Transport Airplane Metallic and Composite Structures Working Group – Recommendation Report to FAA Structural Bonding

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Mr. Guilherme Garcia Momm, ANAC Airframe Engineer and PhD candidate, also provided thoughtful input to our group related to his academic endeavors to address structural bonding and collection of industry case studies.

Mr. Andries Buitenhuis, Fokker Chief Engineer, shared with the WG at late notice presentation material on their experiences with metal bonds, both with service difficulties and quality control programs. This material, incorporated into this report, is helpful in developing our recommendations.

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1.0 Executive Summary

On January 26, 2015, the FAA published a notice of a new task assignment for the Aviation Rulemaking Advisory Committee (ARAC). In short, the FAA assigned and ARAC accepted the task to provide recommendations regarding revision of the damage tolerance and fatigue requirements of Title 14, Code of Federal Regulations (14 CFR), part 25, including subparts C and E of 14 CFR part 26. In addition, the ARAC accepted a related task for development of associated advisory material for metallic, composite, and hybrid structures (structure that includes a combination of composite and metallic parts and assemblies). Under the Transport Airplane and Engine (TAE) Subcommittee, the Transport Airplane Metallic and Composite Structures Working Group (TAMCSWG) provided advice and recommendations on the tasking. The TAMCSWG provided a final report, which included recommendations on a broad variety of related topics to TAE and ARAC. This initial final report, released on June 27, 2018, is publicly available at: (https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAMCSWG%20Recommendation%20Report.pdf).

During the review and acceptance of this report by ARAC, three separate follow-on tasks required an extension of the original tasking to include:

1. Develop requirements and guidance material for single load path (SLP) structure
2. Provide further clarification on how to address disbonds and weak bonds as a manufacturing defect in both monolithic bonded and sandwich structure (composite and metal)
3. Provide requirements and guidance on how to address crack interaction when establishing inspection programs

None of these three tasks change the primary recommendations made in 2018. Each of the three topics used the same approach applied in the original tasking effort, which includes:

A. Evaluate current § 25.571, subparts C and E of part 26, and guidance material
B. Recommend Rule or Guidance changes
C. Estimate the Costs and Benefits associated with any changes

With concurrence from TAE and ARAC, the Working Group decided to address each of the three extension topics in standalone reports supplemental to the original report released in 2018. The final report on the topic of SLP structure, released on November 20, 2020, is publicly available at: https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAMCSWG%20SLP%20Recommendation%20Report%20December%202020%20(Submitted%2012-11-2020).pdf. This report addresses the second topic, bonded structures. At the time of the release of this report, the TAMCSWG was still developing the report to address the third topic on crack interaction. Although each report has its own recommendations, there is some overlap between the subjects. For example, the TAMCSWG recommended that guidance should note current best design practice for SLP principal structural elements (PSE) does not include bonded structural details within the critical load path of such parts. In addition, any considerations that would allow exceptions to the best practice should be identified during certification.

As discussed in this report, the TAMCSWG recommends no additional rule changes beyond that described in the initial 2018 report. As a result, this report provides the recommendations and rationale for guidance changes, the rationale for no rule changes, and lastly the cost and benefit analyses associated with these recommendations for the topic of bonded structures. It also discusses the knowledge transfer challenges in sharing Original Equipment Manufacturer (OEM) (herein also referred to as type certificate holder, TCH) composite structural substantiation experiences such as those used for repair and inspection procedures development with end users, which include the airlines, cargo air transportation and maintenance organizations. Such efforts will be even more important in the future, as the use of composite and metallic hybrid bonded assemblies expand and increase in complexity.

As detailed in the final 2018 TAMCSWG Report, bonded structural repair, rework and concessions received significant coverage. That report recommended no rule changes because repairs must meet the same certification standard as the original or modified structure. However, the 2018 TAMCSWG Report recommended that the FAA add guidance in Advisory Circular (AC) 25.571-1D and AC 20-107B to address bonded repairs. This guidance would clarify that repairs accomplished in a production facility can occur in-service if incorporating the same stringent quality controls. Since field repair substantiation is difficult, the TAMCSWG recommends support by the TCH and regulator to develop affordable, approved data for repair design, which meet the original certification regulations. *It is important to note that the TCH often adds their own requirements to certification regulations and, if essential to safe applications, the TCH must help ensure sufficient knowledge transfer exist for field repair efforts to avoid any future problems.* All of the 2018 TAMCSWG Report recommendations in this area remain valid.

In addition, the 2018 TAMCSWG Report recommended the FAA clarify that the same stringent structural damage capabilities (SDC) stated in FAA policy letter PS-AIR-20-130-01 applies to in service and production repairs. Expectations prescribed in AC 20-107B for production repairs/rework/concessions accomplished by the TCH and its suppliers, are within the size limit established by TCH to meet no less than limit load if repair fails. The wording in both documents needs to be consistent to avoid any confusion. This report not only clarifies that expectation but also clarifies that any bonded baseline structure classified as a PSE, typically has a consistent SDC, or equivalent level of fail safety, in today's existing company-specific design criteria.

This report further addresses bonding considerations during product design, production and maintenance. Field inspection and repair practices are critical items covered in a dedicated section of the report. Over the last 15 years, standards organizations such as Composite Materials Handbook 17 (CMH)-17 and SAE Commercial Aircraft Composite Repair Committee (CACRC) have further benchmarked current bonding practices. During those efforts, the OEM, airlines and maintenance organizations have identified the root causes of field problems, many of which started with a general lack of overall inspection and repair standardization. This remains a significant challenge for industry, given all of the new composite applications currently occurring for modern aircraft.

The industry is pursuing more bonded structure standards, considering the limited few that publicly exist. There is also a need for new resources and facilities, with skills, equipment and tooling to deal with the quickly expanding applications. The FAA considers this challenge as a serious safety threat that must not be overlooked for the industry to efficiently move forward and realize the advantages possible with more standard design details (e.g., repair materials, structural features), procedures, and an associated knowledge base that promotes the ease of distance learning and continuous education. The CMH-17 next revision will have many additions in practical guidelines and best industry practices for bonded structure.

The TAMCSWG bonded structure extension effort started by seeking clarity from the FAA on the tasking statement, which simply requested support on how to address disbond and weak bonds as manufacturing defects. Bonding is an essential subject for composite structural integrity and appears in many sections of the primary related guidance, AC 20-107B, including design and fabrication development, material and process control, static strength, fatigue & damage tolerance and continued operational safety. Bonding is not mentioned in §25.571 or AC 25.571-1D, despite the fact it was a significant safety concern for past metal-bonded PSE details. Figure 1 gives a synopsis of the bonded structure extension efforts, whereby priorities for safety risk mitigation appear in order with the highest priority on top. This notional hierarchy helped guide the TAMCSWG efforts in documenting the proposals contained within. It is ***the TAMCSWG's position that all of the recommendations shown in this figure need guidance updates, without specific rule changes.*** Standards organizations should continue to work the challenges of knowledge transfer by documenting more consistent and efficient standard practices for structural bond design, structural substantiation, maintenance inspection and repair processing (in process quality control and post-process non-destructive inspection (NDI)).

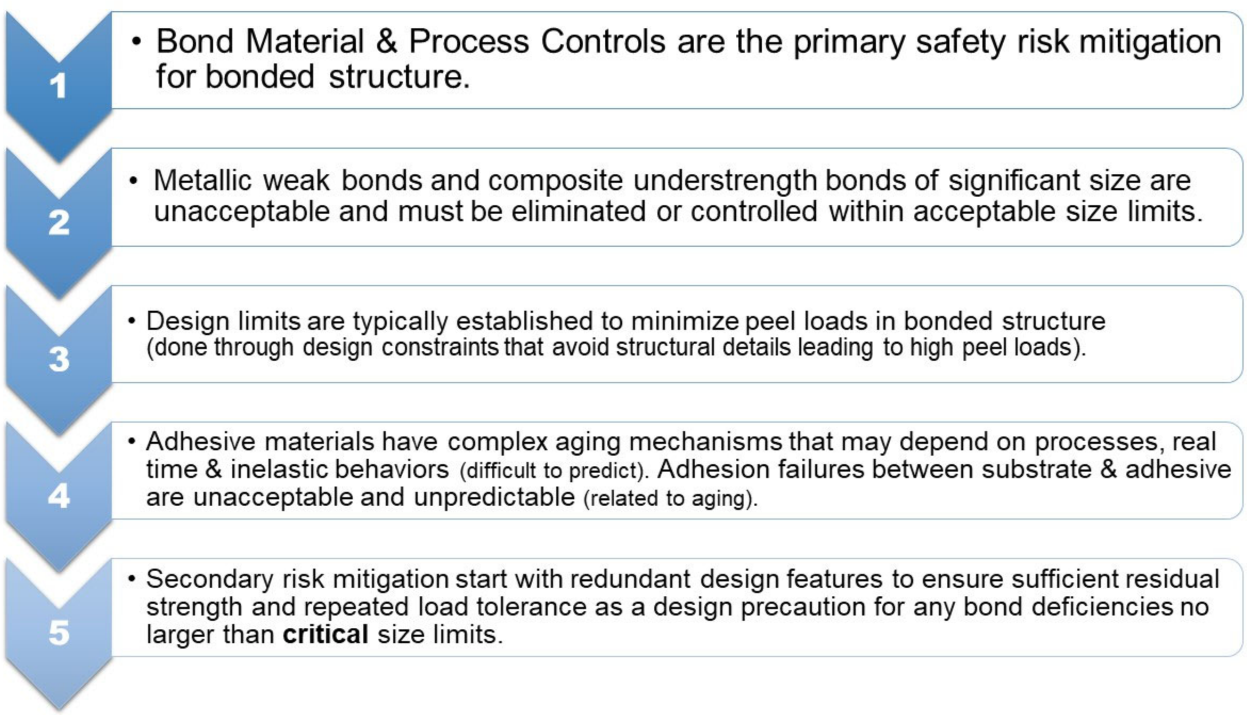

Figure 1. Bonded Structural Integrity Priorities listed from top to bottom in order of importance.

It is clear that stringent material and process controls are an essential prerequisite for use of bonded structures in critical structures. As noted in AC 20-107B, PSE are critical structures for Transport Category Aircraft. In principle, all bonded structures that may fail in flight due to a lack of such controls and potentially depart the aircraft, may cause safety problems for other structures and; therefore, best industry practice is to establish stringent material and process controls for bonding.

Figure 1 also lists safety priorities for use of bonded structures. Manufacturing defects called weak bonds for metallic structure and weak or understrength bonds for composite structure are unacceptable, and their existence needs to be extremely rare. They should also be no larger than structural redundant features, which can reliably retain limit load until found with proven inspection procedures. Note that this industry expectation goes beyond past protocol, to include substantiation of damage tolerant repeated load tolerance. Any significant bond adhesion failures found in process qualification, certification testing, production or service use are unacceptable and require immediate corrective action. Traditional damage tolerance procedures used for metallic and composite structures for fatigue (slow and arrested growth), accidental damage and environmental degradation have proven acceptable for bonded structures subjected to stringent material and process controls, assuming proper coverage of the other design and failure conditions shown in Figure 1. Nevertheless, the industry prefers the composite bonded design approach involving "no growth," whereby structural details and related design strains are kept at levels where damage growth is suppressed. These general thoughts require further attention in updates to AC 25.571-1D and AC 20-107B, as noted in this report, including example detailed changes provided in appendices. In combination, the bonded structural integrity priorities identified in Figure 1 recommends that the design use of SLP with bonded structural details in the critical load path be avoided (in essence, it is believed that such structure may have critical flaw sizes that are too small to safely control even with stringent bond material and process controls). Under certain circumstances, a given bonded SLP design may overcome this limitation without specific redundant design features through low design stress levels and other considerations, which yield sufficient damage tolerance and service life goals.

This report justifies the need, and provides detailed specific recommendations, for changes to AC 20-107B and AC 25.571-1D, as identified in appendix 3 and appendix 4, with the former continuing to contain most bonding guidance. All items listed in Figure 1 have importance with priorities previously defined and the recommendations given in appendices provide example updates. The existing composite guidance is very good at giving bonded structure material and process controls the highest priority of issues described in Figure 1.

One significant update recommended for AC 20-107B is the dual classification of the large SDC, currently covered as the structural redundancy expectation in the section for Material and Fabrication Design Development (*Paragraph 6c: Structural Bonding*), to now also be explicitly treated as a Category 2 damage threat for Paragraph 8 (*Proof of Structure – Fatigue & Damage Tolerance*) because a scheduled inspection will be needed to ensure it was found. This recommendation was added because a disbonding or delamination threat for some structural details may be hard to find using the selected damage detection methods (note that most composite damage detection initially use visual methods to first detect damage prior to NDI inspection for a complete damage characterization) and the large Category 3 damage is defined such that it will be found within a few flights of occurrence.

When using visual detection methods such as surveillance or detailed visual approaches, the disbond or delamination must be large and the structure should have sufficient damage tolerance to be found during heavy maintenance checks with access to fuselage or torque box internal structures. Such classification requires a fatigue no growth demonstration of a traditional SDC-type disbond defined in company-specific damage tolerance design criteria (DTDC) for a Category 2 damage. TAMCSWG members all agreed on the size of the traditional SDC-type damage but two members did not want classification of such damage as Category 2 due to the added recurring costs of periodic inspections and added structural substantiation to find such damage per selected inspection methods and a specified interval without a defined threat associated with that damage. In effect, two members did not want added costs of related damage tolerance risk mitigation for arbitrary damage scenarios. Most members believed it was good practice to closely inspect the structure with substantiated maintenance procedures for evidence of large disbonds as a practical safeguard even though the intent of stringent bond material and process controls is to ensure such events are extremely rare.

Most of the AC 25.571-1D recommended updates brought bonding into damage descriptions, including the potential that early stages of weak bond formation would potentially have a significant effect on damage tolerance analyses. AC 21-26A also requires updates. This AC contains very generic guidance on Bonding (materials, process parameters and quality control plan), identified in §10.c.(3) Secondary Bonding of AC 21-26A, without any recommendation on design principle or any recommendation on the complex interactions between both materials and design principles. The TAMCSWG recommends creating a cross reference to AC 20-107 B and not update AC 21-26A to avoid any not consistent information.

2.0 Bonded Structure Task Extension

2.1 Extended Tasking Description and Work Plan Summary

The FAA requested further clarification from the working group on how to address disbond and weak bonds as manufacturing defects. This appeared to be a simplification of the task to be performed and subsequent discussion with the FAA made it clear that industry should address both metal and composite bonding (for both serial production of the base structure and factory or field repair), including relationships with material and process control, as noted by the current Paragraph 6 of AC 20-107B.

In addition, the FAA requested TAMCSWG to provide additional advice and recommendations on any secondary considerations for bonded structure, including options given in the current AC 20-107B based on 10 years of experience since the publication date in September, 2009. In particular, the FAA requested the TAMCSWG to agree on *Structural Damage Capability (SDC)* or the existing words already appearing in AC 20-107B (implying fail safety) as a supplement to stringent material and processing control of bonded structure. The FAA further noted that a specific SDC for bonded structure is evident in many transport applications to date; however, other product types have used very large damage sizes as opposed to specific arresting features. Some further FAA clarification for details on the specific tasking also appear below, which summarizes the technical basis for existing content in AC 20-107B.

- Bonding has a number of manufacturing defects that need consideration in a threat assessment for structural fatigue and damage tolerance substantiation. Of these, the two main types include: 1) small disbonds & other bond discrepancies (e.g., porosity) and 2) understrength or weak bonds not reliably detected by factory post-bond inspections. Existing composite guidance controls the former manufacturing defects in a manner similar to small or rogue flaws for metallic fatigue and damage tolerance. In the vast majority of cases, small composite defects can be classified as Category 1 damage and proven to be allowable based on a no-growth demonstration for a lifetime of fatigue, while retaining strength at ultimate loads (with small disbonds at the limits of factory NDI detection likely critical versus acceptable porosity). In the past, industry has generally complied with composite defect and damage guidance recommendations by demonstrating No-Growth, Slow Growth or Arrested Growth options in analyses supported by tests as described in the existing AC 20-107B.

- Understrength bonds are manufacturing defects that result from under specified or controlled manufacturing processes (chemistry). The resulting bond may have mechanical properties that are below the specification minimum values and/or require further consideration once discovered. These defects may occur within the range of manufacturing quality at the time they are discovered and should be further addressed in the static strength and damage tolerance evaluations as described in the existing AC 20-107B. Note that the terminology understrength bonds has been adopted to distinguish bond phenomena that may still allow the use of damage tolerance principles in reliably controlling damage growth until found and repaired, whereas weak bonds have not.

- "Weak bonds" are also a manufacturing defect that is outside of the range of expected production quality (i.e. a quality escape). These can be confusing when compared to other manufacturing defects considered for purposes of fatigue and damage tolerance substantiation. Although it is clearly a manufacturing defect, if sufficiently large, it is unlike any other manufacturing defect that are typically used by industry (i.e., all others are relatively small and either starter flaws for metal fatigue or allowable defects for composites).

- When weak bonds are large and of an unknown size and distribution, they become a serious safety threat. They are typically caused by contamination of the bonding surfaces, ultimately leading to lost adhesion. They have implications for static (ultimate) strength and must be addressed quickly with a terminating action. The evaluation and disposition must consider the specifics of the bonding and the residual strength of the structure. Without SDC/fail-safety, such problems would often require grounding the affected airplanes until the terminating action can be applied. It is well recognized throughout the industry that this issue cannot be managed using structural analysis and tests or reliably detected by practical maintenance procedures, including NDI. Weak bonds may also degrade due to environment and real-time aging or repeated load in a way that will not allow reliable prediction of when a maintenance action is needed to address the safety concern. As a result, the use of stringent material and process quality controls is the primary constraint to allow bonding in a PSE and further mitigate safety risks associated with weak bonds through use of a secondary constraint of structural redundancy. As posed in current guidance (AC 20-107B), recommended industry bonding protocol notes that: "stringent/reliable manufacturing in-process quality control practices are in place to ensure that any weak bonds are: 1) extremely rare (justifying a specific size constraint) and 2) localized to a size at or within arresting design features."

Under the TAMCSWG, a Structural Bonding task group (TG) was formed, which included subject matter experts in bonding from OEM, airlines and the FAA. The TG established a work plan that is summarized below (details appear in Section 2.4):

- Review Existing References, Including Existing Guidance and Industry Standards
- Identify Guidance versus Standards Recommendations
- Address Consistent Design and Maintenance Practices for Bonding

Early in the study, the TAMCSWG Structural Bond TG realized that no specific existing rule changes would be needed for structural bonding but the rationale for this decision still needed to be documented. The detailed work plan described in Section 2.4 yielded several deliverables as listed below:

Deliverables: Produce report containing the following recommendations

- Recommendations on appropriate performance-based requirements
- Recommendations on any new guidance or changes to existing guidance
- Recommendations for continued work on standard best industry bond maintenance practices
- Qualitative and quantitative costs and benefits of the recommendations

2.2 Introduction

Several FAA documents exist on "Structural Bonding," with a strong focus over the last 15 years on composite technologies from initial product design to maintenance and repairs activities. These topic areas have been the basis of a few guidance documents issued by the FAA, covering metal and composite bonded structure. In 2005, the FAA released a policy statement called *Bonded Joints and Structures - Technical Issues and Certification* (Ref. 4). In 2009, bonding was also covered in AC 20-107B, Composite Aircraft Structure (Ref. 5). In 2014, a policy on bonded repair size limits was released to ensure the thoughts already contained in AC 20-107B were consistently understood for the production of aircraft products and field repair (Ref. 6).

Additional tasking for structural bonding as related to fatigue and damage tolerance has as much to do with a need for industry guidelines as it does for regulatory guidance updates. There is a general lack of sufficient knowledge transfer on the subject of structural bonding. In general, safe bonded structure for PSE starts with stringent material and process controls. Adhesion science for metal and composite aircraft structure has a strong theoretical basis but the specific relationships between available substrate and adhesive material types, bond preparation, and further control of other processing steps lack understanding at the overall system level. Changes in any of the materials or processes can lead to less reliable bonding practices and changes in long-term strength and durability. As a result, bond process qualification often requires numerous process trials with the specific materials and process steps to identify a successful process window and the numerous in-process controls needed to ensure success.

Post-process NDI is required for manufacturing defects, including those that are properly controlled through fatigue, damage tolerance and related practical maintenance procedures. Unfortunately, the manufacturing defects that relate to weak or understrength bonds in metallic and composite bonded joints, respectively, and the onset and/or growth of weak bonds cannot reliably be detected using practical NDI currently suitable for factory or field use. As a result, the primary safety risk mitigation currently available for bonded structure comes through stringent in-process controls to ensure a very small risk of weak or understrength bonds that are of a size within the bounds of redundant design features (e.g., mechanically fastened, co-cured or an additional, separately bonded detail) or use of an increased SDC in design.

In recent years, Composite Material Handbook 17 (CMH-17) emphasized the need for structural bond content in base design, material and process control, structural substantiation, manufacturing & repair implementation and any other areas where guidelines were needed to help the industry control bonding for acceptable application needs. Bonded structure content will exist in Polymer Matrix Composite (PMC) Volumes 1 through 3, Rev. H and Sandwich Volume 6, Rev. A. These details are long overdue considering the number of aerospace applications to date but conservative industry practice and application limits have sustained acceptable levels of safety throughout the commercial transport industry without these advancements being made public.

In addition to published documents, two Industry/FAA Workshops were held in 2004 (Seattle, WA and Gatwick, England) with the objective to document the technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. Some conclusions appear in the FAA report (Ref. 1).

A survey contained in the report covered three main technical areas:

1. Materials and processes
2. Manufacturing and design integration
3. Product development, substantiation, and support

2.3 Summary of the Bonding Task from 2018 Final Report

In the original tasking for the TAMCSWG, bonding only appeared as a bolted or bonded repair task. The findings from that effort recommended no rule change to §25.571. In effect, any repairs, bolted or bonded, must meet the same certification standard as the original or modification structure (Ref. 7).

Additional guidance recommendations added to AC 25.571-1D address bonded repairs. Although AC 20-107B and AC 43-214 address composite structure compliance matters, including fatigue and damage tolerance, bonding is a process not solely unique to composite structure, and presents a challenge for continued airworthiness. Additional guidance to the FAA Policy Statement on Bonded Repair Size Limit (BRSL), PS-AIR-20-130-01, and harmonized European Union Aviation Safety Agency (EASA) Certification Memo CM-S-005 (Ref. 6) was also recommended. This guidance would clarify that repairs accomplished and substantiated by the OEM in a production facility are acceptable in-service if achieving the same stringent quality controls. Since field repair substantiation is difficult, the guidance should also recommend support by the TCH and regulator to develop affordable, approved data for repair design, meeting all the original certification requirements.

Additionally, the T recommended the FAA clarify wording in FAA policy letter PS-AIR-20-130-01 and AC 20-107B to be consistent and avoiding any confusion. Finally, recommendations for cross-references between the various guidance and policy should help ensure consistent field and factory practice, assuming the same level of bond quality control.

2.4 Detailed Work Plan

OEM/Maintenance Repair Organization (MRO) Sub-team to draft a bonded structure report: Chantal Fualdes, Allen Fawcett, Doug Jury, Eric Chesmar

NAA draft report support: Larry Ilcewicz (FAA), Simon Waite (EASA)

Review Existing References. Identify gaps in documentation for current industry best practices and regulatory guidance materials for bonded structure, noting differences between metal and composite bonded structures. This should include the technical subjects of structural bond design, material and process control, structural substantiation, production and repair. Some existing industry documents to review include industry reports, published technical references and other industry guidelines (e.g., CMH-17). Most important regulatory documents to review are mentioned above. The following areas need consideration:

- Published reports of service difficulties, incidents or accidents involving bonding
- Published industry reports covering the key technical subjects and any unpublished unique approaches used by different OEM representing the TAMCSWG or others approached by the ARAC working group
- Focus on AC 20-107B structural bonding content, which was commented in the initial ARAC activity ending in 2018, with additional points to cover material environmental degradation
- Any other guidance materials covering bonded technologies, including sandwich structure
- Any likely technology advancements that could make the guidance obsolete

Identify Guidance versus Standards Recommendations: One particular point of reference requiring attention is how to adopt the previous §23.573 rule language as acceptable best industry practice, as needed for future guidance. This is an important issue because the TAMCSWG did not anticipate such prescriptive rule language for the future. Since the content of §23.573 is generally accepted by industry, it was achieved by adding the same words to an industry standard guideline in CMH-17, with some reinforcing general loads kept in regulatory guidance. In practice, many bonded joints and attachments use fail-safe design practices as related to this previous small airplane regulation for composite damage tolerance. Alternate load paths achieved using fasteners or additional splices attached in a second bonding operation are common. Due to the mechanisms of bonded and bolted joints, design of the joint or attachment capability assumes only the bond or bolts are transferring loads.

Some existing guidance materials that address an important aspect of bonded structure, including stringent quality control need update. For example, past industry/regulatory discussions on AC 21-26A have realized it is limited in scope and somewhat outdated. Some comments/recommendation are needed in moving forward per current FAA plans to establish performance-based guidance as appears in such areas of AC 20-107B.

As related to design and structural substantiation, limited rules and guidance on the subject of bonded structure exist. As a result, the sub-team effort will review content in ACE100-2005-10038 (Ref. 4) to highlight areas or emphasis for guidance update or publication in industry standards.

A close review of the current industry-initiatives active with CMH-17 and CACRC with a goal to provide best detailed industry practices for bond material and process control, design, analysis, structural substantiation and maintenance (repair in-process controls) is another important step in the work plan. One area needing the most significant work will come from review of documentation on maintenance practices. Currently, much of the maintenance industry is fully dependent on OEM assistance because related supporting technologies for inspection, repair design, structural substantiation, processing, and related knowledge transfer are proprietary and not universally shared.

Address Consistent Design and Maintenance Practices for Bonding: As discussed previously, bond material and process control is paramount to safe applications. Some of the biggest challenges occurring with bonded structure come in how to achieve control in the field versus the factory. In principle, both can coexist and achieve the same goals; however, significant knowledge transfer provides a strong basis for that accomplishment. The fact that different airplane products may use differing approaches for controlling the required quality of a bonded structure or repair to a structure, knowledge transfer is even more important to success.

The work plan will include some future recommendations on how the challenges in knowledge transfer between OEM, operators and maintenance organizations will benefit from regulatory guidance and industry standards efforts. The primary focus of guidance will be on PSE parts requiring some constraints in repair size limits. The guidance will also be limited to those areas of knowledge transfer that relate to critical design details and essential material and process controls for production and service repair. Industry standards will focus on essential technical details for bonded repair substantiation and repair technician training.

3.0 Rules recommendations

3.1 Rule changes

The TAMCSWG reviewed the existing rules that support the development of materials, the effects of their environments and associated mature quality control plans. This review considered both technologies, metallic and composite, and their bonding characteristics. ARAC members considered the critical steps in the design and validation of bonding processes from both OEM and Maintenance & Repair Organizations (MRO). The TAMCSWG understood that bonding is an assembly of technologies with a sensitivity to fabrication methods and associated potential manufacturing defects. Other potential threat sources to address include accidental damages, aging and repeated loads.

The following are relevant excerpts from current published CFR the TAMCSWG considered to address the discussed structural bonding concerns.

CFR §25.601 – General

The airplane may not have design features or details that experience has shown to be hazardous or unreliable. The suitability of each questionable design detail and part must be established by tests.

CFR §25.603 – Materials

The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must--
(a) Be established on the basis of experience or tests;
(b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
(c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

CFR §25.605 - Fabrication methods

(a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process (such as gluing, spot welding, or heat treating) requires close control to reach this objective, the process

must be performed under an approved process specification.
(b) Each new aircraft fabrication method must be substantiated by a test program.

CFR §25.609 - Protection of Structures

Each part of the structure must -

(a) Be suitably protected against deterioration or loss of strength in service due to any cause, including -

(1) Weathering;

(2) Corrosion; and

(3) Abrasion; and

(b) Have provisions for ventilation and drainage where necessary for protection.

CFR §25.613 - Material strength properties and material design values

(b) Material design values must be chosen to minimize the probability of structural failures due to material variability…..
(c) The effects of environmental conditions, such as temperature and moisture, on material design values used in an essential component or structure must be considered where these effects are significant within the airplane operating envelope.

These paragraphs are explicit and address varying materials, their associated manufacturing processes, operating environments and design validation. They address the link between materials, fabrication methods and other design details addressed in structural sizing.

CFR §25.571 is of a major importance in the evaluation of any bonding processes durability.

Damage-tolerance and fatigue evaluation of structure.

(a) *General.* An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion, manufacturing defects, or accidental damage, will be avoided throughout the operational life of the airplane…….

(b) Damage-tolerance evaluation. The evaluation must include a determination of the probable locations and modes of damage due to fatigue, corrosion, or accidental damage. Repeated load and static analyses supported by test evidence and (if available) service experience must also be incorporated in the evaluation…….

Qualification and structural substantiation should provide sufficient data to demonstrate reliable bonding processes and materials, including the issues associated with manufacturing scaling. Fatigue, Damage Tolerance and Fail-Safe practices remain valid for structure constructed using a well-qualified bonding process that is under control. They will help cover the rare, local disbonding that may occur even for reliable bonding processes. The industry-recommended guidance updates in Section 4.2 for fail-safety (or more generally SDC) and damage tolerance cover damage threat, design, damage tolerance and inspection expectations within the realm of current industry best practices without a need for rule changes.

In conclusion: Existing paragraphs, CFR §25.601/25.603/ 605 /613 and CFR §25.571 are sufficient and correctly address the regulations needed for both composite and metallic reliable bonding manufacturing processes and the structural ability to sustain required loads under their operating environments.

4.0 Guidance recommendations

4.1 Historic Perspectives on Existing Guidance

The most complete regulatory guidance that currently exists for bonded structure is a policy statement called *Bonded Joints and Structures - Technical Issues and Certification,* which was issued in 2005 (Ref. 4). Although released as a small airplanes policy, it was derived from an interface with the industry for many aircraft product types, including transport airplanes, small and transport rotorcraft, engines and propellers. It addresses three types of bonding:

a) composite to composite,

b) metal to metal, and

c) composite to metal.

Appendix 1 details the historical background gathered through benchmarks of Industries practices. Main processes steps are developed with associated experiences and recommendations, on:

- Materials and process controls qualifications procedures
- Highlights between metal and composite bonding process controls
- Challenges in substitution (substrate materials, adhesives, bond process, etc.)
- Challenges in Manufacturing: manufacturing defects and inspections challenges
- Design and Structural substantiation

4.2 Experiences of OEM and Best Practices Guidance Improvements

4.2.1 AC 25.571-1D

This advisory circular provides guidance pertaining to the requirements for damage tolerance and fatigue evaluation of transport category aircraft structure, including the evaluation of widespread fatigue damage (WFD) and establishing a limit of validity of the engineering data that supports the structural-maintenance program (hereafter referred to as LOV). The requirements of § 25.571 apply equally to metallic and composite structure, although the focus of this AC is metallic structure. Refer to AC 20-107B for guidance on composite structure and for material and process control guidance relative to both composite and metal bond. All recommended changes proposed for AC 25.571-1D from the 2018 Main TAMCSWG Report (Ref. 7) remain valid. Below are generic descriptions of many additional word or phrase updates proposed for metal bond for AC 25.571-1D with added linkages to AC 20-107B where appropriate. See Appendix 4 for the specific word or phrase additions used in edits recommended for AC 25.571-1D.

Proposed change (1): First proposed change is a change of "corrosion damage" to "environmental damage" and "crack" to "damage" where appropriate. Note that there are still locations in this AC where "corrosion" and "crack" are appropriate for the given wording.

Reason for change: To be consistent with rule updates.

Proposed change (2): See Appendix 4 for the exact wording. Proposed change for the primary purpose of adding metal bond in a given paragraph.

Reason for change: Multiple purposes recognizing metal (or metal to composite) bonded structure may require consideration.

Proposed change (3): Proposed change is to 5(a)(1) under Introduction. It states that further guidance exists in AC 20-107B on metal bonding with a focus on material and process control.

Reason for change: Cross reference to other guidance of relevance.

Proposed change (4): Proposed change is to 5(a)(6) under Introduction. The sentence affected is; "Replacement times, inspections, or other procedures to address fatigue cracking and disbonding in metal bonded details must be established as necessary" This introduces disbonding in metal bonded structure relative to the discussion on replacement times and inspection.

Reason for change: Unique behavior of metal bonded structure may require consideration.

Proposed change (5): Proposed change is to 5(c) under Introduction, Structure to be Evaluated. This adds bonded joints to the list of structure to be evaluated.

Reason for change: Unique behavior of metal bonded structure may require consideration.

Proposed change (6): Proposed change is to 6(a)(4) under Damage Tolerance Evaluation, "design features that should be considered in attaining a damage-tolerant structure include the following:". Added (4) "Using disbond arrestment for metal bond joints as described in paragraph 6c(3) of AC20-107B and focusing on material and process reliability as stated in paragraphs 6c(2) and 6c(4) of AC20-107B."

Reason for change: Consideration of design features that provide damage arrestment in metal bonded joints, including recognition that stringent bond material and process controls are still paramount.

Proposed change (7): Proposed change is to 6(d)(7) under Damage Tolerance Evaluation, Extent of Damage, "The following are examples of partial failures that should be considered in the evaluation:". Added (7) "A detectable disbond of a stiffener or tear strap between arrestment features."

Reason for change: Consideration of disbonding representing partial failure in metal bonded structure.

Proposed change (8): Proposed change is to 6(h)(2) under Damage Tolerance Evaluation, Damage-tolerance Analysis and Tests. Updated (2) to include other environmental effects, "The repeated loads should be as defined in the loading, temperature, and humidity spectra while considering environmental effects caused from hydraulic fluids, fuels, cleaners and other detrimental materials found in operations."

Reason for change: Other environmental considerations for bonded structure damage tolerance.

Proposed change (9): Proposed change is to 7b.(1) under Establishing a LOV, WFD. Adding multiple stringer disbonds and/or weak bonds as possible items that could have an influence on WFD for metal bonded structure, “Global damage may occur in a large structural element, such as a single rivet line of a lap splice joining two large skin panels (multiple site damage). Such damage may be affected by multiple stringer disbonds or weak bonds in a panel that is using bonded structure to resist crack growth.” The end of 7.b.(1) was further updated with an added sentence to note: “The existence of metal bonded structure that has other aging mechanisms, including hydration phenomena, which strongly depends on moisture entrapment, will further complicate such degradation.” As a result, such phenomena would need to be evaluated using other procedures because the tests and analyses considered for WFD may not be updated to cover a repeatable or reliable simulation of accelerated hydration. Therefore; the onset of hydration noted for any metal bonded structure of such significance would invalidate other LOV assessments and require action.

Although disbonding could potentially be a WFD item it is not supported under the current rules as how WFD is calculated. It is also not an item currently simulated in a full-scale fatigue test or similar testing and would be difficult to address without better understanding of accelerated aging. Analysis for mechanical growth under environmental conditions may help to determine possible issues with failure modes but currently not reliable in understanding disbond growth. Consider tracking the fleet for any evidence of corrosion near important metal bonded structure as a better secondary consideration for ensuring this issue does not become a challenge for LOV of metal structure. As discussed in the 2018 report, Section 3.8.3, the baseline MSG-3 inspection program is the recommended means to track the fleet for any evidence of corrosion near metal bonded structure.

Proposed change (10): See Appendix 4 for the exact wording. Add definition of “environmental damage” in Appendix 2 of AC 25.571-1D.

Additionally, the premise of paramount importance is that we have a robust bond process where the existence of multiple weak bonds or failing bonds is remote. This is discussed throughout this report and is also the primary thesis controlling bonding within AC 20-107B. If properly achieved, it would require a systemic process failure to achieve multiple stringer disbonds and affect WFD. This needs to be noted within updates to AC 25.571-1D but that document has little existing supporting guidance to ensure that stringent bond process control is achieved. As a result, the reference to AC 20-107B simply needs to be reinforced throughout the document when bonded metal structure is any part of the critical structures affecting load paths, damage growth and other damage accumulation, particularly the phenomena of hydration, for metal structure having damage tolerance expectations and an LOV.

UK CAA WG NAA participant member also recommended that for consistency, AC 120-104: *Establishing and Implementing Limit of Validity to Prevent Widespread Fatigue Damage*, the objective to ensure protection for bond strength is maintained throughout the airplane LOV when such bond is relied on for protection from WFD (through enhanced manufacturing/process control, design and inspection programs) then such awareness should be highlighted in this AC as well. This recommendation was not extensively debated but no WG member shared any objection to this suggestion.

Reason for change: The influence of metal bond hydration is an obvious factor affecting aging, whether or not it is coupled with WFD in metal structure. It is supported by wording change from corrosion damage to environmental damage; however, there is no further guidance in AC 25.571-1D. Related sentences were added to the end of the definition of WFD in Appendix 1 and Step 4 of fatigue considerations in Appendix 3.

4.2.2 AC 20-107B

The procedures outlined in AC 20-107B provide guidance material for composite structures, particularly those that are essential in maintaining the overall flight safety of the aircraft and are considered acceptable to the FAA for showing compliance with certification requirements of civil composite aircraft. This circular is published to aid in the evaluation of certification programs for composite applications and these proposed changes reflect the status of composite technology. As noted at the start of this advisory circular, periodic modifications will reflect the continued evolution of composite technology and the data collected from service experience and expanding applications. All recommended changes proposed for AC 20-107B from the 2018 Main TAMCSWG Report (Ref. 7) remain valid.

The additional changes proposed for AC 20-107B below focus on a need for SDC (Structural Damage Capability[1]) or fail safety and calls for periodic inspection to reliably find disbonds between arrestment features substantiated as a category 2 damage threat. The former clarification is needed in Paragraph 6, as relating both SDC and fail safety applied as design attributes, while the latter clarification is needed in Paragraph 8 for inspection reliability and damage tolerance. In addition, the primary emphasis of stringent material and process controls, while treating bonding as an integrated system is further reinforced. Finally, there was a need to clarify the historical 23.573 requirement in AC 20-107B as suitable for all product types, with an emphasis on the quality system. In response to changes in Part 23 regulation to performance-based rules, industry has adopted the past expectation in best bonded structure design practices documented as CMH-17 guidelines (Ref. 2). This should be recognized in updates to AC 20-107B, while considering some exceptions for parts on other product types (e.g., rotor blades).

<u>Proposed change (1):</u> Proposed change is to 8(a)(1)(c)(ii) Category 2. See Appendix 3 for the exact wording. Add SDC or a failsafe condition for a disbond between arrestment features as a Category 2 damage threat to require inspections to find the damage, making it similar to the inspection done for visible impact damage. The change also recommends similarities in the inspection type used.

Reason for change:

The guidance material is clear in regard to the necessity of a residual strength check with a failed bondline between arresting features. By adding this material to the Category 2 definition it is asking for this damage state to be treated like other category 2 damage. This necessitates an inspection to look for the damage state to ensure detection of the disbond and the airplane does not remain under regulatory load requirements for its remaining life. See AC20-107B figure in Appendix 3. It is not a desired state to remain below ultimate load for an extended period. Also added to this paragraph is a recommendation stating that General Visual Inspection (GVI) is considered inadequate to visually detect bondline failures between arrestment. Instead, a detailed visual inspection (DVI) will find bondline cracks at a bonded flange edge. Industry will need to determine what is the most efficient, including a need for instrumented

[1] **Structural Damage Capability**, SDC, is the attribute of the structure (that) which permits it to retain its required residual strength in the presence of large damage. This definition is from 2003 Generalized Structures Harmonization Working Group.

NDI for some structural design details and other factors affecting detection. In addition, there are likely some cases where DVI and instrumented NDI would be ineffective for metal-bonded structures. See section 4.2.4.1 for discussions of the design criteria that could be tied to a large disbond damage threat, a specified inspection method and appropriate repeat inspection interval that requires structural substantiation data but provides additional damage tolerance in the event local processing mistakes that yield such damage. As with many design criteria the details can be based on specific structural capabilities and needs in specified locations.

Proposed change (2): Proposed change is to 6(c) Structural Bonding: See Appendix 3 for the exact wording. Add language to ensure the reliability of structural bonds both during manufacture and in-service. The design and execution of any structural bonded joint uses tests and analyses to demonstrate a strong and durable bond along with consideration of the full processing windows allowed by the governing specifications. The definition of a "Bonded System" is a joint consisting of the adherend material, surface preparation method, adhesive, and bonding process conditions used. Each component of the Bonded System needs thoughtful selection and rigorous evaluation for any variables that could affect bondline quality. Evaluate any proposed changes in a Qualified Bonded System made during manufacturing or the life of the production system by multiple methods that interrogate adhesion, consistent bondline performance, and durability across the spectrum of variables.[15].

Reason for change:

Add treating bonding as a system and any change in the system must be investigated (prep, adhesive, adherents, bond process) and tested within the process envelope. This lesson learned, derived by the OEMs from program experiences has been communicated in CMH-17, CACRC and other forums. It will be a part of CMH-17 Volume 3 Chapter 10 revision H release as well.

Also, as an added recommendation, use of bonding in single load path structure, where failure of the bond would result in the airframe's inability to maintain regulatory load levels (limit loads), is consistent with the other recommended AC 20-107B changes and updates in this section.

Proposed change (3): See Appendix 3 for the exact wording. Proposed changes to 6(c)(3), 6(c)(3)(a) and 6(c)(3)(b) all under Structural Bonding. The purpose of this change was to remove 23.573 reference, which no longer exists, but to keep its intent. In addition, this same wording needs to be appropriate for factory and field repair. Initially BRSL policy (PS-AIR-100-14-130-001) did not include factory repair but was intended for operator in-service repairs only.

A stronger emphasis is needed linking the SDC or failsafe criterion of a single disbond between arrestment back to quality. This is to emphasize that the design must have a highly reliable bonding system to allow this damage tolerant failsafe check to consist of only a single disbond. Updates should address the fault of relying on proof loading for the detection of weak bonds.

Reason for change:

- *Needed an update for the old §23.573 reference.*
- *Changed the first sentence in paragraph 6(C)(3)(a) "For any factory or in-service bonded joint including repair" to emphasize that bonded repair, in-service or factory installed, should satisfy limit load residual strength with a failure; the same as a factory production bond. This relates to an update to the BRSL policy to affect the same change.*

- *Add a link to paragraph 6 to emphasize quality and state that assumption of single disbond between arrestment features still relies on strict adherence to stringent process control requirements.*
- *Clarified the drawbacks to proof loading and its inability to detect weak bonds.*

Proposed change (4): See Appendix 3 for the exact wording recommendations. Propose change is to 10(c) Substantiation of Repair. The purpose was to add BRSL policy guidance to the section covering bonded repair.

Reason for change:

10(c) was updated to emphasize that when stating "Bonded repair is subjected to the same structural bonding considerations as the base design" that also meant that they must meet limit load with a failed bond between arrestment, as stated in bonded repair size limits (BRSL) policy.

4.2.3 AC 21-26A Quality System for the Manufacture of Composite Structure

AC 21-26A includes very generic guidance on 'bonding' materials, processes parameters and quality control plan, with no particular emphasis to structural bonding as reported in the extract from the existing AC below.

Extract from AC21-26A **(**07/23/2010) shown below refers to "Bonding" as part of a quality control plan in Paragraph 10.a:

> **a. General.** The following are manufacturing process controls that should be included in a manufacturer's quality system:
>
> (1) The PAH (Production Approval Holder) should develop integrated quality and production control procedures for operations that define product configuration, selection of materials, tooling and facility equipment, Calibration, sequence of manufacturing operations, critical in-process parameters and processing tolerances, and conformity to quality standards.
>
> (2) Environmental parameters (temperature, humidity, chemical contamination) should be defined and controlled, as required, where composite parts and structures will be produced, in particular, cutting, layup, *and bonding areas*.

Paragraph 10.c (note, only relevant excerpts are included here; unrelated excerpts are omitted):

> **c. Assembly of components.** The following are manufacturing controls unique to the assembly of manufactured composite parts and structures that a manufacturer's quality system should include:
>
> (1) Sandwich construction.
>
> (b) Cured laminates should be inspected for dimensional conformity. Faying surfaces should be properly cleaned and protected from contamination before subsequent assembly and bonding operations.

(3) *Secondary Bonding.*

(a) Cleaning procedures for surfaces to be bonded together should specify the chemicals and abrasives to be used on faying surfaces. Standards for determining properly cleaned surfaces and methods for protecting clean surfaces from contamination (including peel plies) should be available at the place of manufacture.

(b) Manufacturing standards should establish adhesive bondline thickness and pressure to be applied along the bondline during the cure cycle.

(c) Tool proofing procedures should demonstrate the capability of the tooling to maintain correct bondline thickness, equal pressure distribution along the bondline and properly cured adhesive.

(d) Before the application of adhesives, the production parts should be preassembled and inspected in the tooling to determine that the expected bondline thickness and pressure distribution on the bondline will be within design limits. Shims required to fill bonding gaps should only be used in accordance with an approved quality system procedure.

To avoid conflicting information in two separate guidance documents addressing the same topic the proposal is to delete the paragraphs on bonding in AC 21-26A.

Reason for change:

All points mentioned in AC 21-26A are covered with more detail (processes parameters) and dedicated design guidance in the AC 20-107B in:

(1) Paragraph 6 & 6a: Material and Fabrication Development, Material and Process Control points out very generic guidance on need of a reliable process, within Paragraph 5, need to identified key characteristics and process parameters for monitoring. And,

(2) Paragraph 6c: Structural Bonding, also applies to metal bonds, as it is stated bonded structures include multiple interfaces (e.g., composite-to composite, composite-to-metal, or metal-to-metal).

AC 20-107B is much more complete and detailed than what is presented in AC 21-26A today.

Therefore, the TAMCSWG recommendation is to update AC 21-26A to include a cross reference to AC 20-107B specifying, for any bonding technologies including design and quality control, the AC 20-107B is the relevant document.

4.2.4 Bonded Structural Considerations

4.2.4.1 Structural Redundancy – SLP and SDC

SLP discussion

The guidance for composite materials given in AC 20-107B recommends that the use of SLP design or a design that behaves like a SLP metallic structure be avoided. Although the AC sufficiently addresses these concepts for composite structures, Bonding requires clarification with the additional wording proposed in appendix 3. The proposed wording in appendix 3 states; "Even with this in place (rigorous material process control), bonding in single load path structure may not practically be used without further considerations as safety cannot be ensured through maintenance practices alone." Outside of bonding, no clarification is needed to the AC to adequately address structural redundancy and beyond by following the 5 Categories of Damage achieving the safety objective for these materials and construction.

This guidance developed by the structural bonding sub-team does not cover SLP bond-lines by recommending fail-safe features to maintain residual strength to limit loads.

Single load-path designs are only acceptable where deemed necessary due to the constraints of the design, but because disbonds are more difficult to detect than damage considered obviously detectable, additional evaluations and procedures are necessary in defining a bonded SLP inspection program. By adding guidance for disbond arrestment to category 2 structure as recommended in the edit of AC 20-107B in appendix 3, inspection required to ensure limit load structural capability with a failed bondline is maintained for the airframe service objectives. For SLP structure compared to designs with SDC, this typically dictates an instrumented NDI to look for disbonds before they could become critical. This damage state will likely be non-visible and much more difficult to find than looking for a large disbond between arresting features in Multiple Load Path (MLP) structure. Still the recommendation currently stands for bonded SLP structures as the inspection intervals used to capture disbond growth require structural methods and testing that are not well established within an existing design environment. Also noted here, is an added maintenance recommendation in applying an instrumented NDI burden for bonded SLP. Furthermore, NDI detection of weak bonds is not normal practice and, as a result, bonded SLP for metal bonded structures is strongly discouraged.

As discussed in the final TAMCSWG report, the historical record supports the continued emphasis on MLP construction for most of the airframe structure. However, a review of the accident records and OEM experience does not indicate an issue with SLP construction if applying the principles of damage tolerance. Although for SLP bonded structure, this OEM experience has very limited application and service history as compared to metallic construction and needs further consideration. It is worthy of note that bonded rotor blades (both metal and composite), which have traditionally been SLP, have had several catastrophic bond failures leading to loss of life (Ref. 3).

- SLP composite structures are acceptable if supported by a proper damage tolerance based inspection program. However, an understanding of reliable analysis methods, testing and a suitable inspection program to establish inspection intervals for composite bonded SLP joints have little past experience for critical transport structure and likely depend on initial flaw size assumptions. In addition, accidental and environmental damage tend to rely on conservative design criteria that, by definition, would likely not include visually obvious damage for a SLP.

- For composite material construction in general, the concepts of MLP and SLP do not have the same level of definition as for metallic construction for reasons described in the previous bullet. Also, the benefits of fastened vs. bonded structures are not fully established. The safety objectives are outlined in AC 20-107B and require no rule change to support them. However, for SLP bonded structure the TAMCSWG recommends further guidance in AC 20-107B.

As noted for other SLP, SLP bonded designs should have much higher reliability compared to redundant bonded designs or those with SDC. Although this is a good basic statement, high reliability of bond materials and processes is already required regardless of structural redundancy. However, bondline in-process controls and service inspections for SLP repair designs should be the most rigorous possible to ensure safety is maintained, bringing significant economic impacts into such decisions.

- If MLP structure is impractical, the applicant should perform these additional steps to support the SLP design

  - Minimization of environmental and accidental damage (i.e. consider protection, different materials)

  - Perform a fatigue test (including consideration for any real-time environment and aging effects) or complete fatigue analysis based on test to demonstrate an acceptable level of durability and environmental reliability. This would be a challenge considering current knowledge relating to accelerated tests in this area but future developments may be possible.

  - Develop a manufacturing process control and tracking plan document, including a thorough assessment of processing windows and all possible interactions between various parts of the Bond System. In the end, The document should include details of the bond surface preparation and subsequent handling controls leading up to the bond assembly and cure, and how they are to be controlled in time, exposure to environment and contamination since these are essential parts of these documents for a given bond system.

  - A fleet leader strategy would benefit such practice (similar to what is done with rotor blades), including regular NDI inspections and more extensive destructive testing when possible. However, it should be noted that airlines and other transport airplane owners are not required to participate in such efforts and/or share the results with OEM. Regardless, any reports of bondline degradation in primary structure is a reportable condition under 21.3(c)(8).

    Note, NAA participants with this WG have strongly endorsed the value of applicants employing a fleet leader strategy to assess service-aged bond integrity, which may include enhanced inspections beyond normal maintenance (NDI) and, or destructive teardown on appropriate, high-timed sacrificial samples.

  - SLP bondlines are particularly critical with respect to quality escapes (i.e. weak bonds) and use of a conservative approach to setting inspection intervals is recommended.

Structural Damage Capability discussion

Structural Damage Capability (SDC) is the attribute of the structure which permits it to retain its required residual strength in the presence of large damage. The overall purpose is to prevent catastrophic failure resulting from damage not accounted for in damage tolerance analysis. SDC is a characteristic of the design of a structure, and is therefore, not specifically tied to any one aspect of a maintenance program. However, current TAMCSWG recommendations are to supplement the SDC and/or fail safe design recommendations with data supporting reliable Category 2 damage tolerance classifications. This is still relying on stringent bond process controls that would very rarely allow the large damage formation within the extent of redundant design features or larger areas covered by design criteria. Transport experience has indicated that bond processing challenges remain an issue that requires such safety measures.

The TAMCSWG Bond TG discussed defining SDC within AC 20-107B as general design attributes set as company design criteria for purposes of maintaining consistent design practices and some additional level of safety for a particular part, location or feature of the structure that would benefit from a specified level of robustness. Details of a given SDC may be product, part and location specific, enveloping a range of damage scenarios from damage threat assessment (a generalized "redundancy parameter"), facilitate efficient maintenance practices and supplement the categories of damage as defined in AC 20-107B. This definition of SDC, unlike Category 3 damage, does not require it be in a structural location whereby the damage would be found in a short period of service time. It is still consistent with primary expectations for bonded structure that process controls are sufficient to ensure such damage is extremely rare; hence an allowance that it can be of that size for long periods of time. Although these discussions seemed relevant since current composite Categories of Damage allow applicants to define their own related damage tolerance design criteria for such purpose, the TAMCSWG decided not to redefine SDC as a generalized term used for composite damage tolerance design criteria because that is significantly different than the original definition derived for metallic structure at a time when composite damage tolerance was considered separately and not included in AC 25.571 guidance.

Instead, the specific damage tolerance design criteria (DTDC) used for updated Categories of Damage encompass the above discussions, while not causing confusion with the term SDC that has been considered for metallic structures and accepted by industry only if there is no specific regulatory requirement or recommendations given in metallic guidance. As a result, AC 20-107B could continue to encourage industry define specific composite DTDC to cover structural bond design and process needs, as is currently the case for guidance supporting categories of damage given in Paragraph 8 (see Ref. 2 for composite industry guidelines in this area, including the current discussions that encourage large disbonds subjected to Category 2 expectations to substantiate inspection intervals based on damage tolerance and practical DTI field inspection methods). Note that the following examples for DTDC involve bonding but similar approaches may be applied to other damaged composite structure to supplement damage tolerance.

- Specific DTDC applied for Category 2 damage or other Category 3, large damage scenarios in areas *not obviously detectable* to an extent it would be reliably found while still protecting safety. In this case, the DTDC would specify how damage is simulated in test and analysis, as well as define the detection/inspection procedure used to reliably find the damage. When the damage threat is larger the risk that it exists must be very rare, as currently noted for both the fail safe and SDC condition. The difference comes in generating the necessary structures data to allow such rare but large damage to exist for long periods based on the supporting damage tolerance data and a long inspection interval. As implied by current AC 20-107B supporting logic, the closer such a damage threat gets to limit load capability, the potential for its existence must be extremely rare. However, the long inspection interval must be substantiated as part of the damage tolerance data.

- Example 1: DTDC for a large disbond within the spacing of arrestment features for bonded stiffening elements where visual detection schemes would find the damage using the same existing DVI procedures applied for Category 2 impact damages detectable within a torque box or fuselage shell structure. The detailed inspection would look for a disbond due to a weak or understrength bond, as well as a severe impact event that does not include other evidence of such an impact (e.g., fiber breakout over wide areas).
- Example 2: DTDC for the bondline within the critical load path of a SLP structure whereby the design can sustain a conservatively small but detectable disbond with no growth and Limit load strength over repeated load cycles protected by maintenance inspection intervals.
- Example 3: DTDC for a hidden structural design bondline that does not require specified "arrestment features" to sustain a large arrested disbond and limit load for an inspection interval.

These examples also help the reader realize that DTDC would not only be reserved for a large damage in acreage structure but also for other design criteria of a smaller damage that spans a significant part of a cross-section. It should also retain attributes of being easily detectable bondline damage in SLP structure that reliably demonstrates "no growth". In effect, the DTDC used for a company-specific barely visible impact damage (BVID), category 1 damage follows the same logic and requires a given companies approach used in defining allowable damage for different parts of a composite structure and further identified in maintenance manuals that zone allowable damage limits (ADL) throughout the structure.

Coming back to the existing definition of SDC, it still has relevance in comparison to bonded structure fail safety, even when obvious redundant design features don't exist (e.g., bonded structure capable of large SDC, without fastened redundant design features). In this case it remains supplemental to damage tolerance for bonded composite, metal and composite to metal structures and should be considered an appropriate alternate design means of compliance because the primary safety risk mitigation is maintained through stringent process controls that very rarely allows large areas of disbonding, which is still expected to have the fail safe or SDC capability to safely cover those occurrences.

Gulfstream pointed out that the use of a category 2 DTDC may not be appropriate for metallic structures because the primary threats to bondline integrity are due to hydration and associated corrosion. These threats should be managed through the MSG-3 ED inspections as discussed in the 2018 report, Section 3.8.1. While the specific disbonding of the adhesive layer may not be detectable, evidence of corrosion in the metallic structure adjacent to the bond will provide a visual indication of damage to be investigated further.

For metal bond structure, several NAA members recommended that the corrosion prevention and control program (CPCP) include a fleet leader component for tracking any corrosion noted in the vicinity of bonded joints and if present, rendering the structure for further inspection that may or may not allow an extension in the corresponding LOV.

However, as discussed in the 2018 report, Section 3.4.2, a Fleet Leader approach has not been applied or recommended:

It was discussed among manufacturers whether a fleet leader program is a current practice and it was concluded that no systematic fleet leader approach is applied.

A specific fleet leader program is not recommended because:

- There are no provisions in Part 25 to implement a fleet leader program beyond mandating special inspections for the 'high time' airplane in the ALS. This would be very burdensome for the affected operator and would not be practical.
- The MSG-3 program is a 'fleet leader' program in that it is calendar based, is universally applied to the fleet and has provisions for tracking, feedback of results and even fleet leader inspections. These inspections should form the basis of the corrosion protection program and be referenced in the ALS as discussed in the 2018 report, Section 3.8.3.
- Instead of the above recommendation, the guidance should state that the applicant should clearly identify in the ICA (per CFR 25.1529) the follow-on NDT and other procedures necessary when evidence of corrosion exceeding the limits is found in the vicinity of bonded joints, and that the findings should be reported IAW 14 CFR 21.3 and implications on the LOV evaluated as a service difficulty.

Damage tolerance is the ability of structure to sustain anticipated loads in the presence of damage until it is detected through inspection or malfunction, and repaired. It should be emphasized that SDC is not a replacement for damage tolerance – SDC adds robustness to the inherent structural design and typically aids any damage tolerant inspection practices through ease of detection. As a result, SDC like fail safety addresses unforeseen damage and complements existing damage tolerance inspection requirements. It does not generate any additional inspection or inspection threshold requirements; these should already be accounted for by existing baseline and damage tolerance based maintenance programs. However, inherent SDC for a given design may prove to be a replacement for structural redundancy when specific arrestment features are not required in achieving desired load levels when large, clearly obvious damage is present (depending on load levels and design details, this is sometimes the case for sandwich construction capable of meeting damage tolerance load requirements with larger damage than a redundant structural design).

Again SDC is defined as an inherent design attribute and is not specified by regulation, instead it is adopted by a company through their own design criteria for consistent design practices for many different damage threat considerations. It complements the more formal inspection programs derived through damage tolerance evaluation (DTE). At a high level, types of damage could include wear, environmental deterioration, impact, heat damage, disbond and delamination. General sources of damage could be from loading in service, the environment, accidental damage, maintenance errors, discrete events and manufacturing defects. The evaluation of a given critical structure for SDC is intended to ensure that, in the event of a certain level of damage, the remaining intact structure is capable of carrying the required residual strength loads. In this aspect it can be thought to represent a generalized fail safe condition. When assigning an additional DTDC to a hidden SDC-type damage, requiring proof of structure involving repeated loads, residual strength and corresponding inspection methods/intervals, it is best to refer to it as a DTDC and not use the acronym SDC, which usually only provides proof of residual strength.

4.2.4.2 Other Structural Considerations

The remaining focus of this discussion will be on bonding in MLP structure. For SLP structure see the previous dedicated section focusing on that subject at the start of Section 4.2.4.1.

i. Bonding definition per AC 20-107B: 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.

ii. MLP definition for bonding: Multiple load path structure with damage arrest features, i.e. bonded composite structures which incorporate 'damage containment features'.

This is applicable to co-bonded and secondarily bonded critical structure and applies to composite-to-composite, composite-to-metal and metal-to-metal bonds in multiple load path (MLP) structure. To satisfy DTDC the structure should:

(1) Establish that non-obvious damage to a bond line due to manufacturing, environmental or accidental causes, does not create or cannot propagate to a condition where less than limit load capability for the critical structure remains; or,

(2) Prevent disbonded structural configurations possessing less than limit load residual strength capability by tangible features of the design that will arrest disbond propagation.

(3) Achieve predominately cohesive or interlaminar failure modes demonstrating high bondline quality. This is possible when using stringent process controls, incorporating proven surface preparation methods that achieve a clean and active bond surface.

Any disbond which would result in structure having less than ultimate load capability for the design service goal (DSG) of the aircraft, must:

(1) Be detectable by visual means which may be accomplished by using the baseline maintenance program (ED/AD); or,

(2) A repeated instrumented inspection (NDI) shall be required as part of the baseline in-service inspection plan. This is expected to have significant cost impact, particularly in the case of metal bonded structure where a threat relating to weak bond hydration phenomena may also be very difficult to substantiate.

4.2.4.3 Adhesion Failure

Adhesion failures, which indicate the lack of chemical bonding between substrate and adhesive materials, are considered an unacceptable failure mode for both MLP and SLP structure in all test types and under any design environment. Changes to qualified bonding systems (substrate, surface preparation, adhesive or processing) should be assessed for risk and validated by test as appropriate. Other issues to consider:

(1) Damage arrestment features may be needed to reduce the risk of disbonded areas on adjacent stiffeners overlapping in a structural cross section. For example, fastening

stringers to the skin at each frame reduces the risk of a disbond in one frame bay propagating into the next bay where an adjacent stringer may also have a disbond.

(2) If significant changes in structural stiffness, geometry, or both, follow from a structural disbond or partial disbond, the effect on flutter must be assessed as a result of the structural disbond.

(3) Cyclic load testing should demonstrate no detrimental damage growth unless an arrested growth or slow growth approach is used. See AC 20-107B for further guidance on these approaches.

(4) Limit load residual strength should be demonstrated after cyclic loads testing. Appropriate environments should be accounted for.

4.2.5 Maintenance Repair and Inspection Considerations

This TAMCSWG identifies a potential gap between the technical knowledge between TCHs using complex bonding systems in the product design and the non-TCH organizations which are engaged with the on-going maintenance. Certain industry and regulatory coordinated activities have intended to help mitigate this knowledge gap with the shared objective to ensure the safety objectives are seamlessly met between TCHs and other properly delegated MROs.

The FAA and Industry have made a concerted effort for knowledge transfer (documentation and course development) as related to composite bonded and bolted repair substantiation, as well as a need to report any challenges and the subsequent root cause analyses of base bonded structure or repair failures found in the field. Of particular concern are any challenges that involve adhesion failure of the structural bonds. In recent years, the FAA and EASA have supported several free seminars given by Max Davis at the SAE Commercial Aircraft Composite Repair Committee (CACRC) and CMH-17 Meetings on bond failure forensics, with some emphasis on metal bonding.

The SAE CACRC made a concerted effort for knowledge transfer by establishing multiple training curriculums for inspectors, technicians, engineers, managers and auditors. Table 1 below provides the report numbers, document names and most recent publication dates.

AIR4938C	Composite and Bonded Structure Technician/Specialist Training Document	Sep 19, 2018
AIR5278	Composite and Bonded Structure Engineers: Training Document	Oct 13, 2016
AIR5279	Composite and Bonded Structure Inspector: Training Document	Oct 13, 2016
AIR5719A	Teaching Points for a Class on “Critical Issues in Composite Maintenance, Repair and Overhaul”	Sep 05, 2018
ARP6262A	Basic Composite Repair Technician Certification Standard	Sep 10, 2019

Table 1. CACRC Standards for composite training.

Further industry & regulatory partnerships exist in advancing the science of structural failure analyses performed with failed structures subjected to post-crash fire conditions, where significant evidence may be altered and require special considerations or advanced techniques to generate useful results. Known causes of past adhesion failures (e.g., various forms of surface contamination, including evidence of certain chemicals, peel ply residue, amine blush, etc.) remains an emphasis within this work because they suggest improper bond execution and/or an unqualified bond system. In many cases, these processing challenges were minimized by design practices and good manufacturing records. However, there is still evidence that the problems and related solutions have remained unpublished as a specific industry problem and became recurring in the experiences of other applications. Regulatory efforts to share this safety knowledge throughout the industry have been successful but work needs to continue researching typical root causes and adopting in-process controls to eliminate the potential. Unfortunately, the field is generally the last to receive knowledge needed to avoid bonding problems. As such, this TAMCSWG recommends continuation of these types of industry & regulatory collaborative activities.

Content in the following section summarizes past composite guidance focused on bonded structures as part of the continued work on standard best industry bonded structure maintenance practices. The content best belongs in future industry standards, maintained by an international standards organization that represents the industry interest in safe and efficient engineering and related maintenance practices.

Service Experiences, Including Benefits from Fleet Surveillance

Many of the technical issues discussed in Appendix 1 under the headings of *Material and Process Control*, *Manufacturing Challenges*, and *Design & Structural Substantiation* are important to maintenance implementation, including bonded repair and inspection. This subsection will emphasize the unique aspects related to damage detection, subsequent inspection for a full characterization of the damage and the proper execution of a substantiated bonded repair.

An assessment of the full extent of damage that requires a bonded repair is the starting point for current discussions. In most cases, damage detected visually still requires NDI of the damaged area to characterize the full extent of damage. Once characterized and found to be within repair size limits given in the structural repair manual (SRM), it may be determined whether previously substantiated repair procedures exist. If not, considerable pre-repair efforts need to establish a qualified bonded repair system to specify with a repair design and gather the necessary structural substantiation data (usually bounded by the tests and analyses performed). The same SRM-based qualified bonded repair system may be a candidate for use outside the repair size limits given in an SRM but *not* without additional structural substantiation, including consideration of regulatory guidance covered in the next subsection.

Service experience of bonded structures and repairs provide the final proof of a properly executed and reliable bonding process. Discovery of bond adhesion failures in the base structure or a bonded repair in service justify immediate directed inspections and repair actions. Thorough production or repair records are important to tracing the probable cause of such a problem. Some experts believe that service monitoring of bonded structures or repairs, including selected NDI, and teardown inspections for retired aircraft, provides data to correlate accelerated test results from qualification and in-process control with real time service exposure. The FAA has led research in this area with help from industry. Please see some case studies assembled with the help of airlines and documented to initiate additional research, guidance and training developments (Ref. 8). In addition to the CMH-17 Revision H efforts in Volume 3, Chapter 14 to provide guidelines and industry best practices for bonded repair substantiation, the FAA is developing a related short course on this subject that is scheduled to be available to industry by 2021. Future plans to continue research, includes studies on aged repairs following years of service and the repair of aged composite and metal substrate materials/structures to ensure that approved surface preparation and other bonded repair process steps remain effective. The TACMACSWG recommends the FAA continue to sponsor these activities and to make timely publications sharing the results with industry and National Aviation Authorities (NAAs) in supporting or guiding any future guidance or policy, as appropriate.

Repair Size Limits

In late 2014, the FAA released policy (Ref. 6), which reviewed the regulatory basis and established guidance in setting size limits for bonded repair to critical composite (monolithic and sandwich structures) and metallic structure. Bonded repair of critical structure (as defined in AC 20-107B) must first be constrained to the sizes allowed by substantiating design data. This policy informs Aircraft Certification Office (ACO) engineers and designees that due to inspection limitations, bonded repair must be further limited to a maximum size whereby the structure retains limit load residual strength with a complete or partial failure of the bond within the repair or base structure arresting design features. EASA has a corresponding Certification Memo CM-S-005.

The FAA and EASA documented bonded repair size limits, which are consistent with other composite guidance (Ref. 5), provide additional details on the limits of structural repair substantiation. In some cases, repair size limits defined by the substantiating data are smaller than that constrained by the maximum size capable of limit load residual strength with a complete or partial failure of the bond within the repair or base structure arresting design features. This will naturally occur if a given OEM does not assume liability for larger repairs performed per approved documentation. In fact, it is common industry practice to give some repair facilities larger limits than other shops based on past repair achievements and/or added in-process quality controls.

The current policy for bonded repairs follows similar safety risk mitigation procedures adopted by industry for structural bonding and rework with critical structures. General best practices for many critical structures use failsafe design features whenever safety threats exist for manufacturing defects, accidental damage, fatigue loading and environmental degradation. Bonding challenges exist in each of these areas. The first issue associated with "rare bond processing mistakes" leads to common design criteria that ensures the structure has sufficient bond strength to carry limit load if bonding is lost between arresting design features. This has often been referred to as the use of "chicken fasteners" but that is clearly not the case when realizing that many critical structural designs can't carry limit load if disbonding occurs in adjacent bays of bonded structural details (e.g., wing stringers disbonding past two mechanically fastened rib stations). When considering accidental damage caused by significant impact damage events for thinner skin gages (e.g., outer wing skins for a wide body transport and empennage skin panels for narrow body transport), the disbonding occurring at skin/stinger interfaces may approach this critical size because the resulting peak shear loads cause that much damage. Finally, environmental degradation is always a challenge for further bond degradation, particularly in the case of metal bonding.

Bonded repairs require approved design and strict processing control to ensure good quality for specific materials and processes used. Common process errors such as high humidity, improper surface prep, bondline contamination, insufficient temperature control (overall heat management to avoid overheating or under-cure), loss of vacuum or pressure, and use of materials outside time and temperature or calendar life limits can cause low bondline strengths. Finally, no reliable post-process NDI techniques currently exist to ensure a bonded repair has full strength.

FAA approved substantiation data is required to demonstrate compliance with regulations. The data starts with approved material and process specifications followed when installing a repair. Experience has shown that when experienced technicians install approved repair designs using proper tooling, equipment and procedures in accordance with specifications there is reasonable confidence the bondline will achieve full strength. The substantiating data that supports proof of structure for the bonded repair must also include the tests or analyses supported by tests that meet the applicable regulatory requirements for fatigue and damage tolerance, static and dynamic strength, material and fabrications specification, statistical material design values, flutter behavior, and lightning protection.

An industry composite working group met over several years prior to release of this policy to discuss the technical issues for bonded structural repairs and the best practices needed to show compliance with the regulations. Supplementary background information compiled in these meetings is included in a public reference (Ref. 9). Attachment 1 to Ref. 6 further documents some of the discussions associated with experience in bonded field repairs and a need to follow approved documentation, while avoiding reverse engineering approaches for specific critical composite structure.

AC 20-107B (Ref. 5) provides some further discussion of the bonded structure or repair qualification, quality controls and reliable procedures needed to ensure weak bonds are rare. The bonded repair size limits are first constrained by the data collected in establishing sound fabrication processes and substantiating the design. In addition, the bonded repair may be no larger than needed in demonstrating residual strength for a failed repair. All other approaches applied in establishing bonded repair size limits must have approved substantiating data, inspections or other procedures, as necessary, to prevent catastrophic failure. Residual strength requirements with the repair failed must be shown by tests or analysis supported by tests. Some structures have limit load capability, even with a very large failed repair. If significant changes in structural stiffness and/or geometry result from the failed repair, analysis for flutter and other aeroelastic instabilities are performed to ensure the failed repair does not lead to other flight safety issues.

Documentation on all repairs added to the maintenance records for the specific part number supports future damage disposition and repair activities performed on the same part. It also helps ensure the associated data, including repair design and process details, structural substantiation evidence, and inspection procedures, are available to those evaluating airworthiness. Some specific guidance on the engineering data and procedures, including the information needed for repairs not in compliance with the existing Design Approval Holders' Manuals, appears in AC 43-214 (Ref. 10).

Any failed bonded metal or composite repairs should be reported through the normal incident or accident reporting process (e.g., failure, malfunction, or defect reports required by 14 CFR 21.3 or service difficulty reports required by 14 CFR 121.703).

The inspection of bonded repairs, including the specified inspection methods, interval and detection criteria, must be defined based on substantiating tests, analyses, trials, and other safety risk mitigation procedures. With so many, different organizations reacting to the challenges of generally non-standard, best industry composite and bonded structure maintenance procedures, the TAMCSWG recommends that the FAA continue to seek international standards in this area.

OEM to Operator/Maintenance Knowledge Transfer

An Industry/Regulatory Composite Working Group (IRCWG) has addressed bonded structure, damage tolerance and maintenance since 2005. Industry knowledge of many field design and application details for these subjects were not widely documented in public reports before these efforts. Charter members for the IRCWG were Airbus, Boeing, EASA and the FAA. Figure 2 shows some of the important milestones relating to IRCWG efforts over the time of its existence. The group remained active during current ARAC WG efforts, helping to educate members not readily involved in composite applications. As also noted in Figure 2, other members joined in this effort from the Bombardier and Transport Canada Civil Aviation (TCCA) near 2011. In fact, most TAMCSWG members having experiences in bonding contributed to the milestones shown in Figure 2. Those TAMCSWG members felt that it may be difficult to continue such support at this level into the future given retirements and other related factors.

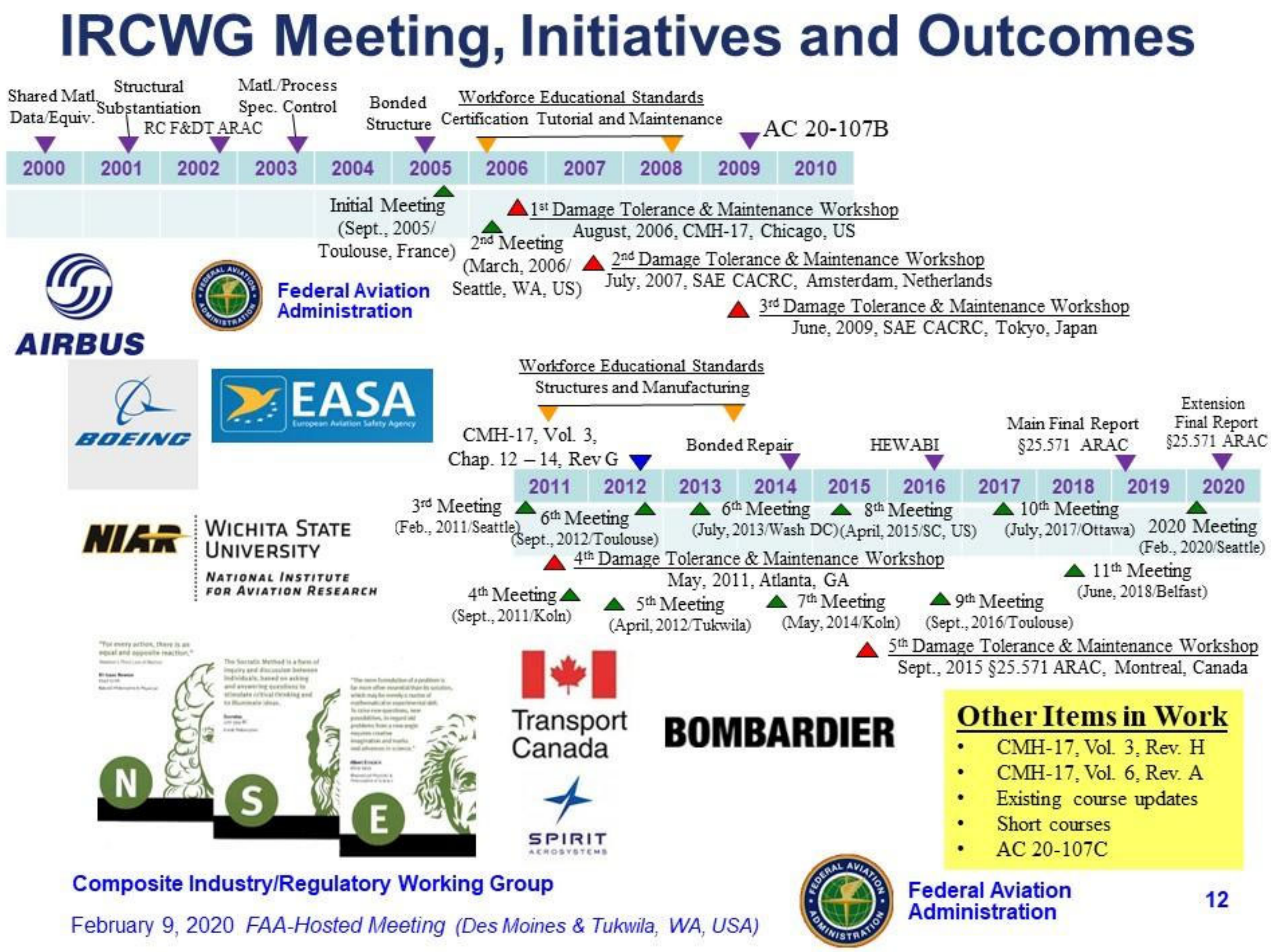

Figure 2. A timeline showing Composite Damage Tolerance and Maintenance Initiatives affecting related FAA, EASA and TCCA regulatory guidance releases and educational materials.

Early meetings in 2005 and 2006 were associated with the development of a Composite Certification Tutorial presented before CMH-17 Meetings and a composite maintenance, safety awareness, course developed for the industry and FAA Flight Standards Inspectors. The composite maintenance course, which was co-developed with the SAE CACRC, has a related standards document on the key objectives and teaching points to facilitate the development of an international course standard. This document has undergone periodic updates over time and most recently revised as AIR-5719B (Ref. 11). The IRCWG also led three industry/regulatory workshops (2006-2009), expanding industry and regulatory involvement, and creation of CMH-17 Volume 3, Revision G updates for fatigue, damage tolerance and maintenance. The related efforts made best industry practices public, forming a basis for the primary regulatory guidance under development, AC 20-107B (Ref. 5), released in 2009. This regulatory guidance as harmonized with EASA AMC 20-29, includes the most complete coverage on fatigue and damage tolerance and related maintenance practices for composite structures.

Note that the Composite Maintenance Technology (CMT) Course, taught for Flight Standards Inspectors for more than 10 years, was also available to the industry through Wichita State University (WSU) for several years after it was first developed. The WSU CMT course had industry instructors from United Airlines and Delta Air Lines when it was last taught. It is currently under reconsideration at WSU and potentially restarted in the coming years. The FAA course remains available to the FAA only through ABARIS Training Resources, Inc.

In 2011 and 2012, the CMH-17 Revision G documents were released, supporting the more general guidance from AC 20-107B with means of compliance details for an industry that has not achieved the same level of standardization as metallic applications. One of the primary reasons for delays in standardization is that the composite fatigue, damage tolerance and maintenance practices are far more data intensive and dependent on design criteria, empirical design values and related design constraints; and hence, company-specific structural design and processing details than metallic designs.

Metallic damage tolerance uses mature analytical methods and shared material data to address crack growth and establish maintenance practices for many different structural details. Growth of a limited number of small cracks typically do not affect composites. Instead, the damage tolerance of bonded composite structural details depends on accidental damage that include countless matrix cracks, relatively large delamination in multiple layers and fiber failures, which is difficult, if not impossible to analyze due to an unbounded number of interacting damage metrics, which affect damage stress concentrations and load redistribution. This is true even though composite damage assumed for purposes of design typically only grows in residual strength tests with increased loads approaching final failure. However, growth is not evident in smaller accidental damage or manufacturing defects under realistic fatigue load conditions. As a result, tests and supporting analyses demonstrate that these defects may exist for the life of the structure, without loss of Ultimate load strength capability. Use of composite structures is desirable in modern aircraft design due to significant weight savings (about 20 to 25%), the associated reduced fuel costs, as well as advances towards reduced manufacturing and maintenance costs.

Composite damage tolerance focuses on residual strength predictions which may be semi-empirically managed using stress concentrations and load redistribution factors similar to metals when assuming the largest accidental damage sizes behave similar to large notches (e.g., Category 3 company-specific, design criteria). Even smaller accidental damages use a process for deriving the appropriate design values and no-growth demonstrations for conservative Category 1 and Category 2 design criteria. Stiffened panel tests of sufficient size help establish conservative design curves for static strength (with allowable barely visible impact damage, BVID) and clearly visible impact damage (CVID) damage tolerance repeat inspection intervals. Unfortunately, OEM have not combined efforts to standardize these design criteria, conservative design value test practices and the specific materials and processes used to manufacture composite fuselage, wing, empennage and control surface principle structural elements (curved shell structures, torque boxes and the associated attachment details). With the current state of the industry and standards for associated materials and processes, it seems unreasonable for such standardization to occur. However, efforts are underway to make the specific design practices more visible, allowing end users (airlines and cargo transport companies) and third party maintenance organizations to better understand how design criteria and constraints can facilitate affordable solutions for related engineering problems that require significant structural testing.

The areas where composite damage tolerance analyses have advanced to support the specific damage threats include checks for lost bonded structural capabilities between base design arrestment features and lost bonded repair skin patch/element details. In both of these cases a representative damage state can be defined and simulated in the analyses to predict disbond or delamination growth and the effect on structural residual strength. Such analyses require an assessment of the in-plane stress concentration, including loads redistributing due to element buckling and any growth occurring between bonded elements. The approach for the former still relies on semi-empirical data and/or failure criteria for the specific skin laminates, which may have in-plane stress concentrations such as holes or other structural design details (e.g., as applied in meeting expectations to define bonded repair size limits for limit residual strength assessments). The design and related analysis approach for lost bonded attachments between bolted structural arrestment details have used more analytically-based fracture mechanics approaches. The associated fracture toughness data to address composite design details may require more material properties (Mode I, II and III fracture properties) and interaction criteria for the most general, mixed mode cases arrested by fastened design details. When growth is possible, this effort may require affordable NDI options or it becomes further complicated because visual detection of larger disbonds require internal access to composite structures and; hence, the desirable inspection interval has longer time periods to accommodate the higher costs associated with access.

Figure 2 shows that efforts to create additional composite safety awareness courses spanned the times from 2011 through 2013, covering both structures and manufacturing disciplines. The most extensive course was for structures technology, which spans two full weeks of classroom time to cover material and process control, design, structural substantiation, manufacturing interface, maintenance interface and other considerations. In this same timeframe, Bombardier and Transport Canada became active members of the IRCWG, supporting CMH-17 efforts for Volume 1 & 3, Revision H and Volume 6 (Sandwich), Revision A, all of which had related bonded structures, damage tolerance and maintenance initiatives that expanded with the onset of the current ARAC TAMCSWG efforts. In 2014, the IRCWG Bonded Repair Initiatives completed initial efforts in developing the detailed basis for CMH-17 and CACRC guidelines supporting bonded repair size limits. The FAA and EASA published related guidance late in 2014. In 2015, a fifth Damage Tolerance and Maintenance Workshop conducted in combination with a special session of the TAMCSWG (at Bombardier in Montreal, Canada) helped provide some of the first public information on experienced industry guidelines for hybrid composite fatigue, damage tolerance and maintenance practices. Both bonded repair structural substantiation and High Energy Wide Area Blunt Impact (HEWABI) damage also had special sessions at the workshop.

As shown in Figure 2, the FAA initial release of the HEWABI policy statement came in 2016. Concerns for significant disbonding and delamination with HEWABI occurring to bonded and co-cured composite structures relate to observations that very large areas of such damage are possible, without obvious external visual evidence of failure because the skin panels may spring back following such an event.

Detection of the significant lost structural integrity is possible using practical NDI procedures, including those spanning large areas of the structure with lower-frequency bending waves but the trigger for such an inspection depends on reliable reporting of the occurrence of impact damage. The TAMCSWG Final Report (Ref. 7) has ARAC discussions on other considerations relating to HEWABI, including recommendations for future FAA policy updates.

The IRCWG Meetings held from 2017 into 2020 have focused on further efforts that support composite maintenance technology, knowledge transfer from OEM to operators and maintenance repair organizations. Two main areas have been active. The first relates to sandwich disbond phenomena, which can potentially lead to additional undesirable failure modes (e.g., fluid ingression, freeze/thaw honeycomb core degradation) that can yield lost structural integrity. This phenomenon is undesirable and is very difficult to predict beyond the initial disbond growth, as the additional failures are very complex and dependent on several contributing variables, many of which lack practical understanding and solutions. As a result, the focus of the effort is to establish sandwich panel designs whereby relatively large disbonds are quickly arrested or unable to grow. Ref. 12 provides a summary of this industry/regulatory initiative, which has plans for CMH-17 Vol. 3 (Rev. H) and Vol. 6 (Rev. A) documentation by 2022.

The other area of recent IRCWG focus was that of substantiation of bonded repairs (SoBR), which traditionally proved to be a challenge for the field of both metals and composites. The Safety Management portion of CMH-17 PMC Volume 3, (Chapter 17) provided a continued operational safety (COS) basis for this initiative in Revision G (released in 2012) when it documented real-world case study highlights relating to Ref. 8. Multiple field repairs developed without the assistance of an OEM and beyond repair options documented in a Structural Repair Manual for the specific part on a given product have proved to lack structural integrity, leading to unsafe conditions. The delinquent repair typically linked to a root cause involving inappropriate/unqualified material or process substitutions, avoidance of tooling, and little or no proof of structural substantiation for the actual repair design/process details performed and approved by designated engineering representatives of the FAA. The SoBR WG (comprised of both OEM and non-OEM industry and regulatory subject matter expert representatives) is presently working to update CMH-17 PMC Volume 3, Chapter 14 for Rev. H (plans for a 2022 release).

In addition to documenting SoBR information, the FAA is also investing in the development of a related short course to be made available for regulatory industry designated engineering representatives supporting both OEM and field design efforts; the TAMCSWG encourages and advocates the FAA to take lead for this training development and execution. The overall goal to support both these deliverables is to establish guidelines and document best design, analysis, test and processing practices, assuming that the repair may not be based on publicly available information (without support from the OEM). This leads to bonded composite or metal structural challenges that differ for conventional metal construction where reverse engineering procedures are relatively straight forward and without the added tasks commonly needed for composites and bonding (material & process qualifications, fabrication & bond assembly tooling development; repair process trials; simplifying design criteria; structural tests and empirical analysis developments; and more complex internal load estimates). This essential part of the work, designated as prerequisite SoBR tasks, were the first, major addition to Chapter 14, taking more than a year to create.

Many of the efforts by an independent maintenance organization with design approval authority remain focused on the details of a given damage scenario and repair, providing the benefits of a focus, whereas OEM repair development efforts often address multiple repair scenarios and the more general capabilities of many airlines or repair organizations involved in product maintenance. As a result, the specific task focus and any engineering assumptions may be simplified and the cost or weight optimum solutions will often depend on differing cost centers due to a lack of previous data for the part repaired. The SoBR Task Group determined that one of the best ways to demonstrate such repair challenges is to create a series of *case studies* for specific repair details affect the repair solution. All case studies meet the same regulatory expectations for related technical issues, but show how the precise location of the repair and certain knowledge held by the repair team may promote simplifying SoBR assumptions and; then, follow by explaining why that solution would not work for a different damage scenario occurring to the same part.

One final FAA & industry initiative of note for purposes of advancing *composite and bonded maintenance knowledge transfer* is the possible future use of an advanced Technical Standard Order (TSO). A TSO may be one regulatory mechanism whereby the additional work to approve SoBR options is completed prior to facing a repair or inspection challenge not available in existing data. The FAA is already pursuing two classes of design data under the TSO: 1) basic material qualification information, including basic material allowables & associated material procurement and process specifications and 2) long-lead design data generation (e.g., empirical design values, criteria, processing Quality Control trials and related constraints essential for affordable composite developments). Both classes of data support affordable or more efficient design, particularly when occurring in organizations not currently classified as an Organization Designation Authorization. The use of a TSO for maintenance purposes could include:

- global standardization of specific composite practices applied to past, current and future airplanes
- added structural repair design options, created by a partnership of end users & part manufacturers
- OEM, airline customers and selected maintenance partnerships expanding approved specific part maintenance options for inspection, repair and operational functionality
- industry consortium establishing new maintenance options for after-market airplane usage

Key members of the TAMCSWG recognize that their support to the many years of composite knowledge sharing described in this section may not be sustainable. The several industry & regulatory actions undertaken to-date (reference Figure 2) have resulted in clear progress in minimizing the knowledge gap. And, accordingly, the TAMCSWG recognizes the advantage of assembling such experiences and knowledge in a more formal way through the international standards organizations that have documented such information to date. Future efforts should continue with the help of a sustainable industry/regulatory sub-team and new members recruited from all organizations currently gaining transport airplane experience, even if many existing working group members retire by re-assembling those that remain via other forums.

4.2.6 Practical Inspection Considerations

Quality management is important to many aspects of bonded repair. Some combination of in-process controls and post-bond inspections are required. As is the case for structural bonding in a factory, NDI alone provides necessary, but not sufficient, evidence on the achievement of proper bonding. Other repair in-process controls applied to surface preparation, adhesive mixing, bond assembly, and cure provide the necessary complement to post-bond NDI.

Two SAE CACRC standards were written to document industry best practices for metal bond (AIR 6291 [Ref 14]) and composite bonded repairs (AIR 6292 [Ref 15]). Each report provides detailed explanation of the process steps, including: use of tooling, roles and responsibilities of personnel, material storage, in-process controls and inspection. The report includes case studies that illustrate typical field problems and how they can be avoided. Both reports are the responsibility of the CACRC Procedures Task Group and undergo periodic updates for purposes of reaffirmation. The report standardized the common best practices among OEMs and MROs, however it assumes an approved part-specific Repair Document for all the part and material specific requirements. A future CACRC standard is in draft for damage characterization and reporting. The document is intended to standardized industry best practices with the goal of reducing time for interactions with the OEM and other repair support. Repair design and its substantiating data first requires accurate damage description and NDI findings, followed by coordination with a number of supporting parties or individuals.

Another part-specific document that integrates the bond process and design and certification is the inspection for and disposition of manufacturing processing defects and discrepancies. As discussed previously, design data development and structural substantiation support control of manufacturing flaw sizes via documentation of the tolerances for normal manufacturing deviations. These documents are necessarily along with enough detail to properly cover the range of materials used. For example, honeycomb documentation can be over 20 pages for the tolerances for cell shapes, node disbond, potting, splicing, orientation, surface waviness, edge waviness, chamfering, machining, cleaning. etc. Documentation for the manufacturing deviations of prepreg and laminate should include tolerances for waviness, orientation, yarn or weave distortion, wrinkles, porosity, ply splicing gaps and overlaps, resin starvation, resin rich, inclusions, trimming, machining, marking, use of filler plies, compaction temperature allowed. The assembly should include guidance on deviations such as cure cycle deviations, thermocouple placement, inclusions, uneven faying surfaces, surface depressions, contour warpage, hole quality, fiber breakout of holes, delaminations and disbonds, etc. The deviation documentation should include, at a minimum, the limits to accept or reject, and the option to include documented limits and procedures if rework is possible. These in-process manufacturing quality standards, which are used during the OEM manufacturing, also apply for in-service repairs and should be implemented in the manuals available to MROs for repairs. As a result, they should be part of MRO training and quality control program. We recommend inclusion of such details in manuals, in training materials and as potential area for standardizations such as CMH17 or SAE-CACRC.

The quality control process for repairs or manufacturing should include a write-up for any deviations and review by engineering. The engineering review will result in accept, reject or rework, as justified by stress analysis and/or testing that is consistent with the original design certification basis including materials and processes. For in-service repairs by MROs, if the data is not accessible then consultation with the OEM is required.

Once a repair is completed the part will be reinstalled an aircraft and subject to the existing aircraft maintenance program and inspections. Therefore, during the repair design consideration is given to whether the exiting instructions for continued airworthiness are still applicable including change of the failure mode, change to visual indications of failure, and the effect of the repair on the non-destructive testing. NDI methods and equipment for repair inspections may have to be adjusted, or additional reference standards produced, to account for increase in porosity. This is due to the attenuation of repair material that is different from the original, additional bondlines and surface roughness.

OEMs typically collect data regarding typical minor defects (e.g., porosity, resin thinning, fiber distortion, etc.) for bonded repairs as the repair techniques and processes are established for fleet support. Revised limits for typical bond anomalies may be published with the OEM structural repair manual procedures.

Additionally, some anomalies may be acceptable with the addition of mandated inspections using NDI techniques although this is typically avoided.

This section was assembled by a few TAMCSWG members that have knowledge in this area. Other OEM, MRO or airline experiences may also have related knowledge. There has been great promise of advanced inspection procedures for a very long time but there are no guarantees for such technology and a team of users are needed to make judgments on what is and isn't practical for the field environments.

4.2.7 Possible Aging Limits to Metal and Composite Bonding

There is a distinct difference between metal and composite bonding aging mechanisms, favoring the latter for long-term reliable performance. Metal bonded structure and repairs will typically degrade through a complex process of hydration that will depend on design details, process quality and remain undetected by current practical NDI methods. When hydration is active, failures will first appear with some mixed mode surface characteristics indicating both adhesion and cohesive failures. Composites are sensitive to several different forms of contamination, including moisture and known contaminates (e.g., fragments of peel ply, amine blush); however, in many cases they don't have the equivalent phenomena of hydration where the bond continues to degrade unpredictably from a weak bond to no strength. Instead, composite bonding problems often yield an understrength bond that may allow subsequent reliable estimates of growth, residual strength and reliable inspection intervals. The TAMSCWG recommends future research to understand such composite challenges.

Both metal and composite bonding have aging mechanisms that are extremely dependent on stringent in-process control of many critical steps, with the process itself yielding manufacturing defects that remain the problem in weak or understrength bond degradation. The important process considerations include: a) substrate surface preparation, b) adhesive mixing and application, c) bond process known contamination and environmental controls, with some added concern for moisture challenges for on-wing field repairs, d) mating surface contact and heat management throughout cure, and e) assurance that the overall *bond system* is qualified. There should never be material substitutions based solely on individual mechanical or physical properties because the bond system requires compatible substrate and repair materials (patch and adhesive), and process steps as identified above. Any indication of adhesion failures during bond qualification testing, structural substantiation, production and repair applications is cause to be suspicious of the bond system. It is either not properly controlled during processing or is using unqualified materials and requires immediate attention. It is not plausible or possible to manage adhesion failures through damage tolerance practices that predict related damage accumulation with reliable inspection methods and intervals. Similarly, life demonstrations that end in adhesion failures also suggest that the life estimates and any perceived conservatism is unreliable.

The aging limits for metal and composite bonded structure has been challenging to document because many problems that occurred in early applications were not documented as the aging occurred relatively quickly and often involved numerous bond process and design challenges for companies new to the specific adhesive materials applied to such critical applications. As a result, the company derived improved bond process and design practices, while the challenges remained undocumented in public literature. As this is one area where the state of the art is still controlled by hard learned lessons, which are not shared throughout the industry, the TAMCSWG recommends that industry document past experiences for future avoidance of the same mistakes occurring with those not previously exposed to significant structural bond experiences. Again, the best location for such documentation would be international standards documents that welcome such knowledge shared after the wounds have healed and industry members have moved into better bonded structure aging experiences.

5.0 Costs & Benefits Analysis

This section focuses on the cost and benefits analysis of the changes to guidance discussed in Section 4. These proposed changes capture the current industry practices employed by the companies supporting the TAMCSWG. Most of these changes are already part of current OEM practices, nevertheless for completion of the report, some cost details are provided in the following sections

5.1 Cost

We propose to review 3 points as potential cost impact

- **1. Cost of redundant design** specifically to illustrate this principle: the "*Disbonds and related delaminations of each bonded joint greater than this must be prevented by design features.* Additional costs are associated with some typical designs requiring 'chicken bolts' (bolts and implementation cost and also the weight impact). Reference Figure 3 for illustration of application of such fasteners.

Estimated number of anti-peeling rivets (chicken rivets) is around 1000 for conventional composite fuselage mainly around all types of doors / access holes.

The total cost is about $2.9k for drilling and installing these fasteners. (assumption of lockbolts with semi auto or auto drilling and -3 or -3A dia).

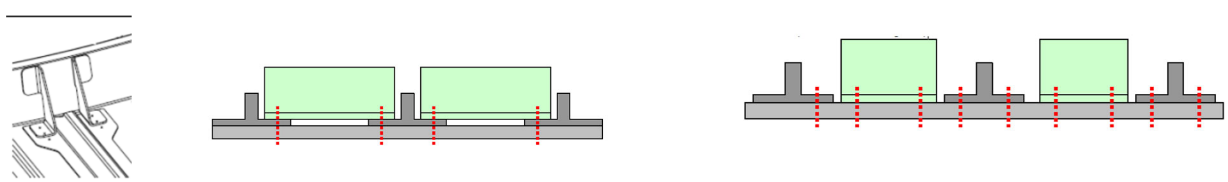

Figure 3. Illustration of use of mechanical fasteners (chicken rivets/bolts) in structural bond applications.

- **2. Cost of a robust quality control plan**

Two levels are presented: standard one (stabilized production) and "reinforced" ones on earlier production of new technologies with process control specimen for bonding performances) at production level and also in bonded repair conditions (repairs level including MRO)

Current industry practices for bonding processes already include some stringent qualification processes with, potential temporary bonding performance tests done on new design and/or new technologies/manufacturing processes/cost of such additional tests is on top of any materials and manufacturing processes and can be represented by a peeling test (G1C as example)

The associated cost induces serial productions cost: Today G1C cost is around $580.

Cost for G1C, example on VTP

If we assume $1200 per specimen, 3 specimen per autoclave cycle representing both skins, 600 airplanes per year. Total cost for specimen is $2.2M. This is just specimen manufacture, testing and report.

- **3. Cost of an inspection principle for life extension and potential large Cat 2 DTDC, as a potential mitigation on life extension , to detect any 'aging' phenomena or scheduled inspection need.**

"AC 20-107B, 8.c. Combined Damage Tolerance and Fatigue Evaluation. *Generally, it is appropriate for a given structure to establish both an inspection program and demonstrate a service life to cover all detectable and non-detectable damage, respectively, which is anticipated for the intended aircraft usage. Extensions in service life should include evidence from component repeated load testing, fleet leader programs (including NDI and destructive tear-down inspections), and appropriate statistical assessments of accidental damage and environmental service data considerations. " for bonded structure on PSE.*

In Manufacturing:

- The detection by "Visual Inspection" is possible in "obvious" cases. In most cases this is done with ultrasonics.

In-Service:

- Usually there are other indications that lead us to perform a visual inspection of the bond-lines. For example, impact damage, or a top-layer delamination, provide an indication of possible debonding. By experience it can be detected by visual inspection if there is a gap between the skin and the stringer foot. At a touching distance, with specific light conditions (including torch), inspectors must look for a "black" line (= the gap) that is a visibly evident color (a grey color for example). In an in-service aircraft, the surface must be cleaned, otherwise identification of a disbond can be challenging:

Regarding the inspection time (In-Service), the most efficient technique currently is to use an ultrasonic roller probe**.** Time necessary for inspection can be an average considered as 15 minutes per stringer per meter. On the top cover (Wing/HTP….) it should be faster (good ergonomic position), on the lower cover it is a difficult job (much worse ergonomic position).

Assuming approx. 240 m of stringer in 1 skin, this is ~60 hours. It could take 1 week for the upper skin of a wing, and around 1.5 weeks for a lower skin.

5.2 Benefits

A robust quality control plan and associated qualification data are part of the bonding technologies qualification under §25.603 and 605, and therefore not included, additional effort for a robust quality control plan is already common practice for structural bonding in the Industry. This is considered acceptable given the benefits to safety and industrial impact.

Design precaution as "chicken bolts" when implemented, should remain reasonable effort understanding the MLP of a given detail design, but should not be a strict requirement to address MLP (see previous sections addressing redundancy and sufficient SDC).

Life Extension: Past experience for extending life for bonded structure has not resulted in any additional inspections and costs compared to bolted structure or for metallic structure, except in cases where in-service reliability issues had previous resulted in a decrease of inspection interval in order to reduce schedule interruptions.

Most of these cases are due to corrosion of aluminum honeycomb sandwich structure, or galvanic corrosion of metal in hybrid graphite composite parts.

6.0 References

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7.0 APPENDIX

7.1 Appendix 1: Historic review of existing guidance

The most complete regulatory guidance that currently exists for bonded structure is a policy statement called *Bonded Joints and Structures - Technical Issues and Certification,* which was issued in 2005 (Ref. 4). Although released as a small airplanes policy, it was derived from an interface with the industry for many aircraft product types, including transport airplanes, small and transport rotorcraft, engines and propellers. It addresses three types of bonding: a) composite to composite, b) metal to metal and c) composite to metal.

In 2004, tasks to benchmark industry practices for structural bonding initiated. The efforts included a survey and two bonded structures workshops (June 2004 in Seattle, Washington and October 2004 in London, United Kingdom) to engage experts from around the world. These efforts addressed the full scope of certification from type design to production and continued operational safety, ultimately leading to a strong industry basis for the 2005 FAA policy statement (Ref. 4). Technically, the policy covers (1) material and process qualification and control, (2) design development and structural substantiation, (3) manufacturing implementation and experience, and (4) maintenance implementation and experience. FAA Technical Report [DOT/FAA/AR-05/13] documents the results of data collected in the survey and 2004 workshops (Ref. 1).

In 2009, content from the 2004 policy statement was generalized and combined with five more years of experience gained from an industry interface to create bonding content added to several sections in AC 20-107B, *Composite Aircraft Structure* (Ref. 5). In the same timeframe, studies performed with several airlines evaluated bonded repair for transport airplanes. At this point in history, some of the maintenance work previously performed by airlines started off-loading to maintenance repair organizations as a cost savings initiative. Some problems with composite bonded and bolted repairs led to a number of case studies jointly documented by the FAA and selected airlines (Ref. 8). The findings from these studies were such that there were more case studies than the FAA had funding to document, leading to an additional interface with the composite maintenance industry. In 2014, the FAA created another policy statement, *Bonded Repair Size Limits*, PS-AIR-20-130-01 (Ref. 6). This policy reinforced the same bonding expectations outlined in AC 20-107B for base structure and repairs but with additional details and under a title emphasizing repair applications.

Material and Process Controls

All existing regulatory guidance emphasizes stringent material and process control as the primary requirement for safe and long-lasting applications of bonded structure. Without attention to bonded in-process controls, such structural joints can become unreliable and degrade at an unpredictable rate, making safety management nearly impossible to achieve using modern day damage tolerance principles and practical maintenance practices. Industry recognizes that bonded structure relies on in-process material and fabrication controls to ensure success. Post-process inspection methods, including state-of-the-art nondestructive techniques are unable to reliably detect understrength or weak bonds caused by a number of challenges that, left unchecked, may arise during the course of several bond-processing steps. The FAA policy statement called *Bonded Joints and Structures - Technical Issues and Certification* from 2005 (Ref. 4) discusses the related issues within the four key areas summarized below.

Qualified Materials and Processes Demand a Systems Approach

Qualification procedures demonstrate the stiffness, strength, durability and reliability of bond materials and processes for aircraft applications. Qualification tests evaluate structural performance, environmental effects and long-term durability. For composites, qualification testing is initially performed for new materials and the processes used for fabrication purposes. This material qualification becomes a prerequisite to subsequent bonding process qualification. The series of material and bond process qualifications constitute an overall *bond system qualification* that starts with the base material qualifications and ends with a final qualification that systematically combines the base material qualification, adhesive qualification, and a final qualification that combines all key bond process steps essential for all representative bonded structural joints. Any major changes within this bond system may require a *new bond system qualification*. Unfortunately, all contributing factors leading to a successful *bond system qualification* are not understood theoretically and; hence the need for the empirical data trials that demonstrate bond qualification.

For bond processes applied to composites or metals, such efforts start with defining key bonding processing steps and selecting compatible substrate, adhesive, surface preparation procedures, other processing details and any ancillary materials essential to achieving a chemical bond. In coordination with qualification, it is also important to establish (1) processing tolerances, (2) material handling and storage limits, and (3) key characteristics and process parameters to monitor in quality control. Most bond failures and service problems trace to invalid qualifications, material or process step substitutions, uncontrolled processing limits or insufficient quality control of key production or repair bond process steps. For example, substituting apparently similar adhesives or surface preparation process steps with a given substrate can result in bond failures.

Bond fabrication procedures should include trials that demonstrate compatibility between the substrates, adhesive, and processes. Some of the most important process steps relate to substrate storage, handling, and surface preparation. Reliable adhesive bonding depends on:

1) a surface free of contamination,
2) a chemically active surface, and
3) a dry surface.

The storage, handling, and surface preparation procedures needed to accomplish all three of these characteristics will depend on the specific substrate and adhesive materials. There are distinct differences for composite and metal substrate materials. Sandwich core materials such as honeycomb and foam will also have unique process differences, depending on the base material type. Film adhesives have storage and handling requirements similar to pre-impregnated, uncured composite materials. Paste adhesives will likely have different components that require precise mixing before application.

Another important aspect of the bonding process is adhesive cure. The bonding surfaces must contact the adhesive with sufficient pressure and temperature to accomplish cure and bond adhesion. The cure cycle defines the sequence, ramp rates, and dwell times for temperature and pressure application. Explore bond process tolerances to define the acceptable range for resin mixing, surface preparation, and cure processing steps in documenting preliminary specifications during material compatibility trials. Such trials serve a purpose before proceeding with complete material and process qualifications. It is also wise to perform some bond process trials with representative structural geometry and tooling to ensure valid bonding procedures beyond laboratory trials and into structural scales.

Bonding materials and processes are qualified for use in structural applications. The overall goal of qualification testing is a basic characterization, which best represents the materials and processes in the application. As a result, specific specimen types and test conditions used in qualification likely depend on the application. Most programs use some qualification tests to help set benchmarks in chemical, physical, process, and mechanical properties, which combine with other quality checks for subsequent material and process control. Enough unique batches of materials, independent bonding process trials and test repetitions ensure a representative population for reliable benchmarks, albeit at the lower scales. It is noteworthy to mention that successful qualifications often follow established material selection procedures, which check several candidate materials in case some prove to be a challenge that affects schedule milestones. Alternate choices to start may cost a little more but the payoff comes in avoidance of negative schedule impact near the start. It also gives different functional disciplines to help decide the best choices with some data in areas of interest.

Substrate materials used in aircraft products are typically qualified before bond processes. Adhesive material qualification may also occur separate from bond process qualification. This is a common industry practice when an adhesive combines with several different substrate materials because it is desirable to control the adhesive material with a set of properties that are not dependent on each specific bonding application. As discussed previously, a separate bond process qualification supports each unique combination of materials because of the complex interface between substrate and adhesive, which depends on many variables (for example, material compatibility, surface preparation and cure kinetics).

Further guidance on adhesive and bond process qualifications appear in Ref. 4. The industry uses several different physical, chemical, and mechanical tests for adhesive material and bond process qualification. Physical and chemical tests may be used to control surface preparation. Although useful for material characterization and design, shear tests do not provide a reliable measure of long-term durability and environmental degradation associated with poor bonding processes. Some form of a peel test has proven more reliable for evaluating proper adhesion. Any ***adhesion failure***, which appears as evidence of chemical bond failures between substrate and adhesive materials found during the course of bond system qualification are unacceptable and require further evaluation before progressing with qualification.

Adhesive and substrate material selections should also consider the bonded joint design configuration, loading requirements, manufacturing process constraints, environmental conditions and chemical resistance to fluids found in service. Reduction in strength properties at the maximum and minimum operating temperature supports each application. Both temperature and moisture content affect the properties of polymer composite substrate and adhesive materials, with a significant decrease in strength above the wet glass transition temperature (T_{gwet}). Simple guidelines often used in selecting composite substrate materials is for the T_{gwet} to be 50 °F greater than the maximum operating temperature of structural applications. The analogous guideline for adhesive materials is for the T_{gwet} to be 30 °F greater than the maximum operating temperature. Use more rigorous environmental testing for specific design detail when selected polymer materials do not meet such guidelines.

Differences between Metal and Composite Bonding

There are many similarities in the processing controls used for successful metal, composite and composite to metal bonding, starting with control of the joint tolerances to ensure good contact in an assembled joint and precise application of the cure cycle, including heat management, heating/cooling ramps and time at the peak cure temperature. Many experts consider surface preparation to be the most important process step for structural bonding. There are distinct differences in the surface preparation techniques used for metal and composite substrates. Phosphoric acid anodizing, sol-gel and grit-blast/silane processes are examples of surface preparation techniques that have worked for aluminum substrates. Sanding, media blasting, and peel ply surface preparation techniques exist for composite bonding, but success depends on the specific substrate and adhesive combinations, as well as other processing variables. Bonded sandwich construction, which uses honeycomb or foam core material (composite or metal), requires specific procedures for core surface control applied to achieve successful bonding.

The corresponding in-process and post-process NDI controls applied for composite and metal bonding also have similarities and differences. The in-process methods used to determine the success of achieving good contact between mating surfaces before applying adhesive often use an ancillary material such as verafilm, which requires close control within the factory or shop to avoid contamination. This are also important in-process checks for achieving bond-line thickness control. Cure cycles use thermocouples and other aids to ensure proper temperature, vacuum and pressure controls. Surface chemical testing and water drop testing have had good success in determining if a prepared metal or composite substrate surface has proper activation to continue the bonding process. For composites, a plasma treatment following the surface prep processing step has provided additional assurance in removing any contaminate prior to the final bonding process steps. Through transmission, pulse-echo and guided wave ultrasonic methods vary in wave frequency and amplitude content to inspect metals or composites but are reliable post-process NDI methods.

As discussed previously, post-process mechanical testing helps further ensure bond success and forms a basis for the qualification of specific substrate, adhesive and process combinations or for any changes to the bond materials or processes over time. A wedge specimen that combines peel loads and extreme environmental conditions has proven to be a reliable accelerated lab test for detecting unacceptable metal bond processes, which would subsequently degrade over time and lead to adhesion failures in service. Other specimen types used to evaluate weak or understrength bonds for composites include double cantilever beam or a traveling wedge test. Bonded sandwich specimens often use rolling drum peel or flatwise tension tests but more recently a single cantilever beam has proven more reliable for similar assessments, although the processes and mechanisms of sandwich bonding is distinctly different than both metal and composite bonding. Nevertheless, some form of peel testing appears most successful in establishing reliable bonding processes for bonded sandwich applications as well as solid substrate bonding.

Substitution Challenges

Extensive field experience has shown the suitability of a given qualified adhesive, substrate and bond processes applied in a particular application, assuming the execution of all related in-process controls. This would supersede the need for additional post-process tests unless questions arise on whether a particular bond problem exists. Although convenient, avoid any significant substitution in the specific qualified adhesive, substrate materials and bond process steps unless performing additional qualification testing. There may also not be properly defined (or understood) boundaries and insufficient documentation for approved substitutions under a given repair program. The temptation is always greatest in the field environment when one of the qualified materials is not available, no longer exists or process steps can’t be performed due lack of special equipment or ancillary materials. The associated rework for an unsuccessful bonding operation is not worth the risk and if a bad bond passes inspection and is returned to the field there are potentially high safety risks because bond material and process control is the primary means of achieving reliable structural bonds.

Regardless of meeting guidelines, any changes in material properties at temperatures above the maximum operating temperature (for example, runway sun exposure) also need to be understood for their potential effect on subsequent bond processing such as needed for repair. Facility controls on minimum and maximum factory or shop temperatures, moisture and altitude can all affect the bonding and repair processes. An understanding of the intended manufacturing or repair facility's tooling concepts and process steps is also useful in achieving reliable bonded structure. Material suppliers often have data that can aid in selecting compatible materials for use in bonding but that may not meet the full rigor of a bond system qualification focused on specific process steps applied for a given application. The necessary time to qualify new combinations of substrate, adhesive and bond process steps is always worth the added time and expense when considered against the safety concern and potential lost time and cost that may come from using unqualified bond systems.

Bonded Structure Checks and Emerging Technology Evaluations by TAMSCWG

The TAMCSWG members, which have utilized bonded structures in the PSE for their aircraft products, perform stringent in-process and post-process controls for production and field applications. There is a clear consensus that such efforts are the most important and primary steps for structural bonding of materials and manufacturing processes. The bond system first requires qualification and then, the related serial/continuous quality control. Each OEM has differing levels of periodic checks to ensure continued success and in the current proprietary state of the technologies, require such freedom to economically achieve similar safety goals.

Some TAMCSWG members still make extensive use of metal bonded structures as dictated by experiences. Most members use co-cured composite structures and apply bonded structures with the added in-process controls felt necessary to achieve success in a somewhat more demanding set of bond fabrication steps, including surface preparation. All members using bonded structures start with a system qualification for specific combinations of substrate, adhesive and critical bond process steps. Whenever using peel ply for surface preparation, it needs quality controls as a material critical to the success of bonding, often including destructive bond cleavage test trials for specimens created with each new batch of peel ply received at the factory. The bond process cell uses a controlled environment, free of contamination and tolerance control for bond process tooling are always applied. Knowledge transfer of key process control parameters, serial control of material and process verifications, some post-process quality control tests and first part manufacturing destructive tests are essential precautionary actions whenever moving production facilities to new partners.

Finally, bonded structures in service always receive periodic fleet management or surveillance by way of visual inspection, usually during the Maintenance Steering Group (MSG-3) process. It is common to use visual inspection when applying redundant design practices for bonded structure that will maintain limit load in the rare case of a significant disbonding scenario within arresting features.

Many TAMCSWG members are currently evaluating new methods to improve the reliability of bonded structure. Emerging technologies are likely for improvements to structural bond in-process controls and post-process nondestructive inspection in the future. Despite past challenges, bonded structure continues to advance reliability through a multi-faceted approach that starts with stringent material and process controls. Documentation of these advances in expanded knowledge transfer of traditionally proprietary data appear as significant updates to industry references such as CMH-17 (Ref. 2). Staying with a theme of bond material and process control being paramount to structural integrity, some bond materials and processes are restricted and not used on PSE.

Other main points identified on the state of the art of *Best Industries Practices* for material and manufacturing processes appear in the DOT/FAA/AR-05/13 (Ref. 1). One thought extracted in the section on MATERIAL AND PROCESS QUALIFICATION AND CONTROL notes: *"the specific combinations of materials and processes used for bonding must be qualified for structural applications"*. This is currently reinforced by the performance-based regulations (e.g., Title 14 CFR 25.603), which state that the structural suitability and durability of materials used in aircraft products must account for environmental effects and be established by experience or tests. In addition, a companion regulation (e.g., 14 CFR 25.605) state *"fabrication methods must produce consistently sound structure."* The data generated in material and process qualification serves as a basis for subsequent quality control. Use an approved process specification to ensure sufficient reliability for fabrication methods such as bonding.

Over the last twenty years, the FAA has conducted research in bonding material and process qualification and control with the help of industry. Some initial key areas of focus include composite bonding surface preparation and the ancillary materials (removable surface layers such as peel plies and release fabrics) used by industry. The research showed the importance of qualifying all the materials and process steps used to develop a reliable bond (Refs. 1, 2). It also identified different test methods suitable for making such a judgment. This work showed that release fabrics, which contain chemical release agents, are unacceptable for use on composite surfaces that will be bonded because subsequent surface preparation steps, such as grit blasting and sanding, cannot remove all the contamination. Peel plies, which do not contain chemical release agents, should have different product designations. Use of peel plies in the bonding process and whether sufficient surface preparation occurs with their removal appears to depend on the specific substrate & adhesive combinations; the process used to cure the parts and other bonding steps. Control multiple processing cycles at high temperature, such as occurs in element rework, must also be controlled within proven limits because they affect peel ply performance in subsequent surface preparation. Research continues in this important area, and the industry has adopted the practice of distinguishing release fabrics from peel plies.

Manufacturing Challenges

Material and process control is an essential prerequisite for manufacturing implementation, but scaling issues need early consideration to realize key facets of controlling the materials and processes at the time of qualification. When implementing new bonding facilities and fabrication processes, manufacturing trials help develop an understanding of structural details that permit reliable producibility. Scaling issues, which directly relate to structural details, are likely for several bond process steps including surface preparation, adhesive application, and cure control.

Tooling used for bond assembly and cure will depend on mating part geometry, cured tolerance controls, and other factors that also relate to design details. An iterative process of defining structural details and performing manufacturing trials, and testing for performance has proven successful for new design development in the past. Such efforts become more efficient as a manufacturer gains experience in structural bond applications.

Special facilities and procedures manage and control materials and key bonding process steps at the product scale. The associated issues relate to cleanliness, environmental conditions, storage, material life, processing records, staff training, and maintenance. Material control discussed in the previous section start with procurement specifications applied to ensure batch-to-batch consistency. Factory procedures and records manage the storage conditions, shelf life, out life and handling of all uncured materials to ensure they meet the associated specification requirements. Cold storage conditions and handling procedures (for example, time required in the ambient environment before unpacking for use to avoid condensation) are needed for some types of adhesives. The environmental storage conditions of some substrate materials may also need to be controlled (substrate materials and bonding processes affected by pre-bond moisture). Develop facilities and procedures to control of the bond assembly environment, equipment, tooling, and training of factory personnel to avoid sources of contamination. Process specifications outline the important in-process and post-process controls that ensure success. The specifications often identify Key Characteristics (KC) and Key Processing Parameters (KPP), to control during individual processing steps to avoid potential manufacturing defects.

Primary Manufacturing Defects and Associated Inspection Challenges

The most concerning challenge in bonded structure manufacturing defects comes from potential weak or understrength bonds for both metal and composite bonded joints. Unlike many manufacturing defects, these types of defects can be of significant size and escape detection through post-process NDI. The weak bond or understrength flaws may also further degrade over time in a manner that is reliably predictable or not reliably predictable. As a result, any bond process step that may lead to such primary manufacturing defects must have sufficient in-process controls to ensure that these defects are extremely rare and, in the remote chance that they form, must be smaller than allowed by redundant design features.

As discussed previously, many experts consider surface preparation to be the most important process step in avoiding structural bond manufacturing defects. Depending on the specific materials in a given bond system, surface preparation challenges also often depend on controlled process step timing (e.g., mixing and application of paste adhesives), success in executing abrasion techniques (abrasion, grit blasting), peel ply aging phenomena and the elimination of any other sources of contamination.

Manufacturing scaling issues for a proven bond system should not change when applied to a given structure. As a result, scaling issues need careful consideration when selecting a surface preparation for bond process qualification. The substrate surface morphology and chemistry, which exist when using a qualified surface preparation process, should not change in production implementation or the qualification testing may be invalid. Since specific bonded part geometries are often more complex than specimens used for qualification, additional processing challenges exist. Some production process controls used to monitor surface preparation include visual checks, polarized light checks, water break tests, chemical analysis, and mechanical tests using samples from bonded witness panels. Once a surface is prepared, some processes rely on time constraints during bond assembly, requiring a repeated surface preparation if the bonding operation is not completed within the specified time.

Control expendable materials used in composite and metal bonding processes to manage sources of contamination and avoid changes in bond process steps. For example, chemicals and blast media used for different surface preparation techniques are controlled, discarded, and replaced as needed to maintain process standards. Factory maintenance of facilities, equipment, and tooling ensures the cleanliness and material and process controls needed for repeatable production of bonded structure.

There has been considerable experience generated over the years from use of peel ply to prepare composite bonding surfaces of bonded stiffening attachments for transport aircraft primary structural elements. The most common use of peel ply is for surface preparation of pre-cured stiffeners for co-bonding with uncured composite skins for empennage and wing skin panels. Most of the challenges with particular peel ply types were found during the bond system qualification efforts but a few escaped initial qualification studies and were not understood until production experiences in large-scale fabrication.

Some of the challenges occurred with aircraft released to service. The root cause was tracked to a lack of sufficient peel ply batch material testing, factory mistakes (e.g., substitution of release fabrics for approved peel plies) and the influence of other factory processing steps (e.g., multiple cure cycles for purposes of cured stiffener rework, degrading the peel ply before removal). These challenges highlighted the inability of post-process NDI to detect the problem but even though they were not realized until later, structural redundancy achieved safe flight until repair and factory records were sufficient to properly solve the problem through airworthiness directives.

For the manufacturing of any metal bonded structure, many OEM rely on experienced metal bonding shops, such as Fokker, Gulfstream and Textron. The TAMCSWG contacted the former for a discussion on their experience and both Textron and Gulfstream contributed to this report as a member of the ARAC Team. Cessna first developed adhesive bonding of metal structure in the mid 1960's in secondary structure. During the late 1960's, metal-to-metal bonding was extended to primary structure with design and certification of the Cessna Citation (Model 500). Cessna continued to expand the use of metal-to-metal bonding during the 1970's in both Part 23 and Part 25 airplanes. The expansion was both methodical and intentional, resulting in an approach and philosophy used by Cessna on the Cessna Citation III (Model 680) in early 1980's. This approach continues to provide the foundation used today at Textron Aviation and is based on both the lessons from previous experience. Data from other industry leaders in metal bond, and extensive development tests allows Cessna to take advantage of the benefits of metal-to-metal bonded structure such as reducing stress concentrations due to fasteners, reduce weight, improve joint sealing, and enhanced appearance.

Airbus had some lessons learned on the A300, as they collected significant in-service experience. Early A300 metal-bonded shell design details did not use chromate acid anodizing, which lead to bond line corrosion. All major companies had challenges with early metal bonded structures. Although from the early days of bonding, one of the best references for metal bonded structures derived from the Primary Adhesively Bonded Structure Technology (PABST) Air Force Program documented by Douglas Aircraft Company (Ref. 13). Many OEMs with bonding experience have developed design/manufacturing improvements that benefited products that use the technology. Unfortunately, the knowledge transfer is just starting through organizations such as CMH-17 and SAE CACRC. The process of knowledge sharing should continue for purposes of safety because many OEM have developed additional experience and lessons learned that will continue to promote safe and efficient process/design improvements.

Bonded sandwich construction, which uses honeycomb or foam core material (composite or metal), requires specific procedures for core surface control applied to achieve successful bonding. The use of some solvents on honeycomb core surfaces can cause subsequent bonding problems. The surface preparation procedures used for wood sandwich core materials (e.g., balsa) typically include abrasion.

Other bond process steps must also have in-process controls that need proper scaling for production applications. There are geometric, fit-up and other timing issues to consider in bond assembly. Control cured dimensional tolerances and warpage for mating parts. Since the bondline thickness affects the local bond stress distribution and strength, also monitor it using process checks. Assembly jigs and procedures can provide pre-bond gap assessment. Processing aids (for example, verafilm) assess the tight tolerances needed for some bonding processes. Handling requirements and procedures exist to control the film adhesive lay-up process. The mixing and application of paste adhesive require additional processing steps and controls. The mixing ratios of paste adhesive constituents and filler content are controlled and monitored. Tight controls also help determine the completeness of the mixing process. Depending on the type of paste adhesive used, implement bond assembly time constraints from adhesive mix to mated surface contact. Monitor and maintain tolerances of assembly jigs over time.

Control the cure of bonded structures to ensure that the adhesive properly wets the substrate surfaces and dwells at temperatures needed in fully developing the properties for intended applications, without overheating. As discussed previously, the scaling issues associated with bonding large-scale airframe structures are complex. Heat transfer, bond surface contact pressure, and adhesive characteristics during different stages of the cure cycle all combine to affect the final state of the bond at local points throughout the structure. Typically apply manufacturing trials for new combinations of parts, tooling, and equipment. Establish tolerances and implement in-process controls to locally manage the bond cure cycle and avoid overheating. Cure tooling and the equipment used to apply temperature to structures during bonding is controlled and maintained. Validate and regularly calibrate procedures used for in-process control.

Use of continuous training for factory technicians and quality personnel involved in various bond process steps in specific areas of responsibility. Identify adhesion failures found during bond qualification, factory production or field repairs involving bonding and correct the associated root cause. Keep records on material usage, process steps, and quality checks applied to each bonded structure. Experience has shown that factory or service problems associated with weak bonds or de-bonding traced to specific material batches or manufacturing mistakes can be minimized even if related parts have reached service.

Likely Future Advances

Manufacturing quality management is important to many aspects of bonding. Use a combination of both strict in-process controls and post-bond inspections. Currently, the NDI of bonded structure provides necessary, but not sufficient, evidence of proper bonding. There is always hope that technology advancements will yield reliable NDI measurements of the final bond strength but that hope has existed since the 1960s and most progress has come in destructive test methods applied locally to produce local failures, which are detectable with conventional NDI, after applying high energy pulses to understrength bonds. Looking towards the future, the most promising NDI techniques are using oblique angle ultrasound or guided wave propagation over a range of frequencies with amplitudes or velocities that are sensitive to the onset of weak or understrength bonds. Witness panel tests consider the combined effect of several process steps but for a simplified geometry. As a result, other post-process quality measures and controls can provide supplemental checks on the real structure but in order to avoid the manufacturing defects of primary concern, stringent in-process controls are most effective.

Secondary Defect Considerations

Current NDI methods, such as ultrasonic methods, can locate areas of de-bonding, porosity and foreign inclusions (for example, significant pieces of peel ply or backing paper left in the bond line) but are unable to reliably detect defective bonds resulting from contamination or incorrect materials or processing. Small fragments of peel ply left on a bonding surface, may generally not be detectable by current factory NDI methods and depending on the size of affected areas, potentially leading to understrength composite bonds.

Most small manufacturing defects detected by current factory NDI are generally not a problem because they will not grow and, with supporting data, controlled through conservative factory or repair manufacturing defect dispositions. As a result, they often do not become important for damage tolerance substantiation. Nevertheless, they still require analysis and test substantiation. For example, allowable defect limits are defined for small de-bonds, porosity and relatively small foreign inclusions in PSE This may require considerable empirical data generated to ensure that the defect won't grow to demonstrate Ultimate strength will not be lost for the life of the bonded structure. As discussed above, minimize the primary defect conditions of weak or understrength bonds resulting from contamination, inappropriate material substitutions or incorrect bond processes through in-process checks. Apply proven in-process controls to surface preparation, adhesive mixing, bond assembly and cure.

Design and Structural Substantiation

Most bonded joints and attachments generally have the primary purpose to transfer shear loads. Local peel forces are also present in a bond stress distribution, but typically controlled using structural details designed to minimize such stress. The stress distribution and strength of a bonded joint or attachment relates to the substrate geometry (for example, thickness, taper angles), bondline thickness bond overlap length and, if using composite substrates, laminate lay-up or fiber architecture. Residual stresses can be an important design consideration, depending on the directional differences in thermal expansion and stiffness of substrate materials. Any bond between metal and composite substrate will typically yield the largest residual stresses. Many bonded joints and attachments are designed to be fail-safe (see the subsection entitled *Structural Redundancy* for additional discussions). Achieve alternate load paths by using fasteners or additional splices attached in a second bonding operation. Due to the mechanisms of joints with bonded and bolted features, design the joint or attachment capability assuming only the bond or bolts over any given segment of the joint are transferring loads. The bond will dominate load carrying until failure and needs Ultimate load capability, while the bolts typically meet the failsafe condition of Limit load capability with a failed bond.

An integrated product team (IPT) helps address important manufacturing, tooling, and maintenance considerations for bonded joint design. One related IPT goal is to design structural detail reliably produced in the factory to meet the performance requirements, while minimizing manufacturing defects. Similarly, the IPT needs to recognize the maintenance implications of future inspection and repair activities for bonded structural details, which do not allow easy disassembly.

Analysis methods used by the industry to design bonded joints and attachments range from crude models for preliminary design to simple two-dimensional analyses added to software-based tools, which include more refined structural definition. Crude models, which convert shear flow and other loads to an average shear stress, usually calculate bonded joint capability using very conservative design values. Despite the inherent conservatism, such an approach requires considerable testing of specific design detail in structural substantiation or overload factors that conservatively cover bonded joint reliability.

Both simple analyses and software-based tools predict local shear and peel stress distributions, which help design joint parameters for optimal performance. Some models include nonlinear elastic and plastic adhesive behavior for further joint optimization. Design sufficient bond overlap length to ensure plastic deformation occurs without a risk to bond integrity or damage accumulation. Design criteria and guidelines often ensure constraints that minimize bonded joint data needs. In one guideline, design the overlap length to carry all loads by adhesive plastic deformation, with sufficient elastic trough away from the joint ends to provide creep resistance. Software models of adhesive joint geometry and load conditions allow further design refinement (for example, analysis of joggles).

Use design criteria & objectives, analyses, and test data for timely disposition of manufacturing defects and service damage found in the factory and field, respectively. Sophisticated analysis methods used to predict the effects of bond defects and damage scenarios continue to evolve; however, most applications to date depend on test data. This is particularly true when considering damage as complex as that caused by foreign object impact.

The design of bonded repairs uses many of the same design procedures and analysis tools applied to bonded joints and attachments. A typical bonded repair considers the patch geometry, scarf angle, and bond-line thickness. Residual stresses resulting from a difference in the laminate lay-up, stiffness, and thermal expansion properties between the bonded patch and base part also need consideration in repair design and analysis. The associated placement tolerances for repair patches may require some attention to avoid conservative assumptions of related stress concentrations.

As discussed in AC 20-107B (Ref. 5), the overall approach applied for composite structural substantiation dictates design data development. The same philosophy applies for bonded structures. Some benefits are possible using a building block approach with refined analyses and test correlations for structural details, which range in size and assembly completeness (coupons, elements, subcomponents and components). Alternative approaches, based on crude analyses and a conservative demonstration of strength at the large scale, typically have more constraint. There is more freedom to expand beyond the specific structural details, damages, defects, and repairs addressed in large-scale tests if there is a more refined correlation between the analysis and tests, within the allowances of design criteria and other constraints within the building block approach.

Design data development includes characterization for minimum and maximum service temperatures, as well as the moisture content possible after years in service, typically established as conservative design criteria. A threat assessment of service damage should define the full scope of structural tests and analyses. The materials, conditions, and processes used for repair in the factory and field often differ and need substantiation within the building block approach. Train technicians involved in bonded joint testing to identify adhesion failures. Consider any adhesion failures noted through the course of structural substantiation unacceptable and identify the source before proceeding to additional tests and analyses.

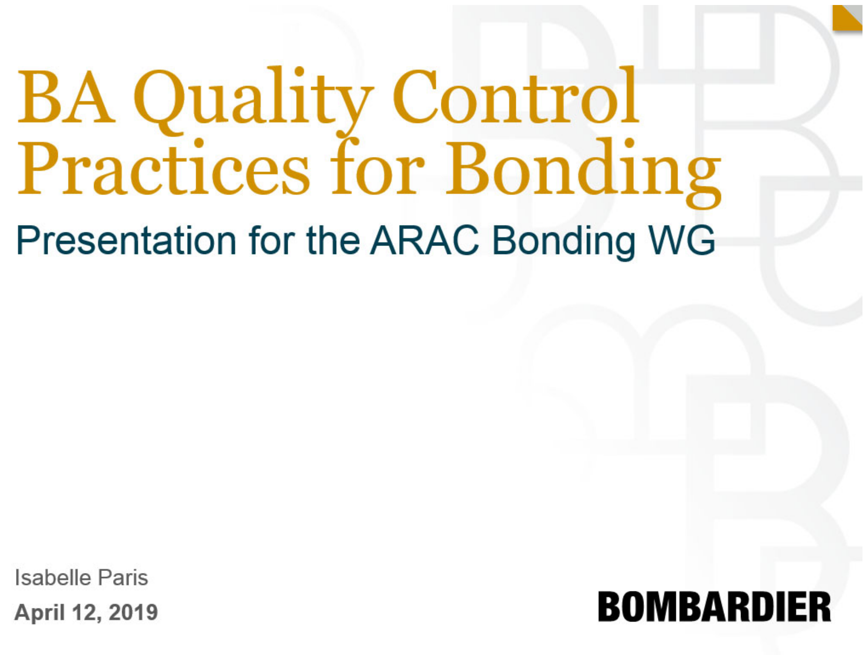
Address the long-term durability of bonded joints by understanding degradation mechanisms and tracking long-term performance. As discussed in previous sections, bond process qualifications usually initiate these efforts using accelerated test procedures that conservatively force an assessment of the chemical bonding. Correlations between accelerated tests and actual long-term performance will ensure sufficient conservatism. This is also true in evaluating the long-term environmental exposure to temperature, moisture and other fluids found in service by substantiating accelerated testing known to be more severe in the short-term. Element and subcomponent tests provide further proof of acceptable bonding processes applied at larger structural scales.

Final substantiation of static strength, fatigue, and damage tolerance relies on large-scale test components or tests that contain full-scale details manufactured using production processes. Careful attention to test boundary conditions and attachments will yield representative results. Building block analyses and tests support design value determination for most of the effects of structural details, damage, defects and repair, again with careful attention to proper simulation of structural behavior. However, large-scale tests provide final overall proof of the design and manufacturing characteristics of configured structures, which include bonded joints, cutouts, damage, repairs and combined loads. This includes validation of load path predictions and final strength assessments, based on structural detail design values. For example, integrally bonded airframes may have secondary load paths and complex failure modes that are difficult to predict, without careful consideration of manufacturing tolerances and load redistribution following individual failures.

Practical consideration of moisture and temperature property degradation in large-scale tests often uses overload factors derived from smaller scale tests. One issue that is difficult to address directly in large-scale tests is the completed cure of the adhesive and the availability of related peak moisture and temperature-dependent properties at the structural level. In addition to the process controls measuring thermal profiles to ensure sufficient temperature conditions for the required cure cycle during fabrication, some laboratory testing of samples cut from the bonded structure can provide the necessary substantiation of manufacturing processes.

7.2 Appendix 2: Quality control plan for composite bonding in OEM

Several TAMCSWG members provided presentations on example quality control plans for composite bonding. The following includes the material shared by WG members (Bombardier, Dassault, Airbus, Textron) and invited participant (Fokker).



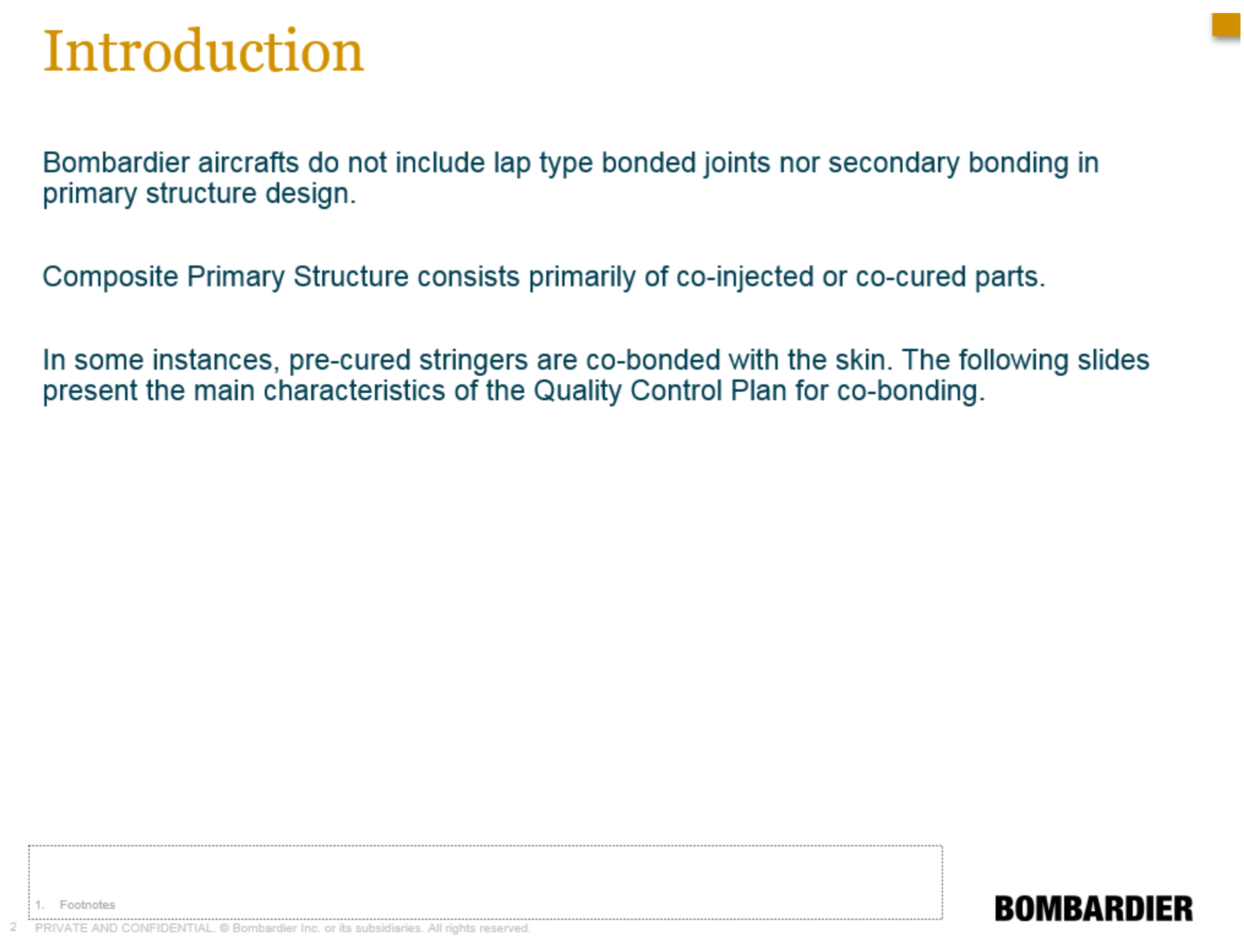


Figure A2.1 (sheet 1 of 3): Bombardier presentation to TAMCSWG on structural bonding

Quality Control Plan for Co-Bonding

Controlled and validated materials and process specifications are used to closely monitor and control the bonding key parameters.

Materials :

- qualified and controlled structural adhesive film system (full qualification to address variables such as environment)
- qualified and controlled polyester peel ply fabric without finish or release agent
- qualified and controlled prepreg materials

Process:

- follow requirements for handling of materials used in structural bonding and composite fabrication
- remove peel ply just prior bonding in controlled environment (Air cleanliness per industry specs such as ASTM F50 and ISO 14644-1)
- clean faying surface with solvent
- completely cover with adhesive film within a prescribed time limit
- ensure proper control of temperature in bondline with thermocouples (temperature survey, location of load thermocouple)
- ensure proper control of pressure on bondline through monitoring of autoclave pressure through entire cycle
- control of all critical process parameters for each component through use of technique sheets
- destructive testing of first production article to validate quality and Non-Destructive Inspection (NDI) technique

1. Footnotes

BOMBARDIER

3

Quality Control Plan for Co-Bonding

Process Control coupons:

- Single lap shear ASTM D3165
- manufactured exactly with the same procedures as the production part (same material and same manufacturing requirements) and be cured under the same vacuum bag
- 100% cohesive failure or 100% substrate failure of the bonded area

Inspections:

- After curing ultrasonic inspection to detect manufacturing defects (delamination, void, FOD, volume porosity)
- 100% part inspection

Fleet management:

- MSG3 visual inspections for environmental and accidental damage (validated by mechanical tests for fatigue)

1. Footnotes

BOMBARDIER

4

Figure A2.1 (sheet 2 of 3): Bombardier presentation to TAMCSWG on structural bonding

Structural Bonded Repairs

BA doesn't currently approve structural bonded repairs.

Developing structural bonded repairs Quality Control Plan would require:

- damage removal specifications
- machining (scarf or stepped) established process
- surface preparation specifications
- established process for repair plies preparation and installation
- control of temperature and process
- control of environment
- NDI specifications and NDI calibration panels

It would also be desirable to establish:

- training and certification of repair technicians
- database of performed repairs in fleet

1. Footnotes

5

BOMBARDIER

Figure A2.1 (sheet 3 of 3): Bombardier presentation to TAMCSWG on structural bonding

Material selection & qualification

- No co-bonded element in DA civil aircraft / Few parts in military aircraft.
- Bonding material characterization :
  - Compatibility with panel material (chemical, cure cycle ...)
  - Chemical and Physical characterization...
  - Mechanical characterization consistent with the article design ... including environmental effect
  - Bond line thickness definition and boundaries
  - Sensibility to fluids
  - Max storage and process duration ...
  - Definition of incoming test (made by the material supplier) : physico-chimie / mechanical test specification & acceptable values
  - Incoming validation tests definition & acceptable values

  ...

Figure A2.2 (sheet 1 of 3): Dassault presentation to TAMCSWG on structural bonding

Process definition

DASSAULT AVIATION

- Definition of tooling and tolerances
- Definition of the process
  - Surface preparation
  - Layup, bond line application
  - Bagging arrangement and ancillary material defined and qualified : peel ply, release film etc …
  - Cure cycle characterization and associated process window (heating/cooling rates, cures temperature & plateau duration, vacuum level, pressure…)
- Specification of clean room, (temp, humidity, contamination) in relation with material characterization
- Quality documents :
  - Definition of controls (visual, geometrical, porosity, foreign objects, US spec, acceptable values / zoning …),
  - Description of procedures for each step of the process
  - Definition of the process key parameters
- Operator qualifications
- First articles manufacturing dedicated to destructive tests in particular used for bond line thickness measurement.

In production QC

DASSAULT AVIATION

- Validation of batchs conformity
  - Supplier incoming tests results (under DA spec),
  - verification tests performed at DA
  - Batch traceability (ref batch used, date of reception, date of layup, date or cure)
- Process verification
  - Surface preparation according to specifications
  - Bond line layup control before assembly (visual)
  - Cure cycle monitoring
  - Preventive maintenance plan of tooling
- Final product verification
  - Inspection visual / US (thickness, porosity, foreign objects…)
  - Traveler coupons (manufactured under same process / same cure cycle as article, if possible extracted in the article)
- Process key parameters data are stored.
- In case of non conformity : parameters out of defined windows are validated by additional tests or article is scrapped.

Figure A2.2 (sheet 2 of 3): Dassault presentation to TAMCSWG on structural bonding

Fleet survey ?

DASSAULT AVIATION

- Effect of environment and fatigue behaviour is well characterized and conservatively taken into account during sizing of the part.
- Impact damages threat may be difficult to precisely characterize
- Combined effect of environment en fatigue may be difficult to assess although monolithique structures exhibit no major in-service issues
- Fleet leader program may be performed to confirm the assumptions considered for sizing (e.g. NDI in some specific area – see TAMCSWG recommendations §3.5)
- Sandwich structures may be particularly subjected to ageing, a visual inspections may show evidence of bonding degradation (blistering …) and can be added in the maintenance program.

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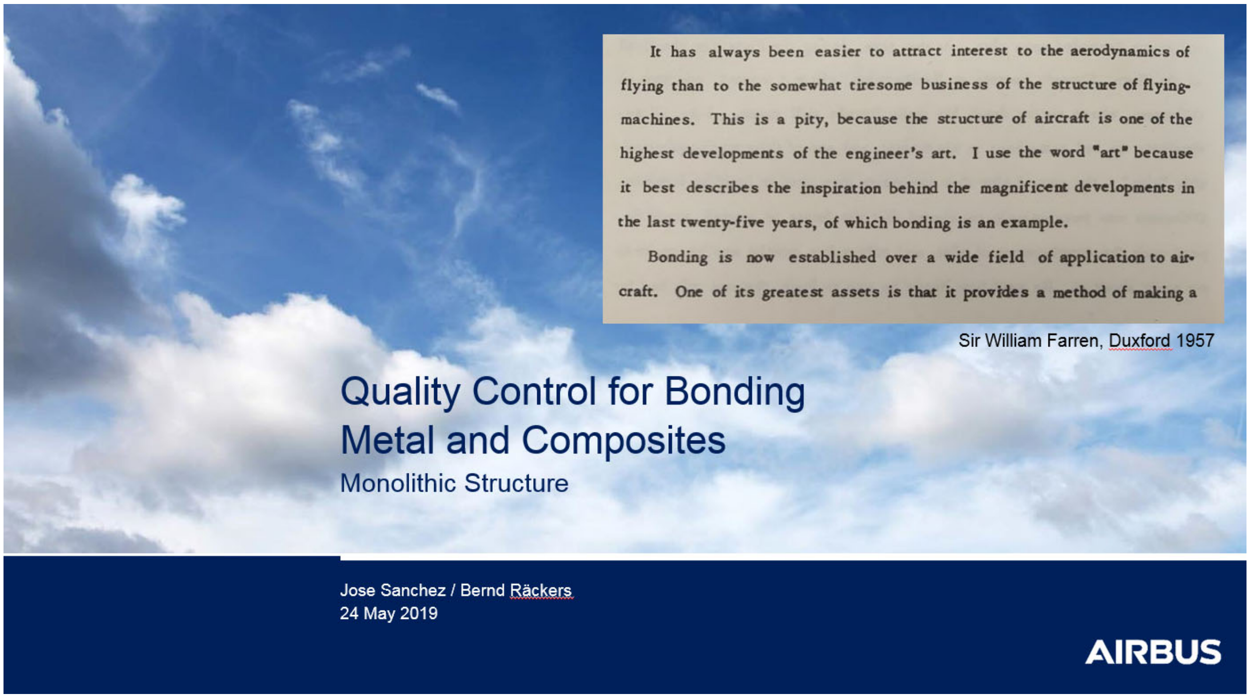
Figure A2.2 (sheet 3 of 3): Dassault presentation to TAMCSWG on structural bonding



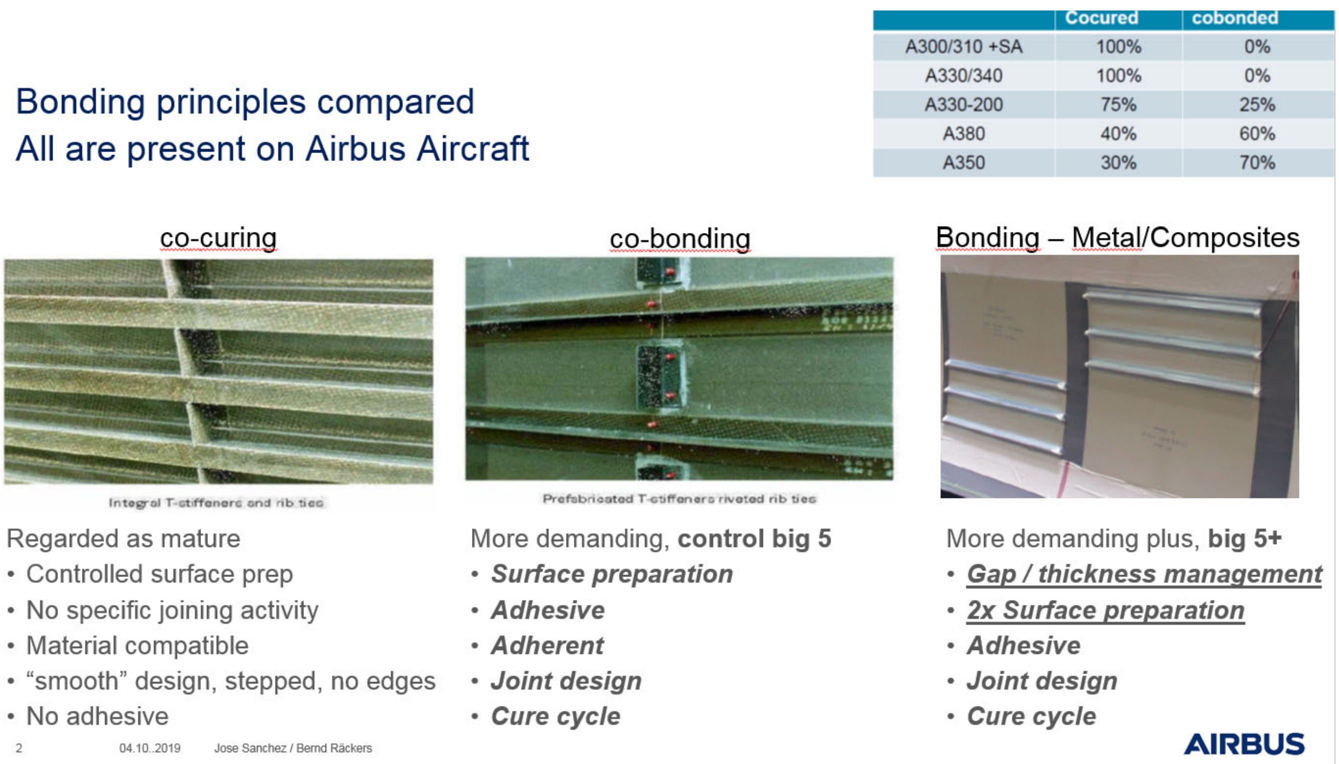


Figure A2.3 (sheet 1 of 5): Airbus presentation to TAMCSWG on structural bonding

Quality control for bonding
Pre- / In- / Post- Processing

- Pre = all qualification efforts
  - Materials, Cure Cycle, Process, Surface preparation for **full environmental envelope / process window**
  - Compatibility of surface, adhesive/adherent cure cycle for **all selected** combinations
  - Bonding performance established on $\mathbf{G_{1c}}$ as SLS do not address issues
  - First Part Qualification and tear down used to cover **joint geometry** and inner quality (section cuts)
  - Structure validation to confirm **no growth** and **damage tolerance** capability (to cover joint designs)
  - Design features to limit max dis-bond to LL capability
- In process quality control (preferred)
  - In-coming inspection for all peel plies, treated as flying material (rigid bath control for metal)
  - Airbus Process Specification to guarantee repeatable and reliable processes
  - Pre—PCS by G1c or drum peel to identify systematic issues up-front (batches representative for parts)
- Post process quality control (historical, but to be moved to in-process)
  - SLS/CDP for metal bonding found to be reliable in combination with bath pre-treatment (CAA/PSA)
  - NDI to detect critical porosity and delamination, Fokker bond test applied for metal bonding

3 04.10..2019 Jose Sanchez / Bernd Räckers AIRBUS

Experience at Airbus with QS plans
We may state that we have **never observed kissing bond** at Airbus
Airbus have compiled Lessons Learned on Bonding/Bonded repair, all Business Units

Historic Bonding Mishap for first Airbus A/C in the 70ies: bond-line corrosion (no CAA)
Two major issues happened in `90ies and early 2000s
- Serial aircrafts affected by use of wrong peel-ply (SRB) => Peel-Ply incoming tests
- Flight test aircrafts affected by wrong peel-ply/adhesive combination => G_{1c} PCS introduced

Both issues were systematic, and are prevented by todays quality plan, PCS not necessary

Very rare examples of misconduct, and false alarms of G1c PCS / FBT observed
- Cleaning with release agent in a qualified bond shop => parts fell apart, no need for PCS
- Prepreg wrong release paper => identified by "Pre-PCS"
- Apparent failure of G1c, poor specimen preparation => wedge tests all ok, no failure > 500 examples
- Fokker Bond Test (metal bonding): no bonding failure
  many false alarms leading to NCs => Test obsolete, visual inspection sufficient

4 04.10..2019 Jose Sanchez / Bernd Räckers AIRBUS

Figure A2.3 (sheet 2 of 5): Airbus presentation to TAMCSWG on structural bonding

Improvements for bonding / bonded repair maturity

Even if todays concept is mature we must improve depending on application scenario

- Better guidance for **Training** is essential if bonding is applied in less experienced shops
- Design for bonding rules to **reduce peak stresses** that potentially destroy any good or bad bond

Alternatives to AC 20-107B

(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

- Full size bonding control specimen **BCS** (patent applied)
- Advanced surface analysis to confirm **ready to bond surface** (patent applied)

5 04.10..2019 Jose Sanchez / Bernd Räckers AIRBUS

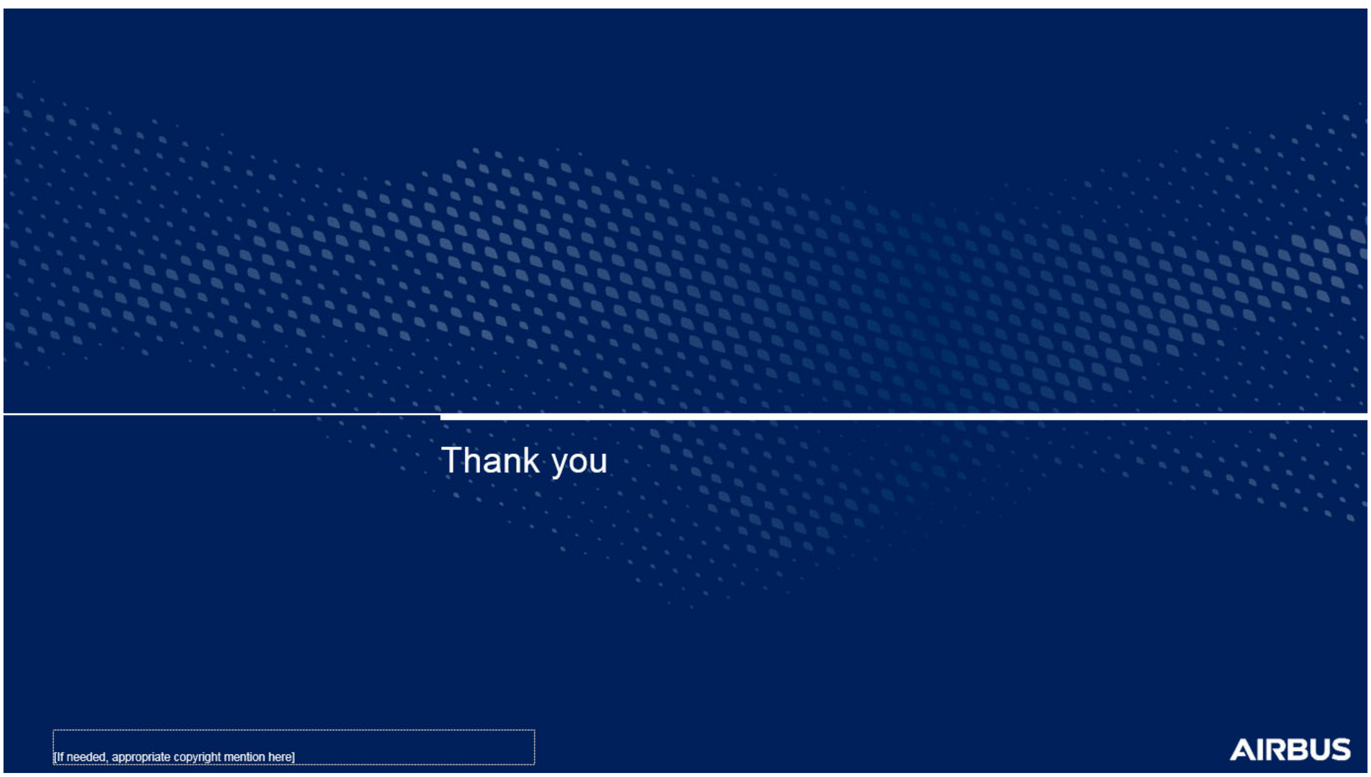
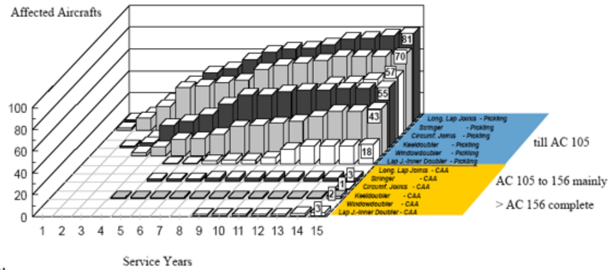


Figure A2.3 (sheet 3 of 5): Airbus presentation to TAMCSWG on structural bonding

Maturity of Metal Bonding

Corrective measures implemented > AC156 / A300

- New qualified processses (CAA) and materials (adhesive film 2nd generation)
- Design:
  - Change from 2 to 3 rivet rows for lap joints.
  - Resetted doublers.
  - Edge protection by CAA + bonding primer.
  - Adhesive squeeze out
  - Removal of metal bonding from environmental C categories: (bilge area)
- Requirements:
  - Limit Level for Bondline corrosion



=> Mature Advanced Quality Control Approach established

Thanks to basic research structural metal bonding is a reliable and robust technology:

- **'Lead fleet' did not show any corrosion in metal bonding after 30 years in-service**
- **Over 30 years there are almost no bonding issues reported from in-service operation of the entire fleet.**
- **Re-opened the possibility to bond in environmental C categories**
- **No NDI requested during "scheduled maintenance" for metal-metal bond lines**

Page 1

Quality Control Approach

- **Material qualification:**
  - **adhesive film (**together with bonding primer)
  - **bonding primer** (together with adhesive film)
    - Long-term durability of metal bonded joints by means of coupon testing
      - Long term test in different (aggressive) media and moisture simulating full aircraft life
      - Bondline corrosion simulation test AITM 5-0009 based on service experience
    - Test of individual triple combination (i.e. alloy, pre-treatment, primer and adhesive) to ensure compatibility.

- **Bonding process specification including primer process:**
  - process specification
    - specified KC (Key Characteristics) factors
  - Process Instruction
    - KPP (Key Process Parameters) worked out based of KC requirements
    - Definition of serial checks manufactured exactly with the same procedures as in serial production
      - Check for surface treatment *
      - Check for bonding process

Note*: PSA (REACH compliant) qualified as replacement for CAA

- **NDI in production:**

Mainly applied

- Ultrasonic through transmission inspection in squirter and immersion technique of adhesively joined metal parts
- Ultrasonic Resonance Impedance Inspection using Fokker Bond Tester

Optional

- Resonance Frequency Inspection Using Bondmaster
- Tap Test
- X-Radiographic Inspection General

Page 2

Figure A2.3 (sheet 4 of 5): Airbus presentation to TAMCSWG on structural bonding

Process Key Characteristics

		Airbus process KC's
Material (primer/adhesive) Handling and Storage		Material storage and worklife definition. Primer thickness Follow requirements acc. structural bonding spec's
Quality pre-treatment		Series production inspection (Batch composition) Ensure proper fuctionality galvanic process by Test
Part dimensional tolerance control	FPQ	Squeeze out requirement Porosity
Primer/Adhesive application		Positioning, completely cover with adhesive film within a prescribed time limit
Bondline thickness control, porosity	FPQ	Destructive Inspection of first production article to validate quality and Non-Destructive Inspection (NDI) technique (bondline quality, bondline thickness, porosity, squeeze-out criteria)
Bonded part cure		Ensure proper control of temperature by test with thermocouples (temp.survey, location of load thermo-couple) for both primer and adhesive interfaces. Ensure proper control of pressure on bondline through monitoring of pressure through entitre cycle.
Cured part inspection		Acc. AIPS 100% inspection, seperate bonding and seperate NDI of bonded doubler and stringer

Qualification and Mature Quality Control Approach

- **Certfified bonded AC primary structures are based on**
  - Qualified material suppliers
  - Qualified material & material combinations (compatibility)
  - Qualified manufacturing processes including FPQ, pre-treatment
  - Qualified & experienced bonding shops
  - Control & monitoring of process parameters, worklife, cure cycle, tooling, visual inspection…
  - Qualified NDI processes; qualified NDI shops & certified NDI inspectors
  - Surveillance of manufacturing shops & NDI shops (NADCAP)

If all individual manufacturing steps are well controlled and validated, then the sum of all well controlled and documented manufacturing steps, provides the required quality of the final bonded structure

Page 4

Figure A2.3 (sheet 5 of 5): Airbus presentation to TAMCSWG on structural bonding

Part 23 Re-Write Summary of applicable rules

14 CFR 23 Amdt 23-64

23.2240 Structural Durability (a) The applicant must develop and implement inspections or other procedures to prevent structural failures due to foreseeable causes of strength degradation, which could result in serious or fatal injuries, or extended periods of operation with reduced safety margins. Each of the inspections or other procedures developed under this section must be included in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness required by §23.1529.

14 CFR Part 23 Amdt 23-63	**14 CFR 23 Amdt 23-64 (Means of Compliance)**
23.573 (a)	**ASTM F3115-15**
(5) For any bonded joint, 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--	6.1 For composite airframe structure on Level II, III, and IV aircraft, the residual strength of bonded joints needs to be addressed as follows: for any bonded joint, 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	6.1.1 The maximum disbonds of each bonded joint consistent with the capability to withstand the residual strength loads in 4.7 or 5.2.3 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	6.1.2 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.	6.1.3 Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.

Textron Aviation approach to metal-to-metal bond.

The adhesive bonding of metal structure at Cessna was first developed and introduced in the mid 1960's in secondary structure. During the late 1960's, metal-to-metal bonding was extended to primary structure with design and certification of the Cessna Citation (Model 500). Cessna continued to expand the use of metal-to-metal bonding during the 1970's in both Part 23 and Part 25 airplanes. The expansion was both methodical and intentional, resulting in an approach and philosophy used by Cessna on the Cessna Citation III (Model 680) in early 1980's. This approach continues to provide the foundation used today at Textron Aviation and is based on both the lessons from previous experience, data from other industry leaders in metal bond, and extensive development tests allows Cessna to take advantage of the benefits of metal-to-metal bonded structure such as reducing stress concentrations due to fasteners, reduce weight, improve joint sealing, and enhanced appearance.

The approach utilized by Cessna can be viewed as 3 primary areas of focus and understanding. As with a 3-legged stool, each leg is crucial or the stool will not function even if the remaining legs are sound.

Figure A2.4 (sheet 1 of 3): Textron presentation to TAMCSWG on structural bonding

Design Considerations:

The design considerations are made up of both the structural philosophy and the adhesive philosophy. The structural philosophy requires a good understanding of the areas that lend themselves to good bonding practices. These practices include an understanding of the geometry that results in repeatable good bonds (producibility), the resulting load paths that are uniform and eliminate eccentricities or stress concentration, exposure to adverse environmental conditions, and designs that eliminate peel type loading in the bond lines. For the Adhesive philosophy, an understanding of the adhesive strength, it resistance to environmental factors, the resistance to damage such as impact or drilling (often referred to as flexibility or brittleness), and the adhesive's track record.

Cessna design considerations are generally as follows:

- Ultimate stress levels at the Bond line are a small percentage of the proven capability of the adhesive
- Operating Stress levels are low
- The maximum disbonds of each bonded joint consistent with the capability to withstand the residual strength loads (Reference 14 CFR 23.573(a)(5). Textron typical uses design features such as mechanical fasteners reinforcement, increased in stiffness (frame stringer intersections), or increase contact area (local width increase).
- The expected strength of the adhesive will decrease over time and should be accounted for in residual strength calculations.
- Loading of Bond lines in peel is to be avoided.
- Critical bonded joints, such as fuselage skin splices have adequate mechanical fasteners that a bond failure would not reduce load capability below residual strength requirements.

Production Quality and Control

Cessna understand that there is no substitution for a well-executed and controlled production process. The quality control aspects as defined in AC 120-107B provide a good foundation. This is one area where concerns for metal-to-metal bonding are most similar for composites build-up. Therefore, I will not spend much time or detail in this area.

Fleet Maintenance and Monitoring

One of the areas where there has been significant concern is the aging mechanism that exist for metal-to-metal bonding. The concern typically surrounds the hydration of the bond line which will continue to degrade and weaken the bond line as a function of time. The impact of this phenomena can be lessened by the strict adherence to a set of Design Criteria and Production Quality Control Criteria that compromise bond lines beyond anticipated degradation. It also requires a good understanding of the capability of the bond line over time as shown in figure below for AF-126. This will also affect the design stress level chosen for the design.

Maintenance can also play an important part in preserving bond line integrity. Typically the same mechanism that leads to a reduction in strength over time of the bond line is coupled with the mechanism that leads to degradation of the metallic surface itself. Strict adherence to the CPCP, including the cleaning and application of CIC's (Corrosion Inhibiting Compounds) such as Corban are critical to reducing the moisture intrusion. Cessna's experience shows that the baseline or MSG-3

Figure A2.4 (sheet 2 of 3): Textron presentation to TAMCSWG on structural bonding

inspections for corrosion are key to also detecting deterioration of bonds and typically a bond line that is experiencing extensive hydration will be accompanied by detectable corrosion of the adjacent metallic structure.

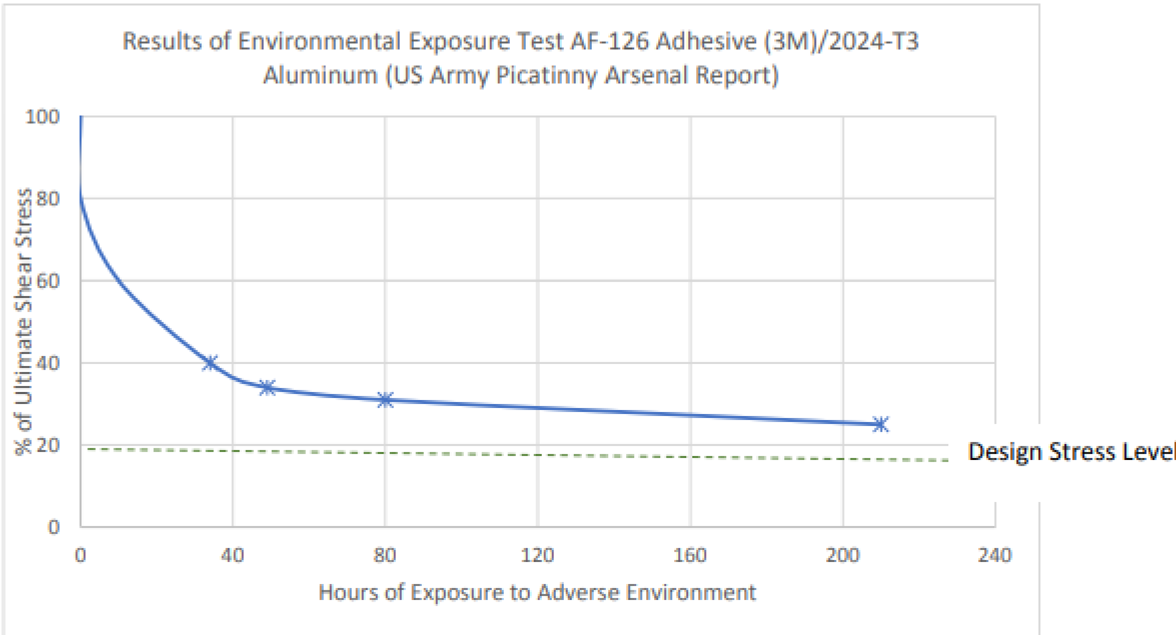


Figure A2.4 (sheet 3 of 3): Textron presentation to TAMCSWG on structural bonding

GKN-Fokker Quality Control Practices for Metal Bonding

ARAC meeting Oct. 9th, 2019

Andries Buitenhuis
GKN Aerospace - Fokker

 2

Introduction

Considering Safety & Certification of (metal) bonded, thermoset and thermoplastic structures, interesting parallels:

- Reliance on surface preparation and process adherence to ensure correct failure modes and strength
- Need to control changes after TC and structural mods
- Importance of out-of-plane or matrix properties for in-service damage, especially impact
- Need to correlate inspection methods with damage detectability and substantiate presence of damage (both after initial manufacture as well as in service)
- Certification (testing) requirements e.g. testing with artificial defects present under fatigue and static loads

"Although it is understood that co-cured structures can generally provide relatively more robust bonding between the constituent parts of the structure than other bonding processes, e.g. co-bonding, it should be noted that the potential exists for any bonded joint to present a challenge." – from Ref. [3] – i.e. the same damage tolerance philosophy should be applied in all cases.

References:

[1] CMH-17 Delft Sept. 2011: Certification of metal-to-metal bonded structures – Jan Waleson
[2] CMH-17 Delft Sept. 2011: Certification of Thermoplastic structures – Andries Buitenhuis
[3] EASA June 2016 Proposed CM No.: Proposed CM-S-010 Issue 01:
The Safe Design and Use of Monocoque Sandwich Structures in Critical Structure Applications – Simon Waite

Figure A2.5 (sheet 1 of 3): Fokker presentation to TAMCSWG on structural bonding

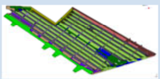
Proprietary and confidential restrictions on title slide apply throughout this presentation 3

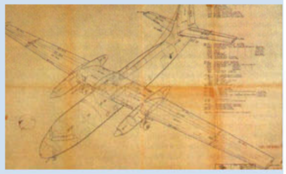
Metal bonding - introduction

Technology description:
Metal Bonding is an old but still very relevant technology for joining aluminum sheet metal parts.

TRL
9

Fokker Legacy
- Legacy Fokker Aircraft programs on which Metal Bonding was used:
  F27, Fokker 50, Fokker 60, F28, Fokker 70 and Fokker 100
- Application Areas:
  Fuselage-, Wing- and Stabilizer Panels.



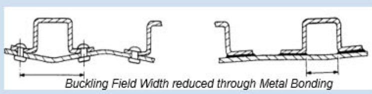


Recent Applications
In recent years new epoxy bond systems (better temperature resistance than older phenolic systems) have been added, certified for Dassault F7X/F8X flaps / Gulfstream G650.
Fokker provided design & stress guidelines and M&P specs to Gulfstream for detail design of the G650 fuselage.

Dassault F7X/F8X Flap

Gulfstream G650 Fuselage

Advantages of Metal Bonded Structures:
- Weight reduction (5 – 10%).
- Reduced assembly time.
- Less fasteners.
- Reduced cost.
- Improved buckling behavior.
- Improved F/DT performance (crack-stopper effect, less crack initiation locations)
- Improved corrosion resistance.
- Excellent long term durability (>90,000 flights for Fokker regional aircraft).



Proprietary and confidential restrictions on title slide apply throughout this presentation 4

Metal bonding - introduction

Frequently, OEM's have requested composite solutions while in the end, the conclusion was that metal bonding provided a more cost effective solution. E.g. impact resistance for flaps, post-buckled empennage skins.

Cert. plans to change CAA processing to PSA have been FAA approved, process development testing is complete, M&P specs have been FAA approved. Production line testing completed recently. All programs will transition to PSA processing in the course of 2019 – 2020.

The CAA -> PSA change is considered major insignificant – new part numbers on a bonded panel level.

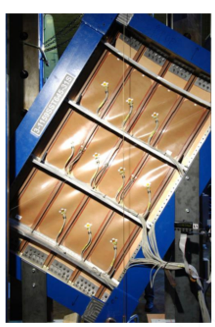


Figure A2.5 (sheet 2 of 3): Fokker presentation to TAMCSWG on structural bonding

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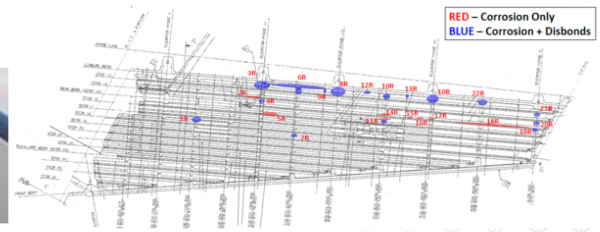
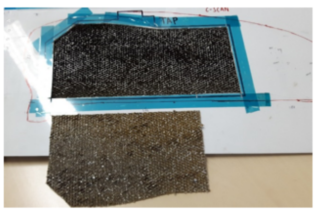
Metal bonding – examples of in-service challenges (2017-)





After severe in-flight hail, in about 90 flights significant debonding of metal sandwich face sheets. As a result of cyclic loading on the upper skin panel (internal pressure and aerodynamic suction loading) the crushed core has cracked and eventually it failed leading to the bulged skin observed during flight.

Note parallel with honeycomb issues on rudders reported by Airbus.

No severe issues with bondline corrosion (BLC) have been reported for the Fokker fleet.

Recently however some issues have been reported for business jets in more severe environments.

Inspection requirements had to be tightened – from visual after 16 years to NDI* after 12 years. There will be an AD soon for older aircraft that missed the 12 years inspection.

 6

Metal bonding – Quality Control Processes

An overview of current (CAA) QC methodology is shown on the right.

For the CAA->PSA change, and following discussions with the FAA, we also introduced wedge testing to get good information on bond line durability with an in-process test.

Note BLC testing takes long (45, 90, 180, 300 days) and cannot be used to release products.

Alkaline degreasing	monitoring of: solution composition, temperature immersion time
	visual inspection water break free surface on product
Acidic pickling	new pickling solution: electron microscopical examination travelers
	start of each day: peel test travelers inspection travelers (esp. etch rate)
	monitoring of: solution composition, temperature immersion time
	visual inspection product
Chromic acid anodizing	once every month: weight of travelers corrosion resistance of travelers
	start of each day: peel test
	monitoring of: solution composition, temperature immersion time voltage and amperage
	visual inspection product
Application of adhesive primer	incoming inspection testing
	start of each week: thickness on test panels (as part of the weekly operator qualification)
	thickness on product
	mechanical tests on travelers
	visual inspection product
Application of adhesive and curing in the autoclave	incoming inspection testing
	monitoring of cure cycle parameters
	mechanical testing on travelers
	visual inspection of product after curing

Figure A2.5 (sheet 3 of 3): Fokker presentation to TAMCSWG on structural bonding

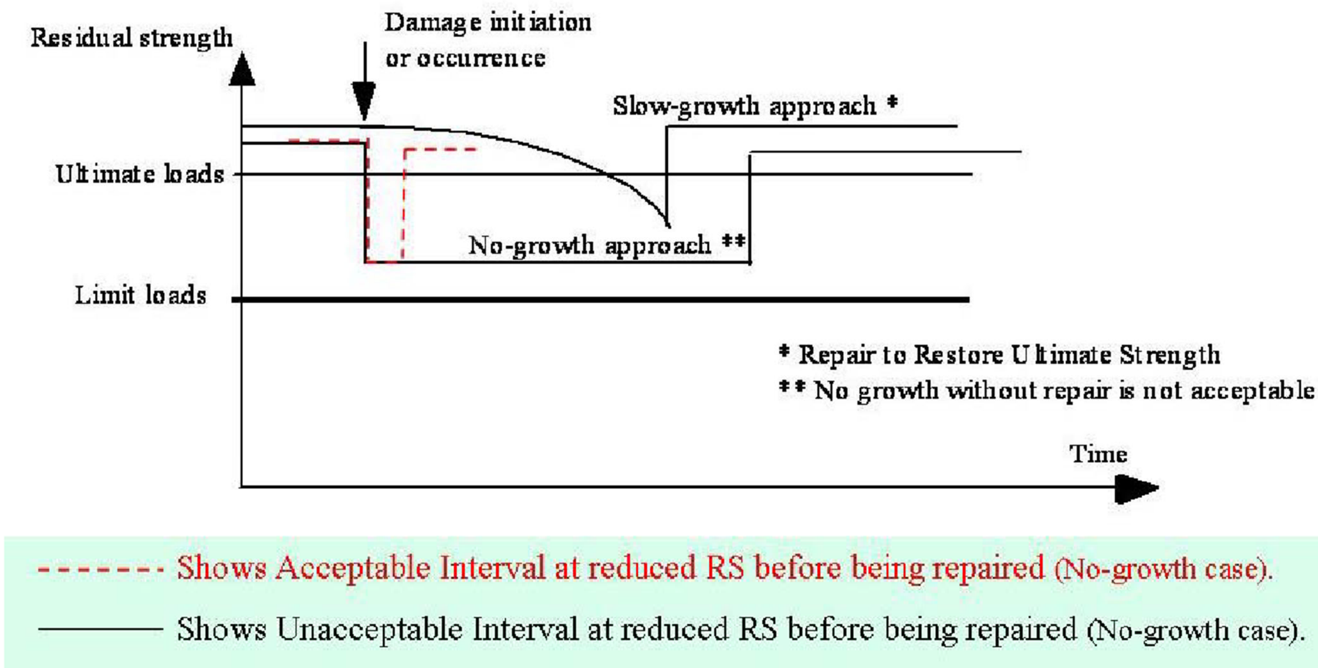
7.3 Appendix 3: Recommended AC 20-107B Updates

Update over existing guidance is highlighted. Each paragraph proposed to change is followed by the *reasoning* for that change. Since there are other aircraft products covered by AC 20-107B, the TAMCSWG recognizes that the changes below may need to be generalized to allow differing "best practices" for small airplanes, rotorcraft and even smaller transport business jets such as those members who may elect to follow the current bonded structural expectations of AC 20-107B as stated in 6C(3)(a), while further advancing bond material and process controls to ensure bond integrity and durability. The use of DTDC as explained in Section 4.2.4.1 of this report provides such a generalization, even for SLP structures that may need to lower stress levels to an extent that larger detectable disbonds would be found before failure. For example, rotor blades have an SLP bond that is damage tolerant and typically follows a slow growth curve that is typically self-inspecting when active via blade vibrational characteristics.

Category 2: Damage that can be reliably detected by scheduled or directed field inspections performed at specified intervals. Structural substantiation for Category 2 damage includes demonstration of a reliable inspection method and interval while retaining loads above limit load capability. The residual strength for a given Category 2 damage may depend on the chosen inspection interval and method of inspection. Certain inspection methods may not be adequate for particular damage states such as using general visual to find disbonds in bonded structure. Some examples of Category 2 damage include visible impact damage (VID), VID (ranging in size from small to large), deep gouges or scratches, manufacturing mistakes not evident in the factory, disbonding, possibly between arresting features, other detectable delamination or disbonds, and major local heat or environmental degradation that will sustain sufficient residual strength until found. This type of damage should not grow or, if slow or arrested growth occurs, the level of residual strength retained for the inspection interval is sufficiently above limit load capability.

Reason for change:

The guidance material is clear in regards to the necessity of a residual strength check with a failed bondline between arresting features. By adding this material to the Category 2 definition it is asking for this damage state to be treated like other category 2 damage. This necessitates an inspection to look for the damage state to ensure that the disbond is found and the airplane does not remain under regulatory load requirements for its remaining life. See AC 20-107B figure in Appendix 3. It is not a desired state to remain below ultimate load for an extended period of time. Also added to this paragraph is a recommendation stating that GVI is considered inadequate to visually detect bondline failures between arrestment. Detail inspection is recommended to find bondline cracks at a bonded flange edge.



6C 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. The general nature of technical parameters that govern different types of bonded structures are similar. The bonding system typically consists of the substrate, adhesive, surface preparation and the qualified bonding process. The bonding system must validate the system performance throughout the material and process window. Characterization outside the process limits is recommended to ensure process robustness. Reassessment of the bonding system must occur when changes happen that may affect the performance of the system constituents. A qualified bonding process is documented after demonstrating repeatable and reliable processing steps . In the case of bonding composite interfaces, a qualified surface preparation of all previously cured substrates is needed to activate their surface for chemical adhesion. All metal interfaces in a bonded structure also have chemically activated surfaces created by a qualified preparation process. Many technical issues for bonding require cross-functional teams for successful applications. Applications require stringent process control and a thorough substantiation of structural integrity. Even with this in place, bonding in single load path structure may not practically be used without further considerations.

Reason for change:

Add treating bonding as a system and any change in the system must be investigated (prep, adhesive, adherents, bond process) and tested within the process envelope. This is a lesson learned by the OEMs and has been communicated in CMH-17, CACRC and other forums. It will be a part of several chapter updates in CMH-17 Volume 3, revision H release as well.

Also added recommendation to only use bonding in single load path structure, where failure of the bond would result in the airframe's capability to maintain regulatory load levels (limit loads), when adopting additional design, maintenance or other considerations that mitigate associated safety risks.

6C (3) Previous to Amendment level 64, 14 CFR §23.573(a) set forth requirements for substantiating the critical composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. These performance standards are expected with Part 23 general aviation, large transport and rotorcraft category aircraft (typically via special conditions and issue papers). Industry guidelines such as provided in Reference 2 indicate that the design of bonded structures should meet the redundant structural expectations identified below.

(a) For any factory or in-service bonded joint including repair: "*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 test or analysis supported by test. 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.*"

(b) These options do not supersede the need for a qualified bonding process and rigorous quality controls for bonded structures that further helps ensure bond environmental durability. 6(a) “Material and Process Control” and 6(b) “Manufacturing Implementation” shown above should be adhered to. For example, fail safety implied by the first option is not intended to provide adequate safety for the systematic problem of a bad bonding process applied to a fleet of aircraft structures. Instead, it gives fail safety against bonding problems that may occasionally occur over local areas (e.g., insufficient local bond contact pressure or contamination). Following this rigorous approach allows the consideration of a single bond failure on a bond assembly to ensure adequate safety. Performing static proof tests to limit load, which is the second option, has shown not to reliably detect weak bonds requiring environmental exposure and time to degrade bonded joint strength. This issue should be covered by adequately demonstrating that qualified bonding materials and processes have long-term environmental durability. Finally, the third option is open for future advancement and validation of non-destructive inspection (NDI) technology to detect weak bonds, which degrade over time and lead to adhesion failures. Such technology has not been reliably demonstrated at a production scale to date.

Reason for change:

- *Needed an update for the old §23.573 reference*
- *Changed the first sentence in paragraph 6(C)(3)(a) “*For any factory or in-service bonded joint including repair*” at the request of the airlines to emphasize that bonded repair, in-service or factory installed, should satisfy limit load residual strength with a failure; the*

same as a factory production bond. This was discussed relative to an update to the BRSL policy to affect the same change.

- *Add a link to paragraph 6 to emphasize quality and state that assumption of single disbond between arrestment is only allowed due to strict adherence to stringent process control requirements, which further helps to ensure bond environmental durability.*
- *Clarified the drawbacks to proof loading and its inability to detect weak bonds.*

Para 10. Continued Airworthiness
Sentences related to Repair substantiation are highlighted. Only 10(c) and paragraph 6(c)(3)(a) has proposed changes.

b. Maintenance Practices.
(3) Repair. All bolted and bonded repair design and processing procedures applied for a given structure shall be substantiated to meet the appropriate requirements. Of particular safety concern are the issues associated with bond material compatibilities, bond surface preparation (including drying, cleaning, and chemical activation), cure thermal management, composite machining, special composite fasteners, and installation techniques, and the associated in-process control procedures. The surface layers (e.g., paints and coatings) that provide structural protection against ultraviolet exposure, structural temperatures, and the lightning strike protection system must also be properly repaired.

c. Substantiation of Repair.
(1) When repair procedures are provided in FAA-approved documents or the maintenance manual, it should be demonstrated by analysis and/or test that the method and techniques of repair will restore the structure to an airworthy condition. Repairable damage limits (RDL), which outline the details for damage to structural components that may be repaired based on existing data, must be clearly defined and documented. Allowable damage limits (ADL), which do not require repair, must also be clearly defined and documented. Both RDL and ADL must be based on sufficient analysis and test data to meet the appropriate structural substantiation requirements and other considerations outlined in this AC. Additional substantiation data will generally be needed for damage types and sizes not previously considered in design development. Some damage types may require special instructions for field repair and the associated quality control. Bonded repair is subjected to the same structural bonding considerations as the base design (refer to paragraph 6.c) including bonded repair size limits for critical structure.

Add to par 6.c: (see above for addition, reworded to fit existing paragraph): In-factory and in-service repairs must be capable of limit load with a failed repair, and have the option of adding arrestment features.

(2) Operators and maintenance repair organizations (MRO) wishing to complete major repairs or alterations outside the scope of approved repair documentation should be aware of the extensive analysis, design, process, and test substantiation required to ensure the airworthiness of a certificated structure. Documented records and the certification approval of this substantiation should be retained to support any subsequent maintenance activities.

d. Damage Detection, Inspection and Repair Competency.

(1) All technicians, inspectors, and engineers involved in damage disposition and repair should have the necessary skills to perform their supporting maintenance tasks on a specific composite structural part. The continuous demonstration of acquired skills goes beyond initial training (e.g., similar to a welder qualification). The repair design, inspection methods, and repair procedures used will require approved structural substantiation data for the particular composite part. Society of Automotive Engineers International (SAE) Aerospace Information Report (AIR) 5719 outlines training for an awareness of the safety issues for composite maintenance and repair. Additional training for specific skill-building will be needed to execute particular engineering, inspection, and repair tasks.

Reason for change:

10(c) was updated to emphasize that when stating "Bonded repair is subjected to the same structural bonding considerations as the base design" that also meant that they must meet limit load with a failed bond between arrestment, as stated in bonded repair size limits (BRSL) policy

7.4 Appendix 4: Recommended AC25.571-1D Updates

Note: The following updates are not intended to supersede any existing recommendations in reference 7, rather to supplement those already suggested. The updates are shown with red revision bars in left hand margin.

U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: Damage Tolerance and Fatigue Evaluation of Structure

Date: 1/13/2011
Initiated By: ANM-115

AC No: 25.571-1D

1. Purpose.

a. This advisory circular (AC) provides guidance for compliance with the provisions of Title 14, Code of Federal Regulations (14 CFR) part 25, pertaining to the requirements for damage-tolerance and fatigue evaluation of transport category aircraft structure, including evaluation of widespread fatigue damage (WFD) and establishing a limit of validity of the engineering data that supports the structural-maintenance program (hereafter referred to as the LOV). This AC also includes guidance pertaining to discrete source damage and metal bonding.

b. The following appendices appear at the end of this AC:

- Appendix 1 – References and Definitions
- Appendix 2 – Full-Scale Fatigue Testing
- Appendix 3 – Process for Compliance with 14 CFR 25.571(a), (b) and (c) for Fatigue Damage

- Appendix 4 – Examples of Alterations that May Require Full-Scale Fatigue Testing
- Appendix 5 – PSE, FCS and WFD-Susceptible Structure
- Appendix 6 – Acronyms and Abbreviations Used in this AC

2. Applicability.

a. The guidance provided in this document is directed to airplane manufacturers, modifiers, foreign civil-aviation authorities, and Federal Aviation Administration (FAA) transport airplane type certification engineers and designees.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. The FAA will consider other methods of demonstrating compliance that an applicant may elect to present. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. On the other hand, if the FAA becomes aware of circumstances that convince us that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation or design changes as a basis for finding compliance.

c. This material does not change, create additional, authorize changes in, or permit deviation from regulatory requirements.

3. Cancellation. AC 25.571-1C, dated April 29, 1998, is canceled.

4. Background.

a. Since the early 1970s, there have been significant developments in the state-of-the-art and industry-practice in the area of structural-fatigue and fail-safe strength evaluation of transport category airplanes. Recognizing that these developments could warrant some revision of the existing fatigue requirements of §§ 25.571 and 25.573, on November 18, 1976 (41 FR 50956), the FAA gave notice of the Transport Category Airplane Fatigue Regulatory Review Program, inviting interested persons to submit proposals to amend those requirements. The proposals and related discussions formed the basis for the revision of the structural-fatigue-evaluation standards of §§ 25.571 and 25.573, and the development of guidance material. To that end, § 25.571 was revised, § 25.573 was deleted (the scope of § 25.571 was expanded to cover the substance of the deleted section), and guidance material (AC 25.571-1) was prepared.

b. After issuance of AC 25.571-1 on September 28, 1978, additional guidance material, including guidance on discrete source damage, was developed and incorporated in revision 1A, issued on March 5, 1986. The AC was further revised on February 18, 1997; revision 1B added guidance on the elements to be considered in developing scatter factors for certification. Revision 1C of the AC was issued April 29, 1998, to add guidance pertaining to precluding widespread fatigue damage within the design service goal of the airplane and determining thresholds for fatigue inspection. This revision removes guidance material for precluding WFD up to the design service goal and replaces it with guidance material for precluding WFD up to the LOV.

5. Introduction.

a. General. The FAA considers the contents of this AC in determining compliance with the damage-tolerance, fatigue, and discrete source damage requirements of § 25.571.

(1) The requirements of § 25.571 apply equally to metallic and composite structure. The focus of this AC is metallic structure. Refer to AC 20-107B for guidance on composite structure and further guidance on the material and process control of metal bonding .

(2) Section 25.571 requires applicants to evaluate all structure that could contribute to catastrophic failure of the airplane with respect to its susceptibility to fatigue, environmental, and accidental damage. The applicant must establish inspections or other procedures (herein also referred to as maintenance actions) as necessary to avoid catastrophic failure during the operational life of the airplane based on the results of these evaluations. Section 25.571 also requires the applicant to establish an LOV. The LOV, in effect, is the operational life of the airplane consistent with evaluations accomplished and maintenance actions established to prevent WFD. Although the LOV is established based on WFD considerations, it is intended that all maintenance actions required to address fatigue, environmental, and accidental damage up to the LOV are identified in the structural-maintenance program. All inspections and other procedures (e.g., modification times, replacement times) that are necessary to prevent a catastrophic failure due to fatigue, up to the LOV, must be included in the Airworthiness Limitations section (ALS) of the Instructions for Continued Airworthiness (ICA), as required by § 25.1529, along with the LOV.

(3) Although a uniform approach to the evaluation required by § 25.571 is desirable, the FAA recognizes that, in such a complex field, new design features and methods of fabrication, new approaches to the evaluation, and new configurations could necessitate variations and deviations from the procedures described in this AC.

(4) Compliance with § 25.571(b), *Damage-tolerance evaluation*, is not required if the applicant establishes that it is impracticable to apply the regulation to particular structure. An example of structure that may not be conducive to damage-tolerant design is the landing gear and its attachments. In this case, the applicant may comply instead with § 25.571(c), *Fatigue (safe-life) evaluation*. The FAA does not allow exclusive reliance on damage-tolerance-based inspections for structure susceptible to WFD. The applicant must demonstrate that WFD is unlikely to occur prior to the LOV for the airplane. An applicant may use damage-tolerance-based inspections for multiple site damage (MSD)/multiple element damage (MED) to supplement replacement or modification required to preclude WFD when shown to be practical.

(5) The applicant should perform damage-growth and residual-strength testing to produce the design data needed to support damage-growth and residual-strength analyses. Full-scale fatigue-test evidence is required to support the evaluation of structure that is susceptible to

WFD. Test evidence is needed to support analysis used to establish safe-life replacement times.

(6) Replacement times, inspections, or other procedures to address fatigue cracking and disbonding in metal bonded details must be established as necessary. These actions must be based on quantitative evaluations of the fatigue characteristics of the structure. In general, analysis supported by test evidence will be necessary to generate the information needed; service experience may also be used. The applicant should identify the intended approach in a compliance plan. All inspections, modification times, replacement times, and LOVs that are necessary to prevent a catastrophic failure – based on the damage-tolerance, fatigue, and WFD evaluations – must be included in the ALS of the ICA as required by § 25.1529.

(7) The applicant must establish inspections or other procedures for environmental damage and accidental damage as necessary to prevent catastrophic failure. Guidance for establishing environmental damage and accidental damage maintenance actions is included in section 6 of this AC.

b. Typical loading spectrum expected in service. The loading spectrum used for damage-growth and fatigue- damage-initiation assessments (tests or analyses) should be based on measured statistical data of the type derived from government and industry load-history studies and, where data is insufficient or unavailable, on a conservative estimate of the anticipated use of the airplane. The principal loads that should be considered in establishing a loading spectrum are flight loads (gust and maneuver), ground loads (taxiing, landing impact, turning, engine run-up, braking, thrust reversing, and towing), and pressurization loads. The development of the loading spectrum includes the definition of the expected flight plan, which involves climb, cruise, descent, flight times, operational speeds and altitudes, and the approximate time to be spent in each of the operating regimes. Operations for crew training and other pertinent factors, such as the dynamic stress characteristics of any flexible structure excited by turbulence or buffeting, should also be considered. For pressurized cabins, the loading spectrum should include the repeated application of the normal operating differential pressure, and the superimposed effects of flight loads and external aerodynamic pressures.

c. Structure to be evaluated. When assessing the possibility of fatigue failures, the applicant should examine the design to determine probable points of failure in service. In this examination, consideration should be given, as necessary, to (1) the results of stress analyses, static tests, fatigue tests, strain-gauge surveys, and tests of similar structural configurations and (2) service experience. Service experience has shown that special attention should be focused on the design details of important discontinuities, attachment fittings, tension joints, splices, bonded joints and cutouts such as windows, doors, and other openings. Locations prone to accidental damage (such as that due to impact with ground servicing equipment near airplane doors) or to environmental damage should also be considered.

d. Analyses and tests. Repeated load analyses or tests should be conducted on structures representative of components or subcomponents of the wing, control surfaces, empennage, fuselage, landing gear, and their related primary attachments. Analyses and tests need not be conducted if it is determined from the foregoing examination that the normal operating stresses in specific regions of the structure are of such a low order that significant damage growth is extremely improbable. Test articles should include structure representative of attachment fittings, tension joints, splices, changes in section, cutouts, and discontinuities. Any method used in the analyses should be supported, as necessary, by test or service experience. Typical (average) values of material properties that account for the quantifiable effects of environment and other parameters may be used in residual-strength, crack-growth, and damage-detection analyses for damage-tolerance assessments and for discrete source damage. These are described, respectively, in sections 6 and 9 of this AC.

6. Damage-Tolerance Evaluation.

a. **General.** The damage-tolerance evaluation of structure is intended to ensure that—should fatigue, environmental, or accidental damage occur within the LOV of the airplane—the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected. The damage-tolerance evaluation should include the following:

- identification of the structure to be evaluated,
- definition of the loading conditions and extent of damage,
- structural tests or analyses, or both, to substantiate that the design objective has been achieved, and
- generation of supporting data for inspection programs to ensure detection of damage.

Although this evaluation applies to either single- or multiple-load-path structure, the use of multiple load path structure should be given high priority in achieving a damage-tolerant design. Design features that should be considered in attaining a damage-tolerant structure include the following:

(1) Multiple load path construction, and the use of crack stoppers to control the rate of crack growth and to provide adequate residual strength;

(2) Materials and stress levels that, after initiation of cracks provide a controlled slow rate of crack propagation combined with high residual strength;

(3) Arrangement of design details to ensure a high probability that a failure in any critical structural element will be detected before the strength of the element has been reduced below the level necessary to withstand the loading conditions specified in § 25.571(b), thereby allowing timely replacement or repair of the failed elements.

(4) Using disbond arrestment for metal bond joints as described in paragraph 6c(3) of AC20-107B and focusing on achieving high material and process reliability as stated in paragraphs 6c(2) and 6c(4) of AC20-107B.

b. **Damage-Tolerance Assessment Methodologies.** Normally, the damage-tolerance assessment consists of a deterministic evaluation of the design features described in this section. Sections 6c through 6j below provide guidelines for this approach. In certain specific instances, however, damage-tolerant design might be more realistically assessed by a probabilistic evaluation, employing methods such as risk analysis. Risk analyses are routinely employed in fail-safe evaluations of airplane systems and have occasionally been used where structure and systems are interrelated. These methods can be of particular value for structure consisting of discrete elements, where damage tolerance depends on the ability of the structure to sustain redistributed loads after failures resulting from fatigue, environmental, or accidental damage. Where considered appropriate on multiple load path structure, a probabilistic analysis may be used if it can be shown that (1) loss of the airplane is extremely improbable, and (2) the statistical data employed in the analysis of similar structure is based on tests or operational experience, or both.

c. **Identification of principal structural elements.** As defined in this AC, a principal structural element is an element of structure that contributes significantly to the carrying of flight, ground, or pressurization loads and whose integrity is essential in maintaining the overall structural integrity of the airplane. Principal structural elements include all structure susceptible to fatigue damage, which could contribute to a catastrophic failure. Refer to appendix 5 of this AC for clarification on how this term relates to the terms, fatigue critical structure (FCS) and WFD – susceptible structure. Examples of such elements are as follows:

(1) Wing and empennage.

(a) Control surfaces, slats, flaps, and their mechanical systems and attachments (hinges, tracks, and fittings);

(b) Integrally stiffened plates;

(c) Primary fittings;

(d) Principal splices;

(e) Skin or reinforcement around cutouts or discontinuities;

(f) Skin-stringer combinations;

(g) Spar caps; and

(h) Spar webs.

(2) Fuselage.

(a) Circumferential frames and adjacent skin;

(b) Door frames;

(c) Pilot-window posts;

(d) Pressure bulkheads;

(e) Skin and any single frame or stiffener element around a cutout;

(f) Skin or skin splices, or both, under circumferential loads;

(g) Skin or skin splices, or both, under fore and aft loads;

(h) Skin around a cutout;

(i) Skin and stiffener combinations under fore and aft loads;

(j) Door skins, frames, and latches; and

(k) Window frames.

(3) Landing gear and their attachments.

(4) Engine mounts.

d. Extent of damage. Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage-extension characteristics. In any damage determination, including those involving multiple damage, it is possible to establish the extent of damage in terms of the following parameters:

- detectability with the inspection techniques to be used,
- the associated, initially detectable damage size,
- the residual-strength capabilities of the structure, and
- the likely damage-extension rate.

This determination should consider the expected stress redistribution under the repeated loads expected in service at the expected inspection frequency. Thus, an obvious partial failure could be the extent of the damage for residual-strength assessment, provided that the fatigue cracks or disbonds will be detectable at a sufficiently early stage of development. The following are examples of partial failures that should be considered in the evaluation:

(1) Detectable skin cracks emanating from the edge of structural openings or cutouts;

(2) A detectable circumferential or longitudinal skin crack in the basic fuselage structure;

(3) Complete severance of interior frame elements or stiffeners in addition to a detectable crack in the adjacent skin;

(4) A detectable failure of one element of components in which dual construction is used, such as spar caps, window posts, window or door frames, and skin structure;

(5) A detectable fatigue failure in at least the tension portion of the spar web or similar element; and

(6) The detectable failure of a primary attachment, including a control surface hinge and fitting.

(7) A detectable disbond of a stiffener or tear strap between arrestment features.

e. **Inaccessible areas.** Every reasonable effort should be made to ensure inspectability of all structural parts and to qualify those parts under the damage-tolerance provisions (see § 25.611).

f. **Testing of principal structural elements.** The nature and extent of residual-strength tests on complete structures or on portions of the primary structure depends upon applicable previous design, construction, tests, and service experience with similar structures. Simulated cracks should be as representative as possible of actual fatigue damage. Where it is not practical to produce actual fatigue cracks, damage can be simulated by cuts made with a fine saw, sharp blade, guillotine, or other suitable means. If saw cuts in primary structure are used to simulate sharp fatigue cracks, sufficient evidence should be available from element tests to indicate equivalent residual strength. In those cases where bolt failure or its equivalent is to be simulated as part of a possible damage configuration in joints or fittings, bolts can be removed to provide that part of the simulation.

g. **Identification of locations to be evaluated.** The locations of damage to structure for damage-tolerance evaluation should be identified as follows:

(1) Determination of general damage locations. The evaluation would include a determination of the probable locations and modes of damage due to fatigue, environmental, or accidental damage. Repeated load and static analyses, supported by test evidence and (if available) service experience, would also be incorporated in the evaluation. Special consideration for widespread fatigue damage must be included where the design is such that this type of damage could occur. The location and modes of damage can be determined by analysis or service experience, or by fatigue tests on complete structures or subcomponents. However, tests may be necessary when the basis for analytical prediction is not reliable, such as for complex components. If less than the complete structure is tested, ensure that the internal loads and boundary conditions are valid.

(a) If a determination is made by analysis, take into account factors such as the following:

1 Strain data on undamaged structure to establish points of high-stress concentration as well as the magnitude of the concentration;

2 Locations where permanent deformation occurred in static tests;

3 Locations of potential fatigue damage identified by fatigue analysis; and

4 Design details that service experience, of similarly designed components, indicates are prone to fatigue or other damage.

(b) In addition, the areas of probable damage from other sources, such as severe environmental or accidental damage, should be determined from a review of the design and past service experience.

(2) Selection of critical damage areas. The process of actually locating where damage should be simulated in principal structural elements (identified in section 6d of this AC) should take into account factors such as the following:

(a) Review analysis to locate areas of maximum stress and low margin of safety;

(b) Select locations in an element where the stresses in adjacent elements would be the maximum with the damage present;

(c) Select partial-fracture locations in an element where high stress concentrations are present in the residual structure; and

(d) Select locations where detection would be difficult.

h. Damage-tolerance analysis and tests.

(1) Analysis, supported by test evidence, should determine that:

(a) The structure with the extent of damage established for residual-strength evaluation can withstand the specified design-limit loads (considered as ultimate loads); and

(b) The damage-growth rate under the repeated loads expected in service – between the time the damage becomes initially detectable and the time the extent of damage reaches the value for residual-strength evaluation – provides a practical basis for development of the inspection program and procedures described in section 6j of this AC.

(2) The repeated loads should be as defined in the loading, temperature, and humidity spectra while considering environmental effects caused from hydraulic fluids, fuels, cleaners and other detrimental materials found in operations, particularly when bonded structure is used to react metallic crack growth. The loading conditions should take into account the effects of structural flexibility and rate of loading where they are significant.

(3) The damage-tolerance characteristics can be shown analytically by reliable or conservative methods, such as the following:

(a) Demonstrating quantitative relationships with structure already verified as damage tolerant;

(b) Demonstrating that the damage would be detected before it reaches the value for residual-strength evaluation; or

(c) Demonstrating that the repeated loads and limit-load stresses do not exceed those of previously verified designs of similar configuration, materials, and inspectability.

(4) The maximum extent of immediately obvious damage from discrete sources should be determined, and the remaining structure shown to have static strength for the maximum load (considered as ultimate load) expected during the remainder of the flight. Normally, this would be an analytical assessment. In the case of uncontained engine failure, the fragments and paths to be considered should be consistent with those used in showing compliance with § 25.903(d)(1) and with typical damage experienced in service. (See AC 20-128, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor and Fan Blade Failures.")

i. Inspection.

(1) Detection of damage before it becomes critical is the ultimate control in ensuring the damage-tolerance characteristics of the structure. For this reason, Amendment 25-54 revised § 25.571 to require that the applicant (1) establish inspections or other procedures, as necessary, to prevent catastrophic failure from accidental, environmental, or fatigue damage, and (2) include those inspections and procedures in the ALS of the ICA, as required by § 25.1529 (see also appendix H to part 25).

(2) Due to the complex interactions of the many parameters affecting damage tolerance – such as operating practices, environmental effects, load sequence on damage growth, and variations in inspection methods – take into account related operational experience in establishing inspection procedures. Additionally, give careful consideration to the practical nature of inspection procedures.

(3) Comparison with past successful practice is the primary means of substantiating inspections or other procedures for accidental and environmental damage. For a new-model transport category airplane, the Maintenance Review Board generally conducts such comparison to substantiate inspections or other actions using the Air Transport Association of America, Inc. (ATA) Maintenance Steering Group's MSG-3 or other accepted version of the "Operator/Manufacturer Scheduled Maintenance Development" procedures. If this process is used, the required maintenance actions for accidental and environmental damage must be documented in the Maintenance Review Board Report for the airplane model and must be complete not later than when the first airplane enters service. These inspections or other procedures, as necessary to prevent catastrophic failure of the airplane, must be included in the Airworthiness Limitations section of the ICA. Alternatively, the applicant may reference, in the ALS of the ICA, the maintenance documents that contain those tasks. The ALS should also contain reference to any corrosion prevention and control program (CPCP) developed to maintain corrosion to "Level 1" or better for that airplane model. "Level 1" corrosion is damage occurring between successive inspections that is local and can be reworked/blended-out within allowable limits as defined by the manufacturer's service information, such as structural-repair manuals and service bulletins.

(4) In some cases, the experience of an operator may indicate that different inspections or other procedures are appropriate for that operator. Title 14 CFR 43.16 and 14 CFR 91.403(c) provide a means for FAA approval of alternatives to the airworthiness limitations. The FAA will evaluate such proposed alternatives, using the methods described in this AC or other acceptable methods proposed by the type-certificate holder and operators, to ensure that the objectives of 14 CFR 25.571 continue to be met.

j. Threshold for Inspections.

(1) Where it can be shown by observation, analysis, and/or test that a load path failure in multiple load path "fail-safe" structure or partial failure in damage-arrest "fail-safe" structure will be detected and repaired during normal maintenance, inspection, or operation of an airplane prior to failure of the remaining structure, the thresholds can be established using either:

(a) Fatigue analysis and tests with an appropriate scatter factor; or

(b) Slow- damage-growth analyses and tests, based on appropriate initial manufacturing damage.

(2) For single load path structure and for multiple load path and damage-arrest "fail-safe" structure – where it cannot be demonstrated that load-path failure, partial failure, or damage arrest will be detected and repaired during the normal maintenance, inspection, or operation of an airplane prior to failure of the remaining structure – the thresholds should be established based on damage-growth analyses and/or tests, assuming the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing- or service-induced damage.

7. Establishing an LOV.

a. Structural-maintenance program.

(1) If an airplane is properly maintained, theoretically it could be operated indefinitely. However, it should be noted that structural-maintenance tasks for an airplane are not constant with time. Tasks typically are added to the maintenance program as the airplane ages. It is reasonable to expect, then, that confidence in the effectiveness of current structural-maintenance tasks may not, at some future point, be sufficient for continued operation. Maintenance tasks for a particular airplane can only be determined based on what is known about that airplane model at any given time; from analyses, tests, service experience, and teardown inspections. Widespread fatigue damage is of particular concern because inspection methods cannot be relied on solely to ensure the continued airworthiness of airplanes indefinitely. To prevent WFD from occurring, the structure occasionally must be modified or replaced. Establishing all the replacements and modifications required to operate the airplane indefinitely is an unbounded problem. This problem is solved by establishing limit of validity of the engineering data that supports the structural-maintenance program. All necessary modifications and replacements are required to be established to ensure continued airworthiness relative to WFD up to the LOV. To operate beyond the LOV, the full-scale fatigue-test evidence and the structural maintenance program must be re-evaluated to determine if additional modifications or replacements are required. See paragraph 7.g for the steps to extend the LOV.

b. Widespread Fatigue Damage.

(1) Structural fatigue damage is progressive. It begins as minute cracks, and those cracks grow under repeated stresses. It can initiate as a result of normal operational conditions and design attributes, or from isolated incidents, such as material defects, poor fabrication quality, or corrosion pits, dings, or scratches. Fatigue damage can occur locally, in small areas or structural design details, or globally. Global fatigue damage is a general degradation of large areas of structure that share similar structural details and stress levels. Global damage may occur in a large structural element, such as a single rivet line of a lap splice joining two large skin panels (multiple site damage). Such damage may be affected by multiple stringer disbonds or rare weak bonds in a panel that is using bonded structure to enhance fatigue performance.

Global damage may also be found in multiple elements, such as adjacent frames or stringers (multiple element damage). Multiple site damage and multiple element damage cracks are typically too small, initially, to be reliably detected with normal inspection methods. Without intervention, these cracks will grow, and eventually compromise the structural integrity of the airplane, in a condition known as widespread fatigue damage. Widespread fatigue damage is increasingly likely as an airplane ages, and is certain if an airplane is operated long enough without any intervention. The existence of metal bonded structure that has other aging mechanisms, including hydration phenomena, which strongly depends on moisture entrapment, will further complicate such degradation.

c. Steps for Establishing an LOV.

(1) Under § 25.571, persons applying for type certificates (TC) must establish an LOV for each new type design. For new airplane models, or design changes to existing models that are added to the TC, the type-certificate holder must either establish an LOV for the new or design-changed model, or show that the LOV for the originally certificated model can also be applied to the new or design-changed model. The LOV is the period of time (in flight cycles, flight hours, or both) up to which it has been demonstrated that widespread fatigue damage is unlikely to occur in an airplane's structure by virtue of its inherent design characteristics and any required maintenance actions. An airplane may not operate beyond the LOV. To support establishment of the LOV, the applicant must demonstrate, by test evidence and analysis at a minimum and, if available, service experience, or service experience and teardown-inspection results of high-time airplanes, that WFD is unlikely to occur in that airplane up to the LOV. An LOV applies to an airplane structural configuration common to a fleet.

(2) The process for establishing an LOV involves four steps—

- Identifying a "candidate LOV."
- Identifying WFD-susceptible structure.
- Performing a WFD evaluation of all susceptible structure.
- Finalizing the LOV and establishing necessary maintenance actions.

(a) Step 1 – Candidate LOV. Any LOV can be valid as long as it has been demonstrated that the airplane model will be free from WFD up to the LOV based on the airplane's inherent fatigue characteristics and any required maintenance actions. Early in the certification process, applicants typically establish design service goals or their equivalent and set a design service objective to have structure remain relatively free from damage, up to the design service goal. A recommended approach sets the "candidate LOV" equal to the design service goal. The final LOV would depend on both how well that design objective was met and the applicant's consideration of the economic impact of maintenance actions required to preclude WFD up to the final LOV.

(b) Step 2 – Identify WFD-Susceptible Structure. The applicant should identify the structure that is susceptible to WFD to support post-fatigue-test teardown inspections or residual-strength testing necessary to demonstrate that WFD will not occur in the airplane structure up to the LOV. Appendix 5 of AC 120-104 provides examples and illustrations of structure where multiple site damage or multiple element damage has been documented. The list in appendix 5 is not meant to be inclusive of all structure that might be susceptible on any given airplane model and it should only be used for general guidance. It should not be used to exclude any particular structure. The applicant should do the following when developing the list of structure susceptible to WFD:

1 Establish criteria that could be used for identifying what structure is susceptible to WFD based on the definitions (see appendix 1) of multiple site damage, multiple element damage, and WFD. For example, structural details and elements that are repeated over large areas and operate at the same stress levels are obvious candidates. The criteria should be part of the applicant's compliance data.

2 Provide supporting rationale for including and excluding specific structural areas. This should be part of the applicant's compliance data.

3 Identify the structure to a level of detail required to support post-test activities that the applicant will use to evaluate the residual-strength capabilities of the structure. Structure is free from WFD if the residual strength meets or exceeds that required by § 25.571(b). Therefore, the post-test activities, such as teardown inspections and residual-strength tests, must provide data that support the determination of strength.

- For teardown inspections, specific structural details (e.g., holes, radii, fillets, cutouts) need to be identified.

- For residual-strength testing, the identification at the component or subcomponent level (e.g., longitudinal skin splices) may be sufficient.

(c) Step 3 – Evaluation of WFD-Susceptible Structure. Applicants must evaluate all susceptible structure identified in Step 2. Applicants must demonstrate, by full-scale fatigue-test evidence, that WFD will not occur in the airplane structure prior to the LOV. This demonstration typically entails full-scale fatigue testing, followed by teardown inspections and a quantitative evaluation of any finding or residual-strength testing, or both. Additional guidance about full-scale fatigue-test evidence is included in appendix 2 of this AC.

(d) Step 4 – Finalize LOV. After all susceptible structure has been evaluated, finalize the LOV. The results of the evaluations performed in Step 3 will either demonstrate that the strength at the candidate LOV meets or exceeds the levels required by § 25.571(b), or not. If it is demonstrated that the strength is equal to or greater than that required, the final LOV could be set to the candidate LOV without further showing. If it is demonstrated that the strength is less than the required level, at least two outcomes are possible.

1 Final LOV may equal the candidate LOV. However, this would result in maintenance actions, design changes, or both maintenance actions and design changes to support operation of airplanes up to LOV. For MSD/MED, an applicant may use damage-tolerance-based inspections to supplement replacement or

modification required to preclude WFD when those inspections have been shown to be practical and reliable.

(aa) Maintenance actions. In some cases, maintenance actions may be necessary for an airplane to reach its LOV. These maintenance actions could include inspections, modifications, replacements, or any combination of these. The applicant must substantiate the maintenance actions per the guidance contained in this AC.

- For initial certification, these actions should be both specified as airworthiness-limitation items and incorporated into the ALS of the ICA.

- For post-certification airplanes, these actions should be specified as service information by the TC holder and may be mandated by FAA airworthiness directives. Refer to AC 120-104 for additional maintenance-action guidance.

(bb) Design changes. The applicant may determine that developing design changes to prevent WFD in future production airplanes is to their advantage. The applicant must substantiate the design changes per the guidance contained in this AC.

2 Final LOV may be less than the candidate LOV. This could preclude having maintenances actions or making design changes.

(aa) In addition to the technical considerations, the LOV may be based on several other factors, including—

- Maintenance considerations.

- Operator input.

- Economics.

d. Airworthiness Limitations section (ALS). In accordance with 14 CFR 21.50, the type-certificate holder must provide the ICA, which includes the ALS, with the airplane. However, the type-certificate holder may or may not have completed the full-scale fatigue-test program at the time of type certification.

(1) Fatigue testing is not completed. Under 14 CFR 25.571, the FAA may issue a type certificate for an airplane model prior to the applicant's completion of full-scale fatigue testing, provided that the Administrator has approved a plan for completing the required tests. Until the full-scale fatigue testing is completed and the FAA has approved the LOV, the type-certificate holder must establish a limitation that is equal to one-half the number of cycles accumulated on the test article. (See appendix 2 in this AC for more information about the test article.) At the time of type certification, the applicant should show that at least one calendar year of safe operation has been substantiated using fatigue-test evidence. Under appendix H to part 25, the ALS must contain a defined limitation equal to one-half the number of cycles accumulated on the fatigue-test article approved under § 25.571. This

limitation is an airworthiness limitation. No airplane may be operated beyond this limitation until the fatigue testing is completed and an LOV is approved. As additional cycles on the fatigue-test article are accumulated, this limitation may be adjusted accordingly. Upon completion of the full-scale fatigue test, applicants should perform specific inspections and analyses to determine whether WFD has occurred. Additional guidance about post-test WFD evaluations is included in appendix 2 of this AC.

(2) Fatigue testing is completed. After the full-scale fatigue test has been completed, the applicant must include the following in the ALS (see appendix 2 of this AC for additional guidance):

- Under appendix H to part 25, the ALS must contain the LOV stated as a number of total accumulated flight cycles or flight hours approved under § 25.571.

- Depending on the results of the evaluation under Step 3, the ALS may also include requirements to inspect, modify, or replace structure.

e. Type-design changes (Amendment 25-96 or later). Any person applying for an amended type certificate or a supplemental type certificate to introduce a type design change that adds or affects WFD-susceptible structure must demonstrate that new and affected structure are free from WFD up to the LOV of the airplane. This demonstration may include analysis supported by fatigue-test evidence (see appendix 2 of this AC), analysis that correlates to relevant existing full-scale fatigue-test results, or both. Where analysis supported by test evidence demonstrates freedom from WFD, the applicant may use one of the following approaches to demonstrate freedom from WFD. One approach is based on fatigue-crack initiation and relies on fatigue data. Another approach is based on crack growth and requires the application of fracture-mechanics methods. Inspections or other procedures necessary to prevent catastrophic failure from accidental, environmental, or fatigue damage (including WFD) up to the LOV must be included in the ALS of the ICA, as required by § 25.1529. (See also appendix H to part 25). As an alternative for accidental and environmental damage, the documents containing the ICA may be referenced in the ALS of the ICA. See section 6i of this AC for further guidance.

f. Repairs (Amendment 25-96 or later). Any person performing a major repair that adds or affects WFD-susceptible structure must demonstrate that any new and affected structure is free from WFD up to the LOV of the airplane. If a repair does not add or affect WFD-susceptible structure, no further WFD evaluation is required. Where analysis supported by test evidence demonstrates freedom from WFD, the applicant may use one of the following approaches to demonstrate freedom from WFD. One approach is based on fatigue-crack initiation and relies on fatigue data. Another approach is based on crack growth and requires the application of fracture-mechanics methods. Refer to appendix 5 of AC 120-93 for the repair-approval process. If WFD is determined likely to occur before the LOV is reached, the applicant must either—

(1) redesign the proposed repair to preclude WFD from occurring before the airplane reaches the LOV, or

(2) develop maintenance actions to preclude WFD from occurring before the airplane reaches the LOV. For repairs, an applicant must identify and include these actions as part of the repair data.

g. Extended LOV. If an applicant proposes to extend an LOV, they must comply with the requirements of 14 CFR 26.23. Refer to AC 120-104 for guidance on extending an LOV. Typically, the data necessary to extend an LOV includes additional full-scale fatigue-test evidence. The primary source of this test evidence should be full-scale fatigue testing. This testing should follow the guidance contained in appendix 2 of this AC.

8. Fatigue Evaluation.

a. General. The evaluation of structure under the following fatigue- (safe-life) strength-evaluation methods is intended to ensure that catastrophic fatigue failure – as a result of the repeated loads of variable magnitude expected in service – will be avoided throughout the structure's operational life. Under these methods, the fatigue life of the structure should be determined. The evaluation should include the following:

(1) Estimating or measuring the expected loading spectra for the structure;

(2) Conducting a structural analysis, including consideration of the stress concentration effects;

(3) Performing fatigue testing of structure that cannot be evaluated, based on previous testing, to establish response to the typical loading spectrum expected in service;

(4) Determining reliable replacement times by interpreting the loading history, variable-load analyses, fatigue-test data, service experience, and fatigue analyses;

(5) Evaluating the possibility of fatigue initiation from sources, such as stress corrosion, disbonding, environmental (e.g., corrosion) and accidental damage, and manufacturing defects, based on a review of the design, quality control, and past service experience; and

(6) Providing necessary maintenance programs and replacement times to the operators. The maintenance program should be included in the ICA in accordance with 14 CFR 25.1529.

b. Scatter Factor for Safe-life Determination. In the interpretation of fatigue analyses and test data under § 25.571(c), the effect of variability should be accounted for by an appropriate scatter factor. The applicant should justify the scatter factor chosen for any safe-life part. The following guidance is provided (See Figure 1):

(1) The base scatter factors applicable to test results are BSF_1= 3.0 and $BSF_2 \geq 3.0$ (see section 8b(5) of this AC). If the applicant can meet the criteria of section 8b(3) of this AC, they may use BSF_1. As an option, the applicant may elect to use BSF_2. If the applicant cannot meet the criteria of section 8b(3) of this AC, they must use BSF_2.

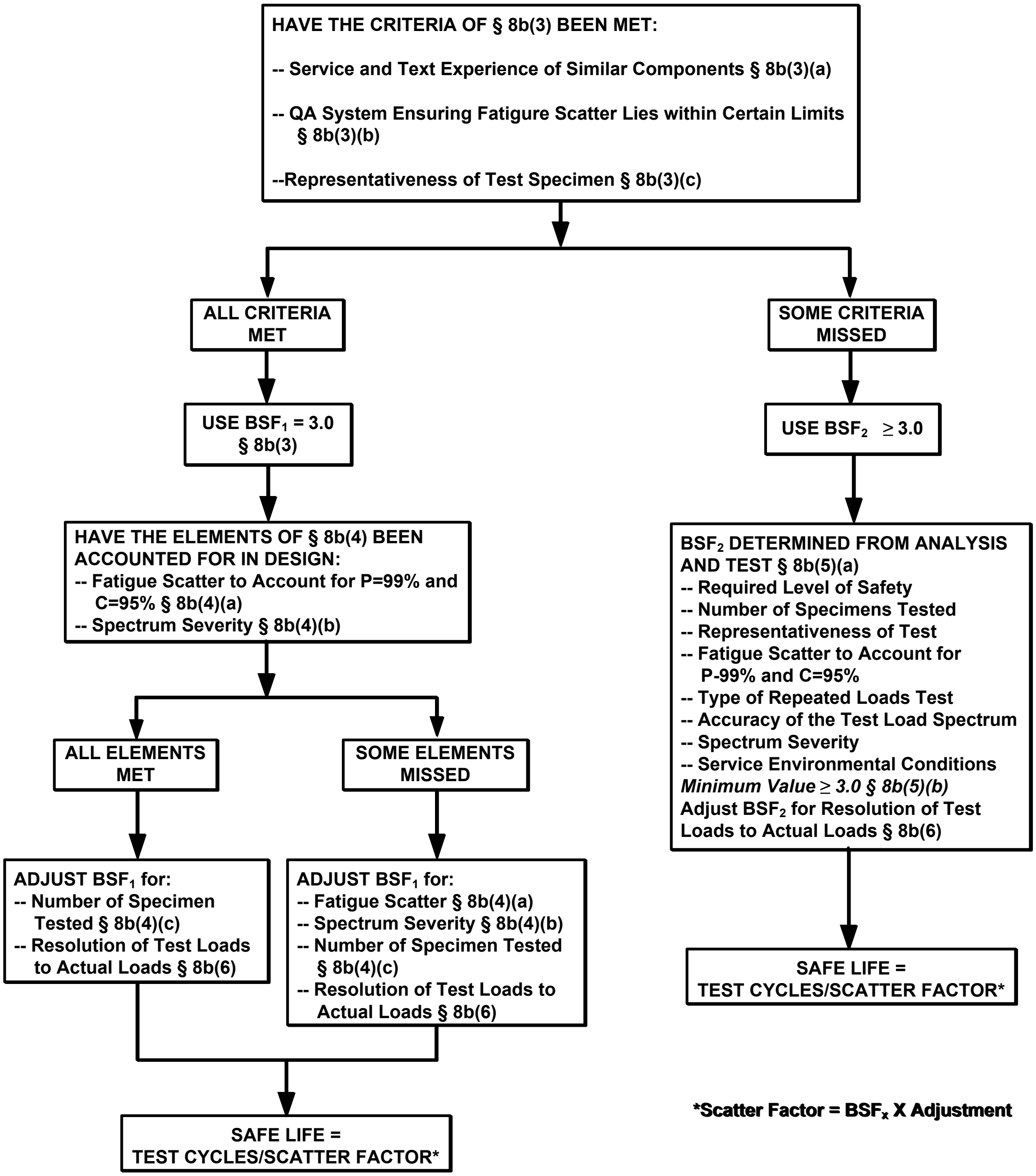
(2) Base scatter factor BSF_1 development. The base scatter factor BSF_1 is developed using test results of one representative test specimen.

(3) Justification for use of BSF_1. BSF_1 may be used only if the following criteria are met:

(a) Understanding of load paths and failure modes. Service and test experience of similar in-service components that were designed using similar design criteria and methods should demonstrate that the load paths and potential failure modes of the components are well understood.

(b) Control of design, material, and manufacturing process quality. The applicant should demonstrate that his quality system (e.g., design, process control, and material standards) ensures that the scatter in fatigue properties is controlled and that the design of the fatigue-critical areas of the part account for the material scatter.

Figure 1 – Safe-Life Determination



(c) Representativeness of the test specimen.

1 The test article should be full-scale (component or sub-component) and represent that portion of the production aircraft requiring test. All differences between the test article and production article should be accounted for either by analysis supported by test evidence or by testing itself.

2 Construction details, such as bracket attachments and clips, should be accounted for, even though the items themselves may be non-load bearing.

3 Points of load application and reaction should accurately reflect those of the aircraft, ensure correct behavior of the test article, and guard against uncharacteristic failures.

4 Systems used to protect the structure against environmental degradation can have a negative effect on fatigue life and, therefore, should be included as part of the test article.

(4) Adjustments to base scatter factor BSF_1. If the criteria in section 8b(3) justifying the use of BSF_1 have been met, the base value of 3.0 should be adjusted to account for the following factors, where these factors are not wholly taken into account by design analysis. As a result of the adjustments, the final scatter factor may be less than, equal to, or greater than 3.0.

(a) Material fatigue scatter. Material properties should be investigated up to a 99% probability of survival and a 95% level of confidence.

(b) Spectrum severity. The test-loads spectrum should be derived, based on a spectrum-sensitive analysis accounting for variations in utilization (e.g., aircraft weight and center of gravity), as well as for the occurrence and size of loads. The test-loads spectrum applied to the structure should be demonstrated to be conservative when compared to the usage expected in service.

(c) Number of representative test specimens. Well established statistical methods should be used that associate the number of items tested with the distribution chosen to obtain an adjustment to the base scatter factor.

(5) Adjustments to base scatter factor BSF_2. If section 8b(3) of this AC cannot be satisfied in its entirety, the applicant should use BSF_2.

(a) The applicant should propose scatter factor BSF_2 based on careful consideration of the following issues:

- required level of safety,
- number of representative test specimens,
- how representative the test is,
- expected fatigue scatter,

- type of repeated load test,
- accuracy of the test-loads spectrum,
- spectrum severity, and
- expected service environmental conditions.

(b) In no case should the value of BSF_2 be less than 3.0.

(6) Resolution of test loadings to actual loadings. The applicant may use a number of different approaches to reduce both the number of load cycles and number of test set-ups required. These include the following:

- spectrum blocking (i.e., a change in the spectrum load sequence to reduce the total number of test setups);
- high-load clipping (i.e., reduction of the highest spectrum loads to a level at which the beneficial effects of compression yield are reduced or eliminated); and
- low-load truncation (i.e., the removal of non-damaging load cycles to simplify the spectrum).

(7) Due to the modifications to the flight-by-flight loading sequence caused by these changes, the applicant should propose either analytical or empirical approaches to quantify an adjustment to the number of test cycles which represents the difference between the test spectrum and the assumed flight-by-flight spectrum. In addition, an adjustment to the number of test cycles may be justified by raising or lowering the test-load levels, as long as data support such adjustment. Other effects to consider are different failure locations, different response to fretting conditions, and temperature effects. The analytical approach should either use well-established methods or be supported by test evidence.

c. Replacement times. Under § 25.571(a)(3), replacement times should be established for parts with established safe-lives and should be included in the ALS of the ICA. These replacement times can be extended if additional data indicate an extension is warranted. Factors that should be considered for such extensions include the following:

(1) Comparison of original evaluation with service experience.

(2) Recorded load and stress data. Recorded load and stress data entails the installation of instrumentation on airplanes in service to obtain a representative sampling of actual loads and stresses experienced. The data to be measured include airspeed, altitude, and load-factor-versus-time data; or airspeed, altitude, and strain-ranges-versus-time data; or similar data. The data obtained from airplanes in service provide a basis for correlating the estimated loading spectrum with the actual service experience.

(3) Additional analyses and tests. If test data and analyses are obtained based on repeated load tests of additional specimens, a re-evaluation of the established safe-life can be made.

(4) Tests of parts removed from service. Repeated load tests of replaced parts can be used to re-evaluate the established safe-life. The tests should closely simulate service loading conditions. Repeated load testing of parts removed from service is especially useful where recorded load data obtained in service are available, since the actual loading experienced by the part prior to replacement is known.

(5) Repair or rework of the structure. In some cases, repair or rework of the structure can gain further life.

d. Type-design developments and changes. For design developments or design changes involving structural configurations similar to those of a design already shown to comply with the applicable provisions of § 25.571(c), it may be possible to evaluate the variations in critical portions of the structure on a comparative basis. Examples would be (1) redesign of the wing structure for increased loads or (2) the introduction, in pressurized cabins, of cutouts having different locations or different shapes, or both. This evaluation should involve analysis of the predicted stresses of the redesigned primary structure, and correlation of the analysis with the analytical and test results used in showing compliance with § 25.571(c) of the original design.

e. Environmental effects such as temperature and humidity should be considered in the damage-tolerance and fatigue analysis, and should be demonstrated through suitable testing.

9. Discrete Source Damage.

a. General. The purpose of this section is to establish FAA guidelines for consistent selection of load conditions for residual-strength substantiation in showing compliance with § 25.571(e), *Damage-tolerance (discrete source) evaluation*. The intent of these guidelines is to define, with a satisfactory level of confidence, load conditions that will not be exceeded on the flight during which the specified incident of § 25.571(e) occurs. In defining these load conditions, consideration has been given to the expected damage to the airplane, the anticipated response of the pilot at the time of the incident, and the actions of the pilot to avoid severe load environments for the remainder of the flight consistent with pilot knowledge that the airplane may be in a damaged state. With these considerations in mind, use the following ultimate loading conditions to establish residual strength of the damaged structure.

b. The maximum extent of immediately obvious damage from discrete sources (§ 25.571(e)) should be determined, and the remaining structure shown with an acceptable level of confidence, to have static strength for the maximum load (considered as ultimate load) expected during completion of the flight.

c. The ultimate loading conditions should not be less than those developed from the following conditions:

(1) At the time of the incident:

(a) The maximum, normal, operating differential pressure, multiplied by a 1.1 factor, plus the expected external aerodynamic pressures during 1g level flight combined with 1g flight loads.

(b) The airplane, assumed to be in 1g level flight, should be shown to be able to survive any maneuver or any other flight-path deviation caused by the specified incident of § 25.571(e), taking into account any likely damage to the flight controls and pilot normal corrective action.

(2) Following the incident:

(a) Seventy percent (70%) limit flight-maneuver loads and, separately, 40% of the limit gust velocity (vertical and lateral) at the specified speeds, each combined with the maximum appropriate cabin differential pressure (including the expected external aerodynamic pressure).

(b) The airplane must be shown by analysis to be free from flutter up to V_D/M_D with any change in structural stiffness resulting from the incident.

Appendix 1
References and Definitions

1. References.

a. AC 20-107B, "Composite Aircraft Structure"

b. AC 25.1529-1A, "Instructions for Continued Airworthiness of Structural Repairs on Transport Airplanes"

c. AC 91-56B, "Continuing Structural Integrity Program for Airplanes"

d. AC 120-93, "Damage Tolerance Inspections for Repairs and Alterations"

e. AC 120-104, "Widespread Fatigue Damage and Establishing LOV"

2. Definitions of Terms Used in this AC.

a. Airworthiness Limitation item (ALI) — A mandatory-maintenance action identified in the Airworthiness Limitations section of a design-approval holder's Instructions for Continued Airworthiness. These items may contain mandatory modification or replacement times, mandatory inspection thresholds, intervals, and inspection procedures.

b. Airworthiness Limitations section (ALS) — Relative to the Instructions for Continued Airworthiness, the ALS is a collection of mandatory-maintenance actions required for airplane structure and fuel-tank systems. For structural-maintenance actions, the ALS includes structural-modification times, structural-replacement times, structural-inspection thresholds and intervals, and structural-inspection procedures.

c. Alteration or modification — A design change that is made to an airplane. Within the context of this AC, the two terms are synonymous.

d. 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, or accidental or discrete source damage.

e. Design service goal — The period of time (in flight cycles or flight hours, or both) established at design and/or certification during which the airplane structure is reasonably free from significant damage.

f. Environmental Damage – Environmental damage includes many things beyond temperature and moisture effects, it includes degradation caused by erosion, aggressive fluids, ultraviolet radiation and lightning for examples. You must also consider cycling of temperature and moisture, which can cause various forms of matrix degradation that cause other problems , including permeability and associated challenges with certain design details (e.g., fluid ingression into sandwich panels, internal systems exposed to fluids, and fuel tank leakage).

f. **Fail-safe** — The attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element.

g. **Instructions for Continued Airworthiness (ICA)** — Documentation that sets forth instructions and requirements for the maintenance that is essential to the continued airworthiness of an aircraft, engine, or propeller.

h. **Multiple load path** — Applies to structure, the applied loads of which are distributed through redundant structural members, so that the failure of a single structural member does not result in the loss of structural capability to carry the applied loads.

i. **Limit of validity** (of the engineering data that supports the structural maintenance program) — The period of time (in flight cycles, flight hours, or both), up to which it has been demonstrated by test evidence, analysis and, if available, service experience and teardown inspection results of high-time airplanes, that widespread fatigue damage will not occur in the airplane structure.

j. **Principal structural element (PSE)** — An element that contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall structural integrity of the airplane. Principal structural elements include all structure susceptible to fatigue damage, which could contribute to a catastrophic failure. Refer to appendix 5 of this AC for clarification on how this term relates to the terms, fatigue critical structure (FCS) and WFD – susceptible structure.

k. **Safe-life** — The number of events, such as flight cycles, landings, or flight hours, within which the structure strength has a low probability of degrading below its design ultimate value due to fatigue cracking.

l. **Scatter factor** — A life-reduction factor used in interpreting fatigue analysis and test results.

m. **Single load path** — Describes structure, the applied loads of which are eventually distributed through a single structural member, the failure of which would result in the loss of the structural capability to carry the applied loads.

n. Teardown inspection — The term used for the process of disassembling structure and using destructive inspection techniques or visual (e.g., magnifying glass and dye penetrant) or other non-destructive (e.g., eddy current, ultrasound) inspection techniques to identify the extent of damage, within a structure, caused by fatigue, environmental, and accidental damage.

o. Widespread fatigue damage (WFD) — The simultaneous presence of damage at multiple structural locations that are of sufficient size and density such that the structure will no longer meet the residual-strength requirements of § 25.571(b). Note that WFD may further be affected by environmental degradation in metal-bonded structural details subjected to other aging phenomena (e.g., hydration).

(1) Multiple site damage (MSD) — A source of widespread fatigue damage characterized by the simultaneous presence of fatigue damage in the same structural element.

(2) Multiple element damage (MED) — A source of widespread fatigue damage characterized by the simultaneous presence of fatigue damage in adjacent structural elements.

(3) Structural modification point (SMP) — The point in time when a structural area must be modified to preclude WFD.

(4) Inspection start point — The point in time when special inspections of the fleet are initiated due to a specific probability of having a MSD/MED condition.

p. $\mathbf{WFD}_{\text{(average behavior)}}$ — The point in time, without intervention, when 50% of the fleet is expected to develop WFD for a particular structure.

Appendix 2
Full-Scale Fatigue Testing

1. Overview. Section 25.571(b) requires that special consideration for WFD be included where the design is such that this type of damage could occur. Many such areas typically are found in metallic transport airplane structure. Refer to AC 120-104 for examples of WFD-susceptible structure. These areas have in common the same or similar structural details over large areas that are subject to similar repeated tension-stress levels.

a. Without intervention, simultaneous fatigue damage would eventually occur at multiple locations that would be very difficult to detect before the structure strength degrades below required levels. A strategy must be in place to prevent such fatigue damage from occurring, as mere inspection of these areas is not reliable to maintain continued airworthiness of the airplane. Section 25.571(b) requires the applicant to demonstrate with sufficient full-scale fatigue-test evidence that WFD will not occur in any susceptible area within the LOV of the airplane.

b. As discussed in section 2 of this appendix, full-scale fatigue-test evidence may be obtained from in-service experience. Testing should involve subjecting a full-scale fatigue-test article to repeated loads followed by an evaluation to determine residual-strength capability. For new type certificates and derivative models, the applicant should use the results of the evaluation to help establish the LOV for the airplane as discussed in section 7 of this AC.

c. Section 3 of this appendix discusses the key elements of a full-scale fatigue-test program. The scope of the full-scale fatigue-test article required will depend on the type of the certification project as discussed in section 4 of this appendix. For the purposes of this AC, certification projects include: (1) new type certificates, (2) derivative models, (3) type design changes – service bulletins, (4) type design changes – supplemental type certificates, and (5) major repairs. In some cases, data from previous full-scale fatigue testing may exist and may be relevant to the certification project.

d. Applicants must consider the issues identified in section 5 of this appendix when using existing test data as evidence to support compliance.

e. Applicants must consider the issues identified in section 6 of this appendix when using in-service data as evidence to support compliance.

2. Full-Scale Fatigue-Test Evidence. Full-scale fatigue-test evidence in the context of § 25.571 makes up the body of evidence (which may also include service experience) that supports the WFD evaluation for a certification project. It includes data used in determining or bounding the time to develop MSD/MED damage of a certain size, MSD/MED damage-growth scenarios, and residual-strength capability with MSD/MED damage present. Types of data include strain-survey results, non-destructive and destructive inspection results, and residual-strength test results. The primary source of full-scale fatigue-test evidence is full-scale fatigue testing. The guidelines contained herein should ensure that sufficient test evidence is produced to provide a high degree of confidence that WFD will not occur within the LOV. This involves a laboratory test in which structure that is representative of the type design being considered is subjected to loading that simulates typical service operation. The test article may be the entire airframe or a portion of it. A source of data that may supplement full-scale fatigue-test evidence is data from operational airplanes. This "in-service" data includes maintenance findings and results of teardown inspections.

3. Elements of a Full-Scale Fatigue-Test Program. The following guidance addresses elements of a test program used in generating the data necessary to support compliance. It is generally applicable to all certification projects.

a. Article. The test article should be representative of the structure of the airplane to be certificated (i.e., a production article). The test article should be conformed in accordance with 14 CFR 21.23. Attributes of the type design that could affect MSD/MED initiation, growth, and subsequent residual-strength capability should be replicated as closely as possible on the test article. Critical attributes include, but are not limited to, the following:

- material types and forms,
- dimensions,
- joining methods and details,
- coating and plating,
- use of faying surface sealant,
- assembly processes and sequences and,
- influence of secondary structure (e.g., loads induced due to proximity to the structure under evaluation).

b. Test setup and loading. The test setup and loading should result in a realistic simulation of expected operational loads.

(1) Test setup. The test setup dictates how the loads are introduced into the structure and reacted. Every effort should be made to introduce and react loads as realistically as possible. When compromises are made (e.g., wing-air loading), the resulting internal loads should be evaluated (e.g., using finite-element methods) to ensure that the structure is not being unrealistically underloaded or overloaded, locally or globally.

(2) Test loading. Test loading includes the sequence of statically balanced end conditions that are applied to represent some amount of operational usage. Typically, a test sequence representing 1/10 of an anticipated service life is repeated over and over again until the desired test duration is achieved. The sequence used should include loads from all sources (e.g., cabin pressurization, maneuvers, gusts, engine thrust, control-surface deflection, and landing impact) that are significant for the structure being evaluated. The applicant should provide supporting rationale when a load source is not included in the sequence. Differences between the test sequence and expected operational sequence should be justified. For example, standard practice eliminates low loads considered to be non-damaging, and clip high, infrequent loads that may bias the outcome, but care should be taken in both cases so that the test results are representative. Section 8b(6) of this AC provides guidance on resolving test loading to actual loading.

c. $\textbf{WFD}_{\textbf{(average behavior)}}$. Fatigue damage is the gradual deterioration of a material subjected to repeated loads. This gradual deterioration is a function of use and can be statistically quantified. Widespread fatigue damage therefore can be statistically quantified. Widespread fatigue damage cannot be absolutely precluded because there is always some probability of occurrence. The average time in flight cycles and/or flight hours to develop WFD is referred to as the $\text{WFD}_{\text{(average behavior)}}$ for WFD-susceptible structure. AC 120-104 provides guidance how to determine when structure should be modified or replaced to minimize the probability of having WFD in the fleet. The point at which a modification or replacement is undertaken is referred to as the “structural modification point” (SMP). The SMP is generally a fraction of the number representing the point in time when $\text{WFD}_{\text{(average behavior)}}$ will occur. As an example, the SMP may be determined by dividing the number representing the timing of when $\text{WFD}_{\text{(average behavior)}}$ will occur by a factor of 2 if inspections are deemed effective, or by a factor of 3 if inspections are not effective. If an inspection is determined to be effective, the “inspection start point” (ISP) may be determined by dividing the number representing the timing of when $\text{WFD}_{\text{(average behavior)}}$ will occur by a factor of 3.

d. Test duration. The duration of the full-scale fatigue test varies depending on the test objective, and whether the test is to be used for a new type certificate, design change, or repair. It is standard practice to interpret the unfactored fatigue life of one specimen as the average life. It follows, then, that if one full-scale fatigue-test article maintains the minimum residual-strength requirements of § 25.571(b) for test duration X, one can conservatively assume that the $WFD_{(\text{average behavior})}$ of all WFD-susceptible structure is equal to X. Assuming inspection for MSD/MED is impractical, replacement or modification would be required at X divided by 3 per the guidance in AC 120-104. For areas where inspections for MSD/MED are practical, the applicant may defer replacement or modification until X divided by 2, provided inspections for MSD/MED start at X divided by 3. The applicant should consider these factors when deciding on the duration of a full-scale fatigue test.

(1) New type certificates and derivatives. The applicant must establish an LOV for new type certificates and derivative models. There are no requirements regarding the value of LOV. The full-scale fatigue-test duration should not be less than 2 times the LOV. Although not required, a longer test may identify unanticipated fatigue-sensitive areas as well as help validate damage sites, damage scenarios, damage-growth lives, and residual-strength capabilities. The applicant may also use a longer test to reduce or eliminate the need for WFD-related mandatory-maintenance actions. Consistent with the guidance in section (3)(d) of this appendix, and AC 120-104, a test duration of 3 times the LOV, without an occurrence of WFD, would eliminate the need for WFD-related mandatory-maintenance requirements. On the other hand, a test duration of 2 times the LOV may result in required inspections and/or replacements/modifications prior to the LOV.

(2) Repairs and type design changes. The test duration should support the installation of repairs and type design changes up to the LOV of the affected airplane model. If it is conservatively assumed that the repair or type-design change is implemented before an airplane has accumulated any time in service, the rationale discussed in section 3d(1), above, applies. A test duration of 3 times the LOV would be recommended. However, consideration of the age of the airplane being repaired or modified could reduce the test duration. For example, an applicant for a repair or type design change to an airplane that has reached an age equivalent to 75 percent of its LOV must demonstrate that the repaired or modified airplane will be free from WFD for at least the remaining 25 percent of the LOV. In this example, a test duration of 75% of the LOV would be recommended (i.e., 3 times the time remaining until the LOV is reached).

e. **Post-test evaluation.** One of the primary objectives of the full-scale fatigue test is to generate data needed to determine the $WFD_{(\text{average behavior})}$ for each susceptible area or establish a lower bound. The definition of $WFD_{(\text{average behavior})}$ is the average time required for MSD/MED to initiate and grow to the point that the static-strength capability of the structure is reduced below the residual-strength requirements of

§ 25.571(b). A residual-strength assessment is required at the end of the full-scale fatigue test to demonstrate that the structure meets this requirement.

(1) Residual-strength tests. The direct way to demonstrate freedom from WFD at the end of a full-scale fatigue test is to subject the article to the required residual-strength loads specified in § 25.571(b). If the test article sustains these loads, the applicant has demonstrated that the structure has a minimum $WFD_{(average\ behavior)}$ equal to the number of flight cycles and/or flight hours tested. However, because fatigue damage that might exist at the end of the test are not quantified, it is not possible to determine how far beyond the test duration WFD would occur in any of the susceptible areas without additional work (e.g., teardown inspection). Residual-strength testing could preclude the possibility of using an article for additional fatigue testing. For example, the application of loads in excess of representative operational loads on a metallic test article may result in local material yielding at existing crack tips that may slow or temporarily stop crack growth.

(2) Teardown inspections. The residual-strength capability may be evaluated indirectly by performing teardown inspections to quantify the size of any MSD/MED damage that might be present, or to establish a lower bound on damage size based on inspection-method capability. After this is done, the residual-strength capability can be estimated analytically. Depending on the results, damage-growth analyses may also be required to project backward or forward in time to estimate the $WFD_{(average\ behavior)}$ for an area. As a minimum, teardown-inspection methods should be capable of detecting the minimum size of MSD or MED damage that would result in a WFD condition (i.e., residual strength degraded to below the level specified in § 25.571(b)). Effective teardown inspections required to demonstrate freedom from WFD typically require significant resources. They usually require disassembly (e.g., fastener removal) and destruction of the test article. All areas that are susceptible to WFD should be identified and examined.

4. Scope of the Full-Scale Fatigue-Test Article. The scope of the full-scale fatigue-test article is generally dependent on the type of certification project. Guidance on the expected scope for various certification projects is as follows:

a. New type certificates. As previously discussed, for any metallic airplane design, it is likely that multiple areas are susceptible to WFD based on the examples given in AC 120-104. Likewise, testing a complete airframe is probably the most practical approach. Regardless, the applicant is expected to subject all susceptible areas to full-scale fatigue testing. The only exception involves existing full-scale fatigue-test evidence that could be used to support compliance.

b. Derivative models – amended type certificates. The default for a derivative model would be to test the entire airframe. However, it is considered likely that existing data was developed and is available to support compliance of the original model. If this is the case, the article may be limited to only a portion or portions of the complete airframe.

c. Type-design changes – service bulletins. The default for a type-certificate holder's type design change is to test an article consisting of the design change and any original structure that is susceptible to WFD, and which the design change could negatively affect in terms of fatigue. See appendix 4 for examples of types of alterations for which the type-certificate holder should perform full-scale fatigue tests, unless the type-certificate holder can show that fatigue testing is not required (e.g., an alteration is not susceptible to WFD, or sufficient test data already exists). It is expected that the type-certificate holder has existing relevant data. If this is the case, this type of certification project would not require a test, provided that the type-certificate holder demonstrates, with the existing data, that the design change and any of the original structure that it affects will be free from WFD up to the LOV of the airplane to which the design change applies.

d. Type-design changes – supplemental type certificates. Because supplemental type certificate applicants often do not have access to the type-certificate holder's full-scale fatigue-test data, a full-scale fatigue-test article is expected. The article should consist of the design change and any original structure that is susceptible to WFD, and any structure that the design change could negatively affect in terms of fatigue. See appendix 4 for examples of types of alterations for which the applicant for an supplemental type certificate should perform full-scale fatigue tests, unless the applicant can show that fatigue testing is not required (e.g., an alteration is not susceptible to WFD, or sufficient test data already exists).

e. Major repairs. In general, major repairs do not require testing of a full-scale test article. For those repairs where testing is required, the test article should consist of the repair and any original structure that is susceptible to WFD, and which the repair could negatively affect in terms of fatigue.

(1) Published repair instructions (Amendment 25-96 or later). The applicant for a type certificate usually develops published repair instructions, such as a structural repair manual, for an airplane model. The applicant should perform analyses, such as fatigue and damage-tolerance analyses, that correlate to results of relevant full-scale fatigue tests to show the repairs in that manual are free from WFD up to the LOV. Alternatively, the applicant could perform component fatigue testing to show the published repairs are free from WFD up to the LOV.

(2) Non-published repair instructions (Amendment 25-96 or later). The applicant should correlate analysis methods to results of relevant full-scale fatigue tests, or perform component fatigue testing to evaluate the repair. Repairs for which correlated analysis is acceptable are those that are the same as, or comparable to, those found in FAA-approved published data, such as the type-certificate holder's structural repair manual. For the purpose of this AC, a repair is comparable when the operating stress levels and fatigue characteristics are approximately the same as those of the FAA-approved published data. To achieve this, the repair needs to have design aspects, such as design details, airframe materials, and production processes that are similar to the FAA-approved published data. For other repairs and depending on the type of repair, the applicant may need to perform full-scale fatigue testing. Alternatively, the applicant may propose analysis methods, such as fatigue and damage-tolerance analyses, that compare the fatigue characteristics of the original type design to the repaired structure and affected areas.

5. Use of Existing Full-Scale Fatigue-Test Data. In some cases, especially for derivative models and type-design changes the type-certificate holder accomplished, existing full-scale fatigue-test data may be used in supporting compliance and mitigating the need to perform additional testing. This is most probable when the data are from testing performed to support compliance with § 25.571 at Amendment 25-96 or later. This is less likely with other data.

a. Amendment 25-96 or later. Because the primary objective for developing the original full-scale fatigue-test data is to establish an absolute or lower-bound $WFD_{(average\ behavior)}$, for WFD-susceptible areas to support compliance, the original test article should be conformed and a rigorous post-test evaluation should be completed to demonstrate the remaining residual-strength capability. In addition to demonstrating residual-strength capability, the applicant must identify and reconcile any physical differences between the structure originally tested and the structure being considered that could affect its fatigue behavior. Differences that should be addressed include, but are not limited to, differences in any of the physical attributes listed in section 3a of this appendix. Additionally, the applicant should identify and reconcile differences in operational loading. As a minimum, the applicant should address the following:

- Gross weight (e.g., increases)
- Cabin pressurization (e.g., change in maximum cabin or operating altitude)
- Flight-segment parameters

b. Other data. Performing full-scale fatigue testing to support compliance with § 25.571(b) was not required prior to Amendment 25-96. It was accepted that fatigue would be managed solely by inspection, and that inspection requirements adequately could be determined based on analysis supported by limited testing at the coupon and component level. Nevertheless, many OEMs performed their own full-scale fatigue tests with the primary objective to evaluate the economic life of the structure. However, most test articles were not conformed in accordance with 14 CFR 21.33. Since no regulation required such tests, applicants did not submit test plans or reports to the FAA. Testing philosophies and protocols were not standardized, and the rigor of methods used for load-sequence development varied significantly over the years and from one OEM to another. Post-test evaluations (if performed) varied significantly and, in some cases, consisted of nothing more than limited visual inspections. An applicant may propose to use full-scale fatigue-test data from airplanes certificated to 14 CFR 25.571 (pre-Amendment 25-96) to support compliance with Amendment 25-96 or later requirements. In such cases, the applicant must consider the issues identified in section 5a of this appendix.

6. Use of In-Service Data. In-service data may be available to be used in supporting WFD evaluations. Examples of such data are as follows:

- Documented positive findings of MSD/MED damage that include location, size, and the time in service of the affected airplane, along with a credible record of how the airplane had been operated since original delivery.

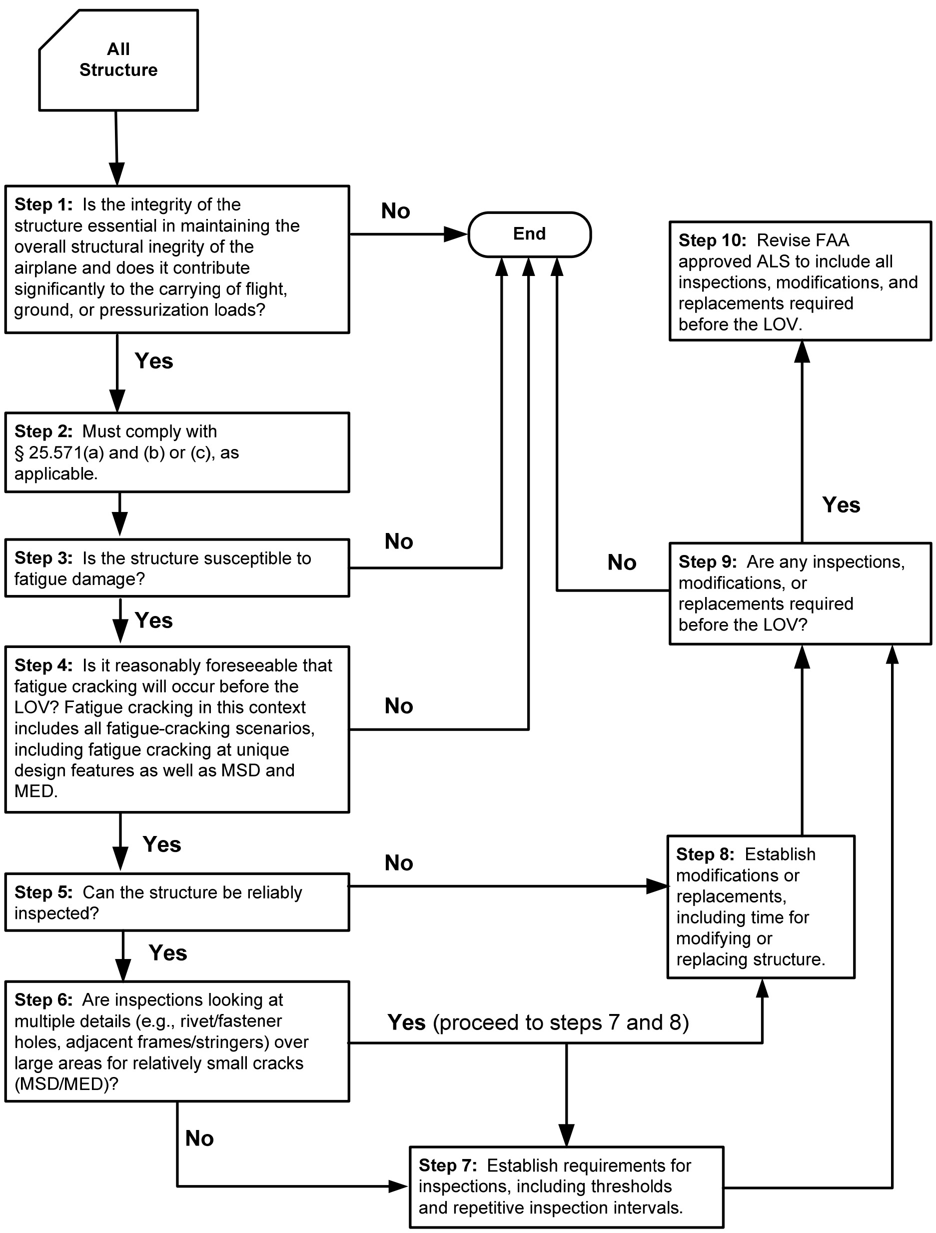
- Documented negative findings from in-service inspections for MSD/MED damage on a statistically significant number of airplanes, with the time in service of each aircraft and a credible record of how each aircraft had been operated since original delivery. For this data to be useful, the inspection methods used should be capable of detecting MSD/MED damage sizes equal to or smaller than those sizes that could reduce the strength of the structure below the residual-strength levels specified in § 25.571(b).

- Documented findings from the destructive teardown inspection of structure from in-service airplanes. This might be structure (e.g., fuselage splices) removed from airplanes that were subsequently returned to service or from retired airplanes. It would also be necessary to have a credible record of the operational loading the subject structure experienced up to the time it was taken out of service.

a. Prior to using in-service data, any physical and loading differences that exist between the structure of the in-service or retired airplanes, and the structure being certified, should be identified and reconciled as discussed in section 5a of this appendix.

Appendix 3
Process for Compliance with 14 CFR 25.571(a), (b) and (c) for Fatigue Damage

This chart applies only to § 25.571(a), (b), and (c) for fatigue damage (FD), relative to LOV.



For the purposes of this flowchart "All Structure" refers to all structure within the scope of § 25.571. This includes fatigue critical structure, as defined in 14 CFR 26.41.

Step 1: Is the integrity of the structure essential in maintaining the overall structural integrity of the airplane, and does it contribute significantly to the carrying of flight, ground, or pressurization loads?

If **Yes**, go to Step 2. Structure meeting these criteria are within the scope of § 25.571. See section 6c of this AC for examples.

If **No**, then the structure under consideration is not within the scope of § 25.571. Terminate the process.

Step 2: Evaluate each structure in accordance with § 25.571(a) and (b) or (c), as applicable.

Structure identified to be within the scope of the § 25.571 requires a showing of compliance with § 25.571 (a) and (b) or (c), as applicable, relative to fatigue damage. Environmental damage and accidental damage, including manufacturing defects, are not addressed in this flowchart.

- Corrosion typically has been addressed by maintaining corrosion to Level 1 or better, and to corrosion control and accidental damage programs. These programs are developed under the Air Transport Association of America, Inc. (ATA) Maintenance Steering Group's MSG-3 or other accepted version of the "Operator/Manufacturer Scheduled Maintenance Development" procedures.

- As airplanes are subjected to these programs, operators should evaluate the programs and adjust them to fit their operations.

Note: Section 25.571 requires applicants to evaluate the strength, detail design, and fabrication to show that catastrophic failure due to fatigue, environmental, manufacturing defects, or accidental damage will be avoided throughout the operational life of the airplane. It also requires that, based on the evaluations, inspections, or other procedures be established, as necessary, to prevent catastrophic failure, and be included in the ALS of the ICA, as required by § 25.1529.

As discussed in section 6i(3) of this AC, the applicant may use the Maintenance Review Board process to develop maintenance tasks that require inspections or other procedures for addressing accidental and environmental (corrosion) damage. If this process is used as a means of compliance, the applicant should reference, in the ALS, the maintenance documents that contain those tasks.

Step 3: Is the structure susceptible to fatigue damage?

If **Yes**, go to Step 4.

If **No,** no further showing of compliance is necessary. Terminate the process.

Structure that is susceptible to fatigue damage, which could, without intervention, eventually lead to catastrophic failure of an airplane, typically includes structure critical to carrying flight, ground, or pressurization loads that are subjected to tension-dominated repeated loads during operation (as discussed previously in this document). This structure also includes structure which, if repaired or altered, could be susceptible to fatigue damage and contribute to a catastrophic failure.

Step 4: Is it reasonably foreseeable that fatigue damage will occur before the LOV? Fatigue damage in this context includes all fatigue-cracking scenarios, including fatigue cracking at unique design feature as well as MSD and MED. If the fatigue performance of the structure relies on a bond, that bond must perform as intended throughout the LOV. See AC20-107B, para. 6(d), for guidance on the means to address aging of bonded structure and verify bondline integrity within the LOV.

If **No**, no further showing of compliance is necessary. Terminate the process. Note that sufficient evidence must support a high degree of confidence that WFD will not occur within the LOV.

If **Yes**, go to Step 5.

To address this question, estimate the fatigue life for all susceptible structure. The evaluation should be based on analysis, test, or service experience, or a combination of these, as necessary. An applicant may screen out areas that exhibit long fatigue lives. This means that the average fatigue life is a multiple of the LOV. Typically, the predicted fatigue life should be at least 3 times the LOV to justify eliminating the structure from further consideration. This may be the case for basic fuselage structure, away from discontinuities such as splices, windows, or doors, where the working-stress levels are relatively low. For structure that cannot be eliminated, additional evaluations are required.

Step 5: Can the structure be inspected reliably?

If **Yes**, go to Step 6.

If **No**, go to Step 8.

To address this question, crack-growth and residual-strength evaluations (damage-tolerance evaluation) must be performed. These evaluations typically are based on analyses supported by test evidence. Sections 6, 7, and 8 of this AC contain discussions of damage-tolerance evaluations, and fatigue and widespread-fatigue evaluations. Use the results to determine if inspections reliably can detect damage before it reduces the material strength below the required strength level. For the purposes of this AC, an inspection is "effective" if, when performed by properly trained maintenance personnel, the inspection readily detects the damage in question.[2]

Step 6: Are inspections looking at multiple details (e.g., rivet/fastener holes, adjacent frames/stringers, etc.) over large areas for relatively small cracks (MSD/MED)?

If **Yes**, go to **Step 7** to establish inspections, **then** to **Step 8** to establish modifications or replacements.

If **No**, go to **Step 7**, then to **Step 9**.

This step determines whether inspections by themselves are adequate for precluding a catastrophic failure, or whether they are supplementary to modifying or replacing structure.

- When inspections are focused on details in small areas and have a high probability of detection, they may be used by themselves to ensure continued airworthiness, unless or until there are in-service findings. Based on findings, these inspections may need to be modified, and it may be necessary to modify or replace structure.

- When inspections examine multiple details over large areas for relatively small cracks, they should not be used by themselves. Rather, they should be used to supplement the modification or replacement of structure. This is because it would be difficult to achieve the probability of detection required to allow inspection to be used indefinitely as a means to ensure continued operational safety.

Step 7: Establish requirements for inspections, including thresholds and repetitive inspection intervals.

Using the results of your damage-tolerance evaluation, select an inspection method (or methods), and establish the inspection threshold and repetitive inspection interval.

- Inspection thresholds must be based on damage-growth analyses and/or tests, with the assumption that the structure contains an initial flaw of the maximum

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[2] The cracking identified in airworthiness directive 2002-07-09 is an example of the type of cracking that MSD inspections effectively detect. These cracks grow from fastener holes in the lower row of the lower skin panel in such a way that the cracking is readily detectable using non-destructive inspection methods. The cracking identified in airworthiness directive 2002-07-08 is an example of where MSD inspections are not "effective." These cracks grow in the outer surface and between fastener holes in the lower row of the lower skin panel in such a way that the cracking is not readily detectable using non-destructive inspection methods. Therefore, modification is the only option to address this type of cracking.

probable size that could exist as a result of manufacturing or service-induced damage.

- Thresholds established for damage at multiple details that are over large areas (WFD-related damage) should be determined through a statistical analysis of damage initiation based on fatigue testing, teardown, or in-service experience of similar structure. If an inspection is determined to be effective, the "inspection start point" (ISP) may be determined by dividing the number representing the timing of when $WFD_{(average\ behavior)}$ will occur by a factor of 3.

If the answer to the question in **Step 6** was **Yes**, go to **Step 8** to establish modifications or replacements.

If the answer to the question in **Step 6** is **No**, go to **Step 9** to determine if the inspection requirements established in this step need to go into the ALS.

Step 8: Establish modifications or replacements, including time for modifying or replacing structure.

Based on the results of the fatigue and damage-tolerance evaluations performed, determine the replacement time or SMP (i.e., replacement time or modification time) for affected structure.

- For structure that is not susceptible to damage at multiple sites and where the applicant has shown that the damage-tolerance-based inspections are impractical, a replacement time must be established per § 25.571(c). See section 8 of this AC for further guidance.

- For structure that is susceptible to damage at multiple sites and where the applicant has shown that damage-tolerance-based inspections are practical, a SMP must be established per § 25.571(b). The Step 6 inspections supplement the required SMP. An acceptable approach for determining the SMP is to divide the $WFD_{(average\ behavior)}$ by a factor of 2. To determine ISP, divide the $WFD_{(average\ behavior)}$ by a factor of 3. See AC 120-104 for further guidance on establishing SMP and ISP.

- For structure that is susceptible to damage at multiple sites and where the applicant has shown that damage-tolerance-based inspections are not reliable in Step 5, an SMP must be established per § 25.571(b). An acceptable approach would be to divide the $WFD_{(average\ behavior)}$ by a factor of 3.

Go to Step 9 to determine if the modification or replacement requirements need to be included in the ALS.

Step 9: Are any inspections, modifications, or replacements required before the LOV?

If **Yes**, go to Step 10.

If **No**, terminate the process.

Based on the results of Steps 7 and 8, determine if any maintenance actions need to be included in the ALS of the ICA. Any inspection with thresholds less than the LOV, or replacements or modifications that must occur prior to the LOV, must be included in the ALS.

Step 10: Revise the FAA-approved ALS to include all inspections, modifications, and replacements required before the LOV.

Based on the results of Step 9, include, in the ALS of the ICA (per § 25.1529), the inspections or other procedures determined to be necessary to prevent catastrophic failure up to the LOV. The LOV must also be included.

For each required inspection, the operator should include—

- The structure to be inspected.
- The method of inspection.
- The inspection threshold (the point in time at which to begin inspections).
- The inspection repetitive interval.

For required modifications or replacements, the operator should include—

- The structure to be modified or replaced.
- The method of modification or replacement.
- The replacement time or structural-modification point (the point in time to begin the modification), as applicable.

Appendix 4
Examples of Alterations that May Require Full-Scale Fatigue Testing

1. The following are examples of types of alterations that may require full-scale fatigue testing:

a. passenger-to-freighter conversions (including addition of cargo doors);

b. gross-weight increases (e.g., increased operating weights, increased zero-fuel weights, increased landing weights, and increased maximum-takeoff weights);

c. installation of fuselage cutouts (e.g., passenger-entry doors, emergency-exit doors or crew-escape hatches, fuselage-access doors, and cabin-window relocations);

d. complete re-engine or pylon alteration;

e. engine-hush kits;

f. wing alterations (e.g., installation of winglets; changes in flight-control settings such as flap droop; and alteration of wing trailing-edge structure);

g. modified or replaced skin splice;

h. any alteration that affects three or more stiffening members (e.g., wing stringers and fuselage frames);

i. an alteration that results in operational-mission change, which significantly changes the original equipment manufacturer's load/stress spectrum (e.g., extending the flight duration from 2 hours to 10 hours); and

j. an alteration that changes areas of the fuselage from being externally inspectable using visual means to being uninspectable (e.g., installation of a large, external, fuselage doubler that results in hiding details beneath it).

Appendix 5
PSE, FCS and WFD-Susceptible Structure

1. Overview. Three key terms used when showing compliance to the damage-tolerance and fatigue requirements of 14 CFR parts 25 and 26 are, “principle structural element” (PSE), “fatigue critical structure” (FCS), and “widespread fatigue damage (WFD) susceptible structure.” This appendix provides clarification on the intended meanings of these terms and how they relate to one another. This appendix describes the items that should be included in an airplane’s Airworthiness Limitations section based on the evaluation of each PSE, FCS, and WFD-susceptible structure.

2. PSE – Principal Structural Element.

a. The term “principal structural element” (PSE) is defined in this AC as follows:

b. Principal structural element, PSE, is an element that contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall integrity of the airplane.

c. While this definition does not specifically address the fatigue susceptibility of structure, or environmental or accidental damage, it is intended to address all structure that must be evaluated under § 25.571. Section 25.571(a) states the following:

> “This evaluation must be conducted … for each part of the structure that could contribute to a catastrophic failure (such as wing, empennage, control surfaces and their systems, the fuselage, engine mounting, landing gear, and their related primary attachments).”

d. The above reinforces the notion that the identification of PSEs should be based solely on the importance of the structure to assure the overall airplane integrity.

e. Section 6c of this AC provides guidance for identifying PSEs. Many manufacturers use this list as a starting point for their list of fatigue critical structure (FCS), because AC 120-93 specifically refers to this AC for identifying FCS. Section 25.571 is intended to address all structure that could contribute to a catastrophic failure resulting from fatigue, environmental, and accidental damage, and therefore may include some structure that is not considered FCS. Nevertheless, PSE should be considered when developing a list of FCS.

f. The definitions used by applicants to identify PSEs have not been consistent between applicants and, in some cases, between models produced by the same applicant. The lack of standardization of the usage and understanding of the term “PSE,” and the resultant diversity that exists between type-design PSE lists, have required the FAA to introduce a new term, "fatigue-critical structure," in the *Aging Airplane Safety—Damage Tolerance Data for Repairs and Alterations* found in 14 CFR part 26, subpart E, and corresponding advisory material.

3. FCS – Fatigue Critical Structure.

a. Under 14 CFR 26.41, fatigue critical structure is defined as airplane structure that is susceptible to fatigue damage, which could contribute to a catastrophic failure, as determined in accordance with 14 CFR 25.571. Fatigue critical structure includes structure susceptible to fatigue damage, which could contribute to a catastrophic failure. Fatigue-critical structure also includes structure which, if repaired or altered, could be susceptible to fatigue damage and contribute to a catastrophic failure. Structure may be susceptible to fatigue cracking when subjected to tension-dominated repeated loads during operation or bondlines susceptible to disbonds due to out-of-plane peel and shear stresses. Such structure may be part of the baseline structure or part of an alteration. "Baseline structure" means structure that is designed under the original type certificate or amended type certificate for that airplane model (i.e., the as-delivered airplane model configuration).

b. Fatigue critical structure is a subset of principal structural elements, specifically those elements that are susceptible to fatigue damage.

4. Widespread Fatigue Damage Susceptible Structure.

a. Widespread fatigue damage is the simultaneous presence of cracks at multiple structural locations, which are of sufficient size and density such that the structure no longer meets the residual-strength requirements of § 25.571(b).

b. Multiple site damage (MSD) and multiple-element damage (MED) are conditions that, with no intervention, can lead to WFD. The term "WFD-susceptible structure" refers to areas of structure that, under normal circumstances, could be expected to eventually develop MSD and/or MED cracks, which could lead to WFD.

c. Although not explicitly stated, structure susceptible to WFD cannot be inspected reliably to preclude WFD. Unless a flight cycles and/or flight hours limit is placed on an airplane, modifications may be needed to preclude WFD. Structure susceptible to WFD is a subset of FCS, which, in turn, is a subset of PSE.

Appendix 6
Acronyms and Abbreviations used in this AC

Term	Definition
AC	Advisory circular
ALI	Airworthiness Limitation item
ALS	Airworthiness Limitations section
FCS	Fatigue critical structure
ICA	Instructions for Continued Airworthiness
ISP	Inspection start point
LOV	Limit of validity of the engineering data that supports the structural maintenance program
MED	Multiple element damage
MSD	Multiple site damage
PSE	Principal structural element
SMP	Structural modification point
WFD	Widespread fatigue damage

/s/

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8.0 List of Acronyms

AC	Advisory Circular
ACO	Aircraft Certification Office
ADL	Allowable Damage Limit
ARAC	Aviation Rulemaking Advisory Committee
BRSL	Bonded Repair Size Limit
BVID	Barely Visible Impact Damage
CACRC	Commercial Aircraft Composite Repair Committee
CMH	Composite Materials Handbook
CFR	Code of Federal Regulations
CM	Certification Memo
CMT	Composite Maintenance Technology
COS	Continued Operational Safety
CPCP	Corrosion Prevention and Control Program
CVID	Clearly Visible Impact Damage
DSG	Design Service Goal
DTDC	Damage Tolerance Design Criteria
DTE	Damage Tolerance Evaluation
DVI	Detailed Visual Inspection
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
GVI	General Visual Inspection
HEWABI	High Energy Wide Area Blunt Impact
IPT	Integrated Product Team
IRCWG	Industry/Regulatory Composite Working Group
LOV	Limit of Validity
MLP	Multiple Load Path
MRO	Maintenance & Repair Organization
MSG	Maintenance Steering Group
NAA	National Aviation Authority
OEM	Original Equipment Manufacturer
NDI	Non-destructive Inspection
PAH	Production Approval Holder
PMC	Polymer Matrix Composite
PSE	Principal Structural Element
RDL	Repairable Damage Limit
SAE	Society of Automotive Engineers
SDC	Structural Damage Capability
SLP	Single Load Path
SoBR	Substantiation of Bonded Repair
SRM	Structural Repair Manual

TAE	Transport Airplane and Engine
TAMCSWG	Transport Airplane Metallic and Composites Structures Working Group
TCCA	Transport Canada Civil Aviation
TCH	Type Certificate Holder
TG	Task Group
TSO	Technical Standard Order
VID	Visual Impact Damage
WFD	Widespread Fatigue Damage
WSU	Wichita State University