niu, M.C.Y., "Airframe stress analysis and sizing," Second Edition, Conmilit Press Ltd., 2001

Other Design Curve Considerations

Theoretical/Physics-Based Response

- Design curves that are based on theoretical functional forms representing the physics of the problem are preferred since they will likely capture the key structural response trends.
- Physics-based design curves can be calibrated to testing and/or analysis.

Supported by Testing

- Testing is needed to establish baseline structural response and trends, verify failure modes, and provide a basis for strength allowables.
- Testing is also needed to validate detailed analysis models.

Supported by Detailed Analysis

- Detailed, “pre-run” FE analysis can be performed to explore a wide design space.
- The analysis matrix can use a Design of Experiments (DOE) approach to study variables.

Design Space & Limits of Applicability

- The applicability of design curves must be constrained by the limits of the underlying analysis and test data.

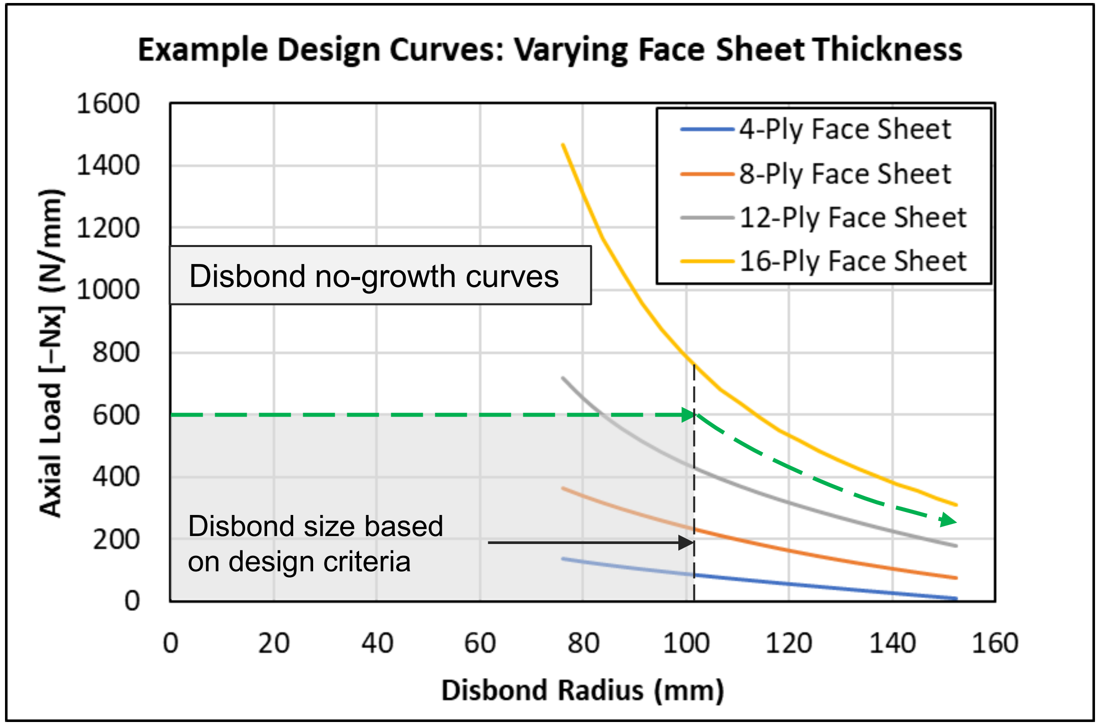
Example Design Curves / Sensitivity Studies for Sandwich Disbond

Engineering Design Curves

- Carpet plots using multiple curves for a range of a specific design variable.
- Design criteria might include a minimum disbond size (for defects and/or allowable damage).

Extension to Multiple Variables

- Example response surfaces developed using analyses covering the design and loading space.
- Address key design variables in equation form.
  - *Face sheet stiffness and/or orthotropy*
  - *Face sheet thickness*
  - *Disbond size and aspect ratio*
  - *Biaxial loading ratio, pressure*
  - *Static and fatigue loading?*



Discussion

- The family of curves shows how the maximum size of disbond that is not predicted to grow varies for different face sheet thicknesses with axial compression loading, at an altitude of 12200 m.
- OEMs may start with a critical size based on damage threat assessment and then determine the minimum face sheet thickness based on the applied strain.