19 Effects of Defects and Repair Concepts

The purpose of this section is to provide guidance on evaluating the effect of defects or damage on the structural integrity of composite airframe structure. The section also addresses the design and analysis of composite structural repairs. The section content is based on a survey of existing effects of defects test data, repair concepts, analysis methods, and best practices used by Lockheed Martin Aeronautics and the aerospace industry.

Section 19 Table of Contents

19.1 References and Nomenclature

19-1 L.K. Flansburg, *PM-4057 Metallic Structural Analysis Manual*, Lockheed Martin Aeronautics Procedures Manual, Fort Worth, TX, 2008.

19-2 Staff, *LTV Composite Structures Analysis Manual*, LTV Aircraft Products Group, Grand Prairie, TX, August, 1984.

19-3 P. A. Gaillet *PM-4007 Engineering Design Manual*, Lockheed Martin Aeronautics Procedures Manual, 2008.

19-4 Anon., *CMH-17 Composite Materials Handbook*, Revision G, Materials Sciences Corporation, Secretariat, Philadelphia, PA, 2012.[1]

19-5 Mueller, B. E., and MacKaron, N. G., "Structural Analysis Methods and Design Criteria (SAMDC)", 2ZSB00001 Rev. E, F-35 Program, Lockheed Martin Aeronautics, Oct. 2006.

19-6 Armstrong, K. B., and Barrett, R. T., *Care and Repair of Advanced Composites*, Society of Automotive Engineers, Inc., 1998.

19-7 Niu, M. C., *Composite Airframe Structures, Practical Design Information and Data*, Conmilit Press Ltd., Hong Kong, 1992.

19-8 Christenson, T. L., “Requirements for Ultrasonic Inspection of Bonded and Composite Structures”, LMA-PC001, 18 March 2003.

19-9 Adams, J. M., “Inspection, Acceptance Criteria for Composite Parts and Assemblies”, LMA-PC005, 19 May 2003.

19-10 Leone, J., “Radiographic Inspection, General Requirements for,” LMA-PC301, 25 June 2003.

19-11 Eisenmann, J. R., “Effects of Defects in Graphite-Epoxy Laminates”, ERR-FW-1645, 31 December 1975.

19-12 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 1 General”, 5PPYA081-01, December 1994.

19-13 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 5 Graphite Epoxy”, 5PPYA081-05, December 1994.

19-14 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 6 Graphite Bismaleimide”, 5PPYA081-06, December 1994.

19-15 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 7 Thermoplastics”, 5PPYA081-07A, March 1995.

19-16 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 9 Effects of Defects”, 5PPYA081-09A, August 2003.

19-17 Anon., “F/A-22 Structural Development Tests, Coupon Test Results and Evaluation, Volume 10 SMART Program Repair Materials”, 5PPYA081-10, October 2005.

19-18 Owens, S. D., and Eisenmann, J. R., “Composite Material Effects of Manufacturing Defects Data”, 2ZSA00021, March 2008.

19-19 Rousseau, C. Q., “IM7/MTM45-1 Fabric Summary Data and Allowables”, FZM-9947 Engineering Test Report, 30 June 2014.

[1] In 2002, administration of MIL-HDBK-17 was transferred to Materials Sciences Corporation. Future releases will be released as Composite Materials Handbook CMH-17, Materials Sciences Corporation, Secretariat.

19-20 Rousseau, C. Q., “IM7/MTM45-1 Tape Summary Data and Allowables”, FZM-9948 Engineering Test Report, 30 June 2014.
19-21 Anon., “Corrective Action and Disposition for Nonconforming Material”, MIL-STD-1520C, 27 June 1986.
19-22 J. J. Luby, “Identification and Disposition of Nonconforming Material Process”, Lockheed Martin Aero Code AC-4276, August 2013.
19-23 Griffin, R. D., “F-16 Preliminary Review Manual”, 16PR035B, Issue 7, 19 September 2007.
19-24 Griffin, R. D., “F-16 Material Review Manual”, 16PR700B, Issue 11, 19 September 2007.
19-25 Watkins, K. E., “F-22 Material Review Manual”, 1999.
19-26 Porter, M. E., et al, “F-35 Material Review (MR) Standard Repair Manual”, 2ZZA00162G, 9 December 2013.
19-27 Rousseau, C. Q., “JSF Structural Repair Development (JSRD) Methods”, WI-09-SDI-003, 30 May 2013.
19-28 Rousseau, C. Q., “Generic Negligible and Repairable Damage Limits”, WI-09-SDI-004, 30 May 2013.
19-29 Rousseau, C. Q., et al,” JSRD Standard Structural Repair Criteria Document”, 2ZSA00064C, 30 September 2014
19-30 Acres, P. H., “NDI/NDT Procedures/Techniques for the F-35 Program Criteria Document”, 2ZSA00066, 2013.
19-31 Anon., “Aircraft Battle Damage Repair, USAF Series F-16A and F-16B Aircraft”, F-16 A-39, 13 August 1990.
19-32 Anon., *USAF Technical Manual: General Advanced Composite Repair Processes Manual*, T. O. 1-1-690, 9 July 2001.
19-33 Anon., *NAVAIR Technical Manual: General Composite Repair*, NAVAIR 01-1A-21, 1 Sep 2008.
19-34 Anon., *Aviation Maintenance Technician Handbook – Airframe*, Volume 1, FAA-H-8083-31, U.S. Dept. of Transportation, Federal Aviation Administration, Flight Standards Service, 2012.
19-35 Anon., *Acceptable Methods, Techniques, and Practices – Aircraft Inspection and Repair*, Advisory Circular No. 43.13-1B, U.S. Dept. of Transportation, Federal Aviation Administration, Flight Standards Service, Sep. 1998.
19-36 Link to Figure: http://www.ndt- ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/DataPres.htm.
19-37 Fiorenzi, C. J., “Standard Test Procedures for Advanced Fiber Reinforced Composite Materials,” LMA-PT001B, Lockheed Martin Aeronautics Company, April 2004.
19-38 Adams, J. M., "Standard Test Procedures for Reinforced Plastic, Adhesives, Core, Structural Potting Compounds and Thermoplastic Sheet Material", LMA-PT008B, June 2005.

Table 19.1-1 Nomenclature

Symbol	Definition	Units
A	Delamination area	in.^{2}
A, B	IBOLT element dimensions	in.
BUS, BYS	Bearing Ultimate Strength, Bearing Yield Strength	psi
C	Normalization factor based on ultrasonic inspection technique	-
CAI	Compression After Impact	psi
CSK	Countersink (or flush fastener)	-
CT Scan	X-ray Computed Tomography Scan	-
D	Disbond length, fastener diameter, hole diameter	in.
d	Characteristic damage parameter	in.
$dB_{porosity}$	Defective laminate sound wave attenuation (decibel)	dB
$dB_{pristine}$	Pristine reference sound wave attenuation (decibel)	dB
EOD	Effect of defect	-
EOP	End or edge of part	-

Symbol	Definition	Units
F_{allow}	Allowable stress (or strain) at the design environmental condition	psi (or in/in)
F_{bra} (Design)	Bearing cutoff allowable used for "as-designed" margin of safety	psi
F_{bra} (Resin Filler)	Bearing allowable for resin filler	psi
F_{dam}	Allowable stress (or strain) for an equivalent damage condition	psi (or in/in)
f_{dam}	Peak critical stress (or strain) for a defective or damaged condition	psi (or in/in)
f_{des}	Applied design stress (or strain) for a pristine condition	psi (or in/in)
FHC, FHT	Filled Hole Compression, Filled Hole Tension	psi
F_{OHCS}	0.25 in. open hole compression strength allowable	psi
H/C	Honeycomb sandwich core	-
h_{EOD}	Measured or actual cured laminate thickness	in.
h_{nom}	Nominal cured laminate thickness	in.
ILS, ILT	Interlaminar Shear Strength, Interlaminar Tension Strength	psi
IML	Aircraft inner mold-line	-
IPT	Integrated Product Team	-
IR	Infra-Red	-
K(d)	Experimentally determined strength retention factor	-
K_{EOD}	EOD strength retention factor	-
L	Delamination length (major axis or maximum dimension)	in.
$M.S._{EOD}$	Margin of safety for a defective or damaged condition	-
$M.S._{No\ Defect}$	Margin of safety for a pristine condition with no defect or damage	-
n	Number of structural plies	in.
N1 - N4	IBOLT element normal running loads	lbs/in
NC	Nonconformance	-
NDI	Non-Destructive Inspection	-
N/P	Nutplate	-
OHC, OHT	Open Hole Compression, Open Hole Tension	psi
OML	Aircraft outer mold-line	-
PE	Pulse Echo	-
PX, PY	IBOLT fastener bearing loads	lbs
QAR	Quality Assurance Record/Report	-
SPATE	Stress Pattern Analysis by Thermal Emission	-
TTU, B/N/R	Through-Transmission Ultrasonic, Broadband/Narrowband/Reflected	-
t	Nominal laminate thickness	in.
t'	Minimum effective laminate thickness below the fastener head	in.
T1 - T4	IBOLT element shear running loads	lbs/in
TAI	Tension After Impact	psi
t_{dam}	Thickness of damaged structural plies	in.
t_{EOD}	Measured or actual cured ply thickness	in.
t_{nom}	Nominal cured ply thickness	in.
t_{total}	Total thickness of laminate structural plies	in.
$t_{undam} = t_{total} - t_{dam}$	Thickness of undamaged structural plie	in.
UNC, UNT	Unnotched Compression Strength, Unnotched Tension Strength	psi
UT	Ultrasonic Technology	-
W	Assumed bond width	in.
ΔdB	Relative sound wave attenuation (decibel)	dB

19.2 Introduction

The repair of composite structure is no more complex than for conventional metallic structure once the basic principles of design, analysis and manufacture of composites are understood. The standard analysis methods and tools developed throughout this manual may be directly applied to composite repair concepts. The guidance herein is specific to composite materials and should be followed in conjunction with PM-4057 (Section 18.0 Structural Repair, Reference 19-1) and any program specific guidance.

19.2.1 Repair of Composite Structure

A structural repair refers to the modification or alteration of an existing structural part or assembly as a corrective action to address defects or damage. Defects/damage can prevent a part from satisfying the intended design requirements including “form, fit and function.” But more importantly, defects/damage can prevent the part from meeting structural integrity requirements by reduced static strength or service life.

The repair of any structure is a function of the facilities, equipment and skills available to perform the repair. Accordingly, three “levels” of repair have been defined for U. S. Military Aircraft (Reference 19-2).

Production (Material Review) Level – Repair of defects or damage identified during the manufacture and production of the aircraft. These repairs are accomplished by the contractor or sub-contractors at the production facilities. This level addresses defects/damage that are incurred during fabrication, assembly, finishing and/or handling where repairs are accomplished prior to delivery of the material or product to the customer.

Field Level – Repairs performed at the squadron level which might be performed in the field (deployed location) or at the home base. These repairs are for damage that occurs during service and includes battle damage repairs that may need to be accomplished in a hostile environment. This is the lowest level in terms of facilities, equipment, skills and available material.

Depot Level – Repairs performed at the military maintenance depot. These repairs are for major damage that occur during service. The depot is assumed to have the same capability as the military contractor in terms of facilities, equipment, skills and available material. This is generally true for metallic repairs, but some limitations may exist for composite repairs.

Repair methods are usually defined for any given structure in terms of the “level” of repair. Thus, Depot level repairs may be different than Field level repairs in order to accommodate the differences in facilities, equipment, skills and available material.

A structural analyst may directly support the disposition of Production Level repairs as part of deployment to a Material Review team. A structural analyst may directly or indirectly support the disposition of Field and Depot level repairs as part of a contracted team to develop standard repair methods, guidance, limitations, and/or structural repair design data for particular instances of in-service damage.

19.2.2 Composite Defects/Damage and Repair Methods

Table 19.2-1 provides a summary list of the composite defects/damage discussed in Section 19.6 along with the disposition and repair method options discussed in Section 19.8. Repair methods listed in the table are classified as either “Structural” or “Cosmetic.” Repair methods classified as “Structural” are designed to either fully or partially restore the structural integrity of the defective or damaged part or assembly. In contrast, repairs classified as “Cosmetic” are intended to fully or partially restore form, fit and/or function; yet no benefit is accounted for in the structural analysis.

Table 19.2-1 Typical Composite Defects/Damage and Repair Methods (1/2).

		REPAIR METHODS (S = Structural, C = Cosmetic)																		
Defect or Damage Type		S	S	S	S	S	S	C	C	C	C	C	S	C	S	S	S	S	S	S
		Oversize Fastener and Sleeve Repair	Bushing Hole Repair	Resin Filler Repair for Misdrilled Holes	Fastener Filled Hole Repair	Blind Fastener Repair	Delamination Repair Using Fasteners	Resin Injection for Delaminated Holes, Edges	Resin Injection for Sandwich Disbonds	Resin Injection for Bonded Joint Disbonds	Blend and Smooth or Laminate Trim Repair	Resin Surface Repair	Resin Filler Repair to Restore Part Contour	Resin Filler or Laminate Plug Repair	Honeycomb Core Repairs	Flush Scarf Patch Repair	Bolted Doubler Repair	Bonded Doubler Repair	Other Laminate Repair Configurations	Metallic Fitting Repair
Damage Section	Repair Section	19.8.1	19.8.2	19.8.3	19.8.4	19.8.5	19.8.6	19.8.7	19.8.8	19.8.9	19.8.10	19.8.11	19.8.12	19.8.13	19.8.14	19.8.15	19.8.16	19.8.17	19.8.18	19.8.19
19.6.1.1	Planar Delamination						X					X				X				
19.6.1.2	Edge Delamination						X	X								X	X	X		X
19.6.1.3	Curved Lam Delam						X										X	X		X
19.6.1.4	Sandwich Disbonds								X						X	X	X	X		
19.6.1.5	Bond Joint Disbonds						X			X						X				
19.6.2	Scratches or Gouges											X	X			X	X	X		X
19.6.3	Surface Dents											X	X			X	X	X		X
19.6.4	EOP Damage										X	X	X			X	X	X		X
19.6.5	Penetrations														X	X	X	X	X	X
19.6.6	H/C Core Defects														X	X	X	X		X
19.6.7	Porosity											X				X	X	X		X
19.6.8	Sub-Nom Thickness															X	X	X		X
19.6.9	Waviness or Wrinkles											X	X				X	X		X
19.6.10	Tool Marks										X	X	X				X	X		X
19.6.11	Fiber Misalignment															X				
19.6.12	Ply Overlaps & Gaps																			
19.6.13	Trim or Machine NC										X	X	X				X	X		X
19.6.14	OML Mismatch												X							
19.6.15	Fastener Short e/D																	X		X
19.6.16	Fastener Hole Spacing																	X		X

Table 19.2-2 Typical Composite Defects/Damage and Repair Methods (2/2).

Defect or Damage Type		Oversize Fastener and Sleeve Repair	Bushing Hole Repair	Resin Filler Repair for Misdrilled Holes	Fastener Filled Hole Repair	Blind Fastener Repair	Delamination Repair Using Fasteners	Resin Injection for Delaminated Holes, Edges	Resin Injection for Sandwich Disbonds	Resin Injection for Bonded Joint Disbonds	Blend and Smooth or Laminate Trim Repair	Resin Surface Repair	Resin Filler Repair to Restore Part Contour	Resin Filler or Laminate Plug Repair	Honeycomb Core Repairs	Flush Scarf Patch Repair	Bolted Doubler Repair	Bonded Doubler Repair	Other Laminate Repair Configurations	Metallic Fitting Repair
	REPAIR METHODS (S = Structural, C = Cosmetic)	S	S	S	S	S	S	C	C	C	C	C	S	C	S	S	S	S	S	S
Damage Section	Repair Section	19.8.1	19.8.2	19.8.3	19.8.4	19.8.5	19.8.6	19.8.7	19.8.8	19.8.9	19.8.10	19.8.11	19.8.12	19.8.13	19.8.14	19.8.15	19.8.16	19.8.17	19.8.18	19.8.19
19.6.17	Increased Fast Dia																X	X		X
19.6.18.1	Deep Countersink		X	X																
19.6.18.2	CSK Anomalies	X	X	X									X							
19.6.18.3	Inadvert CSK		X																	
19.6.19	Counterbore NC	X	X																	
19.6.20	Mislocated Fast Holes			X		X														
19.6.21	Missing or Spun N/P				X															
19.6.22.1	Fast Hole Damage	X	X	X																
19.6.22.2	Delaminated Holes			X				X				X								
19.6.22.3	Misdrilled Pilot Holes			X																
Disposition Options: USE-AS-IS, REPAIR or SCRAP.																				

19.2.3 Key Resources and Tools

A list of key resources and tools that are available to support structural analysis of composite effects of defects and repairs is provided below.

- PM-4057 Metallic Structural Analysis Manual, Section 18 Structural Repair (19-1)
- PM-4007 Lockheed Martin Design Manual, Section 4.1.6 Composite Repair (19-2)
- CMH-17 Composite Materials Handbook (19-4)
- Integrated Detail Analysis Tools (IDAT), refer to individual tool User Guides
    - SQ5 Composite Lamination Theory Analysis
    - IBOLT Composite Bolted Joint Analysis
    - BEND Composite Curved Beam Interlaminar Stress Analysis
    - PULLTHRU Composite Bolted Joint Pull-Through Analysis
    - CDADT Composite Durability and Damage Tolerance
    - A4EI Bonded Joint Strength Analysis (predicts bondline shear stress only)
    - IBOND (Bonded Joint Strength Analysis (predicts bondline shear & tension stress)

Structural analysis methods and guidance currently used on the F-35 program are provided in Reference 19-5 and subsequent work instructions (19-27, 19-28). General references for composite repair methods used in the aerospace industry may be found in References 19-6 and 19-7. Lockheed Martin Aeronautics engineering specifications for inspection and acceptance criteria for composites parts and assemblies are provided in References 19-8 through 19-10.

LM Aero composite effects of defects (EOD) test results and design guidance developed from legacy programs and internal research and development projects are documented in References 19-11 through 19-20. These EOD test results are discussed in Section 19.6. Implementation of EOD test results into IDAT analysis tools are also discussed in Section 19.6 and are summarized in Table 19.10-2.

USG guidance for corrective action and disposition of nonconforming material may be found in Reference 19-21. LM Aero guidance for identification and disposition of nonconforming material is provided in Reference 19-22. LM Aero legacy program standard repairs (F-16, F-22, F-35) for production material review are documented in References 19-23 through 19-26. LM Aero legacy program guidance for field and depot level repairs is provided in References 19-27 through 19-30. USAF and NAVAIR composite repair guidance is documented in References 19-31 through 19-33. Federal Aviation Administration repair methods and practices are documented in References 19-34 and 19-35.

19.2.4 Definitions of Terms

A list of terms and definitions that are commonly used to describe the composite defects and repair concepts for airframe structure are provided below for reference.

- **Abrasion** – mechanical wearing of a composite surface material by natural or human action.
- **Disbond** – A void, absence or lack of adhesion within a bondline or bonded area.
- **Delamination** – The separation of adjacent layers within a cured laminate. A delamination may occur along a single layer; or across multiple layers as a result of impact, overload, or adverse environment. If caused by impact, there may also be associated matrix cracks and/or broken fibers.
- **Depot Level Repair** – Repairs performed during aircraft maintenance intervals at the military depot. This repair addresses any major damage that occurs during service. The depot is assumed to have the same capability as the OEM military contractor in terms of facilities, equipment, skills and available material. This is generally true for metallic repairs, but some limitations may exist for composite repairs.
- **Elongated Hole** – A finished hole with out-of-round geometry.

- **Field Level Repair** – Repairs performed at the aircraft squadron level to address damage which might occur in the field (deployed location) or at the home base. This repair addresses damage that occurs while in-service and includes battle damage repairs that may need to be accomplished in a hostile environment. This is the lowest level of repair capability in terms of facilities, equipment, skills and available material.
- **Gouge** – To cut holes or grooves into the part surface from an impact or abrasion with a sharp object.
- **Inclusion** – A foreign material that has been inadvertently cured within a composite laminate and detected during post-cure inspection. Common examples are chips, film separator backing paper, tape or other particles that are accidently embedded in the laminate.
- **Lightning Strike Material** – A fabric or mesh bonded to the outer surface of a composite part to help dissipate the energy from a surface lightning strike. A common material used for lightning strike protection for composite skins is an expanded copper foil (ECF) mesh.
- **Nonconformance** – A condition of rejection for a part or assembly that does not meet acceptable limits or requirements as called out in the engineering drawing or specifications.
- **Non-recurring** – A single, unique event, condition, or environmental exposure that is not repeated over time. Generally, non-recurring refers to events, conditions, or exposures outside of the normal operational design envelope of the item in question.
- **Porosity** – A condition of trapped pockets of air, gas, or void within a resin or matrix material. A condition where regions of small voids exist within a composite laminate. Porosity may be caused by insufficient resin flow during cure, localized excessive heating or resin contamination.
- **Ply Distortion, Waviness or Wrinkling** – Local unintended variations in the laminate usually caused by improper part lay-up or tool placement prior to cure. A problem usually associated with co-cured assemblies, complicated details, or tight radius features.
- **Ply Gaps or Overlaps** – Refers to out-of-tolerance gaps or overlapping of adjacent plies that are laid side by side to form a single lamina or layer with a given fiber orientation. This also may be the gaps or overlaps in individual layers of tape laid using the fiber placement process.
- **QADS** – Quality Assurance Documentation System.
- **QAR** – Quality Assurance Record or Report.
- **Recurring** – An event or condition including a process anomaly that occurs time after time or at some interval in time.
- **Resin Rich** – A condition of excessive resin usually detected visually on the surface of the laminate. Usually caused by improperly controlled bleeding or fiber bridging during cure; usually at a radius, step or chamfer.
- **Resin Starved** – A condition of a lack of resin that is usually detected visually on the laminate surface and is characterized by a dry appearance, excessive voids and/or loose fibers. Can sometimes be assessed from laminate thickness checks. It occurs from improperly controlled bleeding during cure.
- **Scratch** – A depression caused by marking, breaking or cutting the surface slightly with a sharp or pointed object. A scratch can result in broken fibers. The scratch depth should be measured.
- **Short Edge Distance** – Fastener center to laminate edge spacing for a composite bolted joint that is below the recommended minimum of 2.5 times the hole diameter.
- **Surface Dent or Depression** – A hollow or shallow depression on a laminate surface usually caused by a tool, or foreign object on a tool, during the cure cycle; will usually have deformed, but unbroken fibers.
- **SQAR** – Supplier Quality Assurance Report,
- **TDA** – Temporary Deviation Authorization (Ref. AC-6299).
- **Tool Mark** – Surface distortion of plies within a composite laminate caused by mismatches or misalignment between tool details.
- **Void** – An empty space or gap within a composite laminate. Voids are associated with bridging or resin starved areas.
- **Wallowed Holes** – A condition resulting from improper drilling in which the hole interior surface is not smooth and through the thickness variations exist in the hole geometry.

19.3 Production Aircraft Material Review

A nonconforming material is any material or product which does not conform to engineering requirements or design specifications. Material Review (MR) is the process for identifying, documenting and disposition of non-conforming materials or products. The internal process for Material Review and disposition is documented by AC-4276 (Reference 19-22). As a member of the Material Review team, the Stress engineer is responsible for evaluating the structural integrity of a proposed disposition. The disposition options and structural integrity requirements for damaged or defective parts are provided in Table 19.3-1.

Table 19.3-1 Dispositions for Damaged or Defective Parts

No.	Disposition	Requirement	Discussion
1	Use-As-Is and Non-Structural Repairs	Perform an effect of defect (EOD) analysis to determine impact of defect on structural integrity of the part. The analysis must demonstrate: a. Static Strength[1] M.S. ≥ 0.0 b. All RTR ≥ 1.0 (including stability and deflection criteria) c. DADT Life has not been compromised.	This category includes: "Use-As-Is" with no repair; and Non-Structural Repairs that restores form, fit and/or function; but has no impact on structural integrity.[2] Engineering judgment based on past experience may be used to disposition without structural analysis.
2	Structural Repairs	Perform an effect of defect (EOD) analysis to determine impact of defect on structural integrity of the part. Notify the liaison group of any necessary repairs and work with them to determine repair options. Repair analysis must demonstrate: a. Static Strength[1] M.S. ≥ 0.0 b. All RTR ≥ 1.0 (including stability and deflection criteria) c. DADT Life has not been compromised.	For multiple defects on the same QAR, there may be multiple repairs or multiple dispositions.
3	Scrap	Perform an effect of defect (EOD) analysis to determine impact of defect on structural integrity of the part. If a repair option is not available which results in positive static strength margin of safety, meeting all stability and deflection requirements and full DADT life requirements, the part is scrapped.	Scrapped parts are deemed unfit for use on a flying aircraft. They may be sent to engineering for further evaluation and testing. If not, per customer requirements they are indelibly marked and cut-up.
Where: Structural Repair = a repair that partially or fully restores structural integrity. Non-Structural Repair = a repair that restores form, fit and/or function; but has no impact on structural integrity. M.S. = Margin of Safety DADT = Durability and Damage Tolerance RTR = Ratio-To-Requirement (= Buckling Load/Design Ultimate Load)			
Notes: 1. See PM-4057, Section 18.2.1.1 for recommendations if margin has been reduced from Design Margins. 2. If the defect/and or repair has no impact on the part structural integrity, then a statement of "no impact to structural integrity" and a restatement of the blueprint margin of safety and life may be documented on the QAR for completeness.			

It is the Stress engineer's responsibility to evaluate structural defects and determine if they are minor enough to be used with no repair, can be repaired, or must be scrapped and replaced with a non-defective part. All parts which get installed on the aircraft must have:

• Design ultimate strength capability
• Equivalent structural stiffness
• Full service life
• Meet control surface imbalance limits
• And, if applicable, meet required fail-safe damage tolerance concepts.

Each aircraft program typically develops a set of standard repairs for internal use only that are unique to the materials and design features of that aircraft and are applicable to common defects and damage. Refer to references 19-23 to 19-26 for examples. Over the life of the program, this set of standard repairs is likely to grow as recurring defects and repair methods are developed and adopted. Standard repair procedures may be grouped into the following two categories:

Preliminary Review (PR) Standard Repairs – These are common "low-level" repairs that may be applied by PR authorized Quality Assurance personnel or MR authorized Engineering personnel without any additional approvals required as long as all of the limitations listed in the Standard Repair are met. Thus, once published, PR Standard Repairs do not require review or approval of Stress personnel.

Material Review (MR) Standard Repairs – These are higher level repairs that may be used at the discretion of the MR Authorized Engineering personnel. As long as all of the limitations listed in the Standard Repair are met, no additional approvals are required. However, even when all limitations are met, sound case by case engineering judgment shall be used by the MR Engineering personnel in the application of these Standard Repairs including coordination or approval from other Engineering disciplines as needed. Thus, MR Standard Repairs may or may not require a case-by-case review and approval of Stress personnel.

These repairs have specific limitations in applicability and extent of damage and in general, have no negative impact on the structural integrity of the airframe when used correctly. Any nonconformance that exceeds the level of a PR or MR standard repair will require the review and approval of Stress personnel.

19.4 Field and Depot Level Aircraft Repair

Most major aircraft System Development and Demonstration (SDD) programs will include a contracted effort to develop Field and/or Depot Level aircraft structural repairs and guidance to help support the deployment, maintenance and supportability of the aircraft while in service. This deliverable may be in the form of a repair manual or guide that defines inspections, damage evaluation criteria, repair limits, and detailed repair guidance. The development of Field and/or Depot Level repairs and guidance are usually accomplished after the aircraft design has been completed and the aircraft is in the initial production phase.

The objective of the repair program is to provide the Field or Depot Level technician with a guide for inspection and assessment of damage found on an aircraft part or assembly, recommended repair dispositions based on damage type and dimension(s), and repair limitations. For a given location on the aircraft, the technician should be able to identify and quantify the damage and then determine the structural repair and its limitations based on the guidance. Standard repair materials, processes and procedures must be clearly defined for all repair methods included in the guide. The selection of repair methods should be guided by the aircraft materials and structural design details and based on the available facilities, equipment, materials and skilled personnel for the desired level of repair. All required development testing should be identified to determine if any design data are needed to support implementation of new repair materials, processes or structural designs.

The role of the Stress engineer for a Structural Repair Program is to evaluate the feasibility and limits of various repair options for their structure. A list of damage types and repair options are usually assigned based on structural type, such as solid skins, honeycomb sandwich structure, sub-structure, etc. The Stress engineer is to conduct structural analyses of the various damage types and repair options to determine acceptable sizes of unrepaired or repaired damage for which positive margins of safety are obtained. Depending on the structure and design loads, it may be helpful to define structural zones for which specific repairs and associated limitations may be designated.

The Stress engineer is thus responsible for creating a set of appropriate Use-As-Is and repair limits for the defined zone, as well as assisting Design and Materials & Processes engineering in developing appropriate repair designs.

In addition to a Structural Repair Program, LM Aero may also be contracted to provide engineering support for major structural repairs, beyond the scope of standard field or depot level repairs, for aircraft deployed in service. The role of the Stress engineer will be to support the damage assessment, repair method selection, and required structural integrity analysis.

19.5 Inspection Techniques and Acceptance Criteria

This section describes inspection techniques used for identifying and quantifying composite defects/damage and the LM Aero acceptance criteria used for composite parts and bonded assemblies.

19.5.1 Inspection Techniques

A summary of the different inspection techniques used within Lockheed Martin Aeronautics for composite parts and the types of defects or damage that are identified by each are listed in Table 19.5-1.

Table 19.5-1 Defects Detected by Various Inspection Techniques.

Defect Type	Visual Inspection	Dimensional Check	Tap Test	Ultrasonic Inspection	Radiographic Inspection	Thermographic Inspection	Shearographic Inspection	Destructive Inspection
Thru-thickness fiber waviness	X				X[1]			X
Surface Anomalies	X	X						
Part Dimensions		X			X[2]			X
Reduced Laminate Thickness		X						X
Delamination (within laminate)			X[3]	X		X	X	X
Disbonds (laminate to laminate)				X		X[4]		X
Bond Anomalies in Honeycomb Sandwich Structures	X		X		X		X	X
Cracks in Honeycomb Cells, Closeouts, Core Damage					X			X
Moisture Ingress in Honeycomb Cells				X[6]	X	X		
Fiber Misalignment	X[5]				X[1]			X
Porosity	X[7]			X				X
Voids	X[7]			X		X		X
Foreign Material	X[7]			X	X	X		X

[1]Detection of fiber misalignment or waviness for composite laminates requires pre-installed tracer fiber and hence applicable only if implemented during the early stages of the part development.
[2]For hidden part dimensions.
[3]Limited to thin laminates (~0.05" thick) and a quiet environment
[4]Primarily for disbonds between coating and laminate.
[5]Surface only
[6]Thru-transmission UT
[7]For thin glass laminates only

19.5.1.1 Visual Inspection

This is one of the first methods for detecting a defect in a part. Surface defects or defects on edges can be detected using this method. A handheld magnifying glass and illuminating the discrepant surface with a source of light at an angle aids this inspection process. Once a defect is detected then more detailed NDI techniques discussed below are used to further examine the defect.

Wormtracks, which are surface resin rich pockets often seen as lines on the surface of the laminate, are detected visually (**Figure 19.5-1**).

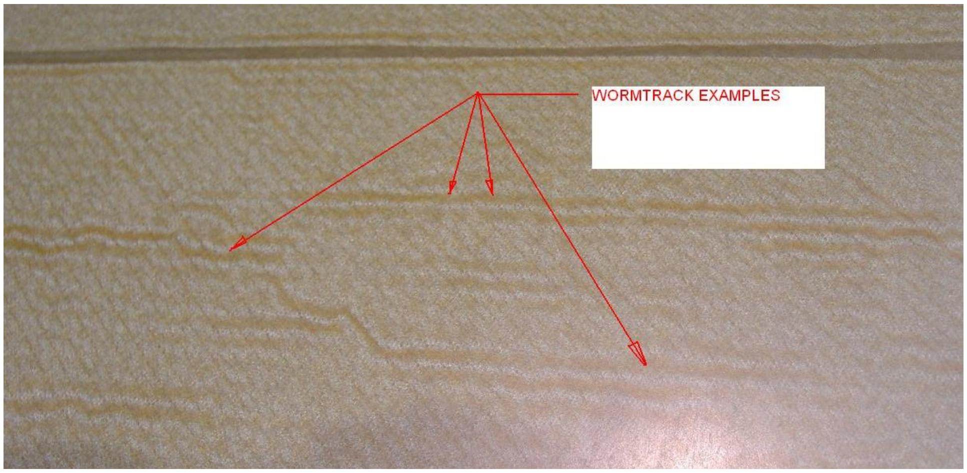


Figure 19.5-1 Wormtracks observed on the surface of a laminate.

19.5.1.2 Dimensional Checks

Part dimensions are only measured if specifically called out on the drawing. Parts are also measured to verify visual inconsistencies or to quantify observed defects. These can be checked using a measurement scale or automated using a Coordinate Measuring Machine (CMM). Composite part thickness measurements are usually taken in early stages of part development until the fabrication process has stabilized.

19.5.1.3 Tap Test

In a tap test the structure is tapped with a hammer or coin and the resulting sound is used to determine if delamination or disbond exists in a structure. The inspector, in a quiet environment, uses the tap test to listen for variations in sound with location that may indicate the existence of an anomaly within the structure. The sounds produced by the tap test are in the audible range, usually in the frequency range between 10 – 20Hz. When a well bonded structure is tapped it results in a sharp ringing tone. However if delamination or disbond is present a dull thud may be heard. The difference may be subtle, so careful attention to the sound is required. A tap test is usually performed when a UT scan cannot be used due to the danger of the couplant entering the damaged area. Once damage is located using tap test, a UT scan from the opposite surface of the solid laminate may be used to further precisely quantify the damage. A tap test using a tap hammer is shown in Figure 19.5-2. Tap tests are restricted to thin laminates that are usually less than 0.05 inches thick.

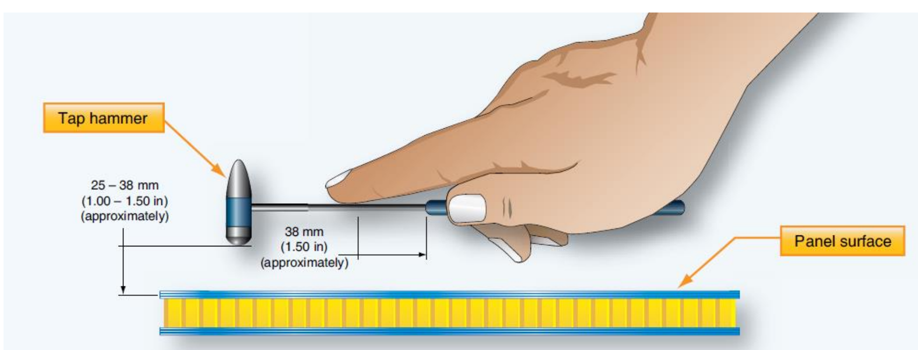


Figure 19.5-2 Tap Test (Reference 19-27).

19.5.1.4 Ultrasonic Inspection

Ultrasonic techniques measure defects such as delamination, disbonds, foreign material inclusions, voids or porosity using sound waves in the high frequency range (usually at 2.5 and 5 MHz), which is well above the audible range. For sandwich structures a lower frequency of 1 MHz may be used. This technique identifies those defects that cannot be visually observed or detected through tap testing or dimensional checks. The technique employs the differences in the densities between the solid material and the porosity, inclusion or delamination to obtain a measure of the defects. This difference in density causes the sound signals to drop or attenuate since sound waves are either reflected or absorbed at the interfaces between the solid part and the defect. The reflected sound waves or the portion of the sound wave that is transmitted through the part can be collected by a transducer and displayed on a chart or oscilloscope. By comparing this attenuated signal with the attenuation in an equivalent Inspection Reference Part (IRP), the existence of porosity, void or delamination can be estimated. The UT equipment is calibrated using the IRP.

It is relatively easy to use the ultrasonic technique in a manufacturing environment where the instruments are tuned to specific parts and there is practically no need to change the settings over a long period of time apart from minor adjustments. This is different than a repair set-up where different parts from the same aircraft or different aircraft have to be scanned. This will require frequent calibration of the ultrasound equipment. Furthermore, the in-service parts which have had a prolonged exposure to the in-service environment will transmit sound differently than the same part that is scanned immediately after manufacture. This is also true for parts that have been modified due to repairs. These differences have to be accounted for in the procedures and scan forms included in the inspection instructions primarily intended for the repair environment.

Since the difference in density between air and the part is large, significant loss in sound energy occurs if the sound is transmitted through the air. To prevent this, a gel or liquid coupling agent is used to introduce the sound into the part. Since the liquid coupling agent, usually water, can enter into parts with cavities such as sandwich structures, these structures are usually x-ray inspected after ultrasonic inspection to detect any water ingress.

There are two general types of ultrasonic techniques – the Pulse-Echo (PE) and the Through-Transmission Ultrasonic (TTU) Inspection. The Through-Transmission Ultrasonic inspection is further classified as Broadband Through-Transmission technique (BTTU) and Narrowband Through-Transmission technique (NTTU). The NTTU employs a reflector and is therefore also known as Reflected Through-Transmission Ultrasonic (RTTU) Inspection. Additional details regarding the Ultrasonic techniques are provided in LMA-PC005 (**Reference 19-9**).

Pulse-Echo Technique

The PE technique is single sided where both the transmitting and receiving units are contained in a single scan unit and the part is scanned on a single side as shown in Figure 19.5-3**.**

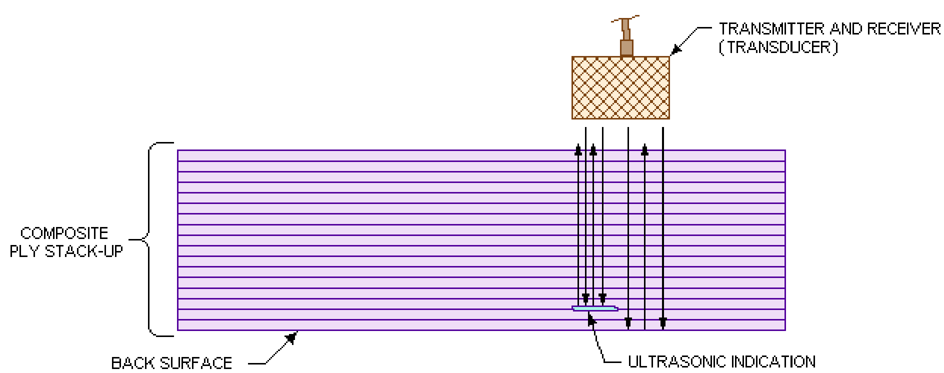


Figure 19.5-3 Pulse-Echo Ultrasonic Technique

The sound wave travels into the part through Teflon or methacrylate located at the tip of the scanner. Any change in the time taken for the echo to travel back to the transducer or change in the amplitude of the received signal indicates the presence of a defect. The PE technique is usually used for detecting delaminations, cracks, porosity, and disbonds in bonded parts. Because of its ease of use the PE technique is well suited for field work. PE cannot be used to detect flaws in the core of sandwich structures since the density difference between the core and facesheets is significant. However, it can be used to detect disbonds between the facesheet and core closest to the surface. Some of the advantages and disadvantages of Pulse Echo are given in Table 19.5-2**.**

Table 19.5-2 Advantages and Disadvantages of Pulse Echo Ultrasonic Inspection.

Advantages	Disadvantages
• Access on only one side is required. Only one transducer is needed. • Detects a wide variety of included material compared to TTU. • Provides both size and depth information of the defect. • Can be automated and records data in C-scan format.	• Since sound waves have to traverse the same path twice more energy is required for this method. Higher energy also implies lower sound frequency and lower resolutions. • Non-parallel surface, abrupt changes in thickness, and extreme surfaces affect PE inspection.

Broadband Through-Transmission Technique (BTTU)
The BTTU technique uses a transducer to generate sound waves that are located on one side of the part and a receiver on the other side to receive the sound signals (**Figure 19.5-4**).

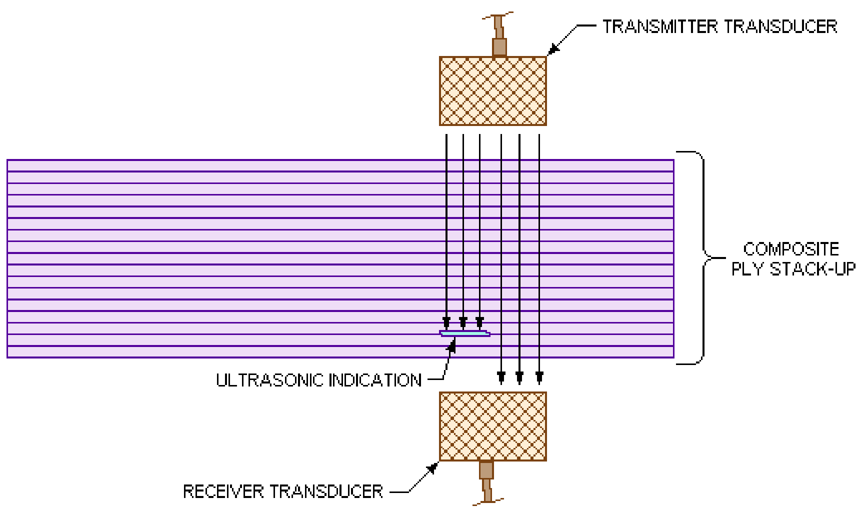
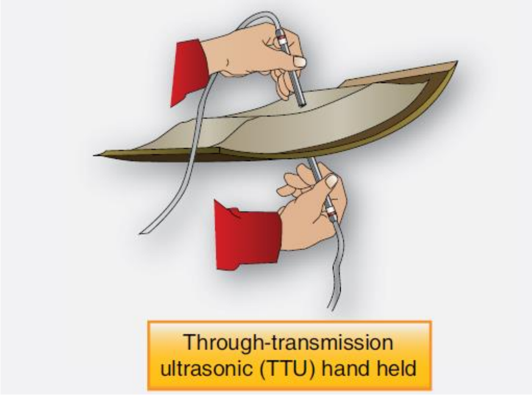


Figure 19.5-4 Broadband Through-Transmission Ultrasonic Technique

The sound waves can either be transmitted through intimate contact with the part via a coupling agent or through a water yoke as shown in Figure 19.5-5.



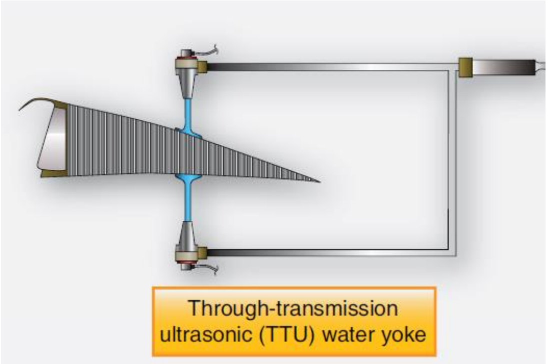


Figure 19.5-5 Hand held and water yoke Through-Transmission Ultrasonic Technique (Reference 19-27).

The intensity of the transmitted signal is measured and compared against the IRP. Loss in intensity is indicative of a defect. This method can be employed to detect delaminations and disbonds in solid laminates and disbonds between the facesheet and core in a sandwich. Advantages and disadvantages of Through Transmission inspection are given in Table 19.5-3.

Table 19.5-3 Advantages and Disadvantages of Through-Transmission Ultrasonic Inspection.

Advantages	Disadvantages
• Attenuation of ultrasonic is low since the sound waves travel in only one direction through the part. • Thicker laminates can be inspected. • Non-parallel surfaces can be inspected. • Can be faster and less complicated than PE. • Can be automated and records data in C-scan format.	• Two transducers required which must be precisely aligned (within 3º). • Gives only defect size but no depth information. • Not all foreign materials can be detected.

Narrowband Through-Transmission Technique (NTTU/RTTU)
Reflected Through-Transmission Technique (RTTU) employs a reflector plate made from stainless steel, aluminum or glass situated below the inspected part that reflects back the sound waves through the part and is received by a transducer (refer to Figure 19.5-6).

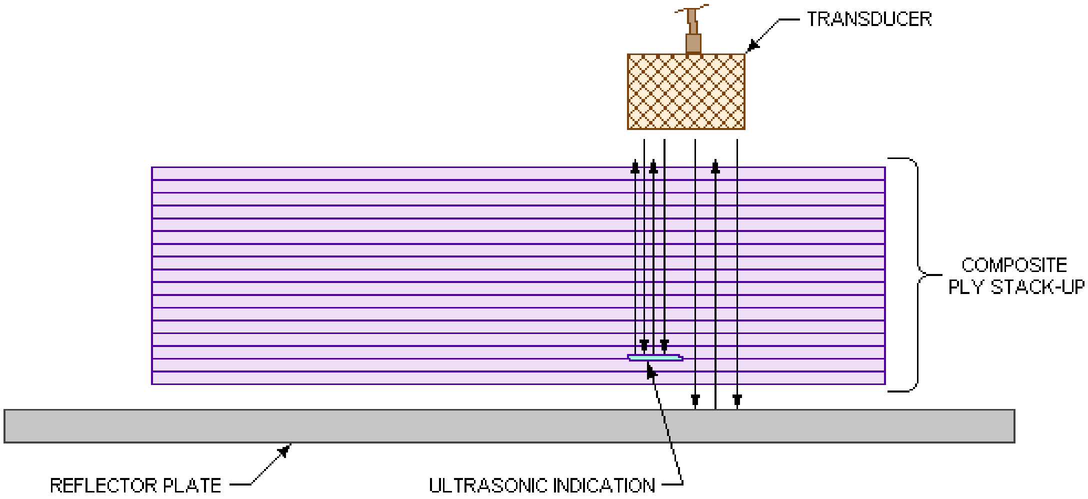


Figure 19.5-6 Reflected Through-Transmission Ultrasonic Technique

The RTTU technique is also known as the Double Through-Transmission Ultrasonic Technique. Some of the advantages and disadvantages of the Reflected Through-Transmission technique are given in Table 19.5-4.

Table 19.5-4 Advantages and Disadvantages of Reflected Through-Transmission Ultrasonic Inspection.

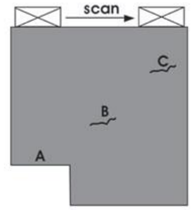
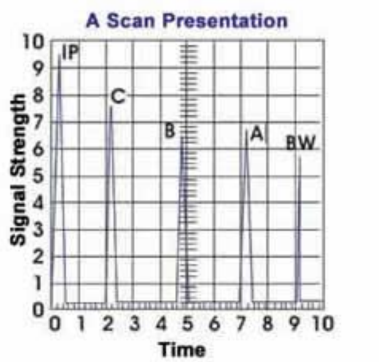
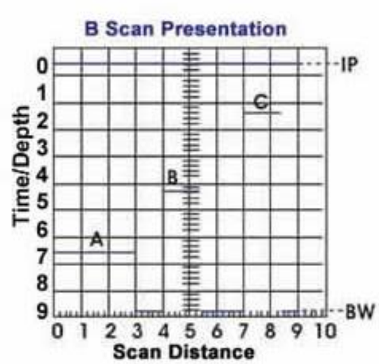
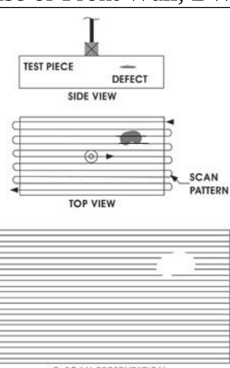
Advantages	Disadvantages
• RTTU is very sensitive to flaw detection and changes in structure. • Records data in C-scan format.	• Limited by size of the reflector plate. • Material must have surfaces parallel to the plate. • Transducer must remain within 2^o of the plate.

Through-Transmission UT cannot be used to detect defects in the sandwich core except for detecting moisture ingress in the core. Pulse Echo UT can be used to inspect facesheet and the facesheet-core bond lines. In general UT cannot be used to detect defects in bondlines where adhesive is present but is not perfectly bonded to the adherends (also known as kissing bonds).

Ultrasonic Data Presentation

The ultrasonic data is usually presented in A-Scan, B-Scan and/or C-Scan format. Table 19.5-5 shows the data presentation formats. The A-scan and C-scan are the most widely used formats to display defect information. C-scan provides a planar view of the defect over a wide area while the A-scan provides a more focused depth-wise distribution of the defect.

Table 19.5-5 Data Presentation Formats for Ultrasonic Inspection (Reference 19-36)

Presentation Format		Description
The A-Scan and B-Scan presentation formats shown in this table are discussed relative to the defective part shown below 		
A-Scan	 IP=Initial Pulse or Front Wall, BW=Back Wall	• Measures amplitude of signal and transit time of signal • Provides through depth image at transducer location • Plots amplitude along Y axis and signal-to-transducer time along X axis which can be used to estimate defect depth • Reference panel of known thickness needed to scale time • Provides size, depth and type of defect information
B-Scan	 IP=Initial Pulse or Front Wall, BW=Back Wall	• Provides view of the cross-section of the part • Plots time along Y-axis and scan distance along X-axis • Provides depth of defects and its linear dimension along the direction of scan
C-Scan		• Measures amplitude and transit time of signal • Displays inspection results in plan form • Suitable for automation

LASER Ultrasonic Technology (UT) is an NDI technique where the LASER is employed to generate the ultrasonic wave. The LASER impacts the surface material and induces thermo-elastic expansion which generates the ultrasonic wave. The sound waves travel normal to the surface irrespective of the LASER incident angle. Defects reflect the sound waves which interact again with the surface and causes surface vibrations which are picked up by a detector LASER. This information is processed and the defect is displayed as A-, B-, or C-Scan formats, which facilitates both rapid and detailed characterization of defects. The quality of ultrasonic energy generated depends on the surface material. A glass or a nylon peel ply has good ultrasonic energy generation capability compared to a carbon laminate. Therefore a peel ply is recommended for carbon laminates that have to be inspected using the LASER UT. Advantages and disadvantages of Laser Ultrasonic Inspection are given in Table 19.5-6**.**

Table 19.5-6 Advantages and Disadvantages of Laser Ultrasonic Inspection.

Advantages	Disadvantages
• Is a non-contact technique that requires no couplant such as water. • Can inspect complex structures 10 times faster than other UT techniques. • Requires minimum fixture cost.	• Is a PE technique and cannot be used for Through Transmission Ultrasonic inspection. • The depth of material that can be inspected depends on the material. In general, material thickness up to 0.5 inches can be inspected.

An embedded delamination as it appears in a LASER UT C-scan is shown in Figure 19.5-7**.**

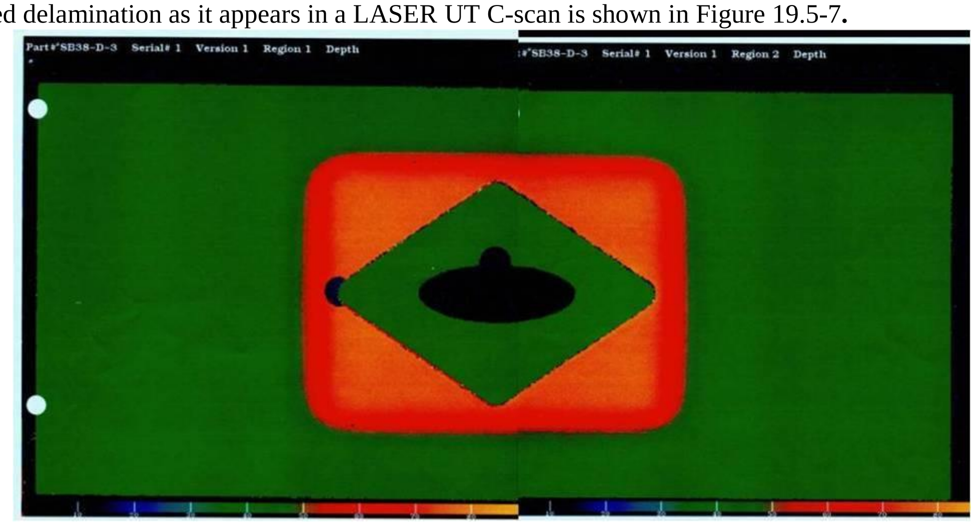


Figure 19.5-7 Embedded delamination as it appears in an LASER UT C-scan.

19.5.1.5 Radiographic Inspection

Radiographic inspection involves the use of different types of radiation including x-rays, gamma rays, neutrons, etc. Since x-ray inspection is the most common form of inspection for aircraft parts, it is discussed further in this section. The x-ray inspection technique utilizes the differences in the radiation absorption capacities of the fiber, matrix and the defect to detect the indication. It is a through transmission technique where the x-ray travels through the structure and creates an image of the defect on a film as shown in Figure 19.5-8Table 19.5-7 or the image can be displayed real-time on a screen. Typically, in a production environment, parts are first examined real-time and if a defect is detected, a film is used to capture the defect and a QAR is written against the defect. Sometimes a three-dimensional X-ray Computed Tomography (CT) scan may be required to get a better understanding of the defects such as cracks in honeycomb sandwich core, closeouts and embedded antennas. CT scan can also be used to determine part dimensions that are hidden. However, CT scans are expensive.

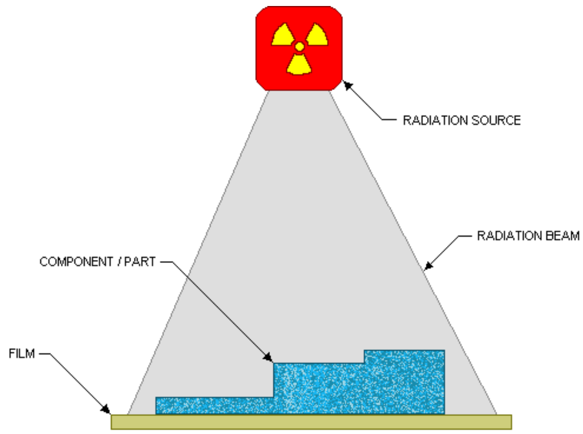


Figure 19.5-8 Radiographic Inspection Technique.

The radiation absorption characteristics of carbon fiber and epoxy are the same and furthermore their radiation absorption capacity is low. Therefore, to facilitate detection of defects such as fiber misalignment, a lead glass tracer fiber is incorporated into the part during manufacturing. However, this requires additional effort and increases cost. Therefore this is restricted to unique situations. Also, to obtain an accurate image of the surface crack defect, a radio-opaque penetrant may be used.

X-ray techniques are typically used to detect core damage in honeycomb sandwich structures such as node bond separation, crushed core, distorted core, moisture ingress in core, cracks in core, etc. They are also used to detect defects in foam adhesive bond line in sandwich core. In addition X-ray techniques detect foreign objects such as peel plies that are accidently left behind during curing.

CT scan radiographic technique detects defects that are in a plane perpendicular to what can be detected using UT technique. Therefore, CT techniques complement UT techniques. This type of testing is usually used to detect defects that cannot be detected using ultrasonic inspection. Advantages and disadvantages of Radiographic Inspection are given in Table 19.5-7.

Table 19.5-7 Advantages and Disadvantages of Radiographic Inspection.

Advantages	Disadvantages
• Can be used to detect small density changes as little as 2%. • Can be used to detect flaws in honeycomb core.	• Requires access on both sides of the part. • This technique is time intensive and expensive. • Poses radiation risk and inspection personnel should be appropriately protected.

19.5.1.6 Thermography

The Thermographic method employs the surface temperature of the structure to determine if defects exist in the structure. The surface temperature is usually monitored using an infrared camera. The main advantage of this method is it can be used to perform inspection of large areas quickly. It can be used to find delaminations, disbonds, Honeycomb moisture ingress, inclusions and voids. The thermal conductivity of the defect must be different than the parent material. However, the UT method is better at detecting delamination and disbonds. The main disadvantage of this method is that the equipment cost is high and it requires skilled personnel for interpreting the data.

There are two types of Thermographic inspection methods:
1) Passive: where the response of the structure to an applied heating or cooling is determined as a function of time.
2) Active: where the heat is generated internally within the structure due to the applied cyclical external load. This method is also known as SPATE (Stress Pattern Analysis by Thermal Emission).

The Infrared (IR) thermographic passive inspection technique is currently used by Lockheed Martin Aeronautics to inspect for voids and coating disbonds. The voids must be present close to the surface, usually within 0.25” of the surface. Furthermore, the surface should have low reflectivity or else it should be painted with a washable black paint. In the case of coating disbonds the coating should be less than 0.1” thick.

19.5.1.7 Shearography

In the Shearographic technique, the image of the deformation of the surface of a part is compared under two different stress states. By combining the two images an interference fringe pattern is generated which is a measure of the surface strain, which in turn may be a manifestation of a sub-surface anomaly. The surface of a part is illuminated by a laser light and the reflected laser from the surface is captured by a camera. Next the part is stressed (usually by vibration, heat or vacuum) , which causes a shift in the reflected image and when combined with the earlier image of the same part in its unstressed state and processed by a computer, results in an interference fringe pattern which is indicative of any defects that might be present.

Shearographic technique is used by LM Aero primarily for bonded honeycomb structures to inspect bonded areas for disbonds. It is not used for inspecting laminates. When an indication is detected by Shearography, it should be verified and quantified by another designated NDI technique. Shearography works best when the surface is not highly contoured and has good reflectivity.

19.5.1.8 Destructive Inspection

In destructive inspection, a portion of the part or assembly, with the defect, is removed. This defective part is cut into several pieces, which are subsequently polished and examined under a microscope. This method provides actual visual details of the defects such as porosity, void or delamination. It also helps to identify damage to fiber and/or matrix which are not possible through other NDI techniques. This is often done during manufacturing development to aid in tool or manufacturing technique improvement. In practice, because the part is destroyed, it is used only when there is no other means of inspecting for an anomaly that has repeatedly shown up on parts.

Traveler and/or cut-out specimens can be planned for destructive or non-destructive inspection to verify/understand effects of manufacturing processes. Traveler is a small piece of the same product as the part, which is made along with the part but not integrally attached to the part. Travelers are typically used to establish the effect of environment such as moisture on the mechanical properties of test articles. Since the test articles are large and have tabs, to measure the moisture content accurately the Traveler specimen is used instead. Cut-outs are test specimens that are attached to the part and later machined and removed. A piece that is machined out of a part to create a designed opening; the edge of a part that is trimmed are examples of cut-out specimen. Cut-outs are similar in function to Tabouts and Prolongations used in metals. Cut-outs are superior to Traveler since they are integral to the part that is manufactured. However, depending on its intended purpose care should be taken to ensure that the Cut-out is not in a region where the resin is likely to get squeezed out or where the ply count is not representative of the part.

19.5.2 Acceptance Criteria

An acceptance criterion establishes the acceptable limits for a defect in a composite laminate, bonded assembly or sandwich structure using nondestructive inspection (NDI) techniques. Inspection technique and acceptance requirements are usually called out by the engineering drawing or specifications.

A summary of inspection techniques is provided followed by a discussion of the indication size (length and area) requirements for rejecting the indication and criteria for grouping indications. This is followed by discussion of evaluation criteria for laminates, bonded assemblies, and sandwich structures.

19.5.2.1 Inspection Techniques Summary

Different inspection techniques were discussed in detail in Section 19.5.1**.** A summary of the three main inspection techniques is provided below in Table 19.5-8**.**

Table 19.5-8 Summary of Non-Destructive Inspection Techniques.

Technique	Types of indication
Ultrasonic inspection. Includes narrow band through-transmission (NTTU), broadband through-transmission and pulse echo	Voids, delamination, foreign materials and porosity in laminates and bonded structures. Disbonds in the bondline of bonded structures.
Radiographic inspection	Sandwich core anomalies such as cracks, blown core, crushed core etc. in cocured, cobonded and secondary bonded sandwich structures.
Visual Inspection	Surface anomalies, dimensional features of laminates and bonded assemblies.

There may be areas on a part that are inaccessible for inspection such as corners with sharp radius. These parts have to be carefully designed with the effects of variability of the manufacturing process, loads and environment built into the design so that it can be shown that inspection is not required during the life cycle of the part. This may entail that test part(s) be built using the same process employed for the actual part and be destructively examined to ensure that the design did capture the effects of variability of the manufacturing process.

19.5.2.2 Indication size requirements

Most inspection techniques detect a minimum single indication size of 0.25 x 0.25” (0.063 in^2) for a laminate or a laminate-laminate bonded assembly. For a honeycomb core structure, the smallest indication size that can be detected by inspection technique is usually 0.25” x 0.25” (0.063 in^2) or the width of two core cells, whichever is larger.

The ultrasonic and radiographic techniques, on surfaces and along radii greater than 1”, typically detect indications of a prescribed length and area. If the radii are less than 1” and if the indication is a void, disbond, foreign material, crack, or delamination, only the length of indication is prescribed as a criterion to reject the indication. If the radii are greater than 1”, the indications are rejected if the length or area requirement is exceeded. For an individual indication, the indication length, if not determined digitally, is determined as shown in Figure 19.5-9. The indication area is determined by multiplying the indication length (major axis) with the width (minor axis).

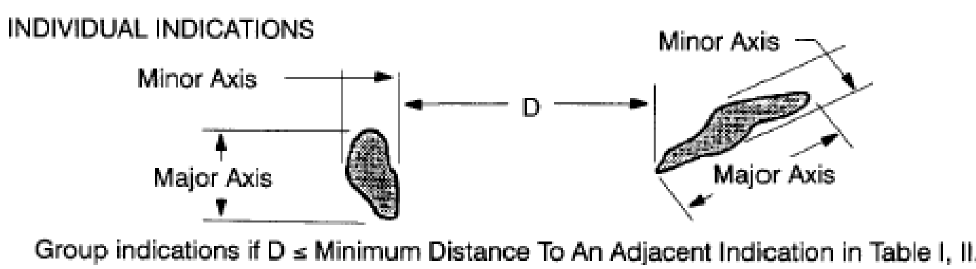


Figure 19.5-9 Individual Indication Evaluation Criteria (Reference 19-9).

If indications detected by ultrasonic or radiographic technique satisfy the minimum size requirement and are located close to each other, they can be grouped based on grouping criteria. The grouping criteria specifies that if the shortest distance between the indications (D) as shown in Figure 19.5-9 is below a prescribed allowable distance then the indication can be grouped as shown in Figure 19.5-10.

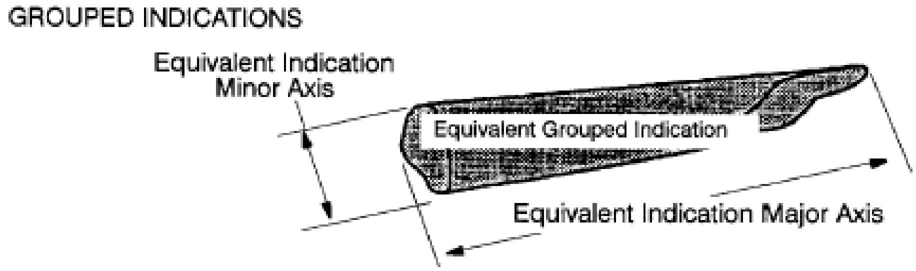


Figure 19.5-10 Group Indication Evaluation Criteria (Reference 19-9).

The equivalent group length and width is used to determine the indication length and area. The grouped indication is rejected if the equivalent indication exceeds the maximum allowable length or area, which will be discussed in the next section. The allowable distance for grouping depends on the inspection zone which is next discussed.

On some programs, a composite part/assembly is typically divided into inspection zones to facilitate ultrasonic or radiographic inspection and application of evaluation criteria. In the inspection process specification, three parameters are usually specified for each inspection zone – maximum indication length, maximum indication area, and minimum distance to adjacent indication (grouping criteria). The inspection zone and part thickness (required for UT inspection) is specified in the engineering drawing. The Integrated Product Team (IPT) is responsible for assigning inspection zones. In some cases, the entire part is a single inspection zone or class.

19.5.2.3 Evaluation Criteria

The evaluation criteria specify the limiting values that are employed to accept or reject an indication. If the defect is rejected, then a Quality Assurance Record/Report (QAR) is written against the defect and a disposition must be determined. The acceptance criteria are a function of the inspection technique and the type of structure that is inspected (e.g. laminates, bonded structure, honeycomb etc.). Evaluation criteria are discussed below for: (i) Visual Inspection, (ii) Ultrasonic Inspection, and (iii) Radiographic Inspection.

Visual Inspection – Visual inspection is performed with the aid of a magnification glass in a well-lighted area. Indications on the outer surfaces and edges are usually detected using this method. For example, anomalies in the noodle region (Figure 19.5-11) and thru-thickness fiber waviness can be visually detected if they are on the edge of the part. Also, wormtracks on the laminate surface can be visually detected. LM-PC005 (Reference 19-9) provides details on other indications that can be detected visually and the criteria for accepting them.

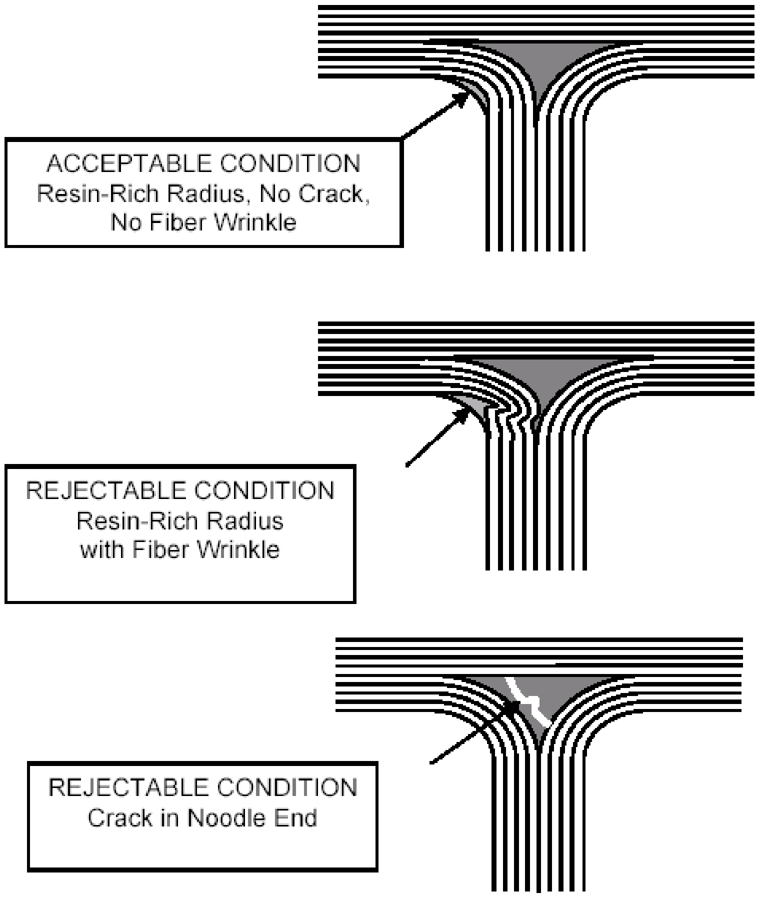


Figure 19.5-11 Filler Insert (Noodle) Anomalies.

Ultrasonic Inspection – For ultrasonic inspection, the evaluation criteria are provided in a tabular form in Table 19.5-9. The values given in the table are obtained from LM-PC005 and are shown here for demonstration purposes only. Programs may specify their own unique requirements and these should be consulted in-lieu of Table 19.5-9.

Table 19.5-9 Typical Allowable Ultrasonic Indication Sizes and Requirements (Reference 19-9).

Acceptance Class	Voids/Delaminations/ Disbonds/Foreign Material			Porosity		Minimum Distance to an Adjacent Relevant Indication (Inches)
	General Surfaces (Laminates), Radii > 1”		Radii ≤ 1”			
	Maximum Area (Inches^2)	Maximum Length (Inches)	Maximum Length (Inches)	Maximum Area (Inches^2)	Maximum Length (Inches)	
A	0.063	0.25	0.25	0.25	1.0	1.0
B	0.25	1.0	0.5	0.56	1.5	1.0
C	0.56	1.5	0.75	1.0	2.0	1.0
D	1.0	2.0	1.0	1.56	2.5	1.0
E	1.56	2.5	1.25	2.25	3.0	1.0

In the above table, the first column (Acceptance Class) lists the inspection zones that are specified on the engineering drawing. If it is not provided, the default is Class B. The length and area criteria are specified for two groups of indications. Group-1: voids, delaminations, disbonds and foreign material, and Group-2: porosity. For Group-1 indications, if the radii are less than 1” then the acceptance criteria are specified by length of the indication only. Note that for UT inspection to be feasible, the radii have to be larger than 0.25”. The last column (Minimum Distance to an Adjacent Relevant Indication) specifies the minimum distance below which the indications can be grouped.

Porosity indications that exceed either the maximum area or maximum length criteria are rejected only if additional conditions which are discussed in LM-PC005 (Reference 19-9) are satisfied. These conditions include specifications for the maximum allowable attenuation level at a specific frequency as a function of part thickness.

For bonded assemblies and cocured honeycomb facesheets, criteria similar to those specified in Table 19.5-9 are used for evaluating indications unless otherwise specified on the engineering drawing. For cocured honeycomb facesheets, a lower frequency is employed for UT inspection. The maximum allowable relative attenuation is 12 ΔdB using through transmission technique.

Radiographic inspection techniques are very useful to inspect core (metallic and non-metallic) anomalies which cannot be detected by ultrasonic techniques. A table similar to Table 19.5-9 (without porosity) is used for acceptance criteria unless otherwise specified on the engineering drawing. Further details are provided in LM-PC005 (Reference 19-9).

Typical core defects detected by Radiographic inspection techniques are shown Figure 19.5-12. LM-PC005 (Reference 19-9) provides details on acceptance criteria for these types of defects.

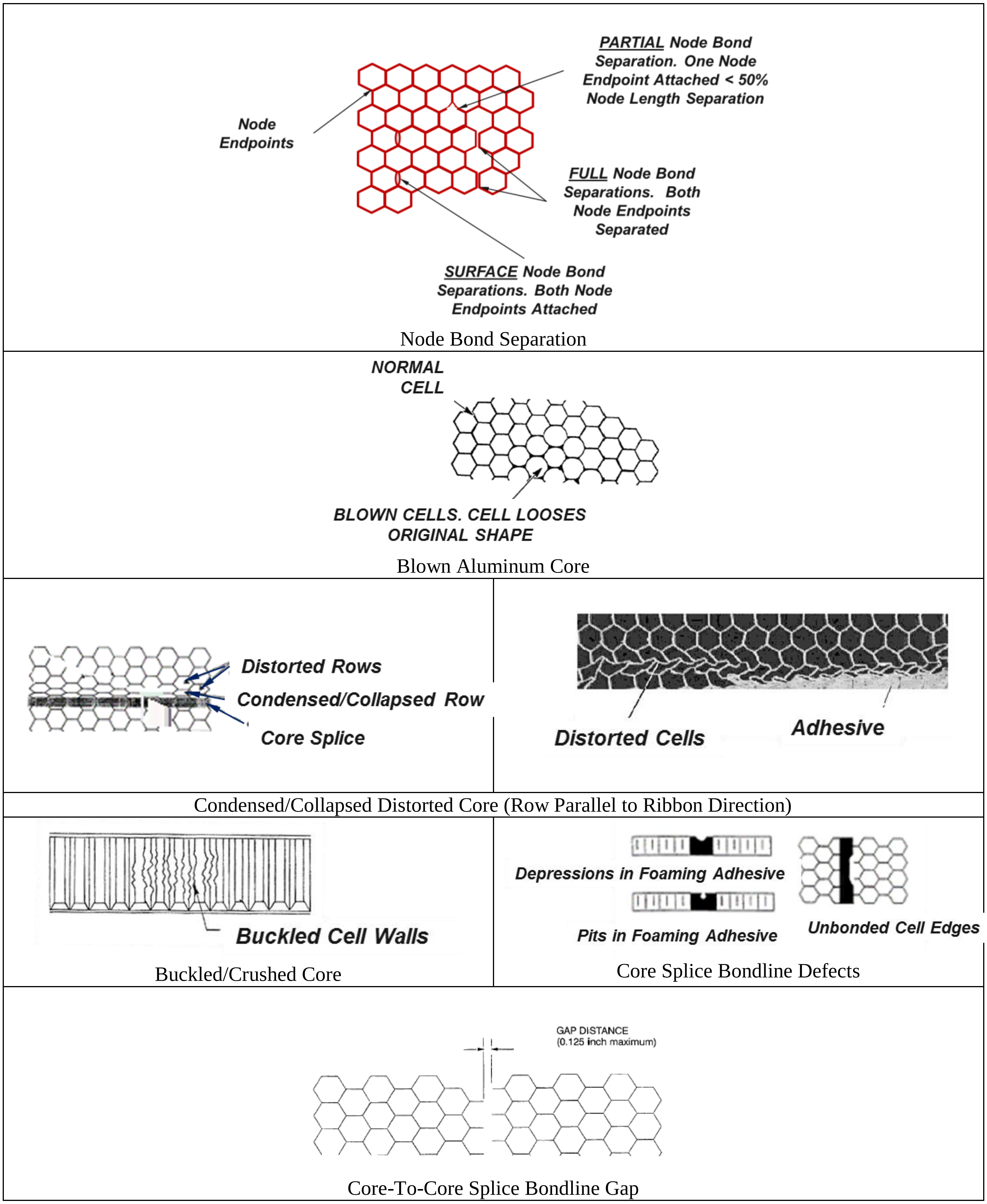


Figure 19.5-12 Typical Core Defects in Honeycomb Structures (Reference 19-9)

19.6 Disposition and Repair Guidance for Common Defects or Damage

This section provides disposition and repair guidance for common nonconformances that typically occur in composite airframe structures in the manufacturing or service environment. The types of defect/damage addressed are nonconformances that exceed the acceptable limits to engineering requirements as defined by the engineering drawing and/or specifications. The composite defects or damage included in this section are listed in Table 19.6-1). Each sub-section focuses on a given defect/damage type providing a description, parameters used to characterize and quantify the degree of damage, disposition and repair guidance, and, wherever applicable, effect of defect (EOD) residual static strength analysis guidance for evaluating a defective "AS-IS" condition. Composite structural repairs for the defects/damage described herein are provided in Section 19.8.

Table 19.6-1. Common Composite Defects or Damage.

Section	Description
After Cure, Handling or Impact Events	
19.6.1	Delaminations, Voids or Inclusions
19.6.1.1	Planar Delaminations
19.6.1.2	Edge Delaminations
19.6.1.3	Delaminations in Curved Laminate Sections
19.6.1.4	Disbonds in Bonded Sandwich Construction
19.6.1.5	Disbonds in Adhesively Bonded Joints
19.6.2	Surface Scratches or Gouges
19.6.3	Surface Dents
19.6.4	Edge of Part Damage
19.6.5	Penetration
19.6.6	Honeycomb Core Structural Defects or Damage
19.6.7	Porosity
19.6.8	Sub-Nominal Thickness
19.6.9	Waviness or Wrinkles
19.6.10	Tool Marks
19.6.11	Fiber Misalignment
19.6.12	Ply Overlaps or Gaps
Drilling, Trimming and Assembly	
19.6.13	Trimming or Machining Nonconformances
19.6.14	OML Mismatch
19.6.15	Fastener Hole Short Edge Distance
19.6.16	Fastener Hole Spacing
19.6.17	Increased Fastener Diameter
19.6.18	Countersink Nonconformances
19.6.18.1	Deep Countersink
19.6.18.2	Countersink Geometric Anomalies
19.6.18.3	Inadvertent Countersink
19.6.19	Counterbore Nonconformances
19.6.20	Mislocated or Inadvertent Fastener Holes
19.6.21	Missing or Detached (Spun) Nutplates
19.6.22	Misdrilled Damaged Holes
19.6.22.1	Fastener Hole Defects or Damage
19.6.22.2	Delaminated Fastener Holes
19.6.22.3	Misdrilled Pilot Holes

Common margin of safety equations used for EOD residual strength analysis that are referred to in this section are summarized in Table 19.6-2. The margin of safety calculation for a pristine "as designed" condition with no defects or damage can usually be written as Equation 19.6-1. The effect of a defect or damage on the margin of safety can be accounted for through a strength retention factor K_{EOD} multiplied times the load, stress (or strain) allowable as shown in Equation 19.6-2. In other words, the residual static strength of the defective condition may be calculated using Equation 19.6-2. Another useful form is obtained by substituting Equation 19.6-1 into Equation 19.6-2 to obtain Equation 19.6-3. This equation allows calculation of the EOD margin of safety from the original "no defect" margin using the strength retention factor K_{EOD}. These equations have been written in generic form where the margin may be a load, stress or strain based calculation. The analyst must ensure that the design allowable accurately reflects the predicted failure mode at the critical design environmental condition.

Table 19.6-2 Commonly Used Margin of Safety Equations for EOD Residual Strength Analysis.

$M.S._{No\,Defect} = \dfrac{F_{allow}}{f_{des}} - 1$	**Equation 19.6-1**
$M.S._{EOD} = \dfrac{F_{allow} \bullet K_{EOD}}{f_{des}} - 1$	**Equation 19.6-2**
$M.S._{EOD} = \left(M.S._{No\,Defect} + 1\right) \bullet K_{EOD} - 1$	**Equation 19.6-3**

Where:
$M.S._{No\,Defect}$ = Margin of Safety for a pristine condition with no defect or damage.
F_{allow} = Allowable load, stress (or strain) at the design environmental condition.
f_{des} = Applied design load, stress (or strain) for a pristine condition with no defect or damage.
$M.S._{EOD}$ = Margin of Safety for a defective or damaged condition.
K_{EOD} = EOD Strength Retention Factor

Three common approaches to defining an EOD strength retention factor K_{EOD} are listed in Table 19.6-3 and are described below.

Table 19.6-3 Commonly Used Approaches to Defining K_{EOD} Strength Retention Factors.

Empirically Based	$K_{EOD} = K(d)$	**Equation 19.6-4**
Equivalent Damage	$K_{EOD} = \dfrac{F_{dam}}{F_{allow}}$	**Equation 19.6-5**
Damage Modeling	$K_{EOD} = \dfrac{f_{des}}{f_{dam}}$	**Equation 19.6-6**
Damage Modeling Based on Thickness Ratio	$K_{EOD} = \dfrac{t_{undam}}{t_{total}}$	**Equation 19.6-7**

Where:
$K(d)$ = Experimentally determined strength retention as a function of defect/damage parameter d.
d = Defect/damage characteristic parameter.
F_{dam} = Allowable stress (or strain) for an equivalent damage condition (for example: notched or DADT allowable).
F_{allow} = Allowable stress (or strain) at the design environmental condition.
f_{des} = Applied design stress (or strain) for a pristine condition with no defect or damage.
f_{dam} = Peak applied critical stress (or strain) for a defective or damaged condition.
$t_{undam} = t_{total} - t_{dam}$ = thickness of undamaged structural plies.
t_{dam} = thickness of damaged structural plies.
t_{total} = total thickness of laminate structural plies.

1.) Empirically Based

An empirical strength retention factor K_{EOD} is experimentally determined from coupon or element level tests that are designed to evaluate the effect of defect/damage on static strength for a given mode of failure. The defect/damage severity is usually quantified by a relevant parameter such as a characteristic dimension. The strength retention factor can often be expressed as design curves plotted as a function of the defect/damage parameter as described in Equation 19.6-4. Static strength tests are typically conducted at room temperature ambient conditions using the assumption that the design environment, e.g. hot/wet, is accounted for through the appropriate design allowable. This assumption should be verified by previous results or with a reduced set of specimens tested at the design environment. Any reduction in strength due to fatigue loading should also be verified by test.

2.) Equivalent Damage

The strength retention factor K_{EOD} is obtained analytically by representing the actual defect/damage by an equivalent damage state that can be characterized by an allowable. An equivalent damage allowable is an allowable strength for a damage condition that is considered equivalent to or more severe as compared to actual condition. For example, a planar delamination may be represented by equivalent sized impact damage that can be characterized by a durability or damage tolerance allowable as modeled by IDAT/CDADT analysis. For more minor damage, a notched allowable, such as for open or filled hole tension/compression strength, might be used to represent the defect/damage. The EOD strength retention factor K_{EOD} is determined from the ratio of the equivalent damage allowable to the pristine allowable for no defect/damage as shown in Equation 19.6-5.

3.) Damage Modeling Approach

The strength retention factor K_{EOD} is obtained by revising the original design strength analysis to account for the presence of the defect/damage. In this approach, the EOD strength retention factor K_{EOD} is calculated from a comparison of the peak applied stresses (or strains) as a ratio of the undamaged / damaged condition as given in Equation 19.6-6. Alternatively, the damage may be modeled as a reduction in effective stiffness or strength properties or by assuming the damaged laminate is totally ineffective. For example, a strength retention factor K_{EOD} for surface damage to a laminate may be obtained by the thickness ratio of undamaged / total plies as shown in Equation 19.6-7.

IDAT/SQ5, IBOLT and BEND analyses support a material review feature where the analysis can be run with plies removed from the top or bottom of the laminate (refer to Table 19.10-1). Bear in mind that this process may result in an asymmetric laminate where linear classical plate theory can over-predict the localized reduction in strength. In such cases, it may be appropriate to assume smeared laminate properties and simply ratio the stresses by the relative increase in laminate thickness as given in Equation 19.6-7.

For complex structural designs or defects/damage, a finite element analysis may be required to determine any resulting stress or strain concentrations.

Empirically based effects of defects data have been generated by Lockheed Martin for a number of composite material systems as part of aircraft development and IRAD test programs (References 19-16 through 19-20). The composite materials include:

- IM7/977-3 Carbon Epoxy Tape and Fabric
- IM7/5250-4 Carbon/Bismaleimide (BMI) Tape and Fabric
- IM8/8320 Radel Carbon/Thermoplastic Tape
- IM7/MTM45-1 Tape and Fabric

EOD test results from reference 19-16 were used to establish the acceptance criteria for LM Aero specification LMA-PC005 (19-9) for "Inspection, Acceptance Criteria, for Composite Parts and Assemblies." The LM test data has been used to create EOD design curves that are documented in (19-18, 19-19, and 19-20) and are presented in this section. As shown in Table 19.10-2 in and as described in this section, this EOD design data has been implemented, wherever applicable, into the IDAT analysis tools to support material review analysis. The exception is the IM7/MTM45-1 EOD curves which were recently released and have not yet been incorporated into the IDAT analysis toolset.

As future aircraft programs move to newer composite material systems, similar EOD design data should be developed and implemented into the IDAT analysis tools. In the interim, while the data trends for effects of defects may be similar for other toughened Epoxy and Bismaleimide thermoset composite material systems, the predictions should be used with caution until validation test data can be obtained.

19.6.1 Delaminations, Disbonds, Voids or Inclusions

A delamination, disbond, void and foreign material inclusion are each defined as follows:

- *Delamination* – A planar crack or separation that exists between adjacent plies or lamina within a composite laminate. The term delamination usually implies a force (or displacement) induced crack that has been introduced into the laminate after cure. The most common causes are by a surface impact with a foreign body or by an unanticipated overloading of the structure. Delaminations can also be caused by improper drilling processes (refer to Section 19.6.22.2 for treatment of delaminated fastener holes). These events might occur during manufacturing or while in-service. A delamination can occur at a single ply interface; or across multiple plies within the laminate. A delamination may be accompanied with localized matrix cracks and broken or splintered fibers, particularly if caused by an impact event. An impact may also produce a visible surface indentation or more severe damage characterized by broken fibers and even surface penetration. Impact damage is discussed further in Section 15.

- *Disbond* – A planar separation, empty space or gap within the bondline of an adhesively bonded joint. Disbonds are typically identified by post-cure non-destructive inspection. Disbonds are usually caused by a lack of film adhesive, failure of the film adhesive to bond (such as caused by poor surface preparation), or trapped gases during cure.

- *Void* – A planar separation, empty space or gap between adjacent plies or within a composite ply. Voids are typically identified as a distinct finite indication by post-cure non-destructive inspection. Voids that occur on a micro-level are referred to as porosity and are not usually detected as a distinct indication. Porosity is a treated separately as a unique type of defect in Section 19.6.7. A void usually implies a manufacturing related defect that arises during cure rather than a load or displacement induced event. Voids are usually caused by trapped gases or insufficient resin flow during cure. They are often associated with tooling misalignment, lack of pressure, local fiber bridging, or resin starved areas.

- *Inclusion* – A material inclusion is Foreign Object Debris (FOD) that has been inadvertently cured within a composite laminate and detected by post-cure non-destructive inspection. Common examples are chips, film separator backing paper, tape or other particles that are accidently embedded in the laminate.

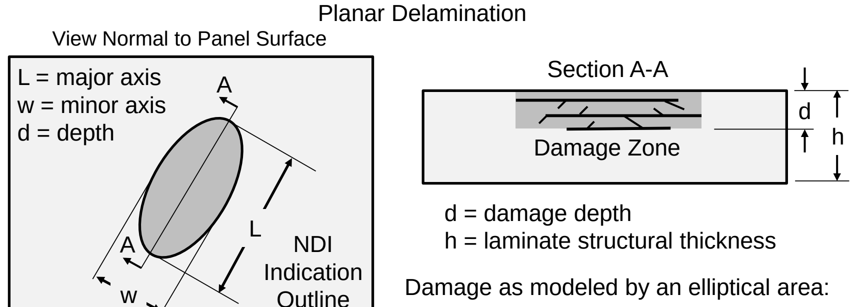
Whether induced during manufacturing or while in-service, delaminations, disbonds, voids and foreign material inclusions all may have a similar geometric appearance or indication when evaluated using non-destructive inspection. In the absence of corroborating data (witness of the damage event, visual surface indications, characteristic shape, etc.), the four types of defects may be indistinguishable from one another. As such, the definition herein of a delamination includes for analytical purposes, disbonds, voids and foreign material inclusions.

Delaminations are typically identified and characterized using an ultrasonic inspection or tap test. The defect image may be available electronically or outlined on the part using a pen. The defect boundary may contain a single continuous indication or a grouping of multiple indications. The delamination may be single layered or multi-layered. The inspector may be able to provide more details on the nature of the indication such as the depth positions of multiple delaminations. As stated in Section 19.6, Effects of Defects (EOD) tests were conducted on a legacy program to evaluate the effect of delamination in composite parts using either Kapton or Teflon inserts. Tests were conducted on specimens with single and multiple circular planar delaminations, edge delamination, and curved laminates with a delamination embedded in the corner radii. The remaining sub-sections address the following delamination types including those detected within bondlines (disbonds):

- Planar Delaminations
- Edge Delaminations
- Delaminations in Curved Laminate Sections
- Disbonds in Bonded Sandwich Construction
- Disbonds in Adhesively Bonded Joints

19.6.1.1 Planar Delaminations

Defect/Damage: PLANAR DELAMINATIONS



$$Area\,(ellipse) = \frac{\pi \bullet L \bullet w}{4}$$

Description:
An encapsulated delamination, void or foreign material inclusion that exists in the composite laminate interior away from fastener holes or free edges and whose maximum length or area exceeds acceptable inspection criteria limits.*

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9; or as otherwise specified by the engineering drawing.

Characterization:
A planar delamination is characterized by:

- Defect size (length x width) and/or area.
- Defect location and orientation
- Defect depth (when possible to determine)
- Defect type (delamination, void, foreign inclusion, porosity**).
- Acceptance class or criteria

** Porosity is addressed in Section 19.6.3.
The length measurement is oriented to capture the maximum dimension (major axis) and the width is measured perpendicular to that direction (minor axis).

Disposition and Repair Guidance:

- Planar delaminations in composites, whether from initial manufacturing, service, or maintenance induced, are capable of reducing the compressive static strength of the laminate.
- Cyclic loading is known to round out and extend delaminations. Residual strength is usually proportional to the effective thickness of the load carrying sublaminate.
- A planar delamination can be allowed to exist within a laminate provided that positive margins of safety are obtained for the EOD Residual Strength Analysis described below.
  - o Whenever feasible, a Delamination Repair Fastener should be installed as described in Section 19.8.6 to inhibit delamination growth. Any repair benefit in compression strength from fastener reinforcement must be supported by test results.
  - o Laminate surface damage should be sealed with a Resin Surface Repair (Section 19.8.11).
  - o Delaminations greater than 1.0 inch in length should be carefully reviewed to ensure that they are adequately represented by compression after impact data. Loads, geometry, through-thickness damage, existing test data and EOD margins should be all considered for acceptance.
- A more extensive repair should be considered for cases of severe damage that provides an alternate load path and possible removal of damage to prevent foreign object debris (FOD).

EOD Residual Strength Analysis:
The residual strength for an existing planar delamination can be determined using the analysis described in Table 19.6-4 for composite materials included in the IDAT material database (see materials listed in MATUTL). Alternatively, use the analysis described in Table 19.6-5 for composite materials not included in the IDAT material database. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Table 19.6-4 EOD Residual Strength Analysis for Planar Delaminations (for IDAT materials).

1. **Damage Tolerance Strength Check**

   Evaluate the delamination as a dimensionally equivalent impact damage area using IDAT/CDADT.

   a) Calculate a delamination area based on a circular configuration assuming that the delamination rounds out under cyclic loading (Note: Use engineering judgment to calculate the area for a narrow delamination).

   $$A = \frac{\pi \bullet L^2}{4} \qquad \textbf{Equation 19.6-8}$$

   Where:

   A = Delamination area, in.^{2}

   L = Delamination length (major axis or maximum dimension), in.

   b) Enter into CDADT the laminate design properties at the critical design environmental condition.

   c) Select Criticality as "Fracture Critical Criteria", Special Threats as "Damage Area", and enter the "Damage Area Value (in^2)" calculated in Step a.

   d) Run CDADT analyses for the most critical Design Ultimate Load cases to obtain margins of safety for Compression After Impact (CAI) and Tension After Impact (TAI) strengths. These load cases should include cases for maximum and minimum principal loads.

2. **Residual Unnotched Compression Strength Check**

   a) Calculate a strength retention factor K_{EOD} using Equation 19.6-7 with the thickness ratio of the undamaged sub-laminate thickness to the total laminate thickness.

   b) Calculate the margin of safety using Equation 19.6-2 using the unnotched compression strength allowable (stress or strain, from IDAT/MATUTL) at the critical design environmental condition. (Note: IDAT/SQ5 analysis may be used with Equation 19.6-3 for complex load conditions).

3. **Minimum Margin of Safety**

   Use the lower margin of safety from either Step 1 or 2.

Reference notes:

1. CDADT User's Guide.
2. Section 15, Durability and Damage Tolerance.

Table 19.6-5 EOD Residual Strength Analysis for Planar Delaminations (for non-IDAT materials).

1. **Damage Tolerance Strength Check**

   Evaluate the laminate strength using an open hole compression strength allowable at the critical design environmental condition.

   $$M.S._{EOD} = \frac{F_{OHCS}}{f_{des}} - 1 \qquad \textbf{Equation 19.6-9}$$

   Where:

   F_{OHCS} = 0.25 in. open hole compression allowable (stress or strain).

   f_{des} = design stress (or strain) with no defects or damage.

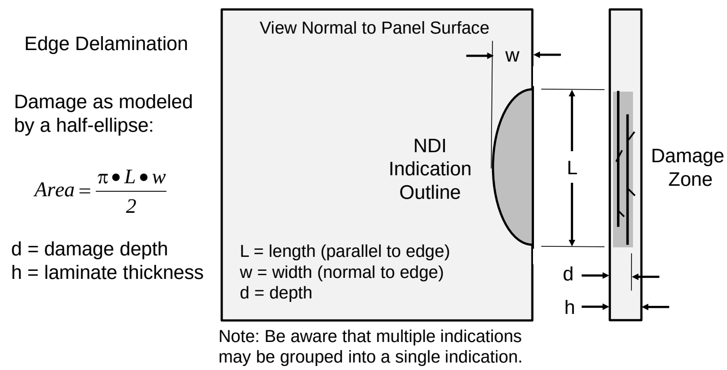
2. **Residual Unnotched Compression Strength Check**

   Same as Step 2, Table 19.6-4.

3. Use the lower margin of safety from either Step 1 or 2.

19.6.1.2 Edge Delaminations

Defect/Damage: EDGE DELAMINATIONS



Description:
A delamination, void or foreign material inclusion that exists along a free edge of a laminated panel, cutout or other design detail whose maximum length or area exceeds acceptable inspection criteria limits.* An edge delamination is commonly caused by an edge impact that can occur during manufacture or in-service.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9; or as otherwise specified by the engineering drawing.

Characterization:
An edge delamination is characterized by:

- Defect size (length x width) and/or area.
- Defect location and orientation
- Defect depth (when possible to determine)
- Defect type (delamination, void, foreign inclusion, porosity**).
- Acceptance class or criteria

** Refer to Section 19.6.3 for porosity.

Disposition and Repair Guidance:

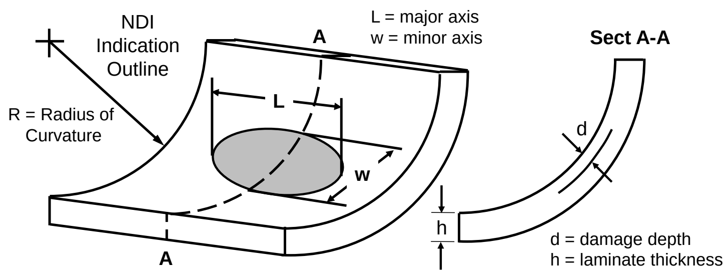
- EOD static strength tests (19-16, 19-18) for edge delaminations ranging in length from 1.3 to 2.2 inches and in width from 0.3 to 0.4 inches have shown:
  - An edge delamination can reduce unnotched compression strength by almost 40%.
  - A Resin Injection Repair (Section 19.8.7) can reduce the unnotched compression strength reduction by half; however, the strength benefit shall not be accounted for due to process variability.
  - The clamping effect of a Delamination Repair Fastener (Section 19.8.6) of an edge delamination can retain the notched strength capability of the laminate.
  - K_{EOD} strength retention factors have been implemented into IDAT/SQ5 and BEND analyses as an edge delamination manufacturing defect option for unnotched compression strength:
    - $K_{EOD} = 0.62$ is used for an Unrepaired Edge Delamination; and
    - $K_{EOD} = 0.81$ is used for a Resin Injection Repair (not recommended due to process variability).
- Disposition and repair is dependent upon the defect/damage geometry and laminate design details.
  - A Resin Injection Repair (19.8.7) is recommended to seal the edge and eliminate moisture intrusion. Any strength benefit must be neglected by analysis. Small pilot holes may be used to facilitate and bear witness to injection flow for delaminations that extend beyond 1.0 inch from the edge.
  - A Delamination Repair Fastener (19.8.6) is recommended to recover notched compression strength capability. Existing blueprint fasteners may be used and should be supplemented for delaminations that extend 1.0 inch beyond the fastener line. For larger scale edge delamination, engineering judgment may be required for a more complicated repair with an alternate load path.
  - Highly loaded laminates designed to unnotched strength (such as beams, stiffeners) would require a reinforcement Doubler or Fitting Repair (19.8.16, 19.8.17, 19.8.19) that provides an alternate load path.
  - For edge impacts with surface damage, a Blend and Smooth Repair (Section 19.8.10) followed by a Resin Filler Repair (Section 19.8.12) may be required to restore contour and address FOD risk.

EOD Residual Strength Analysis:
Recommendation is to REPAIR using Resin Injection (19.8.7) and Delamination Repair Fasteners (19.8.6).

19.6.1.3 Delaminations in Curved Laminate Sections

Defect/Damage: DELAMINATIONS IN CURVED LAMINATE SECTIONS

Delamination in a Curved Laminate Section



Damage as modeled by an elliptical area:

$$Area\,(ellipse) = \frac{\pi \bullet L \bullet w}{4}$$

Description:
A delamination, void or foreign material inclusion that exists within the plies of a curved or cylindrical laminate section whose maximum length or area exceeds acceptable inspection criteria limits.*

Acceptance limits are dependent upon the part inner radius of curvature (whether above or below 1.0 in).

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9; or as otherwise specified by the engineering drawing.

Characterization:
A delamination in a curved section is characterized by:

- Defect size (length x width) and/or area.
- Defect location, orientation and part radius
- Defect depth (when possible to determine)
- Defect type (delamination, void, foreign inclusion, porosity**).
- Acceptance class or criteria

** Refer to Section 19.6.3 for porosity.

Disposition and Repair Guidance:

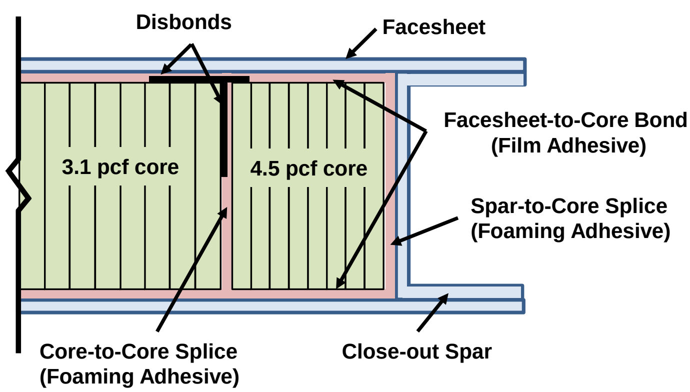
- EOD static strength tests (19-16, 19-18) for Angle Bend test specimens with simulated delaminations (R = 0.25 in., mid-plane delaminations of various dimensions) have shown:
  - Delaminations reduce interlaminar tension strength.
  - Test results indicate that delamination can reduce interlaminar tension strength by 60%.
  - K_{EOD} strength retention factors have been implemented into IDAT/BEND analysis as a corner delamination manufacturing defect option for interlaminar tension strength:
    - $K_{EOD} = 0.40$ for a delamination that extend up to 25% of part length; and
    - $K_{EOD} = 0.37$ for a delamination that extend 25% or greater of part length

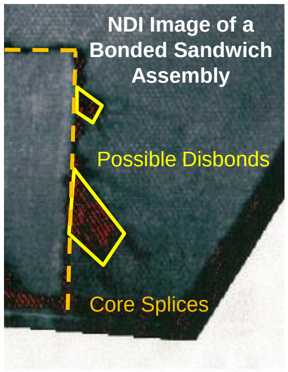
      Where part length is the dimension normal to the plane of curvature.
- Disposition and repair is highly dependent upon the specific laminate design details and loading.
  - A Resin Injection Repair (19.8.7) can be used for delaminations that extend to an accessible edge, but no strength benefit may be accounted for since the process is variable and the effectiveness indeterminate.
  - Due to the narrow range of test results, a USE-AS-IS disposition is only allowed for laminates with delaminations up to 25 % of the part length, not to exceed 1.0 inch in length, and provided that the positive margins are obtained for the EOD residual strength analysis.
  - Delaminations in corner radii are typically repaired by providing reinforcement and an alternate load path, such as with a nested Doubler Repair or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19).

EOD Residual Strength Analysis:
As described above, the effect of a corner radii delamination has been implemented into the IDAT/SQ5 and BEND analyses. The test data is limited to laminates with inner radius = 0.25 in., so the applicability of the derived factors for EOD residual strength is limited. Additional tests would be required to evaluate delaminations for other radii. Axial compression loads acting in the direction of the part-length should be checked for sub-laminate buckling using column stability.

19.6.1.4 Disbonds in Bonded Sandwich Construction

Defect/Damage: DISBONDS IN BONDED SANDWICH CONSTRUCTION





Description:
A disbond or void that exists within a bondline of a bonded sandwich assembly whose maximum length or area exceeds acceptable inspection criteria limits.*
Disbonds or voids may occur at:

- Core-to-facesheet (film adhesive)
- Core-to-core splice (foam adhesive)
- Core-to-substructure splice (foam adhesive)

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9; or as otherwise specified by the engineering drawing.

Characterization:
A bondline delamination is characterized by:

- Defect size (length x width) and/or area.
- Defect location and orientation
- Defect type (delamination, void, foreign inclusion, porosity**).
- Acceptance class or criteria

** Refer to Section 19.6.3 for porosity.

Disposition and Repair Guidance:

- Disbonds up to equivalent area of a 2.0” diameter disbond may be repaired using Resin Injection (Section 19.8.8) provided that positive margins of safety are obtained for the EOD Residual Strength Analysis. No analytical strength benefit for the Resin Injection Repair is accounted for since the process is variable and the effectiveness indeterminate (Figure 19.6-1).
- If positive margins are not obtained from EOD residual strength analysis, then an extensive repair is required whereby a local section of facesheet is removed and the defective area is repaired using a combination (19.8.18) of Honeycomb Core (19.8.14), Flush Scarf (19.8.15), and/or Doubler Repairs (19.8.16, 19.8.17).

EOD Residual Strength Analysis:

- Recommended disposition is to REPAIR. For Core-to-Facesheet disbonds, the analyses described in Table 19.6-6 should be performed to determine the type of repair to be implemented (Resin Injection versus Structural Repair). For core splice disbonds in Core-to-Core or Core-to-Substructure joints, the analyses described in Table 19.6-7 should be performed to determine the type of repair to be implemented (Resin Injection versus Structural Repair).

Table 19.6-6 EOD Residual Strength Analysis for Core-to-Facesheet Disbonds.

1. **Facesheet Stability Check**
   A conservative buckling check of the disbonded facesheet is made assuming simple supported boundary conditions on all edges and under the most critical case of design ultimate NX, NY, and NXY running loads (Refer to Figure 19.6-2 and Figure 19.6-3). Use IDAT/SO0 for flat panels or IDAT/SS8 for curved panels.
2. **Facesheet Interlaminar Shear Strength Check**
   The facesheet interlaminar strength must be checked to account for any increase in interlaminar shear stress due to loss of core support using an IDAT/SQ5 Interlaminar Shear Strength analysis. The transverse shear running load should be equally divided between the two facesheets.
3. **Core Shear Strength Check Accounting for Disbonded Area**
   a) Find the edge closest to the disbond and use 2x that edge distance to calculate the bond width. If the width is greater than 12 inches, use 12 inches as your width.
   b) Calculate a strength retention factor:

   $$K_{EOD} = (W - D) / (1.1 \bullet W) \qquad \text{Equation 19.6-10}$$

   W = Assumed bond width
   D = Disbond length
   1.1 = Empirical stress concentration factor based on Legacy Data (Figure 19.6-4).

   c) Calculate an EOD margin of safety using Equation 19.6-2 or Equation 19.6-3.
4. **Minimum Margin of Safety**
   Use the lower margin of safety from Step 1, 2 or 3.

Reference notes:
1. SQ5 User's Guide.

Table 19.6-7 EOD Residual Strength Analysis for Core Splice Disbonds.

1. **Facesheet Interlaminar Shear Strength Check**
   The facesheet interlaminar strength must be checked to account for any increase in interlaminar shear stress due to loss of core support using an IDAT/SQ5 Interlaminar Shear Strength analysis. The transverse shear running load should be equally divided between the two facesheets.
2. **Core Splice Shear Strength Check Accounting for Disbonded Area**
   a) Find the edge closest to the disbond and use 2x that edge distance to calculate the bond width. If the width is greater than 12 inches, use 12 inches as your width. As an alternative, the splice bond length may be used.
   b) Calculate a strength retention factor:

   $$K_{EOD} = (W - D) / (1.2 \bullet W) \qquad \text{Equation 19.6-11}$$

   W = Assumed bond width
   D = Disbond length
   1.2 = Assumed stress concentration factor for core splice disbonds.

   c) Calculate an EOD margin of safety using Equation 19.6-2 or Equation 19.6-3.
3. **Minimum Margin of Safety**
   Use the lower margin of safety from Step 1 or 2.

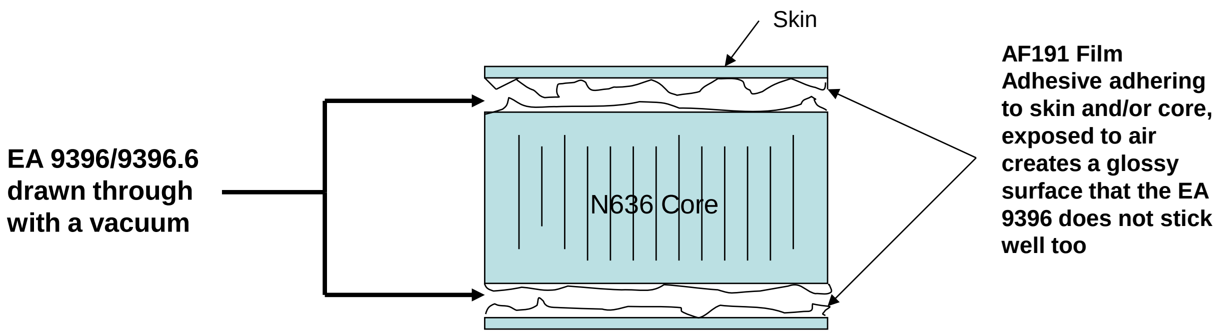


Figure 19.6-1. Core-to-Facesheet Disbond Resin Injection Repair.

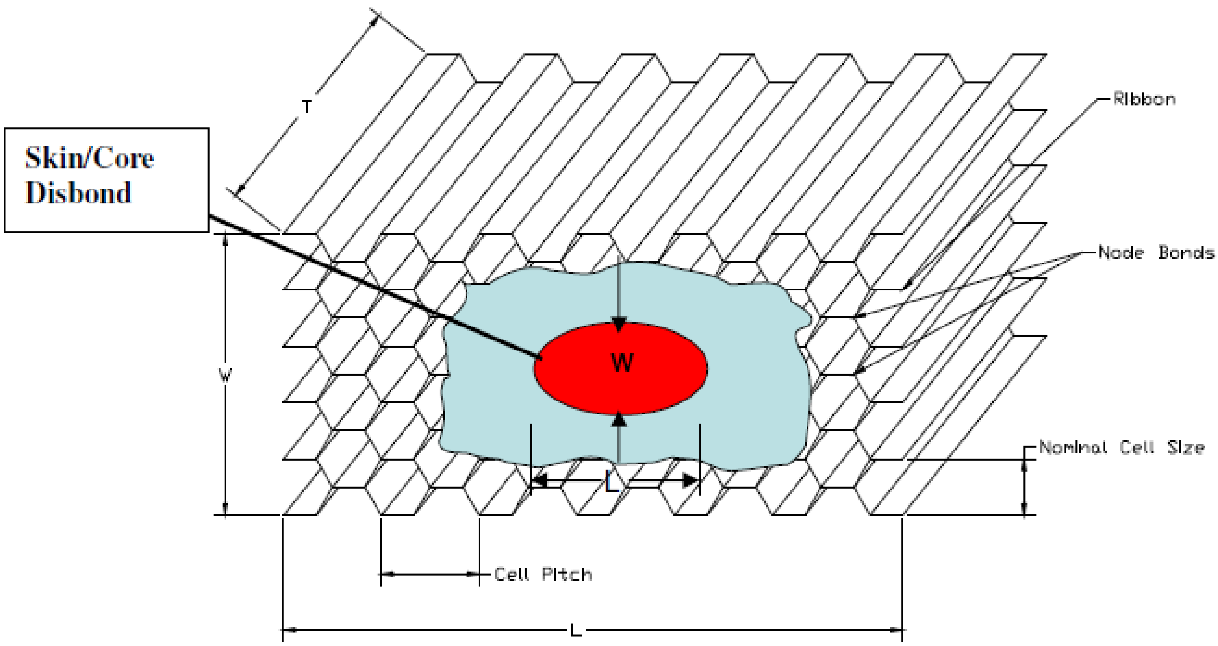


Figure 19.6-2. Core-to-Facesheet Disbond.

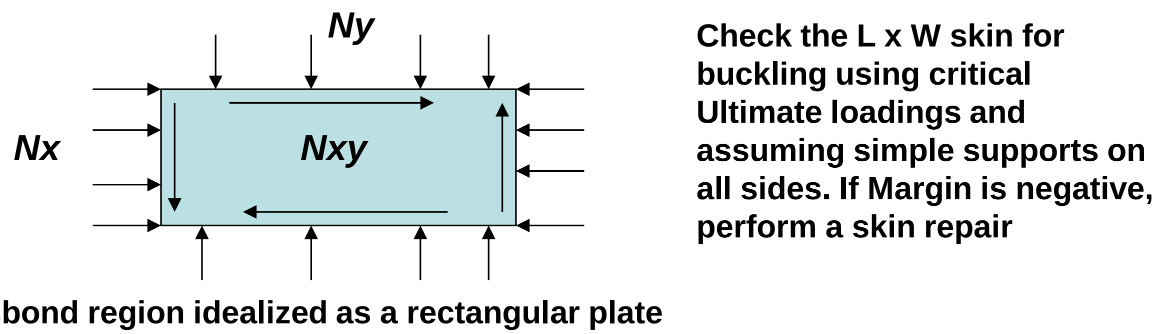


Figure 19.6-3. Core-to-Facesheet Disbond Idealized as a Rectangular Laminated Plate.

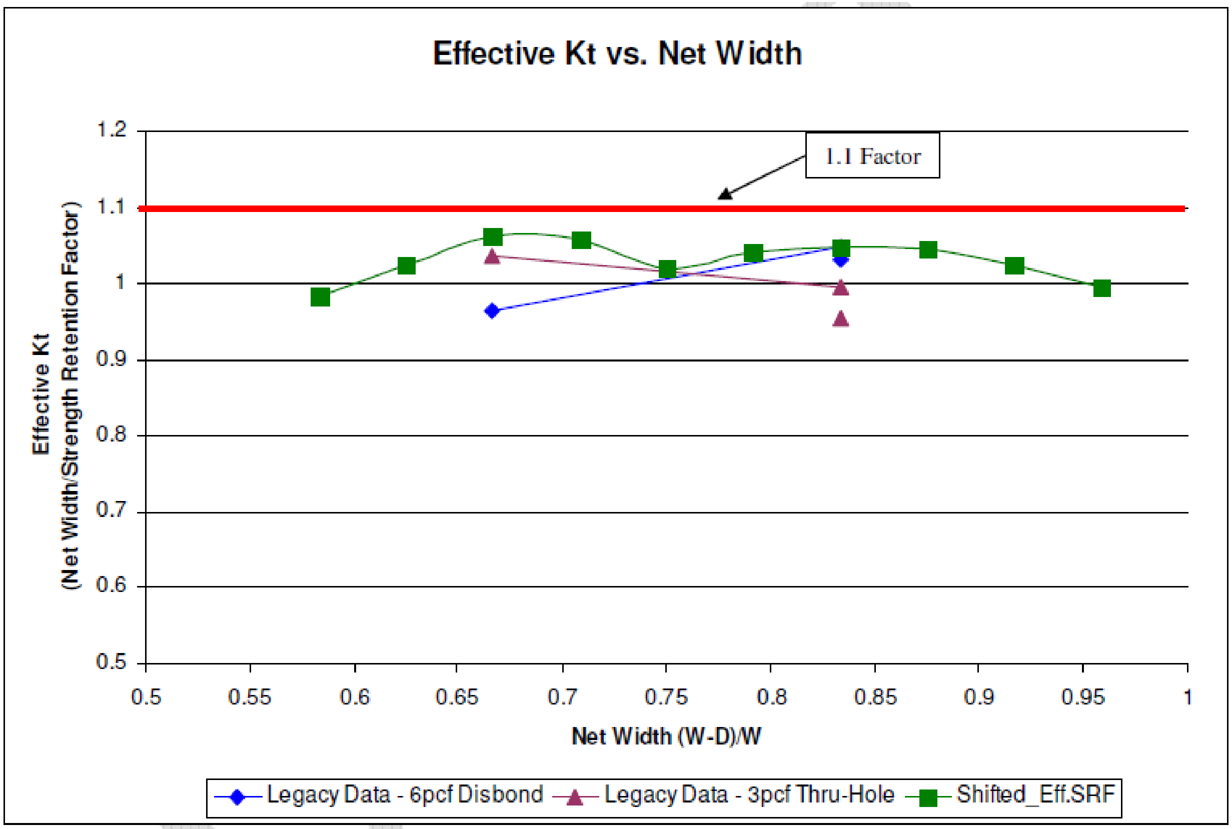
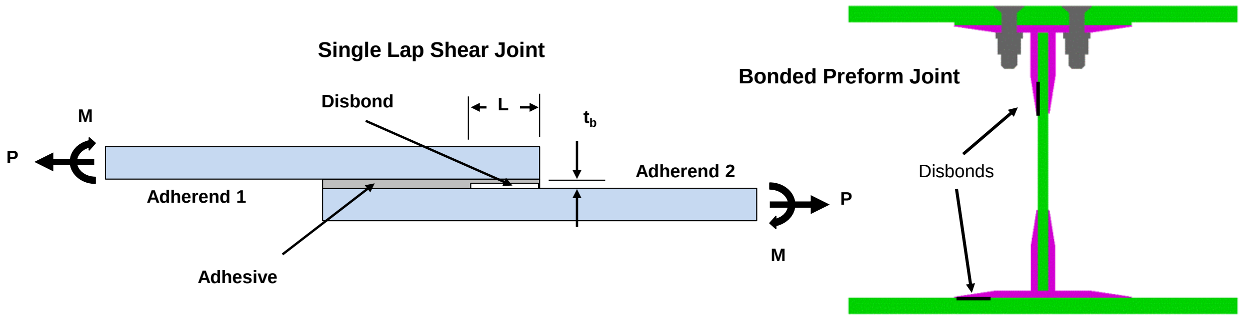


Figure 19.6-4. Effective Stress Concentration Factor versus Net Section Width.

19.6.1.5 Disbonds in Adhesively Bonded Joints

Defect/Damage: DISBONDS IN ADHESIVELY BONDED JOINTS



Description:
A delamination, void or foreign material inclusion that exists within a bondline of a bonded joint whose maximum length or area exceeds acceptable inspection criteria limits.*

A typical bondline thickness may vary from 0.003 to 0.015 in. The term bondline may be generally used to describe composite details that have been co-cured, co-bonded or secondarily bonded together (refer to Section 12 Bonded Joints for more background information).

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9; or as otherwise specified by the engineering drawing.

Characterization:
A bondline delamination is characterized by:

- Defect size (length x width) and/or area.
- Defect location and orientation
- Defect depth (when possible to determine)
- Defect type (delamination, void, foreign inclusion, porosity**).
- Acceptance class or criteria

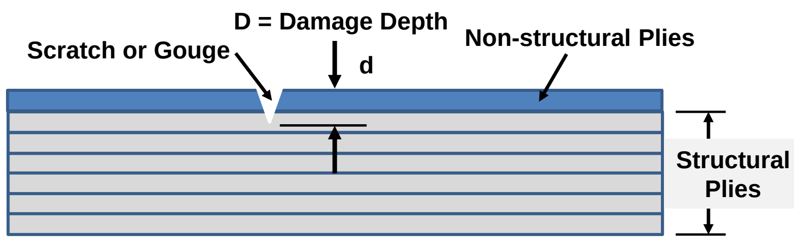
** Refer to Section 19.6.3 for porosity.

Disposition and Repair Guidance:
- In general, the recommended disposition is to repair the delamination using Resin Injection Repair (Section 19.8.9) and a Delamination Repair Fastener (Section 19.8.6) where the fasteners transfer tension and shear loads across the bondline.
- Metallic fittings such as radius blocks (Section 19.8.19) may also be installed if a larger area of through-thickness reinforcement is required. For complicated joint geometries and load transfer, the installation of specially designed metallic fittings may be required.
- The installation of metallic fittings will require a galvanic barrier between the composite outer surface.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

19.6.2 Surface Scratches or Gouges

Defect/Damage: SURFACE SCRATCHES OR GOUGES



Description:
Marking, breaking or cutting of a part outer surface with a sharp or pointed object. This includes scrapes, scuffs, gouges or lacerations on part surfaces.

Surface scratches which penetrate only the surface resin or peel plies are usually acceptable. Surface scratches which penetrate into or damage structural fibers are not acceptable.*

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
A scratch or gouge is characterized by:

- Defect dimensions
- Defect location and orientation
- Maximum depth
- Defect type (scratch, gouge, etc.)

Surface scratches may indicate that an impact event has occurred, especially if the scratch is more than one ply deep. A non-destructive inspection should be conducted to evaluate for internal laminate damage. If an unacceptable delamination is identified, then evaluate the delamination separately per Section 19.6.1.

Disposition and Repair Guidance:

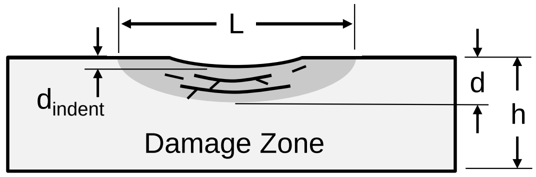
- The recommended disposition is to repair all nonconforming scratches or gouges. The method of repair is dependent on the severity (size and maximum depth) of the defect and its location within the structure.
- Scratches or gouges that are treated with a resin surface or filler repair are usually left "as is" unless loose material needs to be removed with light sanding or a Blend and Smooth Repair (19.8.10) touch up.
- Surface scratches or gouges that are 1 or 2 plies deep may be repaired with a Resin Surface Repair (Section 19.8.11) to restore the surface finish and seal any cut fibers provided that the positive margins are obtained for the EOD residual strength analysis.
- More extensive scratches or gouges deeper than 1 or 2 plies may be repaired with a Resin Filler Repair (Section 19.8.12) provided that the positive margins are obtained for the EOD residual strength analysis.
- If EOD residual strength analysis cannot show a sufficient strength margin, then a Doubler or Metallic Fitting (Sections 19.8.16, 19.8.19) may be required to provide an alternate load path and restore design ultimate load capability.
- Surface scratches or gouges can have a serious effect on thin laminates or laminates designed to unnotched strength. These situations may also require a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) to provide an alternate load path.

EOD Residual Strength Analysis:
Scratches or gouges should be checked using a strength retention factor K_{EOD} based on the ratio of undamaged to total laminate thickness as given by Equation 19.6-7. IDAT/SQ5 analysis may be used for bending cases where damaged plies may be discounted.

For deep gouges, engineering judgment should be used to evaluate whether a notched laminate strength check (using equivalent damage approach) is sufficient to demonstrate adequate residual strength for the presence of the defect.

19.6.3 Surface Dents

Defect/Damage: SURFACE DENTS



Surface Dent

d_{indent} = surface indentation depth
d = total damage depth
h = laminate structural thickness
L = damage zone length

Non-destructive inspection is required to evaluate internal damage.

Description:
Surface dents or depressions are unacceptable if the maximum depth exceeds 5% of the panel thickness or 0.005 inches.*

Surface dents can be caused by:
- A foreign material on the tool or bag surface
- An impact event

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
A surface dent or depression is characterized by:

- Defect dimensions
- Defect location and orientation
- Maximum depth
- Defect description (impact, fabrication issue, etc.)

Fabrication related surface dents or depressions, like waviness, can cause ply distortion through the thickness. If the distortion depth cannot be determined, use a conservative estimate.

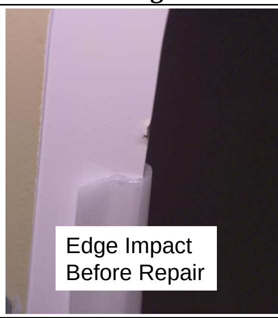
Suspected surface impacts must be non-destructively inspected to determine if there are any delaminations or other detectable damage.

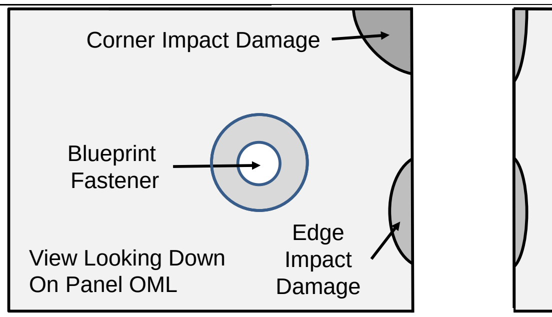
Disposition and Repair Guidance:
- Fabrication related surface dents or depressions must be treated per guidance for Waviness or Wrinkles (Section 19.6.9).
- Unacceptable delaminations must be treated per guidance for Planar Delaminations (Section 19.6.1.1).
- Surface dents that are 1 or 2 plies deep may be repaired with a Resin Surface Repair (Section 19.8.11) to restore the surface finish and seal any cut fibers provided that the positive margins are obtained for the EOD residual strength analysis.
- Surface dents deeper than 1 or 2 plies may be repaired with a Resin Filler Repair (Section 19.8.12) provided that the positive margins are obtained for the EOD residual strength analysis.
- If EOD residual strength analysis cannot show a sufficient strength margin, then a Doubler or Metallic Fitting (Sections 19.8.16, 19.8.19) may be required to provide an alternate load path and restore design ultimate load capability.
- Surface dents can have a serious effect on thin laminates or laminates designed to unnotched strength. These situations may also require a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) to provide an alternate load path.

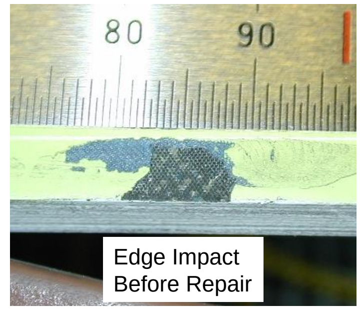
EOD Residual Strength Analysis:
- Cosmetic repairs such as a Resin Surface Repair (Section 19.8.11) or a Resin Filler Repair (Section 19.8.12) should be checked using a strength retention factor K_{EOD} based on the ratio of undamaged to total laminate thickness as given by Equation 19.6-7. IDAT/SQ5 analysis may be used for bending cases where damaged plies may be discounted.

19.6.4 Edge of Part Damage

Defect/Damage: EDGE OF PART DAMAGE







Description:
This defect refers to damage along laminate edges or at corners usually caused by an impact event. Edge/corner impact damage may include:

- Edge/corner delaminations
- Crushed and/or dented surface
- Broken or splintered surface fibers
- Missing portions of laminate

A given part may be judged unacceptable based on acceptance criteria* or for an out-of-tolerance condition with respect to the engineering drawing.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
Edge of Part Damage is characterized by:

- Defect dimensions (length, width)
- Maximum depth
- Defect location and orientation
- Defect type (scratch, gouge, etc.)

Edge/corner impacts must be non-destructively inspected to determine if there are any delaminations or other detectable damage.

Disposition and Repair Guidance:

- Surface damage or dents can be repaired by Resin Surface (19.8.11) or Resin Filler (19.8.12) repair provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- As appropriate, additional Blend & Smooth or Trim Repairs (Section 19.8.10) to clean up the edge or prepare the part for subsequent repair actions.
- Edge delaminations must be treated by guidance per Section 19.6.1.2.
- A Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.18) may be required to restore design ultimate load capability by providing an alternate load path.

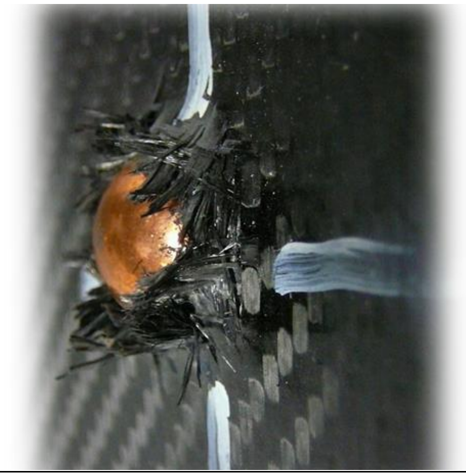
EOD Residual Strength Analysis:

- Edge of part damage that results in a fastener hole short edge distance must be checked per section 19.6.15.
- Laminate edge damage that results in a stress concentration must be checked using the Damage Modeling Approach per Section 19.6.
    - Damaged material must be considered as 100% ineffective and loads must be carried by the undamaged portion of the laminate.
    - For complex geometry, a local finite element analysis may be required with the out-of-tolerance features modeled to determine the maximum stress (or strain) concentration that is induced by the nonconformance.
    - Laminate strength may be evaluated using a point stress (or strain) criterion where the stress is evaluated at a characteristic distance removed from the peak stress (or strain) along the free edge. The un-notched strength (or strain) allowable is used at the design environmental condition (refer to Equation 19.6-6).
    - For displacement based finite element methods such as NASTRAN, a very fine mesh is usually required to obtain an accurate converged stress (or strain) solution.

19.6.5 Laminate Penetrations Due to Impact

Defect/Damage: LAMINATE PENETRATIONS DUE TO IMPACT

Ballistic Impact Damage On Composite Laminates



Description:
This defect refers to a severe impact event that causes a through penetration of the laminate. The risk of through penetration damage is usually limited to thin solid laminate or thin facesheets on bonded sandwich honeycomb core structure.

A given part may be judged unacceptable based on acceptance criteria* or for an out-of-tolerance condition with respect to the engineering drawing.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
A laminate through thickness penetration is characterized by:

- Defect dimensions (Diameter)
- Maximum damage depth (sandwich)
- Defect location and orientation
- Maximum depth

A non-destructive inspection should be conducted to evaluate for delaminations and the extent of internal laminate damage.

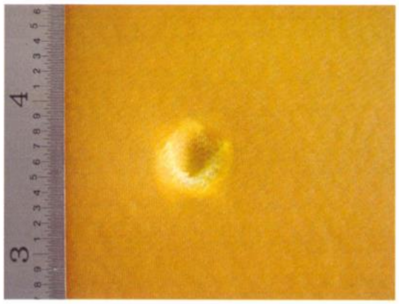
Disposition and Repair Guidance:
- Planar delaminations in solid laminates must be treated by guidance per Section 19.6.1.1.
- Disbonds in bonded sandwich construction must be treated by guidance per Section 19.6.1.4.
- Solid laminates with damage up to 0.5 inches in diameter may be repaired by drilling out the damage and using a Resin Filler Plug Repair (19.8.13) provided that the positive margins are obtained for open hole strength.
- Solid laminate with damage larger than 0.5 inches in diameter must be repaired using a Flush Scarf (19.8.15) and/or Doubler Repair (19.8.16, 19.8.17) as required to restore design ultimate load capability.
- Honeycomb core sandwich structure must be repaired using combinations of Honeycomb Core (19.8.14), Flush Scarf (19.8.15), and/or Doubler Repairs.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

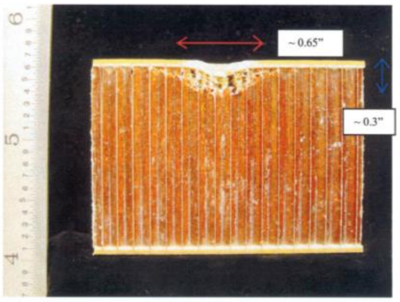
19.6.6 Honeycomb Core Structural Defects or Damage

Defect/Damage: HONEYCOMB CORE STRUCTURAL DEFECTS OR DAMAGE

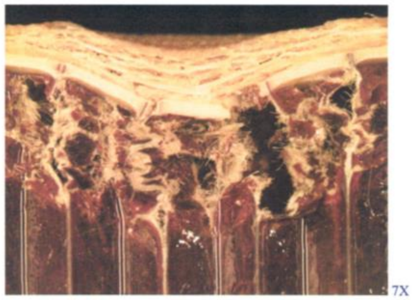
Impact Damage (View Down)



Through Thickness View



Facesheet/Core Damage



Description:
Honeycomb core structural defects/damage that may be identified through non-destructive inspection include:*

- Node bond separations
- Condensed/collapsed core
- Distorted core
- Blown core
- Buckled/crushed core
- Core splice or core closeout cracks
- Foaming adhesive bondline intrusion
- Potting irregularities
- Resin or foam filled cells

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
Honeycomb core structural defects/damage are characterized by:

- Defect dimensions
- Defect location
- Defect type

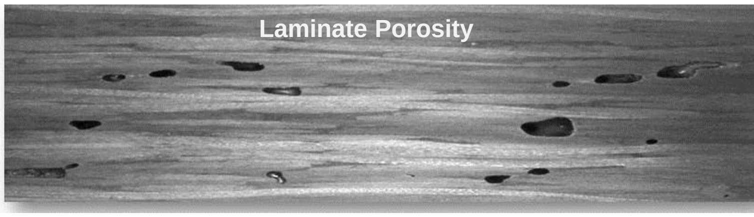
Ultrasonic and radiographic inspection techniques are used for evaluation of honeycomb core sandwich bonded construction. All cracks that are detected by radiographic techniques are rejected except where allowed in core/close-out structure splices and potted/resin filled core cells.

Disposition and Repair Guidance:
- Cracks, gaps, or separations must be treated as disbonds in bonded sandwich construction following the guidance provided in Section 19.6.1.4.
- An extensive repair whereby a local section of facesheet is removed and the defective area is repaired using combinations of Honeycomb Core (19.8.14), Flush Scarf (19.8.15), and/or Doubler Repairs (19.8.16, 19.8.17).

EOD Residual Strength Analysis:
- Recommend disposition is to REPAIR.

19.6.7 Porosity

Defect/Damage: POROSITY



Description:
Porosity is the presence of small voids, gas pores or air pockets within the matrix, and/or bondline of a laminate or bonded panel that exceeds the maximum allowable limits.* This condition can be distributed through–the–thickness (scattered or multi–layered porosity), in discrete layers (laminar porosity), or linearly (line void).

The principal causes of porosity in Epoxy and Bismaleimide (BMI) composite laminates are: 1) localized areas of reduced curing pressure caused by tooling variability; 2) entrapped air and volatiles; and 3) low resin content. Others factors such as humidity and altered cure cycles are less likely to cause significant porosity. Porosity will begin to impact structural strength when the void content exceeds 1.5%.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9. Ultrasonic techniques used for evaluating porosity:

- Pulse Echo (PE)
- Broadband Through Transmission (BTTU)
- Narrowband Through Transmission (NTTU)

Characterization:
Porosity is detected and measured using ultrasonic non-destructive inspection (NDI) techniques. Sound wave attenuation (decibel, *dB*) for the target laminate ($dB_{porosity}$) is compared with that for a pristine reference laminate ($dB_{pristine}$) with known low void content. The values are dependent on NDI technique and transducer frequency. The relative attenuation is given by:

$$\Delta dB = dB_{porosity} - dB_{pristine} \qquad \text{Equation 19.6-12}$$

Porosity is characterized by:

- Defect size (length x width) or area.
- Defect location and orientation
- Defect depth (when possible to determine)
- Defect type (porosity)
- Acceptance class or criteria
- Panel thickness
- Relative attenuation (ΔdB), range (min. - max.)
- Ultrasonic technique (PE, BTTU or NTTU)
- Transducer frequency (5 or 2.25 MHz)

Disposition and Repair Guidance:

- A composite part with porosity can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- EOD tests were conducted on a legacy program (19-16, 19-18) to determine the effect of porosity on laminate strength. The results are described later in this section and have been incorporated in the IDAT toolset.
- A composite part with surface porosity can be used as is if no dry fibers are exposed. Dry surface plies can be sealed with a Resin Surface Repair (Section 19.8.11) provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- Severe localized porosity or voids can often be repaired with a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) that provides an alternate load path.
- A composite part with severe widespread porosity should be SCRAPPED.

EOD Residual Strength Analysis:
The effect of porosity on laminate strength can be determined using the IDAT manufacturing defect tools described in Table 19.6-9. The effect may also be calculated using the strength retention factors from Figure 19.6-5 and Figure 19.6-6 using Equation 19.6-2 or Equation 19.6-3. Porosity that can be confirmed as existing only near the surface may be evaluated using Equation 19.6-7. Positive margins of safety are required for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Effect of Porosity on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of porosity on laminate strength. Strength retention factor K_{EOD} as a function of Porosity Ratio is plotted in Figure 19.6-5 for carbon fiber laminates and in Figure 19.6-6 for S2 glass fiber laminates. The curves may be used for Epoxy and Bismaleimide (BMI) resin solid laminates composed of tape or fabric. As shown in the figures, laminate porosity has a degrading impact on compression strength (unnotched, filled hole, open hole), bearing strength, and interlaminar strength (tension, shear). Porosity is assumed to have no effect on in-plane tension strength. Porosity Ratio (dB/in$^{1/2}$) is a scalar measure of the relative porosity of a laminate and is defined as:

$$Porosity\ Ratio = C\frac{\Delta dB}{\sqrt{t}}$$ **Equation 19.6-13**

Where:
C = Normalization factor based on ultrasonic technique.
ΔdB = Relative sound wave attenuation, dB.
t = Nominal thickness of the laminate, in.

The normalization factors for typical ultrasonic inspection techniques are shown in Table 19.6-8. The normalization factor is a function of the distance traversed by the attenuated sound wave. C = 1 for PE and NTTU techniques since the sound wave is reflected and the attenuated wave travels twice the distance. In contrast, C = 2 for the BTTU technique where the attenuated sound wave traverses the path only once. Surface porosity will attenuate sound waves but it is not considered to affect the strength as long as it is confined to the surface.

Table 19.6-8 Normalization Coefficient C for Typical Ultrasonic Techniques.

Technique	Ultrasonic Technique	C
1	Pulse-echo (PE)	1.0
2	Narrowband Thru-Transmission (NTTU)	1.0
3	Broadband Thru Transmission (BTTU)	2.0

Figure 19.6-5 and Figure 19.6-6 are valid for laminate nominal thicknesses between a single ply to 0.75 in. A carbon fiber solid laminate with a porosity ratio less than 32 $\Delta dB/\sqrt{in}$ retains 100% of its allowable strength. As shown, S2 fiber solid laminate is unaffected by a higher level of porosity as compared to carbon fiber solid laminate. These design curves have been implemented into MRB tools available within the IDAT analysis tools as described in Table 19.6-9. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-9 IDAT Analysis of Porosity Effects on Allowable Strength.

IDAT Analysis	Compression	Bearing	Interlaminar Tension	Interlaminar Shear
SQ5	UNC			ILS
IBOLT	UNC, FHC, OHC	BCT, BCC, BCS		
BEND	UNC		ILT	ILS

IDAT Manufacturing Defect Analysis
1. Select … Main Menu/Tools/MRB Tools/Manufacturing Defects/Porosity
2. Enter: Ultrasonic Test System
   a. Pulse-Echo
   b. Narrow-Band Thru Transmission (NTTU)
   c. Broad Band Thru Transmission (BTTU)
3. Enter: Relative Attenuation delta dB

EOD tests (19-19, 19-20) have also been completed recently on an Out-of-Autoclave 250 °F Cure material system, IM7/MTM45-1 (Refer to Section 19.7.3.2). Effects of porosity curves for Tape and Fabric are provided in Figure 19.6-7 and Figure 19.6-8, respectively.

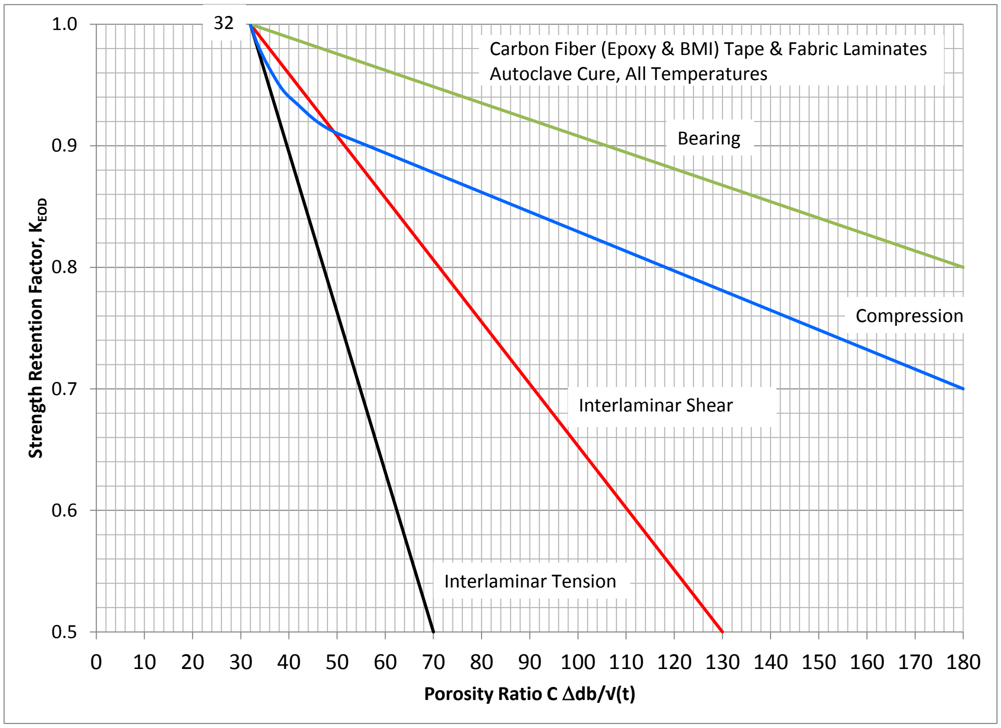


Figure 19.6-5. Effect of Porosity on Carbon Fiber Composites (Epoxy and BMI).

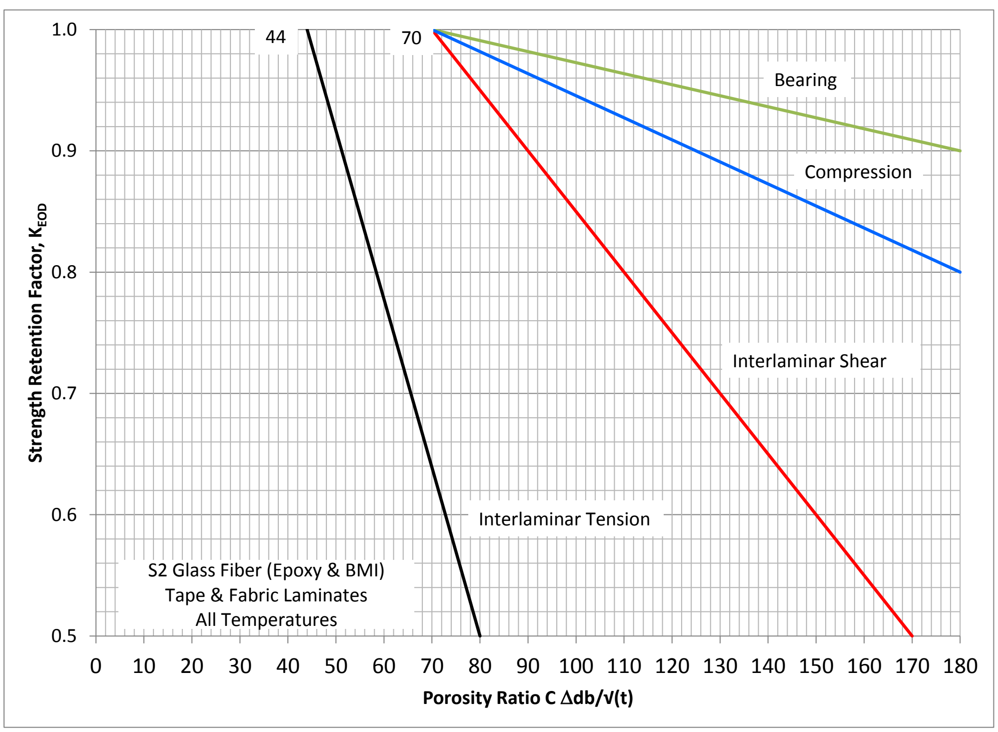


Figure 19.6-6. Effect of Porosity on S2 Glass Fiber Composites (Epoxy and BMI).

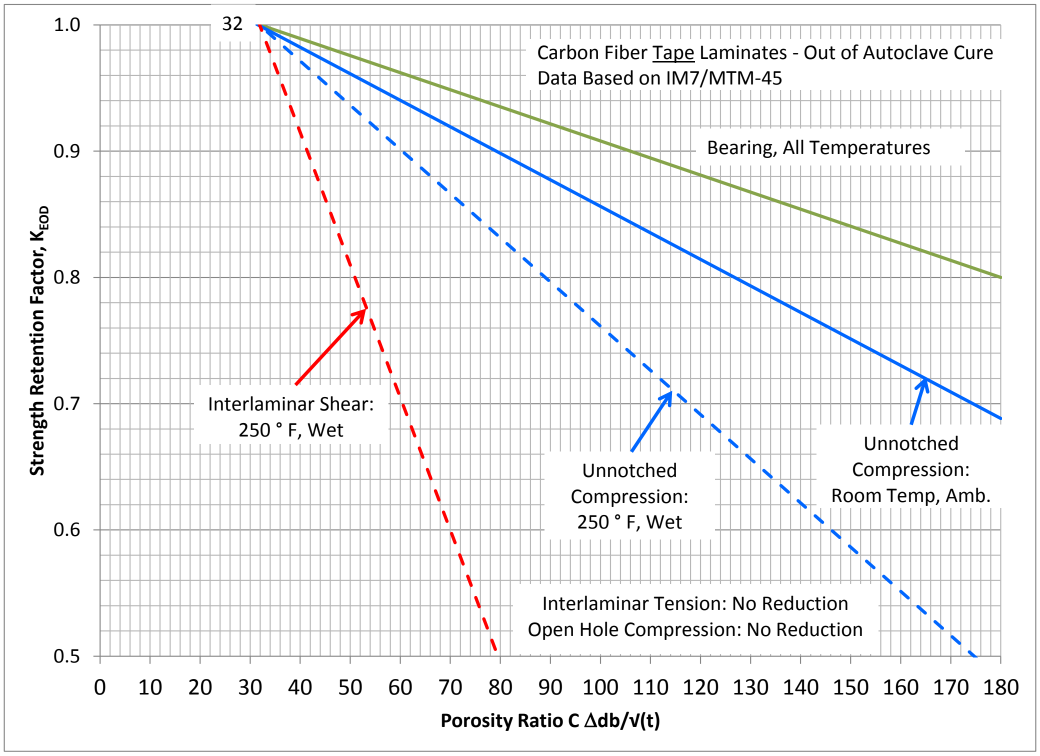


Figure 19.6-7. Effect of Porosity on IM7/MTM45-1 Tape Laminates.

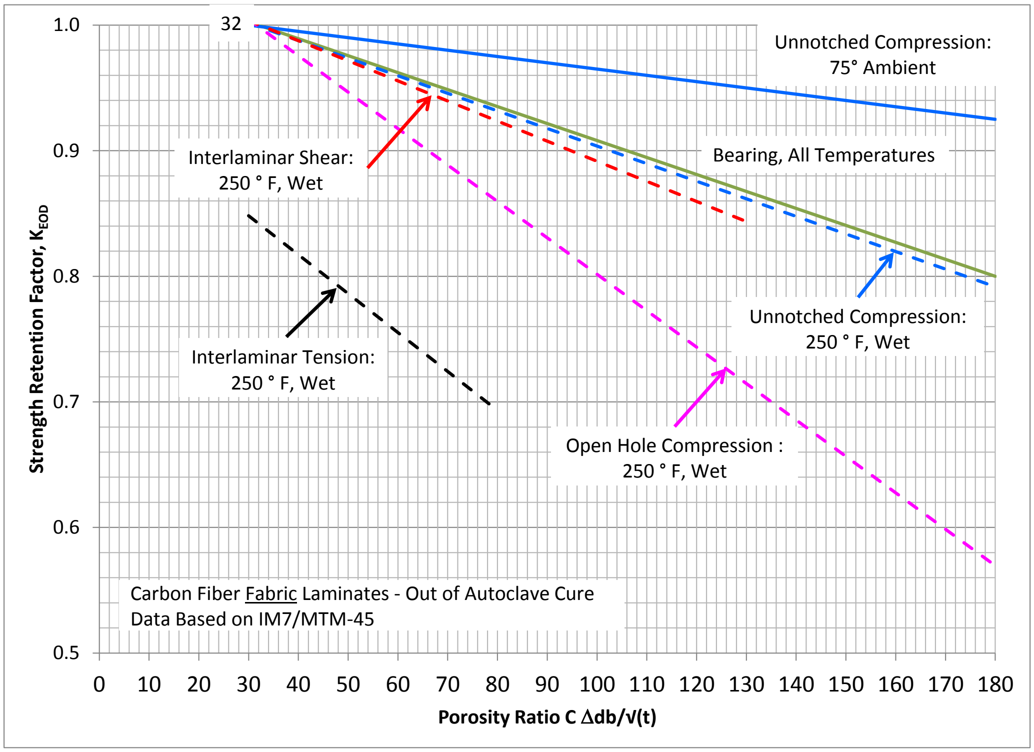
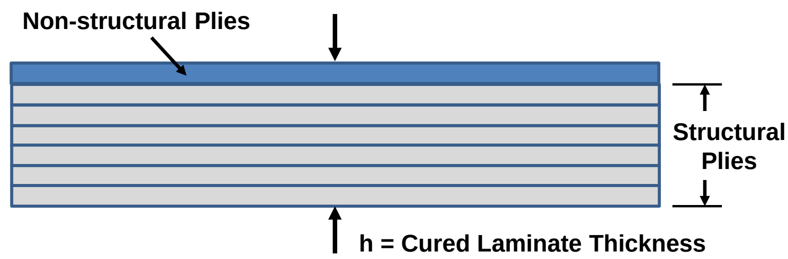


Figure 19.6-8. Effect of Porosity on IM7/MTM45-1 Fabric Laminates.

19.6.8 Sub-Nominal Laminate Thickness

Defect/Damage: SUB-NOMINAL LAMINATE THICKNESS



Description:
A cured composite part has a nominal cured ply thickness below the laminate physical requirements as defined in the material specification (refer to Table 19.6-10).

A sub-nominal thickness condition could be caused by any of the following:

- Low resin content or excessive resin bleed;
- Low fiber areal weight;
- Missing plies;
- Fiber wash; and/or
- Excessive pressure or gravity during autoclave cure.

Laminate thickness variation and thinning commonly occurs in curved laminates with tight radii (R < 0.375 in.) such as in laminate C or I-Sections. Thinning in the radius is usually a result of low resin content caused by bagging and/or tooling pressure around tight radii. Thinning in the radius can reduce laminate interlaminar and bending strength. These effects should be mitigated by manufacturing development and EOD testing.

Characterization:
Sub-Nominal laminate thickness is characterized by:

- Measured laminate thickness.
- Calculated nominal cured ply thickness.

Thickness is not measured unless it is specifically called out in the engineering drawing. Variation in thickness is usually detected using Coordinate Measuring Machine (CMM). Presence of other discrepancies such as surface waviness may cause an alert inspector to measure thickness.

Disposition and Repair Guidance:

- A composite part with sub-nominal thickness can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- EOD tests were conducted on a legacy program (19-16, 19-18) to determine the effect of sub-nominal thickness on laminate strength. The results are described below and have been incorporated in IDAT/IBOLT.
- Localized sub-nominal thickness can sometimes be repaired with a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) that provides an alternate load path.
- A composite part with a cure ply thickness that is 15% below the nominal cured ply thickness should be SCRAPPED.

EOD Residual Strength Analysis:
The effect of sub-nominal laminate thickness on strength can be determined using the IDAT/IBOLT manufacturing defect tool described in Table 19.6-11. The effect may also be calculated using the strength retention factors from Figure 19.6-9 or Figure 19.6-10 using Equation 19.6-2 or Equation 19.6-3 and the appropriate strength allowable at the critical environmental condition. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Effect of Sub-Nominal Thickness on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of sub-nominal laminate thickness on strength. Strength retention factor K_{EOD} as a function of actual/nominal cured ply thickness ratio is plotted in Figure 19.6-9 for tape and in Figure 19.6-10 for fabric. The curves may be used for Epoxy and Bismaleimide (BMI) resin solid laminates composed of tape or fabric. As shown in the figures, reduced cured ply thickness has a degrading impact on compression strength (unnotched, filled hole, open hole, compression after impact), bearing strength (yield, ultimate), and interlaminar strength (tension, shear). The specified limits on cured ply thickness for typical tape and fabric material are shown in Table 19.6-10.

Table 19.6-10 Material Specification Limits for Cured Ply Thickness Levels

Fiber/Resin & Form	Material Specification Limits		
	Resin Content % By Weight	Fiber Areal Weight Grams/Sq. M	Cured Ply Thickness (in) ± Acceptable Variation
IM7/5250-4 TAPE	32 +3,-2	145±5	0.0053±0.0003
IM7/5250-4 FABRIC	38±2	203±8	0.0083±0.0007
IM7/977-3 TAPE	32 +3,-2	145±5	0.0053±0.0003
IM7/977-3 FABRIC	38±2	203±8	0.0083±0.0007
S2/5250-4 FABRIC	35±2	302±15	0.0098±0.0007

The nominal cured laminate thickness h_{nom} can be calculated from the number of plies n and the nominal cured ply thickness t_{nom} using Equation 19.6-14. The actual cured ply thickness t_{act} can be estimated from the actual measured laminate thickness h_{act} using Equation 19.6-15. For hybrid laminates, composed of tape, fabric and/or non-structural plies, then calculate the h_{nom} as a sum of the thicknesses using nominal ply thickness of each constituent ply.

$h_{nom} = n \bullet t_{nom}$	**Equation 19.6-14**
$t_{act} = h_{act} / n$	**Equation 19.6-15**

Where:
n = number of structural plies.
h_{nom} = nominal cured laminate thickness.
t_{nom} = nominal cured ply thickness.
h_{act} = actual measured cured laminate thickness.
t_{act} = actual cured ply thickness.

These design curves have been implemented into MRB tools available within the IDAT/IBOLT analysis as described in Table 19.6-11. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-11 IDAT/IBOLT Analysis of Sub-Nominal Laminate Thickness on Allowable Strength.

IDAT Analysis	Compression	Bearing
IBOLT	UNC, FHC, OHC	BCT, BCC, BCS

IDAT Manufacturing Defect Analysis
1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/ Sub-Nominal Thickness
2. Enter: Cured Ply Thickness (in)

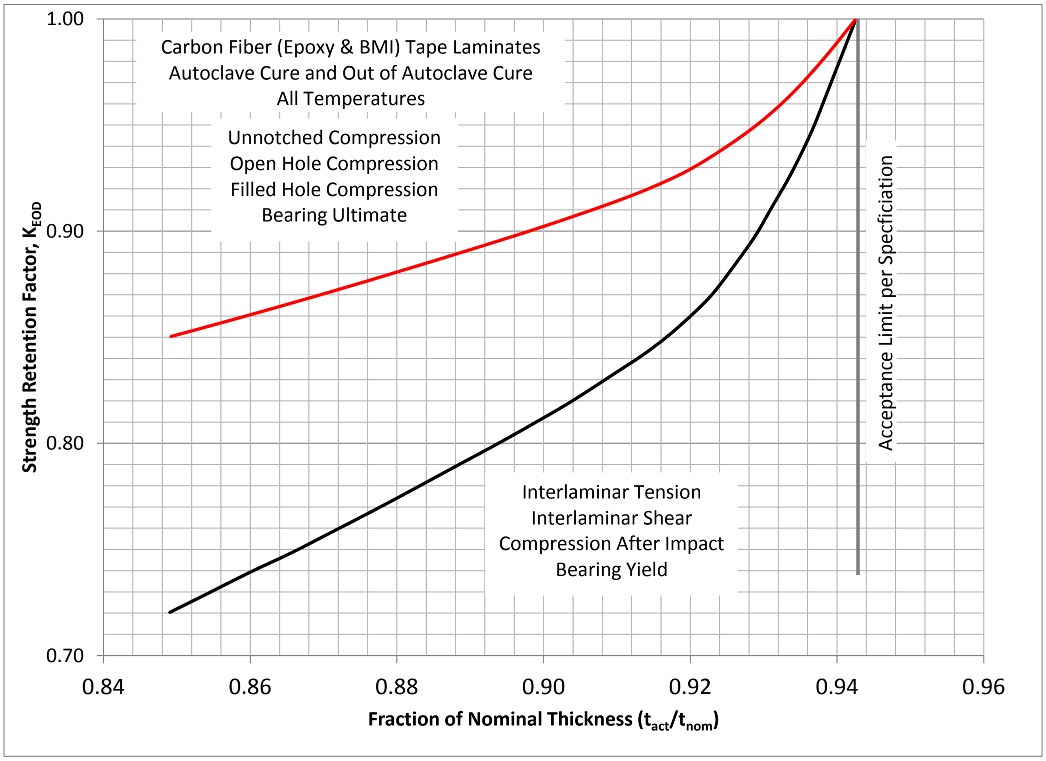


Figure 19.6-9. Effect of Reduced Cured Ply Thickness on Strength for a Tape

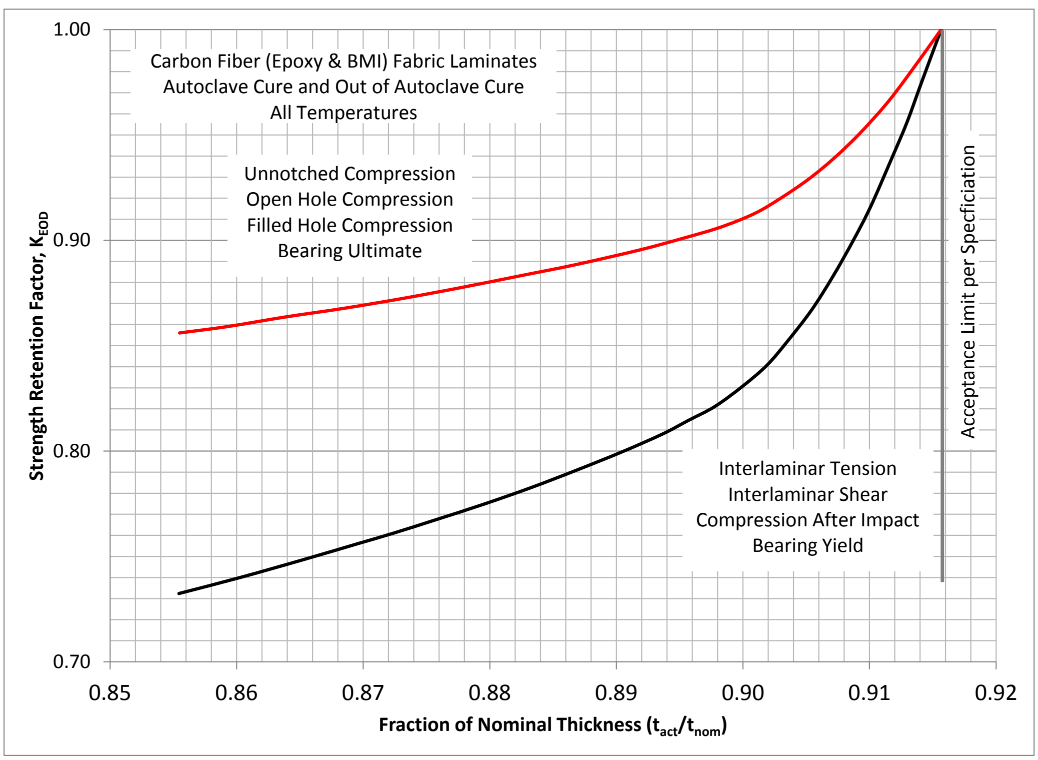


Figure 19.6-10. Effect of Reduced Cured Ply Thickness on Strength for a Fabric

The strength retention curves are valid for cured ply thickness reduction of up to approximately 15%. Laminate thickness reductions that are beyond 15% should be scrapped.

In investigating a sub-nominal laminate thickness nonconformance, it is important to determine the extent of condition. Most often, a sub-nominal thickness condition is caused by low resin content. Low resin content may be the result of excessive resin bleed caused by a tooling mismatch or excessive autoclave pressure. If the area is localized, check for a tooling mismatch or anomaly as a root cause. If the condition is widespread across the part, then the cause might be excessive autoclave pressure or tool pressure if a pressure plate was used. Whether local or widespread, low resin content can often be substantiated by a resin starved surface appearance. Laminate fiber volume and resin content can be determined by excising a small portion of the cured laminate.

If the thickness variation could be accounted for by one or more missing plies, this possibility should be investigated, particularly if the part was fabricated using hand lay-up. A missing ply results in less load-carrying fibers and can often result in an unsymmetric lay-up which can be detected by laminate warpage at a room temperature condition after cure. Unsymmetric laminates that are warped at room temperature should be scrapped. A laminate stacking sequence can be determined from an edge remnant or by excising a small portion of the cured laminate.

If the thickness reduction is due to known missing structural plies whose orientation and location are known, then plies can be removed from the laminate definition and the part can be reanalyzed. If the exact location of the missing structural ply/plies is not known but if it can be ascertained that plies are missing then the critical ply can be removed and the part reanalyzed. If the missing ply/plies is/are non-structural then the part may be used as is.

If porosity is also present in the part in addition to reduced thickness, strength reduction due to porosity should also be applied to the part. However, it should be noted that porosity can result in increased part thickness.

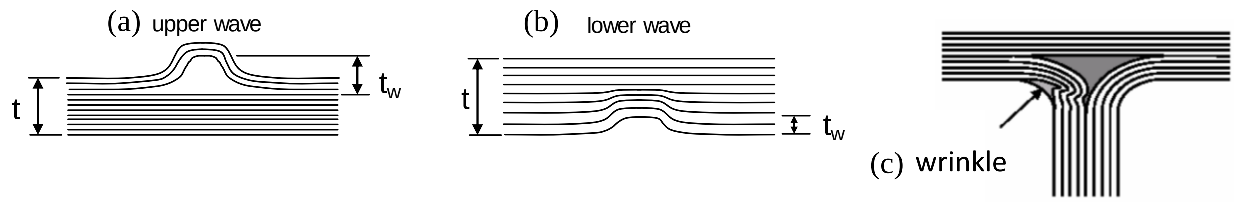
Reduced thickness also affects panel buckling and crippling, since the cross-sectional property such as moment of inertia decreases as a cubic function of thickness. This offsets any increase in in-plane stiffness due to higher fiber volume which is only a linear function of thickness. Therefore the part has to be checked for stability if the part thickness is reduced.

Reduced thickness affects resistance to pressure as well and may result in higher deflections under pressure loading which can lead to violations of external waviness criteria and/or strength issues. If the overall panel is thin and loaded with pressure, these modes need to be examined.

Finally the thinning of the corner of laminate angle sections which are loaded in tension can result in reduced margins due to the t^2 effect of bending in the angle.

19.6.9 Waviness or Wrinkles

Defect/Damage: WAVINESS OR WRINKLES



Description:
Waves are described as out of contour waviness of the laminate surface as shown in (a) and (b). Wrinkles are also out of contour distortions were the plies are folded as shown in (c). The terms waviness and wrinkle are often used interchangeably. A discrepant wave or wrinkle are those whose maximum depth or height exceeds the acceptable inspection criteria limit (Maximum depth/height ≤ 5% of panel thickness or 0.005 inches, whichever is greater).* Waviness extending through the entire thickness to the far side of the laminate is not acceptable.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
Waviness or wrinkles are characterized by:

- Maximum defect depth/height.
- Defect location and orientation.
- Percentage of affected laminate depth.**
- Defect type (wave, wrinkle, etc.)

** Depth of distorted plies cannot be determined by non-destructive inspection. Depth can sometimes be evaluated by drilling small holes or by measurement on edge trim. If unknown, use a conservative estimate. Repetitive occurrences should be scrapped and cut up to determine a cause and corrective action.

Disposition and Repair Guidance:

- A composite part with waviness or wrinkles can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- EOD tests were conducted on a legacy program (References 19-16, 19-18) to determine the effect of waviness on laminate strength. The results are described below and have been incorporated in IDAT/SQ5 and BEND analyses.
- Depending on the depth, concave waves or depressions may be filled with a Resin Surface Repair (Section 19.8.11) or a Resin Filler Repair (Section 19.8.12) provided that positive margins are obtained for the EOD residual strength analysis.
- Convex waves should faired, but not sanded flat as it can result to a loss of fibers.
- A localized wrinkle or wave can sometimes be repaired with a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) that provides an alternate load path.

EOD Residual Strength Analysis:
The effect of waviness on strength can be determined using the IDAT/SQ5 and BEND manufacturing defect tools described in Table 19.6-12. The effect may also be calculated using the strength retention factors from Figure 19.6-11 through Figure 19.6-13 using Equation 19.6-2 or Equation 19.6-3 and the appropriate strength allowable at the critical environmental condition. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Effect of Waviness on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of waves on laminate strength. Strength retention factors K_{EOD} as a function of the percentage of laminate thickness with distortion are plotted in Figure 19.6-9 Figure 19.6-11 through Figure 19.6-14. As shown in the figures, upper or lower waves have a degrading impact on tension (unnotched), compression strength (unnotched), and interlaminar tension strength (given for upper waves only). Waviness is assumed to be localized and to not affect notched strength.

Figure 19.6-11 provides the strength retention factor for unnotched compression strength in BMI and Epoxy, tape and fabric laminates. Figure 19.6-12 provides the strength retention factor for unnotched tension strength in BMI and Epoxy, tape and fabric laminates only. Figure 19.6-13 provides the strength retention factor for interlaminar tension strength for upper waves only in BMI and Epoxy, tape and fabric laminates.

Lower waves affect the UNT strength of tapes more severely than upper waves. The lower and upper waves have the same effect on the UNC strength of tapes and fabric and the UNT strength of the fabric. Upper waves are considered to be more critical for ILT and hence only their effect on the ILT is calculated.

These design curves have been implemented into MRB tools available within the IDAT/SQ5 and BEND analyses as described in Table 19.6-12. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-12 IDAT Analysis of Waves Effects on Allowable Strength.

IDAT Analysis	Tension	Compression	Interlaminar Tension
SQ5	UNT	UNC	
BEND	UNT	UNC	ILT

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Waves
2. Enter: Upper or Lower Wave
3. Enter: Wave Thickness (in)

EOD tests (19-19, 19-20) have also been completed recently on an Out-of-Autoclave 250 °F Cure material system, IM7/MTM45-1 (Refer to Section 19.7.3.2). Effects of waviness curves for Tape and Fabric are provided in Figure 19.6-14.

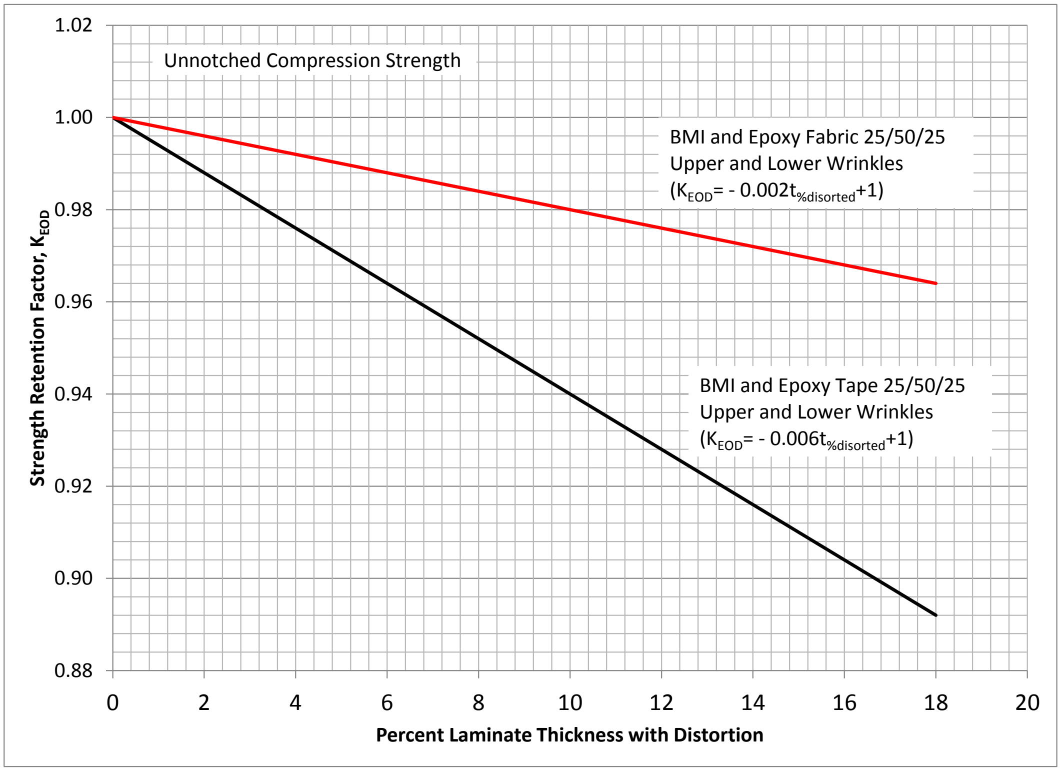


Figure 19.6-11. Effect of Upper or Lower Waves on UNC for BMI and Epoxy, Tape and Fabric Laminates.

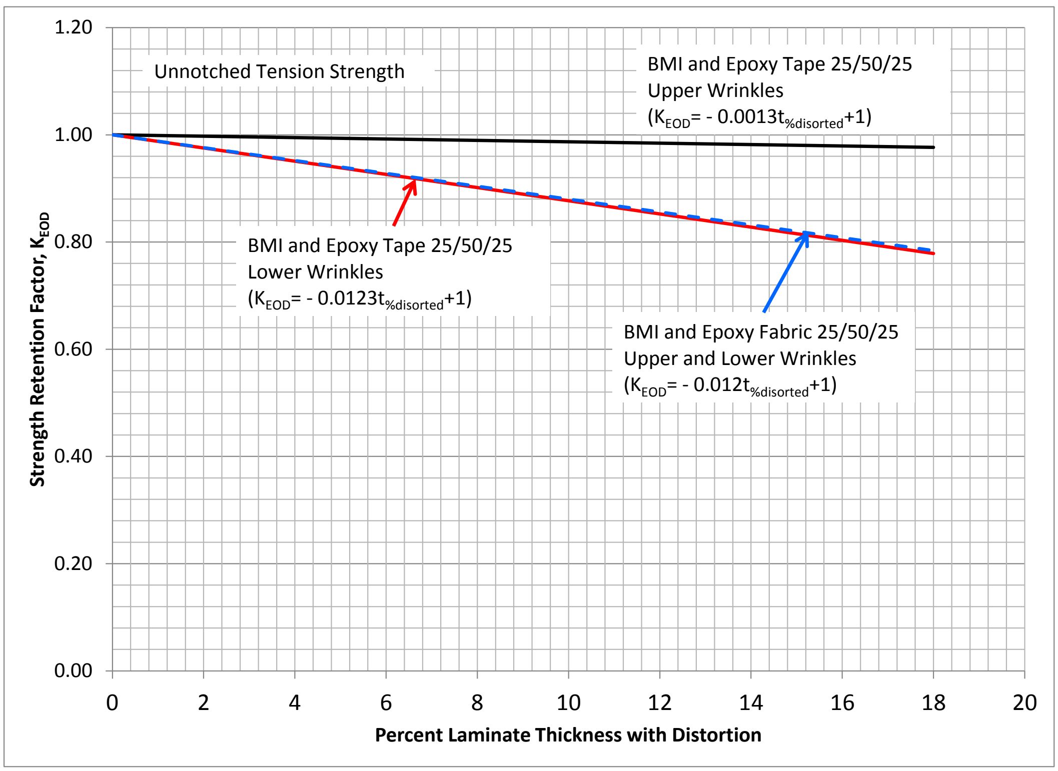


Figure 19.6-12. Effect of Upper or Lower Waves on UNT for BMI and Epoxy Tape Laminates.

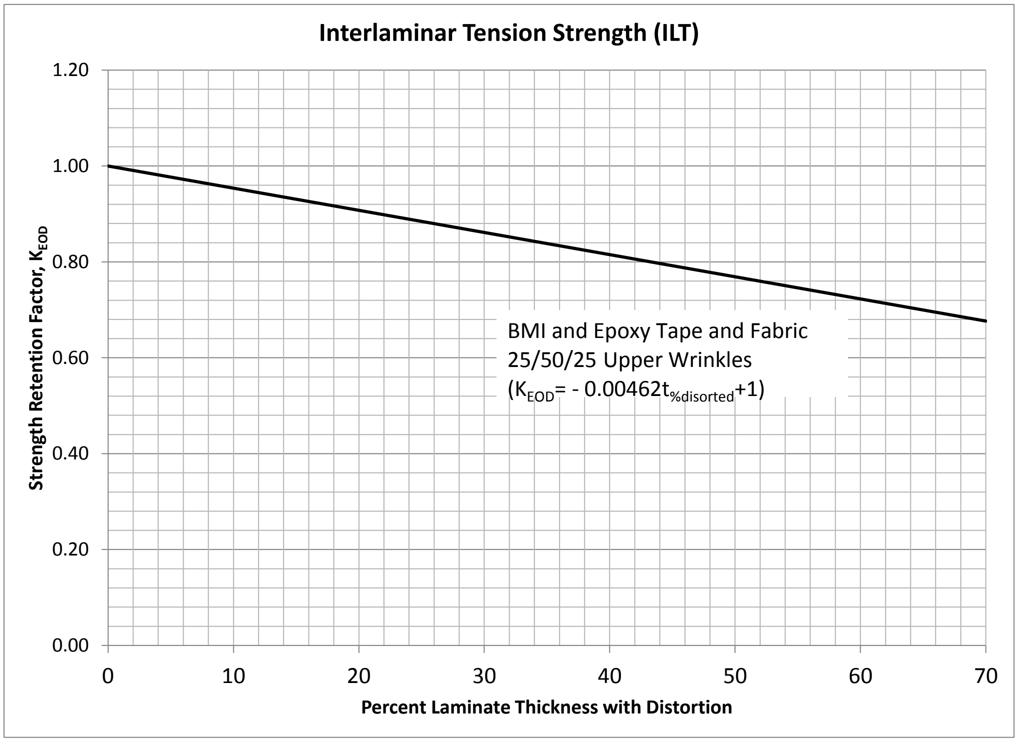


Figure 19.6-13. Effect of an Upper Wave on ILT for BMI and Epoxy, Tape and Fabric Laminates.

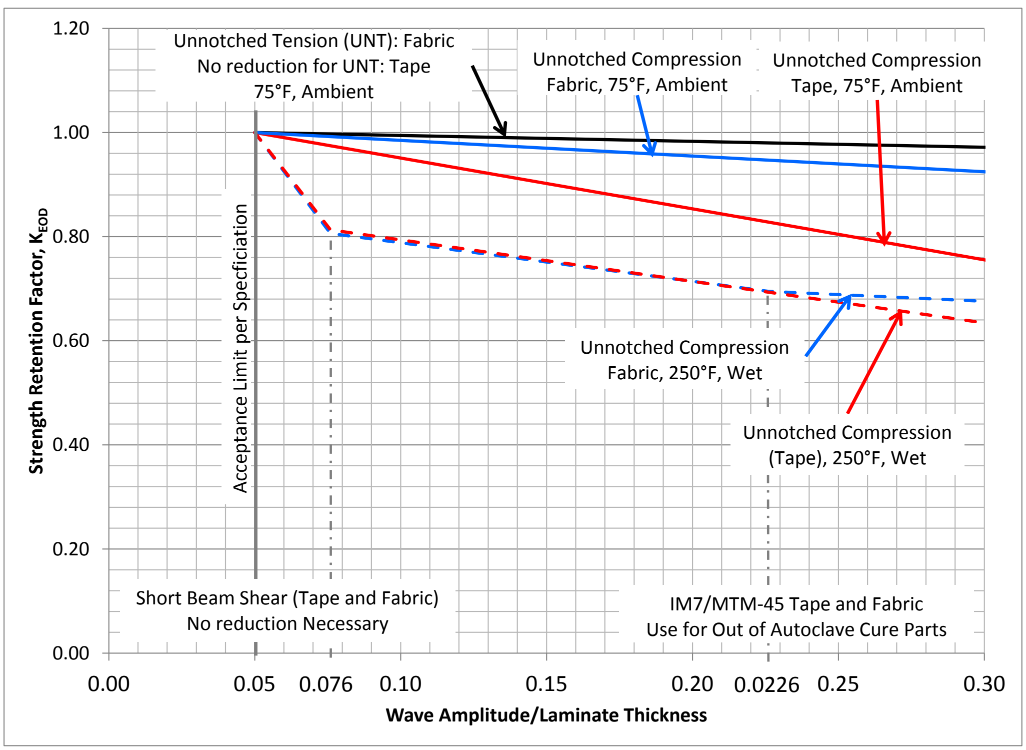
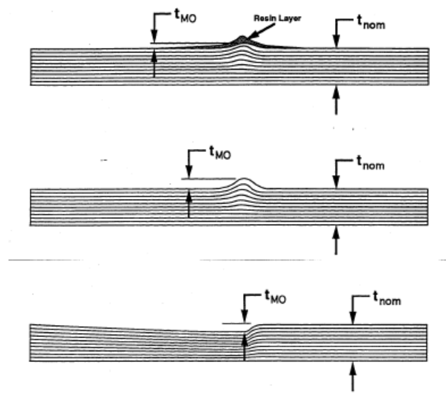


Figure 19.6-14. Effect of Upper or Lower Waves on IM7/MTM45-1 Tape and Fabric Laminates.

19.6.10 Tool Marks

Defect/Damage: TOOL MARKS



Description:
A tool mark is a distortion of plies within a composite laminate induced by mismatches or misalignment between tool details that exceeds the acceptable inspection criteria limit (Maximum depth/height ≤ 5% of panel thickness or 0.005 inches, whichever is greater).*. Tool marks may also be caused by bagging wrinkles. Tool marks may be a resin ridge or step in a pool of resin or it can be a depression or indentation. Oftentimes tool marks only affect surface resin and do not create fiber distortion in the outer plies.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
Tool marks are characterized by:

- Maximum defect depth/height.
- Defect location and orientation.
- Percentage of affected laminate depth.**
- Defect type

** Depth of distorted plies cannot be determined by non-destructive inspection. Depth can sometimes be evaluated drilling small holes. If unknown, use a conservative estimate.

Disposition and Repair Guidance:
- A composite part with tool marks can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- EOD tests were conducted on a legacy program (19-16, 19-18) to determine the effect of tool marks on laminate strength. The results are described below and have been incorporated in IDAT/SQ5 analysis.
- Depending on the tool mark depth, depressions may be filled with a Resin Surface Repair (Section 19.8.11) or a Resin Filler Repair (Section 19.8.12) provided that positive margins are obtained for the EOD residual strength analysis.
- Tool marks that rise above the OML can be removed with a Blend and Smooth Repair (Section 19.8.10) provided that the positive margins are obtained for the EOD residual strength analysis and no fibers are cut.
- A severe localized tool mark can sometimes be repaired with a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) that provides an alternate load path.
- Severe tool marks that result in fiber distortion greater than 10% of the laminate thickness are unacceptable and the part should be scrapped.

EOD Residual Strength Analysis:
The effect of tool marks on strength can be determined using the IDAT/SQ5 manufacturing defect tool described in Table 19.6-13. The effect may also be calculated using the strength retention factors from Figure 19.6-15 using Equation 19.6-2 or Equation 19.6-3 and the appropriate strength allowable at the critical environmental condition. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Effect of Tool Marks on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of tool marks on laminate strength. Tests were limited to carbon fiber tape laminates composed of 977-3 Epoxy, 5250-4 BMI, or Radel Thermoplastic resins. Strength retention factors K_{EOD} as a function of the tool mark indentation depth as a percentage of laminate thickness are plotted for unnotched strength in Figure 19.6-15. Unnotched strength data for tool marks are based only on 50/40/10 laminates. However, it is considered conservative to apply the same factors derived from 50/40/10 laminates to softer laminates. Notched strengths are assumed to be unaffected by these localized defects.

These design curves have been implemented into MRB tools available within the IDAT/SQ5 analysis as described in Table 19.6-13. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-13 IDAT/SQ5 Analysis of Tool Marks on Allowable Strength.

IDAT Analysis	Tension	Compression
SQ5	UNT	UNC

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Tool Marks
2. Enter: Tool Mark Indentation (in)

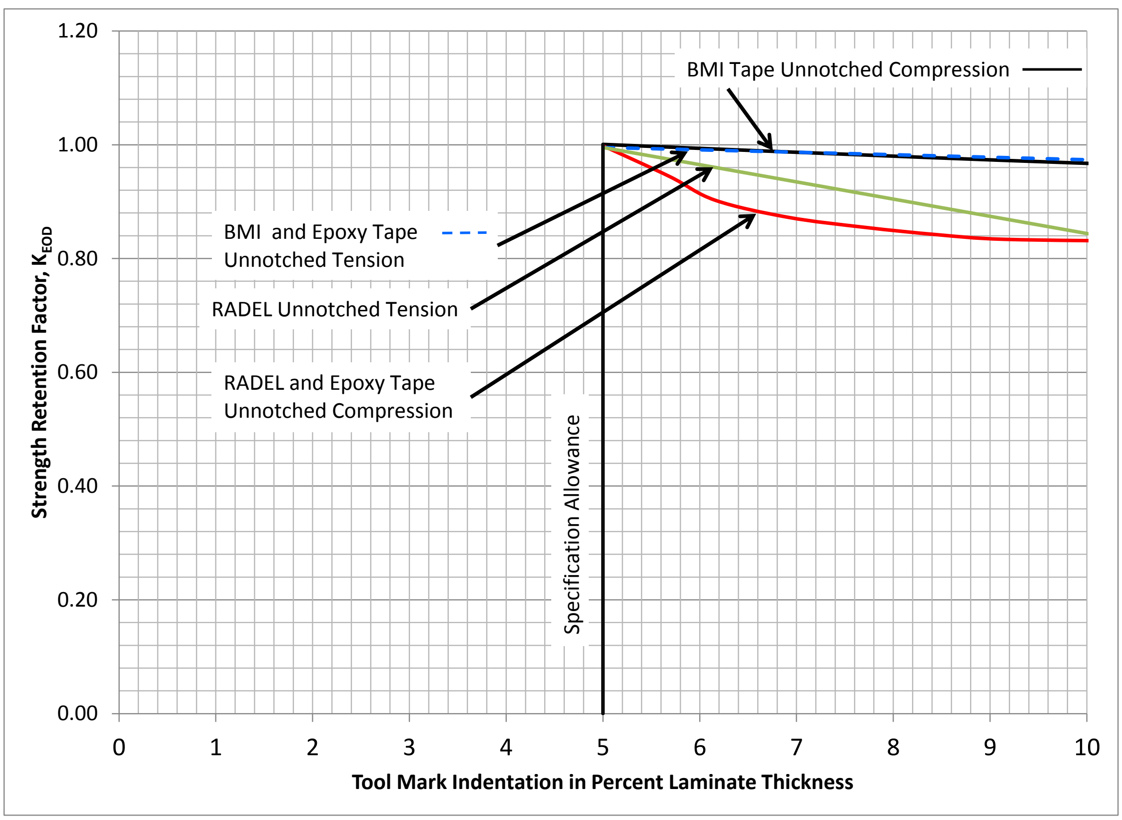
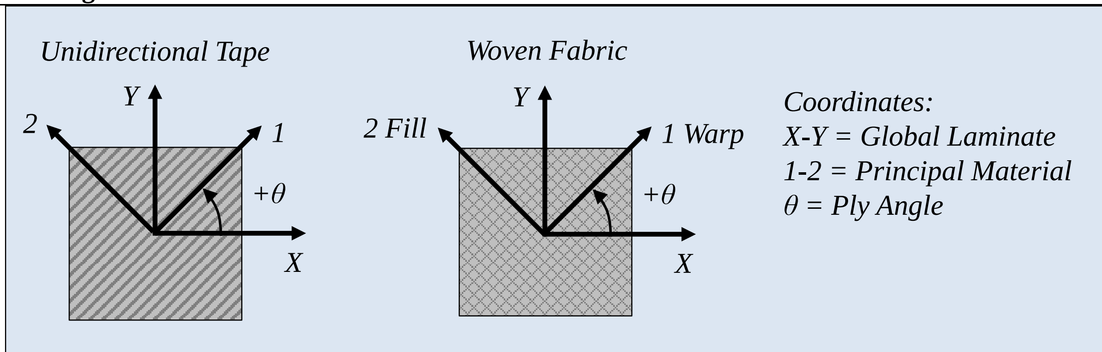


Figure 19.6-15. Unnotched Strength versus Tool Mark Indentation (% Laminate Thickness).

19.6.11 Fiber Misalignment

Defect/Damage: FIBER MISALIGNMENT



Description:
Fiber misalignment occurs during laminate fabrication and refers to the situation when the actual fiber direction of a given ply varies from the ply angle specified by the engineering drawing. That is, the angular difference between the actual versus the intended orientation exceeds the tolerance limit as specified by the laminate fabrication specification.

Misalignment may occur for a single ply, a group of plies, or all plies within the laminate. Fiber misalignment is an uncommon occurrence and is not detectable using standard NDI techniques. Fiber misalignment can occur during filament winding process when a fiber slips or during laminate cure when the fibers shift under temperature and pressure when the matrix is less viscous. Guidance is provided below for situations where they have been identified after cure.

Characterization:
Fiber misalignment is characterized by an angular deviation $\Delta\theta$ (degrees) from the actual fiber direction relative to intended design ply orientation angle.

$$\Delta\theta = \theta_{actual} - \theta_{design}$$ **Equation 19.6-16**

The typical ply orientation angle tolerance for hand lay-up fabrication is:

Unidirectional tape = ± 2°
Woven fabric = ± 3°

In practice, these manufacturing process specification limits are intended to control the cutting and placement of individual plies. They are not applicable to variations in ply orientation that are induced by the geometry of composite parts with complex curvature.

Disposition and Repair Guidance:

- A composite part with misaligned fibers can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- If EOD Residual Strength Analysis cannot show positive margins for a USE-AS-IS disposition, the panel is usually SCRAPPED.

EOD Residual Strength Analysis:
The effect of fiber misalignment on strength can be determined using the IDAT/SQ5 manufacturing defect tool described in Table 19.6-14. The effect may also be calculated using the strength retention factors from Figure 19.6-16 through Figure 19.6-17 using Equation 19.6-2 or Equation 19.6-3 and the appropriate strength allowable at the critical environmental condition. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be SCRAPPED.

If a single ply or ply group is misaligned, then the EOD analysis should evaluate any strength reductions for that ply or the most critical ply within the ply group. If the entire laminate is misaligned as a total, then strength analysis should be performed with applied loads rotated to align with the actual fiber directions. Alternatively, IDAT provides a laminate rotation feature that is available for SQ5, IBOLT, and BEND analyses (refer to Table 19.10-1).

Effect of Fiber Misalignment on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of fiber misalignment on unnotched laminate strength. These tests were used to establish manufacturing process specification limits to control the cutting and placement of individual plies during lay-up. Since the process is controlled at the ply level, a nonconformance identified after cure is an unlikely event. However, if a fiber misalignment nonconformance is identified, an effect of defect strength analysis may be performed as described below.

Strength retention factors K_{EOD} as a function of the fiber orientation misalignment angle are plotted for unnotched strength in Figure 19.6-16 (tape laminates) and Figure 19.6-17 (fabric laminates). Unnotched laminate strength decreases with increasing misalignment angle and was determined empirically for up to a misalignment angle of 12^o. If the misaligned angle is more than 12^o then a strength analysis using a rotated laminate may be performed to determine the reduction in margins (refer to Table 19.10-1).

These design curves have been implemented into MRB tools available within the IDAT/SQ5 analysis as described in Table 19.6-14. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-14 IDAT/SQ5 Analysis of Fiber Misalignment on Allowable Strength.

IDAT Analysis	Tension	Compression
SQ5	UNT	UNC

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Fiber Orientation
2. Enter: Orientation Misalignment (degrees)

The tendency for fibers to shift is high in regions of curvatures such as corners, part edges, or curved surfaces and it is not considered a defect per se. Therefore, to account for the possibility of fiber misalignment a priori, the static strength can be reduced using the charts referenced in this section during the design stage.

The effect of misaligned fibers on open hole or filled hole notched strength may be estimated by applying the strength retention factors obtained from IDAT/SQ5 or from the design curves that follow to the unnotched allowables calculated at the critical hole perimeter positions 3 and 7 within IBOLT. Note that this estimate would account for the effect on hole edge allowable only and neglects any effect on the hole perimeter stresses.

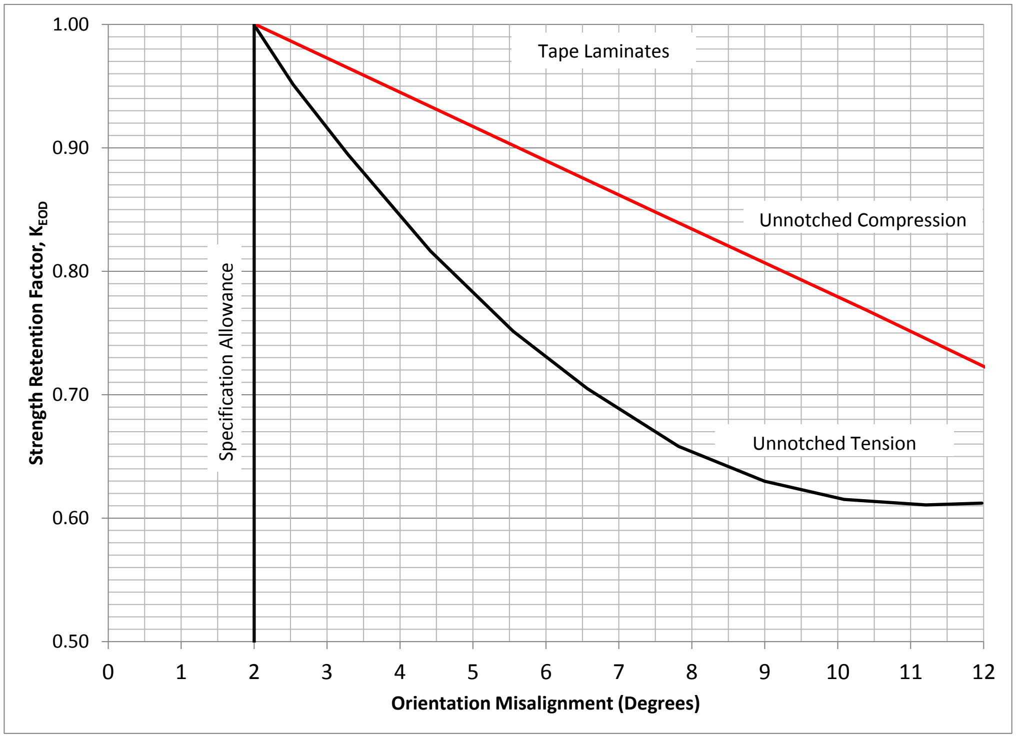


Figure 19.6-16. Unnotched Strength versus Fiber Orientation Angle (Degrees) for Carbon Fiber Tape Laminates (Epoxy and BMI).

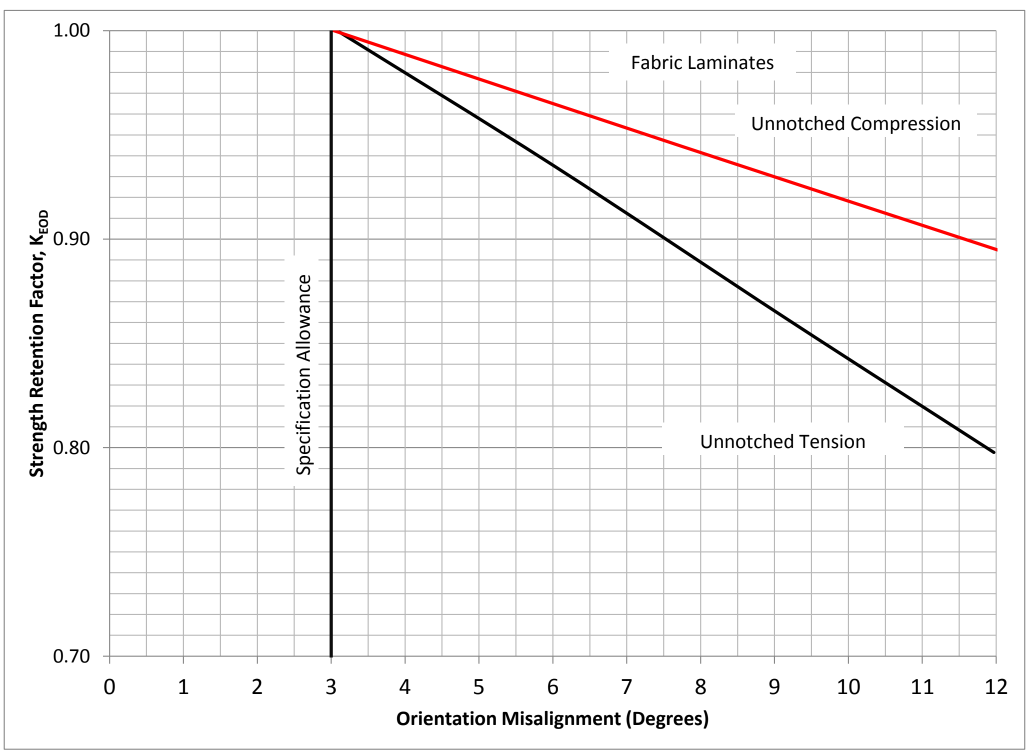
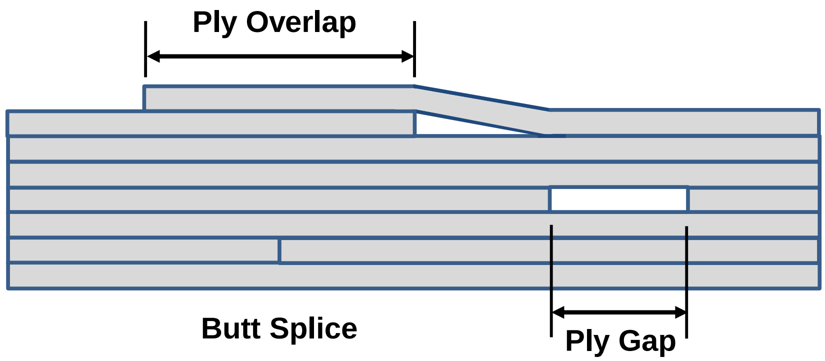


Figure 19.6-17. Unnotched Strength versus Fiber Orientation Angle (Degrees) for Carbon Fiber Fabric Laminates (Epoxy and BMI).

19.6.12 Ply Overlaps or Gaps

Defect/Damage: PLY OVERLAPS OR GAPS



Description:
A ply gap or overlap refers to out-of-tolerance gaps or overlapping of adjacent plies that are laid side by side to form a single ply or layer with a given fiber orientation. These occur as a consequence of splicing together individual pieces of material to form a single ply. This also may be the gaps or overlaps in individual layers of tape laid using the fiber placement process. Acceptable limits for ply overlaps or gaps are usually different for tape and fabric. These limits are typically called out in a laminate fabrication process specification.

Ply gaps or overlaps are usually addressed during lay-up and are difficult to detect using standard NDI techniques. Ply overlap or gap related MRB actions are uncommon and guidance is provided below for situations where they have been identified after cure.

Characterization:
As shown above, a ply overlap or gap is characterized by the overlap or gap dimension in inches.

Disposition and Repair Guidance:

- A composite part with out-of-tolerance ply overlaps or gaps can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- If EOD Residual Strength Analysis cannot show positive margins for a USE-AS-IS disposition, the panel is usually SCRAPPED.

.

EOD Residual Strength Analysis:
The effect of ply overlaps or gaps on strength can be determined using the IDAT/SQ5 manufacturing defect tool described in Table 19.6-14. The effect may also be calculated using the strength retention factors from Figure 19.6-16 through Figure 19.6-20 using Equation 19.6-2 or Equation 19.6-3 and the appropriate strength allowable at the critical environmental condition. Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be SCRAPPED.

Effect of Ply Overlaps or Gaps on Laminate Strength

EOD static strength tests were conducted on a legacy program (19-16, 19-18) to determine the effect of ply overlaps or gaps on laminate strength. Hard laminates (BMI tape) and quasi-isotropic laminates (BMI tape and fabric) were tested for various ply overlap and gap dimensions. Strength retention factors K_{EOD} as a function of ply overlap or gap dimension are plotted for unnotched strength in Figure 19.6-18 through Figure 19.6-20.

Strength retention factor for unnotched strength in fabric laminates as a function of overlap dimension is shown in Figure 19.6-18. The laminate fabrication specification limit for fabric overlaps is 0.5 inches. Unnotched strength data was limited to 0.1, 0.25, and 0.5-inch overlap for the fabric laminate evaluation. The unnotched compression test data supports a strength retention factor of 1.0 between 0.5-inch and 0.1-inch. The unnotched tensions data indicates that strength retention factor decreases from 1.0 to 0.93 between 0.5-inch and 0.1-inch. Material review dispositions of fabric overlaps below 0.1 inch are not allowed as there is no data below this dimension.

Strength retention factor for unnotched compression in tape laminates as a function of overlap dimension is shown in Figure 19.6-19. Splices in tape laminates which cut across the fiber are not allowed. Material review dispositions of tape overlaps greater than 0.050 inch are not allowed.

Strength retention factor for unnotched strength in tape laminates as a function of gap dimension is shown in Figure 19.6-20. The unnotched strength data supports a strength retention factor of 1.0 up to a gap of 0.060 inches. Quasi-isotropic laminates had the most reduction in unnotched strength as a function of gap dimension, so this data was used to establish the strength retention curves. Notched strengths are assumed unaffected by these localized defects.

These design curves have been implemented into MRB tools available within the IDAT/SQ5 analysis as described in Table 19.6-15. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-15 IDAT/SQ5 Analysis of Ply Overlaps or Gaps on Allowable Strength.

IDAT Analysis	Tension	Compression
SQ5	UNT	UNC

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Overlaps and Gaps
2. Enter: Defect Type as “Overlap” or “Gap”
3. Enter: Defect Size (in)

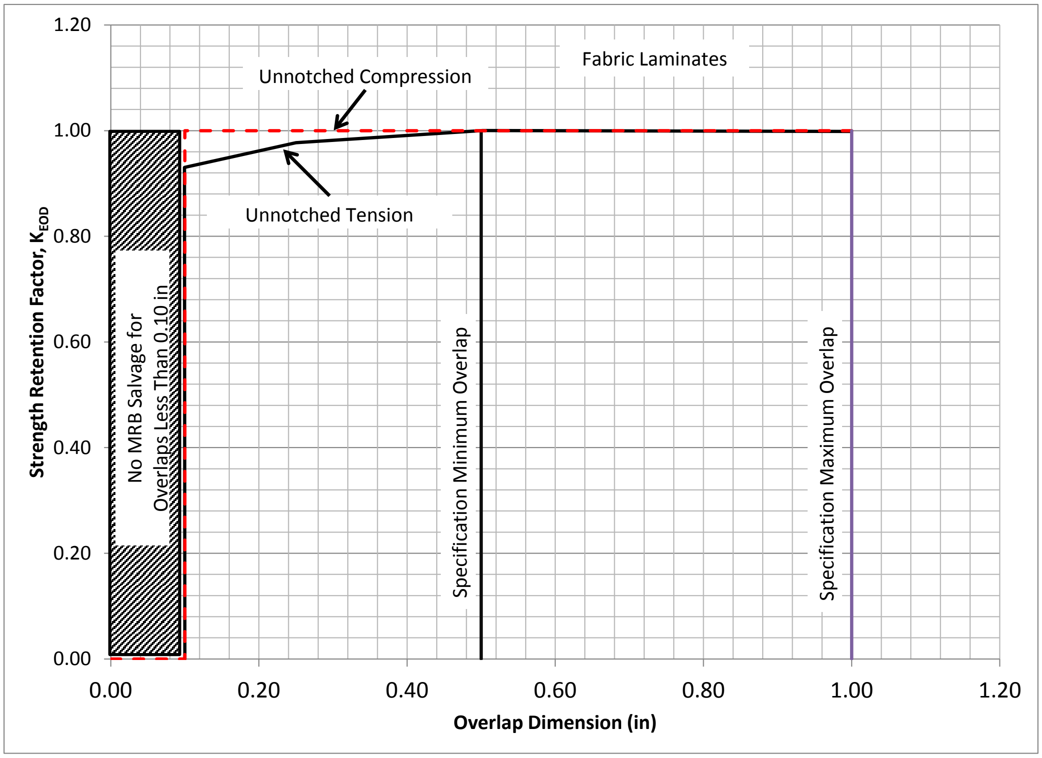


Figure 19.6-18. Unnotched Strength versus Overlap (inch) for Fabric Laminates.

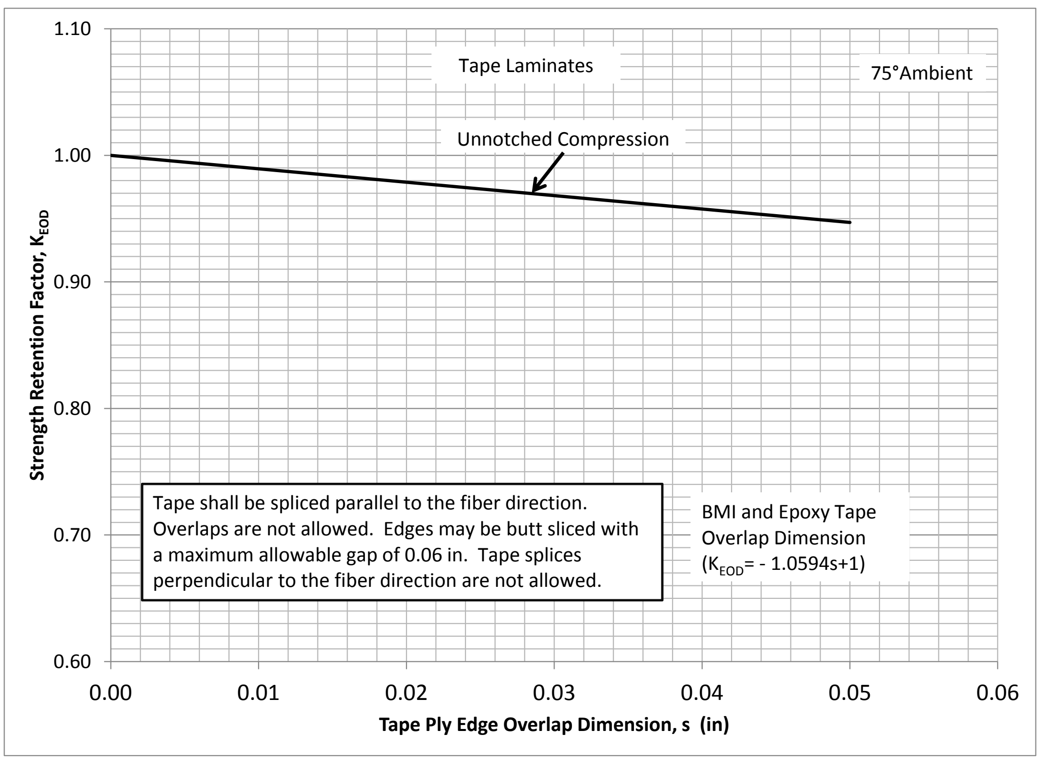


Figure 19.6-19. Unnotched Compression Strength versus Overlap (inch) for Tape Laminates.

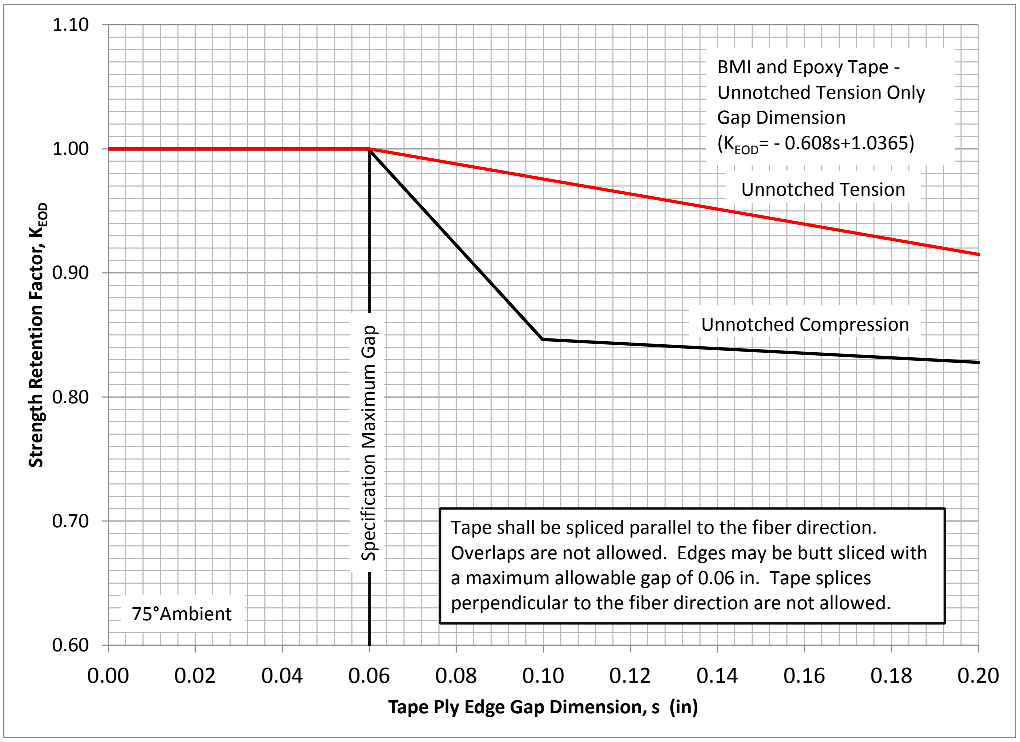
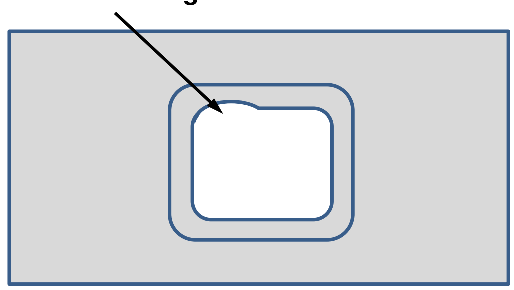


Figure 19.6-20. Unnotched Strength versus Gap (inch) for Tape Laminates.

19.6.13 Trimming or Machining Nonconformances

Defect/Damage: TRIMMING NONCONFORMANCES



Composite Panel Cutout with Recess

Description:
This defect refers to trimming or machining operations on a composite laminate that result in an out-of-tolerance condition with respect to the engineering drawing in which too much material has been removed. This might be caused by an error in numerical control programming or a cutter drifting off a tooling guide.

Characterization:
The overall dimensions and location of the out-of-tolerance condition must be documented for effect of defect or repair structural analysis.

Disposition and Repair Guidance:

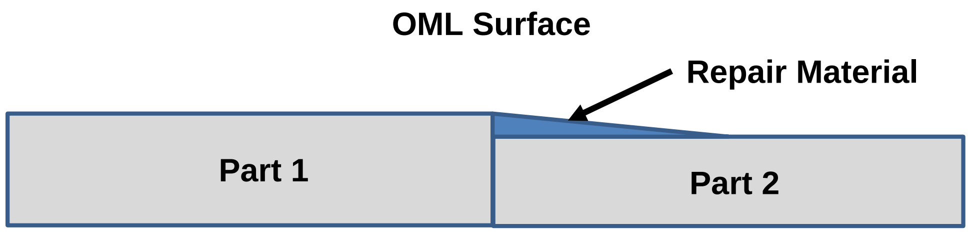
- A composite part with an out-of-tolerance trim geometry can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- As appropriate, additional Blend & Smooth or Trim Repairs (Section 19.8.10) to clean up details or prepare the part for subsequent repair actions.
- In some cases, a Resin Filler Repair (Section 19.8.12) may be required to restore design form, fit and function.
- A Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) may be required to restore design ultimate load capability by providing an alternate load path.
- For cocured or cobonded assemblies, consisting of composite skin and spars/ribs, etc., then a bolted or bonded structural fitting can be designed to help transfer loads.

EOD Residual Strength Analysis:

- Edge of part damage that results in a fastener hole short edge distance must be checked per section 19.6.15.
- Laminate edge damage that results in a stress concentration must be checked using the Damage Modeling Approach per Section 19.6.
    - Simple geometric damage along cutout edges may be analyzed using IDAT/PACT.
    - Damaged material must be considered as 100% ineffective and loads must be carried by the undamaged portion of the laminate.
    - For complex geometry, a local finite element analysis may be required with the out-of-tolerance features modeled to determine the maximum stress (or strain) concentration that is induced by the nonconformance.
    - Laminate strength may be evaluated using a point stress (or strain) criterion where the stress is evaluated at a characteristic distance removed from the peak stress (or strain) along the free edge. The un-notched strength (or strain) allowable is used at the design environmental condition (refer to Equation 19.6-6).
    - For displacement based finite element methods such as NASTRAN, a very fine mesh is usually required to obtain an accurate converged stress (or strain) solution.

19.6.14 OML Mismatch

Defect/Damage: OML MISMATCH



Description:	**Characterization:**
OML mismatch refers to an out-of-tolerance mismatch condition between adjacent parts on the aircraft Outer Mold Line (OML) that has been identified after assembly has been completed.	The overall dimensions and location of the out-of-tolerance condition must be determined.

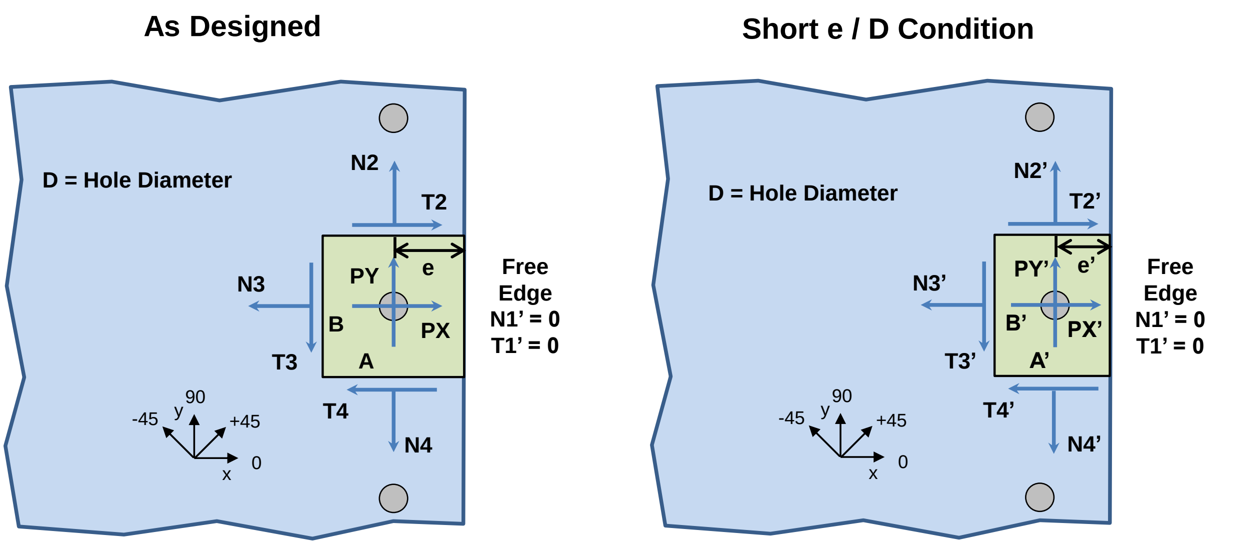
Disposition and Repair Guidance:

- This type of defect usually has no impact on part stresses and no structural analysis is required.
- In general, the recommended disposition is to repair the mismatch by applying a Resin Filler (Section 19.8.12) or a section of woven glass fabric. This is usually a cosmetic repair that requires no strength analysis.

EOD Residual Strength Analysis:
Recommended disposition is to USE-AS-IS or REPAIR.

19.6.15 Fastener Hole Short Edge Distance (e/D)

Defect/Damage: FASTENER HOLE SHORT EDGE DISTANCE



Description:

A fastener hole short edge distance condition exists in a composite joint element when the hole center to edge distance is below the 2.5D minimum required, where D is the hole diameter. A minimum of 2.5D edge distance is required in composite fastener joint elements for both side (e_{side}) and end (e_{end}) edge distance.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:

Fastener hole short edge distance is characterized by:

- Edge distance measured from the fastener hole center to the nearest free edge of the composite laminate. Corner fasteners require edge distances measured to both panel free edges.
- Laminate stacking sequence and principal fiber directions (rosette) relative to the free edge.
- Surrounding fasteners, edge chamfer geometry and any other relevant design features that may influence joint strength should be documented.

Disposition and Repair Guidance:

- A short edge distance condition in a composite laminate bolted joint element can reduce bearing strength, filled hole strength, bearing-bypass strength, and can induce an edge shear out failure mode.
- In general, a fastener hole short edge distance condition can be accepted for a USE-AS-IS disposition down to a minimum edge distance of e/D = 1.5 (where D is the hole diameter) provided that positive margins of safety are obtained for the EOD Residual Strength Analysis. This is the preferred approach as a repair of short edge distance condition can be difficult and complicated.
- If EOD residual strength analysis cannot show a sufficient strength margin, then a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) will be required to provide an alternate load path and restore design ultimate load capability.

EOD Residual Strength Analysis:

- A damage modeling approach is used for evaluating residual strength where the composite bolted joint analysis is performed using the short edge distance geometry.
- Specific guidance for IDAT/IBOLT strength analysis for a short edge distance condition is discussed below.

IBOLT Strength Analysis for Short Edge Distance

The objective is to revise the original "as designed" IBOLT problem to account for the short edge distance condition. The approach may be summarized as:

- IBOLT element dimensions, A and B, are adjusted to account for the short edge distance.
    - The fastener hole is always centered within the IBOLT element.
    - The IBOLT x-direction must be aligned with a laminate fiber direction.
    - Panel edge fasteners are modeled with one edge free; corner fasteners with two edges free.
    - If an edge is chamfered, conservatively use the shorter edge dimension. Otherwise, use the average edge distance dimension.
- Fastener bearing load P and orientation angle will be assumed to remain unchanged.
- Element boundary running loads (N1 – N4, T1 – T4) are adjusted to account for changes in A and B.

IBOLT element loads for the re-balanced short edge distance condition must satisfy the IBOLT element equations of equilibrium given in Table 19.6-16. For guidance on IBOLT problem definition, refer to Section 11.5.2 or the IDAT IBOLT User's Guide. This section provides guidance for IBOLT element orientation (11.5.2.4), dimensions (11.5.2.5) and loads (11.5.3.6).

EDGE FASTENER – Edge fastener elements must have one traction free edge condition. The short edge distance will define one of the IBOLT element dimensions, the other dimension should be extended as much as allowed by Section 11 guidance. Panel loads (NX, NY, NXY) will be reacted by fastener bearing and a bypass load may exist in a direction parallel to the edge. Engineering judgment must be used to determine if this bypass load should be adjusted for the short edge distance condition. If the short edge distance is due to a mislocated or increased diameter fastener, then the bypass load may remain unchanged. If the short edge distance is due to removed laminate material along the edge, then the bypass load may need to be scaled by the change in cross-sectional area.

CORNER FASTENER – Corner fastener elements must have two traction free edge conditions. The distances to both free edges will define the IBOLT element dimensions. Panel loads will be reacted by fastener bearing and there is no bypass loading. As required by equilibrium, the two non-zero shear tractions must be equal to one another.

The IDAT/IBOLT analysis tool has an MRB tool that can be used to balance IBOLT element loads with changes in A and B dimensions. The analysis steps for running a revised IBOLT strength analysis for a short edge condition using the Balance Loads utility is described in Table 19.6-17.

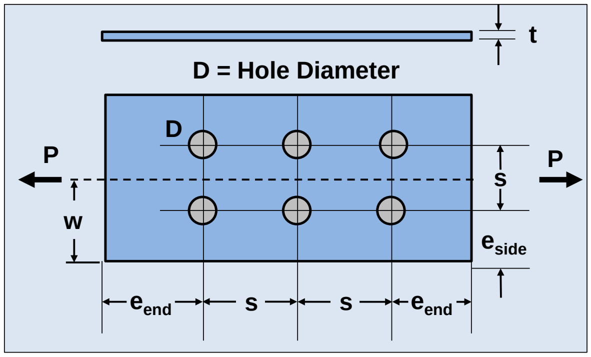
Table 19.6-16 IBOLT element load equilibrium equations.	
IBOLT element load equilibrium: $\sum F_X = B\cdot(N1-N3)+A\cdot(T2-T4)+PX=0$ $\sum F_Y = A\cdot(N2-N4)+B\cdot(T1-T3)+PY=0$ $\sum M_Z = 0.5\cdot A\cdot B\cdot(T1+T3-T2-T4)=0$	**Equation 19.6-17**
Rearranging into a more convenient form: $PX = B\cdot(N3-N1)+A\cdot(T4-T2)$ $PY = A\cdot(N4-N2)+B\cdot(T3-T1)$ $T1+T3=T2+T4$	**Equation 19.6-18**
Where: N1-N4 = IBOLT element boundary normal running loads (lb/in) T1-T4 = IBOLT element boundary shear running loads (lb/in) A, B = IBOLT element dimensions (in) PX, PY = IBOLT fastener bearing loads in the x and y directions, respectively (lbs)	

Table 19.6-17 IDAT/IBOLT Analysis Short Edge Distance Analysis.

1. Set up the original analysis parameters.
2. Select …
   Main Menu/Tools/MRB Tools/Balance Loads …
3. Enter revised element dimensions for the short edge condition.
4. Select and designate Free Edges.
5. Select Balance Loads.
6. Review and adjust as needed, then accept selecting “Apply.”
7. Strength analysis is ready for execution.

19.6.16 Fastener Hole Spacing (s/D)

Defect/Damage: FASTENER HOLE SPACING



Description:
A nonconforming fastener spacing exists in a composite joint element when the fastener pitch or spacing is either below the required 4D minimum or exceeds the 8D maximum, where D is the hole diameter. Fastener spacing in composite fastener joint elements is required to be no less that 4D and no greater than 8D.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:
A nonconforming fastener spacing condition is characterized by:

- Fastener type, diameter, and location.
- Fastener spacing as measured from hole center to hole center in the affected fastener pattern.
- Laminate stacking sequence and principal fiber directions (rosette) relative to fastener line.
- Any additional design features should be noted that may influence the laminate joint strength.

Disposition and Repair Guidance:

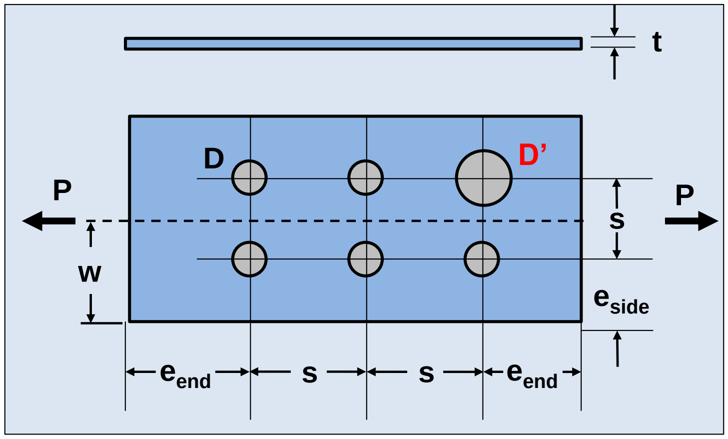
- Fastener spacing below the 4D minimum in a composite laminate bolted joint element can reduce filled hole strength, bearing-bypass strength, and can induce a net tension failure mode. This is due to the interaction of hole stress concentrations and the reduction in net section area.
- Fastener spacing that exceeds 8D maximum in a composite laminate bolted joint element can result in skin section instability between fasteners (similar to inter-rivet buckling) or a fastener pull-through failure mode as fastener tension loads must increase to hold the structure together.
- In general, a nonconforming fastener spacing condition can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis. This is the preferred approach for a below tolerance condition as a repair is difficult and complicated. However, an above tolerance condition can usually be repaired by adding a fastener.
- If EOD residual strength analysis cannot show a sufficient strength margin, then a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) will be required to provide an alternate load path and restore design ultimate load capability.

EOD Residual Strength Analysis:

- For spacing below the 4D minimum, revise the original IDAT/IBOLT strength analysis as required following the IBOLT element dimension guidelines provided in Section 11.5.2.5 and Table 11.5-3.
- IDAT/PACT analysis may be also used to determine any increases in hole edge stress concentrations due to the interaction of a given fastener pattern under panel loads.
- Laminate net tension stress should be checked using the unnotched laminate tension strength at environment.
- For spacing that exceeds the 8D maximum, conduct a skin section stability check for the increased fastener span and conduct a laminate pull through strength check for tension loads induced by the increased spacing.

19.6.17 Inadvertent Increase in Fastener Diameter

Defect/Damage: INCREASED FASTENER DIAMETER



Description:
An installed fastener is larger in diameter than that called out by the engineering drawing. This may be the result of:

- A required repair in which the existing hole diameter was enlarged to clean up and remove laminate hole drilling damage; or
- Hole was inadvertently drilled to a larger diameter size.

As a result, the fastener should be checked for a non-conforming short edge distance or spacing condition.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:
The nonconforming fastener is characterized by:

- Fastener type, diameter and location.
- Fastener edge distance as measured from the hole center to the nearest laminate edge.
- Fastener spacing as measured from hole center to hole center in the affected fastener pattern.
- Laminate stacking sequence and principal fiber directions (rosette) relative to fastener line.
- Any additional design features should be noted that may influence the laminate joint strength.

Disposition and Repair Guidance:

- An increase in fastener diameter in a composite laminate bolted joint element can reduce bearing strength, filled hole strength, bearing-bypass strength, and can induce an edge shear out failure mode.
- In general, an increased fastener diameter can be accepted for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis.
- For a nonconforming fastener edge distance or spacing, refer to Sections 19.6.15 and 19.6.16, respectively.
- If EOD residual strength analysis cannot show a sufficient strength margin, then a Doubler or Metallic Fitting Repair (Sections 19.8.16, 19.8.17, 19.8.19) will be required to provide an alternate load path and restore design ultimate load capability.
- For hybrid composite-metal joints, refer to PM-4057 Section 18.6.1.1 for necessary analysis of the metal structure for oversize fastener repair.

EOD Residual Strength Analysis:
Revise the original bolted joint strength analysis for the increased fastener diameter.

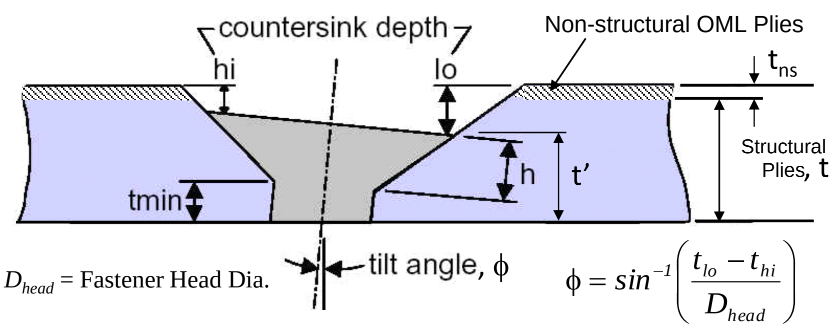
19.6.18 Countersink Nonconformances

Common types of countersink nonconformances are addressed in the following sections:

- Section 19.6.18.1 Deep Countersink
- Section 19.6.18.2 Countersink Geometric Anomalies
- Section 19.6.18.3 Inadvertent Countersink

19.6.18.1 Deep Countersink

Defect/Damage: DEEP COUNTERSINK



D_{head} = Fastener Head Dia.

$$\phi = sin^{-1}\left(\frac{t_{lo} - t_{hi}}{D_{head}}\right)$$

Description:
A deep countersink condition exists when the measured countersink depth exceeds:

- Maximum allowable depth as specified by the engineering drawing or program guidance; or
- 80% of the laminate structural thickness.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:

- Countersink depth is measured from the OML surface to the top of the fastener head.
- If the fastener head is tilted, the countersink depth is measured to the top of the highest side of the fastener.
- Fastener tilt angle ϕ may be estimated from fastener head diameter and high/low side depths using the equation above.
- Many composite parts have curved surfaces, so it is recommended that the analyst visually inspect the hole to determine the minimum effective laminate thickness t'.

Disposition and Repair Guidance:

- In general, a deep countersink condition can be approved for a USE-AS-IS or a Resin Filler Repair (19.8.3) disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis described below.
- If a USE-AS-IS disposition is not acceptable, then a Bushing Repair (Section 19.8.2) may be used to restore static strength.

EOD Residual Strength Analysis:

- The residual strength for a deep countersink condition can be determined using the analysis described in Table 19.6-18 for composite materials included in the IDAT material database.
- Alternatively, use the analysis described in Table 19.6-19 for composite materials <u>not included</u> in the IDAT material database.
- Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

Table 19.6-18 EOD Residual Strength Analysis for materials included in the IDAT database.

1. **IBOLT Strength Analysis for Discrepant Condition**
   a) Review "Deep CSK Hiside" dimension (in) and "Tilt Angle" used in original analysis (entered in the IBOLT Joint Configuration Menu). A nominal tilt angle (such as 1.45 degrees) is often used for structural analysis. Check the original bearing-bypass and bearing cutoff margins of safety under "DEEP COUNTERSINK ANALYSIS" in the output as shown in Figure 11.7-3.
   b) Determine "Deep CSK Hiside" dimension (in) and "Tilt Angle" for current discrepant condition and run IBOLT strength analysis. Initially, the removal of non-structural plies in calculating the countersink depth may be neglected.
   c) If positive margins are obtained, then proceed to Step 2. Suggestions for mitigating negative margins:
      - Remove any OML "non-structural thickness" from the measured countersink depth.
      - Check to see if the actual fastener tilt angle may be used to improve strength.
      - Review IBOLT input for overly conservative assumptions.

2. **Fastener Pull-Through Strength Analysis for Discrepant Condition**
   If a fastener PULLTHRU analysis was originally performed, or if the fastener tension load is high, then conduct a fastener PULLTHRU strength analysis as follows.
   a) Run PULLTHRU strength analysis using the original analysis parameters with the "Head Diameter", "Non Structural Thickness" and "Subflush Depth" dimensions entered in the Main Menu. Assume Subflush Depth equals t_{lo} for a tilted fastener. Initially, the Non Structural Thickness may be assumed to be zero.
   b) If a positive margin is obtained, then the analysis is complete. Suggestions for mitigating negative margins:
      - Remove any OML "non-structural thickness" from the measured countersink depth.
      - Review PULLTHRU input for overly conservative assumptions.

Reference notes:
1. Countersink strength analysis is covered in PM-4056, Sect. 11.7.3 and FZM-9065, Section 3.7.
2. Pull-through strength analysis is covered in PM-4056, Sect. 11.5.3

Table 19.6-19 EOD Residual Strength Analysis for materials NOT INCLUDED in the IDAT database.

1. **Bearing-Bypass Strength Analysis for Discrepant Condition**
   a) Review the input parameters for the original bearing-bypass strength analysis.
   b) Calculate an EOD strength retention ratio K_{EOD} using Equation 19.6-7 based on the deep countersink (refer to figure at the beginning of Section 19.6.18.1):

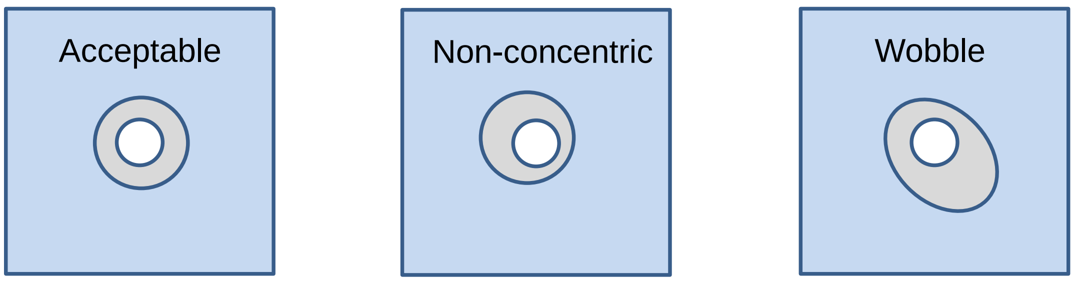
      $t_{undam} = t'$ = minimum effective laminate thickness below the fastener head.
      t_{total} = total laminate structural thickness

   c) Calculate a revised margin of safety MS_{EOD} using Equation 19.6-2 or Equation 19.6-3.
   d) If positive margins are obtained, then proceed to Step 2.

2. **Fastener Pull-Through Strength Analysis for Discrepant Condition**
   If a fastener pull-through strength check was originally performed, then complete steps 2a and 2b.
   a) Review the input parameters for the original fastener pull-through strength analysis.
   b) Using K_{EOD} calculated in step 1b, calculate a revised margin of safety MS_{EOD} for pull-through using Equation 19.6-2 or Equation 19.6-3.

19.6.18.2 Countersink Geometric Anomalies

Defect/Damage: COUNTERSINK GEOMETRIC ANOMALIES



Description:
Countersink geometric anomalies refer to imperfections in the countersink surface that prevent the installed fastener head from seating properly against the laminate. Examples include:

- Countersink geometry that is non-concentric with the hole.
- Countersink geometry that varies around hole (such as a wobble during hand drilling).

Characterization:
It is highly recommended that the hole be visually inspected by the analyst or documented by photograph.

- Record the nature of the defect and any pertinent measurements.

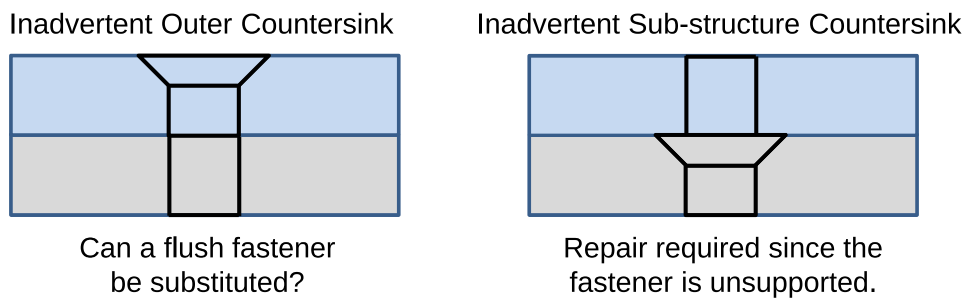
Disposition and Repair Guidance:

- Composite bolted joints require fastener systems with high head/tail fixity to attain full bearing strength and laminate pull-through strength capability. Therefore, it is important that the laminate countersink surface should fully support the fastener head around the perimeter of the fastener.
- In general, countersink geometric anomalies should be repaired by cleaning up the hole geometry with an Oversize Fastener Repair (Section 19.8.1) or Bushing Repair (Section 19.8.2).
- A Resin Filler Repair (Section 19.8.12) may also be used, but it is limited by a 20 ksi bearing strength capability. Therefore, it should only be considered for fasteners with low bearing loads.
- A USE-AS-IS disposition may only be considered for minor nonconformances under these conditions:
  - The joint has high margins for bearing and fastener pull-through strength; and
  - The joint has a bypass strength margin of at least +0.25 or greater.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

19.6.18.3 Inadvertent Countersink

Defect/Damage: INADVERTENT COUNTERSINK



Description:	**Characterization:**
An unrequired countersink is inadvertently drilled in a composite laminate. Two common examples are shown above; • Outer surface countersink • Sub-structure countersink	The fastener hole is identified and the hole diameter and countersink geometry depth and width should be measured.

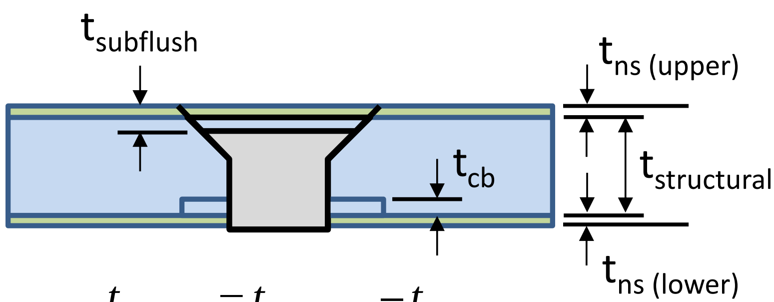
Disposition and Repair Guidance:

- In the case of an outer surface countersink, a simple substitution of a flush fastener of adequate strength may be considered provided that it satisfies all design and structural requirements. Otherwise, a Bushing Repair (Section 19.8.2) is required to accommodate the originally intended protruding head fastener.
- In the case of a sub-structure countersink, a Bushing Repair (Section 19.8.2) is required to support the fastener shank through the laminate.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

19.6.19 Counterbore Nonconformances

Defect/Damage: DEEP COUNTERBORE



$$t_{analysis} = t_{structural} - t_{cb}$$

OML Sub-flush and IML Counterbore Conditions are shown.

Description:
A deep counterbore condition exists when the measured counterbore depth exceeds:

- Maximum allowable depth as specified by the engineering drawing or program guidance; or
- The countersink and counterbore thickness combined should not exceed 80% of the laminate structural thickness.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:

- Counterbore depth is from the IML surface to the counterbore surface.
- The thickness of non-structural plies on the OML should be subtracted from the counterbore depth.

Disposition and Repair Guidance:

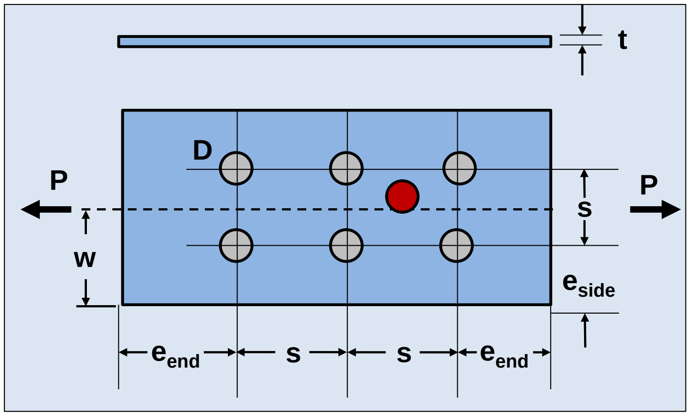
- In general, a deep counterbore condition can be approved for a USE-AS-IS disposition provided that positive margins of safety are obtained for the EOD Residual Strength Analysis described below.
- If a USE-AS-IS disposition is not acceptable, then a sleeve (Section 19.8.1) or bushing repair (Section 19.8.2) may be used to restore static strength.

EOD Residual Strength Analysis:

- The residual strength for a deep counterbore condition can be determined using the analysis approach described in Section 11.7.7.
- Positive margins of safety are required for the residual strength analysis for a USE-AS-IS disposition. Otherwise, the discrepant part (or assembly) must be REPAIRED or SCRAPPED.

19.6.20 Mislocated or Inadvertent Fastener Holes

Defect/Damage: MISLOCATED OR INADVERTENT FASTENER HOLES



Description:
This condition exists when a fastener hole is inadvertently drilled in a location other than that called out by the engineering drawing. Typical repair options are to either install a fastener in this location or plug the hole. As a result, the nonconforming fastener or plugged hole, as well as adjacent fasteners, should be checked for a nonconforming fastener short edge distance or spacing condition.*

* Per Bolted Joint Guidelines PM-4056, Sect. 11.3, unless otherwise specified by engineering drawing or program guidance.

Characterization:
The nonconforming fastener hole is characterized by:

- Fastener type, diameter and location.
- Fastener edge distance as measured from the hole center to the nearest laminate edge.
- Fastener spacing as measured from hole center to hole center in the affected fastener pattern.
- Laminate stacking sequence and principal fiber directions (rosette) relative to fastener line.
- Any additional design features should be noted that may influence the laminate joint strength.

Disposition and Repair Guidance:

- In general, the repair options are:
  - Install a fastener for a Fastener Filled Hole Repair (Section 19.8.4).
  - Plug the hole with a Resin Filler Repair for misdrilled holes (Section 19.8.3**).**
- The feasibility of a Fastener Filled Hole Repair depends upon the location, the surrounding fasteners, and whether it must tie into underlying substructure. A double flush repair fastener can be used provided there is access to both surfaces and sufficient thickness.
- A Resin Filler Repair should be evaluated as a laminate open hole whose strength and impact on surrounding fasteners must be evaluated.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

19.6.21 Missing or Detached (Spun) Nutplates

Defect/Damage: MISSING OR DETACHED (SPUN) NUTPLATES


Description:
This condition refers to a nonconforming or missing nutplate that has been installed in an interior aircraft location that is no longer accessible due to the current state of assembly. This refers to any inaccessible nutplate that must be replaced including damaged, missing, or incorrect type/diameter.

Characterization:
The nonconforming nutplate is characterized by:

- Fastener and nutplate type and diameter.
- Location and cause of nonconformance.

Disposition and Repair Guidance:

- In most cases, the blueprint fastener is replaced with a Blind Fastener Repair (**Section 19.8.5**) requiring a strength check for the substitute blind fastener. Blind bolt installations can vary, so it is recommended that, if possible, the tail-side be inspected after installation with a borescope through a neighboring fastener hole.
- If a nutplate repair can be devised that restores the intended design, then the blueprint fastener is installed and no analysis is required.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

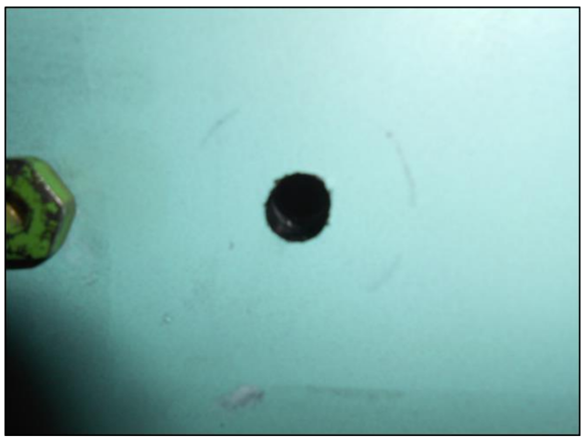
19.6.22 Misdrilled Damaged Holes

Common types of fastener hole drilling nonconformances are addressed in the following sections:

- 19.6.22.1 Fastener Hole Defects or Damage
- 19.6.22.2 Delaminated Fastener Holes
- 19.6.22.3 Misdrilled Pilot Holes

19.6.22.1 Fastener Hole Defects or Damage

Defect/Damage: FASTENER HOLE DEFECTS OR DAMAGE



Description:
Common drilled fastener hole defects:

- Double-drilled hole
- Elongated hole
- Out-of-Round hole
- Non-perpendicular hole
- Holes with rifling or scratches
- Burned or overheated holes

Characterization:
A defective or damaged hole is characterized by:

- Qualitative description of the defect
- Maximum measured hole length and width
- Measured hole perpendicularity
- If the hole has different top and bottom surface dimensions, this is quantified
- Edge distance if nonconforming
- Hole location

Disposition and Repair Guidance:

- In general, the hole is enlarged to remove damage and restore a circular, perpendicular hole geometry.
- If the finished hole is small enough, a first or second oversize fastener is installed (Section 19.8.1). If first or second oversize fasteners are not available, a Sleeve Repair (Section 19.8.1) may be used.
- If the finished hole is larger than a second oversize fastener, then a Bushing Repair (Section 19.8.2) may be used.
- The least preferred option is a Resin Filler Repair (19.8.3) since it is limited by low bearing strength.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

Effect of Wallowed Holes on Laminate Strength

EOD static strength tests were conducted on a legacy program (References 19-16, 19-18) to determine the effect of misdrilled wallowed holes on laminate strength. The limited testing does not address the issue of joint strength, bolt bending effects, and fatigue life on hybrid joints. Allowing for wallowed holes to remain in the structure is not recommended. The preferred disposition is to clean up the hole with an increased diameter repair.

The effect of a wallowed hole on bearing strength was evaluated for the case where the bolt hole was wallowed in the direction of the applied bearing load. The laminate coupons contained a wallowed hole (0.260 in. x 0.249 in.) with a 100-degree countersink. This particular configuration did not degrade the bearing strength of the composite layer as compared to the baseline hole geometry.

The effect of a wallowed hole on filled hole compression strength was also tested. Holes with a nominal 0.25 in. dia. were wallowed out by tilting a drill in the load direction. Strength retention factor K_{EOD} for filled hole compression strength is plotted in Figure 19.6-21 as a function of the difference between the max dia. and nominal dia. Once the diametric difference reached 0.010 in., the beneficial effect of filled hole vanishes and the response is same as open hole configuration.

The design curve has been implemented into MRB tools available within the IDAT/IBOLT analysis as described in Table 19.6-20. These figures do not necessarily apply to other material systems, do not account for bearing-bypass loads, effects on bolt strength, or fatigue life and should be used with caution.

Table 19.6-20 IDAT/IBOLT Analysis of Misdrilled Wallowed Holes on Filled Hole Compression.

IDAT Analysis	Compression
IBOLT	FHC

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Misdrilled Holes
2. Enter: Wallow Max Diameter (inch)

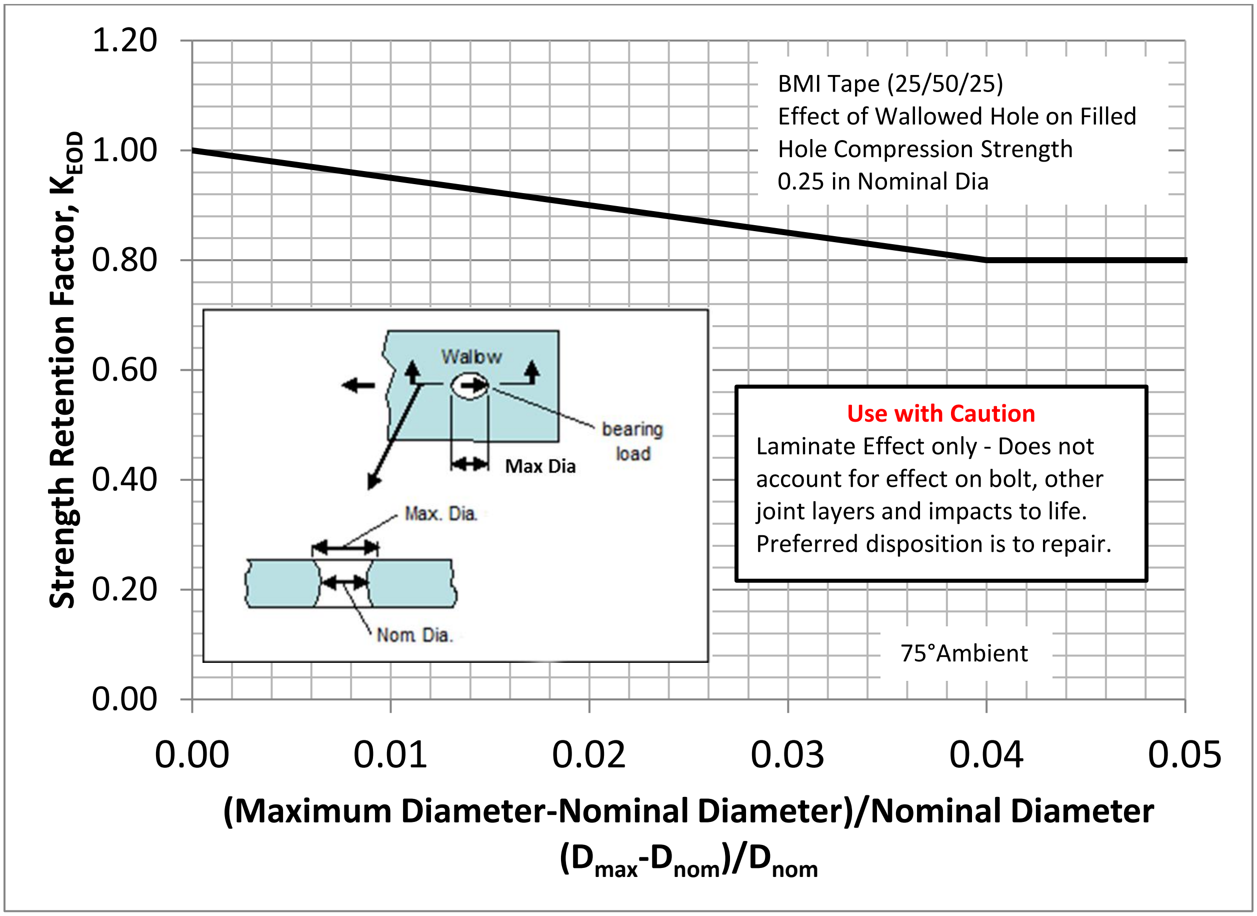


Figure 19.6-21 Effect of wallowed hole on normalized filled hole compressive strength

19.6.22.2 Delaminated Fastener Holes

Defect/Damage: DELAMINATED FASTENER HOLES

Description:
This defect refers to backside fastener hole delaminations that can result from the drilling of fastener holes. Delaminations from drilled fastener holes are subject to the usual NDI acceptance criteria.*

Delaminations around fastener holes may be caused by:

- Unsupported laminate
- Drill speed or feed rate is too high
- Over-tightening of fasteners during install

Delamination can occur at a single location or multiple locations in the laminate around the fastener hole.

* LM Aero Acceptance Criteria for Composite Parts and Assemblies are defined in Reference 19-9.

Characterization:
Fastener hole delamination is characterized by:

- Defect size (length x width) or area.
- Defect location and orientation
- Defect depth (when possible to determine)
- Defect type (delamination, void, foreign material inclusion).
- Acceptance class or criteria

Disposition and Repair Guidance:

- Fastener hole delaminations can affect the bearing strength, filled hole compression strength, open hole compression strength and the interlaminar shear strength (fastener pull-through).
- Small delaminations up to 1.0 in. maximum diameter may be repaired by a Resin Injection Repair (Section 19.8.7).
- Resin injection repairs greater than 1.0 in. maximum diameter must be supplemented with small pilot holes drilled only to the delamination depth.
- Splintered and broken fibers can be sealed and touched up with a Resin Surface Repair (Section 19.8.11) and/or Resin Filler Repair (Section 19.8.3) although the bearing strength is limited.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

.

Effect of Delaminated Fastener Holes on Laminate Strength

EOD static strength tests were conducted on a legacy program (References 19-16, 19-18) to determine the effect of misdrilled delaminated fastener holes on laminate strength. The tests were conducted on IM7/5250-4 BMI laminates, but the knockdowns can be extended to similar materials such as IM7/977-3 Epoxy laminates. Similarly, for some strength parameters, the effect was studied for tape or fabric only but the results can be extended conservatively to both material forms.

The strength retention factor is plotted as a function of the ratio of median delamination diameter to fastener diameter. The effect of fastener hole delamination on the bearing strength for a fabric is shown in Figure 19.6-22. Test results for countersink and protruding head fasteners are plotted. It can be observed that the strength retention is higher for the countersink fastener as compared to the protruding head fastener.

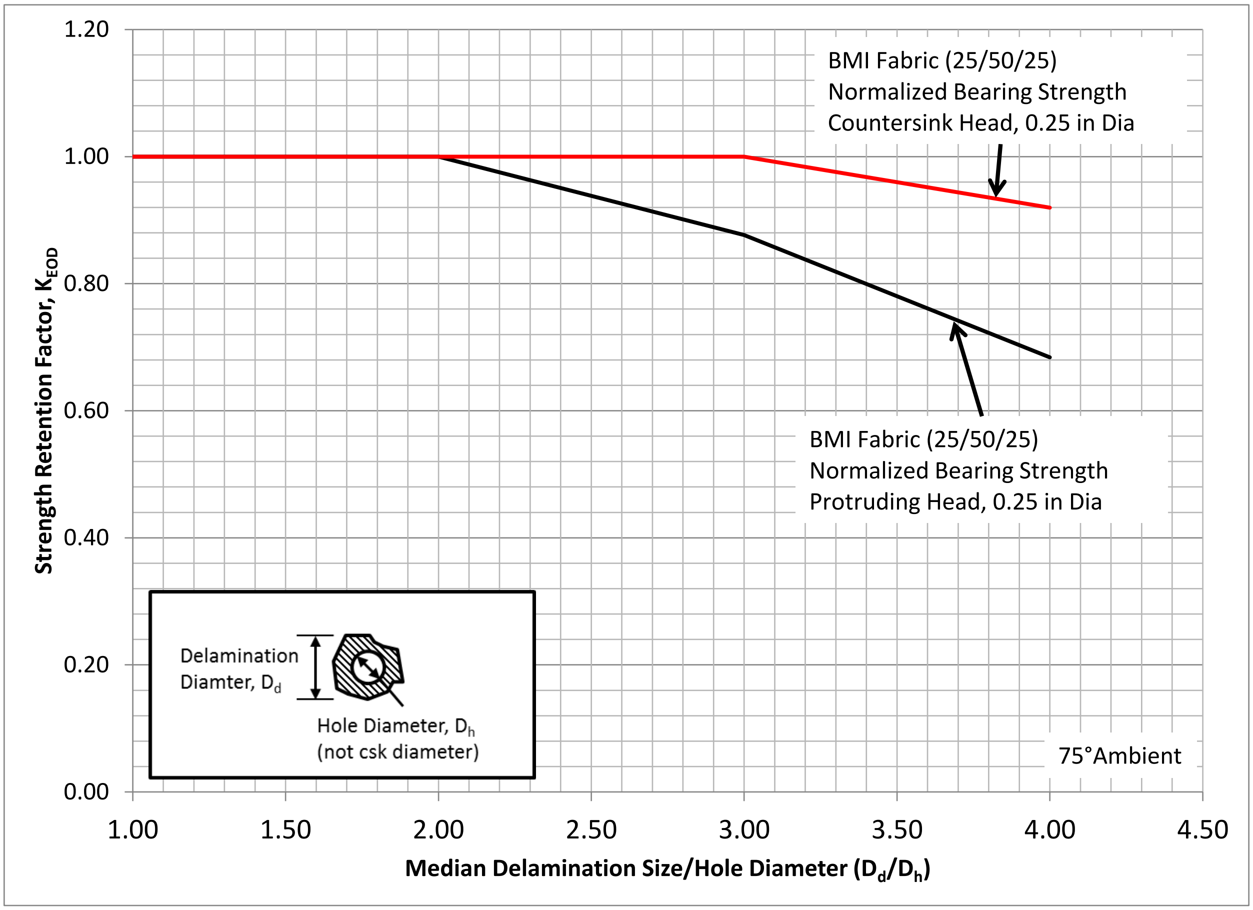


Figure 19.6-22 Bearing strength retention as a function of delamination size.

The effects of fastener hole delamination on Filled Hole Compression (FHC) and Open Hole Compression (OHC) strength are shown in Figure 19.6-23. The strength retention factor is a linear function of delamination size ratio. The OHC strength data indicates that the effect of delamination size is more severe for tape than that observed for fabric.

The FHC strength retention is for a fastener diameter-to-hole clearance of 0.004 inch. The FHC is a function of fastener hole clearance also. For a clearance of 0.010 inch and above the filled hole compression strength is the same as the open hole compression strength. For a fastener hole clearance between 0.004 inch and 0.010 inch the

FHC strength is assumed to vary linearly between the FHC strength at 0.004 inch clearance and OHC strength at 0.010 inch clearance.

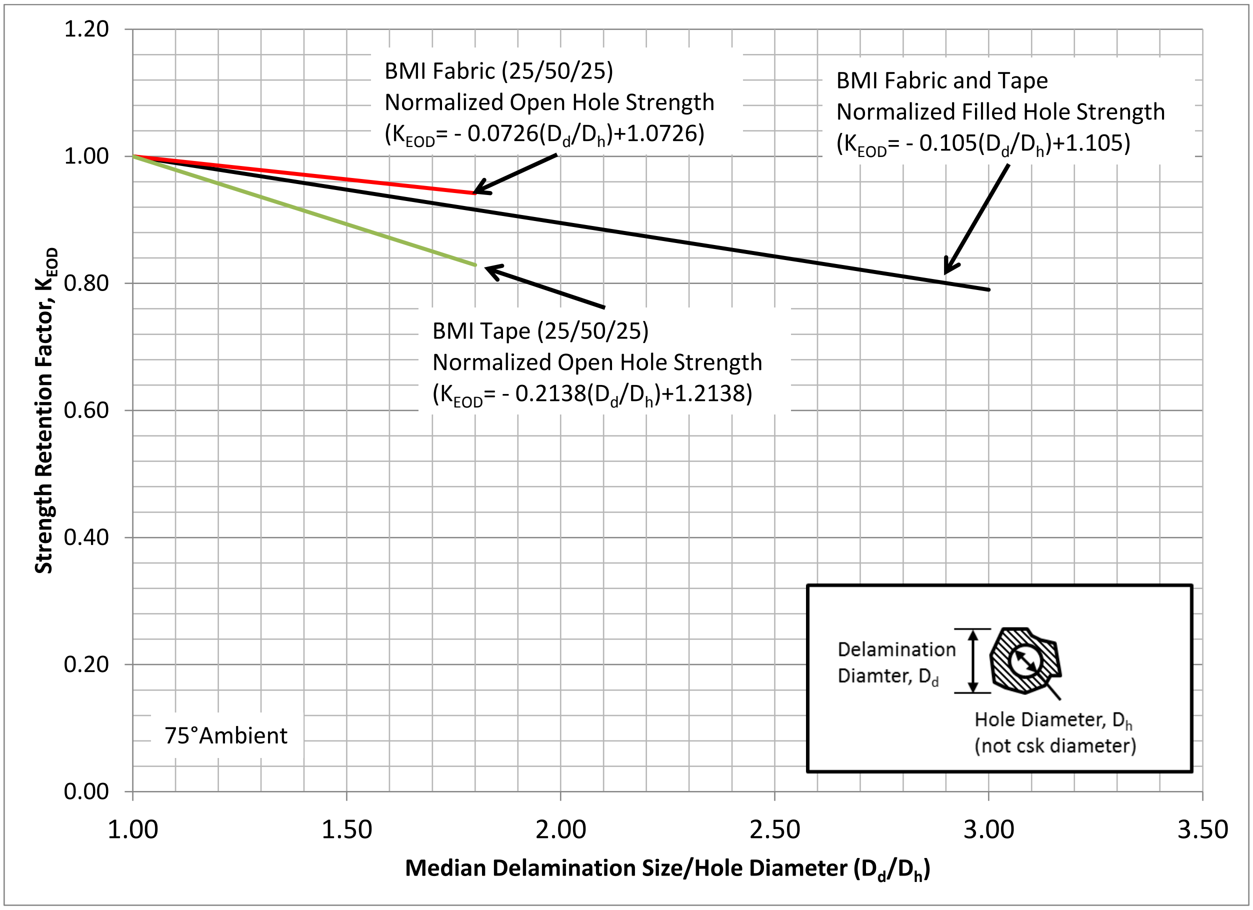


Figure 19.6-23 FHC and OHC strength retention as a function of delamination size.

The effect of fastener hole delamination on fastener pull-through strength is depicted in Figure 19.6-24. The pull-through strength is not apparently affected by delamination size up to 1.25 times the fastener head diameter. Beyond that delamination size the pull-through strength reduces linearly with the delamination size.

These design curves have been implemented into MRB tools available within the IDAT analysis tools as described in Table 19.6-21. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-21 IDAT Analysis of Delaminated Fastener Holes on Allowable Strength.

IDAT Analysis	Compression	Bearing	Interlaminar Shear
IBOLT	FHC, OHC	BCT, BCC, BCS	
PULL-THRU			ILS
IDAT Manufacturing Defect Analysis 1. Select … Main Menu/Tools/MRB Tools/Manufacturing Defects/Delaminated Holes 2. Enter: Delamination Diameter (inch)			

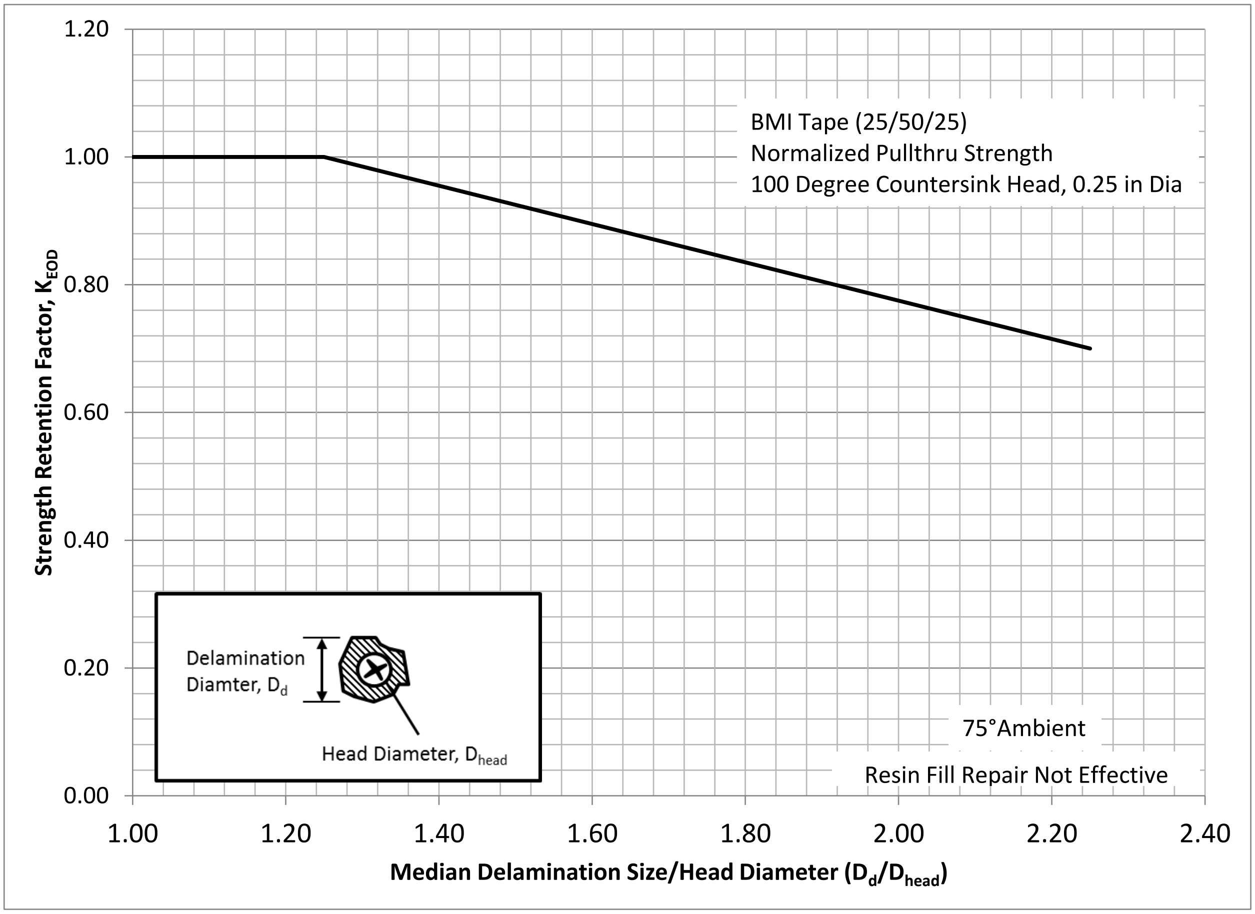
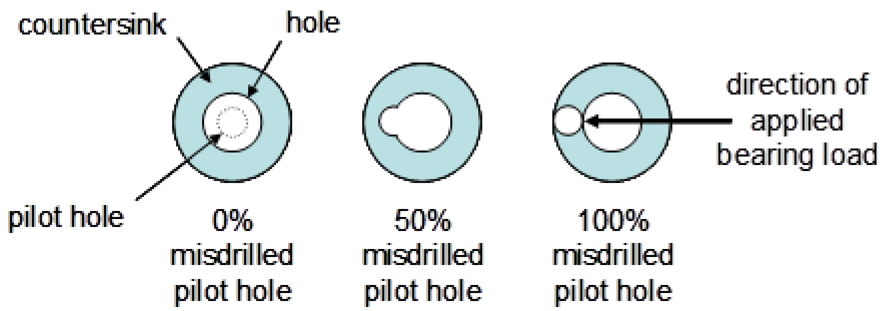


Figure 19.6-24 Pull-through strength retention as a function of delamination size.

19.6.22.3 Misdrilled Pilot Holes

Defect/Damage: MISDRILLED PILOT HOLES



Description:	**Characterization:**
Misdrilled pilot holes are pilot holes that are still visible even after the main hole is drilled. The various locations of the pilot hole with respect to the main hole are shown above.	A misdrilled pilot hole is characterized by: • Hole diameter and location. • Fastener spacing as measured from hole center to hole center in the affected fastener pattern. • Laminate stacking sequence and principal fiber directions (rosette) relative to fastener line. • Any additional design features should be noted that may influence the laminate joint strength

Disposition and Repair Guidance:

- In general, the recommended disposition is to repair the misdrilled pilot holes with a Resin Filler Repair (Section 19.8.12). However, this repair is limited by a low bearing strength.

EOD Residual Strength Analysis:
Recommended disposition is to REPAIR.

<u>Effect of Misdrilled Pilot Holes on Laminate Strength</u>

EOD static strength tests were conducted on a legacy program (References 19-16, 19-18) to determine the effect of a misdrilled pilot hole on laminate bearing and filled hole tension strength.

The bearing strength was shown to be not affected by misdrilled pilot holes. However, this result cannot be extended to mislocated full-size holes without further testing specific to the configuration.

Filled hole tension strength is affected by a misdrilled pilot hole and its effect is depicted in Figure 19.6-25. The maximum knockdown in filled hole tension strength occurs when the pilot hole just touches the full-size hole i.e. 100% misdrilled hole.

The design curve has been implemented into MRB tools available within the IDAT/IBOLT analysis as described in Table 19.6-22. These figures do not necessarily apply to other material systems and should be used with caution until effects of defects testing can be conducted to verify their use. When program specific effect of defects data is available they should be used in lieu of the charts.

Table 19.6-22 IDAT/IBOLT Analysis of Misdrilled Pilot Holes on Filled Hole Tension.	
IDAT Analysis	**Tension**
IBOLT	FHT

IDAT Manufacturing Defect Analysis

1. Select …
   Main Menu/Tools/MRB Tools/Manufacturing Defects/Misdrilled Holes
2. Enter: Misdrill Offset (inch)

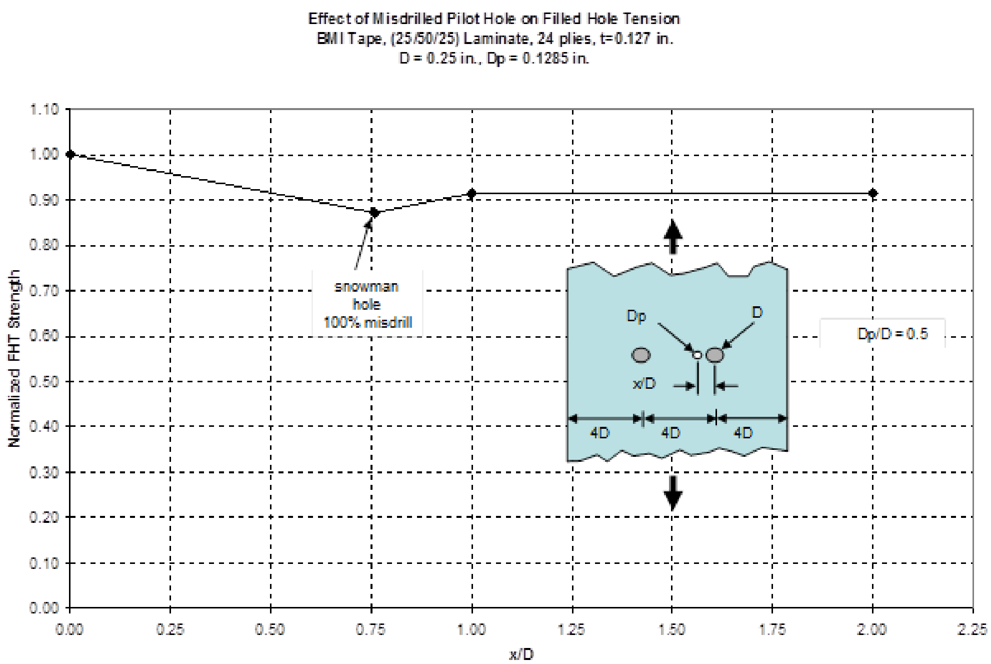


Figure 19.6-25 Effect of misdrilled pilot hole on filled hole tension strength

19.7 Composite Repair Materials & Manufacturing Processes

This section provides a brief overview of common materials and manufacturing processes used in repair of composite aircraft structures. Specific composite repair methods are discussed individually in Section 19.8. This discussion is based on materials and manufacturing processes that are currently in use at LM Aeronautics and within the aerospace industry.

19.7.1 Repair Considerations

The following factors should be considered when selecting composite repair methods for use in production material review support or for in-service field, depot or unit level repairs.

- <u>On-Aircraft versus Off-Aircraft Repairs</u> – Whether or not the defective part or assembly may be removed from the aircraft will dictate which materials, processes, tools and equipment may be used for damage removal, installation of repairs, and final curing of resins and adhesives. Accessibility to the various part surfaces may also impact the available repair options.
- <u>Material Availability</u> – Thermoset composite resins and adhesives have cold storage requirements to keep the materials stable and time limitations with respect to total shelf life, storage out time, and working life prior to cure. In addition, composite part fabrication is becoming increasingly outsourced. These factors impact the ability to keep repair materials on-hand to support production material review and particularly for in-service unit and depot level repairs.
- <u>Availability of Manufacturing Tools & Equipment</u> – For many repairs, the removal of damage and repair installation requires careful workmanship to maintain the required close tolerances. Repair capabilities are directly dependent upon the tools and equipment available. In-service repairs at the field, depot and unit level may be limited by the availability of composite manufacturing tooling and equipment.
- <u>Aircraft Design Requirements</u> – Composite repairs that impact the aircraft outer moldline must be coordinated with Flight Sciences to determine which repair options may be allowable. The presence of lightning strike material, antennas or other electronic equipment may also be adversely affected by a repair. Fuel or environmental sealing must be maintained. Repairs to control surfaces and landing gear that impact mass properties should be coordinated with Flight Dynamics.

19.7.2 Typical Composite Repairs

This section provides a brief overview of common composite repair concepts and terminology. This section describes doubler repairs, resin filler plug repairs, tapered scarf repairs, and repair of bonded honeycomb sandwich structure. A doubler is an added sheet or plate of repair material joined to the lateral surface of a defective plate that is intended to share in-plane load and provide structural reinforcement. The original part and repair doubler may be joined by a bolted, bonded, or bolted-bonded joint. The concept of a bonded tapered doubler is shown in Figure 19.7-1. This figure illustrates a one-sided bonded doubler that provides additional load carrying capability and strength reinforcement to the parent laminate. The doubler is bonded to the parent laminate using film adhesive. The tapered doubler configuration helps to reduce peak tension peel and shear stresses at the edges of the doubler. The doubler may be pre-cured in an autoclave to the required shape or cured in place using an autoclave, oven or heat blanket (refer to Section 19.7.3). A pre-cured doubler with an unsymmetric lay-up will warp at room temperature. This can be overcome by curing the doubler in place on the parent laminate.

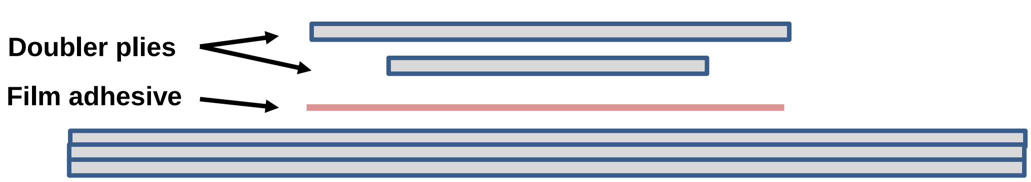


Figure 19.7-1 Bonded Tapered Doubler

Figure 19.7-2 illustrates a laminate plug repair where solid laminate damage has been removed and replaced with a plug of repair material. Plug repairs can be a partial depth or full depth repair. The plug may be a resin filler plug as shown or the void may be filled with a laminate plug. In either case, the plug acts as an elastic inclusion within an elastic plate.

Resin filler is a two-part room temperature cure epoxy that is mixed with filler material such as chopped carbon fiber or milled glass fiber to enhance the design properties (refer to Section 19.7.5). A full depth resin filler plug will have an upper and lower surface chamfer to help stabilize it. A resin filler plug is a preferred choice for small damage areas due to its ease in implementation. The repair plug may also be fabricated from composite repair plies although this repair option is more difficult to install. A laminate plug should have a lay-up similar to the parent laminate to minimize thermo-elastic mismatch stresses.

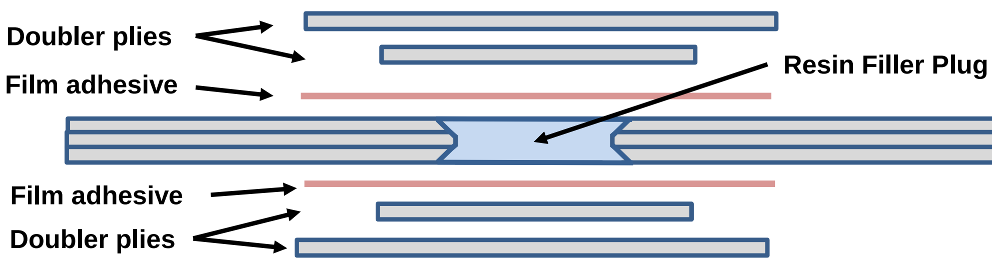


Figure 19.7-2 Resin Filler Plug with Symmetric Bonded Doublers.

Figure 19.7-3 illustrates a flush laminate scarf patch with bonded doublers on both sides for reinforcement. Where a plug repair is intended to fill a void within the structure, a scarf repair is designed to carry in-plane structural loads. A scarf patch will have a taper ratio between 10:1 and 30:1 to help transfer loads across the bond interface. The larger the taper ratio, the lower the peak stresses transferred across the bonded joint. Scarf repairs take careful workmanship to machine the tapered surface and to precisely lay-in the film adhesive and repair plies.

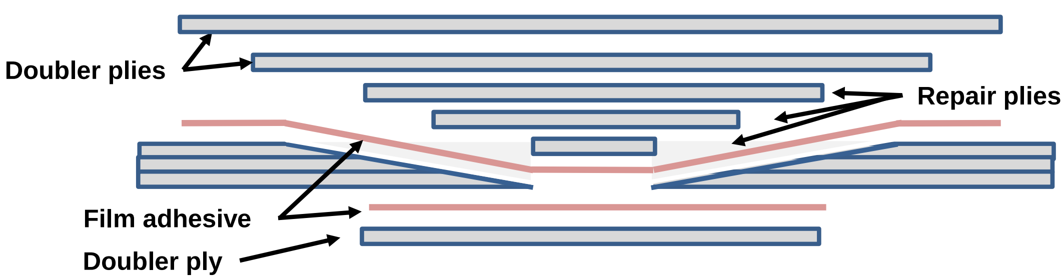


Figure 19.7-3 Flush Scarf Patch with Bonded Doublers.

Figure 19.7-4 illustrates a repair of bonded honeycomb core sandwich structure. This repair includes a bonded plug of honeycomb core material, a flush scarf repair of the upper Facesheet, and bonded doubler plies on the upper surface for structural reinforcement. As shown, this is a robust, complicated repair that requires careful workmanship.

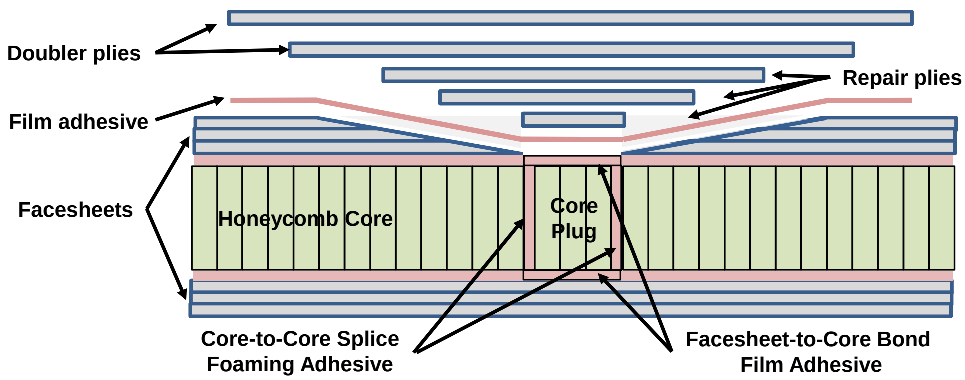


Figure 19.7-4 Repair of bonded honeycomb core sandwich structure.

19.7.3 Resin Cure Processes

The common processes used in the aerospace industry for curing of thermoset resin composites are discussed below. The autoclave cure is the baseline process used for composite part production. Out-of-autoclave cure, heat blanket cure and room temperature cure are common processes used for repair of composite parts.

19.7.3.1 Autoclave Cure

Thermoset polymeric resin composite parts are cured by placing the part under vacuum in an autoclave and activating the cross-linking process using applied temperature and pressure. An autoclave is a heated pressure vessel into which a tooling mold with the un-cured laminate is placed and subjected to an optimal temperature/pressure versus time profile as specified for that resin. The mold and laminate are covered with a release fabric, bleeder cloth, and a vacuum bag. A special pressure caul plate may be used for flat laminates. A vacuum line is attached to the mold for evacuation of volatile gases during cure to eliminate trapped gases which can lead to voids and porosity.

Epoxy resins such as 977-3 are classified as “350 °F cure resin systems” which refers to the approximate maximum holding temperature as specified for the cure process. The minimum span time for an autoclave epoxy cure process is approximately 8 hours. Epoxy resin composites typically have an operational temperature range from –65 °F to +275 °F.

Bismaleimide (BMI) resins such as 5250-4 are thermoset polymeric resins that have a higher temperature capability as compared to epoxy resins. BMI resins typically have an operational temperature range from –65 °F to +325 °F. The cure process for BMI occurs in two phases. The basic cure process requires placing the part under vacuum pressure in an autoclave and subjecting it to a specified temperature and pressure profile with an approximate maximum hold temperature of 350 °F. A vacuum line is attached to the part mold for evacuation of volatile gases during cure to eliminate trapped gases. During the basic cure, the part achieves a consolidated cured state. This is followed by a post-cure process to enhance mechanical properties at high temperature. The post cure process requires temperature only with an approximate maximum hold temperature of 440 °F.

Polyimides are another class of thermoset polymeric resins that have upper operational temperature limits ranging from above +400 °F to +600 °F and beyond. These resins usually have complex cure processes requiring that the part have vacuum pressure with high temperature and pressure autoclave cures. These resins are usually used for specialized high temperature applications such as engine components and supersonic/hypersonic vehicles.

19.7.3.2 Out of Autoclave (OOA) Cure

An Out-of-Autoclave (OOA) composite fabrication process is the curing of a thermoset resin without the use of a traditional autoclave. OOA processes that apply vacuum, pressure and heat by means other than an autoclave include the use of resin transfer molding (RTM), vacuum assisted RTM (VARTM), and other liquid molding processes as well as compression molding of prepregs.

An alternative OOA process is to cure the laminate using an oven with vacuum bag only (VBO) and atmospheric pressure. Oven cured, vacuum bagged material systems usually produce composite parts of higher void content and are limited to secondary structural applications. However, the aerospace industry is currently working toward development of newer oven-cured, vacuum bagged only cure material systems that are capable of reducing void content and delivering autoclave-comparable B-basis design properties. If successful, these resin systems may also be ideal candidates for composite repair applications. LM Aero has recently completed material allowable testing for IM7/MTM45-1 Tape and Fabric. MTM45-1 is an OOA resin system with flexible cure cycles. Refer to IDAT/MATUTL for material properties and Section 19.6 for Effects of Defects design curves.

19.7.3.3 Heat Blanket Cure

There are often repairs that are required for composite parts that cannot be removed from the airframe. If these repairs require the lay-up of uncured composite prepreg, wet lay-up repair material or film adhesive, then out-of-autoclave materials and processes must be used without an oven.

A thermal heat blanket can be used to heat a part to an elevated temperature cure at between 160 °F – 300 °F. The part will not have pressure, but a local bagging set-up must be used to pull a vacuum for the part. The key to a successful repair is to fully control and monitor the process throughout so that no parts of the structure become overheated or damaged, and yet the repair material achieves the full cure cycle. It is also important to carefully evaluate the temperature limits of structure surrounding the repair to ensure that the temperature limitations of those materials are not exceeded.

19.7.3.4 Room Temperature Cure

Room temperature cure adhesive resins are available for composite non-structural repairs. These epoxy resins come as a two-part paste adhesive, a resin and a curing agent, that are mixed together to initiate the cure process. Two part paste adhesives are discussed in detail in Section 19.7.5.1.

19.7.4 Laminate Repair Plies

There are two common forms of uncured composite plies that may be used for composite repair plies. The option is to use composite prepreg available from a qualified material supplier, or alternatively, a wet ply lay-up process can be used to coat dry fabric with a two-part epoxy resin. Both options are described as follows.

19.7.4.1 Prepreg

Prepreg is uncured composite material where the fibers have been “pre-impregnated” or infused with the matrix or resin material. The matrix may be partially cured to allow easy handling. This is called B-Stage material and still requires cold storage to prevent further curing.

Prepreg may be in the form of unidirectional tape or woven fabric. Prepreg tape or fabric is obtained from a qualified material supplier. Composite prepreg must be stored in a cold environment of typically 10 °F or below and has a storage life of about two years from the manufacturing date.

Autoclave cure systems will require an autoclave cure with elevated temperature, pressure and vacuum. Out-of-autoclave cure resins will require an oven or heat blanket cure under vacuum pressure. The material must be available and must be thawed prior to cutting and prep for lay-up.

19.7.4.2 Wet Lay-Up

Wet Lay-up is a composite fabrication process where a ply of dry fiber tape or woven fabric is fully wetted with a two-part epoxy resin just prior to lay-up. This is an alternative to the use of pre-preg material and wet lay-up is often used for composite repair fabrication. Wet Lay-Up is a good option for repair in that it takes advantage of the more flexible cure properties of the two-part epoxy resin. It also helps to reduce the number of materials that must be freezer stored on-hand to facilitate composite repairs. Typically, the ply may consist of carbon or glass fiber. A vacuum or pressure debulk process can be applied to the wet lay-up laminate using vacuum, heat and pressure (optional) to aid in removing entrapped air and to reduce the laminate thickness (consolidate) to near nominal thickness.

The Double Vacuum Bag Debulk (DVBD) is a composite fabrication process used for wet lay-up of composite repair parts. DVBD is a US Navy legacy process that yields lower porosity and structural design allowables comparable with prepreg carbon/epoxy fabric. The DVBD process has been developed by LM Aero for application to F-35 for in-service unit and depot level repairs.

19.7.5 Adhesives and Potting Compounds

This section provides a brief overview of the adhesives and potting compounds used in production manufacturing and for implementing composite structural repairs for production material review support and in the field.

19.7.5.1 Two Part Paste Adhesives

A number of useful composite non-structural repairs can be performed using a room temperature (RT) cure epoxy paste adhesive. Typically RT cure epoxies are available as a two part paste adhesive, with resin and a curing agent, that are mixed together to initiate the cure process. Often, this cure process can be accelerated through the application of moderate temperature (160-180 °F). Vacuum pressure may also be required to reduce void content. Common two-part epoxy paste adhesives used at LM Aero for composites repair are listed in Table 19.7-1.

Table 19.7-1 Common Two-Part Epoxy Paste Adhesives* Used for Composites Repair.

Material Specification	Description	Operating Temperature	Classifications	Product Name	Notes
LMA-ML004B	Room Temperature Curing Two Part Epoxy Laminating Resin	From –65 °F to +350 °F	Form 2, Two-Part adhesive, application time of 120 minutes, minimum.	EA9396 A/B	For use as an adhesive or laminating material in rework applications.
LMA-ML111	Adhesive, Epoxy Paste, Two Part	From -65 °F to +300 °F with short-term excursions to +350 °F	Type I, Two-Part, Metallic-Filled	EA9394, EA9394S, MB6398 A&B	Suitable for use in structural bonding if cured at 200 °F (or above).
			Type III, Two-Part, Non-Metallic-Filled	EA9395	
LMA-ML025B	Epoxy Resins for High Temperature Applications	From –65 °F to +300 °F	Class 1, Two-Part adhesive. Type A, Structural	EPON 828	For use as an adhesive, in sealing applications, or for glass fabric

			Applications.		laminates (Ref. LMA-PL026).
LMA-MK003A	Moldable Plastic Shim (MPS)	From –65 °F to +250 °F	Form 1, Two-Part, moldable plastic shim.	EA9377	Thermoset MPS with high compressive strength and microcrack resistance under thermocycling.
2ZZZ00041	Resin for Use with Double Vacuum Bag Debulk (DVBD) Wet Layup Process	From –65 °F to +250 °F	Type 1, Class 1 Two-Part	EA 9390, MB 7590 A/B	Elevated temperature curing epoxy resin compatible with a DVBD process.
* All materials listed are two-part epoxy paste adhesives. Refer to the Material Specifications for more information.					

Each epoxy resin shown has an operating temperature range of –65° F to +250 °F which is adequate for repair of epoxy resin composite structure. The epoxy resins, LMA-ML004 Form 2 and LMA-ML111 Types I and III, have an upper temperature limit of +325 °F with short excursions to +350 °F which is adequate for repair of many bismaleimide (BMI) resin composite structures.

Epoxy resins may be mixed with added filler materials to enhance their mechanical properties. Filler materials may include metallic powder, chopped carbon fiber, glass beads, or milled glass fiber. These filler materials are mixed in specified weight proportions with respect to the resin. Program specific guidance is usually used to define the allowable mixtures and repair design properties. Some adhesives are available from the vendor with their own proprietary additives to enhance mechanical properties. Examples of these vendor materials are EA9395 (LMA-ML111, Type III) and EA9377 (LMA-MK003A, Form 1).

Composite joint strength testing conducted under a LM legacy program to support repair of bolted joints determined that EA9377 and EA9395 paste adhesives are capable of a 20 ksi bearing strength. The intent was to use EA9377 for repair of carbon fiber composite parts and EA9395 for repair of S-glass fiber composite parts. Recent tests have indicated that a mixture of epoxy resin and carbon flock may yield a bearing strength of 20 – 72 ksi.

The following paste adhesive resin repairs are covered in sections:

- 19.8.11 Resin Surface Repair – An application of epoxy to seal defective or damaged external composite laminate surfaces.
- 19.8.7 Resin Injection Repair – Injection of resin by syringe into the exposed edge of a delamination in a composite laminate.
- 19.8.12 Resin Filler Repair – A cosmetic application of epoxy resin, mixed with a filler to enhance the mechanical properties, to fill in gaps or missing portions of a composite laminate.
- 19.8.3 Resin Filler Repair of Misdrilled Holes – An application of epoxy resin, filled with chopped or milled fiber, to misdrilled holes that restores a 20 ksi bearing strength.

The resin repairs described in Sections 19.8.7, 19.8.11, and 19.8.12 are considered cosmetic repairs since the processes will yield variable results and it is impossible to determine the efficacy of a given repair. The repair described in Section 19.8.3 restores limited structural capability for 20 ksi bearing strength.

19.7.5.2 Film Adhesives

Film adhesives are the primary material form used within adhesive joints in the fabrication of composite bonded structural assemblies. Film adhesives are also used in skin-core and skin-close out structure joints in the fabrication of honeycomb sandwich structures. Common film adhesives used at LM Aero for bonded composite structural assemblies are listed in Table 19.7-2. Epoxy film adhesives are also used in bonded repairs, but the bismaleimide film adhesive is not used for repairs due the required high temperature post-cure.

	Table 19.7-2 Film Adhesives used for Composites Bonded Assemblies.					
Material Specification	Description	Cure Temp	Operating Temp	Class	Product Name	Notes
2ZZZ00002B	Epoxy Film Adhesive 350 °F Cure for 250 °F Service Applications	350 °F	From –65 °F to +250 °F	Type I, Grade 10G	FM300	0.10 lb/ft^2 weight with a tricot knit polyester carrier.
				Type I, Grade 08K		0.08 lb/ft^2 weight with an open knit polyester carrier.
2ZZZ00045A	Epoxy Film Adhesive 250 °F Cure for Repair Applications	250 °F	From –65 °F to +250 °F	Type I, Class A	FM300-2K	0.10 lb/ft^2 weight with a tricot knit polyester carrier.
				Type I, Class B		0.06 lb/ft^2 weight with a 0.006 inch polyester mat carrier.
LMA-MD007	Modified Epoxy Film Adhesive 350°F Cure	350 °F	From –65 °F to +275 °F	Type I, Grade 10G	AF191	0.10 lb/ft^2 weight with 0.015 in. Style 108 glass scrim carrier.
				Type I, Grade 8K		0.08 lb/ft^2 weight with 0.013 in. nylon scrim carrier.
LMA-MD028	Epoxy Film Adhesive	250 °F	From –65 °F to +250 °F	Form 1, Type A	AF563	0.060 lb/ft^2 weight with a random mat carrier.
				Form 1, Type B		0.100 lb/ft^2 weight with a knit carrier.
TBD (Currently in Preparation)	Epoxy Film Adhesive	350 °F	From –65 °F to +250 °F	Form 1M	FM309-1	0.080 lb/ft^2 weight with a polyester mat carrier.
				Form 1G		0.050 lb/ft^2 weight with a woven glass carrier.
LMA-MD107	Bismaleimide Film Adhesive	375 °F with 440 °F Post-Cure	From –65 °F to +325 °F	Type I	FM2550	0.060 lb/ft^2 weight, 0.012 in thickness, Style 104 glass carrier.
				Type III		0.082 lb/ft^2 weight, 0.014 thickness, Style 104 glass carrier.
	Note: Refer to the Material Specification for more information.					

Disbonds within adhesively bonded joints are usually repaired using Resin Injection (Section 19.8.9) with an epoxy paste adhesive such as LMA-ML004 (EA9396). The injection is made with a syringe through an exposed edge or small drilled pilot holes. Care must be taken to not extend the disbond during the injection process. This repair is intended to only partially restore the bond strength and to environmentally seal the disbond. Although the repair may restore strength, there is no credit taken for strength improvement since the repair process is variable, indeterminate, and no surface preparation is performed. The repair is supplemented as necessary with the installation of Delamination Repair Fasteners (19.8.6). Disbonds in honeycomb core sandwich bonded assemblies may also be repaired using a Resin Injection Repair (Section 19.8.8) with an epoxy paste adhesive.

19.7.5.3 Core Splicing Adhesives

Core splicing adhesives are used to splice and stabilize honeycomb core used in the repair of honeycomb sandwich structures. These adhesives may be used for fabricating core-core splice joints and core to close-out structure joints.

An example of an epoxy core-splicing adhesive is LMA-MD003, Grade 50 (AF-3024) that may be cured at 350°F (Type II) or 250°F (Type III). The adhesive has an operating temperature range from -65 °F to +325 °F. An alternative adhesive is LMA-MD019, Form 1 (AF-3002, PL654-1) that may be cured at 250°F for an operating temperature from -65 °F to +250 °F or at 350°F for an operating temperature from -65 °F to +325 °F.

An example of a bismaleimide core-splicing adhesive is LMA-MD002, Grade 50 (EA 9833.1 50 MIL) that may be cured as part of a BMI bonded assembly with an operating temperature from -65 °F to +325 °F.

The repair of core-core and core to structural close-out disbonds is usually accomplished using Resin Injection Repair (Section 19.8.8) with an epoxy paste adhesive such as LMA-ML004 (EA9396). Access to the disbond is usually through a small hole drilled into the bonded assembly which must be filled after the repair.

19.7.5.4 Potting Compounds

Potting compounds are paste adhesives that are suitable for use, among other things, in the reinforcement and edge filling of honeycomb core sandwich structure. Potting compounds have also been used for repair of honeycomb core sandwich structure. For example, potting compounds have been used for filling voids and for reinforcement of localized areas of crushed or damaged core. The use of potting compound for honeycomb core structural repair in control surface edges should be implemented with caution as the compound adds structural weight which may adversely impact the dynamic properties of the structure. When weight becomes an issue, a honeycomb core plug repair may be required (Section 19.8.14).

Epoxy resin potting compound is available as a two-part paste adhesive that can be cured at room temperature, or with an accelerated cure at higher temperature. Epoxy resin potting compound with its room temperature cure and operating temperature range from -65 °F to +350 °F make it a suitable material for use in repair and reinforcement of damaged honeycomb core provided that the core is accessible (skin has been removed). An example of epoxy potting compound used at LM Aero is LMA-MK002, Type IV (Magnolia 81-3 A/B). A substitute potting compound has also been fabricated on legacy programs using a mix of epoxy two part paste adhesive and 20% milled glass fiber by weight.

Bismaleimide potting compound is available as a one-part glass-microsphere filled paste adhesive that requires an autoclave cure and post-cure in an oven. Alternatively, it may also be cured and post-cured at high temperature in an oven only. An example of BMI potting compound used at LM Aero is LMA-MK001, Type I (CORFIL 5250-4).

19.8 Repair Methods

This section provides a summary of common repair methods used for composite airframe structure. The repair methods are adapted from common composite repairs used within the aerospace industry and from standard composite repairs that have been developed for use on LM Aero legacy aircraft programs. A list of the composite repair methods addressed in this section is shown in Table 19.8-1.

Table 19.8-1 Composite Repair Methods

Section	Repair Method
Repair for Fastener Holes (In Descending Order of Preference)	
19.8.1	Oversize Fastener and Sleeve Repair
19.8.2	Bushing Installation Repair
19.8.3	Resin Filler Repair for Misdrilled Fastener Holes
Miscellaneous Fastener Repairs	
19.8.4	Fastener Filled Hole Repair
19.8.5	Blind Fastener Repair
Repair for Voids, Disbonds, and Delaminations	
19.8.6	Delamination Repair using Fastener Reinforcement
19.8.7	Resin Injection for Delaminated Holes or Edges
19.8.8	Resin Injection for Disbonds in Sandwich Construction
19.8.9	Resin Injection for Disbonds in Adhesively Bonded Joints
Repairs for Removing Damage or Interference	
19.8.10	Blend & Smooth or Trim Repair
Replacing Damage with Resin, Resin Filler, Honeycomb Core or Repair Plies	
19.8.11	Resin Surface Repair
19.8.12	Resin Filler Repair to Restore Part Contour
19.8.13	Resin Filler or Laminate Plug Repairs
19.8.14	Honeycomb Core Repairs
19.8.15	Flush Scarf Patch Repair
Structural Reinforcement Repairs	
19.8.16	Bolted Doubler Repair
19.8.17	Bonded Doubler Repair
19.8.18	Combined Repair Configurations
19.8.19	Metallic Fitting Repair

Limitations that are common to these repair methods are:

- Any repairs to control surfaces, control surface back-up structure, landing gear, or landing gear back-up structure should be made in consultation with the Flutter and Dynamics group as the response of these flight critical structures could be affected.
- Any repairs to the Outer Mold-line Surface should be made in compliance with program requirements and/or in consultation with Flight Sciences Critical (FSC) personnel.
- If fracture critical parts are affected, additional DADT analysis is required.
- Room temperature cure, two part paste epoxy repairs should be limited to an operating temperature range of –65° F to +325°F with short excursions to +350°F. Consult with Materials & Processes Engineering to confirm allowable temperature usage limits.

Repair of Defective Fastener Holes

Repairs of defective holes, which might include oversized, elongated, figure-8, non-perpendicular, burned, or rough internal surface finish are typically accomplished by first cleaning up the hole to true (perpendicular to the surface) and round to some diameter larger than blueprint and then evaluating the repair options depending on the size of the hole. These repairs might include using oversize or next-sized fasteners, a sleeve repair, or a bushing repair to achieve blueprint fastener size. These options are described in detail in Sections 19.7.1-19.7.3.

The fit of oversized or sleeved fasteners must be the same as the fit for the standard size fasteners in the same joint and the fit should be noted as part of the repair. If a defective hole can be repaired by an oversize fastener that is generally the best alternative. If not, then a bushing repair is recommended. Many of the Lockheed Martin program specifications allow up to 10% of a fastener pattern to have oversized fasteners installed without material review action.

Defective oversized or irregular holes are detrimental because they:

- reduce joint head/tail fixity leading to higher joint rotation and increased peak bearing stresses
- allow movement of the connected parts which result in wear on the faying surface known as fretting
- wear under the head or nut of the fastener
- overload of adjacent fasteners as the joint must deflect sufficiently before the fastener in the elongated or oversized hole picks up load
- result in bending in the fastener
- increase in stress concentration due to elongated hole shape

It is for these reasons, that defective holes must be repaired.

19.8.1 Oversize Fastener and Sleeve Repairs

Repair: OVERSIZE FASTENER AND SLEEVE REPAIRS

Oversize Fastener Repair Diameters (inches)

Dash No.	08	3	4	5	6	7	8
Diameter	5/32	3/16	1/4	5/16	3/8	7/16	½
Nominal	0.1563	0.1875	0.2500	0.3125	0.3750	0.4375	0.5000
1st O/S	0.1719	0.2031	0.2656	0.3281	0.3906	0.4531	0.5156
2nd O/S	0.1875	0.2188	0.2813	0.3438	0.4063	0.4688	0.5313

Description:
Oversize fasteners are special repair fasteners which have shank diameters that are 1/64th, called a first oversize, or 1/32nd inch, called a second oversize, larger than the baseline fastener. A full fastener size diameter increase is typically 1/16th inch. The heads and threads remain the original diameter so that they use the same nuts, collars or nut plates.

For additional information on oversize fastener repairs, refer to Section 18.4.2 of PM-4057.

Application:
Oversize repair fasteners may be used for holes that have been enlarged to round and true condition to remove and clean up drilling damage but are slightly larger than the hole required by the engineering drawing.

Oversize fastener repairs are dependent upon what diameters and grip lengths are available. When smaller diameter oversize fasteners such as 5/32nd and 3/16th inch are unavailable, a repair will require going to the next size fastener. Another alternative, used by some programs, is to use a sleeve over the blueprint fastener if first and second oversize fasteners are not available. The steel sleeve comes in 1/64th and 1/32nd oversize and has circumferential grooves to allow the mechanic to shorten it to the correct grip length. Some programs do not allow the use of sleeves because of reported problems with the sleeve shearing in service and the sharp edges causing joint damage and downstream fatigue failure.

Limitations:

- An oversize fastener or sleeve repair must satisfy the hole fit tolerance engineering requirements.
- Minimum fastener edge distance and spacing requirements should be maintained in all parts common to the discrepant hole based on the new repair hole size.
- This type of repair is not applicable to interchangeable/replaceable (I/R) designated fasteners since the threads are the same as for standard size fasteners and an oversized fastener could inadvertently be replaced with a standard size fastener during panel removal. Fastener holes in I/R panels must be bushed and the blueprint fastener re-installed.
- If sleeves are used it is recommended that the number of affected fasteners be limited to no more than 2 adjacent and no more than 10% of the total number of fasteners in the joint.

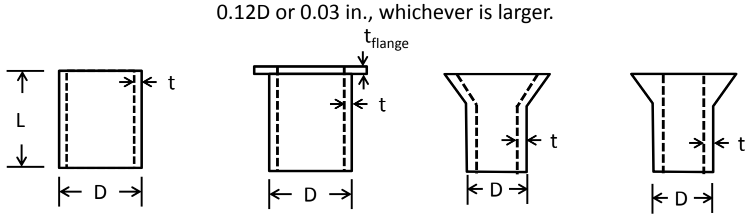
Repair Strength Analysis:

- Many of the Lockheed Martin program specifications allow up to 10% of a fastener pattern to have oversized fasteners installed without material review action.
- If required, laminate bearing-bypass and bearing cutoff strength analysis is performed for the new hole geometry (including countersink) for the oversize fastener or sleeve repair.
- IBOLT strength analysis is capable of assessing the strength of a fastener hole reinforcement such as a grommet, sleeve or bushing. This capability is accessible through selecting “Tools/MRB Tools/Bushings.” Refer to Section 11.7.4 and the IBOLT User’s Guide for guidance.
- For an oversize fastener repair, the fastener shear allowable for protruding head fasteners may be assumed, conservatively, to remain the same as the basic fasteners. The fastener shear allowable for oversized countersunk fasteners is typically the same as the standard size fastener because the countersunk heads are unchanged. The fastener tension allowable remains the same as the basic fastener because the threads or the head are typically the critical area.

19.8.2 Bushing Hole Repair

Repair: BUSHING HOLE REPAIR

Minimum recommended wall thickness:
0.12D or 0.03 in., whichever is larger.



Straight wall bushing	Shoulder Bushing Minimum flange 0.060 in.	For use in countersunk hole	For use in countersunk hole with protruding head fastener

Description:
A bushing is a specially designed cylindrical insert that acts as a load carrying filler material between the fastener and the joint material. As shown, bushings can be manufactured in a number of geometries that are useful in aircraft structure applications and can be made from a variety of materials. Bushings for composite hole repair typically have 0.001 to 0.003" outer diameter clearance fit and are bonded in place with the same type of sealant used to install affected fastener.

For additional information on bushing repairs, refer to PM-4057 Section 18.4.3. For bushing analysis techniques and discussion of wall thickness refer to PM4057 Section 5.2.5.

Application:
Bushings are used in the repair of damaged, elongated or oversized holes. Bushings may be used for repair of holes too large for an oversize fastener or sleeve repair.

Bushing repairs may be used with protruding head and flush fasteners. Acceptable bushing materials include Ti 6AL-4V, 15-5PH, PH13-8 Mo, and Inconel 718 steels.

- Bushing thickness: t_{wall} = 0.030 in. minimum or 12% of bushing outer diameter.
- Flange thickness is 0.060 in. minimum, if flanged

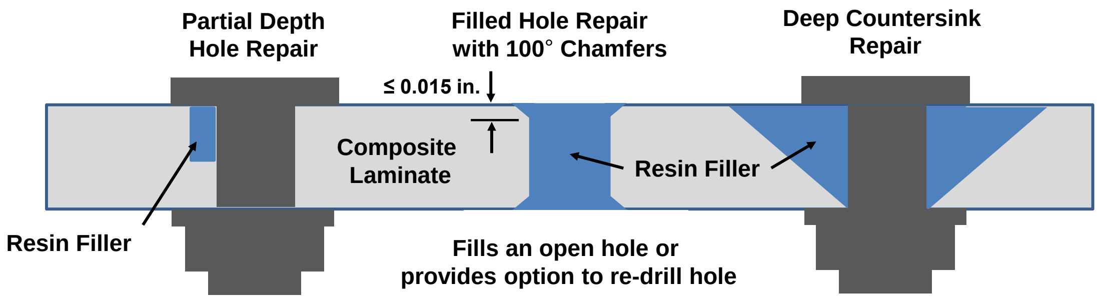
Due to galvanic incompatibility with carbon fibers, aluminum shall not be used as a bushing material in composite laminates.

Limitations:
- Fastener head/nut/washer must overlap repair bushing by .03 inches minimum.
- Bushing is to be common to one part only.
- Repaired hole to meet interchangeable-replaceable hole requirements, if applicable.
- Minimum tear out distance, where "D" is bushing outer diameter:
  - 2.0D - 0.03" to EOP
  - 1.5D - 0.03" to machine step edge
  - 0.050 inch to seal groove edge

Repair Strength Analysis:
- Laminate bearing-bypass and bearing cutoff strength analysis must be performed for the new hole geometry that is needed to accommodate the bushing. The effect of a countersink must also be accounted for in the strength analysis.
- IBOLT strength analysis is capable of assessing the strength of a fastener hole reinforcement such as a grommet, sleeve or bushing. This capability is accessible through selecting "Tools/MRB Tools/Bushings." Refer to Section 11.7.4 and the IBOLT User's Guide for guidance.

19.8.3 Resin Filler Repair for Misdrilled Holes

Repair: RESIN FILLER REPAIR FOR MISDRILLED HOLES



Description:
This repair uses a room temperature cure epoxy paste adhesive mixed with a non-metallic filler that can be used to make a resin filler repair for misdrilled fastener holes. The addition of non-metallic filler such as chopped carbon fiber or milled glass fiber can enhance the structural properties of the resin and provide a limited increase in bearing strength.

Adhesives LMA-ML004 Form 2 (EA9396) and LMA-025 Class 1 (EPON 828) are examples of epoxy resins that may be mixed with non-metallic fillers. Permissible mixtures and their allowable strengths are usually program dependent.

Adhesives LMA-ML111 Type 3 (EA9395) and LMA-MK003 Form 1 (EA9377) are available from the vendor with their own additives that are capable of 20 ksi bearing strength.

Applications:
Resin filler repairs for misdrilled hole may be applied to the following defects or damage:

- Mislocated or oversize holes
- Drill starts or finished double drilled holes
- Countersink nonconformances
- Backside drilling break out damage

The order of preference for misdrilled hole repairs is:

1) Oversize fastener (19.8.1)
2) Sleeve (19.8.1)
3) Bushing (19.8.2)
4) Resin Filler

Limitations:

- EA9395 and 9377 adhesives are limited to 20 ksi bearing strength. Refer to program guidance for other combinations of adhesive and fillers.
- Resin filled fastener hole repairs are not applicable at fuel boundaries. Use a fastener filled hole repair following all required fuel sealing guidelines.
- Not for use on faying surface areas of fuel boundaries or gasket(s).

Repair Strength Analysis:

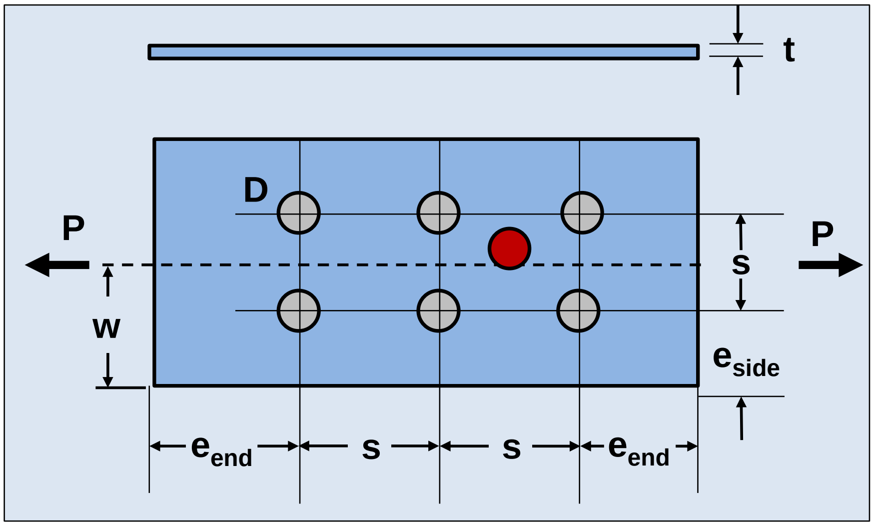
- The bearing cutoff strength margin should be recalculated using the bearing strength allowable for the resin filler material. The bearing cutoff margin can be calculated using Equation 19.6-2 or Equation 19.6-3 with the following Strength Retention Factor:

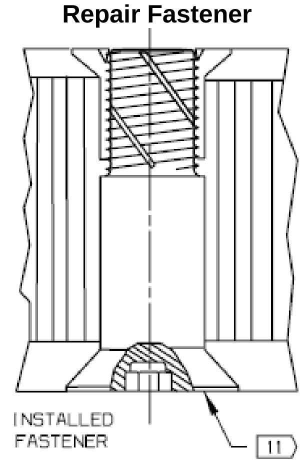
  $K_{EOD} = F_{bra}\,(\text{Resin Filler}) / F_{bra}\,(\text{Design})$

  Where:
  F_{bra} *(Resin Filler) = Bearing allowable for resin filler.*
  F_{bra} *(Design) = Bearing cutoff allowable used for "as-designed" margin of safety.*

19.8.4 Fastener Filled Hole Repair

Repair: Fastener Filled Hole Repair





Description:
This is a filled hole repair for a fastener hole that is inadvertently drilled in a location other than that called out by the engineering drawing.

In composite structure it is recommended that all holes be filled unless they are used as drain holes. An open hole, even as small as 0.125 in. will create an adverse stress concentration, but if the hole is plugged it will reduce the stress concentration to a minimum.

Note that this type of repair does not improve the net section tension stresses which are present and could cause failure. Net section analysis of the structure with the material removed for the hole needs to be performed and a positive margin of safety obtained.

Application:
The options for filled hole repair are:

- Install a fastener into the hole; or
- Fill the hole with a Resin Filler Repair (**Section 19.8.12**).

The repair choice depends upon the hole location, the surrounding fasteners, and whether there is underlying substructure present. Double flush fasteners may be used in applications where flush OML/IML surfaces must be maintained.

Limitations:

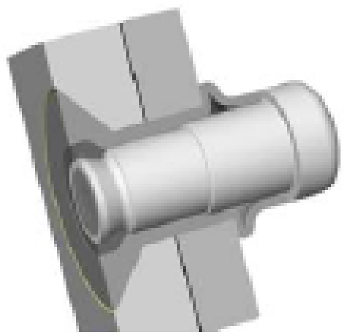
- Resin filled repairs are not applicable at fuel boundaries. A fastener filled hole repair with proper fuel sealing is required.

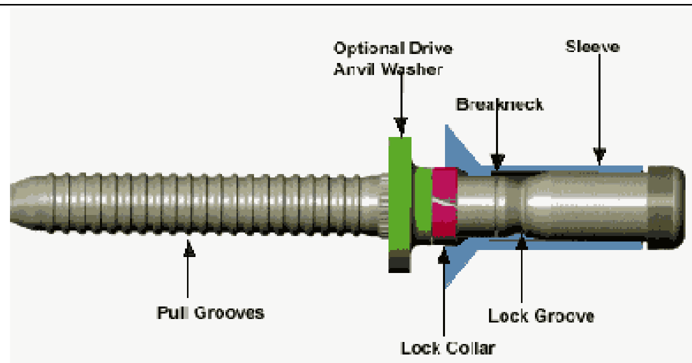
Repair Strength Analysis:

- The laminate strength due to the presence of the filled repair hole must be evaluated.
- A fastener filled hole repair should be evaluated for filled hole tension and compression strength.
- A resin filled hole repair should be conservatively evaluated for open hole tension and compression.
- IBOLT strength analysis or existing test data may be used to evaluate the strength.
- The interaction of stress concentrations due to surrounding fastener holes may be conservatively evaluated using IBOLT strength analysis with conservative element dimensions; or evaluated using the IDAT/PACT routine with each fastener hole modeled individually.

19.8.5 Blind Fastener Repair

Repair: BLIND FASTENER REPAIR





Description:
Blind fasteners require access to only one side of a joint to be installed. Blind fasteners are available in two types: blind rivets and blind bolts. Only blind bolts should be used for repair of composite bolted joints.

Be aware that some blind bolts diameters may only be available as a first oversize repair requiring a larger fastener hole diameter. Blind bolt installations can vary, so it is recommended that, if possible, the tail-side be inspected after installation with a borescope through a neighboring fastener hole.

Application:
Blind fasteners may be used as a substitute for a permanently installed, close-tolerance fit fastener where there is a nonconforming or missing nut-plate that is inaccessible. Various methods may be used to carefully remove a damaged nutplate using through hole access to clear space for the expanding tail-side of the blind fastener.

Blind bolts are typically available for protruding head and 100 degree flush fastener repairs. Bolt materials are typically CRES or Titanium.

Limitations:

- Only blind bolts should be used for repair in composite bolted joints; rivets are not recommended due to lack of clamp up force and potential damage that can occur to the laminate during installation due to the expansion of the shank.
- This repair is not applicable to Interchangeable-Replaceable designated fasteners or loose fit tolerance substructure holes.
- Use of blind fasteners should be avoided through fuel boundaries due to relatively low clamping force and potential leak path between the pin and sleeve. If used at a fuel boundary, a blind bolt with the large footprint is recommended with a sealant install (e.g., tension head BG2082 blind fastener).
- This type of repair is limited to no more than two adjacent fasteners.
- The blind fastener tension strength should be greater than or equal to the tension strength of the joint.
- The fastener fit throughout the joint stack-up must be the same and within the fastener hole requirements of the blind fastener. The fastener fit of the blueprint joint must be maintained.

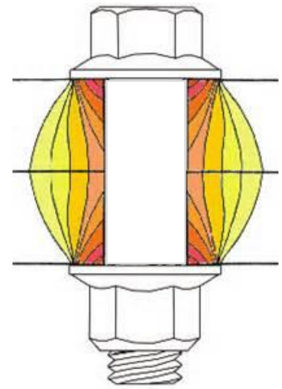
Repair Strength Analysis:

- Be aware that a given blind bolt repair fastener may require a larger fastener hole diameter (such as a first oversize) and this should be accounted for in the strength analysis.
- The substitution of a blind bolt fastener repair may have the following impact on joint strength:
    - Fastener fixity changes may affect predicted fastener bearing/load distributions.
    - Increased fastener hole diameter may affect laminate bearing-bypass and bearing strength.
    - Changes in fastener head geometry may affect laminate pull-through strength.
- Based on these considerations, the following strength analyses may be required.
    - IBOLT strength analysis should be run for the repair blind fastener and final hole diameter.
    - SFBOLT strength analysis should be run for the repair blind fastener and final hole diameter.
    - PULL-THRU strength analysis should be run for the repair blind fastener and any changes in fastener head diameter.

19.8.6 Delamination Repair Using Fastener Reinforcement

Repair: DELAMINATION REPAIR USING FASTENER REINFORCEMENT





Description:
Composite laminate delaminations can be repaired by installing fasteners through and along the periphery of the delamination. Fastener installations can provide localized through-the-thickness tension clamp up stress within a composite joint element that can help resist mode I fracture growth of a delamination.

Repair design depends upon the location, size and depth of the delamination. Depending on design need, the fastener may be a protruding head, single flush, or double flush fastener. A single delamination of up to one inch in diameter may be repaired with a single fastener through its center. Larger delaminations require a group of repair fasteners to clamp up and surround the delamination. Existing blueprint fasteners and substructure should be taken into account. The repair fastener pattern should provide good coverage over the entire delamination area while maintaining fastener edge distance and spacing requirements.

Application:
Delamination repair fasteners are applicable for:

- Planar delaminations
- Edge delaminations
- Disbonds within bonded joints

Delaminations in curved laminate sections should be repaired with a structural reinforcement such as a nested doubler or metallic fitting with a gusset.

A resin injection repair can also be performed on near surface edge delaminations (Section 19.8.7) or bonded joint disbonds (Section 19.8.9).

Limitations:

- This repair is intended to inhibit delamination growth only. The EOD Residual Strength of the laminate due to the presence of the delamination should be evaluated using the methods described in Section 19.6.1. Any repair benefit in compression strength from fastener reinforcement must be supported by test results.
- At fuel boundaries, all required fuel sealing guidelines for a fastener installation must be followed.

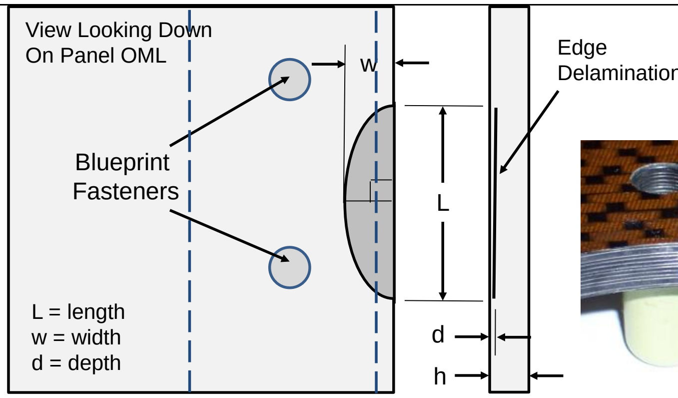
Repair Strength Analysis:

- Each delamination repair fastener should be checked for fastener filled hole tension and compression strength.
- Extensive repairs with a group of fasteners should also be checked for net section strength.
- IBOLT strength analysis or existing test data may be used to evaluate the filled hole strength.
- The interaction of stress concentrations due to surrounding fastener holes may be evaluated using IBOLT strength analysis with conservative element dimensions; or evaluated using the IDAT/PACT routine with each fastener hole modeled individually.

19.8.7 Resin Injection for Delaminated Holes or Edges

Repair: RESIN INJECTION FOR DELAMINATED HOLES OR EDGES

Resin Injection for
Delaminated Holes & Edges



Description:
Delaminations that are adjacent to a free edge may be repaired by injecting epoxy resin with a syringe into the edge. The intent is to environmentally seal the delamination. The repair requires an entry and exit path so that the entrapped air can be displaced by the in-flowing resin. Care must be taken to not grow the delamination during the injection process. Since the injection process effectiveness is variable and indeterminate, there is no benefit accounted for in strength analysis.

Resin injection is more effective at delaminations located near an upper or lower surface where the damage and thickness of the sublaminate may be more flexible and conducive to allowing resin to flow into the laminate. The deeper and longer the delamination, the less likely resin injection is to be effective.

A two-part room temperature cure epoxy resin (no filler) is recommended for injection repair. Examples are:

- LMA-ML004 Form 2 (EA9396) or equivalent
- LMA-ML025 Class 1 (EPON 828) or equivalent

Application:
Resin injection repairs may be applied to:

- Edge or corner delaminations
- Misdrilled delaminated drilled holes

In general, composite edge delaminations are repaired with a combination of Resin Injection and Delamination Repair Fasteners (19.8.6). All existing blueprint fasteners and their clamp-up should be accounted for in the repair design.

Delaminations that extend more than 1.0 inch from an edge (measured perpendicular to the edge) with no existing fastener holes adjacent to the disbond will require the drilling of pilot holes to aid the flow of resin. 0.093 in. diameter pilot holes are drilled such that they extend no more than 0.020 in. below the delamination to provide additional access/exit holes for injecting resin into the delamination.

Delaminated holes greater than 1.0 inch will require engineering judgment to determine if a structural repair is needed.

Limitations:

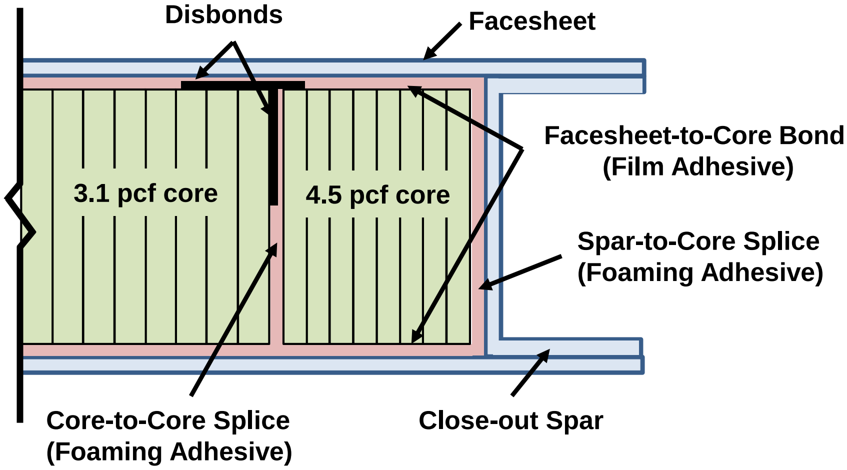
- For edge delamination, if fastener spacing is greater than 5D or no fasteners exist immediately adjacent to the disbond, then Delamination Repair Fasteners (19.8.6) should be used for added reinforcement.

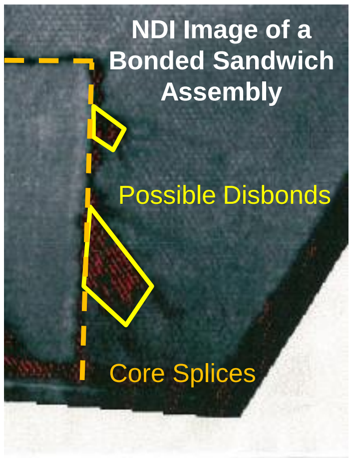
Repair Strength Analysis:

- This repair is intended to environmentally seal the delamination. Although the repair may restore strength, there is no credit taken for strength improvement since the repair process is variable, indeterminate, and no surface preparation is performed.
- Refer to the following Sections for applicable EOD residual strength analysis.
  - 19.6.1.2 Edge Delamination
  - 19.6.1.3 Delaminations in Curved Laminate Sections
  - 19.6.22.2 Delaminated Fastener Holes
- Delamination Repair Fasteners (19.8.6) should be added as required to contain large delaminations.
- Curved laminate sections may require a nested Metallic Fitting Repair (Section 19.8.19).

19.8.8 Resin Injection for Disbonds in Sandwich Panels

Repair: RESIN INJECTION FOR DISBONDS IN SANDWICH PANELS





Description:
Voids or disbonds within sandwich bonded assemblies may be repaired by injecting epoxy resin with a syringe into 0.093 in. diameter pilot holes drilled through the skin or close-out structural members. The intent is to environmentally seal the delamination. The repair requires an entry and exit path so that the entrapped air can be displaced by the in-flowing resin. Care must be taken during injection to prevent further disbond growth or to blow-out honeycomb cell walls.

Since the injection process effectiveness is variable and indeterminate, there is no benefit accounted for in strength analysis. The repair is still recommended for its potential sealing benefit.

A two-part room temperature cure epoxy resin (no filler) is recommended for injection repair. Examples are:

- LMA-ML004 Form 2 (EA9396) or equivalent
- LMA-ML025 Class 1 (EPON 828) or equivalent

Application:
Resin injection repairs may be applied to voids or disbonds in the following adhesively bonded joints:

- Skin-to-core bondlines
- Core-to-core splices
- Substructure-to-core splices

Non-destructive inspection techniques are used to evaluate adhesive bond integrity. These include ultrasonic and radiographic inspection techniques. A hand-held ultrasonic inspection can often be used to further characterize and confirm a skin-to-core disbond.

Limitations:

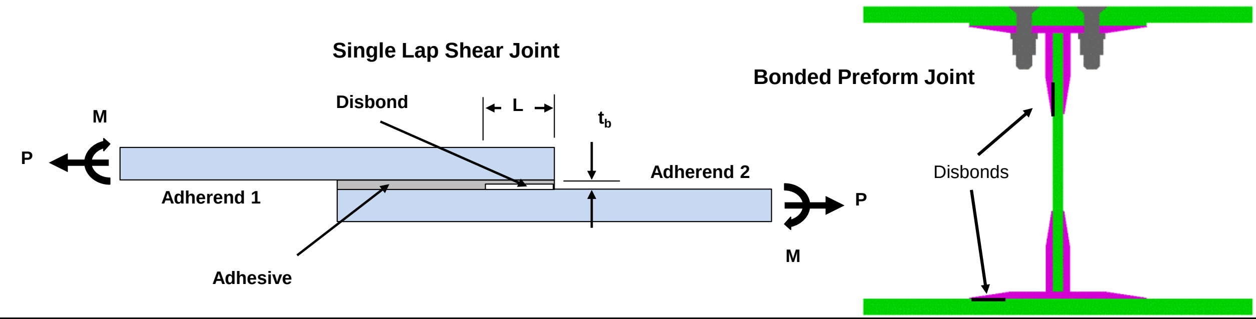
- Total void repair area shall not exceed 25% of the length of the bond, and no single void shall exceed 15% of the length of the bond.

Repair Strength Analysis:

- This repair is intended to environmentally seal the delamination. Although the repair may restore strength, there is no credit taken for strength improvement since the repair process is variable, indeterminate, and no surface preparation is performed.
- Refer to the following Section for applicable EOD residual strength analysis.
    - 19.6.1.4 Disbonds in Bonded Sandwich Structural Assemblies
- If negative margins are obtained for the EOD residual strength analysis, then a robust structural reinforcement will be required (such as a tapered scarf skin repair).

19.8.9 Resin Injection for Disbonds in Adhesively Bonded Joints

Repair: RESIN INJECTION FOR DISBONDS IN ADHESIVELY BONDED JOINTS



Description:

Disbonds within adhesively bonded joints that are adjacent to a free edge may be repaired by injecting epoxy resin with a syringe into the edge. The intent is to environmentally seal the delamination. The repair requires an entry and exit path so that the entrapped air can be displaced by the in-flowing resin. Care must be taken to not grow the delamination during the injection process. Since the injection process effectiveness is variable and indeterminate, there is no benefit accounted for in strength analysis.

Resin injection is more effective at disbond locations where one of the structural elements is flexible and conducive to allowing resin to flow into the laminate. The deeper and longer the disbond, the less likely resin injection is to be effective.

A two-part room temperature cure epoxy resin (no filler) is recommended for injection repair. Examples are:

- LMA-ML004 Form 2 (EA9396) or equivalent
- LMA-ML025 Class 1 (EPON 828) or equivalent

Application:

Resin injection repairs may be applied to voids or disbonds in the following adhesively bonded joints:

- Epoxy film adhesively bonded joints

In general, adhesively bonded joints are designed to carry loads across the bondline, so most resin injection repairs should be supplemented with Delamination Repair Fasteners (19.8.6) that are capable of carrying the entire joint load. All existing blueprint fasteners and their load carrying capability should be accounted for in the repair design.

Delaminations that extend more than 1.0 inch from the edge (measured perpendicular to the edge) must be supplemented with drilling 0.093 in. pilot holes that extend no more than 0.02 in. below the delamination to provide additional access holes for injecting resin into the delamination.

Limitations:

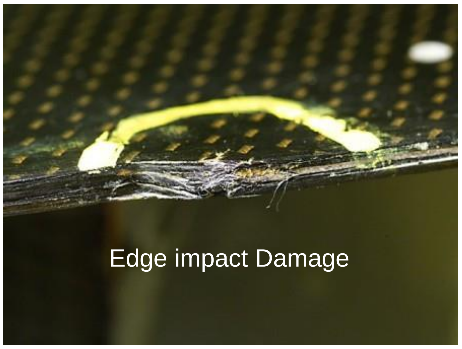
- Resin injection repairs are limited to epoxy film adhesive bonded joints (NOT for BMI adhesive repairs).
- Disbonds must extend to an open accessible edge of part, be visible on that edge by the naked eye and are limited to disbonds that extend less than 1.0 inch from the machined edge.
- Total void repair area shall not exceed 25% of the length of the bond, and no single void shall exceed 15% of the length of the bond.

Repair Strength Analysis:

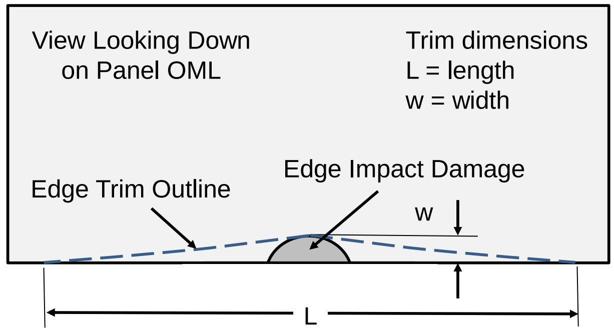
- This repair is intended to environmentally seal the delamination. Although the repair may restore strength, there is no credit taken for strength improvement since the repair process is variable, indeterminate, and no surface preparation is performed.
- Refer to the following Section for applicable EOD residual strength analysis.
  - 19.6.1.4 Bondline Delaminations
- Resin injection repairs should be supplemented with Delamination Repair Fasteners (19.7.6) that are capable of carrying the entire joint load. Only minor disbonds with at least a +0.25 minimum EOD residual strength margin may be exempted from added fastener reinforcement.

19.8.10 Blend and Smooth or Trim Repair

Repair: BLEND AND SMOOTH OR TRIM REPAIR



Edge Trim Repair



Description:
This repair refers to the removal of defective or damaged material through machining or trimming of a composite laminate. This repair may serve any combination of the following purposes:

- Removal or reduction of high stress concentration features
- Remove potential sources of damage propagation (such as a delamination)
- Eliminate possible source of Foreign Object Damage (FOD) material
- Restore a smooth surface contour
- Prepare and clear an area for either a resin filler repair or installation of a structural reinforcement repair (doubler or fitting).

Application:
Blend and Smooth or Laminate Trim repairs may be applied to the following defects or damage:

- Severe scratches or gouges
- Edge or corner impact damage
- Trimming or machining nonconformances
- Drilled fastener hole defects or damage

This repair is highly dependent upon location and severity of the damage. A taper ratio of 10:1 is recommended with a 5:1 minimum. The repair options should be carefully considered and engineering judgment may be required to assess the risks and benefits of the various repair options.

Limitations:

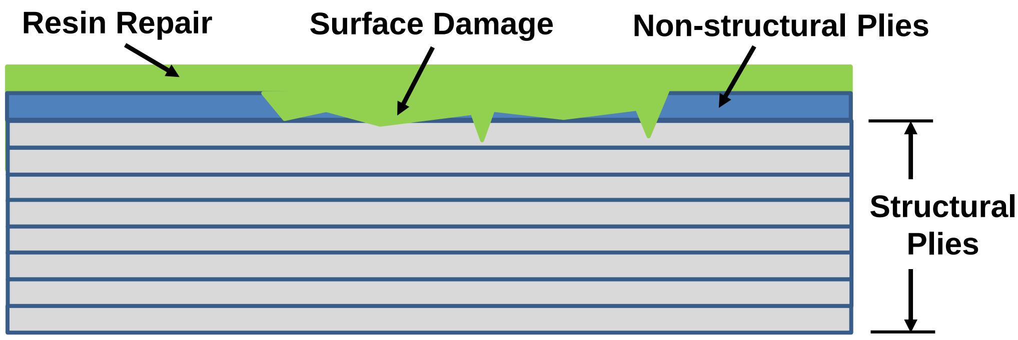
- Any repairs to the Outer Mold-line Surface should be made in compliance with program requirements and/or in consultation with Flight Sciences Critical (FSC) personnel.

Repair Strength Analysis:

- Undamaged plies must be capable of sustaining design ultimate load. Refer to the following Sections for applicable EOD residual strength analysis.
  - Section 19.6.2 Surface Scratches or Gouges
  - Section 0 Trimming or machining nonconformances
- If the undamaged plies are incapable of sustaining design ultimate load, then this repair must be followed with a structural reinforcement repair to restore design ultimate load capability, such as a Doubler Repair or a Fitting Repair. Otherwise, the panel must be SCRAPPED.

19.8.11 Resin Surface Repair

Repair: RESIN SURFACE REPAIR



Description:
A room temperature cure epoxy paste adhesive is applied to seal and repair minor surface damage of a composite laminate. This repair is intended to seal any loose or broken fibers, fill small pits, gaps or depressions, and prevent moisture intrusion. The cosmetic repair does not provide any strength benefit.

Resin surface repair is performed using epoxy resin (with or without filler) such as the following materials:

- LMA-ML004 Form 2 (EA9396) or equivalent
- LMA-ML025 Class 1 (EPON 828) or equivalent

Application:
Resin surface repairs to composite laminate may be applied to the following defects or damage:

- Scratches, gouges, or surface depressions
- Surface pits or cracks in resin rich areas
- Splintered or delaminated drilled holes
- Rough machined edges

A resin surface repair may also be applied to seal a surface following a blend and smooth or trim repair (Section 19.8.13).

Limitations:

- Defect depth limitation is 0.02 inch or 10% of the laminate thickness, whichever is less.
- For splinters deeper than one ply, use a Resin Injection Repair (19.8.8).
- Any repairs to the Outer Mold-line Surface should be made in compliance with program requirements and/or in consultation with Flight Sciences Critical (FSC) personnel.
- Repair is not suitable for surfaces that will be bonded with film adhesive in a later operation.
- Repair is not for use on faying surface areas of fuel boundaries or gasket(s).

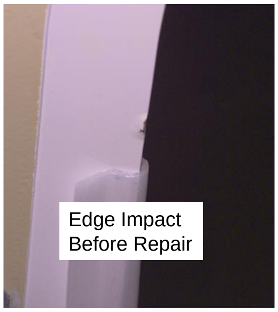
Repair Strength Analysis:

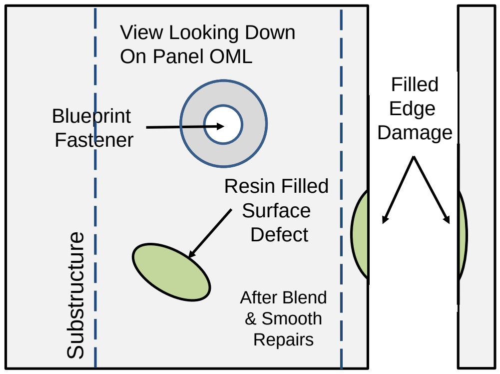
- This is a cosmetic repair intended to seal the laminate and provides no structural strength benefit.
- Undamaged plies must be capable of sustaining design ultimate load. Refer to the following sections for applicable EOD residual strength analysis.
  - Section 19.6.2 Surface Scratches or Gouges
  - Section 19.6.7 Porosity (Surface)
  - Section 19.6.8 Sub-Nominal Laminate Thickness (for a surface resin starved condition)
  - Section 19.6.22.2 Delaminated Fastener Holes
- If the undamaged plies are incapable of sustaining design ultimate load, then this repair must be followed with a structural reinforcement repair to restore design ultimate load capability, such as a Doubler Repair or a Fitting Repair. Otherwise, the part must be SCRAPPED.

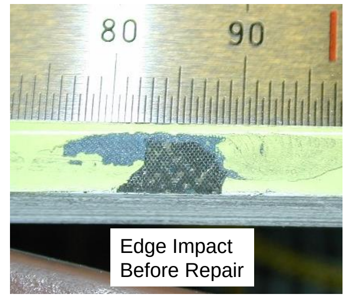
19.8.12 Resin Filler Repair for Restoring Part Contour

Repair: RESIN FILLER REPAIR FOR RESTORING PART CONTOUR

Examples of
Resin Filler Repairs







Description:
This repair uses an epoxy resin mixed with an added filler material that is used to fill missing or damaged portions of laminate to restore part contour. The addition of a filler material such as chopped carbon fiber or milled glass fiber can enhance the structural properties of the resin and provide an increase in bearing strength. Resin filler repairs should be treated primarily as cosmetic repairs intended to restore surface contour since the resin filler material has limited strength.

Adhesives LMA-ML004 Form 2 (EA9396) and LMA-025 Class 1 (EPON 828) are examples of epoxy resins that may be mixed with material fillers. Permissible mixtures and their allowable strengths are usually program dependent.

Adhesives with pre-added filler LMA-ML111 Type 3 (EA9395) and LMA-MK003 Form 1 (EA9377).

Applications:
Resin filler repairs to composite laminate may be applied to the following defects or damage:

- Edge or corner impact damage

This method may be used in addition to a Blend and Smooth Repair (Section 19.8.10) to remove damage and a Resin Injection Repair (19.8.7) for edge delaminations.

Limitations:

- If the damage is a suspected impact, the area should be non-destructively inspected for a delamination.
- Any repairs to the Outer Mold-line Surface should be made in compliance with program requirements and/or in consultation with Flight Sciences Critical (FSC) personnel.
- Not for use on faying surface areas of fuel boundaries or gasket(s).

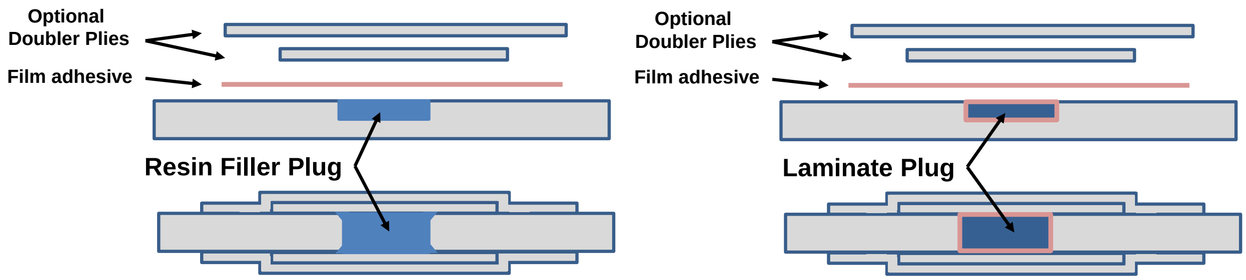
Repair Strength Analysis:

- This is a cosmetic repair intended to fill holes, repair missing laminate, and restore surface contour.
- Refer to the following Sections for applicable EOD residual strength analysis.
  - 19.6.2 Surface Scratches or Gouges
  - 0 Trimming or Machined Edge Nonconformances
  - 19.6.14 OML Mismatch
- If the undamaged plies are incapable of sustaining design ultimate load, then this repair must be followed with a structural reinforcement repair to restore design ultimate load capability, such as a Doubler Repair or a Fitting Repair. Otherwise, the panel must be SCRAPPED.

19.8.13 Resin Filler or Laminate Plug Repairs

Repair: RESIN FILLER OR LAMINATE PLUG REPAIRS

Plug with a Bonded Doubler Repair



Description:
This is a secondary repair that can be used to fill a void after a plug of damaged material has been removed from a composite laminate. The plug repair may be a partial or full depth repair and may be performed in combination with a Bonded Doubler Repair (Section 19.8.16). The repair plug may be composed of a resin filler or laminate plies.

Adhesives LMA-ML004 Form 2 (EA9396) and LMA-025 Class 1 (EPON 828) are examples of epoxy resins that may be mixed with material fillers. Permissible mixtures and their allowable strengths are usually program dependent.

Adhesives with pre-added filler LMA-ML111 Type 3 (EA9395) and LMA-MK003 Form 1 (EA9377) are capable of 20 ksi bearing strength.

Applications:
Plug repairs may be made with either:

- Resin Filler (Epoxy with added filler)
- Laminate repair plies

Resin filler plugs are easier to implement. Full depth repairs should be the same as a filled hole repair described in Section 19.8.3 with 100 degree chamfers on each surface.

Laminate plug repairs should be bonded in with adhesive. They are more difficult to fabricate due to geometric constraints. The laminate plug should be designed to have the same stiffness as the parent laminate.

Both plugs act as an elastic inclusion and should be treated as an open hole for laminate strength purposes.

Limitations:

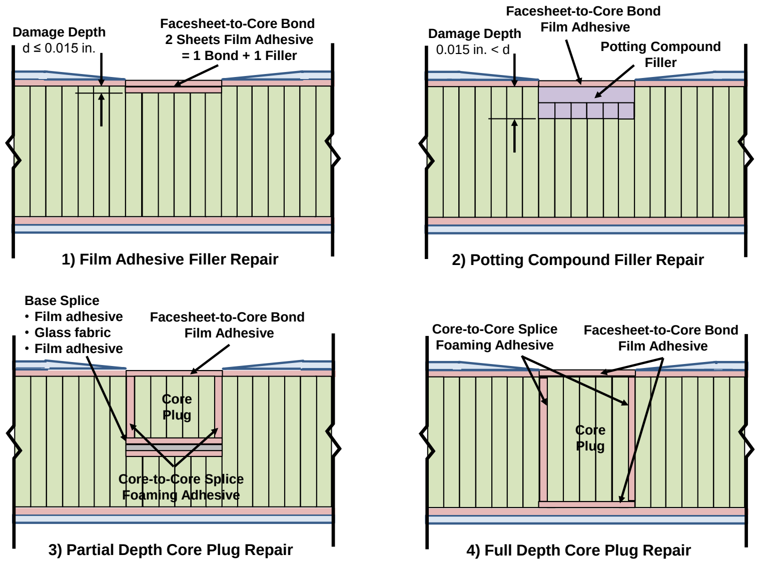
- A resin filler plug may be used for any hole up to a maximum in-plane dimension of 0.5 inch. A laminate plug may be used for holes with a maximum in-plane dimension ranging from 1.0 to 2.0 inches. Otherwise, use a laminate Flush Scarf Patch repair (19.8.15).
- If the damage is a suspected impact, the area should be non-destructively inspected for a delamination.
- Plug repairs are not applicable at fuel boundaries unless combined with a Bonded Doubler Repair (Section 19.8.16).
- Not for use on faying surface areas of fuel boundaries or gasket(s).

Repair Strength Analysis:

- This is a cosmetic repair intended to fill holes, repair missing laminate, and restore surface contour.
- If this repair is not combined with another reinforcement repair, then the laminate should be analyzed with the plug as ineffective and the undamaged laminate must be capable of sustaining design ultimate load.
- If the repair is combined with a Bonded Doubler Repair, then please follow the guidance of Section 19.8.18.

19.8.14 Honeycomb Core Repairs

Repair: HONEYCOMB CORE REPAIRS



Description:
This section describes the various repairs for damaged or crushed honeycomb core. The repair method is selected based on the damage depth and assumes the facesheet has been removed so that the core is accessible.

1) Film Adhesive Filler Repair using a single ply of film adhesive is for damage up to a maximum 0.015 inches.
2) Potting Compound Filler Repair handles damage from 0.015 inches up to where a core plug becomes feasible.
3) Partial Depth Core Plug Repair uses a glass fabric ply to make a base onto which a core plug may be bonded.
4) Full Depth Core Plug Repair bonds in a full depth core section of identical core material.

These repairs could be done for material review prior to cure of the bonded assembly, or after cure, as part of an overall repair of a damaged facesheet/core section where a combined core and facesheet (such as a tapered scarf repair) are cured together.

Application:
These repairs are applicable for repair of crushed or damaged honeycomb core in sandwich construction.

Core plug repair requires the removal of a defective or damaged section of honeycomb core which is replaced with a plug of identical core material. The core plug should be machined to match engineering requirements and surface contour.

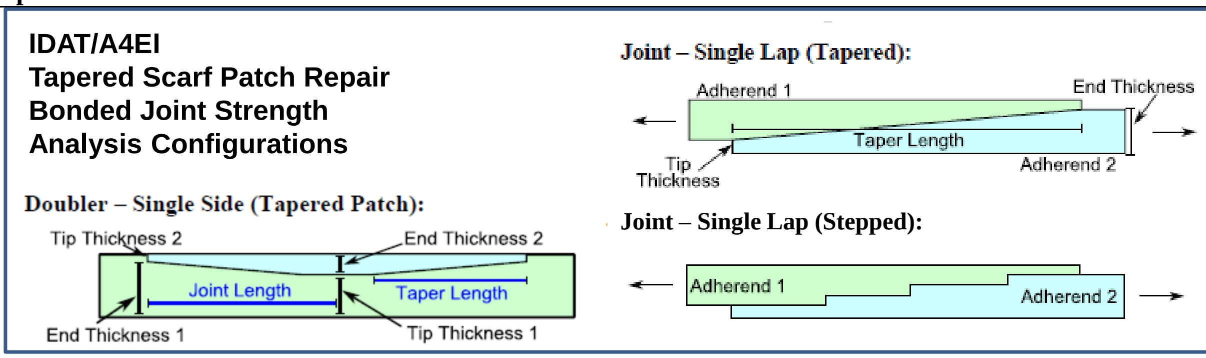
Film adhesive is applied to honeycomb core plug to facesheet interfacial surfaces. Foaming adhesive is used to fill the interfaces between the core plug and the assembly core. The core plug should also have a gap (0.050” maximum) between the plug and the assembly core to allow for splicing with foaming adhesive.

Limitations:
- Optimal repair strength properties can be obtained using autoclave cure process and materials, but requires that the defective part be removed from the structural assembly which is not always possible.
- If the defective part cannot be removed for autoclave cure, then an out-of-autoclave cure process and materials must be available with fully characterized strength properties.

Repair Strength Analysis:
- If the film adhesive and/or foaming adhesive used for the repair is different than the blueprint design, then the joints should be checked for strength at the critical design environment.
- No further strength analysis of the core plug is required if a facesheet structural repair has been used to restore the faceheet design ultimate load strength.

19.8.15 Flush Scarf Patch Repair

Repair: FLUSH SCARF PATCH REPAIR



Description:
A tapered scarf repair is designed to remove defective or damaged laminate material and replace it with an adhesively bonded "patch" of laminate filler material. The laminate patch is designed to carry in-plane loads and features a tapered scarf joint to optimize load transfer across the bondline. Film adhesive is recommended for all bonded joints. Industry practice is to use a taper ratio (length: depth) from 10:1 to 30:1. The larger the taper ratio, the more peak shear and tension peel stresses are reduced, but the larger the area required for the repair. A taper ratio of 10:1 to 20:1 is recommended for structural repairs. The repair patch may be a pre-cured laminate bonded into place; or an uncured laminate that is cured along with the adhesive.

Application:
A tapered scarf repair may be applicable where:

- The removal of defective or damaged laminate material is necessary or desired; and/or
- OML/IML design constraints or accessibility eliminate the possibility of using only a doubler repair (Section 19.8.16).

The repair patch may extend only partially or through the entire thickness of the original part. Depending upon OML/IML design requirements, the tapered scarf repair may be reinforced in strength by adding doubler plies (Section 19.8.16) to the OML and/or IML of the original part.

Limitations:
A tapered scarf repair can be difficult to implement due to the following manufacturing related factors:

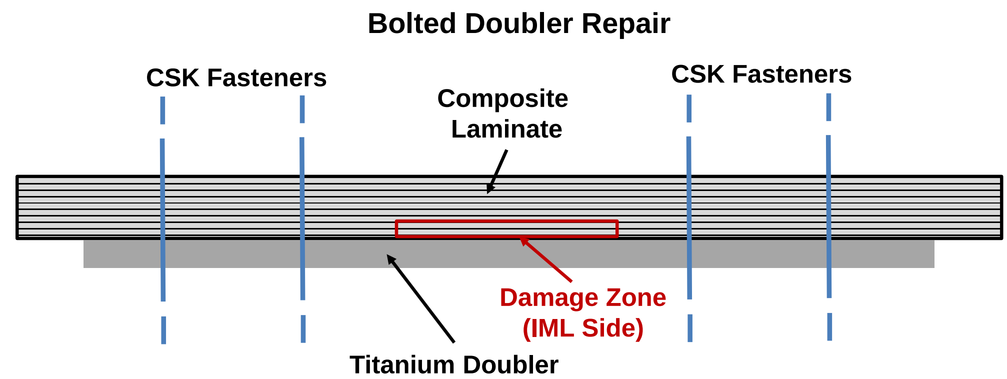
- In general, tapered scarf patch repairs typically require up-front development of materials, processes and design data before they can be successfully implemented.
- Machining of the defective part to remove damage and create the tapered scarf joint requires a carefully controlled process. Splash tooling may be used to capture the final machined geometry for a custom patch.
- Lay-up of the film adhesive and laminate patch requires careful workmanship to properly align the repair plies and avoid ply overlaps.
- Optimal repair strength properties can be obtained using autoclave cure process and materials, but requires that the defective part be removed from the structural assembly which is not always possible.
- If the defective part cannot be removed for autoclave cure, then an out-of-autoclave cure process with a heat blanket may be used to bond in a pre-cured laminate patch with film adhesive.

Repair Strength Analysis:

- The bonded joint static strength analysis can be performed using IDAT/A4EI or by finite element analysis.
  - A4EI analysis accounts for one-dimensional axial (no bending) and thermal loading. The analysis predicts bondline shear stresses only; tension peel stresses are neglected. The adhesive shear may be modeled as linear elastic or linear elastic-perfectly plastic.
  - Bonded joint strength analysis should account for mechanical and thermal loads.
  - Bonded joint stresses predicted using finite element analysis should be carefully checked for solution convergence since shear and tension stresses exhibit high gradients at joint terminations.
  - Structural repair validation tests are strongly recommended for flight safety critical structure.
- Repairs supplemented with fasteners should be checked by IDAT/IBOLT (or equivalent) strength analysis.

19.8.16 Bolted Doubler Repair

Repair: BOLTED DOUBLER REPAIR



Description:
A bolted doubler repair is added sheet or plate repair material joined to the lateral surface of a defective part that is intended to share in-plane load and provide structural reinforcement. The objective is to salvage a defective original part that can no longer sustain design ultimate load and/or has insufficient fatigue life.

The original part and repair doubler plate may be joined by a bolted or bonded-bolted joint. This section describes a bolted doubler repair of a composite part. The doubler repair plate may be fabricated using CRES steel, aluminum or titanium sheet or plate.

A doubler repair can be limited by OML profile requirements or lack of IML surface access. A single sided doubler will have eccentric load transfer and induced bending. A symmetric doubler can balance the load eccentricity, but will require access to both sides of the original part for installation.

Application:
A doubler repair may applicable to:

- beam caps, webs, bulkhead flanges, stiffeners, straps, skin panels, and fastener lines.

Doubler repairs should be checked for mechanical and thermal loads and should be designed with thermo-elastic compatibility between the original part and doubler to minimize mismatch loads.

Bolted joints should have a minimal bolt to hole clearance for fasteners between doubler and original part to insure reliable shared load transfer. Bolted joint analysis should include a detailed analysis of load transfer between all joint elements.

An IML doubler installation with only OML side access usually requires a multi-piece doubler with complicated tooling aids

Limitations:

- Galvanically dissimilar doubler and original part materials should be separated with a barrier such as a layer of glass fiber woven fabric and faying surface sealant with any fasteners wet installed with sealant.

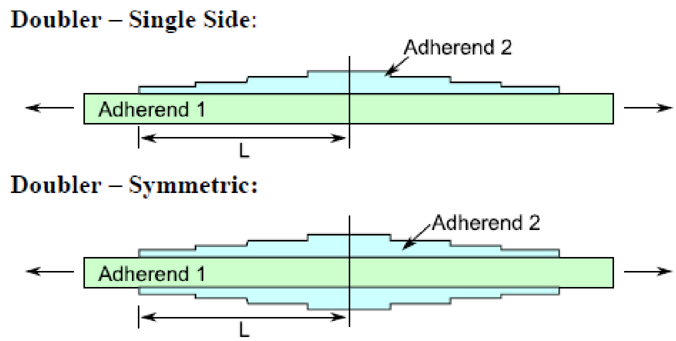
Repair Strength Analysis:

- Bolted joint strength analysis should account for mechanical and thermal loads.
- Bolted joint strength should be checked by IDAT/IBOLT (or equivalent) strength analysis.
    - Fastener loads may be determined from hand analysis, a two-dimensional spring model (such as IDAT/SPRING model), or from finite element analysis.
    - The fastener lay-out should follow fastener spacing and edge distance guidelines.
    - The fastener joints in the defective plate and the doubler should be checked for bearing and bypass strength.
    - Fastener holes in the metallic doublers should be checked for adequate fatigue life.
- Refer to PM-4057 Section 18.4 for guidelines on metallic doublers.

19.8.17 Bonded Doubler Repair

Repair: BONDED DOUBLER REPAIR

IDAT/A4EI
Single or Double Doubler Bonded Joint Strength Analysis Configurations



Description:
A bonded doubler repair is added sheet or plate repair material joined to the lateral surface of a defective part that is intended to share in-plane load and provide structural reinforcement. The objective is to salvage a defective original part that can no longer sustain design ultimate load and/or has insufficient fatigue life.

The original part and repair doubler plate may be joined by a bonded or bonded-bolted joint. This section describes a bonded doubler repair of a composite part. The doubler repair plate may be fabricated using a composite laminate or metallic sheet/plate (CRES steel or titanium).

A doubler repair can be limited by OML profile requirements or lack of IML surface access. A single sided doubler will have eccentric load transfer and induced bending. A symmetric doubler can balance the load eccentricity, but will require access to both sides of the original part for installation.

Application:
A doubler repair may applicable to:

- beam caps, webs, bulkhead flanges, stiffeners, straps, skin panels, and fastener lines.

A composite doubler that is flat or has mild curvature can be cured in an autoclave before installation for optimal strength properties. Doubler plies should be tapered to reduce peak tension stresses at the edges of the bondline. The outermost doubler plies should overlap the inner plies to reduce the peak peel stresses at inner ply terminations (refer to the figures provided in Section 19.7.2).

Doubler repairs should be checked for mechanical and thermal loads and should be designed with thermo-elastic compatibility between the original part and doubler to minimize mismatch loads.

Limitations:

- Film adhesives will require an elevated temperature cure and vacuum bagging. Careful consideration must be made of the temperature limits of affected structural materials. If a heat blanket is used, careful consideration must be made of heat transfer into affected structural materials. Thermocouples should be used to monitor local temperatures during the adhesive cure process.

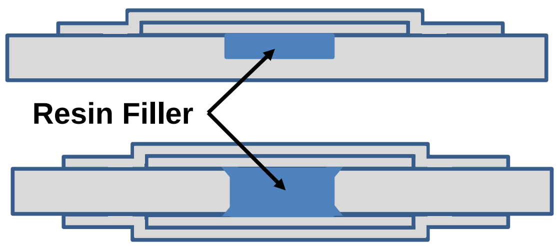
Repair Strength Analysis:

- Bonded joint strength analysis should account for mechanical and thermal loads.
- A bonded joint static strength analysis can be performed using IDAT/A4EI or by finite element analysis.
  - A bonded joint design should use tapered doubler edge features (as shown above) to reduce peak tension peel stresses at the edges of the bondline.
  - A4EI analysis accounts for one-dimensional axial (no bending) and thermal loading. The analysis predicts bondline shear stresses only; tension peel stresses are neglected. The adhesive shear may be modeled as linear elastic or linear elastic-perfectly plastic.
  - Bonded joint stresses predicted using finite element analysis should be carefully checked for solution convergence since shear and tension stresses exhibit high gradients at joint terminations.
- Structural repair validation tests are strongly recommended for flight safety critical structure.

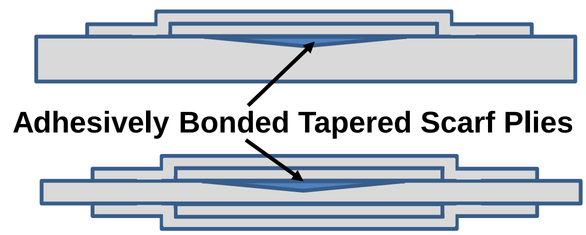
19.8.18 Other Laminate Repair Configurations

Repair: OTHER LAMINATE REPAIR CONFIGURATIONS

Resin Filler-Bonded Doubler Repair



Tapered Scarf-Bonded Doubler Repair



Description:
Basic composite laminate repairs may be integrated together to form other useful repair configurations. The examples shown above illustrate the addition of bonded doubler plies that provide strength reinforcement to a resin filler or a tapered scarf repair. These added doubler plies are sometimes needed to restore design ultimate strength capability. Combined repairs may also provide a convenient solution for unique design features and/or constraints.

Combined laminate repairs must be carefully checked for mechanical and thermal loads over the design temperature range to prevent premature cracking or failures.

Application:
Standard laminate repairs that may be combined (but are not limited to):

- Resin Filler (19.8.3, 19.8.12)
- Bolted (19.8.16) or Bonded Doubler (19.8.17)
- Tapered Scarf (19.8.15)

Limitations:

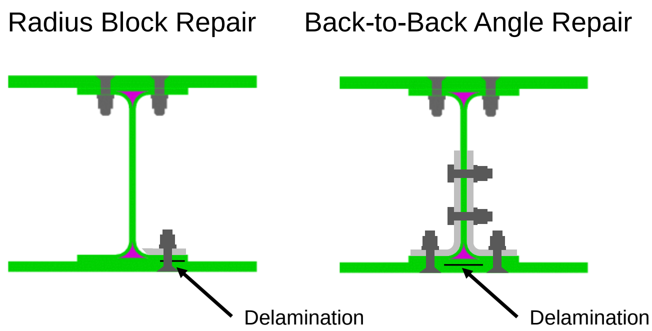
- Combined repairs are still subject to the limitations of each individual standard laminate repair defined elsewhere within the section.

Repair Strength Analysis:

- The bonded joint static strength analysis will most likely require finite element analysis as more complex repair configurations are not available under IDAT/A4EI.
  - Bonded joint strength analysis should account for mechanical and thermal loads.
  - Bonded joint stresses predicted using finite element analysis should be carefully checked for solution convergence since shear and tension stresses exhibit high gradients at joint terminations.
  - Structural repair validation tests are strongly recommended for flight safety critical structure.
- Repairs supplemented with fasteners should be checked by IDAT/IBOLT (or equivalent) strength analysis.

19.8.19 Metallic Fitting Repair

Repair: METALLIC FITTING REPAIR



Description:
This repair is a specialized fitting that is designed to be installed as a structural reinforcement for defective parts or an assembly. The repair fitting and defective part(s) may be metallic or composite. Repair fittings are typically bolted repairs.

The repair objective is to salvage a part or assembly that has defects or damage such that it can no longer sustain design ultimate load and/or has insufficient fatigue life. The reinforcement fitting is intended to share the load with the defective parts and restore static strength and fatigue life.

Application:
Reinforcement fitting repairs may include, but are not limited to, the following configurations:

- Radius blocks
- Angles (shear or tension clips)
- Tees (shear or tension clips)
- Bath-tub fittings

Angles and Tees may also be reinforced with gussets.

Fitting repairs should be checked for mechanical and thermal loads. Fittings should be designed with stiffness compatibility with the defective parts to minimize thermo-elastic mismatch loads.

Bolted connections should have a minimal bolt to hole clearance for fasteners between fitting and defective parts to insure reliable shared load transfer. Bolted joint analysis should include a detailed analysis of load transfer between all joint elements.

Limitations:

- Galvanically dissimilar doubler and original part materials should be separated with a barrier such as a layer of glass fiber woven fabric and faying surface sealant with any fasteners wet installed with sealant.

Repair Strength Analysis:

- Bolted joint strength analysis should account for mechanical and thermal loads.
- Typically, a conservative design approach is used where the metallic fitting is sized such that it can carry 100% of the load.
- Bolted joint strength should be checked by IDAT/IBOLT (or equivalent) strength analysis.
- Fittings should be checked per methods defined in PM-4057 Section 18.4.20 and Section 5.3.
- Radius block analysis should be performed per PM-4057 Section 18.4.16.
- Metallic fittings should be checked for adequate fatigue life.

19.9 Composite EOD & Repair Validation Tests

This section provides basic guidance in the planning and development of composite effect of defect and repair validation tests.

19.9.1 Effect of Defect Tests

The objective of EOD testing is to experimentally determine a strength retention factor K_{EOD} from coupon or element level tests that are designed to evaluate the effect of defect/damage on static strength for a given mode of failure. Ideally, the EOD testing should quantify the strength retention factor K_{EOD} as a function of a relevant defect parameter such as a characteristic dimension. The K_{EOD} strength retention factor can then be expressed as a design curve plotted as a function of the defect parameter and even implemented into the appropriate IDAT strength analysis tool that accounts for the given mode of static failure.

Static strength tests are typically conducted at room temperature ambient conditions using the assumption that the design environment is accounted for through the appropriate design allowable. This assumption should be verified by previous results or with a reduced set of specimens tested at the design environment. Any reduction in strength due to fatigue loading should also be verified by test. Fatigue spectrums used for previous baseline testing should be used whenever possible to support consistent data comparisons.

EOD flat test specimens typically use a quasi-isotropic (25/50/25) lay-up with 24 or 32 plies for tape and 16 plies for fabric. Hard or soft laminates may be included if a dependence on ply percentage is anticipated or if a specific design needs to be evaluated. In notched or bearing strength tests a 0.25 inch hole diameter is typically used as a baseline.

General guidelines for EOD test planning are provided below:

- Identify the mode of failure that the EOD test is intended to characterize.
- Identify the ASTM or LM Aero standard test method that is typically used for the failure mode (Reference 19-37, 19-38).
- Determine the characteristic parameter that quantifies the defect.
- Determine how the defect is to be fabricated or simulated in each specimen. Test specimens should be manufactured using the same materials and processes that are planned for production parts.
- Determine how the defect is to be measured in the test article. It should be representative of the same inspection/acceptance process that is planned for use in production and in-service.
- Plan for strain gages installed on the test specimen to monitor load-strain behavior and identify damage events, damage growth and significant shifts in load path.
- It is good practice to include baseline pristine (no defects) specimens to be tested along with the EOD test specimens so that any material, specimen quality, or test set up related anomalies can be identified.

19.9.2 Repair Validation Tests

Repair validation tests may be required for composite repairs in cases where: 1) there is insufficient test data or analytical uncertainty for the repair configuration; or 2) the structural repair is considered a flight safety risk that must be addressed by testing. The objective of repair validation tests is to demonstrate that the structural repair satisfies all structural integrity requirements. Thus a repair validation test is similar to a “point design” structural certification test.

The tests should be a verification of the repair structural analysis as well as a demonstration of the implementation of the repair. Therefore, the test scope should address the critical failure modes that were identified in the structural analysis. Depending upon the critical failure modes identified, both static strength and fatigue tests may be required. Depending upon the repair scenario, a sufficient number of test articles should be tested to assess strength scatter due to inherent defects and materials and manufacturing process variability.

Typical repair validation test requirements are provided below:

- A static strength test of the structural repair is required for the most critical failure mode to demonstrate design ultimate load capability at the design environment.
- Fatigue tests should demonstrate that the structural repair can sustain design ultimate load at the critical design environment after two lifetimes of service representative loading.

General guidelines for Composite Repair Validation test planning are provided below:

- Identify the critical modes of failure for the Repair Design.
- The design configuration should be as simple as possible, yet capable of achieving design strain levels at the critical locations. The test specimen load path should be known and monitored with strain gages. The specimen should be stable under compression loading. Whenever possible, use an ASTM or LM Aero standard test method that is typically used for the failure mode (Reference 19-37, 19-38).
- Be mindful of the test load and test grip limitations that are available in the laboratory. The test specimen design may need to be altered to accommodate these limitations. Keep in mind that achieving design strain levels is often more important in composite structure than achieving an overall load level.
- Repair test specimens should be manufactured using the same materials and processes as planned for use in the actual repair.
- Plan for strain gages installed on the test specimen to monitor load-strain behavior and identify damage events, damage growth and significant shifts in load path.
- Whenever practical, it is good practice to include baseline pristine (no repair) specimens to be tested along with the repair test specimens so that any material, specimen quality, or test set up related anomalies can be identified.

Refer to PM-4057 Section 18.7 for more guidance on Repair Validation Testing.

19.10 Unix/PC-Based Calculations

This section provides useful reference information on composites EOD and repair related features available in IDAT strength analysis tools. IDAT analysis options available within SQ5, IBOLT and BEND that may be used to modify a laminate are described in Table 19.10-1. Effects of Defects strength analysis options that are available within the IDAT toolset are listed in Table 19.10-2.

Table 19.10-1 Laminate Modification Options available within SQ5, IBOLT, and BEND.

No.	Option	Description
1	Reduce Laminate Thickness	Allows the user to remove a specified thickness from either the bottom (ply 1) or top (ply N) of the laminate. Note: This will often result in an unsymmetric laminate with membrane-flexural coupling.
2	Rotate Laminate	The laminate stacking sequence is modified by rotating each ply orientation angle by the amount specified by the user. Loads are not rotated. The Rotation Offset option is used to rotate X-Y axes for the entire problem.
3	Reverse Laminate Stack	The laminate stacking sequence is reversed (ply 1 => N, Ply 2 => N-1, etc.). This reverses the stacking sequence with respect to the Z-coordinates.

Notes:
1. A modified laminate file is created with a new file name (extension: “*-mod.ls”)
2. Upon execution, the modified laminate is used for analysis with full coupling.

Table 19.10-2 Effect of Defects Strength Analysis using IDAT Tools.

Section	Defect/Damage Type	IDAT Tools						Failure Mode											
		SQ5	IBOLT	PULLTHRU	BEND	CDADT	A4EI	UNT	OHT	FHT	UNC	OHC	FHC	BYS	BUS	ILS	ILT	TAI	CAI
19.6.1.1	Planar Delamination[1]					X												X	X
19.6.1.2	Edge Delamination[1]	X			X						X								
19.6.1.3	Curved Lam Delam[1]	X			X												X		
19.6.1.5	Bondline Disbond[1]						X									X			
19.6.7	Porosity	X	X		X						X	X	X		X	X	X		
19.6.8	Sub-Nominal Thickness		X								X	X	X	X	X	X	X		X
19.6.9	Waviness or Wrinkles	X			X			X			X								
19.6.10	Tool Marks	X						X			X								
19.6.11	Fiber Misalignment	X						X			X								
19.6.12	Ply Overlaps or Gaps	X						X			X								
19.6.15	Fastener Short e/D		X						X	X		X	X		X				
19.6.16	Fastener Spacing		X						X	X		X	X		X				
19.6.18.1	Deep Countersink		X	X					X	X		X	X		X	X			
19.6.19	Deep Counter-bore		X						X	X		X	X		X				
19.6.22.1	Wallowed Holes		X	X								X	X		X	X			
19.6.22.2	Delaminated Holes		X							X					X				
19.6.22.3	Misdrilled Pilot Holes		X										X		X				

Notes:
1) Delaminations, Voids, or Inclusions.

19.11 Examples

This section is to be added at a later date.

19.11.1 Planar Delamination

19.11.2 Edge Delamination

19.11.3 Porosity

19.11.4 Short Edge Distance

19.11.5 Bonded Doubler