12 Bonded Joints

This section provides guidance on the design and analysis of structural bonded joints and assemblies. The content is based on a survey of bonded joint materials, design concepts, analysis methods and best practices used by Lockheed Martin Aeronautics and the aerospace industry. This section is organized as shown in the Table of Contents.

This section begins with a list of references, nomenclature and terminology related to the analysis and design of bonded joints. The introductory section provides an overview of basic concepts. The structural adhesives commonly used in aerospace bonded assemblies are then described including the various adhesive types, material forms, material behavior, and stiffness and strength design properties. Standard test methods are then discussed for adhesive material characterization and for developing bonded joint properties. This is followed with an overview of manufacturing, materials and quality control processes for bonded joints and composite bonded assemblies. Common bonded joint design configurations are then discussed along with recommended design guidelines. The section concludes with recommended structural analysis methods and procedures. Analysis procedures are demonstrated through examples for the most common joint types found in aircraft structure.

Section 12 Table of Contents

12.1 References, Nomenclature and Terminology

12.1.1 References

Reference	Title
12-1	Vinson, J.R. and Sierakowski, R.L., The Behavior of Structures Composed of Composite Materials, Martinus Nijhoff Publishers, 1986.
12-2	Goland, M. and Reissner, E., "The Stresses in Cemented Joints", J. Applied Mechanics, Vol. 11, March 1944, pp A-17 through A-27.
12-3	Niu, M. C., Composite Airframe Structures Practical Design Information and Data, Conmilit Press Ltd., Hong Kong, 1992.
12-4	Anon., IBOND User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, Currently in Preparation.
12-5	Hestlehurst, R.B. and Hart-Smith, L. J., "The Science and Art of Structural Adhesive Bonding", SAMPE Journal, Vol. 38, No. 2, March/April 2002, pp. 60-71.
12-6	Gardiner, G., “Certification of Bonded Composite Primary Structures”, Composites World (2014)
12-7	Gardiner, G., “Building TRUST in Bonded Primary Structures”, Composites World (2015)
12-8	Rousseau, C. Q., Engelstad, S. P., and Owens, S. D., “Industry Perspectives on Composite Structural Certification and Design", 53rd Structures, Structural Dynamics and Materials Conference, 23-26 April 2012, Honolulu, HI.
12-9	Rousseau, C. Q. and Selvarathinam, A., "FZM-9569 Bonded Joint Structural Analysis Methods", IBOND Theory Manual, Currently in Preparation.
12-10	Schmidt, R. P., “3-D Woven Pi Preform Joint Application Design/Manufacturing/Process Guidelines”, FZM-10393, February 2016.
12-11	Anon., CMH-17 Composite Materials Handbook, Revision G, Materials Sciences Corporation, Secretariat, Philadelphia, PA, 2012.
12-12	Anon., “Structural Development Tests, Coupon Tests Results and Evaluation, Volume 01, General” 5PPYA081-01, Lockheed Corporation and The Boeing Company, Dec. 1994.
12-13	Taylor, R. M., "XG-ST-CO-29.2 Final Engineering Assessment Report for Structural Characterization of FM 300 Adhesive", 2ZSA00025-0001, Aug. 2004.
12-14	Bichsel, S. L., and Ramirez, F., "XG-ST-CO-44 Final Engineering Assessment Report for Thick Adherend Shear and Neat Resin Tension Testing of LMA-MD107 Bismaleimide Adhesive Film", 2ZSA00050-0001, Mar. 2008.
12-15	Morrison, J. L., "XG-ST-CO-46 Final Engineering Assessment Report for Adhesive Peel Strength", 2WSA00500-0001, Dec. 2006.
12-16	Ramirez, F., "XG-ST-CO-13 Final Engineering Assessment Report for 3D Textile Preform Characterization Tests", 2ZSA00006-0001, Nov. 2003.
12-17	Bersuch, L. R., and Taylor, R. M., "XG-ST-EL-09 Final Engineering Assessment Report for 3D Woven Pi-Preform Element Tests", 2CSA00005-0001, Sep. 2004.
12-18	Favela, J., "Engineering Test Report, Pi Preform Joint Allowables, Standard Weight IM7/MTM45-1 and FM309-1M", FZM-10161, Feb. 2016.
12-19	Favela, J., "Engineering Test Report, Pi Preform Joint Allowables, Light Weight IM7/MTM45-1 and FM309-1M", FZM-10162, Feb. 2016.
12-20	Anon., F/A-22 Material Properties and Allowables, Volume 1, 5PD00133-01M, October 2005.
12-21	Garcia, R., "JSF Material Allowables", 2ZYA00001, Rev. D, Jan. 2006.
12-22	Ramirez, F. and Owens, S. D., "Updated Film Adhesive Allowables", ASAN 05-AL-001 Release 01, 11 July 2005.
12-23	Rousseau, C. Q., "Bonded Joint Analysis Methodology", ASAN 05-AN-036 Release 01, 12 December 2005.

12-24	Ramirez, F. and Rousseau, C. Q., "Updated FM 2550G Film Adhesive Allowables", ASAN 07-AL-001 Release 01, 29 March 2007.
12-25	Anon., A4EI Version 1.4 User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, 2011.
12-26	Anon., MATUTL Version 6.10 User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, 2012.
12-27	Anon., SQ5 Version 6.1 User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, 2011.
12-28	Anon., LAMINATE Version 4.3 User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, 2005.
12-29	Anon., LAM_PERCT Version 2.1 User's Guide, Lockheed Martin Aeronautics, Fort Worth, TX, 2005.
12-30	Hart-Smith, L. J., "Adhesive-Bonded Double-Lap Joints", NASA CR-112235, 1973.
12-31	Hart-Smith, L. J., "Adhesive-Bonded Single-Lap Joints", NASA CR-112236, 1973.
12-32	Hart-Smith, L. J., "Adhesive-Bonded Scarf and Stepped-Lap Joints", NASA CR-112237, 1973.
12-33	Hart-Smith, L. J., "Non-Classical Adhesive-Bonded Joints in Practical Aerospace Construction", NASA CR-112238, 1973.
12-34	Hart-Smith, L.J., "Design and Analysis of Adhesive-Bonded Joints", MDC Paper-6059A, Presented at the Air Force Conference on Fibrous Composites in Flight Vehicle Design, Dayton, Ohio, Sep 1972, Conference Proceedings AFFDL-TR-72-130, pp 813-856.
12-35	Hart-Smith, L.J., "Analysis and Design of Advanced Composite Bonded Joints", NASA CR-2218, Jan 1973.
12-36	Hart-Smith, L. J., "Further Developments in the Design and Analysis of Adhesive-Bonded Structural Joints", Joining of Composite Materials, ASTM STP 749, K. T. Kedward, Ed., 1981, pp. 3-31.
12-37	Hart-Smith, L. J., "Adhesive Layer Thickness and Porosity Criteria for Bonded Joints", AFWAL-TR-82-4172, 1982.
12-38	Hart-Smith, L. J., "Adhesively Bonded Joints for Fibrous Composite Structures", Douglas Paper 7740, Presented to the International Symposium on Joining and Repair of Fibre-Reinforced Plastics, London, September 1986.
12-39	Anon., Lockheed Composite Stress Memo Manual, Lockheed Martin Aeronautical Systems, Marietta, GA, Draft Copy 2006.
12-40	Bailie, J. A. (Editor), *Design Guide for FBM Composite Structures*, LMSC-D477785, Aug 1982.
12-41	Anon., Spacecraft Composite Structures Design, Training Course, Lockheed Missiles and Space Company, Dec. 1989.
12-42	Wolff, R. V., "Adhesive Bonded Joints - Lessons Learned", FZM-8621A, October 2002.
12-43	Martin, J. M., “Cobond/Cocure/Paste Bond of Lockheed Martin 3-D Pi-Preform Structures Design Guidelines”, FZM-9025, 23 August 2004.
12-44	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.
12-45	Anon., DOD/NASA Advanced Composites Design Guide, Air Force Wright Aeronautical Laboratories, Dayton, OH, prepared by Rockwell International Corporation, 1983.
12-46	Staff, LTV Composite Structures Analysis Manual, LTV Aircraft Products Group, Grand Prairie, TX, August, 1984.
12-47	Anon., *Bonding Design Guidelines*, Composites Affordability Initiative, 2002.
12-48	Adams, R.D., Wake, W.C., Structural Adhesive Joints in Engineering, Elsevier Applied Science Publishers, London and New York, 1984.
12-49	Campbell, F. C., Manufacturing Technology for Aerospace Structural Materials, Elsevier, 2006.
12-50	Matthews, F. L. (Editor), “Joining Fibre-Reinforced Plastics”, Elsevier Applied Science Publishing Company, 1987.
12-51	Shields, J., *Adhesives Handbook*, Butterworths, Third ed., 1985.
12-52	Thrall, E. W. and Shannon, R. W. (editors), Adhesive Bonding of Aluminum Alloys, Marcel Dekker, Inc., 1985.

12-53	ASTM D638-10, "Standard Test Method for Tensile Properties of Plastics", Annual Book of ASTM Standards, West Conshohocken, PA.
12-54	ASTM D5656-04, "Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading", Annual Book of ASTM Standards, West Conshohocken, PA.
12-55	Krieger, Raymond B. Jr., "Stress Analysis Concepts for Adhesive Bonding of Aircraft Primary Structure," Adhesively Bonded Joints: Testing, Analysis and Design, ASTM STP 981, W.S. Johnson, Ed. American Society for Testing and Materials, Philadelphia 1988, pp. 264-275.
12-56	Gosse, J. and Christensen, S., "Strain Invariant Failure Criteria for Polymers in Composite Materials," 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Seattle, WA, 2001.
12-57	Taylor, R. M., Rousseau, C. Q., Ramirez, F. J., and Morrison, J. L., "A Methodology for Adhesive Peel Allowable Development", AIAA Paper No. 2008-1843, Presented at 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 7 - 10 April 2008, Schaumburg, IL.
12-58	ASTM D 1876-01, "Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)", Annual Book of ASTM Standards, West Conshohocken, PA.
12-59	Adams, J. M., "Standard Test Procedures for Reinforced Plastic, Adhesives, Core, Structural Potting Compounds and Thermoplastic Sheet Material", LMA-PT008B, June 2005.
12-60	ASTM C 297, "Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions", Annual Book of ASTM Standards, West Conshohocken, PA.
12-61	ASTM D 1002-10, "Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)", Annual Book of ASTM Standards, West Conshohocken, PA
12-62	Kassapoglou, C. and Adelmann, John C., "KGR-1 Thick Adherend Specimen Evaluation for the Determination of Adhesive Mechanical Properties," 23rd International SAMPE Conference, Oct. 21–24, 1991.
12-63	ASTM D4896-01, "Use of Adhesive-Bonded Single Lap-Joint Specimen Test Results", Annual Book of ASTM Standards, West Conshohocken, PA.
12-64	Fiorenzi, C. J., "Standard Test Procedures for Advanced Fiber Reinforced Composite Materials," LMA-PT001B, Lockheed Martin Aeronautics Company, April 2004.
12-65	Davis, J. J., "XG - ST - EL – 49.2, Phase II Hat Stiffener Panel Test, Engineering Test Report", Report No. 2WSA00518, 25-Apr-2008.
12-66	Hart-Smith, L.J., Brown, D., Wong, S., "Surface Preparations for Ensuring that the Glue Will Stick in Bonded Composite Structures", 10th DOD/NASA/FAA Conference on Fibrous Composites in Structural Design, Hilton Head, SC, 1-5 Nov. 1993.
12-67	Hart-Smith, L.J., Redmond, D. Davis, M.J., "The Curse of the Nylon Peel Ply", 41st SAMPE International Symposium and Exposition, 25-28 Mar. 1996, Anaheim, CA.
12-68	Selvarathinam, A., and Rousseau, C. Q., "Practical Bonded Joint Stress Analysis", AIAA SciTech, Paper No. 2067, 2015.
12-69	Dickson, S.N., Hsu, T.M., and McKinney, J.M., "Development of an Understanding of the Fatigue Phenomena of Bonded and Bolted Joints in Advanced Filamentary Composite Materials," Vol.1., Analysis Methods, Technical Report AFFDL-TR-72-64, Vol. 1., 1972.
12-70	Grimes, G.C., Greimann, L.F., Wah, T., Commerford, G.E., Blackstone, W.R., and Wolfe, G.K., "The Development of Nonlinear Analysis Methods for Bonded Joints in Advanced Filamentary Composite Structures," SWRI Technical Report AFFDL-TR-72-97, 1972
12-71	Allman, D.J., "Theory for Elastic Stresses in Adhesive Bonded Lap Joints," *Quarterly J. Mech. Appl. Mathematics*, Vol. 30, No. 4, November 1977. pp. 415-436.
12-72	Grant, P., "Analysis of Adhesive Stresses in Bonded Joints," Proc. Symposium: Joining in Fiber Reinforced Plastic, Imperial College, London, IPC Science and Technology Press Ltd., 1978, pg. 41.§
12-73	Volkersen, O., "Die Nietkraftverteilung in Zugbeanspruchten Nietverbindungen mit Konstanten Laschenquerschnitten," Luftfahrtforschung, Vol 15, pp. 4-47, 1938.

12-74	Hahn, K.F., and Fouser, D.F., "Methods for Determining Stress Distribution in Adherends and Adhesives," *The Symposium on Adhesives for Structural Applications*, 1962, pp. 25-29.
12-75	Ojaivo, I.U. and Eidinoff, H.L., "Bond Thickness Effects upon Stresses in Single-Lap Adhesive Joints," *AIAA J.*, Vol. 16 No. 3, March 1978, pp. 204-211.
12-76	Tsai, M.Y., Oplinger, D.W. and Morton, J., "Improved Theoretical Solutions for Adhesive Lap Joints," *Int. J. Solids Structures*, Vol. 35, No. 12, pp. 1163-1185.
12-77	Taylor, Robert M. "3D Woven Preform Bonded Joint Analysis Using StressCheck", 30 May 2003.

12.1.2 Nomenclature

Symbol	Definition	Units
A	Bond area	in^2
C	Intercept of the peel reduction curve	
D	Fastener or hole dia	in
DLS	Double Lap Shear	
E	Young's modulus	psi
E_{init}	Young's modulus, initial	psi
E_{sec}	Young's modulus, secant	psi
F_{11}^{tu}, F_{11}^{cu}	Unnotched tension & compression strength allowable, fiber direction	psi
F_{22}^{tu}, F_{22}^{cu}	Unnotched tension & compression strength allowable, transverse direction	psi
F_{12}^{su}	Unnotched in-plane shear strength allowable	psi
F_{13}^{su}	Interlaminar shear strength allowable	psi
F_{33}^{tu}	Interlaminar tension strength allowable	psi
G	Shear modulus	psi
G_a	Adhesive shear modulus based on the bi-linear representation	psi
$G_{a\text{-}initial}$	Adhesive shear modulus based on the test data	psi
G_{init}	Adhesive shear modulus, initial	psi
G_{sec}	Ahdesive shear modulus, secant	psi
J_1	First strain invariant	in/in
J_{1C}	First strain invariant allowable	in/in
K_B	B-basis reduction factor (K_B=1, if IDAT/MATUTL allowable is used)	
KN	Knee	
k_p	Tension peel reduction factor	
L	Length, Adherend overlap length	in
L_b	Bond-line length	in
LL	Linear Limit	
L_{test}	overlap length of the single lap shear test coupon	in
$(L/t)_{design}$	L/t ratio of the actual design; $(L/t)_{design} \geq 8$	
$(L/t)_{test}$	L/t ratio of a single lap joint configuration for which test data is available	
m	slope of the peel reduction curve	
M	Moment	in-lb
MS_{static}	Static margins of safety	
$MS_{fatigue}$	Fatigue margins of safety	
n	Ramberg-Osgood fit parameter	
$N_{A4EI\text{-}EL\text{-}PL}$	Axial Strength, $N_{A4EI\text{-}EL\text{-}PLAxial}$	lbs/in
$N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$	Axial strength predicted by A4EI in the axial direction	lbs/in
$N_{A4EI\text{-}EL\text{-}PL\text{-}Shear}$	Shear strength predicted by A4EI in the shear direction	lbs/in
$N_{x\text{-}ult}$	Applied ultimate load	lbs/in

Symbol	Definition	Units
$N_{x\text{-}ult}$	Applied ultimate axial load	lbs/in
$N_{xy\text{-}ult}$	Applied ultimate shear load	lbs/in
$N_{x\text{-}limit}$	Design limit or maximum fatigue spectrum load (whichever is greater)	lbs/in
P	Applied axial joint load	lbs
R_a	$(N_{x\text{-}ult})/(N_{A4EI\text{-}EL\text{-}PLAxial})$	
R_s	$(N_{xy\text{-}ult})/(N_{A4EI\text{-}EL\text{-}PL\text{-}Shear})$	
SLS	Single Lap Shear	
T	Operating temperature of the joint	°F
ΔT	Difference between operating temperature and stress free temperature	°F
$T_{stress\text{-}free}$	Adhesive stress free temperature (called cure temp in A4EI output)	°F
t	thickness	in
t_a	thickness of the adhesive	in
t_{top}	thickness of top adherend	in
t_{bot}	thickness of bottom adherend	in
t_b	Bond-line thickness	in
UL	Ultimate Strength	
V	Shear	lbs
W	Width of single lap shear joint	in
δ	Displacement	in
δ_1, δ_2	Displacement of Adherend 1 & 2	in
ε_1	Principal strain in 1 direction	in/in
ε_2	Principal strain in 2 direction	in/in
ε_3	Principal strain in 3 direction	in/in
$\varepsilon_{eqv\text{-}c}$	Equivalent or distortional adhesive strain allowable	in/in
ε_{VM}	Von Mises strain in the adhesive	in/in
γ	Engineering shear strain	in/in
γ_e	Maximum elastic shear strain determined from elastic-plastic curve	in/in
γ_{max}	$\gamma_e + \gamma_p$, Maximum shear strain at failure determined from test data	in/in
γ_p	Plastic shear strain determined from elastic-plastic curve	in/in
ν	Poisson's ratio	
σ	normal stress	psi
$\sigma_1, \sigma_2, \sigma_3, \tau_{12}, \tau_{23}, \tau_{13}$	stress components from fine grid FEM in material coordinate system	psi
$\sigma_{0.70}, \sigma_{0.85}$	Experimental 0.70E and 0.85E secant intercepts (normal stress-strain)	psi
$\sigma_{zz}, \tau_{zx}, \tau_{zy}$	Interlaminer stresses; bond-line stresses	psi
τ	Shear stress	psi
$\tau_{0.7}$	Shear secant intercept for an approximate 45 degree line	psi
τ_{max}	Max adhesive shear stress at which yield begins on elastic-plastic curve	psi

12.1.3 Terminology

A list of terms and definitions that are commonly used to describe the various engineering aspects and manufacturing processes related to bonded joints are provided below for reference.

Adherend – A structural member or element that is joined to another by means of an adhesive substance.
Adhesion – The state in which two surfaces are held together by interfacial forces which may consist of valence forces, interlocking action, or both.
Adhesive – A substance capable of holding materials together through adhesion and transmitting structural loads.

Autoclave Bonding – The layup is covered by a pressure bag, and the entire assembly is placed in an autoclave to cure the part using heat and pressure. The pressure bag is normally vented to the outside.
B-Stage – An intermediate stage in the reaction of an adhesive in which the material softens when heated and swells in contact with certain solvents but does not entirely fuse or dissolve.
Bonding – The adhesion of one surface to another, with or without a bonding agent (adhesive).
Bonded Joint – That part of a structure at which two adherends are held together with a layer of adhesive.
Bonded Lap Joint – A joint made by placing one adherend partly over another and bonding together the over-lapped portions.
Bond-Line Thickness – The thickness of an adhesive layer measured after completion of the cure process.
Bond Strength – The unit load applied in tension, compression, flexure peel, impact, or shear required to break an adhesively bonded assembly with failure occurring either within the adhesive or at the adhesive-adherend interface.
Carrier Ply – A supporting woven fabric or random fiber mat embedded in a film adhesive to improve handling and provide a physical presence to help maintain bond-line thickness during cure.
Co-Bonding – A manufacturing process whereby one cured component is bonded to an uncured component by the addition of a bonding agent and then both are cured.
Co-Cure – A manufacturing process whereby a composite laminate is cured while simultaneously bonding it to some other prepared surface during the same cycle.
Cohesion – The state in which the particles of an adhesive, or in general a single substance, is held together by chemical forces.
Crazing – A network of fine cracks extending on or under the surface of, or through a layer of, adhesive.
Creep – The dimensional change or deformation of a material under load over time, following the initial instantaneous elastic or rapid deformation.
Curing – An irreversible process to change the properties of a thermosetting resin by chemical reaction. Cure may be accomplished by addition of curing agent, with or without catalyst, and with or without heat and pressure.
Cure Agent – That part of a two-part adhesive which combines with the resin (binder) to produce a cured adhesive film.
Curing Stress – A residual internal stress produced upon cooling from an elevated temperature cure when different adherend materials, *e.g.*, aluminum and titanium, of a bonded layup have different thermal coefficients of expansion.
Delamination – A separation or crack lying within the interlaminar plane between adjacent laminae within a composite laminate.
Disbond – A void, absence or lack of adhesion within a bond-line or bonded area. This may be a small local defect or affect an extensive area of the bond surface. It may occur during cure or at any time during the subsequent life of the bond area and may arise from a wide variety of causes.
Faying Surface – That surface of an assembly that interfaces with the surface of another assembly.
Flash – Adhesive extruded from the edges of a joint after curing.
Interface – The surface forming a common boundary between two contacting parts.
Peel Ply – Used for prepping bond surfaces; results in a rough textured surface when removed to promote bonding; material used is typically nylon or glass, 7 – 8 mils thick.
Peel Strength – Bond strength in pounds per inch-width when two adherends are joined and then separated by bond-line tension or peeling stress.
Plasticity – A property of adhesives that permits permanent and continuous deformation without rupture upon the application of a force that exceeds the yield value of the material.
Porosity – A condition of trapped pockets of air, gas, or void within a bond.
Primer – A coating applied to a surface before application of an adhesive to improve the performance of the bond and improve corrosion resistance of the adherends.
Scrim – A protective ply of glass or carbon fiber woven fabric applied to the outer surfaces of a laminate. A light-weight, open weave glass fabric scrim ply may also be used within a film adhesive to maintain bond-line thickness control in a secondary bonding process.
Secondary Bonding – The joining together, by the process of adhesive bonding, of two or more metallic or composite parts that were previously cured.
Set – Conversion of an adhesive into a fixed or hardened state by chemical or physical action. (See also: Cure).
Shelf Life – The length of time a material, substance, or product can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended

function.
Slippage – Undesired movement of the adherends with respect to each other during the bonding process.
Substrate – Material acted upon during the bonding process; adherend.
Void – The absence or lack of adhesive in a bonded area.

12.2 Introduction

Structural joints are an essential design feature of all aerospace structural assemblies. Individual structural parts are typically joined to other parts through mechanically fastened joints, bonded joints, or a combination of both. Refer to PM-4056 Section 11 for guidance on mechanically fastened joints in composite structures. The present section provides an overview of the basic concepts related to bonded joints and composite bonded assemblies. References to related subsequent sections are provided.

In principle, bonded joints are more structurally efficient than mechanically fastened joints due to the elimination of stress concentrations introduced at fastener holes that arise due to bearing and bypass loads. On the other hand, the load transfer across the bond interfacial surfaces in bonded joints can cause shear and normal stress concentrations that require careful strength analysis. The use of bonded joints may also be more cost efficient as compared to mechanically fastened joints in airframe production as they can eliminate the costs of fastener hole preparation, inspection and installation processes. However, this must be weighed against the necessary development cost for bonded joint manufacturing processes; the time, facilities and care that are required to produce reliable parts and assemblies; and for the quality control inspections that ensure reliability requirements are met. These factors must be carefully considered when selecting the best joint concept for a given design requirement.

12.2.1 Basic Concepts

This section describes elementary terms and concepts for aerospace bonded joints and assemblies. An adhesively bonded single lap shear joint is shown in Figure 12.2-1 for reference to identify common joint elements. The bonded joint is viewed edge on. The joint is unsupported and allowed to freely deflect and rotate under tension loading.

Bonding is the manufacturing process of adhering the surface of a structural element to another through the use of an adhesive or bonding agent. An adhesive is a substance or material that is used to join or bond the surfaces of two solid materials together. Aerospace structural adhesives are available in the form or a liquid or paste, a film sheet or foam and, depending on the adhesive, usually requires an elevated temperature cure with autoclave pressure and vacuum to develop full structural strength capability.

The structural elements that are joined together in an adhesively bonded joint are called adherends. An adherend may also be called a substrate in the context that it is a substance acted upon in a bonding process. Common aerospace adherend materials may include metals, fiber reinforced composites, or structural sandwich core. Examples of load transfer for bonded honeycomb core structure are shown in Figure 12.6-7.

A bond-line refers to the layer of adhesive that bonds the surface of the two adherends together. An adhesive bond-line between solid adherends optimally ranges from 0.003 to 0.010 inches in thickness. As the bond-line grows thicker, the joint become less effective in stiffness and strength as the adhesive must transfer load over a greater distance. An adhesive bond-line thickness is sometimes controlled through the use of a woven fabric, referred to as a “carrier ply”, embedded within a film adhesive. The adhesive bond-line between skin and a honeycomb core in sandwich structure has a more variable thickness as the adhesive must flow into and adhere to the cell walls of the honeycomb core to achieve a good bond for transferring shear load.

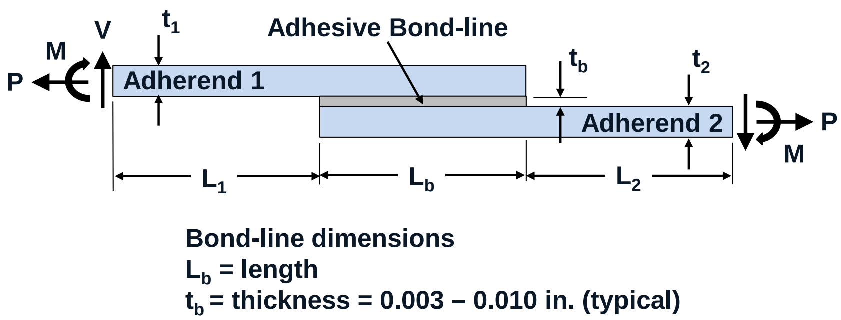


Figure 12.2-1 Adhesively Bonded Single Lap Shear Joint (Unsupported).

12.2.2 Advantages & Disadvantages

The advantages and disadvantages of bonded joints relative to mechanically fastened joints are provided in Table 12.2-1 and Table 12.2-2, respectively. These advantages and disadvantages pertain to the design of composite airframe structure. In addition, adhesively bonded repairs are often the preferred choice for many composite structural restorative and reinforcement repairs as well (refer to PM-4056, Section 19 for more information).

Table 12.2-1 Advantages of Bonded Joints Relative to Mechanically Fastened Joints.

1	Bonded joints offer the potential for weight savings with a higher joint efficiency (relative strength/weight) for low-to-moderately loaded joints as compared to bolted joints.
2	Bonded joints offer the potential for weight savings with a higher joint efficiency (relative strength/weight) for low-to-moderately loaded joints as compared to bolted joints. However, adherends must be sized to accommodate subsequent fastener repairs which can negate these weight savings.
3	Bonded joints offer an inherent fuel sealing capability and eliminate potential leak paths through fastener installations. However, a secondary fuel leak protection scheme is usually required for integral fuel tanks to prevent a leak path in the event of a bond-line failure.
4	Bonded joints greatly reduce the potential corrosion source of metallic fasteners.
5	Bonded joints eliminate fastener hole stress concentrations due to bearing-bypass loads; however, these may be offset by bond-line shear and tension stress concentrations. Through efficient joint design and load transfer over larger areas, these bond-line stress concentrations may be reduced or mitigated.
6	Bonded joints may result in improved fatigue performance due to more uniform stress distribution promoted by the adhesive and elimination of metallic joint elements.
7	Adhesive ductility may be used to relieve stress concentrations provided that mid-span shear stress remains low enough to prevent creep.
8	A bonded joint can enable the design of clean, smooth outer mold-line (OML) surface features and integrally sealed joint capability.
9	Bonded joints can improve structural stiffening and vibration damping characteristics as compared to bolted joints.

Table 12.2-2 Disadvantages of Bonded Joints Relative to Mechanically Fastened Joints.

1	Bond-line strength and durability is highly dependent upon the strict control of manufacturing materials, processes and environment. Slight variations can result in a significant decrease in joint performance.
2	Similar to the low interlaminar strength of reinforced fiber composites, bond-lines are relatively weak for out-of-plane load transfer and vulnerable to ballistic events.
3	Bonded joints are often difficult to inspect and current non-destructive inspection techniques are incapable of assessing bond strength.
4	Bond-line and adherend stress fields are complex and failures are difficult to predict.
5	Bonded joints eliminate the structural reliability, redundancy and yielding benefit of mechanically fastened joints.
6	After the bonding cure process, bonded joints are difficult to disassemble for replacing discrepant parts during manufacturing.
7	Adhesives may be affected by environmental factors such as moisture, temperature, ultraviolet exposure, chemical solvents, *etc.* and can exhibit time dependence effects such as creep and relaxation.
8	Bonded joints require upfront development of materials, manufacturing processes, and joint design properties; and successful production requires well-trained, skilled touch labor to ensure reliable quality.
9	Bond surface preparation requires controlled and reliably repeatable processes to enhance the surface wetting properties and a clean working environment to avoid contamination.

12.2.3 Bond-line Stresses

The load transfer between bonded adherends leads to the development of shear and normal stresses in the adhesive bond-line. Since a typical bond-line is on the order of 0.003 – 0.010 inches thick, the major components of stress at a given point are those normal and shear stress components acting on a plane that is tangential to the bond surface, such as the σ_{zz}, τ_{zx}, and τ_{zy} stresses shown in the figure.

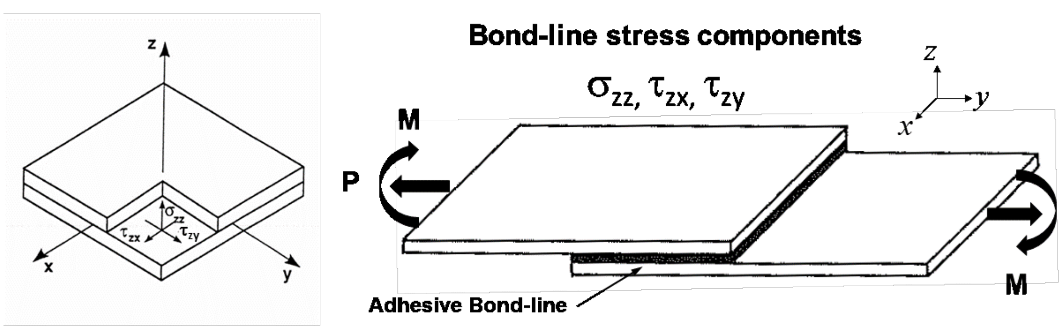


Figure 12.2-2 Major Stress Components for Adhesive Bond-lines (Reference 12-1).

Practical strength analyses of bonded joints have been developed for multiple joint configurations using the assumptions of generalized plane strain. A common example problem is an adhesively bonded single lap shear joint shown in Figure 12.2-3. The joint is symmetric with identical adherends being joined together. The adherends are subjected to an axial load P with assumed clamped conditions at each end and moment reactions M.

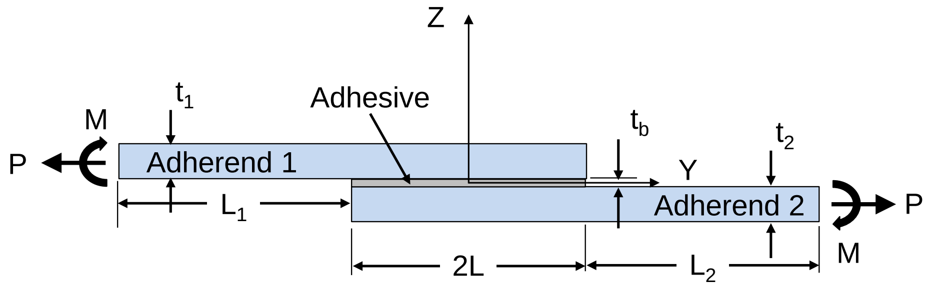


Figure 12.2-3 Adhesively Bonded Single Shear Lap Joint Geometry.

The strength analysis problem may be subdivided into two parts (Reference 12-2). The first part is concerned with determining the loads at each end of the joint as shown. The determination of these loads requires taking into account the deformation of the adjoined adherends as shown in Figure 12.2-4 using geometrically nonlinear (or finite deflection) theory for cylindrically bent plates or beams. The second part is concerned with the determination of the stresses in the joint due to the applied loads. That is the adhesive bond-line stresses and the stresses within the adherends.

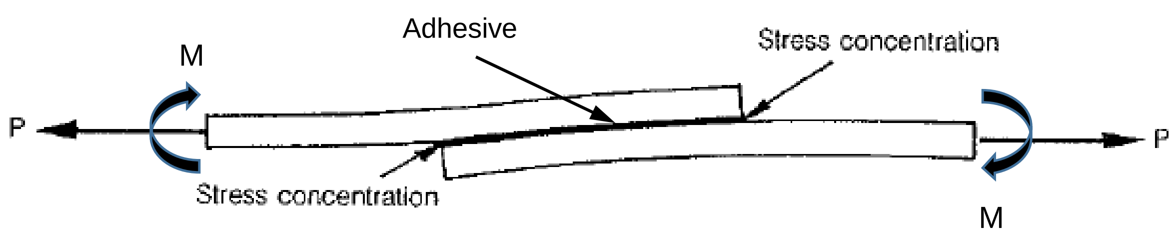


Figure 12.2-4 Rotational Deformation of a Single Lap Shear Joint under Axial Load (Reference 12-3).

The bond-line stresses predicted by IDAT/IBOND closed form bonded joint analysis code (Reference 12-4) are shown in Figure 12.2-5. Bond-line shear stresses τ_{yz} arise due to transfer of axial load between adherends across the bond-line. As shown, the shear stresses peak at each end of the bond-line and these locations will be the first areas for which the adhesive will begin to yield.

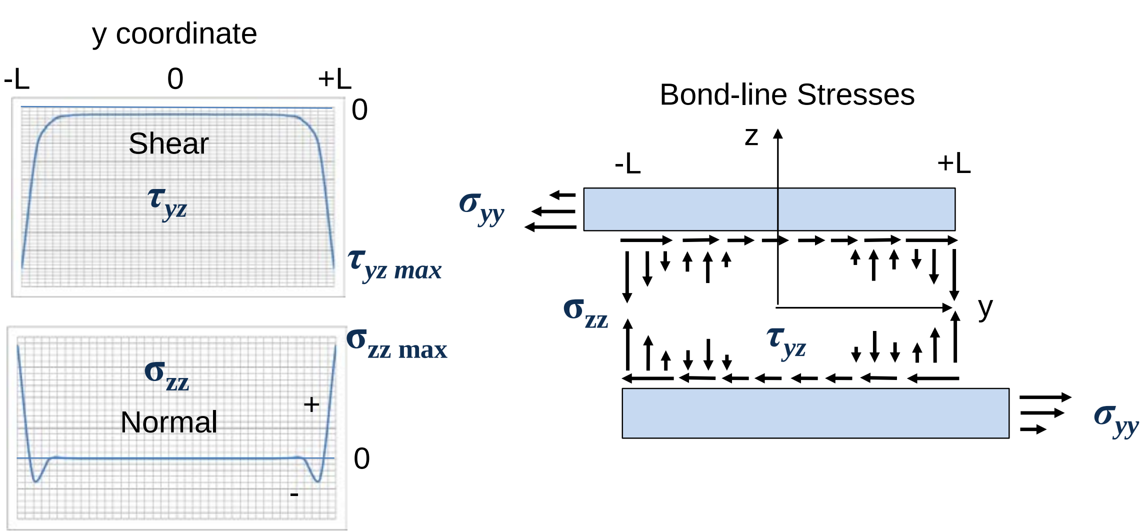


Figure 12.2-5 Single Lap Shear Bond-line Stresses predicted by IDAT/IBOND.

Normal stresses, σ_{zz}, arise to provide a balancing couple to preserve rotational equilibrium. This balancing couple is illustrated in Figure 12.2-6. The σ_{zz} normal stresses are required to preserve equilibrium of the red highlighted element about point A. If there was no joint rotation, the σ_{zz} stresses must balance one another to preserve the force balance in the z-direction. The normal stress area under the tension portion of the curve must equal the compression area. However, as a joint deforms and rotates under eccentric loading as predicted by finite deflection theory, the stress distributions will vary as the bond-line begins to react the axial load as a combination of shear and normal stresses.

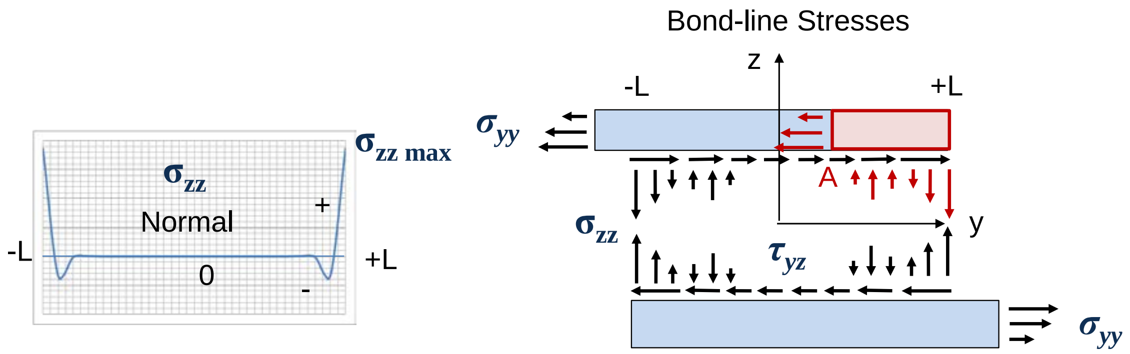


Figure 12.2-6 Bond-line Normal Stress Distribution that preserves Moment Equilibrium near Bond Surface Edges.

As shown, peak bond-line normal stresses exhibit singular behavior at the bond-surface edges making it difficult to obtain a converged stress prediction using a displacement-based finite element method. Therefore peak tension (peel) stresses predicted at a bond-surface edge by displacement-based finite element analysis should not be used alone for strength margins. An alternate approach is to use the predicted joint loads to obtain a closed-form solution such as predicted with IDAT/IBOND that has been correlated to representative bonded joint element test results.

The symmetry of the stress distributions and peak stresses shown are due to the symmetry of adherend stiffness and geometry used in this example. The bond-line stress distributions are dependent upon adherend stiffness and joint length. Changes in these parameters will alter the magnitude of the peak stresses and their overall distribution.

In general for all bonded joints, bond-line shear and normal stress concentrations will exist near the edges of the bond-line where load transfer begins between adjoined adherends. These are locations where the adhesive will first begin to yield. For composite adherends, these will also be locations for peak interlaminar stresses. These stresses decrease away from the bond-line edges as adherends attain equilibrium load balance with respect to one another.

Peak normal stresses can be reduced by tapering the adherend geometry near the ends. Only the stresses due to mechanical axial load and the reaction moments are shown. The stress distribution and peak stresses will change under more general mechanical loads and with the inclusion of thermal or hygroscopic loads. In addition, the stresses shown are predicted using assumed linear elastic material behavior. Predictions that account for the nonlinear elastic-plastic behavior of the adhesive will also vary. These considerations will be discussed further in the subsequent sections.

Although both shear and normal stresses are transferred across the bond-line, the objective of a well-designed bonded joint is to primarily transfer shear load between the two adherends. Ideally, the joint should be designed so that the adherends fail first; thereby preventing the bond-line from being the weak link in the structure to reduce structural integrity risk since a local bond surface defect could result in a catastrophic failure. For composite adherends, the adhesive is usually stronger than the adherend interlaminar strength; thus a composite adherend is naturally the weakest link, unless poor surface preparation leads to a premature adhesion failure at the adhesive/adherend interface. For metallic adherends, the yielding of the adherend must be accounted for as it can cause a corresponding increase in the adhesive strains.

12.2.4 Failure Modes

The possible failure modes of a bonded joint may be classified as (refer to Figure 12.2-7):

Adhesion Failure – Failure at the adhesive/adherend interfacial bond. The failure surface will have the appearance of one adherend surface being "clean" while the full adhesive layer remains attached to the other adherend. This failure is sometime caused by either a failure to properly prepare the adherend bond surface or by an inadvertent contamination of the adherend bond surface prior to bonding.

Cohesion Failure – Internal failure within the adhesive. This is preferred mode of failure when performing adhesive material characterization tests as it confirms that the adhesive strength has been met.

Adherend Failure – Internal failure within the adherend. This is the preferred mode of failure for an actual joint since the adherend material is usually well-characterized with reliable failure predictions. The exception is an interlaminar failure mode of composite adherend which is relatively more difficult to characterize and predict as compared to metals or fiber dominated failures.

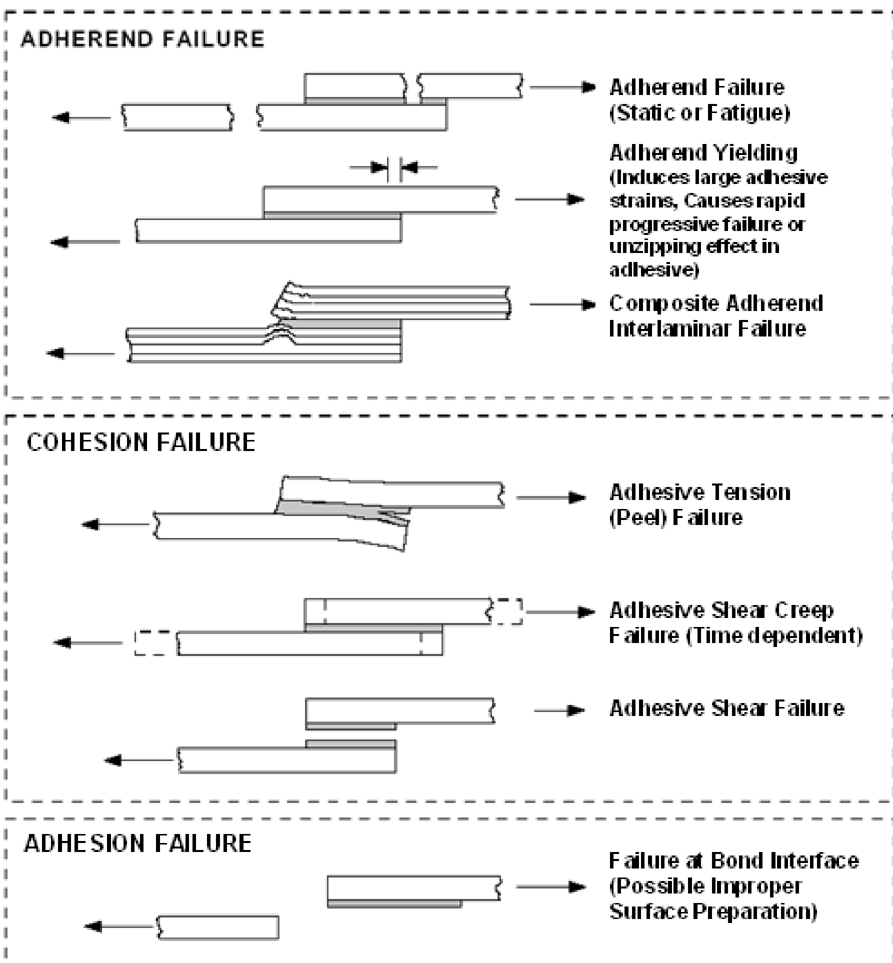


Figure 12.2-7 Bonded Joint Failure Modes (Reference 12-5).

Figure 12.2-7 shows examples of the different possible failure modes while Figure 12.2-8 illustrates the differences in appearance of a composite bonded joint failure surface. As shown, post failure inspection of test specimens often exhibits the characteristics of a combination of these failure modes. Therefore, whenever possible, it is good to record through observation or through video the progressive failure to aid in determination of the initial failure mode. Since peak shear and tension stresses often occur in combination with one another, it may be difficult to determine through post-failure inspection if a failure is driven by shear, tension or the combination of these stresses.

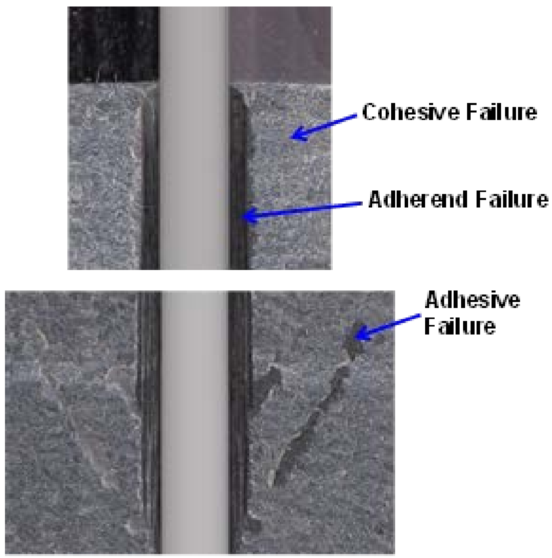


Figure 12.2-8 Examples of different Bonded Joint Failure Modes as illustrated by failure surface photographs of Double Cantilever Beam specimens.

12.2.5 Bonded Joint Design

The following general guidelines should be observed for bonded joint design. Refer to Section 12.7 for a full listing of Bonded Joint Design Guidelines.

1) **An adhesively bonded joint must be designed so that the adhesive is stronger than the adherends.**

Whether the adherends are metallic and/or composite, a bonded joint should be designed for failure in the adherend, not in the adhesive. This prevents the bond-line from being the weak link in the structure, thereby reducing structural integrity risk. The bond could act as a weak-link fuse and fail catastrophically from a local defect.

2) **An adhesively bonded joint must be designed to primarily transfer shear across the bond-line.**

Based on the inherent stiffness and strength properties of the adhesive, the most efficient load transfer for an adhesively bonded joint is through shear acting across the bond-line. Peak adhesive shear and normal stresses occur at or near the bond-surface edges where load transfer begins. These stresses decrease away from the bond-line edges as adherends attain equilibrium load balance with respect to one another.

3) **An adhesively bonded joint must be designed to minimize bond-line tension-peel stresses.**

Tension-peel stresses can not only cause failure in the adhesive, but they can also induce delamination in composite adherends. Peel stresses may be mitigated through joint design by minimizing load path eccentricity, balancing adherend stiffness properties, and using efficient scarf angles, overlapped steps or adherend tapers.

4) **An adhesively bonded joint design must consider the thermal expansion of all joint constituents.**

Thermally induced bond-line residual stresses should be considered for both cool down from the cure temperature and for the range of design service temperatures. The effects of moisture absorption on the adhesive and adherends should also be considered.

5) **Ductile adhesives are preferred over brittle ones as they absorb more strain energy before failure.**

Although brittle adhesives may exhibit a higher ultimate strength, ductile adhesives are more forgiving and absorb more strain energy before final failure. Refer to Section 12.3.3.

6) **Bond surface preparation is the most critical factor in producing reliable, full strength bonded joints.**

Surface preparation procedures must be determined experimentally and must be strictly adhered to for production quality control. The objectives for bond surface preparation are to: 1) clean the bond surface of contaminants and moisture; 2) increase the bond surface free energy to an equal or higher value than the adhesive; and 3) produce an adherend bond surface condition that is reliably consistent.

12.2.6 Structural Certification of Bonded Structure

Composite bonded joints and assemblies provide a potential cost savings benefit in the elimination of fastener installation processes. In addition, there is a potential weight savings benefit as compared to bolted joints; however, this savings is often offset by the need to size adherends to accommodate subsequent fastener repairs. Despite these potential advantages, the present state-of-the-art for bonded structures technology has the following limitations:

- Non-destructive inspection techniques are incapable of assessing bond strength;
- Successful production of bonded structure with reliable quality requires:
  - A good joint design;
  - Carefully controlled fabrication materials, processes and working environment;
  - Consistently reproducible, good quality bond surface preparation; and
  - Experienced skilled workmanship.
- Bond-line and adherend stress fields are complex and failures are difficult to predict; however, the closed-form IDAT/IBOND strength analysis is currently being developed to provide that prediction capability.

These limitations increase the structural integrity risk of bonded joints and assemblies and have thus made it difficult for the certifying agencies to develop an acceptable industry-wide approach for flight certification of composite bonded structures. The present approach to mitigate these structural integrity risk is through comprehensive structures and manufacturing development testing as part of the airframe building block development test program (Refer to Section 18.3 for a description of the Building Block test process). Furthermore, careful quality control of production processes up to actual proof loading of bonded assemblies may be required. Currently, industry and government sponsored research efforts are actively researching methods and procedures to mitigate each of the three disadvantages listed above (References: 12-6, 12-7, 12-8).

Several strategies that have been used by industry and the certifying agencies to mitigate structural integrity risk of bonded structure are:

- Use of travelers to monitor production process quality;
- Proof loading of production bonded parts/assemblies; and
- Fail-safe design:
  - Multiple load path; or
  - Single load path with crack arrest features.

Travelers or tab-out specimens may be used as a means to monitor the quality of manufacturing materials and processes used to produce composite bonded assemblies. Travelers are separate bonded joint specimens that are prepared along-side the production part using the same manufacturing materials, processes and autoclave cure. Tab-outs are bonded joints specimens that can be intentionally designed into the part or excised from trim or scrap portions of the production part. Both travelers and tab-out specimens may be destructively tested to evaluate the production part quality. Travelers must be carefully controlled and evaluated such that unfavorable findings may be relied upon as representative of production materials and processes. Tab-outs should be carefully selected and inspected to avoid thin laminate edges where resin squeeze out has occurred. These areas are normally trimmed away on production composite parts.

Proof loading of production bonded structure requires that each production bonded assembly be proof loaded to a specified load level such that any weak bond or bond-line defect would fail in a detectable manner so that the damage is identified and can be assessed for material review action. All other non-detected flaws are assumed to be acceptable per durability design requirements. The disadvantage of this approach is the time and expense of conducting the proof test and associated inspections for all production articles. Furthermore, proof loading has its practical limitations in that it may not be possible to devise a loading scheme for a given bonded assembly that fully exercises all bond-lines within the structure up to the desired level of loading.

Fail-safe design for multiple load path bonded structure requires that a specified load level must be sustained by the remaining structure at the instant of load path failure of a primary member. This load must be maintained by the secondary member at any time during a specified inspection interval; thus, there is a fatigue life requirement between these service intervals. The load level that must be maintained is based on the inspectability of the bonded structure.

Fail-safe design for single load path structure requires crack arrest design features. An example of this approach may be the introduction of strategically placed mechanical fasteners that serve to arrest crack or damage propagation such that the primary structure can continue to sustain loading.

12.2.7 Key Resources and Analysis Tools

The methods described in Section 12.0 are the recommended approaches for bonded joint analysis at LM Aeronautics. This section provides references for additional background information and analysis tools that are available to support bonded joint analysis. In addition, Tables 12.2-3 and 12.2-4 provide a listing of Lockheed Martin Analysis tools for bonded joints.

1) Bonded Joint Design and Analysis

- FZM-9569 Bonded Joint Structural Analysis Methods (Reference 12-9)
- FZM-10393 3-D Woven Pi-Preform Joint Design/Manufacturing/Process Guidelines (Reference 12-10)
- CMH-17 Composite Materials Handbook (Reference 12-11)
    - Volume 1, Section 7.6 Bonded Joint Tests
    - Volume 3, Section 7.5.6.2 Bonded Joints (Design); Section 7.7 Lessons Learned; Section 10.0 Design and Analysis of Bonded Joints; and Section 14.7.4 Bonded Repairs

2) Related PM-4056 Sections

- Section 13 Composite Design and Analysis Details (includes Co-Bonded 3-D Woven Preform Joints)
- Section 18 Structural Certification and Testing
- Section 19 Effects of Defects and Repair Concepts

3) Lockheed Martin Design Properties and Allowables

- Adhesive Test Reports (Reference 12-12, 12-13, 12-14, 12-15)
- Woven Pi-Preform Joint Test Reports (Reference 12-16, 12-17, 12-18, 12-19)
- Design Allowables (Reference 12-20, 12-21, 12-22, 12-23, 12-24)

An overview of adhesive design properties and applicable test methods are provided in Section 12.3 and 12.4, respectively. A description of common aerospace bonded joint configurations is provided in Section 12.6. Design consideration and guidelines are discussed in Sections 12.7. An overview of bonded joint structural analysis methods with key references is provided in Section 12.8. A list of IDAT analysis tools that support bonded joint strength analysis along with a brief description is provided in Table 12.2-3.

Table 12.2-3 IDAT Tools for Bonded Joint Analysis.

IDAT Tool	Description
A4EI (Reference 12-25)	• Bonded joint strength analysis • Predicts bond-line shear stress only (tension peel stress neglected) • Accounts for one-dimensional axial (no bending) and thermal loading • Adhesive shear modeled as linear elastic or elastic-perfectly plastic
IBOND (Reference 12-3)	• Bonded joint strength analysis • Predicts bond-line normal (tension peel) and shear stress distributions • Accounts for joint flexibility, adherend bending and thermal loading • Adhesive shear modeled as linearly elastic
MATUTL (Reference 12-26)	• Provides interactive access to engineering material property data • Provides access to Adhesive and Adherend properties
SQ5 (Reference 12-27)	• SQ5 provides laminate strength analysis for composite adherends • Accounts for in-plane, bending & thermal loading • Interlaminar strength analysis limited to approximate transverse shear
LAMINATE, LAM_PERCT (Reference 12-28, 12-29)	• Laminate editor tools • Create stacking sequences and calculate laminate properties
Note: Refer to IDAT User Guides for detailed analysis instructions.	

The A4EI analysis program for bonded joint strength analysis was developed by Hart-Smith. His early work on a variety of adhesively bonded joint configurations contributed greatly to the design and practical strength analysis of bonded joints (Reference 12-30 through 12-38). A listing of Bonded Joint Analysis Strength checks for the adhesive bond-line and adherends is provided in Table 12.2-4. Adhesive material forms are described in Section 12.3.2.

Table 12.2-4 Summary of Bonded Joint Analysis Strength Checks

Joint Element	Material Form	Analysis	Tool, if applicable
Adhesive	Liquid, Paste, Film, or Core Splicing	Bond-line Shear & Tension Strength	A4EI**, IBOND, FEA*
Adherend	Metal	Yield, Ultimate Strength	Refer to PM-4057, FEA*
	Composite Laminate	In-plane Strength	SQ5, IBOND, FEA*
		Interlaminar Strength	IBOND, FEA*
	3D Woven Pre-form	Ultimate Strength in Primary Fiber Directions	IBOND, FEA*
* FEA = Finite element analysis (See Section 12.8.6 for guidance). ** A4EI predicts bond-line shear stresses only.			

A listing of other useful key resources that provide valuable guidance in the design, analysis, manufacturing and testing of composite bonded joints and assemblies are provided below.

Other Lockheed Martin Bonded Joint Guidance

- Lockheed Composite Stress Memo Manual, Memo 10 Adhesive Bonded Joints (Reference 12-39)
- Design Guide for FBM Composite Structures, LMSC-D477785, Chapter 11 (Reference 12-40)
- LMSC Introduction to Composites Course, Section 11 Composite Joints (Reference 12-41)
- FZM-8621 Adhesive Bonded Joints - Lessons Learned (Reference 12-42)
- FZM-9025 Cobond/Cocure/Paste Bond of 3-D Pi-Preform Structures Design Guidelines (Reference 12-43)
- F-35 Structural Analysis Methods and Design Criteria (Reference 12-44)

Aerospace Industry Bonded Joint Guidance

- NASA/DOD Advanced Composites Design Guide, Chapter 1.3.1 (Reference 12-45)
- LTV Composite Structural Analysis Manual, Section 12 Joints (Reference 12-46)
- Bonded Joint Design Guidelines, prepared for the Composites Affordability Initiative (Reference 12-47)
- Bonded Joint Related Textbooks (References 12-48, 12-49, 12-50, 12-51, 12-52)

12.3 Structural Adhesives

Structural adhesives are those adhesives that are qualified for use in structural load transfer applications with well-defined structural design properties and whose structural integrity characteristics can reliably be assessed. This section addresses the following topics for structural adhesives commonly used in aerospace applications:

- General types of adhesives (Section 12.3.1);
- Common material forms (Section 12.3.2);
- Material behavior (Section 12.3.3);
- Shear stress-strain curves (Section 12.3.4);
- IDAT Material Files for Adhesives (Section 12.3.5); and
- Adhesive allowable strength (Section 12.3.6).

Aerospace structural adhesives are typically polymeric thermoset resins. They can be used to join together a variety of materials such as metals, ceramics and composite materials. Although the strength of the adhesive may be much less than the adherends, a strong joint may be produced provided that the adhesive layer is thin, continuous and designed to transfer load primarily in shear. Whether the adherends are metallic or composite, a well-designed bonded joint should fail in the adherend and not in the adhesive. The best stiffness and strength properties for thermoset adhesives are obtained using an autoclave cure with applied temperature, pressure, and vacuum bagging per the material specification. Structural adhesives are usually selected based on their ductility and maximum operating temperature and moisture condition.

12.3.1 Types of Adhesives

The general types of structural adhesives commonly used for aerospace airframe structural applications are described in this section (Reference 12-51).

Thermosetting adhesives – A thermosetting resin is a prepolymer in a soft solid or viscous state that changes chemically and irreversibly by curing through the application of heat and/or catalysts into a permanently hard polymer network that is essentially infusible and insoluble. Thermosets do not soften upon subsequent heating and only heating to excessive temperatures beyond the characteristic glass transition temperature causes a severance of crosslink bonds and polymer degradation. As compared to thermoplastics, thermoset polymers are generally harder, stronger, more brittle, more dimensionally stable, more resistant to time dependent creep deformation under load, and display relatively good performance in severe temperature, moisture, chemical and radiation environments. Thermoset resins typically require curing at elevated temperatures with applied pressure and vacuum to attain full strength and stiffness properties. Common aerospace thermoset structural adhesives include epoxy, bismaleimide, phenolic and polyester resins.

Thermoplastic adhesives – Thermoplastic adhesives are classified into the general categories of thermoplastic resin and thermoplastic rubber adhesives. Thermoplastic adhesives are fusible, soluble, soften when heated and harden when cooled. Thermoplastics are usually formed by simultaneous application of heat and pressure. In contrast to thermosets, the heating and cooling processes are totally reversible and can be repeated. Heating to excessive temperatures can cause molecular vibrations to become violent enough to break down the primary covalent bonds resulting in irreversible degradation. As compared to thermosets, thermoplastic polymers are relatively softer, weaker, more ductile and are subject to time dependent creep behavior under load. Thus, thermoplastic adhesives are more suitable for lower load applications.

Rubber-resin blend adhesives – These are adhesives in which rubbers and resins are blended together to obtain the desired properties of both types of materials. Blended adhesives may be used for structural or general purpose bonding applications. Adhesives consisting of thermoset resins modified with synthetic rubber may be used for structural applications with phenolic-nitrile and phenolic-neoprene being examples. The rubber component acts to improve the flexibility of the cured bond providing resistance to impact or shock loading. Thermosets alone tend to be brittle where the rubber-resin blends result in more ductile behavior.

Toughened structural adhesives – Toughened adhesives are adhesives that have been modified to improve their fracture toughness. There materials are typically composed of a glassy thermoset resin into which is incorporated an elastomeric phase that is physically separate but chemically linked to the resin. The resin matrix functions as a load bearing element while the dispersed rubber phase absorbs fracture energy. The elastomer distorts and crazes during energy dissipation. This reduces the risk of catastrophic failure and improves the material fracture toughness and damage resistance. Resistance to fatigue and environmental effects are also improved.

12.3.2 Material Forms

The following adhesive material forms are commonly used for aerospace airframe structural applications.

Liquid or Paste Adhesive – An adhesive typically available as a two-part, room temperature curing epoxy with resin and a curing agent that are mixed together to initiate the cure process. Some liquid or paste adhesives may be stored at room temperature, while others may require cold storage with all having a finite storage life. After mixing, the application time before the adhesive sets, also referred to as the working life or pot life, may be on the order of minutes to hours. Full cure may take up to seven days and the cure process can often be accelerated through the application of moderate temperature (160-180 °F). Storage and working life requirements are typically defined in the material specification. These materials are primarily used as an adhesive or laminating material in aircraft material review (rework) or repair applications. When used for wet lay-up repairs, vacuum pressure may also be required to reduce void content. 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.

Film Adhesive – An adhesive available in an uncured thin sheet form that is suitable for bonding metal, composites, and honeycomb core in any combination. Film adhesives are recommended for use in production of composite bonded assemblies as they allow more uniform adhesive application over large bond areas and aid repeatability and fabrication control of the bonding operation. Film adhesive may be available unsupported (adhesive only) or supported with a carrier ply of woven fabric or random mat. The carrier ply improves handling and can provide a physical presence to help maintain bond-line thickness during cure. Storage and out time requirements for adhesives are comparable to fiber reinforced composites of similar resin type. Adhesion bonding of metal adherends requires the use of a corrosion resistant adhesive primer.

Core Splice Adhesive – An adhesive available as a film or foaming form that may be used for sealing, splicing or reinforcing honeycomb core edge closeouts. These adhesives may be available as a 250 or 350 °F cure epoxy or as a bismaleimide based adhesive for use in co-bonded sandwich core assemblies.

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.

Aerospace structural adhesives are typically thermoset resins such as epoxies and bismaleimides where an elevated temperature cure under autoclave pressure and applied vacuum is required to develop full structural strength capability. Refer to Section 19.7 for more discussion of adhesives that are currently in use for production and repair at Lockheed Martin Aeronautics.

12.3.3 Adhesive Material Behavior

Ideally, the material behavior of structural adhesives, in the absence of reinforcement fibers, are considered isotropic exhibiting identical stiffness and strength properties in all directions. Isotropic materials are characterized by two independent elastic constants, such as Young's modulus, E, and shear modulus, G. Young's modulus and Poisson's ratio, ν, can be measured experimentally by a uniaxial tension test, such as the industry standard test ASTM D638 (Reference 12-53) for testing of thin material sheets. Shear modulus, G, can be measured experimentally by a thick-adherend lap shear test by tension loading, such as the industry standard test ASTM D5656 (Reference 12-44) for testing adhesives. Shear modulus may be related to Young's modulus and Poisson's ratio through the familiar elastic relation given as Equation 12.3-1. These test methods are discussed in further detail in Section 12.4.

$$G = \frac{E}{2(1+\nu)}$$ **Equation 12.3-1**

Where:
G = Shear modulus (psi).
E = Young's modulus (psi).
ν = Poisson's ratio.

A typical uniaxial tension stress-strain curve for FM 300 film adhesive at room temperature ambient (RTA) condition is shown in Figure 12.3-1. The tension stress-strain response is very nonlinear with an elastic limit strain of approximately 12,000 micro-strain and initial modulus E_{init} = 0.320 Msi as compared to an ultimate failure strain of 48,000 micro-strain and secant modulus E_{sec} of 0.184 Msi. The ultimate tension failure stress is just under 9,000 psi. For polymeric adhesives, Poisson's ratio will vary from 0.32 to 0.49.

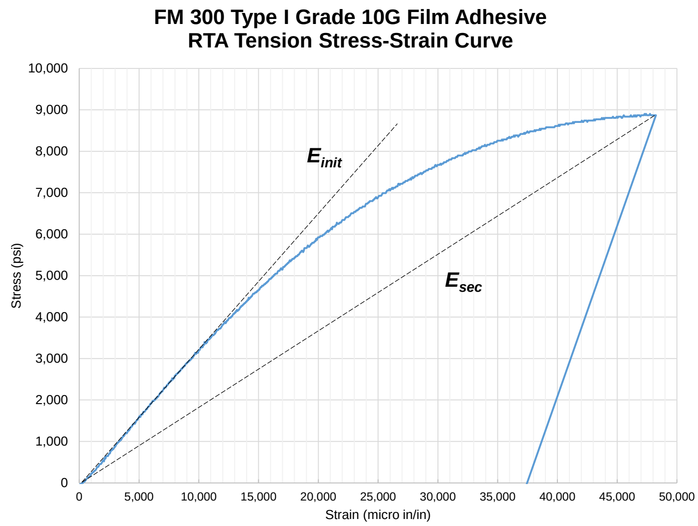


Figure 12.3-1 Uniaxial Tension Stress-Strain Curve for FM 300 Film Adhesive, RTA Condition (Reference 12-13)

A typical shear stress-strain curve for FM 300 film adhesive at room temperature ambient (RTA) condition is shown in Figure 12.3-2. Again, the shear stress-strain response is very nonlinear with an elastic limit strain of approximately 2,000 micro-strain and initial modulus G_{init} = 0.100 Msi as compared to an ultimate failure strain of 243,000 micro-strain and secant modulus G_{sec} of 0.026 Msi. The ultimate shear failure stress is just under 9,000 psi. Although the adhesive is considered isotropic, it is often difficult to correlate measured E, ν, and G values between tension and shear loading test methods using Equation 12.3-1. This will be discussed further in Section 12.4.

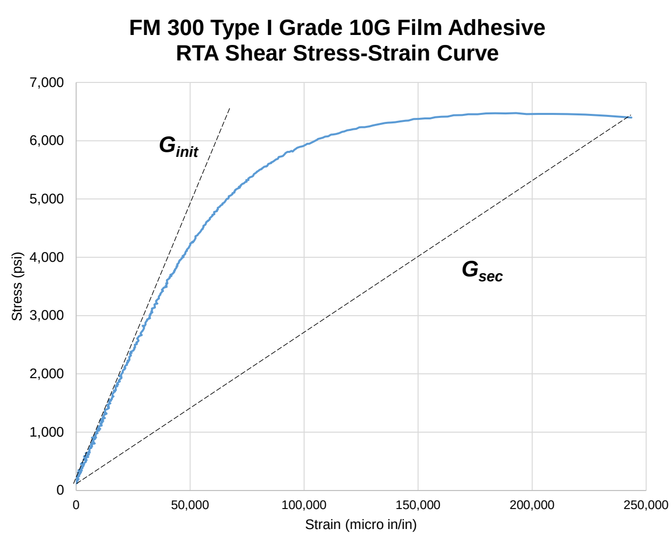


Figure 12.3-2 Shear Stress-Strain Curve for FM 300 Film Adhesive, RTA Condition (Reference 12-13).

As shown above, the elastic and strength properties of polymeric structural adhesives are relatively low as compared to metals. The material behavior of metals are dependent on atom-to-atom force interactions. In contrast, the material behavior of polymeric adhesives are dependent upon the interaction of 3-D cross-linked molecular structures. These differences in mechanisms at the micro-level lead to the observed differences at the macro-level.

Structural adhesives can exhibit brittle or ductile behavior as shown in Figure 12.3-3. As compared to ductile adhesives, brittle adhesives have a higher initial shear stiffness, higher failure stress and lower failure strain. However, as measured by the area under the stress-strain curve, a ductile adhesive is capable of absorbing more strain energy prior to failure and is more capable of supporting a high level of strain at failure. Therefore, ductile adhesives are preferred for structural bonded joint applications.

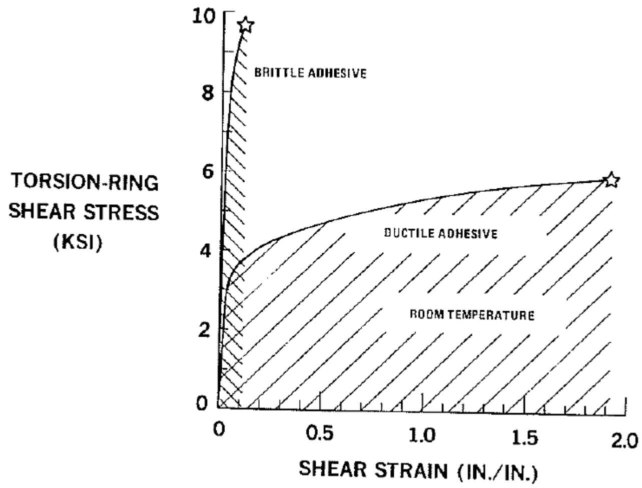


Figure 12.3-3 Typical Shear Stress-Strain Behavior for Brittle and Ductile Adhesives (Chapter 7, Reference 12-50)

Due to their molecular structure, polymer adhesives are relatively more sensitive to temperature and moisture as compared to metals. For example, refer to the shear stress-strain curves for FM300K shown in Figure 12.3-4. The most brittle material response is observed for cold-dry environmental conditions. As the temperature is increased and moisture is introduced, the material behavior becomes more ductile. Typically, the most ductile behavior is observed for the maximum hot-wet operating condition.

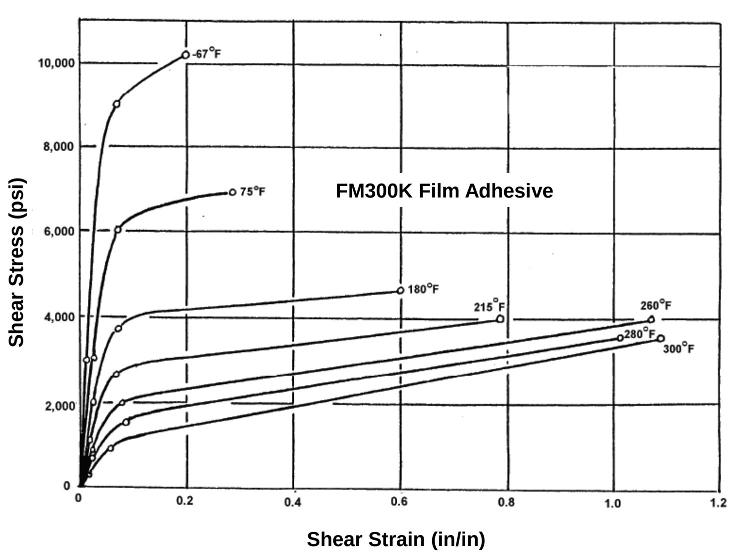


Figure 12.3-4 Shear Stress-Strain Response for FM300 K Adhesive (Reference 12-11, Vol. 1G, Fig. 7.6.2.1.1(b)).

The glass transition temperature, T_g, is a characteristic temperature at which a cured thermoset adhesive transitions from a glassy to a rubbery behavior. Above the T_g, the polymeric adhesive becomes too soft and flexible to act as a structural material. Plasticization of a polymer by absorbed moisture causes a reduction in the glass transition temperature. The maximum operating temperature for all thermoset adhesives must be well below the glass transition temperature.

Structural adhesives can also exhibit more brittle fracture at high load rates. Adhesives can also exhibit time dependent visco-elastic-plastic behavior at elevated temperatures, such as creep and relaxation. These environmental effects can usually be mitigated by thorough adhesive material characterization testing and by careful consideration of the design load and environmental requirements. Approved design material properties for structural adhesives used at Lockheed Martin Aeronautics may be determined for their design environmental conditions using IDAT/MATUTL.

Most bond-line strength predictions require the shear stress-strain curve at the critical design temperature. Ductile behavior of adhesives characteristically exhibits a low secant shear modulus with relatively small shear stress and high shear strains at failure. Therefore, a strain based failure criterion is often used for bond-line strength predictions. A discussion of the various methods used to represent the characteristic shear stress-strain curves for adhesives is provided in the next section.

12.3.4 Adhesive Shear Stress-Strain Curves

This section describes the common features of adhesive shear stress-strain curves and the various methods that may be used to represent them. Be aware that each shear stress-strain curve given for an adhesive pertains to a unique temperature and moisture environmental condition.

12.3.4.1 Common Features for Shear Stress-Strain Curves

The standard test methods for experimentally measuring stress-strain curves for structural adhesives for a given environmental condition are described in Section 12.4. The test method that is currently preferred by the aerospace industry is the ASTM D5656 thick adherend lap shear test under tension loading. A typical shear stress-strain curve (FM300K, RTA condition) measured by this test method is shown in Figure 12.3-2. Two common shear moduli are illustrated on the figure.

***G_{init}* (Initial Shear Modulus)** – This is the initial shear modulus that is the slope of a tangent line drawn through the initial, linearly rising portion of the shear stress-strain curve (Figure 12.3-2). Refer to Linear Limit discussion below for more details.

***G_{sec}* (Secant Shear Modulus)** – This is the shear modulus that is the slope of a secant line drawn through the origin and to a specified point on the shear stress-strain curve. While there can be a different secant modulus for each stress level, for adhesives, the secant modulus is typically defined with respect to the ultimate failure shear stress and strain as is shown in Figure 12.3-2.

The ASTM D5656 thick-adherend lap shear test method defines three characteristic points (Reference 12-54) for adhesives that are usually identified on the load-displacement curve. The three points illustrated in Figure 12.3-5 are: (1) LL (Linear Limit), (2) KN (Knee), and (3) UL (Ultimate Limit or Strength). These points are described as follows in relation to the experimental load-displacement curve from which they are to be identified.

LL (Linear Limit) – If a tangent line is drawn to the initial, linearly rising portion of the load-displacement curve, then the LL point is where the curve begins to deviate from the initial linear load-displacement behavior. This is equivalent to the proportional limit for metals. The corresponding shear stress Tau_LL and strain Gam_LL at this point is used to calculate the initial shear modulus G_{init} (Figure 12.3-5). The Linear Limit point for adhesives may be difficult to identify as the onset of nonlinearity is sometimes gradual, so engineering judgment may be required. Its exact position is not critical as long as it is a valid point on the curve. If the load-displacement curve has no discernable initial linear portion, then the LL coordinates are set at zero shear stress and strain.

KN (Knee) – A second tangent line is drawn to the horizontal or yielded portion of the load displacement curve (Figure 12.3-5). The KN point is determined by bisecting the angle between the initial shear modulus tangent line and the tangent line that best represents the yielded portion of the curve. This point establishes a region where the adhesive stiffness transitions from linear behavior to a rapid reduction in stiffness. At the lower end where the curve diverges from initial linear behavior, the adhesive begins to yield at the peak shear stress locations. This yielding progresses along the bond-line as the load is increased. This region is also where the first discernable effects on fatigue life have been observed experimentally. For loads above the KN point, there appears to be a reduction in fatigue life and for repeated loads near the KN point, a reduction in LL stress and initial shear modulus have been observed. Thus, while metals can be taken beyond yield and still retain stiffness, fatigue life, and environmental durability, the same cannot be safely assumed for adhesives.

UL (Ultimate Strength) – This is the point at which ultimate cohesive failure of the adhesive occurs.

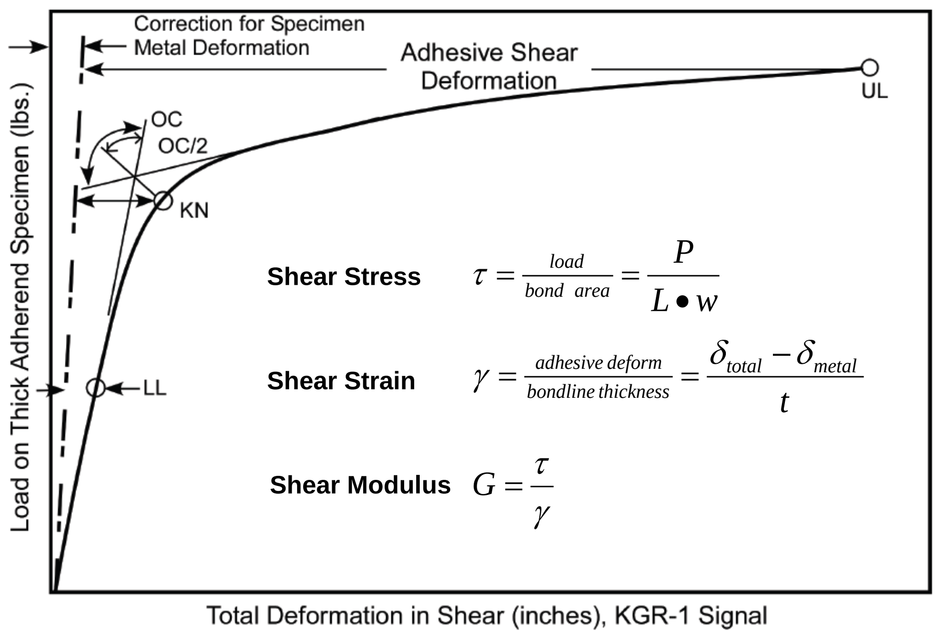


Figure 12.3-5 Adhesive Characteristic Points for a Thick-Adherend Lap Shear Load-Deformation Curve (Reference 12-11, Fig. 7.6.2.1.1c).

12.3.4.2 Ramberg-Osgood Stress-Strain Relationship

The Ramberg-Osgood (R-O) relationship was developed as a convenient means to represent normal stress-strain curves for metals. The R-O relationship for strain in terms of stress for a uniaxial stress-strain curve (tension or compression) is given in Equation 12.3-1 and Equation 12.3-2. The first term represents the linear Hookean stress-strain relation. The second term represents the post-yield nonlinear portion of the stress-strain curve.

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{3}{7}\left(\frac{\sigma}{\sigma_{0.7}}\right)^{n-1}\right]$$ **Equation 12.3-2**

$$n = 1 + \frac{\log\left(\frac{17}{7}\right)}{\log\left(\frac{\sigma_{0.7}}{\sigma_{0.85}}\right)}$$ **Equation 12.3-3**

Where:

ε = normal strain (in/in)

σ = normal stress (psi)

E = Young's modulus (psi)

$\sigma_{0.7}$, $\sigma_{0.85}$ = experimentally determined *0.70E* and *0.85E* secant intercepts for the normal stress-strain curve (psi)

n = Ramberg-Osgood fit parameter

Due to the similarity in curve shape, the Ramberg-Osgood relationship has been modified for use in describing adhesive stress-strain curves. An example of an R-O fit of an adhesive shear stress-strain curve is shown by the red line in Figure 12.3-6.

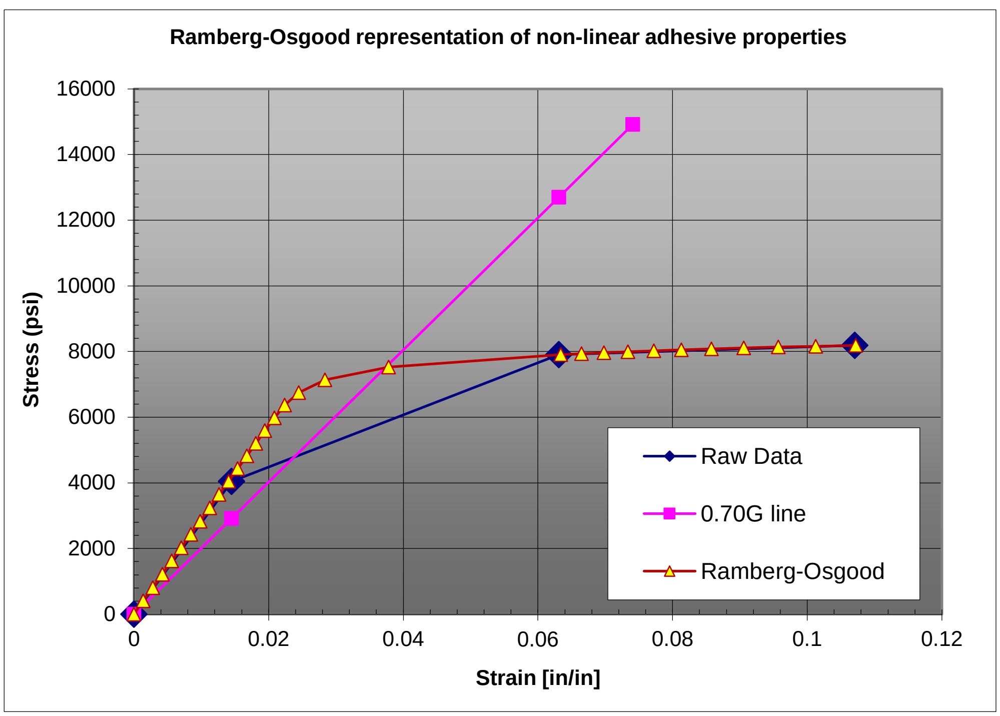


Figure 12.3-6 Ramberg-Osgood Representation of Shear Stress-Strain Curve.

The modified shear R-O relation is given in Equation 12.3-4. The modification uses the stress-strain values at LL, KN, and UL determined from a Thick-Adherend test (refer to navy blue points and line in the figure). The $\tau_{0.7}$ secant intercept is determined by estimating where a 45-degree line (shown in light purple) from the origin intersects the shear stress-strain curve based on the given data. An iterative solution procedure is used to determine the n

parameter that best fits the shear stress-strain curve. This procedure has been implemented into a convenient spreadsheet format.

$$\gamma = \frac{\tau}{G}\left[1 + \frac{3}{7}\left(\frac{\tau}{\tau_{0.7}}\right)^{n-1}\right] \qquad \text{Equation 12.3-4}$$

Where:

γ = engineering shear strain (in/in)

τ = shear stress (psi)

G = initial shear modulus (psi)

$\tau_{0.7}$ = experimentally determined secant intercept for an approximate 45 degree line (psi)

n = Ramberg-Osgood fit parameter

As stated above, thick-adherend test results are used to derive the modified R-O fit for the shear stress-strain curve. However, some finite element analysis codes may require an equivalent normal stress-strain curve for modeling of an assumed isotropic adhesive. An approximate method to derive equivalent normal stress-strain parameters may be calculated using Equation 12.3-5 and Equation 12.3-6. This transformation relates the uniaxial tension stress to the maximum shear stress on the octahedral plane. If Poisson's ratio is unknown, then it can be set to 0.40 as an approximation. For polymeric adhesives, Poisson's ratio is typically between 0.32 and 0.49.

$$\varepsilon = \frac{\sqrt{3}}{2(1+\nu)}\gamma \qquad \textbf{Equation 12.3-5}$$

$$\sigma = \sqrt{3}\tau \qquad \textbf{Equation 12.3-6}$$

This transformation method is viewed as approximate for at least two reasons: 1) the stress state for a uniaxial tension test is assumed to be uniform, while the stresses for a thick adherend test are not; and 2) the damage initiation and failure mechanisms between these two tests are not necessarily the same.

12.3.4.3 Bilinear Stress-Strain

The adhesive stress-strain curve has also been modeled using a bilinear representation. A simple elastic-plastic model proposed by Hart-Smith (Reference 12-5) is shown in Figure 12.3-7. Hart-Smith developed the A4EI closed-form analysis for predicting the shear stress distributions for adhesively bonded joints. The A4EI analysis code has been incorporated into IDAT and is discussed in Section 12.8.4. Hart-Smith concluded that the maximum potential adhesive bond strength is defined by the strain energy in shear. Therefore, strain energy represented by the area under the elastic-plastic bilinear curve must be equal to the strain energy under the actual measured shear stress-strain curve. The Hart-Smith elastic-plastic bilinear model is defined by three parameters: τ_{max}, γ_{max}, and $G_{elastic}$. The first two are measured by test, while $G_{elastic}$ is determined so that it results in the same elastic energy. The linearly elastic portion of the curve is represented by slope $G_{elastic}$. The perfectly plastic portion of the remainder of the curve is defined by τ_{max}, ends at γ_{max}, and has zero slope.

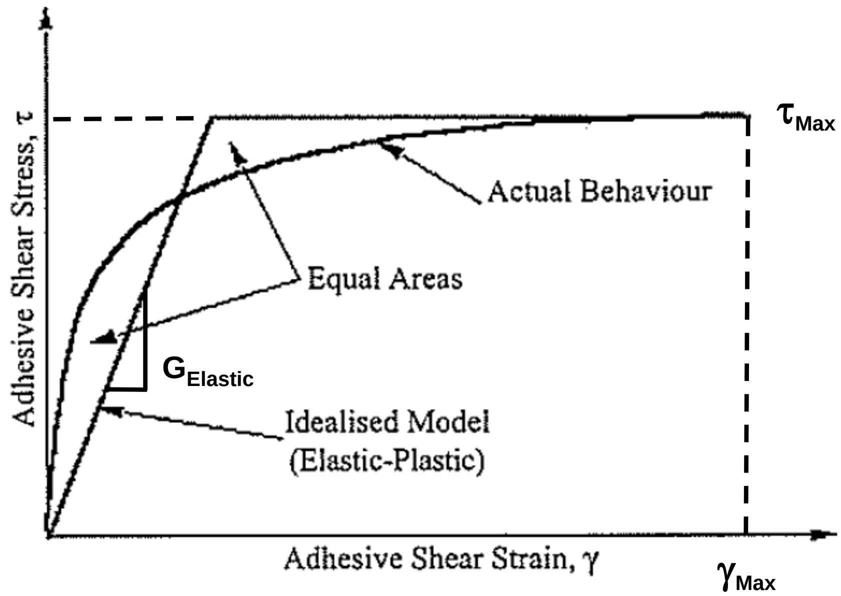


Figure 12.3-7 Adhesive Stress-Strain Curve (Actual) and Idealized Elastic-Perfect Model Used in the Hart-Smith A4EI Analysis (Reference 12-5).

The current version of the IDAT/A4EI analysis application uses a slightly modified version of this elastic-plastic model approach. IDAT/A4EI uses the approximation shown in Figure 12.3-8 which uses the initial shear modulus G_{init} instead of a calculated $G_{elastic}$. The maximum shear stress, τ_{max}, matches the typical measured test value, but the corresponding ultimate shear strain is varied until the total strain energy equals the energy under the nonlinear stress-strain curve. The B-Basis ultimate shear stress allowable indicated as Tau_Ult in IDAT/MATUTL is obtained by adjusting τ_{max} by a B-Basis factor determined from double lap shear coupon tests. The strain, γ_{target}, is not adjusted and becomes the B-Basis ultimate shear strain allowable indicated as Gam_Ult in IDAT/MATUTL.

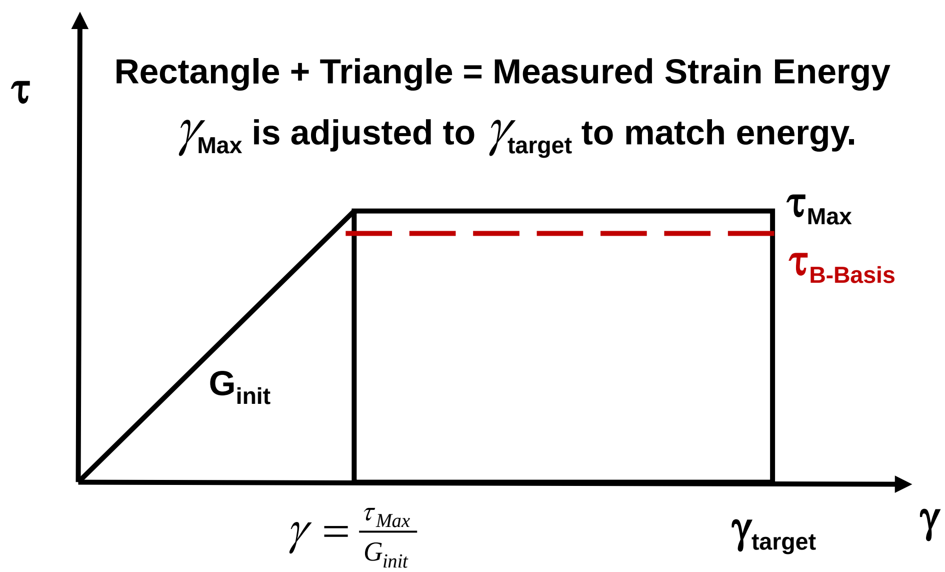


Figure 12.3-8 Idealized Elastic-Perfect Model used in IDAT/A4EI Analysis (Reference 12-25).

12.3.5 IDAT Material Files for Adhesives

A list of the structural adhesives for which a full IDAT material file has been developed for use with A4EI and IBOND bonded joint strength analysis codes are provided in Table 12.3-1.

Table 12.3-1 List of IDAT Material Files for Adhesives.

Product Name	Description	Material Specification	Cure Temp	Operating Temp	Class	Notes
FM300	Epoxy Film Adhesive 350 °F Cure for 250 °F Service Applications	2ZZZ00002B	350 °F	From –65 °F to +250 °F	Type I, Grade 10G	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.
FM300-2K	Epoxy Film Adhesive 250 °F Cure for Repair Applications	2ZZZ00045A	250 °F	From –65 °F to +250 °F	Type I, Class A	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.
AF191	Modified Epoxy Film Adhesive 350°F Cure	LMA-MD007	350 °F	From –65 °F to +275 °F	Type I, Grade 10G	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.
AF563	Epoxy Film Adhesive	LMA-MD028	250 °F	From –65 °F to +250 °F	Form 1, Type A	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.
FM309-1	Epoxy Film Adhesive	TBD (Currently in Preparation)	350 °F	From –65 °F to +250 °F	Form 1M	0.080 lb/ft^2 weight with a polyester mat carrier.
					Form 1G	0.050 lb/ft^2 weight with a woven glass carrier.
FM2550G	Bismaleimide Film Adhesive	LMA-MD107	375 °F with 440 °F Post-Cure	From –65 °F to +325 °F	Type I	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.
EA9394	Adhesive, Epoxy Paste, Two Part	LMA-ML111	Room Temp; or with Elevated Temp	From –65 °F to +300 °F	Type I, Two-Part, Metallic-Filled	Suitable for use in structural bonding if cured at 200 °F (or above).
Note: Refer to the Material Specification for more information.						

A list of the IDAT material file parameters for a structural adhesive are provided in Table 12.3-2. The allowable strength values are described in more detail in Section 12.3.6.

Table 12.3-2 IDAT Material File Parameters for Adhesive Properties.

Z(i) No.	Property	Units	Description
Elastic Properties			
2	E	psi	Initial Axial Modulus (Calculated from G and ν)
4	G	psi	Initial Shear Modulus (1)
6	ν		Poisson's Ratio (2)
Ramberg-Osgood Fit Parameters (including E) for a Normal (Axial) Stress-Strain Curve (1, 3)			
3	S_0.70	psi	0.7E secant intercept for normal stress-strain curve
5	RO-n		n = Ramberg-Osgood fit parameter
Normal Stress-Strain Properties Transformed from ASTM D5656 Test Results (1, 4)			
8	Eps_LL	in/in	LL = Mean Linear Limit Tension Strain (Typical)
13	Sig_LL	psi	LL = Mean Linear Limit Tension Stress (Typical)
11	Eps_Kn	in/in	KN = Mean Knee Tension Strain (Typical)
16	Sig_Kn	psi	KN = Mean Knee Tension Stress (Typical)
9	Eps_Ult	in/in	UL = Mean Ultimate Tension Strain (Typical)
14	Sig_Ult	psi	UL = Mean Ultimate Tension Stress (Typical)
12	Eps_Ballow	in/in	B-Basis Ultimate Tension Strain Allowable (6)
17	Sig_Ballow	psi	B-Basis Ultimate Tension Stress Allowable (6)
A4EI Shear Elastic- Perfectly Plastic Stress-Strain B-Basis Allowables (1,5)			
10	Gam_Ult	in/in	B-Basis Ultimate Shear Strain A4EI Allowable
15	Tau_Ult	psi	B-Basis Ultimate Shear Stress A4EI Allowable
Other Analysis Parameters (6)			
32	K_peel		Adhesive Peel Typical/B-Basis Strength Factor
33	K_su		Adhesive Shear Typical/B-Basis Strength Factor
34	J1C	in/in	B-Basis J1 First Principal Strain Invariant Allowable (7)
35	EPS_EQV	in/in	B-Basis Equivalent Distortional Strain Allowable (7)
45	FWT_HC	psi	S-Basis Honeycomb Core Sandwich Flatwise Tension Allowable (8)
47	TAU_SLS	psi	S-Basis Single Lap Shear Strength Allowable (9)
Physical Properties			
18	OPTEMP	deg F	Operating Temperature
19	SFTEMP	deg F	Stress Free Temperature
7	DEN	lb/in^3	Density
Notes			
1) Measured from an LMA-PT008, Method 4.3 (same as ASTM D5656) Thick-Adherend test. 2) Measured from an ASTM D638 Neat Resin Uni-axial Tension test. Note: Poisson's ratio is difficult to measure and the test method recommends measurement at RTA condition only. Estimated range is 0.32 ~ 0.49. 3) R-O normal stress-strain relation given in Equation 12.3-3 and Equation 12.3-4. These based on ASTM D5656 measured shear stress-strain transformed by Equation 12.3-5 and Equation 12.3-6. 4) Normal stress and strain values are obtained using the transformations, Equation 12.3-5 and Equation 12.3-6. 5) Refer to Section 12.3.4.3 for more information. 6) Refer to Section 12.3.6.1 for more information. 7) Correlated to an ASTM D1876 T-Peel Tension Test to predict adhesive failure. 8) Measured from an LMA-PT008, Method 4.2 (same as ASTM C297) Flatwise Tension for Honeycomb Core. 9) Measured from an LMA-PT008, Method 4.1 (same as ASTM D1002) Single Lap Shear test.			

12.3.6 Adhesive Allowable Strength

This section provides a detailed description of adhesive strength allowables that are stored in the IDAT material file. The section also discusses practical considerations for the development of adhesive design properties and allowable strengths.

12.3.6.1 Adhesive IDAT Material File Allowable Strengths

Additional background for adhesive strength allowables presented in Table 12.3-2 are provided in this section. Adhesive material files have been prepared to support IDAT/A4EI or IBOND bonded joint strength analyses. The properties may be viewed or output in a material property report format using the IDAT/MATUTL program.

k_su, k_peel = Adhesive Typical/B-Basis Strength Factor

These factors are the ratio of the adhesive typical to B-Basis allowable strength values. For a given temperature and moisture condition, k_su is the ratio for adhesive shear strength and k_peel is the ratio for adhesive tension (peel) strength. Refer to Section 18.5 for more information on material typical and B-Basis allowable values.

Eps_Ballow, Sig_Ballow = B-Basis Ultimate Tension Strain and Stress Allowables

These are B-basis adhesive strength allowables for a given temperature and moisture environmental condition that are a statistical reduction of the ultimate stress and strain values for the nonlinear normal (axial) stress-strain curve. Several commercial finite element analysis codes are capable of performing material nonlinear analyses based on a user-provided nonlinear normal (axial) stress-strain curve. Therefore, Ramberg-Osgood fits were derived for adhesive normal stress-strain curves that are based on transformed shear stress-strain curves obtained from thick-adherend tests (refer to Section 12.3.4.2 for a description). The B-basis statistical reduction is used to account for material and manufacturing variability. This is accomplished by reducing the strain energy as represented by the area under the normal stress-strain curve. As shown in Figure 12.3-9, the B-basis allowables represent a point on the normal stress-strain curve at which the total strain energy (area under the stress-strain curve) is reduced by a B-basis reduction factor kdf, where kdf = 1/ k_su. The current statistical allowable reductions for adhesive shear are based on double lap shear adhesive tests conducted under an LM Aero legacy aircraft program.

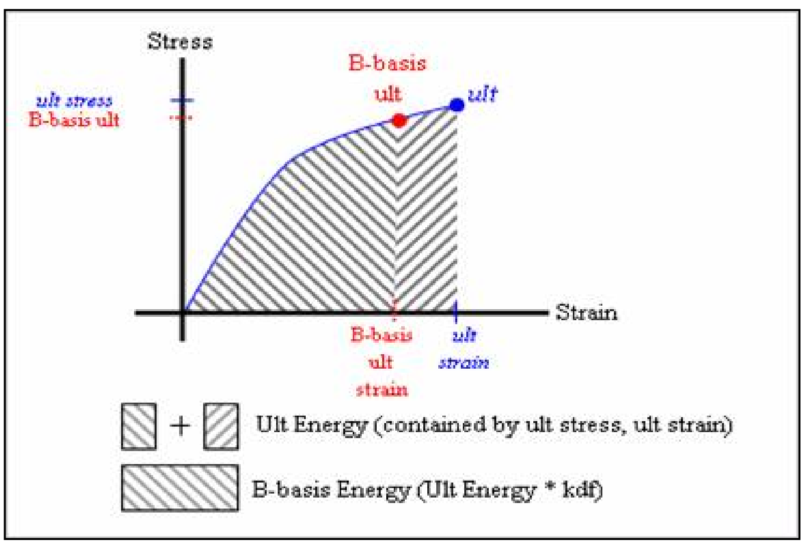


Figure 12.3-9 Strain Energy for an Adhesive Normal Stress-Strain Curve (12-14).

Gam_Ult, Tau_Ult = B-Basis Ultimate Shear Strain and Stress A4EI Allowables

These are B-basis adhesive shear stress and strain allowables for a given temperature and moisture environmental condition that were derived for use in IDAT/A4EI bonded joint analyses. As described in Section 12.3.4.3, the current version of IDAT/A4EI uses a slightly modified version of the Hart-Smith elastic-perfectly plastic model as shown in Figure 12.3-8. τ_{max} matches the typical measured test value, but the corresponding ultimate shear strain is varied until the total strain energy equals the energy under the nonlinear stress-strain curve. The B-basis allowable Tau_Ult is obtained by multiplying τ_{max} times the B-basis allowable reduction factor, *kdf*. However, the ultimate shear strain is not adjusted and simply becomes Gam_Ult.

J1C = B-Basis J1 First Principal Strain Invariant Allowable

J_{1c} is the B-Basis allowable for the 1st invariant (or dilatational) adhesive strain to failure for a given temperature and moisture environmental condition (Reference 12-56, 12-57). This adhesive strain allowable is intended for use with finite element analysis predictions of bonded joints. The J1 strain allowables for various adhesives were set by correlating finite element predictions for ASTM D1876 (Reference 12-58) Adhesive T-peel Tension coupon test results (Reference 12-15). The dilatational margin of safety shown in Equation 12.3-7 is checked only if the J_1 strain invariant is tensile, while the distortional margin of safety shown in Equation 12.3-8 is always checked.

EPS_EQV = B-Basis Equivalent Distortional Strain Allowable

ε_{eqv-c} is the B-Basis allowable equivalent (or distortional) adhesive strain to failure for a given temperature and moisture environmental condition. This adhesive strain allowable is intended for use with finite element analysis predictions of bonded joints. Reference 12-23 recommends that ε_{eqv-c} be set to the *Eps_Ballow*, B-Basis Ultimate Tension Strain (see above description).

$$M.S. = J_{1c} / J_1 - 1.0 \quad (\text{when } J_1 > 0) \qquad \text{Equation 12.3-7}$$

$$M.S. = \varepsilon_{eqv-c} / \varepsilon_{VM} - 1.0 \qquad \text{Equation 12.3-8}$$

Where:

$J_1 = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$, is the 1st invariant of applied strain (in any coordinate system).

$\varepsilon_{VM} = \frac{1}{2}\sqrt{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2}$. ε_{VM} is the applied adhesive Von Mises strain.

ε_1, ε_2, ε_3 are the three normal principal strains.

J_{1c} is the allowable 1st invariant (or dilatational) adhesive strain to failure at a given environmental condition.

ε_{eqv-c} is the allowable equivalent (or distortional) adhesive strain to failure at a given environmental condition.

FWT_HC = S-Basis Honeycomb Core Sandwich Flatwise Tension Allowable

This S-basis allowable is the flatwise tension strength for a bonded aluminum skin and aluminum honeycomb sandwich core section for a given temperature and moisture environmental condition. This value is determined using Test Method 4.2, LMA-PT008 (Reference 12-59), identical to ASTM C297 (Reference 12-60). A minimum required flatwise tension strength for an adhesively bonded aluminum skin and aluminum core sandwich specimen is usually documented in the adhesive material specification for process quality control. The flatwise tension strength allowable should never be used as the adhesive tension strength allowable.

TAU_SLS = S-Basis Single Lap Shear Strength Allowable

This S-basis allowable is the single lap shear strength of an adhesive for a given temperature and moisture environmental condition. This value is determined using test method Method 4.1, LMA-PT008, identical to ASTM

D1002 (Reference 12-61). This test uses two thin aluminum adherends of identical thickness with significant joint rotation. The test is typically conducted for one of two lap length-to-adherend thickness ratios, L/t = 8 and 32. The bond-line has non-uniform shear and normal stresses and only the average bond-line shear failure load is calculated and reported from the test. Therefore, this allowable provides a lower bound on the out-of-plane strength since the test configuration includes peel and peak stress effects. These tests should be used for material comparisons and quality control purposes only. A minimum required tension lap shear strength for $L/t = 8$ is usually documented in the adhesive material specification. <u>The single lap shear allowable should never be used as the adhesive shear strength allowable</u>.

12.3.6.2 Practical Considerations for Allowables Development

This section provides practical considerations for development of strength allowables for adhesives and bonded joints.

<u>Distinction Between Adhesive Strength and Bonded Joint Strength</u>

Ideally, in order to conduct a strength and durability analysis of an adhesive bond-line, it is necessary to determine the adhesive initial elastic properties, E and G; the nonlinear shear stress-strain behavior; and the cohesive shear and tension (peel) strengths. It is also necessary to understand the adhesive damage and failure mechanisms caused by fatigue, environment and time dependent effects such as load rate, creep, relaxation, *etc.* This adhesive material behavior is characterized with coupon level tests using metallic adherends for simplicity and standardization. A reasonable approach is to establish adhesive shear and tension strength allowables that will account for the effects of fatigue, environment, time dependence and material and manufacturing process variations.

However, characterization of the adhesive is only a small portion of what is needed to fully develop a bonded joint design. A bonded joint design is dependent upon joint geometry, constituent materials, loading, environment and manufacturing processes. Bond-line surface preparation and control is extremely important to joint structural integrity. The structural integrity assessment must include adhesive, cohesive and adherend failure modes. Bonded joint testing should ideally confirm that adherend failure is the primary failure mode and that neither the adhesive nor surface preparation are the weak link in the joint system. Bonded joint tests are usually accomplished with element level tests as part of a building block development test program. The test objectives typically include analysis calibration and/or development of joint strength allowables. That said, the preferred approach is always analysis calibration as bonded joints typically have multiple failure modes (each requiring statistical characterization) and developing element level joint allowables is very expensive and time consuming. The tests should include static strength, fatigue, durability, damage tolerance and effects of defects. Manufacturing risk reduction tests are usually required to evaluate surface preparation and to validate engineering specification processes for bonding, inspection and quality control.

<u>Adhesive Allowable Development</u>

As will be discussed in Section 12.4, most of the existing industry standard test methods for adhesives and surface treatment consist of joint configurations where bond-line stresses are non-uniform and both shear and normal peel stresses occur at the bond-line edges. Therefore, the current industry approach is to develop shear strength allowables and to minimize tension peel stresses through design as much as possible.

The ASTM D5656 Thick-Adherend test provides, within the known limitations described in Section 12.4.1, the capability to characterize the adhesive shear stress-strain behavior. As shown in Figure 12.2-1, the allowables should account for the statistical variation of shear stress-strain curves. Cyclic testing should be conducted with loading and unloading to determine if the unloading behavior is elastic, plastic or time dependent. If possible, static strength allowables should be set to account for fatigue life, environment, time dependent effects and manufacturing variations. As discussed in Section 12.3.4, this likely means setting a value between the elastic limit and knee point of the shear stress-strain curve.

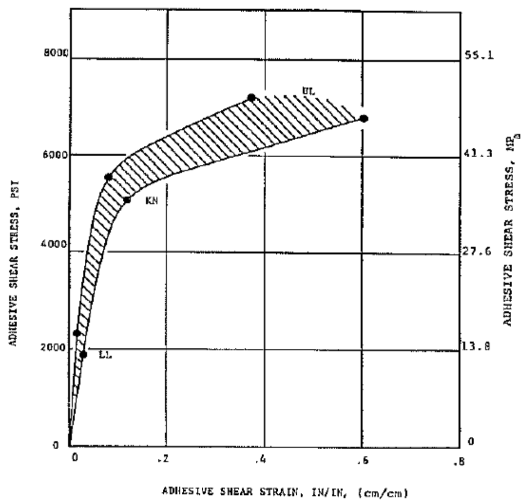


Figure 12.3-10 One Standard Deviation in Shear Stress-Strain for FM300 Adhesive at a Room Temperature Ambient Condition (Reference 12-55).

12.4 Test Methods for Adhesives and Bonded Joints

There are two distinct types of tests that are needed for the development of bonded structure. There are material characterization tests required to determine the adhesive properties needed to perform bond-line structural analysis; and there are the bonded joint design development tests that specifically represent the actual bonded joint design. Design development tests support analysis calibration/correlation and risk reduction and are representative of the joint geometry, constituent materials, loading, environment and production manufacturing processes.

Standard test methods for characterizing structural adhesives are discussed in Section 12.4.1. Most industry standard test methods focus on adhesives and surface treatments, not on bonded joints. Consequently, the adhesive characterization tests have a series of industry standard tests that may be relied upon, although each has its own specific limitations. These test results provide properties for design and analysis, comparative data, and surface preparation effectiveness, but they are not representative of strength of a composite structural joint.

Bonded joint design development tests are discussed in Section 12.4.2. In contrast, the bonded joint development tests are performed with coupons and elements that are representative of the specific joint design. These are more complex tests that may have uni-axial or combined loads.

Structural test objectives for adhesive characterization and bonded joint development may be summarized as follows:

- Adhesive Characterization (Section 12.4.1)
  - Material screening of candidate adhesives or surface treatments for use in a composite bonded structural detailed part or assembly.
  - Material qualification, quality control and acceptance testing of adhesives.
  - Adhesive stiffness and strength properties.

- Bonded Joint Development (Section 12.4.2)
  - Manufacturing development tests for surface preparation, bonding and quality control process verification.
  - Structural development tests for analysis calibration, correlation and/or allowables that include:
    - Static strength, durability, damage tolerance and effects of defects.
    - Generic bonded joint designs and sandwich construction

This section has been adapted from Reference 12-11 (CMH-17-3G, Section 7.6) with additional information based on LM Aero practices and lessons learned. Refer to PM-4056, Section 18 Structural Certification and Test and CMH-17-3G for additional background information.

12.4.1 Adhesive Characterization

The main objectives for adhesive characterization tests are to determine: initial elastic properties, G, E, and ν; the nonlinear shear and axial stress-strain behavior; and the ultimate shear and tension-peel strengths. Standard test methods for adhesives use metallic adherends for simplicity and standardization. In test specimen fabrication, the relevant material and process specifications must be followed for surface preparation, adhesive application and cure to ensure production-representative adhesive material behavior. Specimen failure surfaces should be inspected to verify that a primary cohesive failure mode is obtained.

The adhesive characterization tests described in this section apply to co-bonded and secondary bonded structures as film adhesives may not necessarily be used for co-cured structures. When adhesives are used for co-cure, the film adhesive is free to flow and mix with the pre-preg resin during cure. If less ductile than the adhesive, the interlaminar stress allowables of the pre-preg should be used for structural integrity checks under those circumstances.

Moisture conditioning of adhesive test specimens is achieved by exposure to a specified high relative humidity and elevated temperature environment for a prescribed time duration. LM Aero prescribed moisture conditioning procedures for adhesive test specimens are provided in Section 3.3 of Reference 12-59. Moisture conditioning of adhesive test specimens to an equilibrium with uniform moisture content across the entire bond surface requires prohibitive duration times due to the low moisture diffusivities of common adhesives and the moisture barrier of the metallic adherends. However, this is thought to be mitigated by the existence of peak stresses along the bond surface edges. Therefore, it is important that all bond-line edges are freely exposed to the hot humid environment. As for neat resin dog-bone tension test specimens, the entire specimens should be freely exposed.

Unfortunately, most – if not all – standard test methods consist of joints where the stresses are not uniform. Stress peaks usually occur at the bond-line edges and are typically a mix of shear and normal stresses. This should always be considered when interpreting test results. This variation in stresses will be discussed by test method below.

The standard test methods are grouped by the adhesive properties evaluated: 12.4.1.1 Shear; 12.4.1.2 Tension; and 12.4.1.3 Fracture Toughness properties which discusses test methods and provides comments.

12.4.1.1 Shear

A list of standard test methods for determining the adhesive shear properties are listed in Table 12.4-1. A discussion of these test methods is provided below.

Table 12.4-1 Standard Test Methods for Adhesive Shear Properties.

Test Method	Test Description	ASTM Standard	LMA-PT008 Test Method (Reference 12-59)	Comments
Thick Adherend Lap Shear	Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading	D5656 – 10	Method 4.3 (Section D.3)	Industry preferred test method for determining adhesive shear properties.
Single Lap Shear	Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)	D1002 – 10	None	Recommended for material comparisons and quality control testing only. Do not use for strength allowables.
Modified Single Lap Shear	Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies	D3165-07	Method 4.1 (Section D.1)	Allows for composite adherends which may be used as a quality control traveller. Geometry intended to reduce joint rotation.
Double Lap Shear	Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)	D3528-96	Method 4.1 (Section D.1)	Recommended for material comparisons and quality control testing only. Do not use for strength allowables.
Napkin Ring Shear	Shear Strength and Shear Modulus of Structural Adhesives	E229 (withdrawn 2003)		Tubular specimen loaded in torsion. Older test method that is no longer recommended.
Note: Useful guides for adhesive bonding surface preparation of test specimens are ASTM D2651 for metallic adherends and ASTM D2093 for polymer matrix composite adherends.				

ASTM D5656 Thick-Adherend Lap Shear Test (same as LM Method 4.3, Reference 12-59)

This is currently the industry preferred test method for determining adhesive shear properties including the shear stress-strain curve. The test configuration is a single lap shear specimen loaded in tension with thick metallic adherends that resist bending under the applied tension load. Figure 12.4-1 shows the test set-up for the ASTM D5656 method. This is intended as an improvement to thin adherend single lap-shear tests by reducing joint rotation and providing a more uniform distribution of bond-line shear stress and reduced peel stresses. The test requires a specially designed extensometer (Figure 12.4-1) to measure joint displacement which must be calibrated using a dummy all-metallic test specimen. This provides a joint displacement correction for the metal adherends that is used to obtain the displacement of adhesive only.

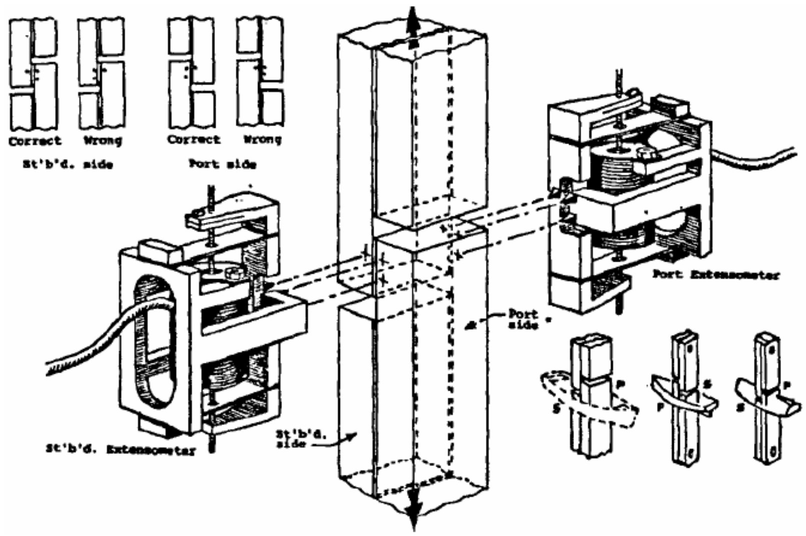
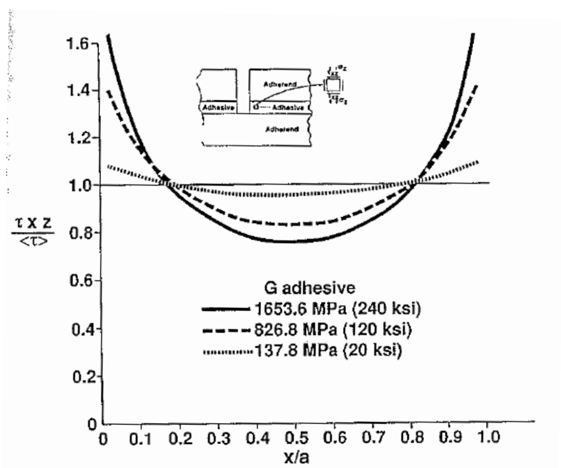
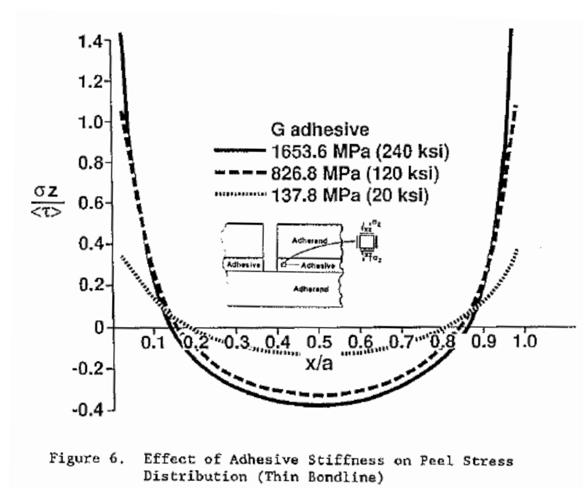


Figure 12.4-1 ASTM D-5656 Thick Adherend Shear Test Set Up.

A description of the test method is provided in Reference 12-54 and 12-55. A description of the shear stress-strain curves obtained from this test are described in Section 12.3.4. An extensive analysis of this test method may be found in Reference 12-62. Finite element analysis results are shown in Figure 12.4-2 and Figure 12.4-3. The effect of adhesive shear stiffness on the bond-line stress distributions is shown in Figure 12.4-2. As shown in Figure a), an increase in adhesive shear stiffness increases the rate of bond-line shear load transfer as the peak stress increases and the trough stress decreases. As shown in Figure b), an increase in adhesive shear stiffness increases both peak tension and compression normal stresses. Note that the shear stress distribution is far from uniform. However, the finite element analysis is for linear elastic behavior. So as the adhesive begins to yield in the peak regions, the shear stress distribution becomes more uniform as the yield region increases.



a) Shear Stress Distribution



b) Normal Stress Distribution

Figure 12.4-2 Effect of Adhesive Stiffness on Bond-Line Stress Distribution (Reference 12-62).

Figure 12.4-3 illustrates the effect of adherend stiffness on bond-line shear stress distribution. A comparison of steel versus aluminum adherends shows that the stiffer adherend (steel) provides a more uniform shear stress distribution. The thick-adherend test is typically intended for aluminum adherends, so the test method is limited to 300 °F. For higher temperature adhesives, titanium adherends have been used to increase the test temperature.

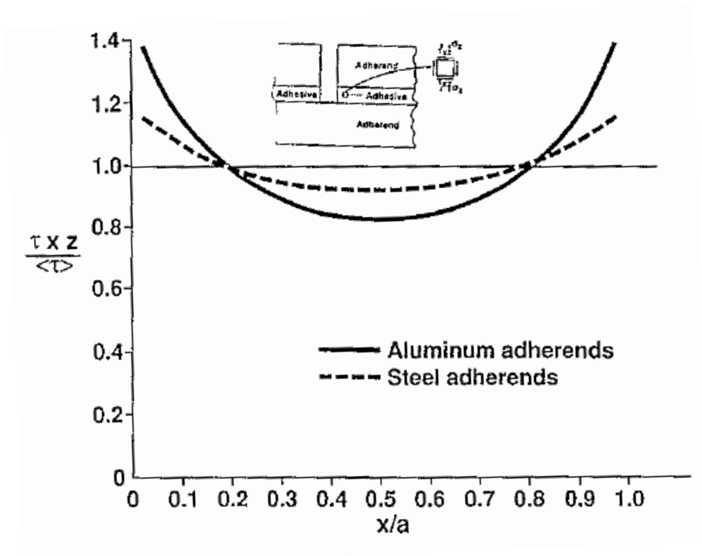


Figure 12.4-3 Effect of Adherend Stiffness on Bond-line Shear Stress Distribution (Reference 12-62).

ASTM D1002 Single Lap Shear Test

The adhesively bonded single lap shear test with thin metallic adherends is used widely by industry due to its simplicity of fabrication and testing. The specimen geometry is shown in Figure 12.4-4. The test is often used for adhesive comparative evaluations, material qualification, and receiving inspections. It may also be used to evaluate surface preparation methods for metallic adherends.

The test reports the ultimate failure load which is used to calculate the average bond area stress, τ_{avg} (refer to Figure 12.4-4). However, as shown in the figure, the bond-line shear and normal stresses are not uniform. High stress concentration factors exist for both shear and tension stresses at the edges of the bond-line. The load eccentricity and thin adherends induce a large degree of specimen bending and rotation. The aluminum adherends can yield and exhibit plastic bending deformation prior to adhesive failure. The peak stresses and distributions are dependent upon:

- Adhesive shear modulus and bond-line thickness;
- Adherend stiffness, a function of elastic properties and thickness; and
- Bond overlap length and specimen length between grips.

A change in any of these parameters will change the stress concentration magnitudes and consequently the average shear stress at failure reported by the test. Therefore, the apparent average shear strength reported by this test is not related to any intrinsic material property. The results should only be used for comparative purposes between specimens of identical adherend material and joint geometry.

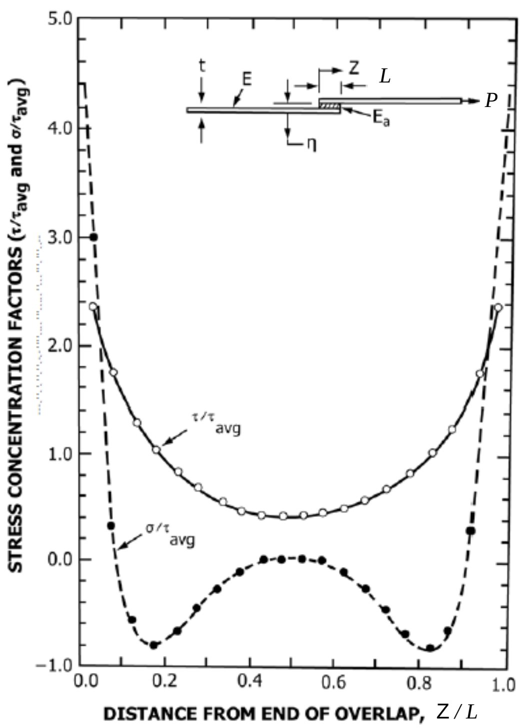
Advantages:

- Simple configuration, inexpensive, uniaxial loading.

Disadvantages:

- Non-uniform bond-line stresses with large peak peel stress.
- Peak stresses and distribution are dependent on joint material and geometric parameters; the apparent shear strength measured is not related to any intrinsic material property.
- Adhesive shear modulus cannot be measured due to large bending.
- Metallic adherends are used; does not provide any insight into surface preparation or adhesion to composite adherends.

Two complementary test standards to ASTM D1002 are ASTM D3163 and ASTM D3164. ASTM D3163 extends the application of the single lap shear joint test configuration to composite adherends. ASTM D3164 extends the application of a single lap shear joint to sandwich configuration where a thin layer of composite is adhesively bonded between two metallic adherends. Guidance regarding the use of adhesively bonded single lap joint test results may be found in ASTM D4896 (Reference 12-63).



Average Shear Stress

$$\tau_{avg} = \frac{load}{bond\ \ area} = \frac{P}{L \bullet w}$$

τ	=	actual adhesive shear stress at a point
τ_{avg}	=	average (nominal) adhesive shear stress in the joint
σ	=	actual adhesive normal stress at a point
E_a	=	adhesive modulus
E	=	adherend modulus
η	=	adhesive layer thickness
t	=	adherend thickness
ν	=	adhesive Poisson's ratio
L	=	overlap length
Z	=	location of a point along the overlap length
P	=	applied test load
w	=	specimen width

Figure 12.4-4 Shear and Normal Stress Concentration Factors for Adhesively Bonded Single Lap Shear Joint (Reference 12-63).

<u>ASTM D3165 Single Lap Shear Test for Laminated Assemblies (same as LM Method 4.1, Reference 12-59)</u>

Another variation of the ASTM D1002 single lap shear test is the ASTM D3165 test for laminated assemblies. The test article configuration is shown in Figure 12.4-5. The joint configuration helps to reduce the bending and joint rotation, but the stress bond-line stress distribution is still non-uniform with peel stresses. The test method has the advantage that it uses composite adherends and simulates the actual joint configuration of many bonded composite assemblies. Surface preparation methods for composite adherends can be compared using this method. The test specimen may also be excised from a scrap edge of bonded assembly for production quality control assessments.

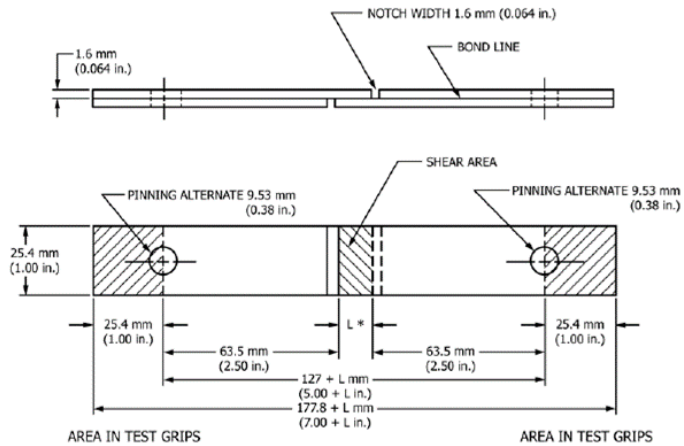


Figure 12.4-5 ASTM D3165 Adhesively Bonded Single Lap Shear Specimen for Laminated Assemblies.

ASTM D3528 Double Lap Shear Test (same as LM Method 4.1, Reference 12-59)

Another variation of a lap shear joint is the ASTM D3528 adhesively bonded double lap shear test shown in Figure 12.4-6. The test method covers two joint configurations, each with metallic adherends: Type A – double lap shear joint; and Type B – double butt-strap joint. Both configurations are symmetric which eliminates test specimen bending. The bond-line stress distributions are shown in the figure. The test specimens tend to fail at the bond-line edges with peak shear and tension (peel) stresses. Note that LM Test Method 4.1 provides guidance for both single and double lap shear test specimens.

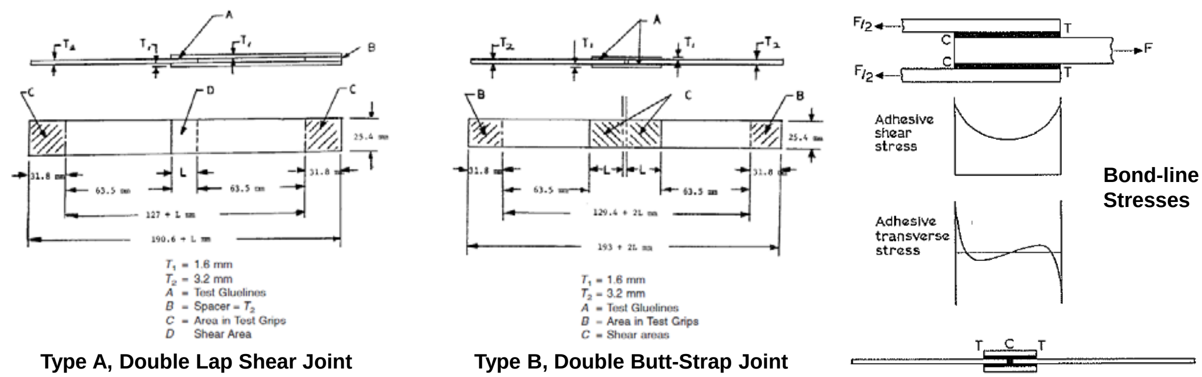
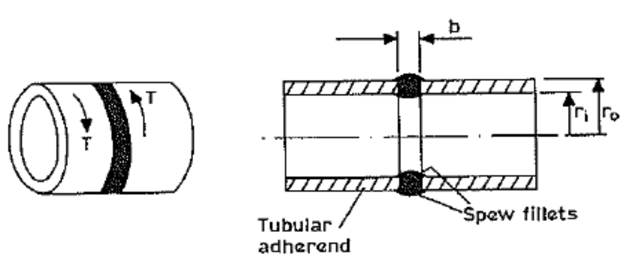


Figure 12.4-6 ASTM D3528 Adhesively Bonded Double Lap Shear Specimen, Type A and B.

ASTM E229 Tubular Shear Specimen Loaded in Torsion (also known as a "Napkin Ring Test")

An older test standard that has been used to generate adhesive shear stiffness and strength data is the ASTM E229 test method. The test method loads a tubular specimen with a bonded joint in torsion also known as the napkin ring test. It is included here as it is sometimes referred to in adhesives literature. The test specimen geometry is shown in Figure 12.4-7. By applying equal and opposed torsion, the adhesive is stressed in pure shear with a maximum shear stress at the outer radius. The test standard recommends that the inner and outer spew fillets are removed prior to testing as it results in test bias. Although the test provides a pure shear stress distribution, the test set-up is complex and requires experienced lab personnel. The ASTM test standard was withdrawn in 2003.



where:

$$\tau = \frac{T r_o}{J} \qquad J = \frac{\pi}{2}\left(r_o^4 - r_i^4\right)$$

The shear modulus G is given by:

$$G = \frac{b}{J}\left(\frac{T}{\phi}\right)$$

Figure 12.4-7 ASTM E229 Tubular Ring Loaded in Torsion or "Napkin Ring" Test

12.4.1.2 Tension

A list of standard test methods for determining the adhesive tension properties are listed in Table 12.4-2.

Table 12.4-2 Standard Test Methods for Adhesive Tension Properties.

Test Method	Test Description	ASTM Standard	LMA-PT008 Test Method (Reference 12-59)	Comments
Uniaxial Tension	Standard Test Method for Tensile Properties of Plastics	D638-10	None	Recommended for determining unixial tension stress-strain curves and room temperature Poisson's ratio.
T-Peel Tension	Peel Resistance of Adhesives (T-Peel Test)	D1876 – 01	None	Determines the relative peel resistance of adhesive bonds between flexible adherends by means of a T-type specimen.
Tension Strength	Tensile Strength of Adhesives by Means of Bar and Rod Specimens	D2095 − 96	None	Determination of the relative adhesive tensile strength by the use of metallic bar- and rod-shaped butt-joined specimens.
Floating Roller Peel Strength	Floating Roller Peel Resistance of Adhesives	D3167-10	None	Determines metal-to-metal peel strength of adhesives; Test method provides good reproducibility with simple specimen preparation & testing.
Tension Strength	Tensile Properties of Adhesive Bonds	D897 − 08	None	Determines comparative tensile properties of the adhesive bonds with standard metallic adherends.
Climbing Drum Tension	Climbing Drum Peel for Adhesives	D1781 − 98	None	Determines adhesive peel resistance between relatively flexible and rigid adherends; and relatively flexible sandwich facesheet and core.
Note: Useful guides for adhesive bonding surface preparation of test specimens are ASTM D2651 for metallic adherends and ASTM D2093 for polymer matrix composite adherends.				

ASTM D638 Uniaxial Tension Test for Neat Resin Specimens

The ASTM D638 test method may be used to conduct a uniaxial tension test for a neat adhesive resin specimen. In this context, a neat resin test specimen is composed of adhesive only (no adherend is used). The test specimen configuration is shown in Figure 12.4-8. A photograph of a D638 test set-up for room temperature is shown in Figure 12.4-9. The test method can be used to determine the adhesive uniaxial tension stress-strain curve, ultimate tension strength, and includes an option of measuring Poisson's ratio at room temperature conditions.

ASTM D638 method can be used for testing materials up to a thickness of 0.55 in. Test Method ASTM D882 is recommended for thin sheeting less than 1.0 mm (0.04 in.) thick. Test specimens are typically cured and machined into the specified geometry. This test method has been used recently by LM Aero (Reference 12-13, 12-14) for characterizing adhesive tension stiffness and strength properties including Poisson's ratio. However, the tension strength obtained by this method is not applicable to bond-line analysis. ASTM D5656 thick-adherend test is the preferred method for characterizing adhesive shear stiffness and strength properties.

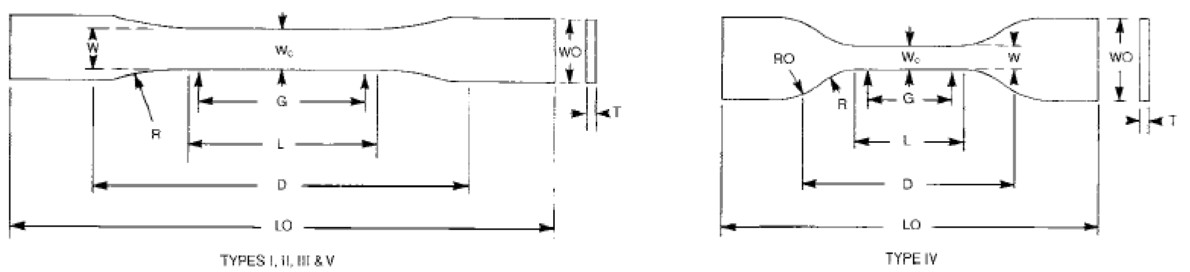


Figure 12.4-8 Neat Adhesive Tension Test Specimen (ASTM D-638)

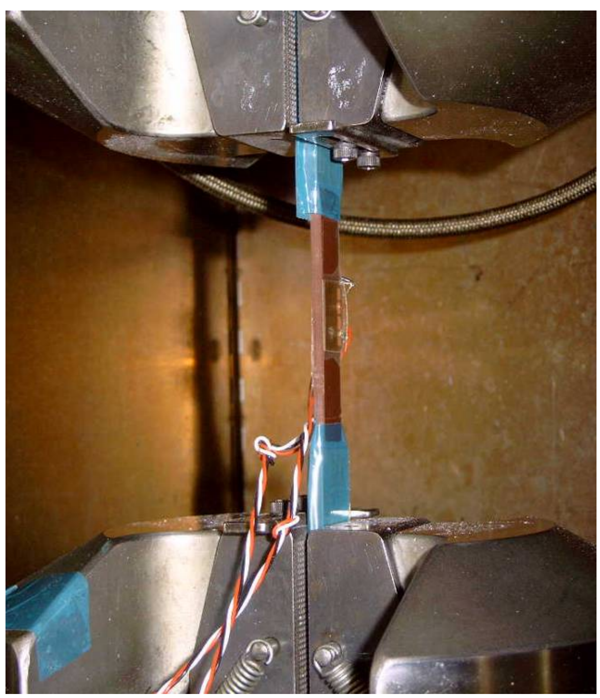


Figure 12.4-9 ASTM D-638 Neat Resin Tension Test Set Up.

ASTM D1876 T-Peel Tension Strength Test

This test method is primarily intended for determining the relative peel resistance of adhesive bonds between flexible adherends by means of a T-type specimen. The test specimen configuration is shown in Figure 12.4-10. The two adherends need not be alike, either in material or thickness. However, they must be capable of being bent through any angle up to 90° without breaking. This test method has been used recently by LM Aero (Reference 12-15) for characterizing adhesive tension (peel) strength.

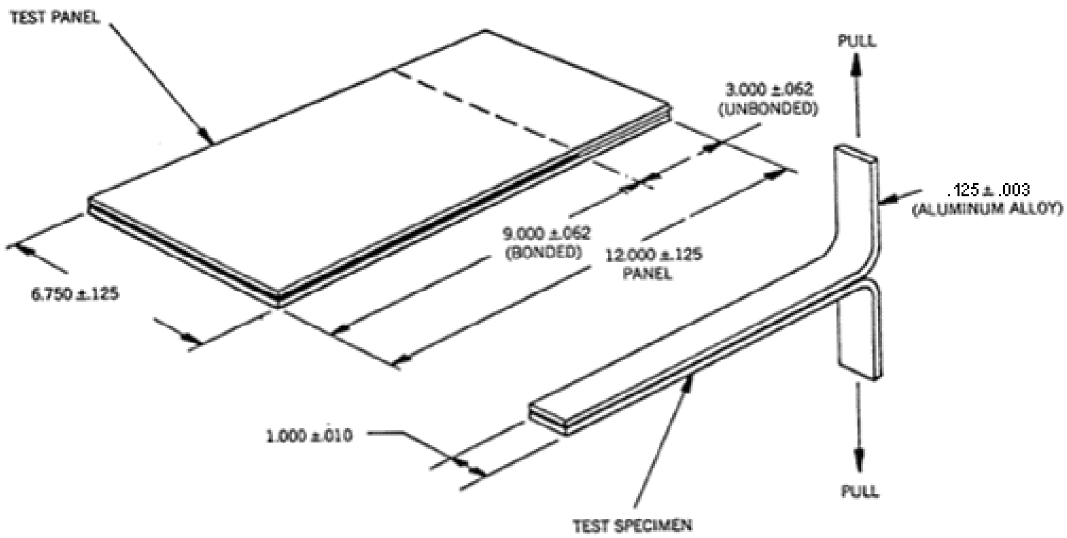


Figure 12.4-10 ASTM D1876 T-Peel Tension Test Specimen.

ASTM D2095 T-Peel Tension Strength Test

This test method determines relative adhesive tensile strength by the use of metallic bar- and rod-shaped butt-joined specimens. The specimen configuration is shown in Figure 12.4-11. The tension strengths obtained by this test should be used with caution as the specimen is susceptible to peel-initiated edge failures.

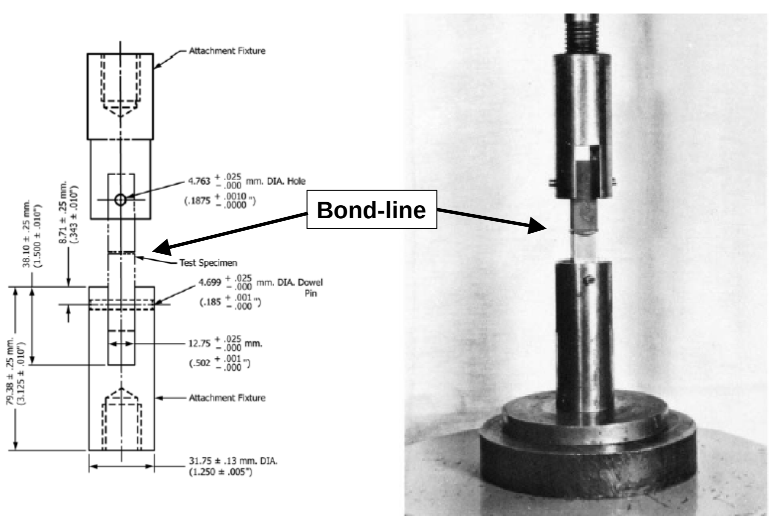
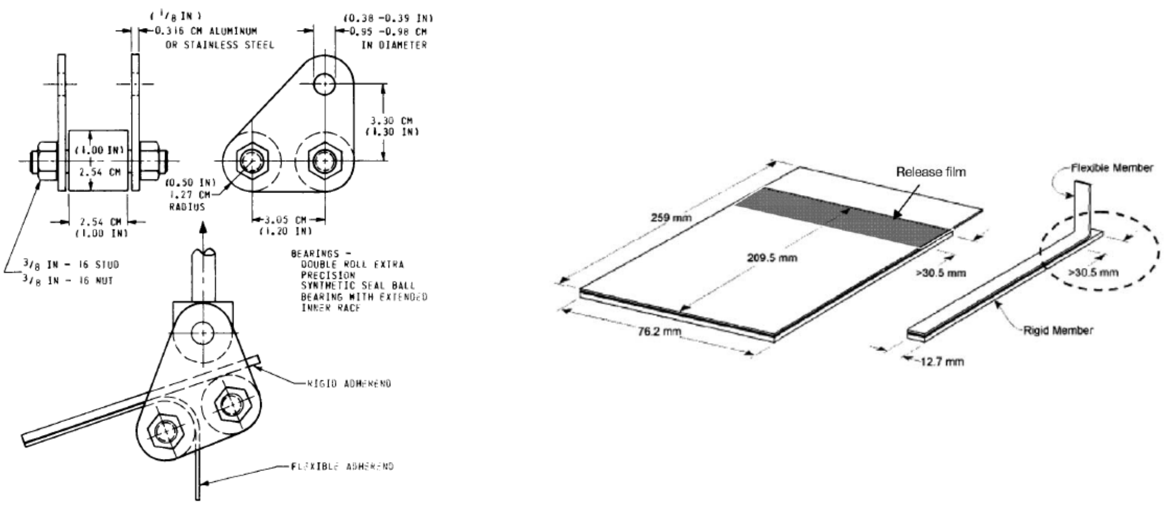


Figure 12.4-11 ASTM D2095 Bar or Rod Tension Test Specimen

ASTM D3167 Floating Roller Peel Strength Test

This test method determines adhesive tension (peel) strength using metallic adherends. The test method provides good reproducibility with a simple test specimen preparation and testing. The test fixture is shown in Figure 12.4-12 (a). The test panel and specimen geometry are shown in Figure 12.4-12 (b).



a) ASTM D3167 Floating Roller Peel Test Fixture. **b) Test panel and test specimen.**

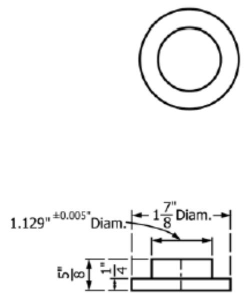
Figure 12.4-12 ASTM D3167 Floating Roller Peel Strength Test Method.

ASTM D897 Adhesive Tension Strength Test

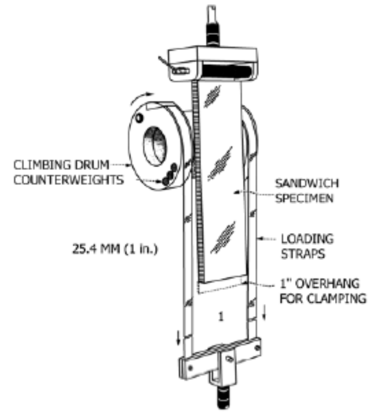
This test method determines the comparative tensile properties of the adhesive bonds of metal to metal adherends. The test specimen geometry is shown in Figure 12.4-13 (a).

ASTM D1781 Climbing Drum Peel for Adhesives

This test method determines the peel resistance of adhesive bonds between: a relatively flexible adherend and a rigid adherend; and the relatively flexible facesheet of a sandwich structure and its core. The climbing drum test apparatus is shown in Figure 12.4-13 (b). This is an older test method that involves a complex set-up and experienced lab personnel. Although not used at LM Aeronautics, it is included here as it is sometimes referred to in the adhesives literature.



a) ASTM D897 Adhesive Tension Test



b) ASTM D1781 Adhesive Climbing Drum Test

Figure 12.4-13 ASTM D897 and D1781 tests.

12.4.1.3 Fracture Toughness

A list of standard test methods for determining the fracture toughness properties for fiber reinforced composites are listed in Table 12.4-3. These test articles can be modified to bond adherends with the purpose of initiating a crack within the adhesive to measure the fracture toughness properties of the adhesive.

Table 12.4-3 Standard Test Methods for Adhesive Fracture Properties.

Test Method	Test Description	ASTM Standard	LMA-PT001 Test Method (Reference 12-64)	Comments
Double Cantilever Beam	Mode I Static Delamination (Double Cantilever Beam Mode I Fracture Toughness)	D5528	Method 4.25 (Section D.25)	
End Notch Flexure	Mode II Static Delamination (End Notched Flexure Mode II Fracture Toughness)	D7905	Method 4.26 (Section D.26)	
Mixed Mode I/II	Mixed Mode I/II Fracture Toughness	D6671	None	

12.4.2 Bonded Joint Development

The tests described in this section are divided into two categories: 1) Bonded Joints; and 2) Bonded Sandwich Construction.

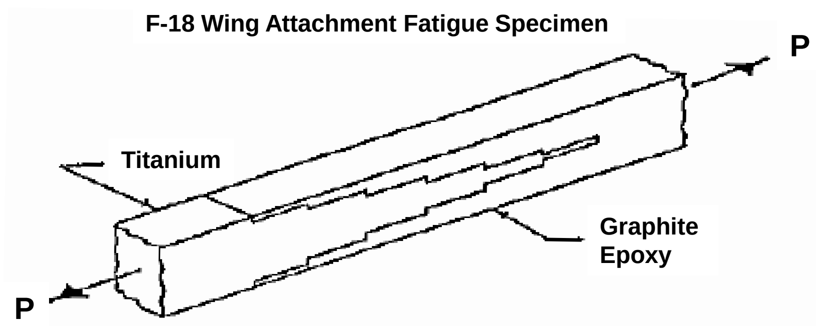
12.4.2.1 Bonded Joint Properties

These are coupon and element level tests that are accurately representative of the actual joint design. They accurately represent the joint geometry, constituent materials, loading, environment and manufacturing processes. The test articles should be prepared following planned production manufacturing processes including bonding surface preparation, assembly, cure processes and inspection.

Test objectives typically include analysis calibration and/or development of joint strength allowables. As stated previously, analysis calibration alone is preferred as developing element level joint allowables is very expensive and time consuming. Structural integrity testing may include static strength, fatigue, durability, damage tolerance and effects of defects. Manufacturing risk reduction tests are usually required to evaluate surface preparation and to validate engineering specification processes for bonding, inspection and quality control.

Examples of bonded joint characterization tests are:

- Simple loading of bonded joint configurations (Refer to Figure 12.4-14)
    - Uniaxial tension/compression, four-point bending
- Bonded skin-stiffener tests (Refer to Figure 12.4-15)
    - Stiffener termination under uniaxial and/or bending loads
- Cocured composite skin-substructure tests (Refer to Figure 12.4-16)
    - Pull-off, shear and combined loads.
- Co-bonded woven Pi-preform joint tests (Refer to Section 13.10.8, PM-4056)
    - Pull-off, shear, lateral bending and combined loads.



ADHESIVE	SPECTRUM FATIGUE LIFE (HRS)	RESIDUAL STATIC LOAD CAPABILITY POUNDS (N)
FM 400	24,000 24,000 2,000	60,000 Avg. (267,000)
FM 300K	24,000 24,000 24,000	130,000 Avg. (5,760,000)

Figure 12.4-14 F-18 Wing Attachment Fatigue Test Specimen (Reference 12-55).

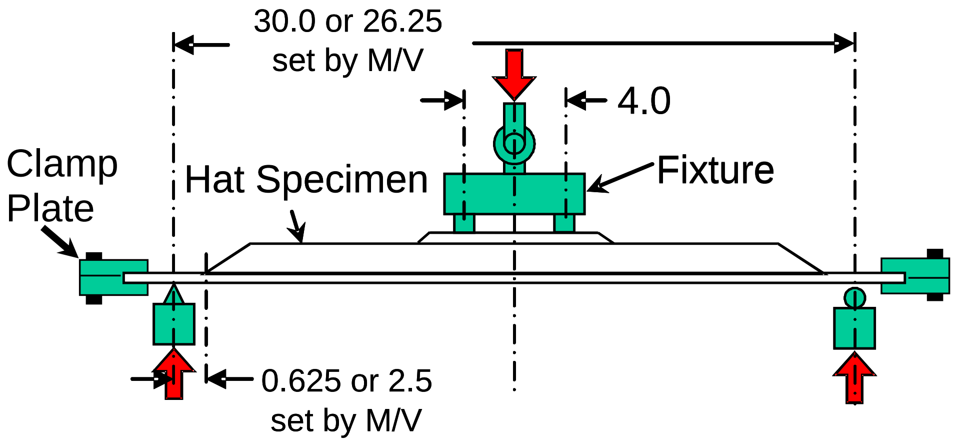
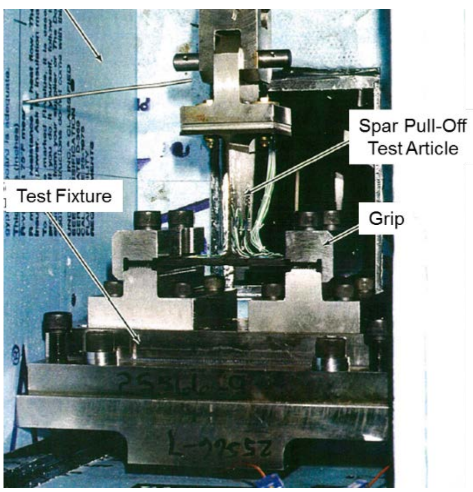
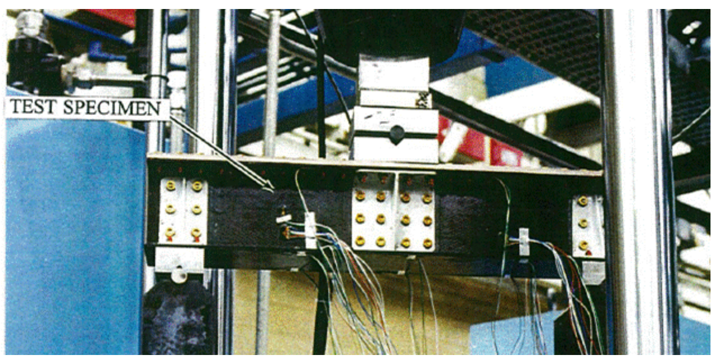


Figure 12.4-15 Four-Point Bend Test for a Hat Stiffener (Reference 12-65).



(a) Spar Pull-Off Test



(b) Three-Point Spar Bend Test

Figure 12.4-16 Co-cured Skin-Spar Element Development Tests.

12.4.2.2 Bonded Sandwich Construction Properties

A list of standard test methods for bonded sandwich construction design properties is provided in Table 12.4-4. These methods include tests for specific core properties and for sandwich construction properties. The table lists ASTM standard methods and related LM Aero test standards. In addition to these standard tests, element tests may be required for analysis calibration of specific sandwich construction features such as panel close-outs, panel edge ramps, or concentrated load areas.

Table 12.4-4 List of Standard Test Methods for Sandwich Core Construction.

Test Method	Test Description	ASTM Standard	LMA-PT008 Test Method (Reference 12-59)
Density	Density of Sandwich Core Materials	C271-16	Method 3.1 (Section C.1)
Water Absorption	Water Absorption of Core Materials for Sandwich Constructions	C272-16	
Shear	Shear Properties of Sandwich Core Materials	C273-16	
Flatwise Tension	Flatwise Tension Strength of Sandwich Constructions	C297-04	Method 4.2 (Section D.2)
Node Tensile Strength	Node Tensile Strength of Honeycomb Core Materials	C363-16	
Edgewise Compression	Edgewise Compression Strength of Sandwich Constructions	C364-16	
Flatwise Compression	Flatwise Compressive Properties of Sandwich Cores	C365-16	Method 4.6 (Section D.6)
Core Thickness	Standard Test Methods for Measurement of Thickness of Sandwich Cores	C366-16	
Core Shear by Beam Flexure	Core Shear Properties of Sandwich Constructions by Beam Flexure	C393-16	Method 4.4, 4.14 (Section D.4, 4.14)
Water Migration	Water Migration in Honeycomb Core Materials	F1645-16	

12.5 Manufacturing Considerations for Bonded Assemblies

The reliable production of bonded structural assemblies requires careful design and strict control of materials and manufacturing processes and environment. This requires an inter-disciplinary development effort between design, structural analysis, materials and processes, manufacturing, and quality assurance engineering. This section provides an overview of the basic concepts, terms and processes regarding the manufacture of bonded structural assemblies.

12.5.1 Common Approaches for Structural Assembly

Four common approaches used for manufacturing aerospace structural assembles are illustrated in Figure 12.5-1. These approaches are described in the following paragraphs.

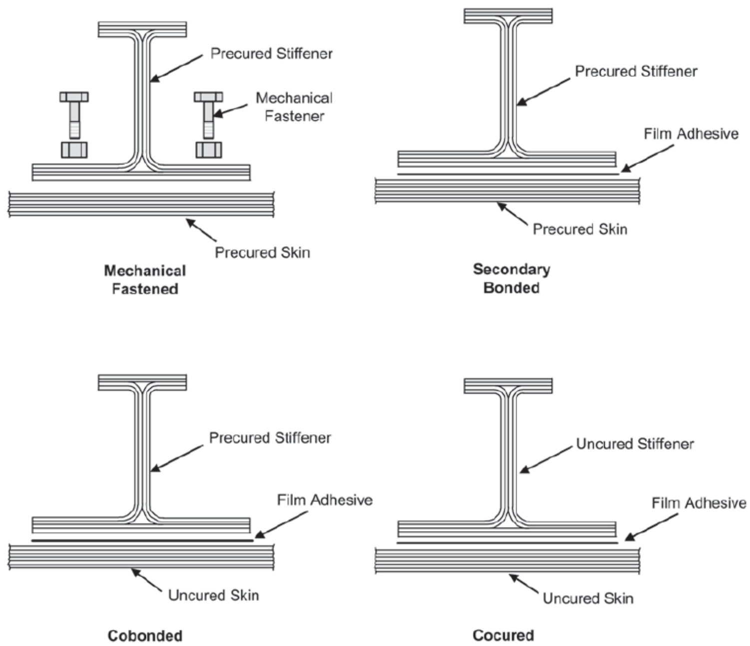


Figure 12.5-1 Common Approaches to Manufacturing Aerospace Structural Assemblies.

Mechanically Fastened – This is the most common approach to joining individual structural elements into more complex airframe sub-assemblies, assemblies and components. The advantages and disadvantages of mechanically fastened joints relative to bonded joints are described in Table 12.2-1 and Table 12.2-2. Although the manufacturing cost of mechanically fastened joints is relatively high, this still remains the preferred approach for critical flight safety joints due to their proven reliability, ductile yielding behavior, and the redundancy in numbers allowing for load redistribution and potential fail-safe capability. Refer to PM-4056 Section 11 on mechanically fastened composite joints for structural analysis guidance.

Secondary Bonding – Composite fabrication process wherein individual metallic and/or pre-cured composite parts are bonded together using an adhesive. This method is distinct from co-cure and co-bond approaches in that all composite parts are pre-cured. Care must be taken to isolate carbon fiber composite from certain metals, particularly aluminum, as the two materials in combination are susceptible to galvanic corrosion. This is usually accomplished by a glass fabric barrier ply.

Co-cure – Composite fabrication process wherein all joint elements are cured together during the same cure cycle. The bond at the joint interface (faying surface) between separate composite parts (such as a skin and spar) is typically achieved by resin flow taking place between the adjacent parts during cure. An optional variation to the process is to lay-up a layer of a cure-compatible film adhesive between the two parts in an effort to thicken the bond-line. Advantages of the co-cured assemblies are cost savings with elimination of fastener installation processes as compared to mechanically fastened assemblies and the elimination of bond surface preparation that is required for secondary bond and co-bonding approaches. Since all composite structural elements are cured together in a single cure cycle, the entire structural assembly must be tooled to define the outer surface geometry. This clearly requires a complex tooling design and careful workmanship to assemble the detailed parts and tooling prior to cure. A simple misalignment or interference in tooling can cause non-conformances such as voids, resin starvation, wrinkles, waviness, or tool marks. The high cost of materials, labor and time required to produce a co-cured assembly increases the need for an “error free” manufacturing process as well as the pressure to repair rather than scrap the assembly when errors do occur. In addition, if the tools are to be reused, there is an extensive cleaning and refurbishment process that must occur post-cure. Thus, a co-cured assembly is a potentially more expensive and higher risk manufacturing approach as compare to secondary bond and co-bond approaches.

Co-bonding – Composite fabrication process wherein a combination of both pre-cured and cured composite structural elements are cured and bonded together using adhesive simultaneously during a single cure cycle. As an option, a co-bonded assembly may also contain metallic adherends.

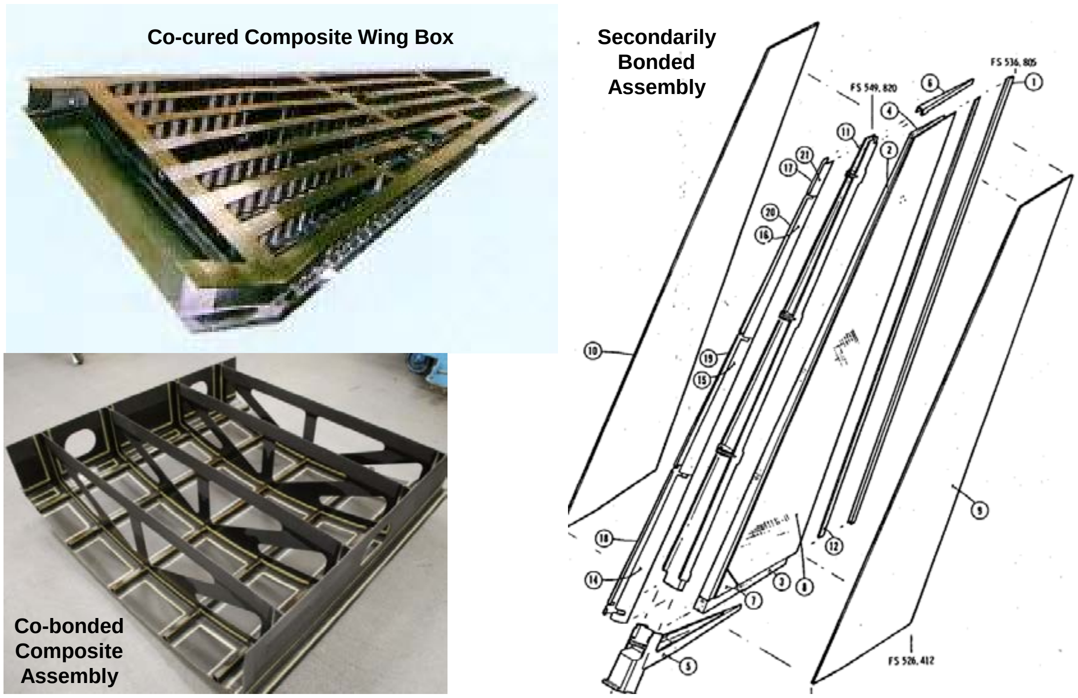


Figure 12.5-2 Examples of Bonded Structural Assemblies.

<u>The Advantages of Co-Bond versus a Co-Cure Approach</u>

The co-bond approach has demonstrated a number of distinct advantages as compared to the other manufacturing approaches (Reference 12-10). The following is a summary of these advantages.

<u>Laminate Quality:</u> Fiber/ply straightness and elimination of matrix porosity are critical in high performance aircraft/space structure. All co-cure type processes yield some level of compromise when realistic large structures are fabricated. Fiber waviness and porosity at 3-D intersections is particularly problematic for most co-cure processes. Co-bonding allows critical skin details to be cured with optimal uniform pressure distribution prior to joining, thereby eliminating this problem. The cured detail parts are inspected prior to co-bond assembly greatly reducing probability of a bad area winding up in a large assembly.

<u>Joint Quality:</u> Pre-cured skin and substructure details act like fly away tooling during the subsequent cure/bond of the joint. The uncured composite joint material is pressed into contact with adjacent pre-cured details by the bag and over press. This allows creation of consistent repeatable preform joints and interfaces without fiber waviness in adjacent laminates.

<u>Material Out-Time:</u> As part size is increased, out time on composite materials used in the assembly becomes critical. This essentially limits the size of a part that can be laid up and cured or co-cured in a single operation. Co-cured assemblies have a finite size limit based on layup process and time required to bag and cure, however co-bonding is primarily limited by acceptable number of cures and autoclave or oven size. Detail parts are first fabricated as large as practical, within out time limits and geometric limits for the particular assembly. These parts are inspected, bond prepped, assembled with preforms and cured. During the co-bond operation out time only applies to the preforms and adhesive. Additional detail parts can then be added in additional co-bond operations up to the repeated cure cycle limit of the base materials. Three subsequent co-bond operations have been routinely demonstrated resulting in parts substantially larger than possible with co-curing.

Tooling: Tooling required to fabricate large structural assemblies with co-bonding is substantially less complex, less expensive, by often an order of magnitude, and easier to modify to accommodate design changes than tooling required to co-cure a similar structure. Co-cure requires that ALL surfaces in a complex 3-D assembly be simultaneously controlled during high temperature and pressure cure operations. Tooling required to do this quickly becomes elaborate, expensive, and often times trapped in the finished part. In addition, co-curing often requires additional layup and de-bulk/compaction tooling so that uncured details can be handled and installed into final co-cure tools. While co-bonding requires tooling to make detail parts such as skins and substructure, the process only requires over press tooling and bagging in the joint areas during assembly. Skin layup tooling only requires control of one surface and is in common use throughout the industry. Substructure for co-bond applications is typically cut out of flat sheet allowing cure on simple flat project plates and Numerically Controlled routing or waterjet trim. For most co-bond operations it is possible to use the skin lay-up tools in combination with determinate fly away details and simple over-pressure bags to accomplish final co-bond assembly.

Risk: The process risk is significantly less with co-bond assembly as compared to a fully co-cured assembly. As full co-cure requires that every part of an assembly cures simultaneously, it is far more difficult to assure quality in the entire assembly, any flaw that occurs is part of the final assembly. Co-bonding is an incremental process so each of the detail parts are pre-cured and pre-inspected prior to going into the assembly. This allows any bad detail to be dispositioned before it goes into the assembly. In addition the parts can sit on a shelf indefinitely until co-bond operations start. With a co-cure assembly the out time clock starts for the first material in the assembly. Two or three cure cycles on composite parts are typically not detrimental; however, if a large number of cure cycles are necessary then testing must be conducted to verify there is no degradation in the part material properties.

Static Strength: Co-bonded assemblies with identical design features as a co-cured assembly typically exhibit higher static strength than the co-cured assembly. This difference is attributed to the slight skin ply waviness that can occur in the joint areas of a co-cured assembly.

12.5.2 Materials and Process Specifications

The successful production of bonded structural assemblies with reliable quality requires the development and strict adherence to engineering drawing requirements, materials and process specifications, manufacturing instructions, and quality control inspections. The various types of materials and process specifications that provide guidance and control of bonded assembly production operations are listed as follows.

- Material Specifications
  - Composite Laminate Prepreg
  - Adhesives
  - Woven Preforms
- Manufacturing Process Specifications
  - Bonding Process and Quality Control
  - Surface Preparation
- Quality Assurance Specifications
  - Inspection Techniques
  - Acceptance Criteria
- Standard Test Method Specifications
  - Composite Materials
  - Adhesives

These specifications are too numerous to specifically list here. They include both LM Aeronautics and program specific specifications. The LM Aero specifications are intended for broad use across all programs and have typically been adapted from older legacy program specifications. M & P Engineering should always be consulted for guidance on the applicability and use of these specifications.

12.5.3 Bonding Processes

The general manufacturing procedures for adhesive bonding may be summarized as follows:

- Fabrication of all detailed structural elements (Sect. 12.5.5);
- Bond surface preparation (Sect. 12.5.6);
- Fit-up check of detailed parts and tooling (Sect. 12.5.7);
- Application of the adhesive (Sect. 12.5.8);
- Mating of detailed parts and adhesive;
- Preparation of bonded assembly for cure;
- Cure of the bonded assembly; and
- Inspection of the bonded assembly (Sect. 12.5.10).

Additional discussion is provided in the indicated sub-sections.

A clean shop working environment with temperature and humidity control is required to prevent the contamination of bond surfaces. Sources of contamination include shop air dust and chemicals such as cleaning and release agents. Temperature control is necessary as it directly affects the out-time life of all un-cured composite parts and adhesives. Humidity control is necessary as moisture can be trapped in the adhesive bond-line or in honeycomb sandwich core. The moisture can adversely impact the cure process or the subsequent static strength of bond-lines.

12.5.4 Working Life and Material Out-Time Constraints

Thermoset resin materials, used in laminate prepreg and as structural adhesives, have storage and working life requirements that are defined in the corresponding company material specifications. As long as these requirements are met, the material will retain properties capable of meeting all specification requirements. All bonded assembly processes for co-cure, co-bonding and secondary bonding must conform to these material time constraints. The storage and working life requirements for composite laminate prepreg, elevated and room temperature cure adhesives are discussed in the subsequent sections.

12.5.4.1 Laminate Prepreg

Laminate prepreg is included in this section as laminate prepreg parts may be included as part of a co-cure or co-bonded structural assembly. Thermoset resins that require an elevated temperature cure are stored at cold temperatures in refrigeration, typically at 10 °F or below, to suspend the cross-linking process and keep them stable until they are ready for use. Common examples of these composite prepreg materials are IM7/977-3, IM7/MTM45-1, and IM7/5250-4. Prepreg life requirements as defined by the material specification are illustrated in Figure 12.5-3.

When material is ready to be used for a manufacturing process, it is removed from refrigeration and allowed to warm to a room temperature ambient condition, typically 65 to 80 °F and less than 65 percent relative humidity. There is a material out-time limit defined in the material specification for which the material is allowed to remain at room temperature ambient conditions, but beyond which the material properties are assumed to begin to degrade. The material out-time is cumulative and the out-time clock is stopped whenever the material is returned to refrigeration. The material out-time limit is also called the open mold life for laminate prepreg.

Prepreg Life – Period of time measured from the supplier manufacture to cure or material expiration, whichever occurs first. Typical limit is two years.

Storage Life – The period of time measured from supplier date of manufacture to out of cold storage.

Open Mold Life – The cumulative period of time between removal of material from refrigeration and cure. Typical limit is 30 days.

Working Life – The period of time between removal of material from refrigeration to completion of the bonded assembly (lay-up, compaction, bonding, etc.). Typical limit is 21 days; requires that cure must occur within 9 days of bonded assembly completion.

All material limits should be verified with Materials and Processes engineering.

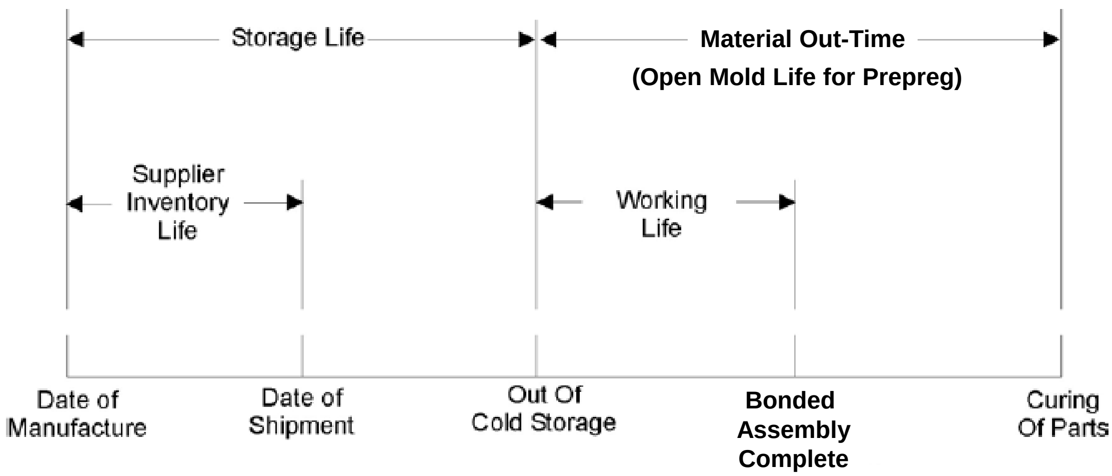


Figure 12.5-3 Prepreg Life Requirements for Bonded Assemblies

12.5.4.2 Elevated Temperature Cure Adhesives

Elevated temperature cure adhesives are also stored at cold temperatures in refrigeration, typically at 10 °F or below, until they are ready for use. When the adhesive is ready to be used for a manufacturing process, it is removed from refrigeration and allowed to warm to a room temperature ambient condition, as defined by the material spec. Like prepreg, there is a material out-time limit defined in the material specification for which the material is allowed to remain at a room temperature ambient condition, but beyond which the material properties are assumed to begin to degrade. The material out-time is cumulative and the out-time clock is stopped whenever the material is returned to refrigeration. Adhesive life requirements as defined by the material specification are illustrated in Figure 12.5-4.

Adhesive Life – Period of time measured from the date of shipment to cure or material expiration, whichever occurs first. Typical limit is 12 months. Exception: AF191 and FM2550 film adhesives have a life limit of two years form the date of supplier manufacture.

Purchaser Storage Life – The period of time measured from date of shipment to out of cold storage.

Ambient Out-Time Life – The cumulative period of time between removal of material from refrigeration and cure. Typical limit varies from 7 to 30 days and depends on adhesive type, ambient temperature and relative humidity.

All material limits should be verified with Materials and Processes engineering.

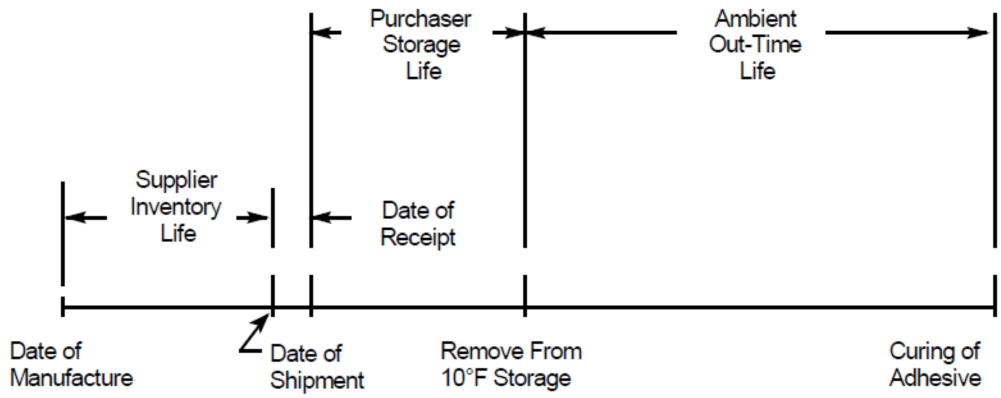


Figure 12.5-4 Adhesive Life Requirements

12.5.4.3 Room-Temperature Cure Adhesives

Room temperature cure adhesives are available in a one- or two-part form. Two-part liquid and paste adhesives usually can be stored at room temperature conditions and have an adhesive life limit of 12 months from the shipment date. After mixing, these adhesives have a very short working or pot life and must be applied in relatively short time period before they become too viscous or eventually solid to work with. This is on the order of 30 to 120 minutes, depending upon the adhesive. Cure times vary by adhesive and some allow for an accelerated cure with the application of moderate heat. The cure, storage and working life limits are defined in the material specification.

12.5.5 Detailed Part Fabrication

Detailed parts for a bonded assembly may include:

- Machined metallic parts;
- Uncured composite parts;
- Cured composite parts; and/or
- Honeycomb sandwich core sections.

The bond surfaces for all detailed parts must be prepared for bonding. Bond surface preparation is discussed in the next section. Once treated, the parts should be protected and stored to prevent contamination from debris or moisture. Uncured composite parts may be laid up and stored in refrigeration to preserve their out-time limit while they await assembly.

12.5.6 Surface Preparation

Bond surface preparation is the most critical factor in producing reliable, full strength bonded joints. Bonded joint strength is not only dependent on the inherent cohesive strength of the adhesive and adherends, but also on the interface strength between the adhesive and adherend (Reference 12-51). The objectives for proper bond surface preparation are:

1) Clean the bond surface of contaminants and moisture;
2) Increase the bond surface free energy to an equal or higher value than the adhesive; and
3) Produce an adherend bond surface condition that is reliably consistent.

When applying adhesive, the wetting of the adherend surface is a function of the adherend surface energy, surface cleanliness, and adhesive viscosity.

The presence of surface contaminants or moisture can adversely impact the interfacial surface bond. The adhesion at the adhesive-adherend interface occurs at the molecular level and surface contaminants which are weakly attached prevent contact between the adhesive and substrate. Therefore, many surface preparations require the cleaning and drying of the bond surfaces. And once prepared, these surfaces must be protected from further exposure until the bonding process is performed. In addition, care must be taken to not let water condensation accumulate on film adhesive that has been removed from refrigerated storage to thaw out.

Other surface preparations are intended to improve the surface free energy of the bond surface through chemical or mechanical methods. Most metals and ceramics exhibit a fairly high surface energy, while fiber reinforced composites do not. Specific methods for metals and composite adherends are discussed below. A way to experimentally determine how well an adherend surface has been prepared for adhesive bonding is the water break test. This test involves the measurement of the Water Contact Angle (WCA) for a drop of clean distilled or deionized water placed on the solid adherend or substrate surface. The WCA is the angle connecting the solid-gas interface and the solid-liquid interface. If the surface energy is high, the WCA will be low ($0° < \theta < 90°$) as water spreads out and wets the surface and makes a slightly arched film on the surface. If the surface energy is low, the WCA will be high ($90° < \theta < 180°$) as the water beads up and does not wet the surface. The range of acceptable WCA values are material dependent. The WCA of a substrate can be measured using a hand held non-destructive inspection device (Surface Analyst, BTG Labs). The lower the WCA, the greater the likelihood that there will be good adhesion at the adhesive-adherend interface. All bond surfaces that have been treated to improve the surface energy are prone to aerial contamination, so these parts should be bonded within a short time.

The ability of a surface preparation method to produce reliably consistent adhesive bond surfaces is just as important as the quality of these surfaces. At present, there are a number of bond surface preparation methods that are used across the industry and there is no consensus on which methods produce the best results. The treatment method depends upon the adherend material and its condition, the adhesive material, the joint design and service life requirements, and processing costs. The selection of the best surface preparation method is determined empirically by manufacturing and structural development testing. Static and fatigue testing is highly desirable to ensure the long-term implications of the chosen surface treatment are quantified for intended applications. The testing should demonstrate the method reliability and that resulting adhesive-adherend interface bond is not the weak link of the bonded joint. Subsequent changes to the materials or processing must be re-evaluated for their potential impact on joint strength and durability.

12.5.6.1 Metallic Adherends

Metallic adherends require careful surface preparation that includes the application of a corrosion inhibiting primer. Bonding surface preparations for metallic adherends are typically defined by either a bonding or surface preparation process specification. The procedures are dependent upon the metallic alloy. Four conventional methods of surface treatment for metallic surface preparation are: chemical immersion treatment, chemical in situ treatment, abrasion, and solvent degreasing (Reference 12-42). The reliability of the processes decreases in the same order as listed above. These processes are documented in company process specifications and are specified on engineering drawings by a general drawing note.

Chemical immersion treatments include acid etches and anodizes. The chemical formulations are monitored and controlled. Chemical in situ treatments involve use of commercial, proprietary chemicals, often etching material in gel form. These materials are used only when they can be applied safely and cleaned up properly.

Abrading processes are less reliable than chemical processing because they are not controlled other than by the experience level of the individual. Abrading is generally accomplished with aluminum oxide grit or “Scotchbrite” pads (3M product).

Solvent degreasing alone as a surface treatment is rarely suitable for structural bonds. For small area bonds, less than one-half inch square, acrylic adhesives have been found to provide "reasonable" strength compared to abrading. Rubbery adhesives are the most reliable choices when solvent wiping is used.

Aluminum Parts: Several different etching or anodizing methods are used to prepare aluminum alloys for adhesive bonding. The main objective of aluminum etching or anodizing procedures is to produce a clean surface that contains a porous oxide layer that the adhesive can flow into and bond onto. Three methods are Chromic-Sulfuric Acid Etch, Chromic Acid Anodize (CAA), and Phosphoric Acid Anodize (PAA). LM Aero has recommended the use of phosphoric acid anodize method per ASTM D3933 for surface preparation of aluminum parts. A primer is typically applied to the surface within eight hours of completing the anodize process. Typically the primer must be reactivated by wiping with Acetone or a similar solvent prior to bonding.

Titanium and Steel Parts: The bonding surfaces of Titanium parts are prepared by a sequence of operations that may include: solvent cleaning, grit blasting, deoxidation, application of an adhesion promoter, and acid etch, with a primer applied to the surface within eight hours of processing completion. Refer to relevant company process specification for specific guidance.

Titanium Honeycomb Core: Titanium honeycomb core may be treated with a special material deposition process that has been proven to be an effective surface preparation for bonded sandwich assemblies. This process was demonstrated on a number of LM Aeronautics IRAD and CRAD programs. The Fort Worth Advanced Structures group of LM Aero Advanced Development Projects may be contacted for more information.

12.5.6.2 Composite Adherends

As stated above, composites exhibit relatively lower surface free energy as compared to metals and ceramics. Furthermore, mold release agents and other normally occurring shop materials can serve as contaminants. Silicon in particular which used for a variety of manufacturing processes can migrate easily and is a potential contaminant. Even touching with recently washed hands can degrade joint quality. Therefore surface treatment of composite bond surface is highly recommended. Common surface preparation methods for composite adherends are as follows.

- Cleaning/Degreasing – intended to remove release agents and/or surface contaminants.
- Mechanical Abrasion/Cleaning
  - Hand Sanding
  - Low-Pressure Grit Blasting
- Peel Ply intended to provide a fractured, clean surface when removed after cure.
  - Using a glass, nylon, or polyester woven fabric ply
  - Do not use ply materials that are coated with a release agent
- Energetic Treatment Methods
  - Flame
  - Atmospheric Plasma
  - Corona Discharge

Mechanical abrasion is intended to clean and alter the surface to improve mechanical adhesion. The intent is to remove weakly adherent material (low molecular weight) to expose more adherent bulk material (high molecular weight). Another proposed benefit is that the rougher the adherend surface, the more surface area available for the adhesive to make contact and lock onto. Hand sanding is difficult to control and risks exposing or damaging fibers, while low-pressure grit blasting has the potential for more control through automation, but at the expense of the development cost.

The use of a peel ply is intended to protect the bonding surface until ready for bonding and to provide a more enhanced surface free energy when the ply is removed. That is, the ply removal leaves a fractured resin matrix layer that is higher in surface energy. Wet woven fabric peel plies are recommended over dry with the selection of fiber, fiber sizing, fabric weave, and resin system being critical to its successful implementation.

LM Aeronautics has obtained good results using a woven glass fabric peel ply as a surface preparation for epoxy and bismaleimide bonded assemblies on a number of production, IRAD and CRAD programs (Reference 12-10). The glass peel ply comes pre-impregnated with the same base resin used in laminate fabrication and is cured with the detail laminate parts. It is removed just prior to application of the adhesive. This type of fiberglass peel ply can be obtained for other resin systems, however sizing on the glass must be compatible with the specific epoxy or BMI. Other peel ply fiber types such as polyesters and nylons are not recommended due to the peel ply residue left on the bonding surface that can adversely impact surface adhesion.

Nylon and polyester woven fiber fabric peel plies have been also used in industry. A peel ply with release agent should not be used due to potential contamination of the bond surfaces. However, non-release coated nylon or polyester nylon fabrics are difficult to remove which can also leave undesirable residue on the bond surface. Hart-Smith has reported on the issues related to release coated peel ply contamination and the use of nylon peel plies in particular (References 12-66 and 12-67).

Another LM Aeronautics CRAD project, the Transition Reliable Unitized STructure (TRUST) project still in progress at the time of this writing, is investigating the implementation of state-of-art manufacturing process control methods that are intended to greatly improve the reliability of bonded structural assemblies. This capability is recognized as an essential need to enable the development and certification of future unitized bonded composite primary structures without redundant fasteners (Reference 12-7).

Physical energetic treatment methods including flame treatments, corona discharge (ionic bombardment in a vacuum), and atmospheric plasma have proven successful for a variety of materials. These methods are believed to cause changes in surface molecular structure that enhance the surface free energy.

12.5.7 Fit-Up Check

A fit-up check is a pre-cure process evaluation where all detailed parts and tooling are pre-assembled before the application of adhesive. The purpose of this check is to mitigate potential problems and trouble areas and thereby reduce the risk of a non-conformance occurring during cure. Temperature, pressure and vacuum may be applied to simulate cure conditions. If necessary, a removable substitute material may be placed in the bond-line to simulate the adhesive but care must be taken to not contaminate the bond surfaces.

The fit-up check is intended to:

- Mitigate bond-line thickness gaps for a potential too thin or thick condition;
- Eliminate part or tool interferences or misalignment; and
- Ensure the tools and bagging are able to provide sufficient pressure.

Adjustments may be made to tooling. Bond-line gaps can be mitigated by additional adhesive up to permissible limits, typically not to exceed a bond-line gap of 0.020 in. This check may be used to validate tooling and processes prior to the start of production or to support cause and corrective action studies for non-conformances such as repetitive voids.

12.5.8 Adhesive Application

The method of application is dependent on the adhesive type. Liquid or paste adhesives may be applied with brushes, rollers or by spraying. Two-part adhesives are mixed right before application and typically must be applied within 30 to 120 minutes before the adhesive begins to set. The amount of adhesive prepared should be limited to that needed for the bonded application.

Film adhesives are typically cut to size and hand laid. Film adhesives may have a carrier ply to help support the film during application and to provide a physical support to maintain a bond-line thickness during cure. Care must be taken to prevent air from being trapped while the adhesive is being laid. Air bubbles can be pricked to allow the air to escape. As discussed previously, the adhesive out-time must be monitored to ensure it does not exceed the allowable limit.

12.5.9 Bond-line Thickness Control

The bond-line thickness must be controlled to prevent a too thin or too thick condition. The bond-line target thickness should optimally be approximately 0.003" – 0.010" after cure. The bond-line thickness can be controlled by matching the amount of adhesive to the bond-line gap when the assembly is subjected to cure temperature and pressure. The bond-line gap can be evaluated using a fit-up check described previously. An additional layer of adhesive may be applied up to approximately 0.020" for problem areas. Larger gaps may require the reworking of detailed parts and/or tooling. Allowable guidance is typically provided by a bonding process specification.

The bond-line thicknesses for liquid or paste adhesives can be reinforced using an embedded woven fabric ply. This provides a physical barrier to prevent the adhesive from being squeezed out from the bond-line. In addition, the fabric can act as a barrier ply between galvanically dissimilar adherends. As discussed above, film adhesives are available with a carrier ply that can provide the same functionality.

12.5.10 Inspection and Quality Control

Adhesively bonded joints and assemblies are non-destructively inspected (NDI) after cure. The common NDI inspection techniques used for bonded structure include:

- Visual
- Dimensional Checks
- Tap Test
- Ultrasonic Inspection
- Radiographic Inspection

NDI techniques are capable of detecting voids, disbonds or porosity within structure. However, although these techniques can verify that no defects are present in the bond-lines, they cannot access the strength of those joints. Bond-line defects such as caused by insufficient cure temperature-pressure, a discrepant adhesive, poor bond surface preparation or contamination could adversely impact the static strength or long term durability of the joint.

Since these non-conformances are not detectable, they must be mitigated by strict adherence to materials and process specifications that are designed to eliminate these defects. This structural integrity risk may be mitigated by the use of travelers, proof loading, and/or fail-safe design as described in Section 12.2.6.

Travelers are used to monitor the quality of manufacturing materials and processes used to produce composite bonded assemblies. These travelers must be produced using the same materials and processes as the production parts. This may be achieved by producing independent traveler parts along-side production parts or by excising trim or scrap portions of the production parts that may be evaluated using destructive inspection. The travelers must be carefully controlled and evaluated such that unfavorable findings may be relied upon as representative of production materials and processes.

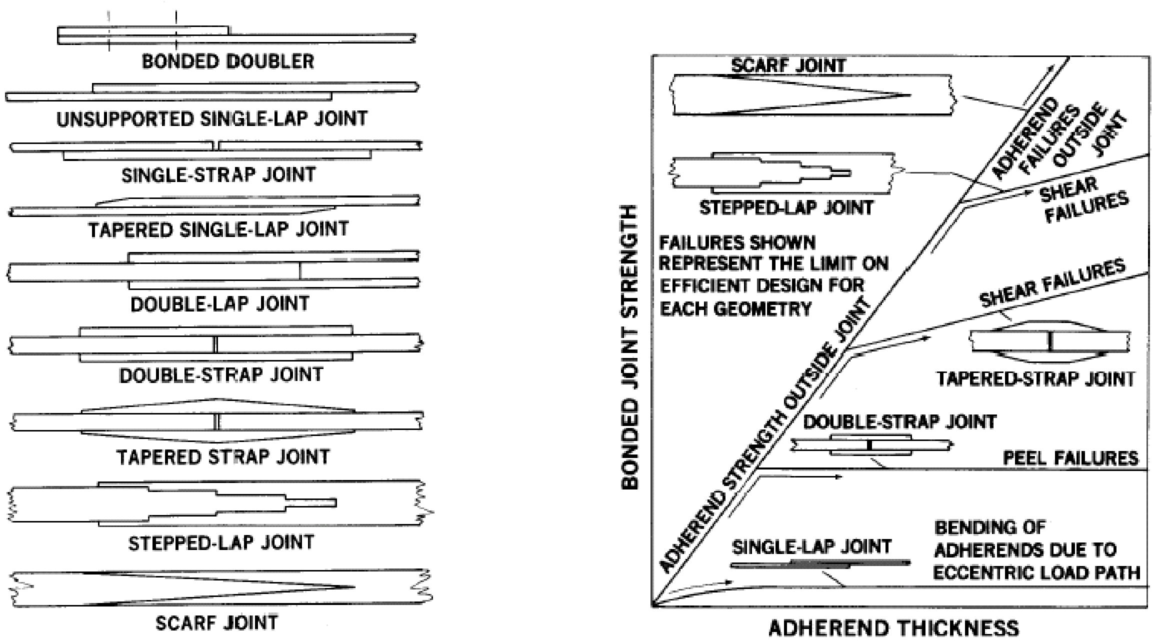
12.6 Types of Bonded Structures

This section provides a brief overview of common types of bonded structures. These types are categorized:

- Adhesively Bonded Splice Joints (Section 12.6.1);
- Bonded Honeycomb-core Sandwich Assemblies (Section 12.6.2); and
- Integrally Stiffened Bonded Structure (Section 12.6.3).

12.6.1 Adhesively Bonded Splice Joints

A number of common adhesively bonded splice joint designs are illustrated in Figure 12.6-1 (a). The joint configurations are presented from top to bottom in order of increasing strength capability. The relative bonded joint strengths are plotted as a function of adherend thickness in Figure 12.6-1 (b). These configurations are classic shear joints intended to carry axial load transferred in shear between adherends across the adhesive bond-line. As described in Section 12.2.3, bond-line normal stresses also exist to preserve local moment equilibrium and increase with joint eccentricity or rotation.



(a) Common Joint Configurations **(b) Bonded Joint Strength vs. Adherend Thickness**

Figure 12.6-1. Adhesively Bonded Splice Joints (Reference 12-38).

Adhesively bonded joints can be classified by four main types: the double-lap joint, single-lap joint, the scarf joint and the stepped-lap joint. Strength analysis of these bonded joints may be conducted using IDAT/A4EI which considers axial loading and predicts bond-line shear stresses only (joint configurations shown in Figure 12.8-6); or IDAT/IBOND which considers general loads and predicts bond-line shear and normal stresses. Analysis methods are discussed in Section 12.8.

Double-Lap Joint: The shear deformations, stresses and strains under increasing axial loads for a double-lap joint are shown in Figure 12.6-2. The typical bond-line stress distributions for double-lap joints are shown in Figure 12.4-6. For a symmetric stiffness balanced joint, the peak shear and normal stresses occur at each end of the joint. The adhesive shear stress distribution for higher loads shown in Figure 12.6-2 indicates yielding and the transition to perfectly plastic behavior at the joint ends. Reference 12-30 documents Hart-Smith's treatment of double-lap joints and provides useful design equations and curves.

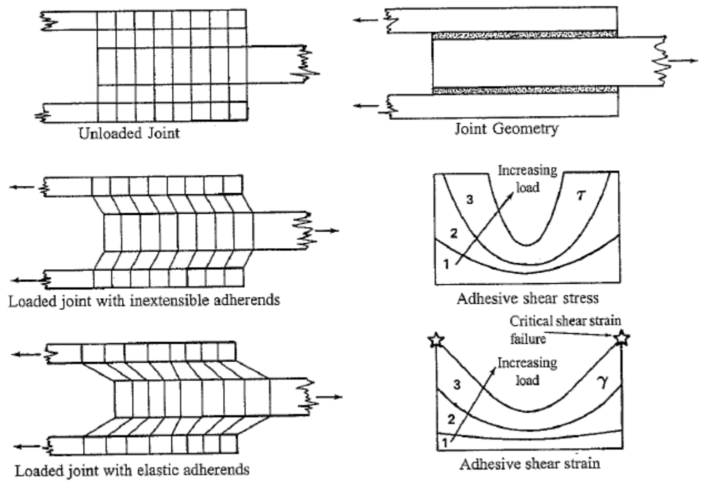
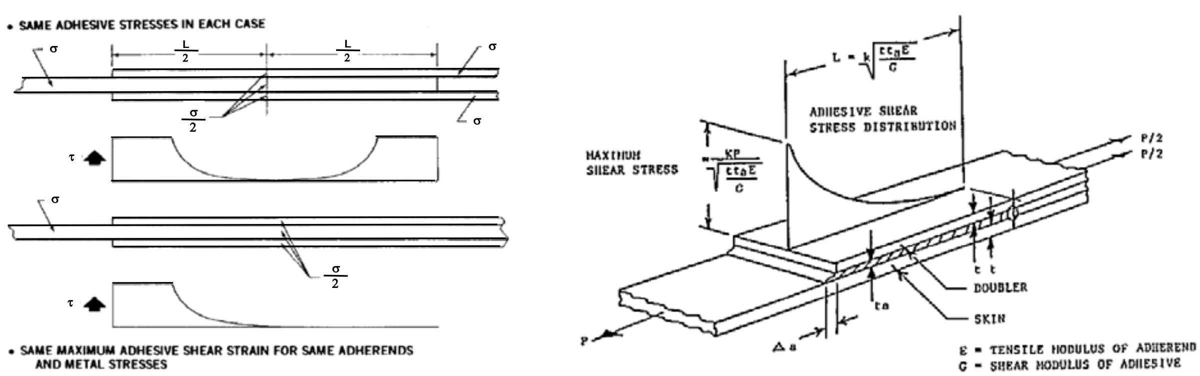


Figure 12.6-2. Double-lap Joint Shear Deformation, Stresses and Strains (Reference 12-5).

A related joint configuration that is useful for structural repairs is the bonded doubler also shown in Figure 12.6-1. The distribution and magnitude of bond-line stresses for bonded doublers are similar to those predicted for similarly sized double-lap joints. In both cases, the peak shear and normal stresses occur near the edges of the doubler. Figure 12.6-3 (a) shows the similarity in shear stresses between a double-lap joint and an identically sized symmetric doubler. The predicted bond-line stress distribution is the same in both cases. The flat region of the bond-line shear stress near the edge indicates that the adhesive has yielded in this area and is undergoing perfectly plastic deformation. Figure 12.6-3 shows the predicted adhesive shear distribution.



(a) Double-lap and Skin-Doubler Joints. **b) Skin-Doubler Adhesive Shear Stress Distribution.**

Figure 12.6-3. Bond-line Shear Stress Distributions.

The adherends may be metallic and/or composite materials where consideration must be given to thermal stresses induced between dissimilar adherends. A woven fabric barrier ply should be placed between galvanically dissimilar adherends. Figure 12.6-4 illustrates the use of tapered adherends that help to smooth the load transfer and reduce peak bond-line shear and tension-peel stresses.

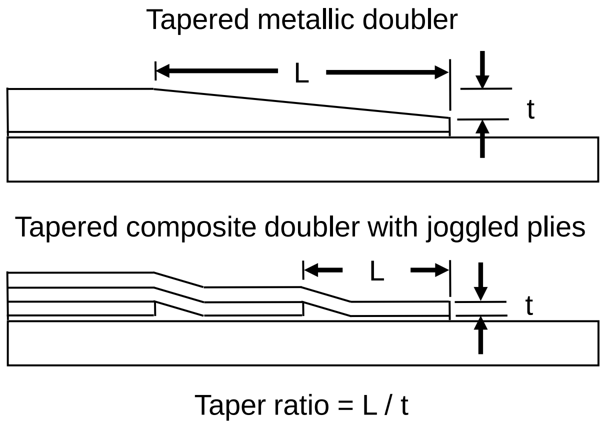


Figure 12.6-4. Tapered Ends in Metallic or Composite Adherends.

Single-Lap Joint: A single-lap joint is the simplest splice joint configuration, but is dominated by load eccentricity. The typical bond-line stress distributions for double-lap joints are shown in Figure 12.4-4. Typical failure modes for single-lap joints are shown in Figure 12.6-5. Unsupported single-lap joints are efficient for in-plane shear transfer but should never be used for compressive loads; the initial eccentricity becomes progressively worse as the load is increased and the joint should be stabilized (Reference 12-38). Reference 12-31 documents Hart-Smith's treatment of single-lap joints and provides useful design equations and curves.

Scarf Joint: The scarf joint, shown in Figure 12.6-1, provides a smooth tapered interface between the adherends. The bonded scarf joint possesses the greatest possible structural efficiency. In theory, it approaches the ideals of strain compatibility in the adherends and uniform stress distribution in the adhesive. In practice, the full potential of scarf joints may not be realized due to the peculiar processing and fabrication problems encountered in machining steep scarf angles, handling the fragile scarf ends, and controlling bond line thicknesses. Reference 12-32 documents Hart-Smith's treatment of scarf and stepped-lap joints and provides useful design equations and curves.

Stepped-Lap Joint: A stepped-lap bonded joint, shown in Figure 12.6-1, obtains higher structural efficiencies through a series of bonded joints. The strength of these joints is sensitive to a number of factors. The most significant is the need for adherend stiffness balance from one end of the joint to the other. The other variables are the length and number of steps.

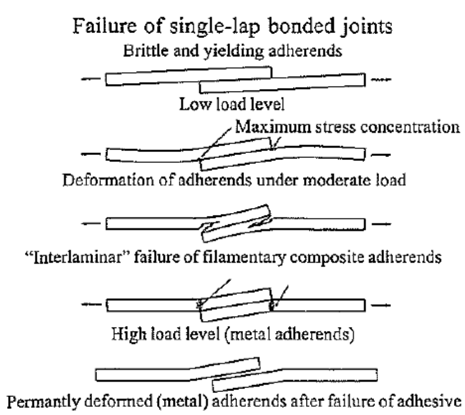


Figure 12.6-5. Single-lap joint failure modes (Reference 12-5).

12.6.2 Bonded Honeycomb-Core Sandwich Assemblies

Honeycomb-core sandwich construction as illustrated in Figure 12.6-6 has been used on all LM Aeronautics legacy aircraft. Sandwich construction provides an increased flexural stiffness and strength capability for a relatively small weight increase. Sandwich construction guidance will be provided in the future release of PM-4056 Section 14.

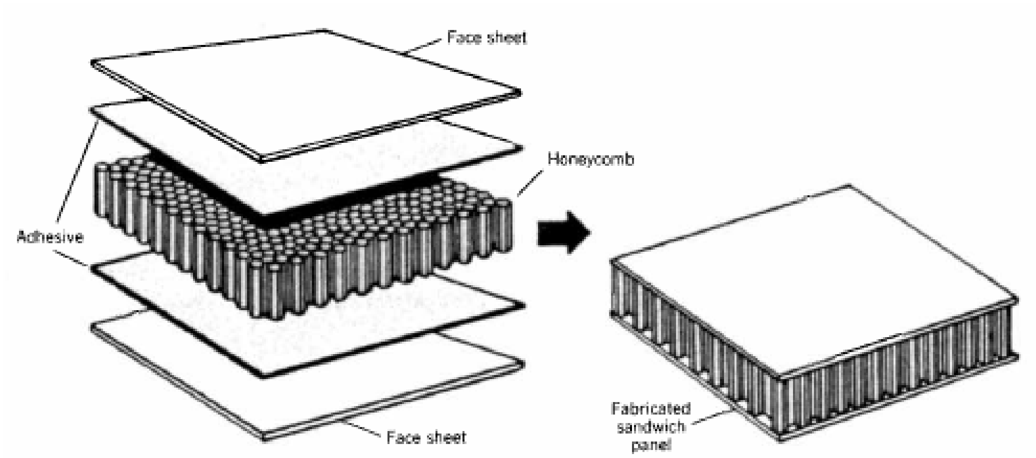


Figure 12.6-6. Honeycomb-Core Sandwich Construction.

Three types of bonded joint load transfer for honeycomb-core sandwich structure are shown in Figure 12.6-7: skin-to-core, core-to-core, and core-to-edge member. Skin-to-core joints use a film adhesive to transfer shear loads. Core-to-core and core-to-edge member splices use a foaming adhesive to transfer shear loads. Ideally, it is desirable to demonstrate through sandwich element testing that the core shear allowable strength is the weak link in the bonded assembly. The structural sizing is then simply based upon the allowable shear strength of the selected honeycomb core.

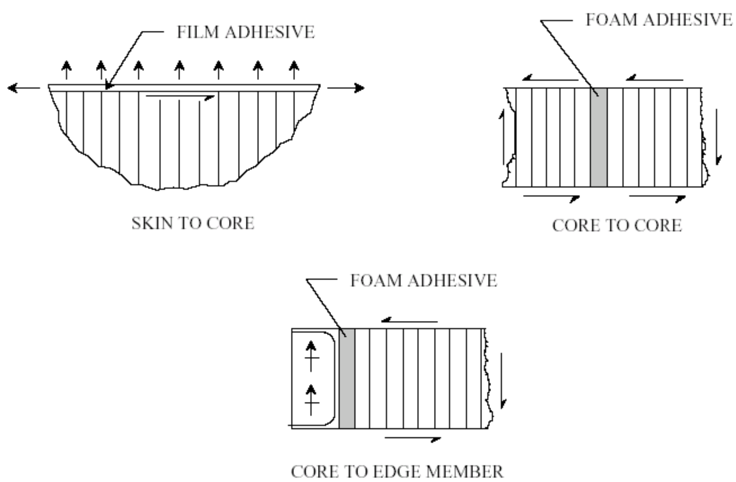


Figure 12.6-7. Load Transfer in Honeycomb-Core Adhesively Bonded Joints.

Other bonded joint design features used in sandwich construction that require special consideration are shown in Figure 12.6-8 and Figure 12.6-9. Figure 12.6-8 shows a bonded joint between a skin and spar, such as a sandwich face-sheet extending over a spar forming an outward facing close-out for the sandwich. This is also known as a "push-pull" joint as the face-sheet may be loaded in tension or compression as the sandwich structure reacts bending loads; or by in-plane shear as the face-sheet reacts torsional load. The bond-line shear stress distribution is very similar to that for a supported single-sided doubler. This type of joint may be analyzed using IDAT/IBOND strength analysis. Load transfer in this joint is concentrated at the rib web. The thickness of the rib web, external radius of the rib, and the adhesive fillet radius have significant impact on joint strength.

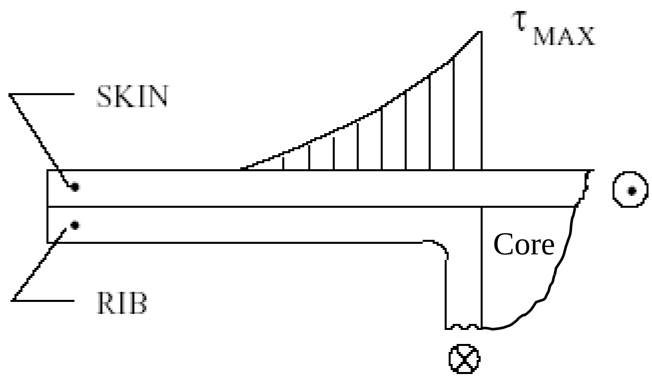


Figure 12.6-8. Bonded Skin-Spar or "Push-Pull" Joints.

Figure 12.6-9 shows a ramped panel edge feature for a bonded sandwich panel. A peak bond-line tension stress can occur at the curved portions of the face-sheet transitions. This stress is dependent upon the face-sheet height, thicknesses and ramp angle and is often mitigated by increasing the radius and/or using a shallow ramp angle. Refer to PM-4056 Section 13.8 for guidance.

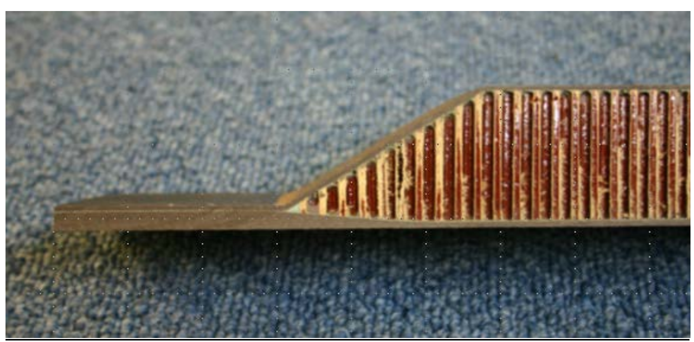


Figure 12.6-9. Ramped Panel Edge Features for Bonded Sandwich Assemblies.

12.6.3 Integrally Stiffened Bonded Structure

Referring to Figure 12.6-10 and Figure 12.6-11, examples of integrally stiffened bonded structure may include:

- Composite skin panels with integrally attached stiffeners:
    - Hat, blade, or constant section stiffeners (including I, C, Z, T, etc.)
- Co-cured box assembly – composite skins, sub-structural elements
- Co-bonded box assembly – composite skin, sub-structural elements joined with 3-D woven preforms.

3-D Woven preform design, strength and testing guidance is provided in Section 13.0.

(a) Co-cured bonded joint. **b) Co-bonded joint using 3-D woven preform joints.**

Figure 12.6-10. Composite Skin-Spar Box Structure.

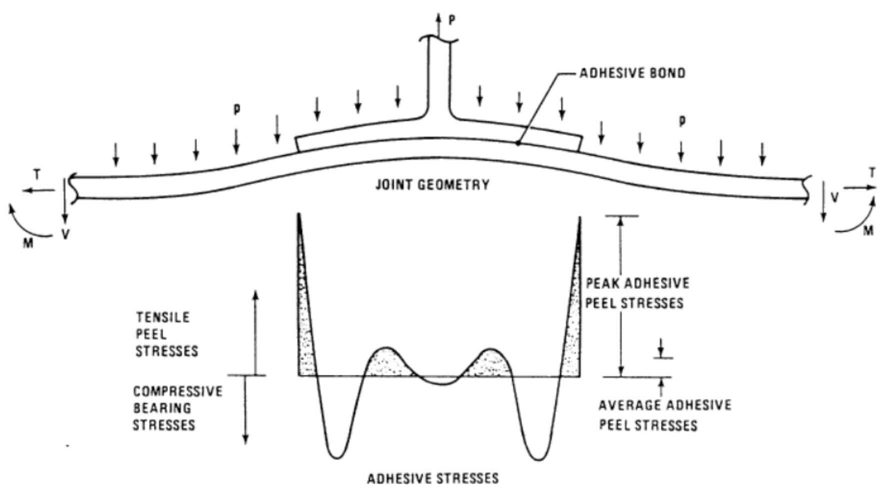


Figure 12.6-11. Co-cured Bonded Joint Normal Stress Distribution (Reference 12-37).

12.7 Bonded Joint Design Guidelines

This section begins with some practical considerations for structural analysis of adhesively bonded joints listed in Table 12.7-2. General design guidelines are provided in Table 12.7-2 that are intended to ensure the structural integrity of bonded joints. They have been adopted from a survey of both industry and Lockheed Martin Aeronautics best practices and lessons learned. Additional bonded joint design guidelines are also presented in Section 2.3.3.

Table 12.7-1 Practical Considerations for Bonded Joint Analysis.

No.	Observation	Remarks
1	Peak shear and normal bond-line stresses occur at or near bond-surface edges where load transfer begins.	These peak stresses reduce along the bond-line as the adherends attain an equilibrium load balance. Peak bond-line stress areas are also where peak interlaminar stresses occur in composite adherends.

2	Typical adhesive shear stress-strain behavior is initially linear elastic with a transition to nonlinear plastic behavior and a significant reduction in shear stiffness.	The adhesive will begin to yield in the bond-line peak stress areas. As the load increases, the remaining elastic portion will carry increased shear load until it also begins to yield.
3	Hot wet or cold dry are usually the most critical for adhesively bonded joints.	Thermoset adhesives are sensitive to temperature and moisture. Hot wet or cold dry conditions are typically the most critical for bonded joints.
4	In general, thermoset adhesives are more brittle at colder temperatures and more ductile at elevated temperatures.	The higher the cure and the use temperatures, the less ductile is the adhesive likely to be.
Note: Refer to Sections 12.2.3 and 12.3.3 for more discussion.		

Table 12.7-2 Bonded Joint Design Guidelines.

No.	Guideline	Remarks
1	An adhesively bonded joint must be designed so that the adhesive is stronger than the adherends.	Prevents the adhesive bond-line from being the weak link in the structure thereby reducing structural integrity risk. The bond could act as a weak-link fuse and fail catastrophically from a local defect.
2	An adhesively bonded joint must be designed to primarily transfer shear load across the bond-line.	The most efficient load transfer for an adhesively bonded joint is through shear acting across the bond-line.
3	An adhesively bonded joint must be designed to minimize bond-line tension-peel stresses.	Tension-peel stresses can not only cause failure in the adhesive, but they can also induce delamination in composite adherends. Peel stresses may be mitigated through joint design by minimizing load path eccentricity, balancing adherend stiffness properties, and using efficient scarf angles, overlapped steps or adherend tapers.
4	An adhesively bonded joint design must consider the thermal expansion of all joint constituents.	Thermally induced bond-line residual stresses must be considered for both cool down from the cure temperature and for the range of design service temperatures. The effect of moisture is accounted for by using the appropriate strength allowable for the design environmental condition.
5	Adhesive bond surface preparation is the most critical factor in producing reliable, full strength bonded joints.	Refer to Section 12.5.6. Surface preparation procedures must be determined experimentally and must be strictly adhered to for production quality control. Surface preparation objectives are to: clean the bond surface of contaminants and moisture; increase the bond surface free energy; and produce an adherend bond surface condition that is reliably consistent.
6	Ductile adhesives are preferred over brittle ones as they absorb more strain energy before failure.	Refer to Section 12.3.3. Although brittle adhesives may exhibit a higher ultimate strength, ductile adhesives are more forgiving and absorb more strain energy before final failure. Brittle adhesives are more sensitive to sudden failure and to assembly tolerances and processing imperfections.
7	The adherend joint overlap should have sufficient length such that the adhesive stays within the elastic range in the majority of the joint.	Larger overlap length to adherend thickness ratios reduce induced moments, peel stresses and adhesive shear stresses. Maintaining a bond-line elastic region is important for ensuring joint durability, preventing creep, and improving tolerance to bond-line defects.
8	Adherend joint overlap length typically has an upper practical limit beyond which the	Extending the overlap length of the joint with an elastic region does little to improve the overall joint strength since

	improvement in overall joint strength diminishes.	most of the load will be transferred in the end regions. However, maintaining an elastic region is still important for the reasons stated in the previous guideline.

12.8 Methods of Analysis

Different types of bonded joint analysis methods are available, from simple one dimensional analysis to complex three dimensional finite element analysis. The choice of analysis method depends on the stage of the design process. In all cases the analysis must be correlated to test data. The various analysis techniques are discussed in the following section.

12.8.1 Preliminary Design Analysis Methods

During the preliminary design stage a simple joint axial load transfer stress calculation coupled with a design curve is employed to design the joint. The joint configuration associated with the design curve, which accounts for tension peel stress, must be representative of the joint that is being analyzed.

Single Lap Shear (SLS) Joint

The average shear stress of the joint is calculated as the applied load divided by the bond area. This stress is compared to a representative single-lap joint allowable obtained from SLS test for laminated adherends (See Section 12.4.1.1). If the adherend overlap length (L) to thickness (t) ratio (L/t) of the test configuration is different than the structural configuration then the effect of peel stresses due to dissimilar L/t ratio has to be accounted for. This is determined using a peel stress reduction factor, which is determined experimentally using single lap joint tests with varying L/t. This method can be applied to a single lap joint. Note that the method prescribed below should be used only when the adhesive B-basis allowables (see **Table 12.8-3** for the list of allowables) are not available. If B-basis allowables are available then the analysis method described in Section 12.8.4 must be used, provided the analysis has been correlated to bonded joint test data.

The steps for preliminary design are as follows

1. Determine the adherend overlap length and thickness of the adherends.
2. Determine the L/t for the adherends and choose the lowest L/t
3. For a single lap joint determine the average applied shear stress, which is P/(W×L), where P is the applied load in lbs, W is the width of the bond area (in), and L is the bond length (in).
4. Determine if the single-lap shear joint strength is available for the joint configuration that is being analyzed. If not available this has to be determined using test methods discussed in Section 12.4.1.1 for quasi-isotropic adherends with L/t ratio of 32 since this is representative of most aircraft structures. For L/t > 32 using the strength values for L/t=32 will be conservative. The joint strength must be determined at the critical environment, which is usually at Elevated Temperature Wet (ETW) using preferably the same material system as the structure that is being analyzed. If the ETW values are not available, then a factor of 0.5 must be applied to the calculated allowable.
5. To account for the peel stresses due to bending of the single-lap joint, the joint strength is modified by a peel factor. The generic peel reduction factor is given by

$$k_p = 1 - m \times \left[\left(\frac{L}{t}\right)_{test} - \left(\frac{L}{t}\right)_{design}\right];\ \ if\left(\frac{L}{t}\right)_{design} \leq \left(\frac{L}{t}\right)_{test}$$

$$k_p = 1\ \ if\left(\frac{L}{t}\right)_{design} > \left(\frac{L}{t}\right)_{test}$$

Equation 12.8-1

where,

k_p	=	peel reduction factor
L	=	length of the overlap (in)
t	=	thickness of the adherend (in)
$(L/t)_{design}$	=	L/t ratio of the actual design; $(L/t)_{design} \geq 8$
$(L/t)_{test}$	=	L/t ratio of the single lap joint configuration for which test data is available
m	=	0.0315 @ Room Temperature Ambient (RTA) & -65F; and 0.0083 @ 275F.

For temperatures between Room Temperature Ambient (RTA) and 275F, determine k_p at RTA and 275F, and interpolate. The above equation may be used for preliminary design only. The peel reduction factor @ RTA as a function of (L/t) when $(L/t)_{test}$ = 32 is shown below.

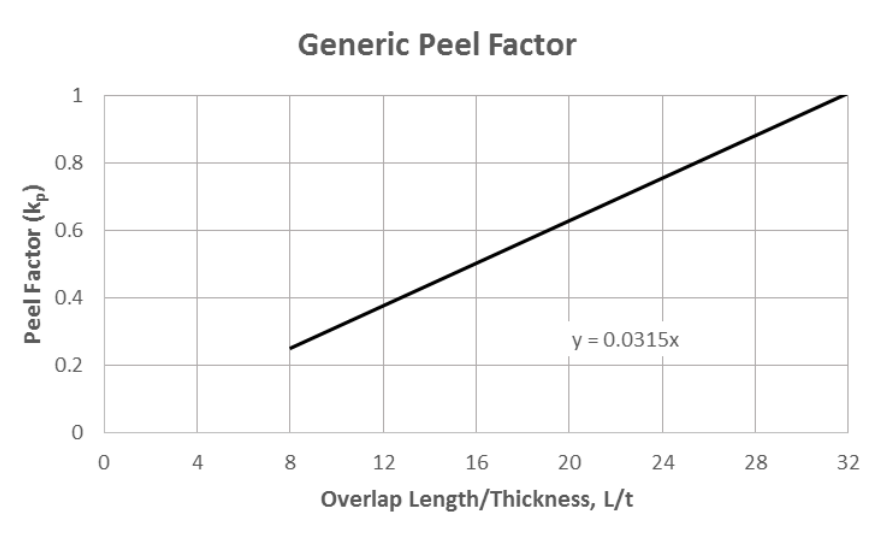


Figure 12.8-1 Generic Reduction Factor For Peel Stress at RTA.

Double Lap Shear (DLS) Joint

For a DLS joint an analysis method similar to a single lap joint can be adopted. The joint strength for the DLS must be based on testing DLS coupons as discussed in Section 12.4.1.1.

Example Problem 1

Given a single-lap joint with the following features, determine the SLS joint strength at 275F.

Adherend material	IM7/977-3 tape
Adherend ply %	(25/50/25)
Top adherend thickness (t_{top})	0.1272 inches
Bottom adherend thickness ()	0.1272 inches
$(L/t)_{design}$	16
Applied load P	1000 lbs
Adhesive	AF191G-108
Width of bonded area (W)	1 in.
Overlap length (L)	2 in. t_{bot}

Average single lap shear (SLS) failure load for quasi-isotropic adherends with $(L/t)_{tes\ t}$= 32 @ RTA is 7900 lbs.

Length of the overlap of SLS test coupon (L_{test}) = 4.6 in.
Width of SLS test coupon = 1 in.

Average SLS strength= 7900/(4.6×1) = 1717 psi
Since the strength is obtained at RTA, to obtain the strength @ 275F, reduce the strength by a factor of 0.5
Joint strength at 275F = 0.5×1717 = 858.5 psi.
This is reduced further to account for peel stresses as follows.
$(L/t)_{design}$ = 2/0.1272 = 16
$(L/t)_{test}$ = 32
Since $(L/t)_{design} < (L/t)_{test}$ using Equation 12.8-1,
k_p = 1-0.0083×(32 – 16) = 0.87
Joint strength at 275F accounting for peel stress = 858.5×0.87 = 747 psi

12.8.2 Detailed Analysis Methods

For detailed design, closed form solutions calibrated to test data are employed to write margins-of-safety of the part. The different closed form analysis methods are reviewed in Reference 12-68 and are summarized in the next section. In addition to closed form analysis methods, the finite element method can also be employed during detail design to analyze bonded structure.

12.8.2.1 Overview of Historical Development of Analysis Methods to Predict Bond-line Stresses

The basis for most aerospace-related articles on bonded joint analysis is the paper by Goland and Reissner (Reference 12-2). The basic problem that they solved, and the resulting adhesive shear and peel stress field, in a SLS joint, is shown in Figure 12.8-2.

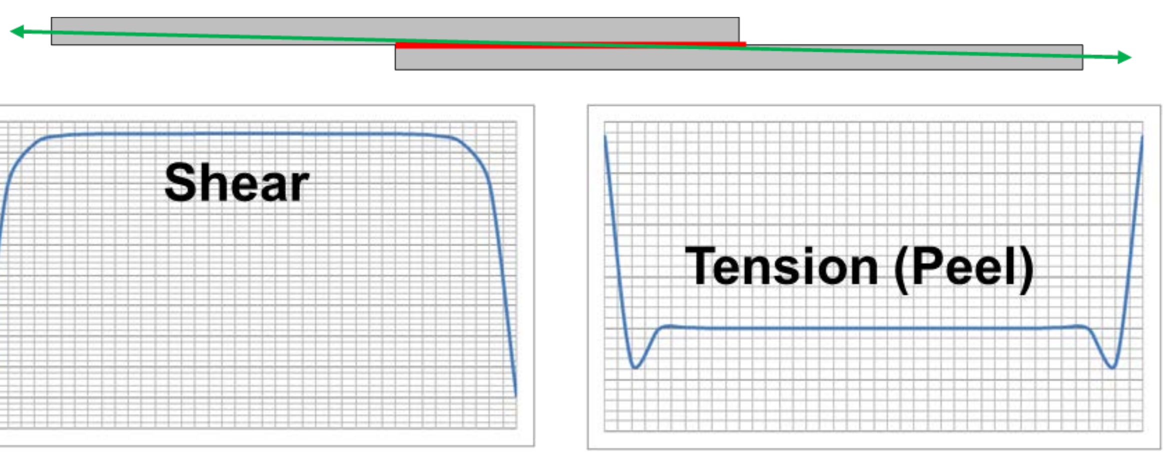


Figure 12.8-2 Goland and Reissner Single Lap Solution.

In the 1960's and early 1970's the USAF and NASA funded a variety of work on this subject for both metallic and composite bonded structure and a variety of bonded joint configuration, and a number of papers/reports were written by Dickson et al., Grimes et al., Hart-Smith, and others (Reference 12-30, 12-31, 12-69, 12-70). Concurrently, similar work was also going on in the U.K (Reference 12-71, 12-72). All generally followed Goland and Reissner's formulation of the problem as plates in tension and cylindrical bending, and solving for the stresses in an adhesive layer between the two.

In general the adherend-adhesive deformation of a single-lap bonded joint can be analyzed using a simple shear lag model or a more complex coupled axial-bending model where both the axial and bending deformation of the adherend are considered in the analysis. The shear lag model is a simplistic model that considers only axial deformation of adherends and predicts shear stresses in the adhesives while ignoring the peel stresses.

Volkersen (Reference 12-73) employed a simple shear lag model where only the shear deformation of the adhesive was considered. The resulting analysis resulted in a second order differential equation which is solved by enforcing the load boundary condition along the two edges where the load enters the joint.

The coupled axial-bending model was first proposed by Goland and Reissner. They assumed a plane-strain stress state for the adherends in bending and a plane-stress condition for the adherends undergoing axial deformation. They accounted for the effect of bending and axial loading of the adherend on the adhesive for a single-lap joint. The solution results in an expression for the shear and peel stress as a function of horizontal position along the adhesive.

Further work in the development of stress based analytical solutions for bonded joints involved improvements to the afore mentioned models. Table 12.8-1 compares the various analysis methods that have been developed to predict adhesive bond-line stress.

Table 12.8-1 Comparison of Bonded Joint Stress Field Assumptions

Author (Reference) [See Key]	Assumptions (see Key below)																			Notes
	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U	
GR (12-2) [a]	√	√	√					√				√		√	√	√				
GR (12-2) [b]	√	√	√						√			√			√	√				1/
HF (12-74)		√	√						√							√	√	√		2/
D (12-69) [c]		√			√	√			√				√	√		√		√		
D (12-69) [d]		√			√	√				√			√	√		√		√		3/4/
GG (12-70)		√	√				√				√		√			√		√	√	4/
HS (12-31) [e]		√							√				√			√		√		
HS (12-30) [f]		√								√			√			√	√	√	√	
A (12-71)		√	√	√					√				√	√	√	√				
G (12-72) [c]		√						√	√				√		√	*(5)		√	√	5/
G (12-72) [g]		√								√			√			√				4/
OE (12-75)	√		√	√					√				√	√	√	√				
TOM (12-76)		√				√			√				√			√		√		

Key	Explanation	Key	Explanation
A	Both adherends have same thickness	P	Free edge condition satisfied
B	Adhesive thickness << adherend thickness	Q	Large over-hanging-adherend deflections included
C	Isotropic adherends	R	Applied T (axial tension and compression) load only
D	Adhesive stresses vary through thickness	S	Peel stress ignored
E	Discrete adherend plies modeled	T	Solved both Single Lap and Double Lap Shear cases
F	Shear-deformable adherends	U	Explicitly derived multi-step cases
G	Elastic-plastic adherends	a	Rigid adhesive solution
H	Rigid adhesive	b	Flexible adhesive solution
J	Elastic adhesive	c	Elastic adhesive solution
K	Elastic-perfectly-plastic adhesive	d	Elastic-perfectly plastic adhesive solution

L	Elastic-plastic adhesive	e	Elastic solution for adhesive peel stress
M	Plane stress	f	Elastic-perfectly plastic solution only for adhesive shear
N	Complete shear-displacement equation	g	Elastic-plastic solution only for adhesive shear

Notes:
1. Mixed plane stress and plane strain in shear- and normal-displacement equations.
2. Mainly focused on adherend stress solution. Only showed adhesive shear stress for Double Lap Shear configuration.
3. Commented on several elastic-plastic approaches that did not work. Assumed peel stress elastic.
4. Noted unresolved numerical issues.
5. Only solved for far-field axial tension and compression loads but carried moments and shear force terms through most equations.

An in-depth discussion of the advantages and disadvantages of the various methods reviewed above is given in Reference 12-68. To summarize, all prior authors essentially limited themselves to the coupon test specimen problem of applied axial loading, T, only. However, Grant’s (Reference 12-72) formulation happened to carry the applied external loading terms M and V through their entire derivation, simply setting their values equal to zero when applying the boundary conditions. Thus Grant’s formulation was modified and implemented in IBOND.

12.8.3 Failure Criteria

The failure criteria for bonded joints can be grouped into two main categories: stress based and strain based.

Stress based failure criterion: The stress based failure criterion can be applied to the adherend or the adhesive. For composite adherends, failure is assumed to have occurred if the adherend UNC, UNT, ILT or ILS is exceeded. When a combined stress state exists, such as when shear and axial loads simultaneously act, a suitable interaction equation has to be used. One such method is the Tsai-Wu criterion. The margins of safety (M.S.) for the adherend under multiaxial stress state is defined as

M.S. = 1 / $\sqrt{R}$ – 1.0, where

R =

$$\left(\frac{\sigma_1^2-\sigma_1\sigma_3}{F_{11}^{tu}F_{11}^{cu}}\right)+\left(\frac{\sigma_2^2-\sigma_2\sigma_3}{F_{22}^{tu}F_{22}^{cu}}\right)+\left(\frac{\sigma_3}{F_{33}^{tu}}\right)^2+\left(\frac{\tau_{13}}{F_{13}^{su}}\right)^2+\left(\frac{\tau_{23}}{F_{13}^{su}}\right)^2+\left(\frac{\tau_{12}}{F_{12}^{su}}\right)^2 \quad \textbf{Equation 12.8-2}$$

.

Where

$\sigma_1, \sigma_2, \sigma_3, \tau_{12}, \tau_{23}, \tau_{13}$	=	stress components from fine grid FEM in material coordinate system (psi)
F_{11}^{tu}	=	In-plane unnotched tension strength in fiber direction (psi)
F_{11}^{cu}	=	In-plane unnotched compression strength in fiber direction (psi)
F_{22}^{tu}	=	In-plane unnotched tension strength transverse to fiber direction (psi)
F_{22}^{cu}	=	In-plane unnotched compression strength transverse to fiber direction (psi)
F_{12}^{su}	=	In-plane shear strength (psi)
F_{13}^{su}	=	Interlaminar shear strength (psi)
F_{33}^{tu}	=	Interlaminar tension strength (psi)

The allowable strengths are obtained from IDAT/MATUTL and the applied stress components are extracted from fine grid FEM as discussed in Reference 12-77. In the IBOND tool (Section 12.8.5) the ILS and ILT checks for the adherends are included.

For adhesives, the maximum peel and interlaminar shear stresses in the adhesives are compared separately (i.e. no interaction) to experimentally determined allowables to determine adhesive failure (Section 4.5.3). This approach is adopted in IBOND.

Strain based failure criterion: The strain based failure criteria is usually applied to the adhesive. In the case of a 3D Finite Element Analysis using a p-version code such as StressCheck, since the strain state in the adhesive is multi-axial, an equivalent strain needs to be evaluated to account for the strain interactions. Furthermore, since the adhesive is constrained between the deformed adherends, the failure in the adhesive could occur due to change in volume (dilation) rather than in distortion as in metals. To account for the multiaxial strain state and the dilation the Strain Invariant Failure Theory (SIFT) is used. This is quantified by the first strain invariant and is expressed as:

$$J_1 = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$ **Equation 12.8-3**

Where
J_1 = first strain invariant
ε_1 = principal strain in 1 direction (in/in)
ε_2 = principal strain in 2 direction (in/in)
ε_3 = principal strain in 3 direction (in/in)

The calculated first invariant J_1 is compared to the critical J_{1c} to determine failure. The strain allowable J_{1c} is extracted from a StressCheck model which is correlated to T-peel test (References 12-15 and 12-53). This failure criteria is applied only when J_1 is positive (tension). J_{1c} allowable can be obtained from IDAT/MATUTL.

To ensure that shear distortion of the adhesive does not cause failure the applied Von Mises strain in the adhesive extracted from the fine-grid finite element model is compared to a critical distortional strain which is deduced from thick adhered test (see Reference 12-23). The SIFT and distortional failure criteria are further discussed in Section 12.3.6 and Reference 12-23 .

In A4EI, adhesive failure is predicted to occur when the adhesive shear strain exceeds the adhesive ultimate shear strain, which is determined experimentally.

A summary of the analysis methods and the failure criteria is provided below.

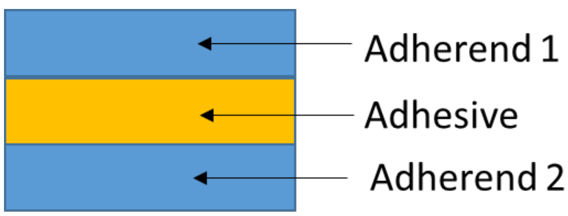
Analysis Method	Joint	Failure Criteria
A4EI[1]	Adhesive	Maximum shear strain
IBOND	Adherend	UNC, UNT, ILT, ILS
	Adhesive	Maximum stress
FEA (StressCheck/Nastran/Abaqus)	Adhesive	SIFT/Maximum Distortional Strain
	Adherend	Tsai-Wu
[1] Adherends can be analyzed outside of A4EI using IDAT/SQ5 as discussed in Section 12.8.4.8.5		

12.8.4 Elastic-Plastic Bond Line Analysis (IDAT/A4EI)

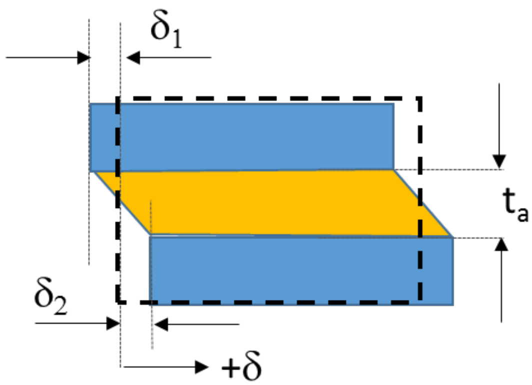
A4EI is a bonded joint analysis tool that was developed by Hart-Smith under a United States Air Force (USAF) at Wright Patterson Air Force Base contract, during the time period extending from 1976 to 1983. A4EI is an extension of Volkersen's method where Volkersen's rigid adherend assumptions are relaxed and treated as deformable. Furthermore, the adhesive properties are assumed to be elastic-perfectly plastic. The implications of this assumption are discussed below and is specific to A4EI bonded joint analysis.

12.8.4.1 Joint Assumptions

A fundamental assumption made in A4EI is that the bonded joint is assumed to deform only in axial direction, which precludes any bending deformation. This forces the load transfer between the adherends to be only shear. Therefore, A4EI cannot be used to analyze bonded joint experiencing bending deformations. Furthermore, it is assumed that the joint has high through-thickness transverse shear stiffness that forces all the shear to be resisted at the bond-line as shown in Figure 12.8-3.



(a) Undeformed



(b) Deformed

Figure 12.8-3 A4EI Assumptions; (a) Undeformed and (b) Deformed Configurations.

From Figure 12.8-3 the engineering shear strain is given as:

$$\gamma = \frac{|\delta_1 - \delta_2|}{t_a}$$ **Equation 12.8-4**

where,

γ	=	shear strain (in/in)
δ_1	=	displacement of the Adherend 1 (in)
δ_2	=	displacement of the Adherend 2 (in)
t_a	=	thickness of the adhesive (in)

In Equation 12.8-4, δ_1 and δ_2 are of opposite signs, hence they add. The joint width is 1 inch (Figure 12.8-4a) and therefore all the loads are running loads with units of lbs/in. The joint is modeled from left to right and the load is applied to the first step of Adherend 1, hence no load is applied to the first step of Adherend 2 as shown in Figure 12.8-4b. Note that the user provides the number of steps (maximum number of steps is 50) for the model as input to A4EI. However, depending on the severity of the stress state in the bondline A4EI can further refine the steps. This is explained in Table 12.8-7.

(a) Single Shear Lap Joint

(b) A4EI Model

Figure 12.8-4 A4EI Model for an Axially Loaded Bonded Joint.

Shear loaded joints are modelled as axial loaded joints after replacing the adherend's Young's modulus with the shear modulus and using the shear load as the axial load. Figure 12.8-5 (a) depicts a shear loaded panel and Figure 12.8-5 (b) depicts an equivalent axially loaded joint where the adherend's Young's modulus is replaced with the shear modulus. Note that Figure 12.8-5 does not show the balancing moments since they are not valid inputs for A4EI.

(a) Single Shear Lap Joint

(b) A4EI Model

Figure 12.8-5 A4EI Model for a Shear Loaded Bonded Joint.

The adhesive stress-strain behavior is non-linear and is approximated as elastic-perfectly plastic curve as shown in Figure 12.8-6. As discussed in Section 12.3.4, the elastic-plastic curve is determined such that the total strain energy based on the elastic-plastic curve is the same as the curve based on test data.

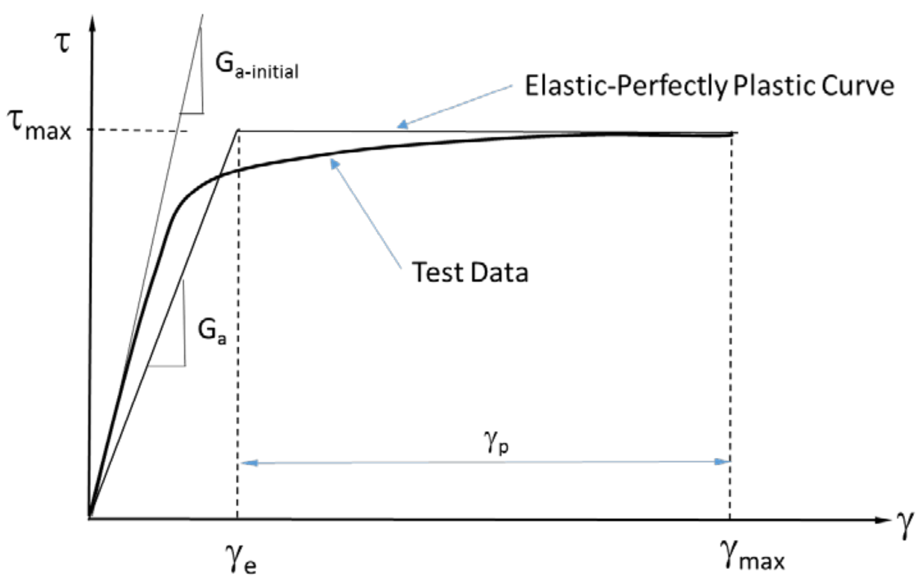


Figure 12.8-6 Elastic-Plastic Shear Stress-Strain Behavior of Adhesive.

In Figure 12.8-6, the quantities shown are:

$G_{a\text{-initial}}$	=	shear modulus of the adhesive based on the test data (psi)
G_a	=	shear modulus of the adhesive based on the bi-linear representation (psi)
τ_{max}	=	max adhesive shear stress at which yield begins as indicated on elastic-plastic curve (psi)
γ_e	=	maximum elastic shear strain determined from elastic-plastic curve (in/in)
γ_p	=	plastic shear strain determined from elastic-plastic curve (in/in)
γ_{max}	=	maximum shear strain at failure determined from test data (in/in).
γ_{max}	=	$\gamma_e + \gamma_p$

The failure strength predicted by A4EI is independent of the shape of the elastic-plastic curve as long as the failure stress, failure strain, and total strain energy enclosed by the curves are the same (Reference 12-52).

12.8.4.2 Capabilities and Limitations

A4EI can be used to determine the elastic, elastic-plastic joint strength of an adhesively bonded joint. Loading can be tension, compression, or shear. The different joint configurations analyzed by A4EI are discussed in Section 12.8.4.3. A4EI can also be employed to analyze the effects of defects such as porosity and disbonds on bond strength. In regions with defects the load transfer across the bond line is reduced and the excess load is redistributed to the surrounding non-defective part. This affects the shear stress distribution along the bond line without affecting the peak stresses.

Since A4EI can handle only axial deformation it cannot be used to predict stresses that arise due to bending such as peel stresses. Furthermore, A4EI cannot predict inter-laminar failure of adherends which are important for composites due to their relatively weak interlaminar properties. IBOND method, discussed in Section 12.8.5, can be used to predict peel and shear stresses in the adhesive and the resulting adherend interlaminar stresses.

A4EI cannot distinguish between cohesion and adhesion failure modes. However, the adhesive allowables used with A4EI are obtained after ascertaining cohesion failure in the test specimen. For example, when determining the maximum shear stress and strain using a thick adherend test, it is ensured that the adhesive fails in cohesion. (Reference 12-54).

12.8.4.3 Configurations Analyzed by A4EI

The bonded-joint configurations analyzed by A4EI are:

- Doublers (single and symmetric)
- Single-lap joints
- Double-lap joints
- Step lap joints (The Single-lap joint shown in the figure is also a stepped lap joint)

These are depicted in Figure 12.8-7.

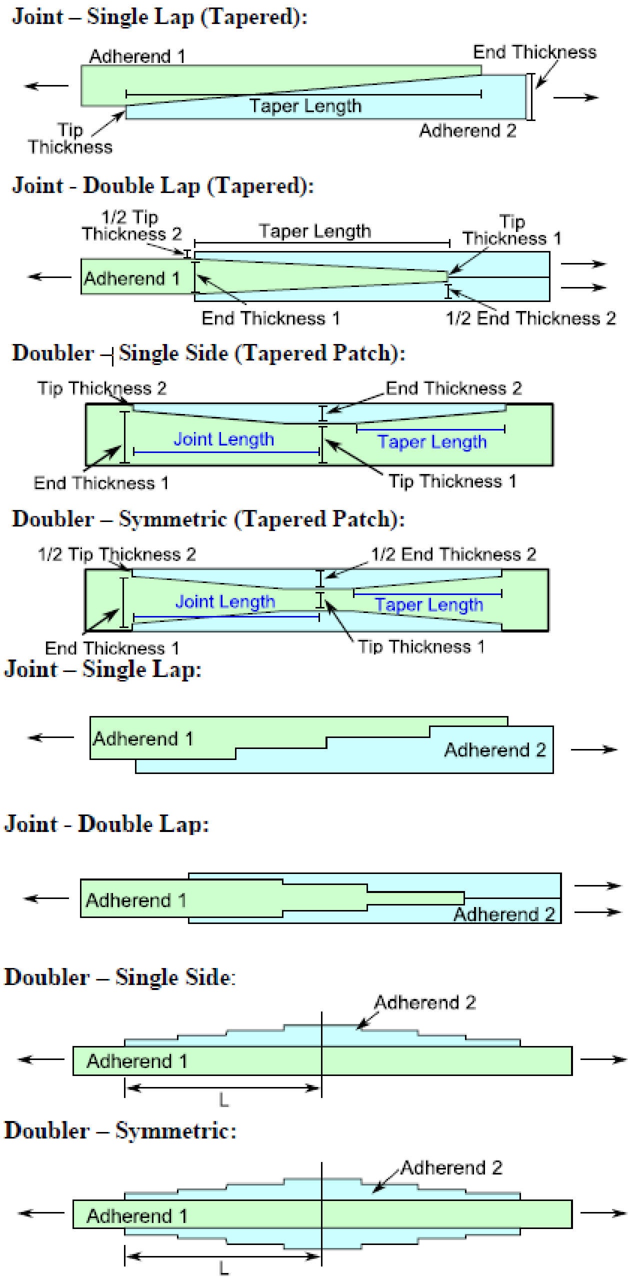


Figure 12.8-7 Bonded Joint Configurations Analyzed by A4EI.

12.8.4.4 Strengths and Failure Modes Predicted by A4EI

A4EI predicts joint strength under uniaxial and/or shear load. Joint strength includes in-plane adherend strength, adhesive elastic strength, and adhesive ultimate strength which are described below. Adherend strength is not predicted by A4EI and is included here for completeness. A4EI is used primarily to predict adhesive elastic limit and ultimate strength only.

Adherend Strength – This is the capacity of the adherend to resist axial load without failing the adhesive. The adherend is assumed to have failed if the adherend load (lbs/in) exceeds the strength of the adherend laminate. The laminate static un-notched strength can be determined using IDAT/SQ5 and the notched strength can be determined using IDAT/IBOLT. If the adherend is required to meet durability and damage tolerance requirements the strength of the laminate can be determined using IDAT/CDADT.

Adhesive Elastic Limit: This is the load in the joint (lbs/in) at which the adhesive reaches the maximum elastic shear strain, γ_e, of the adhesive anywhere in the bond-line. This is shown in Figure 12.8-6. Beyond this load the adhesive begins to yield and incurs damage. In Figure 12.8-6 as long as the adhesive stresses are below τ_{max}, *i.e.* the adhesive strains are below γ_e, the joint operates in the elastic regime.

Adhesive Ultimate (Elastic-Plastic) Strength: This is the load in the joint (lbs/in) at which the adhesive attains the maximum failure strain, γ_{max}. Beyond this load failure occurs in the adhesive. To ensure that a joint allowable for the adhesive is obtained the adherend strength is set to a fictitious high value. This drives the joint failure to the adhesive. Note that the adherend strength is determined separately as discussed earlier in this section.

12.8.4.5 Guidelines for Input Loads for Analysis

The input loads for A4EI typically come from a coarse grid or fine grid finite element model (FEM). If there are several load cases, then the critical load case(s) must be determined.

For large acreage bonded area where the edges of the bonded areas are aligned, as shown in Figure 12.8-8, the input loads for A4EI are the applied loads acting along the straight edges. The modulus used is the transformed modulus in the direction of the load being considered. For example, when analyzing the single lap joint shown in Figure 12.8-8 the effective modulus of the adherends in the X direction E_x would be used when the input load is N_x and the effective modulus E_y would be used when the input load is N_y. For shear load the in-plane shear modulus G_{xy} would be used. These values can be obtained quickly from polar plots using the IDAT/LAMINATE utility.

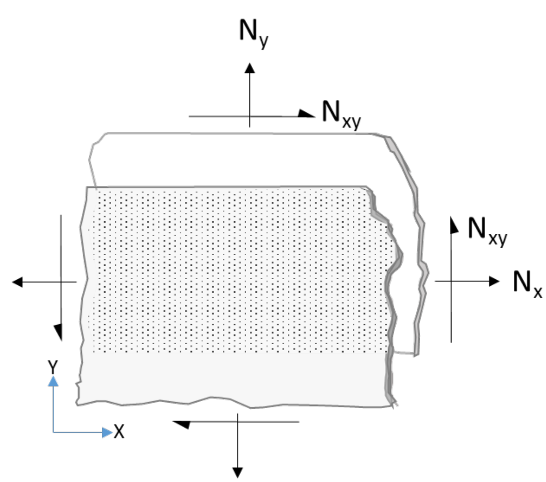
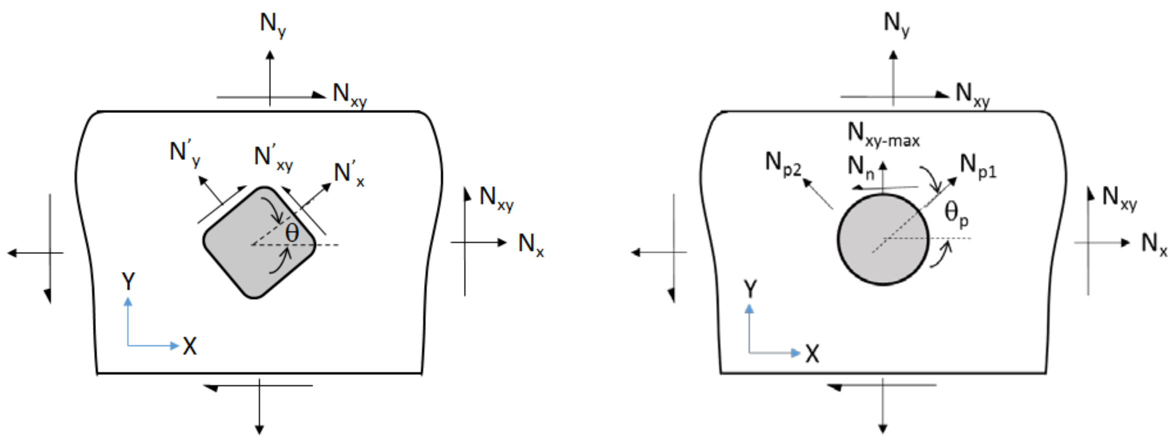


Figure 12.8-8 A4EI Input Loads for a Single Lap Bonded Joint.

When the edges of the bonded area are not aligned, which is generally the case when analyzing repair patches, the loads should be correctly transformed. For patches with a straight edge as shown in Figure 12.8-9 (a), the loads should be resolved along the straight edge of the patch and these loads should be used as A4EI inputs. The adherend modulus should be transformed correspondingly such that the modulus in the direction of the load is used.



a) Rectangular Patch **b) Circular Patch**

Figure 12.8-9 Transformed Loads to be Used in A4EI Analysis

For circular patches, as shown in Figure 12.8-9 (b), principal axial and shear loads should be used as A4EI load inputs. Also, the adherend modulus used should be the transformed modulus in the direction of the loads being considered. The transformed modulus can be obtained using the polar plot utility available in IDAT/LAMINATE. Note that in this case the analysis has to be performed at 3 locations with principal loads N_{p1} and N_{p2}, and the combined max shear load $N_{xy\text{-}max}$ and the normal load N_n.

12.8.4.6 Thermal Loads

Temperature induced loads occur in bonded joints when there is a difference in coefficient of thermal expansion between the adherends. A4EI accounts for thermal stresses when ΔT (delta T) defined below is non-zero.

$$\Delta T = T - T_{stress\text{-}free} \ (^{o}F) \qquad \textbf{Equation 12.8-5}$$

where,

T = Operating temperature of the joint (°F)

$T_{stress\text{-}free}$ = Adhesive stress free temperature also called as cure temperature in A4EI output (°F)

For example the stress free temperature of AF191G-108 adhesive is 350°F. If the operating temperature is -65°F, ΔT = (-65 – 350) = -415°F.

Thermal shear stress distribution is anti-symmetric as shown in Figure 12.8-10.

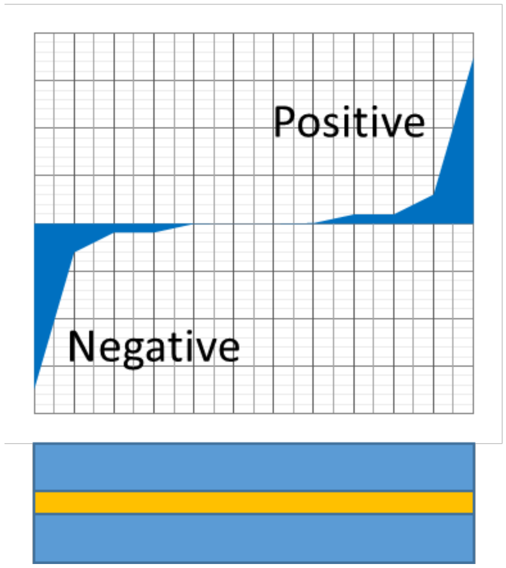


Figure 12.8-10 Thermal Shear Stress Profile in an Adhesive with No Mechanical Load.

Therefore, depending on the sign of the mechanical stress, the thermal stress can add or subtract from the mechanical stress.

Since thermal loads add or subtract from mechanical loads, to be conservative, two analyses are typically performed. The joint is first analyzed with only mechanical load ignoring the thermal loads and subsequently a second analysis is performed with the combined mechanical and thermal load. The lower of these two margins is selected as the joint margin.

12.8.4.7 Peel Reduction Factors

Since A4EI does not account for peel stresses, peel reduction factors are obtained by correlating single lap shear test to A4EI for L/t=32. Peel reduction factor for different adhesives can be expressed in equation form as shown below.

$$k_p = m \times \left(\frac{L}{t}\right) + C \qquad 8 < \frac{L}{t} < 32$$ **Equation 12.8-6**

$$k_p = 1 \qquad \frac{L}{t} > 32$$

where,
L = length of the overlap (in)
t = thickness of the adherend (in)
m and C are shown in Table 12.8-2.

Table 12.8-2. Peel Reduction Factors for Various Adhesives

AF191G-108

	-65F	75F	220F, W	275F, W
m	0.0208	0.0233	0.0154	0
C	0.3333	0.2533	0.5067	1

AF563M

	-65F	75F	220F, W
m	0.0188	0.0238	0.0125
C	0.4	0.24	0.6

EA9395 RT Cure

	75F	220F, W
m	0.0042	0
C	0.8667	1

EA9395 220F Cure

	75F	220F, W	275F, W
m	0.021	0.0167	0.0113
C	0.32	0.4667	0.64

2550G

	-65F	75F	220F, W	275F, W	325F, W
m	0.0208	0.0217	0.0233	0.0167	0.0083
C	0.3333	0.3067	0.2533	0.4667	0.7333

12.8.4.8 Margins of Safety for Static and Fatigue Loading

Static and fatigue margins of safety (MS) are defined for a bonded joint in this section. The joints are designed such that the failure occurs in the adherends rather than in the adhesive.

12.8.4.8.1 Static Margin of Safety for Uniaxial Loading

The static margin of safety for uniaxial loading is defined as:

$$MS_{static} = \frac{K_B \times N_{A4EI-EL-PL-Axial}}{N_{x-ult}} - 1$$

Equation 12.8-7

Where,

MS_{static} = Static Margin of Safety
$N_{A4EI-EL-PL-Axial}$ = Axial Strength, $N_{A4EI-EL-PLAxial}$ (lbs/in)
N_{x-ult} = Applied ultimate load (lbs/in)
K_B = B-basis reduction factor. K_B=1, if IDAT/MATUTL adhesive allowables are used.

$N_{A4EI-EL-PL}$ is the elastic-plastic joint strength obtained from A4EI. This is the case when the adhesive allowables are obtained from IDAT/MATUTL. The A4EI adhesive input values for AF191G10 obtained from IDAT/MATUTL are shown in Figure 12.8-11. In this case K_B = 1.

Figure 12.8-11 AF191G10 Adhesive Input Properties for A4EI

In Table 12.8-3 the IDAT/MATUL adhesive properties are mapped to A4EI input properties.

Table 12.8-3. IDAT/MATUTL Adhesive Properties Mapped to A4EI Input Properties

IDAT/MATUTL	A4EI	Remarks
G12	G	Adhesive shear modulus (psi)
Gam_Ult	GAMMax (γ_{max})	B-basis adhesive maximum shear strain (in/in)
Tau_Ult	TAUMax (τ_{max})	B-basis adhesive maximum shear strength (psi)

If typical values are used, a program specified value must be used for K_B. If K_B is not specified by the program, a value of 0.8 may be conservatively assumed for preliminary design. To account for the environment, the joint must be analyzed using material properties for the worst environment which is usually ETW.

12.8.4.8.2 Static Margin of Safety for Combined Axial and Shear Loading

The static margin of safety for combined axial and shear loading is defined as:

$$MS_{static} = \frac{K_B}{\sqrt{R_a^2 + R_s^2}} - 1$$ **Equation 12.8-8**

Where,

R_a = $(N_{x\text{-}ult})/(N_{A4EI\text{-}EL\text{-}PLAxial})$
R_s = $(N_{xy\text{-}ult})/(N_{A4EI\text{-}EL\text{-}PL\text{-}Shear})$
$N_{x\text{-}ult}$ = applied ultimate axial load (lbs/in)
$N_{xy\text{-}ult}$ = applied ultimate shear load (lbs/in)
$N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$ = Axial strength predicted by A4EI in the axial direction (lbs/in)
$N_{A4EI\text{-}EL\text{-}PL\text{-}Shear}$ = Shear strength predicted by A4EI in the shear direction (lbs/in)
K_B = B-basis reduction factor. Factor. K_B=1, if IDAT/MATUTL adhesive allowables are used.

To account for the environment, the joint must be analyzed using material properties for the worst environment, which is usually ETW.

12.8.4.8.3 Fatigue Margin of Safety for Uniaxial Loading

The fatigue margin of safety for uniaxial loading is defined as:

$$MS_{fatigue} = \frac{K_B \times N_{A4EI-EL-PL-Axial}}{N_{x-limit}} - 1$$ **Equation 12.8-9**

Where

$N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$ = Axial Strength, $N_{A4EI\text{-}EL\text{-}PLAxial}$ (lbs/in)

$N_{x\text{-}limit}$ = design limit load or the maximum fatigue spectrum load whichever is the greatest (lbs/in)

K_B = B-basis reduction factor. K_B=1, if IDAT/MATUTL adhesive allowables are used.

$N_{A4EI\text{-}EL\text{-}PL}$ is the elastic-plastic joint strength obtained from A4EI after reducing the B-basis strength allowables from IDAT/MATUTL by a fatigue reduction factor (K_{fat}). K_{fat} is empirically determined by correlating A4EI strength predictions to single lap shear coupons subjected to representative spectrum fatigue (Reference 12-12). K_{fat} for different adhesives are shown in Table 12.8-4.

Table 12.8-4 Fatigue Reduction Factors for Adhesives

Adhesive	K_{fat}	Allowables Reduced
AF191G-108 (-65F, 75F, 220F, 275F)	0.52	τ_{max}, γ_{max}
AF563M (-65F, 75F, 220F)	0.61	τ_{max}, γ_{max}

The same fatigue reduction factor (K_{fat}) is applied to both τ_{max} and γ_{max}. For other adhesives the fatigue reduction factor must be determined following the procedure discussed in Reference 12-12.

12.8.4.8.4 Fatigue Margin of Safety for Combined Axial and Shear Loading

The fatigue margin of safety for the combined axial and shear load is defined as:

$$MS_{fatigue} = \frac{K_B}{\sqrt{R_a^2 + R_s^2}} - 1$$ **Equation 12.8-10**

Where

R_a = $N_{x\text{-}limit}$/ $N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$

R_s = $N_{xy\text{-}limit}$/ $N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$

N_x = Design Limit Axial Load (lbs/in)

N_{xy} = Design Limit Shear Load (lbs/in)

$N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$ = A4EI predicted average elastic-plastic joint strength (lbs/in)

K_B = B-basis reduction factor (K_B=1, if IDAT/MATUTL adhesive allowables are used)

Note that the $N_{A4EI\text{-}EL\text{-}PL}$ is the elastic-plastic joint strength obtained from A4EI after reducing the B-basis strength allowables from IDAT/MATUTL by a fatigue reduction factor (K_{fat}) as discussed in Section 12.8.4.8.3. K_{fas} values are given in **Table 12.8-4**.

12.8.4.8.5 Adherend Margins of Safety

The adherend margins of safety are determined outside of A4EI as discussed in Section 12.8.4.4 since A4EI lacks the capability to analyze the adherends. IBOND (Section 12.8.5), the bonded joint analysis tool under development, has the capahility to analyze both the bond and the adherends.

The notched/unnotched strengths and compression strength after impact for the adherend can be determined using IDAT tools as discussed in Section 12.8.4.4 and the margins written for the adherend.

12.8.4.9 Input File Format

As discussed in A4EI User's Guide (Reference 12-25) there are several versions of A4EI input files as the program has been updated over time. The data items specific to the input file used with the current version, A4EI V1.4, is shown below.

Table 12.8-5. A4EI V1.4 Input File Data Items

Data Item	Description
FILE VERSION 4	Current input file version. New with A4EI v1.4. Adherend stress S1 & S2 input [psi], previously stress x station thickness.
TAUMax	Adhesive maximum shear strength [psi]
G	Adhesive shear modulus (elastic portion) [psi]
GAMMax	Adhesive maximum shear strain (sum of elastic & plastic strains) [in/in]
ETA	Adhesive thickness [in]
Alpha1	Adherend 1 coefficient of thermal expansion [in/in/(ºF)]
Alpha 2	Adherend 2 coefficient of thermal expansion [in/in/(ºF)]
DISBND	Bond effectivity (0 = 100% effective, 1 = 0% effective)
Thick 1	Adherend 1 thickness at current station [in]
Thick 2	Adherend 2 thickness at current station [in]
Step L	Length of current station [in]
E 1	Modulus of elasticity of Adherend 1 at current station [psi]
E 2	Modulus of elasticity of Adherend 2 at current location [psi]
S 1	Ultimate strength of Adherend 1 at current station [psi]
S 2	Ultimate strength of Adherend 2 at current station [psi]

12.8.4.10 Output File Format

The A4EI output file consists of four sections. The key subheadings in each of these sections are described in Table 12.8-6.

Table 12.8-6. Key Sections in A4EI Input File

DATA ITEM	DESCRIPTION
1. <u>Input Section</u> In this section the input data items are echoed.	+--+ | A4EI | | V1.4c | | Bonded Joint Analysis | | LM AERONAUTICS CO. | +--+ A4EI Example Problem 2: Tapered Single-Sided Doubler STEPPED-LAP ADHESIVE-BONDED DOUBLER INPUT DATA
2. <u>Elastic Joint Strength Section</u> In this section the analyses related to the elastic joint strength predictions are echoed. This section also provides information on the temperature differentials used and the type of loading (tension or compression). The joint steps at which the adhesive, adherend 1 and adherend 2 are most severely loaded are also output.	ELASTIC JOINT STRENGTH (LBS/INCH) = 509.9 TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) = 0.0 ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER 1 ADHEREND(S) ONE MOST SEVERELY LOADED IN STEP NUMBER 11 ADHEREND(S) TWO MOST SEVERELY LOADED IN STEP NUMBER 6 TENSILE LOADING
3. <u>Elastic Plastic Joint Strength Section</u> In this section the analyses related to the elastic-plastic joint strength predictions are echoed. This section also provides information on the temperature differentials used and the type of loading (tension or compression). The joint steps at which the adhesive, adherend 1 and adherend 2 are most severely loaded are also provided.	ELASTIC-PLASTIC JOINT STRENGTH (LBS/INCH) = 509.9 TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) = 0.0 ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER 1 ADHEREND(S) ONE MOST SEVERELY LOADED IN STEP NUMBER 11 ADHEREND(S) TWO MOST SEVERELY LOADED IN STEP NUMBER 6 TENSILE LOADING
4. <u>Potential Bond Strength Section</u> In this section, the potential bond strengths assuming that the adherends don't fail are provided. This output is calculated only if "Include Joint Capability in Output" is checked underneath the Analysis Menu.	POTENTIAL BOND STRENGTH FOR ADHERENDS WITH REAL STIFFNESSES BUT UNLIMITED STRENGTHS (LBS/INCH) = 12031.5 TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) = 0.0 ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER 1 TENSILE LOADING

Three scenarios are possible depending on how the adhesive strength compares to the adherend strength. These scenarios and the resulting A4EI output are discussed below.

Scenario	Description	A4EI output
1	Adherend Strength < Adhesive Elastic Strength The adherend fails first and the adhesive is still elastic.	Elastic Joint Strength = Adherend Strength Elastic Plastic Joint Strength = Adherend Strength Potential Bond Strength = Ultimate Adhesive Strength
2	Adhesive Elastic Strength < Adherend Strength < Adhesive Ultimate Strength The adherend fails first and the adhesive is plastic.	Elastic Joint Strength = Adhesive Elastic Strength Elastic Plastic Joint Strength = Adherend Strength Potential Bond Strength = Ultimate Adhesive Strength
3	Adherend Strength > Adhesive Ultimate Strength The adhesive fails first. Therefore potential bond strength is not output.	Elastic Joint Strength = Adhesive Elastic Strength Elastic Plastic Joint Strength = Ultimate Adhesive Strength.

It is strongly recommended that joints be designed such that only Scenarios 1 and 2 are possible. In other words, by design, the weakest link in an adhesive joint should be the adherend not the adhesive.

Note that at Lockheed Martin Aeronautics, a fictitious high adherend strength is used, which drives the solution always to Scenario 3 and suppresses Scenario 4. Referring back to Table 12.8-6, only items 2 and 3 are possible in the output file when a fictitious high adherend strength is used. Furthermore, the "Elastic-Plastic Joint Strength" is the only strength value from A4EI that is used in writing the margin. This is explained further in Section 12.8.4.11 by means of an example problem.

The details specific to each of the sections in the A4EI output file is next discussed. The discussion follows the subheadings discussed in Table 12.8-6.

Table 12.8-7. Output File Details

Problem Description: The following input data was used to generate the output file data discussed below.

Joint type: Single lap shear
Number of steps: 1

Adherend Properties		
	Adherend 1	Adherend 2
Adherend thickness	0.0498 in	0.0249 in
Adherend strength[1]	2008032 psi	4016064 psi
Adherend Elastic Modulus	3540000 psi	3540000 psi
Adhesive Properties		
Adhesive thickness	0.01 in	
Ultimate shear strength of adhesive	2295 psi	
Ultimate shear strain of adhesive	0.544 in/in	
Shear modulus of adherend	22800 psi	
Disobond	50%	

[1] Fictious high adherend strength to force adhesive failure

A4EI Input data

```
INPUT DATA


      N  STEPL THICK1 THICK2      SONE       STWO     EONE       ETWO    ALPHA1   ALPHA2  DISBOND
        (INCH) (INCH) (INCH)     (PSI)      (PSI)    (PSI)      (PSI)   (/DEG.F) (/DEG.F)

      1 0.5000 0.0498 0.0249  2008032.0  4016064.0  3540000.0  3540000.0 0.000002 0.000002   0.50
      2 0.5000 0.0498 0.0249  2008032.0  4016064.0  3540000.0  3540000.0 0.000002 0.000002   0.50
      3 1.0000 0.0000 0.0498        0.0  2008032.0        0.0  3540000.0 0.000002 0.000002   0.50
0
      N   ETA   TAUMAX     G    GAMMAX GAMMAE
        (INCH)  (PSI)    (PSI)

      1 0.0100  2295.0  22800.0  0.544 0.1007
      2 0.0100  2295.0  22800.0  0.544 0.1007
      3 0.0100  2295.0  22800.0  0.544 0.1007
0
      SINGLE BOND SURFACE
```

Note that A4EI may internally further divide the user input steps if the user input steps are coarse. These user defined steps are further divided when determining the shear stresses in each step. This is further discussed in the output section.

Terms	Description
N	Number of steps in the joint. There is an upper limit of 50.
STEP L	This is the length of each step (in)
THICK1	This is the thickness of the top adherend (in)
THICK2	This is the thickness of the bottom adherend (in)
SONE	Strength of adherend 1 (psi)
STWO	Strength of adherend 2 (psi)
EONE	Modulus of adherend 1 (psi)
ETWO	Modulus of adherend 2 (psi)
ALPHA1	Coefficient of thermal expansion (/ºF) of adherend 1
ALPHA2	Coefficient of thermal expansion (/ºF) of adherend 2
DISBOND	Adhesive disbond expressed as a number from 0 to 1 0 = no disbond 1 = fully disbonded
SINGLE BOND SURFACE	This indicates number of bonds in the joint – Single or Double

1. Output Section

Elastic Joint Strength Section

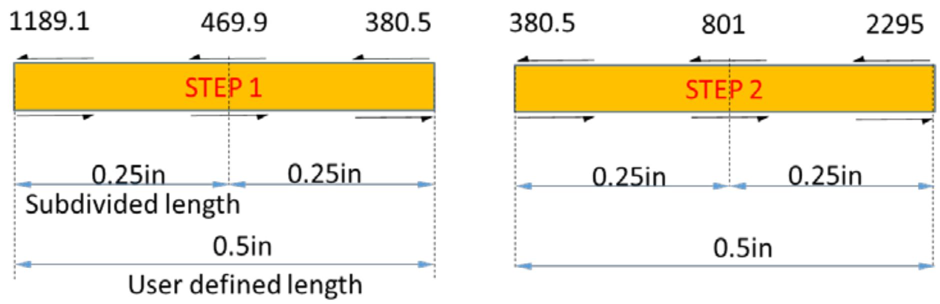
```
    N  STEPL THICK1 THICK2   TAU    GAMMA  DELTA1   DELTA2     TLDONE    STRONE    TLDTWO    STRTWO
      (INCH) (INCH) (INCH)  (PSI)          (INCH)   (INCH)   (LBS/IN)  (LBS/IN)  (LBS/IN)  (LBS/IN)

      1 0.2500 0.0498 0.0249  1189.1  0.052  0.00000  0.00052     386.0  100000.0       0.0  100000.0
      1 0.2500 0.0498 0.0249   469.9  0.021  0.00047  0.00068     291.6  100000.0      94.3  100000.0
      1 0.0000 0.0498 0.0249   380.5  0.017  0.00085  0.00101     243.3  100000.0     142.7  100000.0
      2 0.2500 0.0498 0.0249   380.5  0.017  0.00085  0.00101     243.3  100000.0     142.7  100000.0
      2 0.2500 0.0498 0.0249   801.0  0.035  0.00115  0.00150     176.1  100000.0     209.9  100000.0
      2 0.0000 0.0498 0.0249  2295.0  0.101  0.00130  0.00230       0.0  100000.0     386.0  100000.0
      2 0.0000 0.0498 0.0249  2295.0  0.101  0.00130  0.00230      -0.0  100000.0     386.0  100000.0
      3 0.0000 0.0000 0.0498  2295.0  0.101  0.00130  0.00230      -0.0       0.0     386.0  100000.0
```

Additional terms used are described below

Terms	Description	Type
TAU	Ultimate shear strength of the adhesive (psi)	Input Echo
GAMMA	Ultimate shear strain of the adhesive (in/in)	Input Echo
DELTA1	Adherend 1 displacement	Calculated
DELTA2	Adherend 2 displacement	Calculated
TLDONE	Load per unit width in adherend 1 (lbs/in)	Calculated
TLDTWO	Load per unit width in adherend 2 (lbs/in)	Calculated
STRONE	Strength per unit width of adherend one	Input Echo
STRTWO	Strength per unit width of adherend two	Input Echo

A4EI prints the shear stress distribution in a tabular form as shown above. Two tables are printed; one for the case when the adhesive is in the elastic range (Elastic Joint Section) and the other for the case when the adhesive is fully plastic (Elastic-Plastic Joint Strength Section). When the adhesive is in the elastic range each step is further divided into at least 3 steps to produce a smooth variation of the shear stress profile in the adhesive. If the shear stress variation is severe the user defined steps may be divided into more than three intervals. The shear stress distribution in the adhesive for the two steps is shown below.



In this example the user defined length is 0.5in for each step. This is divided into two intervals with three nodes. The length of the third node is zero since it is at the end of the step. The shear stress (TAU) and the load per unit width in each adherend (TLDONE, TLDTWO) are given at each of the three nodes for each step.

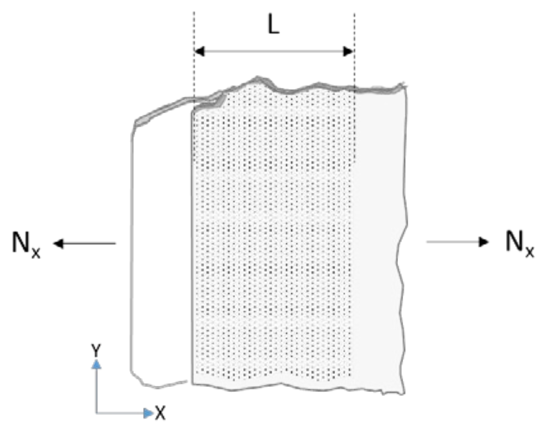
Elastic-Plastic Joint Strength Section

N	STEPL (INCH)	THICK1 (INCH)	THICK2 (INCH)	TAU (PSI)	GAMMA	DELTA1 (INCH)	DELTA2 (INCH)	TLDONE (LBS/IN)	STRONE (LBS/IN)	TLDTWO (LBS/IN)	STRTWO (LBS/IN)
1	0.5000	0.0498	0.0249	2295.0	0.219	0.00000	0.00219	1147.5	100000.0	0.0	100000.0
1	0.0000	0.0498	0.0249	2295.0	0.137	0.00244	0.00381	573.8	100000.0	573.8	100000.0
2	0.5000	0.0498	0.0249	2295.0	0.137	0.00244	0.00381	573.8	100000.0	573.8	100000.0
2	0.0000	0.0498	0.0249	2295.0	0.544	0.00325	0.00869	0.0	100000.0	1147.5	100000.0
3	0.0000	0.0000	0.0498	2295.0	0.544	0.00325	0.00869	0.0	0.0	1147.5	100000.0

When the entire adhesive is in the plastic region, since the shear stress is constant along the entire length of the adhesive, the step lengths can be coarse. Therefore, the user defined steps are not further subdivided.

12.8.4.11 Example Problem

Determine the static and fatigue margins of safety for the following single lap configuration



L = 2.5 inches
Maximum operating Temperature = 275F
Applied limit load = 1000 lbs/in

Adherend Properties		
	Adherend 1	Adherend 2
Material	IM7/977-3	IM7/977-3
Plies	24	24
Ply %	[25/50/25]	[25/50/25]
Adherend thickness[1]	0.1272 in	0.1272 in
Adherend strength[2]	1×10^6 psi	1×10^6 psi
Adherend Elastic Modulus	8.0×10^6 psi	8.0×10^6 psi
CTE	0.9×10^{-6} in/in /ºF	0.9×10^{-6} in/in /ºF

[1]For A4EI analysis using adhesives in IDAT/MATUTL database an adhesive thickness of 0.005 in. is assumed since A4EI is correlated to test data using the aforementioned adhesive thickness.
[2]Fictious high adherend strength to force adhesive failure

AF191G10 Adhesive Properties for Static Analysis from IDAT/MATUTL @ 275F	
Adhesive thickness	0.005 in
Ultimate shear strength of adhesive	1360 psi
Ultimate shear strain of adhesive	0.51 in/in
Shear modulus of adherend	9700 psi
Disbond	0%

STATIC ANALYSIS: STEP 1

To start with, a single step was assumed for the A4EI analysis. To ensure that converged solutions were obtained the steps were increased to 2, 4, and 6 and the elastic-plastic strength was observed to be the same in each of these cases. The effect of coefficient of thermal expansion was not considered in this step. Therefore $\Delta T = 0$.

The echo of the inputs to the A4EI output file is shown below

```
        +---------------------------------------------+
        |                                             |
        |                    A4EI                     |
        |                   V1.4c                     |
        |            Bonded Joint Analysis            |
        |              LM AERONAUTICS CO.             |
        |                                             |
        +---------------------------------------------+



      STEPPED-LAP ADHESIVE-BONDED JOINT


      INPUT DATA


      N  STEPL THICK1 THICK2      SONE       STWO     EONE       ETWO    ALPHA1   ALPHA2  DISBOND
        (INCH) (INCH) (INCH)     (PSI)      (PSI)    (PSI)      (PSI)   (/DEG.F) (/DEG.F)

      1 2.5000 0.1272 0.1272  1000000.0  1000000.0  8000000.0  8000000.0 0.000001 0.000001   0.00
      2 1.0000 0.0000 0.1272        0.0  1000000.0        0.0  8000000.0 0.000001 0.000001   0.00
0
      N   ETA   TAUMAX     G    GAMMAX GAMMAE
        (INCH)  (PSI)    (PSI)

      1 0.0050  1360.0   9700.0  0.510 0.1402
      2 0.0050  1360.0   9700.0  0.510 0.1402
0
      SINGLE BOND SURFACE
1
```

The A4EI elastic-plastic joint strength output is shown next

```
     STEPPED-LAP ADHESIVE-BONDED JOINT


       ELASTIC-PLASTIC JOINT STRENGTH (LBS/INCH) =     3294.9
     TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) =    0.0
     ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER  2
     ADHEREND(S) ONE MOST SEVERELY LOADED IN STEP NUMBER  1
     ADHEREND(S) TWO MOST SEVERELY LOADED IN STEP NUMBER  1
       TENSILE LOADING
0
       N  STEPL THICK1 THICK2   TAU    GAMMA  DELTA1   DELTA2     TLDONE    STRONE     TLDTWO    STRTWO
         (INCH) (INCH) (INCH)  (PSI)          (INCH)   (INCH)    (LBS/IN)  (LBS/IN)   (LBS/IN)  (LBS/IN)

       1 0.9217 0.1272 0.1272  1360.0  0.510  0.00000  0.00255    3294.9  127200.0       0.0  127200.0
       1 0.3283 0.1272 0.1272  1360.0  0.140  0.00242  0.00312    2041.4  127200.0    1253.5  127200.0
       1 0.3283 0.1272 0.1272  1121.5  0.116  0.00301  0.00359    1647.4  127200.0    1647.4  127200.0
       1 0.9217 0.1272 0.1272  1360.0  0.140  0.00348  0.00418    1253.5  127200.0    2041.4  127200.0
       1 0.0000 0.1272 0.1272  1360.0  0.510  0.00405  0.00660      -0.0  127200.0    3294.9  127200.0
       2 0.0000 0.0000 0.1272  1360.0  0.510  0.00405  0.00660      -0.0       0.0    3294.9  127200.0
```

STATIC ANALYSIS: STEP 2

Next the effect of coefficient of thermal expansion is considered. The temperature differential is calculated using **Equation 12.8-5**.

T_{cure} = 350F

$T_{operating}$ = 275F

ΔT= 275F-350F = -75F

```
       STEPPED-LAP ADHESIVE-BONDED JOINT


       ELASTIC-PLASTIC JOINT STRENGTH (LBS/INCH) =     3294.9
     TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) =  -75.0
     ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER  2
     ADHEREND(S) ONE MOST SEVERELY LOADED IN STEP NUMBER  1
     ADHEREND(S) TWO MOST SEVERELY LOADED IN STEP NUMBER  1
       TENSILE LOADING
0
       N  STEPL THICK1 THICK2   TAU    GAMMA  DELTA1   DELTA2     TLDONE    STRONE     TLDTWO    STRTWO
         (INCH) (INCH) (INCH)  (PSI)          (INCH)   (INCH)    (LBS/IN)  (LBS/IN)   (LBS/IN)  (LBS/IN)

       1 0.9217 0.1272 0.1272  1360.0  0.510  0.00000  0.00255    3294.9  127200.0       0.0  127200.0
       1 0.3283 0.1272 0.1272  1360.0  0.140  0.00235  0.00306    2041.4  127200.0    1253.5  127200.0
       1 0.3283 0.1272 0.1272  1121.5  0.116  0.00293  0.00350    1647.4  127200.0    1647.4  127200.0
       1 0.9217 0.1272 0.1272  1360.0  0.140  0.00337  0.00407    1253.5  127200.0    2041.4  127200.0
       1 0.0000 0.1272 0.1272  1360.0  0.510  0.00388  0.00643      -0.0  127200.0    3294.9  127200.0
       2 0.0000 0.0000 0.1272  1360.0  0.510  0.00388  0.00643      -0.0       0.0    3294.9  127200.0
```

	Elastic-Plastic Joint Strength (lbs/in)
Without including thermal mismatch (Mechanical Load)	3295
With thermal mismatch (Mechanical + Thermal)	3295

In this case including the thermal load did not affect the elastic-plastic joint strength with mechanical load only. The joint allowable is 3295 lbs/in.

STATIC ANALYSIS: STEP 3

Next the effect of peel stress is included.

L = 2 inches

t = 0.1272 inches

L/t = 15

From Table 12.8-2

k_p = 1.0

Joint allowable after accounting for peel stress = 1.0×3295

= 3295 lbs/in

STATIC ANALYSIS: STEP 4

Next the Margins of safety are calculated. From Equation 12.8-7,

$$MS_{static} = \frac{K_B \cdot N_{A4EI-EL-PL}}{N_{x-ult}} - 1$$

where,

K_B = 1, since adhesive allowables are from IDAT/MATUTL, which have B-basis reductions already included.
$N_{A4EI\text{-}EL\text{-}PL}$ = 3295 lbs/in
$N_{x\text{-}ult}$ = 1.5 ×1000 = 1500 lbs/in (Limit load is converted to ultimate using the 1.5 factor)
MS_{static} = (1×3295)/1500 -1 = +0.20

FATIGUE ANALYSIS:

The analysis steps are the same as that for static analysis. For fatigue analysis the adhesive allowables are reduced by the fatigue reduction factor (K_{fat}) shown in Table 12.8-4.
K_{fat} = 0.52

AF191G10 Adhesive Properties for Fatigue Analysis from IDAT/MATUTL @ 275F	
Adhesive thickness	0.005 in
Ultimate shear strength of adhesive (K_{fat} applied)	707 psi
Ultimate shear strain of adhesive (K_{fat} applied)	0.265 in/in
Shear modulus of adherend	9700 psi
Disbond	0%

The A4EI output (elastic-plastic joint strength) using the above allowables without the thermal load is shown below

```
ELASTIC-PLASTIC JOINT STRENGTH (LBS/INCH) =     1712.5
    TEMPERATURE DIFFERENTIAL (OPERATING - CURE) (DEG. F) =    0.0
    ADHESIVE MOST SEVERELY LOADED IN STEP NUMBER  2
    ADHEREND(S) ONE MOST SEVERELY LOADED IN STEP NUMBER  1
    ADHEREND(S) TWO MOST SEVERELY LOADED IN STEP NUMBER  1
      TENSILE LOADING
0
      N  STEPL THICK1 THICK2   TAU    GAMMA  DELTA1   DELTA2     TLDONE    STRONE    TLDTWO    STRTWO
        (INCH) (INCH) (INCH)  (PSI)          (INCH)   (INCH)   (LBS/IN)  (LBS/IN)  (LBS/IN)  (LBS/IN)

      1 0.9209 0.1272 0.1272   707.0  0.265  0.00000  0.00133    1712.5  127200.0       0.0  127200.0
      1 0.3291 0.1272 0.1272   707.0  0.073  0.00126  0.00162    1061.4  127200.0     651.1  127200.0
      1 0.3291 0.1272 0.1272   582.5  0.060  0.00156  0.00186     856.3  127200.0     856.3  127200.0
      1 0.9209 0.1272 0.1272   707.0  0.073  0.00181  0.00217     651.1  127200.0    1061.4  127200.0
      1 0.0000 0.1272 0.1272   707.0  0.265  0.00210  0.00343      -0.0  127200.0    1712.5  127200.0
      2 0.0000 0.0000 0.1272   707.0  0.265  0.00210  0.00343      -0.0       0.0    1712.5  127200.0
```

The elastic-plastic joint strength including the thermal loads is the same. Therefore the elastic-plastic joint allowable for fatigue loading is 1712.5 lbs/in.
The joint allowable is reduced to account for peel stress using k_p = 1.
The joint allowable accounting for peel stress = 1712.5×1
= 1712.5

The fatigue margins of safety is given as

$$MS_{fatigue} = \frac{N_{A4EI-EL-PL-Axial}}{N_{x-limit}} - 1$$

Where
$N_{A4EI\text{-}EL\text{-}PL\text{-}Axial}$ = 1712.5 lbs/in
$N_{x\text{-}limit}$ = 1000 lbs/in
$MS_{fatigue}$ = +0.71

12.8.5 IDAT/IBOND

IDAT/IBOND is a Lockheed Martin Aeronautics analysis tool for bonded joints that is currently under development. IBOND can predict bond-line peel and shear stresses and also determine the ensuing peel and shear stresses in the adherend. The tool has capabilities to analyze different bonded joint configurations including Pi-joints. Details regarding this tool are provided in Reference 12-9.

12.8.6 Finite Element Analysis

Reserved for future use.