Structures Bulletin

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Subject: Requirements for Bonded Structural Repairs and Guidance for Bonded Structural Repair Design and Certification

References:

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Introduction and Scope:

Bonded repairs have advantages over bolted repairs in certain applications and should be considered when repairing damage in aircraft structures. Requirements and guidance for design and certification for bonded repairs are provided in this bulletin. This bulletin is applicable to bonding thermoset composite repairs to both metallic and thermoset composite structures and to bonding metallic repairs to metallic structures. This bulletin does not apply to bonding metallic repairs to composite structures or bonded repairs to honeycomb structures. In addition, this bulletin does not apply to thermoplastic structures or thermoplastic repair materials since these applications require additional considerations. Future revisions of this bulletin may address these topics. Aircraft-specific structural Technical Orders (TOs) shall be consulted for damage limitations and specific repairs. For any damage not covered by the aircraft-specific -3 TOs or Technical Order Data, the aircraft engineering authority should be consulted along with general repair TOs and the requirements in this Structures Bulletin for bonded only repairs. The guidance provided herein is not the only means of achieving the requirements for bonded structural repairs, but demonstrate acceptable approaches.

Background:

Lincoln [1] identified five factors needed to ensure that structure's technologies can be successfully transitioned. The five factors as applied to structural bonding are:

1. Stable Materials and Material Processes: Stabilized materials and material processes for adhesives, patch material, and surface preparation, to include established material specifications and acceptance standards, are the foundation for structural integrity. Strict adherence to material specifications and acceptable standards provides safeguards for assuring repair quality and acceptable performance.
2. Producibility: Material selection, repair designs, and the repair pre-bonding and bonding installation processes must consider the temperature and strength limitations of the structure being repaired. Of significant importance are establishment and assurance of strict process controls and verification of repair patch and adhesive bondline quality through nondestructive inspection to assure disbonds and porosity are within acceptable limits.
3. Characterized Mechanical Properties: Properties of bonded repairs are highly dependent on the details of the installation processes so characterization of the repair strength, durability, and damage tolerance should be based on test specimens with representative repair geometry and on-aircraft installation processes. Repair properties should consider the effects of combined stresses due to in-service loading,

interlaminar stresses that may produce critical failure modes, and residual processing stresses.

4. Predictability of Structural Performance: Validation of predictive models for strength, durability and damage tolerance should be established using test articles representative of the repair design. If analytical models have not been established, empirical models and procedures can be used to satisfy this factor when applied with sufficient rigor.
5. Supportability: Inspection methods are available to detect disbonds or areas of bonded repairs that lack adhesive (manufacturing defects); however, there is currently no fielded capability to nondestructively interrogate the strength or durability of bonded repairs. Continued airworthiness may require monitoring of structure damage through the bonded repair and monitoring of the repair itself. Equipment and qualified personnel for both manufacturing and in-service inspections must be made available when they are needed.

Strict process control is critical to manufacturing a quality bonded repair since nondestructive evaluations cannot determine the strength of a bond, but must be used to detect flaws or defects. The introduction of quality assurance checks during processing can be implemented to increase reliability of repair installations, for example using various methods to verify that the surface preparation process was performed properly. For this reason, the criticality of using properly trained personnel to perform the bonding operations cannot be overemphasized. Training and experience in composites or traditional metal bonding technology does not necessarily address issues that are specific to repair bonding. The AFLCMC/EZPT Advanced Composites Office (ACO) should be consulted for recommended repair technician training. The ACO contact information is included in the Recommendations section below.

Figure 1 shows a representation of a bonded repair that includes the repair patch, repair adhesive and primer with underlying substructure. To ensure a reliable bonded repair, adhesive bonding must be developed and maintained as a unified system of materials and processes. The bonded repair system includes the bonded repair, the structural material, the processes used to apply the repair materials, and the application of pressure and temperature during cure.

Bonded Repair System Requirements:

1) <u>Material Environmental Compatibility Assessment</u>

   Repair materials (patch, adhesive, and primer) must be compatible with the service environment of the structure being repaired and not unpredictably degrade with exposure to temperature, humidity, chemicals and corrosive environments that may be encountered during the structure’s service life. The structure must be able to withstand the processing temperature for the adhesives and patch materials without degrading the mechanical or physical properties. For some selected repair adhesives and composite patches, optional lower temperature processing cycles can be used to reduce residual processing stresses if material allowables are developed for the lower temperature processing cycles.

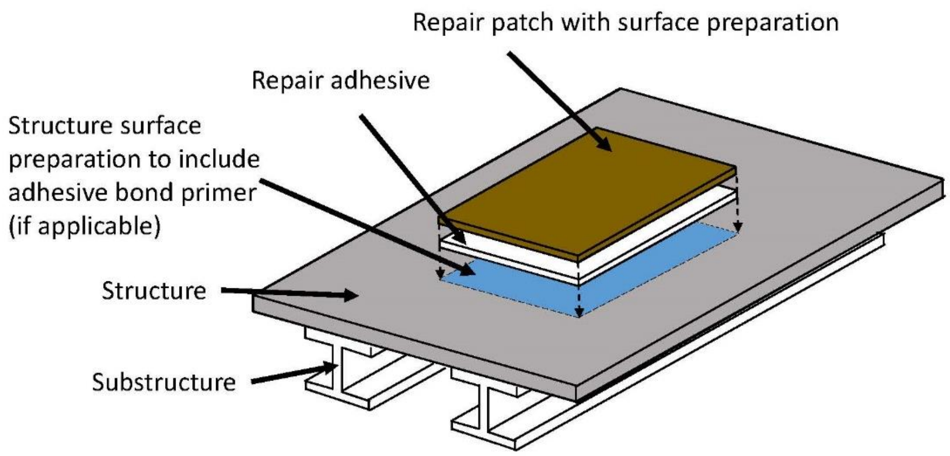

Figure 1. Schematic of a bonded repair

2) Stabilized Materials and Properties and Producibility Assessment

Repair material specifications, property data, process control and manufacturing instruction for material acceptance, processing and installation of repairs must be established. The repair materials, repair processes, installation procedures, and quality assurance procedures must be treated as a system and shown to produce stable and reproducible repairs. Training and certification requirements for personnel involved with repair preparation, repair installation, nondestructive inspection (NDI), etc. must be established.

3) Repair Structural Design Criteria

Repaired structures must meet the structure's strength, durability, damage tolerance, rigidity/stiffness, and mass properties requirements. The criticality of the aircraft part to be repaired shall follow the critical part/process from MIL-STD-1530 [2]. Table 1 summarizes repair scenarios 1 through 7 for the repair of safety-of-flight (SOF) and non-SOF structures with damage tolerance and inspection requirements for the repaired structure. The use of this table is predicated on meeting the following requirements:

- Stable materials and material processes are used for the bonded repair.
- Repair installation process controls are established, verified, followed, and performed by properly trained personnel
- The mechanical properties for the bonded repair are fully characterized in accordance with Section 4 of these requirements.
- The adhesive bondline is inspectable after installation.

If any of these conditions are not met, it is recommended that a bonded repair without fasteners NOT be used.

NDI of the structure must be conducted prior to repair to either verify that damage has been removed or to assess the size or extent of damage if it is not fully removed. An initial NDI of the repair must be conducted after installation of the repair to detect any defects in the repair patch and the adhesive bondline. If any damage beyond repair allowance is detected, it must be dispositioned to meet requirements or removed and replaced. Fracture-based analysis methods for defining acceptable disbond size allowance for bonded repair acceptance may be used. Validated repair and NDI processes must be performed by properly trained or certified individuals with suitable experience [3,4].Considerations for NDI related to damage assessment, monitoring bonded repair integrity and subsequent structural damage propagation are addressed in Appendix A.

A bonded repair will in most circumstances degrade the capability to inspect the structure through the repair. If recurring inspections are required to monitor the structure for damage or damage growth (scenarios 4 and 5 in Table 1), an a_{NDI} for inspection of the structure through the repair (TR), defined as $a_{NDI\text{-}TR}$, must be determined to define recurring inspection intervals for the structure. Inspectablility of damage through a bonded repair should be established early in the repair design and demonstration process. With the exception of scenario 5, all recurring inspections of the repair are based on a visually detectable repair failure. For scenario 5, the inspection is to detect any damage in the repair patch or adhesive bondline; if any damage is detected in the repair during recurring inspections, the repair must be removed and replaced.

For repair scenarios in which the structure damage is not fully removed prior to repair, the remaining damage must be quantified. However, current NDI methods do not provide the means to reliably translate NDI readings into damage size. Therefore, the NDI-based estimate of the damage size should be increased by some amount to cover the uncertainty in the size estimate. This damage size estimate adjustment is defined as Δa in Table 1. A USAF NDI Level III expert must be consulted when determining Δa for a specific configuration and application.

a) Static Strength

The static strength margin of safety (MoS) for the repair and for the repaired structure should include operational thermal stresses and residual processing stresses resulting from the repair installation using validated analysis methods. It should demonstrate that strength and failure modes of the repair are accurately modeled, the structure static strength requirements are restored, and that repair load attraction or load shedding effects have been accurately accounted for in the analysis. The minimum MoS for the repair and the repaired structure should be consistent with the unrepaired design requirements.

Table 1. *Repair scenarios: design and inspection requirements*

Scenario Determination							
Structure Classification	**SOF, Slow Damage Growth (SDG)**					**SOF, Fail-safe**	**Non-SOF**
Q: Is damage growth model accounting for repair benefit validated?	No	Yes	Yes	No	Yes	Yes or No	Yes or No
Q: Is the structure damage inspectable through the repair?	No	No	No	Yes	Yes	Yes or No	Yes or No
Q: Is damage removed?	Yes or No	No	Yes	Yes or No	Yes or No	Yes or No	Yes or No
Scenarios	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bonded repair (w/ no mechanical fasteners) allowed?	No	No	Yes	Yes	Yes	Yes	Yes
Bonded repair credit for DADT and to extend inspection intervals.	N/A	N/A	Yes	No	Yes	N/A	Yes
DADT criteria for structure to establish inspection intervals, residual strength, etc.	N/A	N/A	SDG	SDG	SDG	Fail-safe	Durability
Requirements							
Damage size assumption for repaired structure to establish inspection intervals – Initial	N/A		a_{NDI}	A. If damage is removed: a_{NDI} **-or-** B. If damage is NOT removed: Actual + Δa		Failure of repaired or adjacent structure that is readily detectable or malfunction evident	A. If damage is removed: a_{NDI} **-or-** B. If damage is NOT removed: Actual
Damage size assumption for repaired structure to establish inspection intervals – Recurring	N/A		N/A	A. If damage is removed: a_{NDI-TR} **-or-** B. If damage is NOT removed: Actual + Δa		Same as initial	Same as initial
Inspect for:	N/A		N/A	Damage growth in structure **-and-** Visually detectable repair failure	Damage growth in structure **-and-** Repair damage and disbond	Failure of repaired or adjacent structure that is readily detectable or malfunction evident **-and-** visually detectable repair failure	Visually detectable repair failure
Inspection interval:	N/A		N/A	**The lesser of**: A: (DT life of UNrepaired structure) / 2 **-and-** B: as determined by appropriate risk assessment (e.g., PROF)	**The lesser of**: A: (DT life of repaired structure) / 2 **-and-** B: as determined by appropriate risk assessment (e.g., PROF)	(Safe period of UNrepaired usage for structure) / 2	(Structure durability life) / 2
Bonded repair life limit:	N/A		**The lesser of**: A: (DT life of repaired structure) / 2 **-and-** B: as determined by appropriate risk assessment (e.g., PROF)	N/A	N/A	Fail-safe life limit	N/A

a_{NDI} is the pre-repair $a_{90/95}$ in-service inspection crack size based on EZ-SB-08-012 [5] for metallics or the $a_{90/95}$ in-service inspection damage size for composites validated and verified IAW EZ-SB-15-002 [6].

a_{NDI-TR} is the $a_{90/95}$ in-service inspection damage size for the repaired structure inspecting through the repair (TR) validated and verified IAW EZ-SB-15-002 [6].

Δa = factor based on damage size measurement uncertainty due to nonuniformity of damage front.

b) Durability

Repairs should restore the capability of the airframe to resist fatigue cracking, corrosion, thermal degradation, delamination, and wear such that the operational and maintenance capability of the airframe and the service life and usage requirements are achieved [7]. Application of repairs should be consistent with the methods and processes identified in the platform's Durability and Damage Tolerance Control Plan and the Corrosion Prevention and Control Plan. It should be demonstrated by either analysis or test that the repaired structure can meet the durability requirements by a factor of 2. For major component repairs that significantly affect structural load paths, a full-scale component durability test may be required.

c) Damage Tolerance

The design of repairs for SOF structure must take into consideration the structure's damage tolerance design approach of slow damage growth (SDG) for metals, no damage growth (NDG) for composites, or fail-safety. The repair design for a fail-safe structure must ensure the repair does not compromise the fail-safety of the parent structure (i.e., the repair must not change the inherent load redistribution capability in the event of a load path failure and the repair must not interfere with load path failure being either readily detectable or malfunction evident).

For repairs on SDG structure, particularly for metals, the potential to impact load interaction models (e.g., retardation) due to the repair should be considered in crack growth analyses that account for the repair. Substantiation that the structure meets SDG for metals or NDG for composites requirements with the repair includes demonstration that the long-term damage growth under the repair is predictable, slow, and for scenario 5, detectable by available NDI methods.

NDI capabilities to detect patch and adhesive defects such as delaminations, disbonds, and porosity shall be considerations in accept/reject criteria for the installed repair and for the need to account for effects of defects in the repair allowables testing.

d) Dynamics

For large area bonded repairs or repairs on flight control surfaces, the effects on mass/weight balance and rigidity must be assessed. If analyses show an effect on component stiffness and dynamic properties, validation with ground and flight tests may be warranted.

4) <u>Allowables</u>

a) Patch and Adhesive Material Allowables

Material allowables for the patch should be based on data from or standard practices defined in MMPDS (MIL-HDBK-5) [8] for metals and CMH-17 (MIL-HDBK-17) [9] for composites for the range of expected service environments. Given the current limitations on generating reliable adhesive material allowables for use in structural analysis to determine bonded joint strength, adhesive material test data, if generated, should only be used for preliminary bonded joint sizing.

b) Repair Allowables

Although material allowables for the patch and adhesive provide measures of the potential strength of a bonded repair, they are not sufficient indicators of the expected strength and service performance of a bonded repair. Strength allowables for the bonded repair must be developed and generated using test specimens prepared in a manner representative of the aircraft repair installation. Repair allowables for the most critical combinations of environmental conditions (temperature, moisture, chemical, etc.) must be developed and used for calculating margins of safety. The repair allowables must represent the combined properties of the repair patch, repair adhesives, surface preparation, primers, and structure materials. Specific guidance on test specimen designs, number of test specimens required, allowables basis (e.g., B-basis), etc. are not provided in this SB due to the wide range of potential bonded repair applications. AFLCMC/EZFS and AFLCMC/EZPT-ACO should be consulted when defining the test program to establish the repair allowables. In general, the repair allowables must account for the following:

i. *Surface Preparation*

Surface preparation for the repair allowables specimens must be representative of the conditions and environments of the aircraft repair installation. The repair allowables specimens must include the same repair materials, surface preparation, primer, and structure material used for the actual repair and must be processed in the same manner used for the aircraft repair.

ii. *Adhesive Thickness*

Adhesive thickness can influence bond strength, propensity for microcracking, in-service bondline degradation, and bondline porosity. Repair allowables specimen testing must account for the full range of adhesive thicknesses that could be expected for the on-aircraft repair installation and an acceptable range for adhesive thickness must be established and followed.

iii. *Cure Temperature and Duration*

Obtaining a uniform temperature is not necessarily required for proper adhesive cure, but the repair allowables tests must account for the full range of process heating rates and hold temperatures over the area of the repair for the aircraft repair installation and limits for the processing temperature and duration parameters must be established and followed.

iv. Cure Pressure

Allowables tests should conservatively account for variations in cure pressure within repair specification allowances. The method to apply pressure for fabrication of the repair allowables test specimens must be representative of that used for the on-aircraft repair installation.

v. *Patch Fabrication*

The patch fabrication process (preformed secondarily bonded or in-situ cured co-bonded), the form of the repair patch (scab, step-lap, or scarf) including overlay plies, and installation processes representative of the on-aircraft repair must be used for fabrication of the repair allowables test specimens.

vi. *Repair Geometry and Residual Processing Stresses*

The allowables testing must be sufficient to support stress analysis and margins of safety calculations of the repair to include residual processing stresses due to surface curvature and Coefficient of Thermal Expansion (CTE) mismatches between the patch, adhesive, and structure.

vii. *Additional requirement for metal bonding*

For bonded repairs involving metals (patch, structure, or both), the effects of operationally representative hygrothermal and chemical environments on repair durability must be assessed by wedge tests (ASTM D3762 [10]. Test conditions and pass/fail criteria for the wedge test requires engineering judgment and the Adhesives and Composites Team at AFRL/RXS should be consulted when establishing these requirements.

5) Structures Source Data

Up-to-date structures source data to include loads, strength analyses, durability and damage tolerance (DaDT) analyses, structural design details, etc. must be used when assessing damage and to design repairs for safety-of-flight structures. For durability critical and normal controls structure for which source data are not available, it may be sufficient through examination of the existing structure to design a repair that restores the damaged structure to meet its original design requirements.

6) Correlated Aircraft Durability Analysis for Metallic Structure

As part of the repair disposition process, a root cause analysis should be performed to identify the factors that resulted in the nature, size, location, and timing of the structure damage or damaging event. If the root cause of structural damage is due to repeated loads/fatigue and the aircraft's correlated durability analysis supports that conclusion, then the correlated analysis serves as a baseline for predicting damage growth in the structure with a repair. For fatigue damage not predicted by the durability analysis, the analysis must be corrected and correlated in accordance with EZ-SB-13-002 [11]. Only when durability analyses are correlated to damage findings, should damage growth analyses for the structure with the repair be undertaken.

7) Repair Documentation

All repairs must be fully documented in maintenance records or in a repair disposition report as part of the individual repair substantiation process for the specific part number per the MIL-STD-1530D requirement 5.4.3.1 [2]. The repair report shall include or contain references to:

- Descriptions of the structure/component to be repaired and criticality of the structure (Figure 1 of MIL-STD-1530D [2]).
- Description and photographs of the damage, NDI procedures, NDI data and records, damage removal processes, and the root-cause analysis results.

- Identification of the repair materials including surface preparation chemicals, adhesives, patch material, primers, and coatings.
- Design assumptions, analysis approach, material properties, repair allowables, and design drawings.
- Details of the repair geometry to include the location, size, thickness, lay-up, scarf, step-lap, single or double sided, taper angle, edge taper, etc.
- Details of the structure internal loads for the repair, strength analysis with margins, and DaDT analyses with the service life determination.
- Repair installation details/work instructions to include facilities, tooling, bonding equipment, surface preparation, processing parameters, processing data, and NDI records.
- Inspection requirements for the repair and the repaired structure documented in the Force Structures Maintenance Plan and/or the -6 TOs.
- A photographic record of the installed repair.
- Aircraft markings and/or documentation for special maintenance requirements and restrictions.
- As required by the scenarios in Table 1, requirements, validation and verification procedures for in-service inspection of the structure and repair to include a_{NDI-TR}.
- Documentation of the qualifications of the repair personnel.

Guidance for Repair Design and Certification;

The selection of a secondarily bonded, co-bonded, fastened, or hybrid (bonded and fastened) repair approach for restoring structural integrity should be based on numerous factors that include the structure's operating environment, the extent of damage, accessibility for repair, availability of repair resources, and inspectability. These issues as well as sustainment requirements may be deciding factors in selecting the repair approach.

1) <u>Considerations for Using a Bonded Repair</u>

   a) Foreign Object Damage

   Bonded joints and repairs are inherently vulnerable to damage from out-of-plane loading so placement of bonded repairs in regions with high out-of-plane loads or regions that are highly susceptible to foreign object damage (FOD) or accidental impact damage may require burdensome inspections to monitor repair integrity and require increased maintenance to disposition damaged repairs.

   b) Repair Loads

   Details of the substructure design and the internal loads must be known to design a reliable repair. Bonded repairs are most efficient when the adhesive is loaded in shear so caution should be used in locations where there may be significant out-of-plane and bending loads such as over stringer terminations. Analysis of potential injurious effects of repairs to the structure should include stress concentration effects due to patch edge termination, the effect of residual processing stresses and load attraction/shedding. In general, bonded repairs are most suitable for the repair of relatively thin structure for which the patch is the strength limiting component of the repair. For the repair of thick structure with greater load carrying requirements, the adhesive may not be able to transfer the required load to thick patches to meet strength requirements and thus becomes the strength limiting component of the repair. In no case should a repair be designed such that an interface between the adhesive and structure or adhesive and patch, such as the adhesive bond primer, be the weak link.

c) Repair Installation Constraints

i. *Availability of Resources*

Installation of bonded repairs requires specialized facilities, equipment, materials, and trained personnel. Strict process controls and the requirement to use trained personnel cannot be relaxed.

ii. Structure Geometry and Access Constraints

Specifics of the structure geometry, loading, and required size of the repair should be factors in deciding on a repair approach. Sufficient accessibility for damage removal, repair area preparation, and repair installation (bagging, vacuum port, heating source) all require a minimal working space and accessibility that may dictate the repair approach. The repair area must be large enough to have sufficient repair overlap to transfer load outside of the damage area. It follows that the thicker the structure the higher the loads and the larger the repair area needed to transfer the loads into the repair.

d) Accessibility Requirements

Considerations should include criticality of the structure to be repaired and future accessibility needs that may require removal of the repair for structure disassembly, maintenance or inspections.

2) Repair Structural Analysis Tools Guidance

The fidelity of analysis tools used to design bonded repairs should be commensurate with the complexity and criticality of the structure being repaired. The use of 2-D plane strain or generalized plane strain analyses (repair cross-section view) can provide good approximations of repair edge stresses, but cannot properly account for all of the repair edges and corners. In general, a 3-D analysis is required to accurately model repair and structure stress fields, patch edge tapering, damage in the repaired structure, and repair bending effects for safety-of-flight structures.

a) Static Strength Analysis

Testing to validate a strength criterion for multidirectional loading, bending effects, etc. may be needed if not accounted for in the repair allowables testing. Strength modeling should correctly predict the observed failure modes.

The majority of structural adhesives can deform plastically prior to failure, particularly under shear loading, allowing for local load redistribution [12]. For accurate repair strength predictions, it may be necessary to represent the nonlinear ductile behavior of the adhesive. When the results from geometric linear and nonlinear analyses are expected to differ, nonlinear analysis should be performed and sufficient structurally representative repair tests for nonlinear analysis validation purposes be performed.

For bonded repairs, a significant amount of shear load transfer from the structure to the patch is in critical areas near the edges of the patch and in the area in the immediate vicinity of cracked or damage structure. A repair patch should be designed so that the patch edge areas and the areas in the immediate vicinity of damage structure are sufficiently separated from each other so as to provide an intermediate zone of low adhesive stresses that guards against adhesive creep and helps guard against disbonding [13].

b) Durability and Damage Tolerance (DaDT) Analysis

i. Durability

To prevent fatigue disbonds, repairs should be designed such that adhesive stresses in highly loaded areas do not exceed the stress threshold (endurance limit) for fatigue damage initiation and stresses in lightly loaded areas remain elastic as a result of the mechanical/thermal fatigue loads. Edge region shear and peel stresses can be limited through proper repair design, for example by edge tapering the patch or increasing the adhesive thickness. Even slow initial disbond growth in critical areas is unacceptable since once the disbond reaches the inner part of the taper region, strains dramatically increase and damage growth may become rapid.

ii. Damage Tolerance

For cracked metallic structure, the repair should be designed so that the crack tip stress intensity factor range (ΔK) in the structure is reduced to a value that will result in an acceptable rate of fatigue crack growth; ideally ΔK should be less than the threshold value for crack growth, i.e. the crack should be arrested. The repair patch can be used in combination with other methods for reducing stress intensity factors such as stop-drilling and cold-working. For damaged composite structure, the repair strategy should be to design the repair to reduce the strains in the structure to a value less than the threshold for damage growth. Due to the nature of the stress fields and interaction of structure damage with the repair patch, a 3-D analysis is typically required for assessing structure damage growth with a repair.

3) Repair Design Validation for Certification

Repair design validation substantiates that the repaired structure meets the strength, durability and damage tolerance requirements of the aircraft structure and the sustainment processes and capabilities are established and documented to insure the integrity of the structure during the remaining service life. As appropriate for each of the scenarios in Table 1, validation includes the following:

i. Repair allowables using representative materials and processes to cover the full range of service environments and on-aircraft processing environments for repairs.
ii. Pass/fail criteria for the installed repair to include defined limits on adhesive thickness, cure temperature and pressure, and inspection findings.
iii. Validated strength models for the prediction of the repair failure mode and load.
iv. Testing to substantiate the durability of the bonded repair.
v. Validated analysis models accounting for the repair to predict damage growth rates and/or damage arrest in metallic structure.
vi. Test data to confirm the No Damage Growth requirement is met for composite structure.
vii. Validated NDI procedures to monitor damage in the parent structure and the repair.

Recommendations:

USAF and industry engineers are encouraged to consult with the Adhesives and Composites Team at AFRL/RXS and the Advanced Composites Office at ALFMC/EZPT-ACO on repair materials selection, surface preparation, repair technician training, and NDI requirements and recommendations. Contact information is:

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APPENDIX A: Nondestructive Inspection

A.1 Overview

Execution of bonded repairs requires nondestructive inspections at various stages of the repair lifecycle. Table A.1 provides a summary of various repair types and the inspection considerations for each. Table A.1 applies to the initial repair inspection at installation and to the recurring inspection requirement for scenario 5 of Table 1. These repair scenarios include three primary stages where inspection requirements may be levied. These are summarized as follows:

1. Pre-repair inspection:

Inspection of the unrepaired structure is required to detect and quantify damage. Identifying the damage type and quantifying size in terms of area and depth is key to the design of an effective repair.

Metallic structures:

- Cracks: detection and measurement of crack length and estimate of crack depth if possible. Typical methods include fluorescent penetrant and eddy current inspection.
- Corrosion: measurement of thickness loss area and remaining metal thickness

Composite Laminates: Detection of delamination/disbond and measurement of damage area and depth. Typical methods include pulse-echo ultrasonics, and thermograghy.

Inspection of the repair materials may also be required. For example, ultrasonic inspection of precured composite patches may be required to identify defective patches before repair implementation. If bonded metallic patches are employed, verification of the aluminum patch heat treat condition using conductivity testing may be required.

2. Repair inspection:

Inspections are often required to assess the integrity of the repair once installed. Typical inspections include pulse-echo ultrasonics or low-frequency ultrasonic bond testing to detect repair unbonds. Detection of porosity may be required in some composite repair applications.

3. Post-repair sustainment inspections:

Recurring inspections may be required to assess the ongoing integrity of the repair and the repaired structure. Typical inspections include pulse-echo ultrasonics or pulsed thermography inspections to detect debonding of the repair and underlying composite structure for damage growth. For metallic structures, low frequency eddy current may be used to detect and monitor fatigue crack damage growth in the underlying metallic structure.

A.2 Inspection Development Considerations

1. Consult an Expert

Implementation of an effective bonded repair inspection requires an understanding of the various inspection methods and their limitations with respect to detecting and quantifying damage in unrepaired structure, repair materials, repair adhesive bondlines, and repaired structure. Experience is required for developing inspection solutions, procedures, and references standards as well as characterizing the resulting inspection capability. A qualified NDI Level 3 must be consulted when bonded repairs are being considered. Contact the Air Logistics Complex (ALC) Nondestructive Inspection Program Manager (ALC NDIPM) for assistance. AFRL/RXS is also available to provide consultation as required.

2. Inspection Methods for Typical Repair Scenarios

Table A-1 outlines typical inspection processes and guidance for each stage of the repair lifecycle. General guidance is provided for both metallic and composite bonded repairs. In all cases, an NDI Level 3 must be consulted to develop appropriate inspection procedures and reference standards and to ensure proper validation and verification of the inspection solution [6]. Composite doubler repair inspection options are also summarized in [14].

Table A-1. Repair Types and Inspection Guidance*

Repair Type	Pre-Repair Damage Assessment Options	Repair Material Inspection Options	Repair Inspections Options	Post Repair Systainment Inspection Options	
Metallic to Metallic Bonded Repair	Surface and Rotary Bolt Hole Eddy Current T.O. 33B-1-2 WP 400 through WP 414	Conductivity Testing Heat Treat Verification**	Low Frequency Ultrasonics Resonance Method T.O. 33B-1-2, WP 505	Damage: Fatigue Cracks	Surface and Rotary Bolt Hole Eddy Current T.O. 33B-1-2 WP 400 through WP 414
				Damage: Fatigue Cracks	
	Fluorecent Penetrant Inspection T.O. 33B-1-2 WP 200, 201 and 202	Fluorescent Penetrant of Patch Integrity T.O. 33B-1-2 WP 200, 201 and 202		Damage: Subsurface Fatigue Cracks	Low Frequency Eddy Current
				Damage: Disbonds	Low Frequency Ultrasonics Resonance Method T.O. 33B-1-2, WP 505
Composite to Metallic Bonded Repair	Surface and Rotary Bolt Hole Eddy Current T.O. 33B-1-2 WP 400 through WP 414	Pulse-Echo Ultrasonics of Precured Repair Patch	Pulsed Thermography	Damage: Subsurface Fatigue Cracks	Low Frequency Eddy Current
			Low Frequency Ultrasonics Resonance Method T.O. 33B-1-2, WP 505	Damage: Disbonds	Pulsed Thermography
	Fluorecent Penetrant Inspection T.O. 33B-1-2 WP 200, 201 and 202		Low Frequency Ultrasonics Pitch-Catch Method T.O. 33B-1-2, WP 504		Low Frequency Ultrasonics Resonance Method T.O. 33B-1-2, WP 505
					Low Frequency Ultrasonics Pitch-Catch Method T.O. 33B-1-2, WP 504
Composite to Composite Laminate Bonded Repairs	Pulse-Echo Ultrasonics T.O. 33B-1-2, WP 502	Pulse-Echo Ultrasonics of Precured Repair Patch	Pulse-Echo Ultrasonics T.O. 33B-1-2, WP 502	Damage: Disbonds/Delaminations	Pulse-Echo Ultrasonics T.O. 33B-1-2, WP 502
	Pulsed Thermography		Pulsed Thermography	Damage: Disbonds/Delaminations	Pulsed Thermography

* This table provides general guidance and does not address all possible combinations of materials and bonding configurations

** Conductivity testing is applicable for aluminum alloys only

3. Developing Reference Standards

Development of effective repair inspection solutions requires reference standards. The standards must represent the structure, substructure, repair materials, and repair configuration to be applied. If a range of structural and repair thicknesses and configurations are to be implemented, then the standards must represent this range. Simulated flaws must also be installed within the standards. The simulated flaws must represent the flaw type, location, aspect ratio and size defined by the design acceptance criteria. Teflon pillow inserts are typically used to simulate flaws in adhesive bondlines. Simulated flaws are typically placed within the composite repair patch, above and below the repair adhesive bondline and in the underlying composite laminate (for composite structures). Guidance for building composite inspection reference standards can be found in [15]. Consult an experienced NDI Level 3 as required.

4. Detection Capability

Depending on the repair scenario (Table 1), the inspection process may require quantification of detection capability. Conducting capability demonstrations is not trivial, particularly for complex bonded repair scenarios where local changes in geometry and/or material stack-up may cause significant variability in the inspection response. Guidance for conducting capability demonstrations is provided in MIL-HDBK-1823 [16]; however, this guidance must often be tailored for complex repair scenarios. Consultation with an experienced NDI Level 3 specialist and a statistician may be required.