CHAPTER 7 STRUCTURAL ELEMENT CHARACTERIZATION

7.1 INTRODUCTION

The material in this chapter focuses on test methods and matrices for experimental characterization of composite structures at a laminate/element level of complexity of the building block approach described in Volume 3, Chapter 4. The test elements, discussed here, provide data on notched laminates, bolted and bonded joints, and damage tolerance behavior that is needed for analysis and design of composite structures. General discussion on analysis and design of bolted and bonded joints can be found in Volume 3, Chapter 6, while damage tolerance is covered in Volume 3, Chapter 7.

Any joint in a composite structure is a potential failure site. Without proper design a joint can act as a failure initiation point, which can lead to a loss in structural strength and eventual failure of the component. Two types of joints are in common use: (1) mechanically-fastened joints and (2) adhesively-bonded joints. These guidelines define test types, laminates, environments, and replication that are needed for structurally sound joint design.

For mechanically bolted joints, tests are described that characterize the joint for various failure modes: notched tension/compression, bearing, bearing/by-pass, shear-out, and fastener pull-thru. The tests are drawn from ASTM standards when available. Otherwise common usage tests are recommended. In addition, suggested test matrices are provided that characterize the joint properties for the different variables that affect those properties. The suggested matrices should be considered as the least amount of testing required to obtain design properties. The test matrices are derived from the generic laminate/structural element test matrices in Section 2.3.5, and are included here for completeness. A detailed analysis of the stress distribution around a fastener hole is not presented here but is available in Volume 3, Section 6.3.

For bonded joints, two types of tests are described. One type determines adhesive properties that are needed in design. These tests provide adhesive stiffness and strength properties needed for analysis and design methods of Volume 3, Section 6.2. The second type is used to verify specific designs. Examples of such tests are shown.

The tests in the damage tolerance section are of two types. One type characterizes the damage resistance of a given laminate and the second the damage tolerance of that laminate. The Compression after Impact (CAI) test, an example of the latter type, is used widely in the aerospace industry to gauge damage tolerance potential of composite materials.

7.2 SPECIMEN PREPARATION

7.2.1 Introduction

The general topic of specimen preparation has been described adequately in Section 6.2 of this volume and in ASTM D 5687 for standard flat specimens. This section provides specific guidance for elements that represent mechanically fastened and bonded joints. Additionally, for tests where an ASTM standard exists the standard contains specific specimen preparation guidelines. Specimens for damage tolerance tests are flat plates which require no special specimen preparation procedures other than those in Section 6.2.

7.2.2 Mechanically fastened joint tests

The main concerns with mechanically fastened joint specimens are hole drilling and fastener installation. Holes should be drilled undersized and reamed to final dimensions. Drill back-up plates should be used to prevent delaminations at the drill exit side. Hole diameters should be verified as to their conformity to the specimen drawing. Specimen hole preparation methods should be recorded.

Proper fastener installation procedures are critical for determination of mechanical joint properties. These are specific to each type of bolt tested and are provided either by the bolt manufacturer or part fabricator. Unless finger tight bolt torque is specified, test specimens containing fasteners must be installed per company specification for the data to be meaningful for a given application. Correct grip sizes must also be selected based on the thickness of the mating parts. All bolt installations must be inspected for proper seating and fit.

7.2.3 Bonded joint tests

Test specimens for bonded joint characterization must be fabricated using processing specifications for bonding surface preparation and cure. This requirement is reiterated in the ASTM standards for bonded joint tests described in this chapter (7.6). For the bonded joint data to have any practical use, the specimens must be fabricated to strict processing controls which are the same as for fabrication of actual parts.

7.3 CONDITIONING AND ENVIRONMENTAL EXPOSURE

7.3.1 Introduction

The objective of testing environmentally conditioned specimens is to quantify property changes caused by exposure to humidity, liquid water, or other fluids (gaseous or liquid) under controlled (or at least defined) conditions. In general, the considerations and procedures presented in Section 6.3 of this volume apply to structural elements as well as to the simpler laminate specimens. However, there are some additional issues associated with environmental exposure of structural elements. These special considerations are discussed in the following sections, and cover general specimen preparation (strain gaging, notched laminates, and mechanically fastened joints), bonded joints, damage characterization, and sandwich structure. For the purposes of these discussions, the term “moisture” refers to any absorbed medium (water vapor, liquid water, or other fluid).

7.3.2 General specimen preparation

7.3.2.1 Strain gaging

Structural element tests may involve the use of more strain gages than for small specimens. These gages are frequently applied after exposure to the conditioning medium to prevent the gages from interfering with the conditioning process or to preclude environmental degradation of the gage adhesive leading to premature gage failure. When multiple gages are applied, the test articles are likely to be at ambient conditions for a considerable period of time during the gage bonding process, increasing the risk of significant moisture loss. To minimize this risk, gages should be applied as quickly as possible, and articles should be returned to the conditioning environment or suitable storage container as soon as gaging is complete. If all gages cannot be applied in a single, short session, articles should be returned to the environment or storage between gaging sessions. It is also possible to bag all or portions of the article together with moist towels. Small areas can then be exposed to allow local gaging while minimizing moisture loss of the overall article.

In instances where an elevated temperature cure is required for the gage bonding adhesive, it may be possible to accomplish the cure by returning the specimens to the elevated temperature conditioning environment rather than curing in dry air and risking moisture loss. However, it must be determined if the conditioning environment will have a detrimental effect on the cure reaction.

In some cases it may be necessary to bond gages prior to exposure (for example, if a conditioning fluid like oil would render the specimen surface unsuitable for adhesive bonding). Judgment must be used in determining whether to condition before or after gage bonding. Strain gage and/or gage adhesive manufacturers can often provide valuable advice in making this decision.

7.3.2.2 Notched laminates and mechanically fastened joint specimens

Specimens with drilled holes, such as used for open hole, filled hole, and mechanically fastened joint tests, should be conditioned after drilling to avoid local dry-out around the holes due to heat generated by the drilling process.

7.3.3 Bonded joints

Bonded joint configurations fall into three categories when considering environmental conditioning: articles with thin composite adherends, articles with thick composite adherends, and articles with metallic (non-absorbing) adherends. Thin adherends are defined as those capable of reaching a moisture equilibrium condition within a reasonable period of time. Since bonding adhesives generally absorb at a faster rate than fiber-resin composites, the adhesive is usually at equilibrium when the composite adherends reach equilibrium. In such cases no modifications to the guidelines in Section 6.3 are needed.

Bonded joints which employ thick composite adherends are defined as those geometries which will not reach moisture equilibrium within a time period that is practical for a test program. Indeed, some geometries may require years or even decades for equilibrium to be reached throughout the bond. In such cases, the test articles must be treated in the same manner as joints with metallic (non-absorbing) adherends.

For joints with metallic adherends (and, for practical purposes, thick composite adherends), moisture diffusion can only occur through the edges of the bond. In many cases, the bond length and width dimensions may be such that moisture equilibrium of the adhesive cannot be achieved within a reasonable time period. Estimates of the required diffusion time can be calculated if the diffusivity of the adhesive has been previously determined from neat adhesive specimens (see Section 6.6.8 on moisture diffusivity). Even if it is estimated that moisture equilibrium can be achieved within the timeframe of the test program, tracking of moisture uptake is another problem. Since the mass of non-absorbent metal adherends may be several orders of magnitude greater than the mass of the bonding adhesive, accuracy in determining equilibrium from periodic weighings is poor at best. Travelers consisting of aluminum foil adherends bonded together with the same adhesive as the test article, and in the same bondline thickness and same bond length and width dimensions as the test article, have been used in an attempt to reduce the mass of the adherends relative to the adhesive while still limiting absorption to the bond edges. Theoretically these travelers, when placed in the conditioning environment along with the test articles, offer increased accuracy in determining when moisture equilibrium has been reached. However, the foil and adhesive masses must be known accurately, and foil corrosion introduces another potential interference. Thus, this practice has not been widely adopted. A possible work-around for the corrosion issue is the use of stainless steel or other corrosion-resistant foil, although this has not been documented.

Since conditioning to equilibrium is often either impractical or inaccurate, fixed time conditioning is the only real option in many cases. Although the entire bondline does not, in general, reach a constant moisture content, the region near the edges of the bond will be at, or close to, the equilibrium moisture level. This is the same region where shear and peel stresses are typically highest in a bonded joint under load, and from which the failure of the test article will initiate. Therefore it can be argued that, although the entire bondline is not at the desired moisture level, the areas where bond failures will initiate are at the desired level. 1000 hour exposures at 85-95% relative humidity and elevated temperature (up to 185°F (85°C) for 350°F (177°C) curing epoxies) have been used by some labs as an accelerated fixed time condition for relatively short overlaps. However, this approach and rationale should not be used as a general excuse for short exposure times. Since structural tests of bonded joints evaluate the joint as a system, and not just the bonding adhesive in isolation, other effects of conditioning, such as metal adherend surface preparation degradation, may also contribute to bond failure. Such effects should be taken into consideration when selecting a fixed time environmental condition.

7.3.4 Damage characterization specimens

For testing of post-damage specimens (such as compression after impact), a different result may be obtained depending on whether conditioning was performed prior to or subsequent to the damage event. This may be due to several effects:

1. A moisture conditioned panel may have a different compliance and/or matrix hardness compared to the same panel prior to conditioning. This difference in compliance and/or hardness may result in different types and/or levels of damage for the same test parameters and energy. For example, the delamination area may be less for the conditioned panel due to increased compliance, whereas the front surface dent depth might be higher due to matrix softness.

2. A panel which is conditioned after the damage event might absorb moisture in a non-Fickian manner. That is, in addition to Fickian absorption at the molecular level, liquid water (or other fluid) may start to accumulate in matrix cracks and delaminations. This phenomenon could interfere with weight gain measurements, as these measurements may not accurately represent moisture absorbed by the matrix polymer. Consequently, this will affect the accuracy of moisture equilibrium and moisture content determinations. Non-damaged travelers are recommended in this case.

While there may be valid reasons within a design development or qualification program for conditioning either before or after impact, it is important to keep these effects in mind and to document the order in which impacting, conditioning, and testing were performed.

7.3.5 Sandwich Structure

Conditioning of sandwich structures requires consideration of several issues, depending upon the specific materials of construction and the failure mode under test. Table 7.3.5 shows 12 common combinations of materials and failure modes.

TABLE 7.3.5 *Sandwich materials and failure modes.**

	Non-perforated Metallic Face Sheets		Composite Face Sheets	
	Metallic Core	Organic Core	Metallic Core	Organic Core
Face Sheet Failure (Tension / Compression)	1	2	3	4
Core Failure (Tens. / Comp. / Shear)	5	6	7	8
Adhesive Bond Failure (Tension / Shear)	9	10	11	12

**Note: Table entries refer to numbered notes which follow*

If the core is metallic (aluminum honeycomb, for example) (as in Combinations 1, 3, 5, 7, 9, and 11 in Table 7.3.5), then only the environmental condition of the face sheets and bonding adhesive applies. If the core contains organic constituents (such as in polyamide/phenolic, glass/phenolic, or foam cores, as in Combinations 2, 4, 6, 8, 10, and 12), then the condition of the core material may be of interest, unless core failure is not an expected mode. The following lists each of the 12 combinations in Table 7.3.5, and suggests specific considerations and approaches relative to environmental conditioning.

1. Here everything (except the adhesive) is metallic, and failure is expected in the face sheets. There is no need to condition such test articles since the face sheet strength is not usually affected by moisture exposure (except for corrosion effects, which are not within the scope of MIL-HDBK-17). Even if an unanticipated failure occurs in the adhesive, conditioning would have had a minimal effect on the outcome, since the adhesive is shielded by the skins (except at the edges) from the conditioning medium.

2. As in Combination 1, the metallic face sheets shield the adhesive and core from the conditioning medium. Therefore, even though the core is organic, there is no need to condition such articles, assuming that edge absorption can be ignored.

3. In this combination the face sheets are composite and are expected to fail. Therefore the moisture condition of the skins is of interest and conditioning to moisture equilibrium is desirable. For this configuration, it is difficult to track the test article itself (or even sandwich travelers) during conditioning because of possible liquid accumulation within the metallic cells (assuming the core is a cellular material). In such cases (where there is the assumption of one-sided exposure of the face sheets), it is convenient to prepare solid laminate travelers made of the same material and stacking sequence as the face sheets but twice the thickness. These travelers are placed in the conditioning environment along with the test article. Two sided exposure of the double thick travelers is equivalent to one-sided exposure of the skins on the test article. When the traveler has reached equilibrium, so have the face sheets on the test article.

4. When failure is expected in the face sheets and the core and face sheets are organic, the moisture content of the core is not of particular interest. Therefore, the technique of using solid laminate travelers twice the face sheet thickness (as discussed in 3 above) can be used. This has the added benefit of precluding accumulation of condensation in the cells of the core. Since liquid accumulation in the organic core cells is less likely than with metallic core, moisture tracking of the test article or sandwich travelers can usually be employed as an alternate method.

5. In this case core failure is anticipated. Since the core is metallic, testing of conditioned articles is not needed.

6. See Combination 2.

7. In this combination the face sheets are composite (allowing moisture to reach the interior of the sandwich), but the core (which is expected to fail) is metallic. Assuming an insignificant moisture effect on the metallic core properties, no conditioning should be needed for this configuration.

8. Both the face sheets and the core are absorptive in this combination, and the moisture level of the core (which is expected to fail) is of primary interest. This can be a difficult configuration to assess relative to moisture conditioning. The mass of the skins is frequently greater than the mass of the core; however, the equilibrium moisture content of some core materials may be greater than that of the composite skins. In addition, absorption through the edge of small sandwich travelers may represent a significant proportion of the total moisture absorbed (which may not be the case for test articles with higher surface to edge ratios). Whether tracking is done using the test article or travelers which mimic the test article geometry, accurate determination of equilibrium in the core will be compromised if face sheet absorption is dominant. One possible procedure is as follows:

   - Determine the equilibrium moisture content of the core material alone for the environment of interest using methods discussed in Section 6.4.8 (with modifications as needed).
   - Prepare a large quantity of sandwich travelers that mimic the geometry of the test article.
   - If the surface to edge ratio of the test article is much larger than the travelers, mask the edges of the travelers with foil tape or other suitable barrier material.
   - Place the test article(s) and the travelers in the conditioning environment.

- Periodically remove a traveler and destructively remove the face sheets and adhesive quickly, cleanly, and without generating heat. Weigh the core portion, and then determine the moisture content of the core by desorption.
- Compare the traveler core moisture level to the previously determined equilibrium level.
- When the traveler core reaches the equilibrium level within a defined tolerance, the test article(s) is also at equilibrium.

9. As in Combinations 1 and 5, the metallic face sheets shield the adhesive from the conditioning medium. Therefore, even though the adhesive is expected to fail, there is no need to condition such articles (assuming that edge absorption into the bondline is not significant).

10. As in Combinations 2 and 6, the metallic face sheets shield the adhesive and core from the conditioning medium. Therefore, even though failure is expected in the adhesive, there is no need to condition such articles (assuming that edge absorption into the bondline and organic honeycomb is not significant).

11. In this combination the face sheets are composite, allowing moisture to reach the adhesive (which is expected to fail). Since the adhesive layer is relatively thin and in contact with the face sheets, it is reasonable to assume that the adhesive will be near equilibrium when the composite skins have reached equilibrium. Therefore, the approach of using solid laminate travelers that are twice the thickness of the face sheets can be used (as described for Combination 3 above).

12. See Combination 11.

7.4 NOTCHED LAMINATE TESTS

7.4.1 Overview and general considerations

The most common method of assembling composite structure is by the use of mechanical fasteners, even though bolted joints are relatively inefficient. The stress concentration due to the hole will cause substantial reduction in both the notched tensile and compressive strength of a composite laminate. The magnitude of this reduction varies considerably with a multitude of factors. All composite materials that exhibit a linear elastic stress-strain relationship to failure will be very sensitive to notches. Unlike metallic materials, the effects of the notch on strength will vary with the size of the notch but are relatively independent of notch geometry. Under uniaxial load, large holes will produce a stress concentration factor approaching the theoretical factor for wide plates given by the relationship:

$$K_t = 1 + \left\{ 2\left[\left(\frac{E_x}{E_y}\right)^{\frac{1}{2}} - v_{xy}\right] + \frac{E_x}{G_{xy}} \right\}^{\frac{1}{2}} \qquad 7.4.1(a)$$

For a quasi-isotropic laminate, the above relationship reduces to the well-known value k_t = 3.0 for a circular hole. This relationship also indicates that holes in high modulus laminates have a much greater effect on strength than holes in low modulus laminates. The stress concentration factor described by the above equation is reasonably proportional to the parameter E/G, the laminate axial modulus divided by the laminate shear modulus.

Considerable research literature exists regarding the influence of holes on the strength of composite laminates. An excellent summary of this literature is given in Reference 7.4.1 which includes over 300 citations. While the influence of holes in composites has been researched and reported extensively, there are additional effects to be considered. Two of these effects relate to the influence a fastener has in "filling" a hole in a laminate. The fastener, particularly in tight or interference holes, can induce a biaxial stress field by preventing ovalization of the hole under load. The factor tends to decrease the notch tensile strength of 0°-ply dominated laminates and increase the strength of laminates with predominantly 45°

plies. The second effect is when clamp-up of the fastener prevents damage in the form of longitudinal slits and delaminations from occurring around the hole. These delaminations are the result of "free edge" stresses and are very sensitive to stacking sequence. When damage is suppressed by the fastener, no stress concentration relief occurs and the notch sensitivity increases.

Filled hole compressive strengths are significantly higher than open hole strengths and, in some cases, approach the unnotched strength. This is particularly true with close-fitting holes where load can be transferred through the hole by direct bearing through the fastener. Fabric laminates, because of the balanced nature of fabric materials, tend to have lower stress concentration factors and are less prone to free edge delaminations. The influence of free edge stresses and stacking sequence on delaminations are discussed in Volume 3, Sections 5.6.3 and 5.6.5.

When holes are placed together as in a bolted joint, the stress concentrations at the holes start to interact and the notch strength of the composite laminate decreases. A finite width correction factor is used to account for this interaction effect. For isotropic materials the "finite width correction" factor (FWC) is given by:

$$\mathrm{FWC} = \frac{2 + \left(1 + \frac{\mathrm{D}}{\mathrm{W}}\right)^3}{3\left(1 - \frac{\mathrm{D}}{\mathrm{W}}\right)} \qquad 7.4.1(b)$$

where D = fastener diameter
W = fastener spacing

The correction factor for orthotropic materials cannot be expressed in a closed form. In most cases, the isotropic correction has been found to be reasonably accurate.

When the hole diameter is significantly greater than the laminate thickness, the stress concentration is two-dimensional in nature. Most of the research on holes in laminates is for this case. The notch strength of composites is much more difficult to predict when the thickness of the laminate significantly exceeds the hole diameter. The stress concentration at the hole becomes three-dimensional in nature and stacking sequence effects become more dominant.

There have been many failure models proposed for describing the notch strength of composite laminates. All of the models require some form of empirical "calibration" factor such as a "characteristic dimension". Characteristic dimensions have been used as a measure of notch sensitivity. Once calibrated, all of the models are reasonably accurate in describing the notch strength of composites. The drawback to these models is that many parameters such as laminate composition, temperature, and even hole size require re-calibration of the failure model. Some of the calibration factors are reasonably consistent, over a wide range of application laminates, among various material systems of similar characteristics. Low strength or stiffness fibers, or highly nonlinear toughened resins are examples of material constituents which can produce widely different "calibration" factors. Progressive damage failure models have shown some promise in not being overly dependent on empirical factors. For more discussion on this topic see Volume 3, Chapter 7 (bolted joints).

7.4.2 Notched laminate tension

A uniaxial tension test of a balanced, symmetric laminate with a centrally located 0.250 inch (6.35 mm) diameter hole is performed to determine the notched laminate tensile strength. The test consists of loading an untabbed, straight-sided, 1.5 inch (3.8 cm) wide, 12 inch (30 cm) long laminate specimen in tension until two-part failure occurs. The head travel and load on the specimen are recorded during the test. The tensile load is applied to the specimen through a mechanical shear interface at the ends of the specimen, normally by either wedge or hydraulic grips. The test machine grip wedges must be at least the same width as the specimen, and must be able to grip at least 2.0 inch (5 cm) of each end of the specimen. The recommended specimen configuration is shown in Figure 7.4.2. Both open hole and fastener filled hole specimens are tested. There is no need for tabbing or special gripping treatments unless extremely coarse serrated grips or excessive pressure are used. Normally the large stress concentration at the hole will eliminate problems with grip failures. The test is normally run without instrumentation, recording only maximum load, specimen dimensions, and failure mode and location. The test methods are also applicable to specimens with different fastener types, width/diameter ratios, and hole sizes. The open-hole and filled-hole tensile strength is presented in terms of gross-area strength without any finite-width correction. The following equations are used to calculate the notched tensile strengths:

$$F^{oht} = \frac{P_{max}}{(W)(t)} \quad \text{and} \quad F^{fht} = \frac{P_{max}}{(W)(t)}$$

Where

P_{max}	=	maximum tensile load
W	=	measured width at midsection
t	=	calculated nominal laminate thickness

The calculated nominal thickness is calculated by summing the nominal per-ply thickness of the individual plies in the laminate.

7.4.2.1 Open-hole tensile test methods

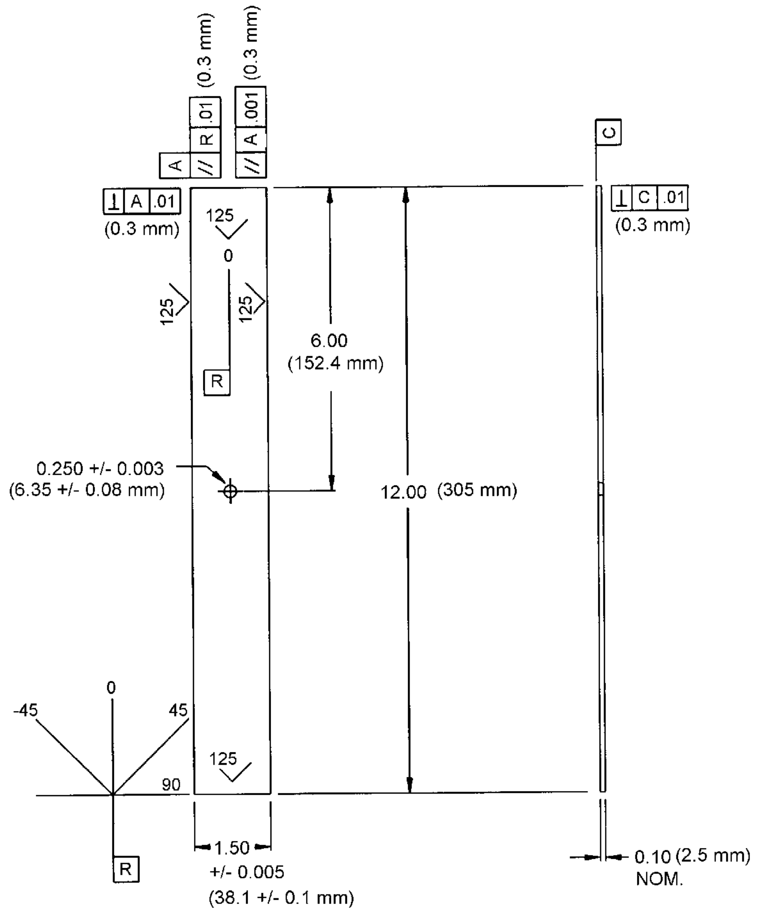
ASTM D 5766 “Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates”. This test method determines the open hole tensile strength of polymer matrix composite laminates reinforced by high-modulus fibers. The composite material forms are limited to continuous-fiber or discontinuous-fiber reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. The standard test laminate is of the $[45/90/-45/0]_{ns}$ stacking sequence family, where the sublaminate repeat index is adjusted to yield a laminate thickness within the range of 0.080 to 0.160 inch (2.03 to 4.06 mm). The standard specimen width is 1.5 inch (3.8 cm) and the length is 8.0 to 12.0 inches (20 to 30 cm). The notch consists of a 0.250 inch (6.35 mm) diameter centrally located hole. Other laminates may be tested provided the laminate configuration is reported with the results, however, the test method is unsatisfactory for unidirectional tape laminates containing only one ply orientation.

7.4.2.2 Filled-hole tensile test methods

The filled-hole tensile test typically uses the open-hole tensile test method procedures to conduct the test. The standard specimen width is 1.5 inch (3.8 cm) and the length is 8.0 to 12.0 inches (20 to 30 cm). The notch consists of a 0.250 inch (6.35 mm) diameter centrally located hole. The standard specimen configuration for this test should have a protruding head, hex drive fastener installed in the hole prior to testing. Filled-hole tensile strength is dependent upon the amount of fastener clamp-up, with a higher clamp-up force generally producing a lower filled-hole tensile strength. Fastener clamp-up is a function of fastener type, nut or collar type, and installation torque. In general, the strengths obtained using this fastener should be conservative relative to most fastener installations in composite structure. The test method procedures are also applicable to specimens with different fastener types, width/diameter ratios, and fastener/hole sizes.

7.4.3 Notched laminate compression

A uniaxial compressive test of a balanced, symmetric laminate with a centrally located 0.250 inch (6.35 mm) diameter hole is performed to determine the notched laminate compressive strength. The test involves loading an untabbed, straight-sided, 1.5 inch (3.8 cm) wide, 12 inch (30 cm) long laminate specimen in compression until two-part failure occurs. The head travel and load on the specimen are recorded during the test. The recommended specimen is shown in Figure 7.4.2 with recommended thickness greater than 0.08 inch (2.0 mm) but less than 0.25 inch (6.3 mm). The multi-piece bolted compressive support fixture shown in Figure 7.4.3 is used to stabilize the specimen from general column buckling failures. The specimen/fixture assembly is clamped in the hydraulic grips and the load is sheared into the specimen. The grips must apply enough lateral pressure to prevent slippage without locally crushing the specimen. Boeing has recently updated the compressive support fixture configuration that has been in common use throughout industry for some time. This update was done to correct some errors and omissions that were found in the original Boeing drawings for these support fixtures. The updated details are contained in the proposed ASTM Open-Hole Compression Test Method and have been supplied to some vendors (MTS and Wyoming Test Fixture Inc.) and test laboratories (Intec and Delson) for incorporation into their fixtures. The open-hole and filled-hole compressive strength is presented in terms of gross-area strength without any finite-width correction. The following equations are used to calculate the notched compressive strengths:



NOTES:

1. UNLESS NOTED ALL TOLERANCES ARE ±0.100
   EDGE ROUGHNESS IN ACCORDANCE WITH ANSI B46.1

2. HOLE MUST NOT HAVE DELAMINATION OR OTHER
   DAMAGE.

3. ALL DIMENSIONS IN INCHES. (MILLIMETERS IN PARENTHESES.)

4. CONFIGURATION SHOWN IS FOR 0.25 in. DIAMETER
   HOLE. FOR ALL OTHER HOLE SIZES, THE WIDTH
   WOULD CHANGE TO MAINTAIN W/D = 6.

FIGURE 7.4.2 *Notched tensile/compressive strength specimen (based on Reference 7.4.1).*

$$F^{ohc} = \frac{P_{max}}{(W)(t)} \quad \text{and} \quad F^{fhc} = \frac{P_{max}}{(W)(t)}$$

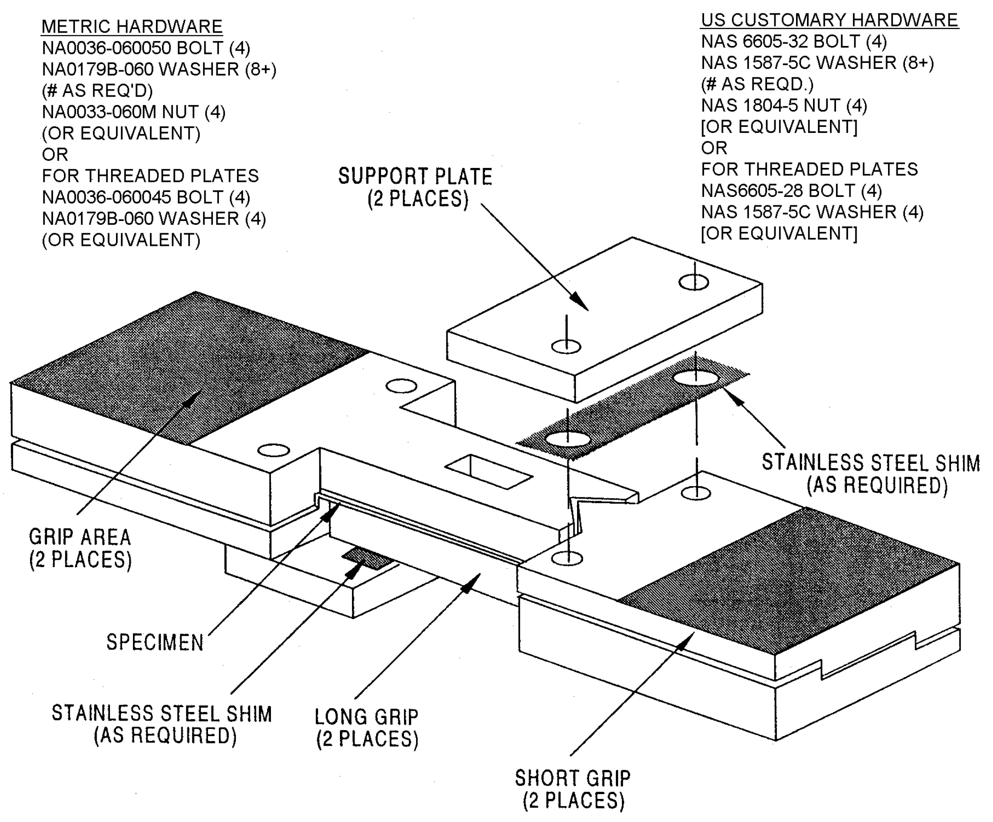


FIGURE 7.4.3 *Notched compressive strength support fixture.*

Where

P_{max} = maximum tensile load
W = measured width at midsection
t = calculated nominal laminate thickness

The calculated nominal thickness is calculated by summing the nominal per-ply thickness of the individual plies in the laminate.

7.4.3.1 Open-hole compressive test methods

SACMA SRM 3 “Open-Hole Compression Properties of Oriented Fiber-Resin Composites”. This method covers the procedure for the determination of the compressive properties of oriented fiber-resin composites laminates reinforced by continuous, high modulus, >3Msi (>20Gpa), fibers containing a circular hole. The standard test laminate for unidirectional tape composites is of the $[45/0/-45/90]_{2S}$ stacking sequence. The standard specimen width is 1.5 inch (3.8 cm) and the length is 12.0 inches (30 cm). The notch consists of a 0.250 inch (6.35 mm) diameter centrally located hole. The commonly used compressive support fixture is used to stabilize the specimen from general column buckling failures. The preferred test method is to hydraulically grip the specimen/fixture assembly, but the test method allows the specimen to be ended loaded as an option. This option was required because many test laboratories did not have the very large hydraulic grips needed to handle the 3 inch (8 cm) wide support fixture. The new side-load hydraulic grips can easily handle the support fixture. The option to end-load the specimen required the tolerances on the ends of the specimen to be much tighter and also required the fixture to be modified.

ASTM D 6484 “Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates”. This method determines the open hole compressive strength of multi-directional polymer matrix composite laminates reinforced by high-modulus fibers. The composite material forms are limited to continuous-fiber or discontinuous-fiber (tape and/or fabric) reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. The standard test laminate is of the $[45/90/-45/0]_{ns}$ stacking sequence family, where the sublaminate repeat index is adjusted to yield a laminate thickness within the range of 0.125 to 0.200 inch (3.17 to 5.08 mm). The standard specimen width is 1.5 inch (3.8 cm) and the length is 12.0 inches (30 cm). The notch consists of a 0.250 inch (6.35 mm) diameter centrally located hole. Figure 7.4.3 compressive support fixture is used to stabilize the specimen from general column buckling failures. The test method uses hydraulic wedge grips to load the specimen/fixture assembly. Other laminates may be tested provided the laminate configuration is reported with the results, however, the test method is unsatisfactory for unidirectional tape laminates containing only one ply orientation.

7.4.3.2 Filled-hole compressive test methods

The filled-hole compression test typically uses the open-hole compressive test method procedures to conduct the test. The standard specimen width is 1.5 inch (3.8 cm) and the length is 12.0 inches (30 cm). The notch consists of a 0.250 inch (6.35 mm) diameter centrally located hole. The standard specimen configuration for this test should have a protruding head, hex drive fastener installed in the hole prior to testing. Filled-hole compressive strength is dependent upon the amount of fastener hole clearance with tighter holes producing a higher filled-hole compressive strength. The test method procedures are also applicable to specimens with different fastener types, width/diameter ratios, and fastener/hole sizes.

7.4.4 Suggested notched laminate test matrix

The minimum recommended test matrix for initial empirical assessment of "calibration" of the various theoretical models and determination of notch strength data for a range of laminates is given in Table 7.4.4. This matrix is just part of the overall development test plan. The matrix requires selective tests to be performed under tensile and compressive loadings in various environments applicable to the design of structural components. The test matrix is for open holes but bolted joint design criteria will also require filled hole test data to be generated. It is recommended that portions of the matrix in Table 7.4.4 be used to spot test for filled hole strengths, particularly in tension. For filled hole strengths, a reduction factor is applied to the open hole strength and the predictive model is not re-calibrated. The matrix represents the range of laminates commonly used in bolted joint designs. This assures that important interactions between laminate stiffness, failure modes, and joint parameters are assessed. If the laminate of interest is significantly outside the range of behavior of the test laminates, open hole tests for that laminate should be added to that matrix.

The procedure, often used to calibrate single-fastener-hole laminate strength methodology, such as for the "characteristic dimension" approaches, starts by evaluating the effect of hole-size on strength data for the isotropic (25/50/25) laminate, using a baseline specimen width/diameter ratio of six. Three fastener diameter sizes are selected for testing which will span the usual application range of fastener hardware. The trend of the effect of hole size on tensile and compressive strength data is established. The characteristic dimension that produces the trend line which best fits the test data is then selected. All other test case predictions now use that selected characteristic dimension.

TABLE 7.4.4 *Notch tensile/compressive strength test matrix.*

Lay-up	Diameter in. (mm)	Width in. (mm)	W/D Ratio	CTD Tension	RTD Tension	RTD Compression	ETW Compression	Total Number of Tests
(10/80/10)	0.250 (6.35)	1.5 (38)	6.0	5	5	5	5	20
(25/50/25)	0.125 (3.18)	1.0 (25)	6.0		5	5		10
		1.5 (38)	8.0		5	5		10
(25/50/25)	0.250 (6.35)	1.5 (38)	6.0	5	5	5	5	20
(25/50/25)	0.500 (12.7)	2.0 (51)	4.0		5	5		10
		2.5 (64)	6.0		5	5		10
(50/40/10) Tape or (40/20/40) Fabric	0.250 (6.35)	1.5 (38)	6.0	5	5	5	5	20
Total				15	35	35	15	100

Lay-up	Ply Stacking Sequence
(10/80/10)	$[45/-45/90/45/-45/45/-45/0/45/-45]_{ns}$
(25/50/25)	$[45/0/-45/90]_{ns}$
(50/40/10)	$[45/0/-45/90/0/0/45/0/-45/0]_{ns}$
(40/20/40)	$[0_f/90_f/0_f/90_f/45_f/-45_f/90_f/0_f/90_f/0_f]_n$

n selected so that total laminate thickness is between 0.1 to 0.2 inches (2.5 to 5.0 mm)

Conditions	
CTD	Cold Temperature Dry
RTD	Room Temperature Dry
ETW	Elevated Temperature Wet

See Section 2.2.7

Further correlations between the model and the data are then performed to assess the generality of this single characteristic dimension. Additional tests provide data for correlation with predicted effects of laminate composition, temperature variation, and finite width variations. The hole-size effect data, used initially to select a characteristic dimension, "builds in" a correlation for finite width of $W/D = 6$. If subsequent theory/test correlations are inconsistent or errors too large, further fitting of the "characteristic" dimension may be required. If still unacceptable, for the application range of variables, the test data will be the basis for other analytical or purely empirical approaches, but significantly more testing may be required to offset the loss of predictive methodology which provided an analytical bridge among the limited test conditions defined in Table 7.4.4.

7.4.5 Notched laminate test methods for MIL-HDBK-17 data submittal

Data provided by the following test methods (Table 7.4.5) are currently being accepted by MIL-HDBK-17 for consideration for inclusion in Volume 2.

TABLE 7.4.5 *Notched laminate test methods for MIL-HDBK-17 data submittal.*

Property	Symbol	All Data Classes	Screening Data Only
Open Hole Tension Strength	F_x^{oht}	D 5766	–
Filled Hole Tension Strength	F_x^{fht}	D 5766 as modified by Section 7.4.2.2	–
Open Hole Compression Strength	F_x^{ohc}	D 6484	–
Filled Hole Compression Strength	F_x^{fhc}	D 6484 as modified by Section 7.4.3.2	–

7.5 MECHANICALLY-FASTENED JOINT TESTS

7.5.1 Overview

7.5.1.1 Definitions

The following definitions are relevant to this section.

Bearing Area -- The diameter of the hole multiplied by the thickness of the specimen.

Bearing Load -- A compressive load on an interface.

Bearing Strain -- The ratio of the deformation of the bearing hole in the direction of the applied force to the pin diameter.

Bearing Strength -- The bearing stress value corresponding to total failure of the test specimen.

Bearing Stress -- The applied load divided by the bearing area.

Bypass Strength -- The load that transfers around a hole divided by the laminate gross section area.

Edge Distance Ratio -- The distance from the center of the bearing hole to the edge of the specimen in the direction of the applied load, divided by the diameter of the hole.

Offset Bearing Strength -- The bearing stress at the intersection of the bearing load-deformation curve with the tangent modulus drawn from a pre-selected offset value. Offset may be 1, 2 or 4% of the nominal hole diameter.

Proportional Limit Bearing Stress -- The bearing stress value corresponding to the deviation from linearity of the bearing stress versus hole elongation curve.

Ultimate Bearing Strength -- The maximum bearing stress that can be sustained.

7.5.1.2 Failure modes

An important consideration in joint testing and analysis is the selection of the type of test method with due attention to the failure mode which is likely to result with a specific joint design in a particular composite system. A brief discussion on various failure modes is provided in this section. The occurrence of a particular failure mode is dependent primarily on joint geometry and laminate lay-up. Composite bolted joints may fail in various modes as shown in Figure 7.5.1.2. The likelihood of a particular failure mode is influenced by bolt diameter (D), laminate width (w), edge distance (e), and thickness (t). The type of fastener used can also influence the occurrence of a particular failure mode. A more detail classification of the failure modes is in Section 7.5.2.6.

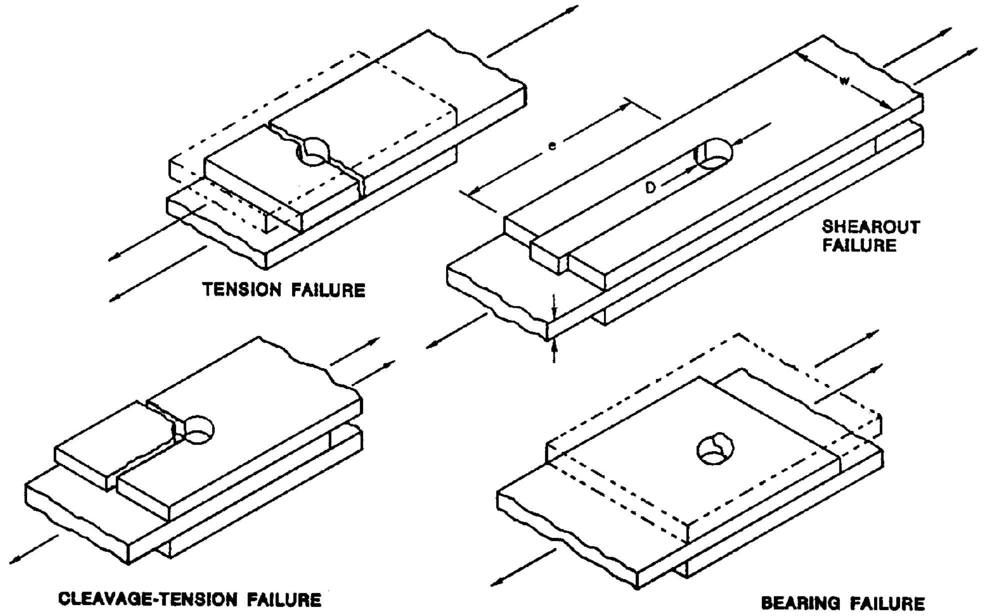


FIGURE 7.5.1.2 *Typical failure modes for bolted joints in advanced composites.*

Net section tensile/compressive failures occur when the bolt diameter is a sufficiently large fraction of the strip width. This fraction is about one-quarter or more (w/D<=4) for near-isotropic lay-ups in graphite/epoxy systems. It is characterized by failure of the plies in the primary load direction. Cleavage failures occur because of the proximity of the end of the specimen. A cleavage failure can be triggered from a net-section tension failure. This type of failure often initiates at the end of the specimen rather than adjacent to the fastener. In some instances the bolt head may be pulled out through the laminate after the bolt is bent and deformed. This mode is frequently associated with countersunk fasteners and is highly dependent on the particular fastener used. Finally, it is important to note that for any given geometry, the failure mode may vary as a function of lay-up and stacking sequence.

7.5.1.3 Design requirements

In order to design against the different failure modes and the interactions between them, the capability of the composite has to be determined by test for:

- Notch/Net Tension/Compression
- Bearing
- Bearing/By-Pass
- Shear-Out

These are described in Sections 7.4.2, 7.4.3 and 7.5.2 to 7.5.4. The amount of testing will vary among manufacturers and certifying agencies depending on the confidence assigned to the analysis capability of each company. The philosophy of MIL-HDBK-17 is to provide guidance as to amount of testing that would be typical, but not necessarily the minimum or maximum. The bearing, net tension/compression, and bearing/by-pass failure mode criticality is best illustrated by a plot shown in Figure 7.5.1.3. This figure, which is typically used by airframe designers, encompasses five failure possibilities as a function of bolt load and strain in the joining members. This plot is usually determined by tests that are described in Section 7.5.3 to 7.5.4. At zero bearing (no bolt load), the failure is in net tension or compression (points A and E). Open-hole or filled-hole specimens described in Sections 7.4.2 and 7.4.3 are used to determine this property. The line between A and C represents the reduction of net tension strength due to the bearing load. Similarly the line from E to C^1 represents the effect of bolt load on net compression strength. Points C and C^1 are the strengths of a single fastener joint where the load is reacted by the bolt. Section 7.5.3 describes the tests required to establish this design point for different joint variables. In practice, joints C and C^1 are not much different so that a tension-bearing test is usually sufficient. Plots such as Figure 7.5.1.3 may be different for each distinct laminate, fastener type, and environmental condition, but many application ranges may be covered by one plot. The shape of the curves could also change depending on the percentage of 0°, 90° or ±45° direction plies in the laminate. The intent of the sections that follow is to provide guidance on how to establish by test the critical points of Figure 7.5.1.3. The number of laminates to be tested is governed by analysis capability and degree of confidence in extrapolation. The shear-out mode of failure is usually avoided in design by providing sufficient edge distance between the holes or the free edge and balanced laminate configuration. However, in certain rework situations shear-out critical joints cannot be avoided. In those situations, a test program must be undertaken to establish design values (see Section 7.5.4).

7.5.2 Bearing Tests

7.5.2.1 Overview

Bearing tests are used to determine bearing response of composites. From the experimental load displacement curve, the bearing strength at maximum load and at some intermediate value (identified as yield or offset) are calculated using the following equation

$$F^{br} = P/\,tD \qquad 7.5.2.1$$

where

F^{br}	=	bearing strength, psi (Pa)
P	=	bearing load, lb_f (N)
D	=	bearing hole diameter, in. (m)
t	=	specimen thickness, in. (m)

Superscripts bry and bru are commonly used to differentiate between yield and ultimate bearing strengths. An offset bearing strength may be determined to represent the yield value. In that case, the subscript bro should be used.

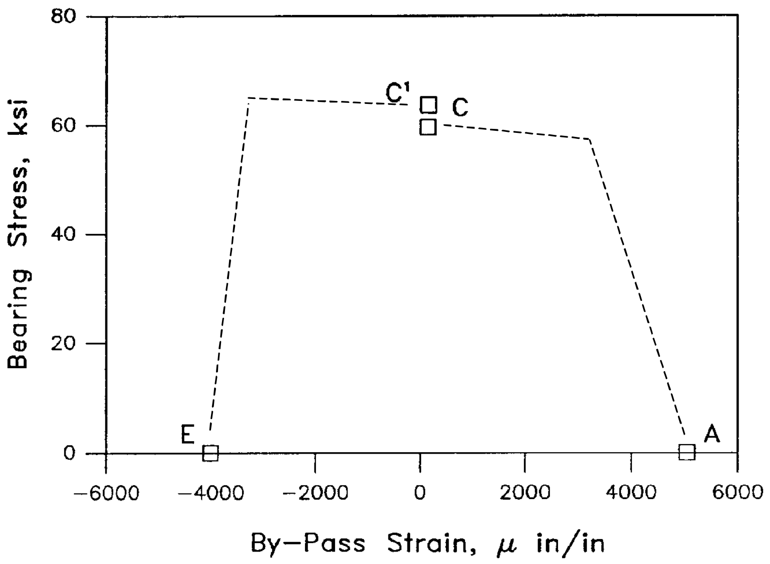


FIGURE 7.5.1.3 *Example of bearing/by-pass interaction.*

The bearing test is conducted either in double or single shear with configurations that range from simple pin to a two bolt single shear load introduction, the latter being the closest to representing an actual joint. A suggested test matrix is described in Section 7.5.2.4 that can be used to establish bearing design values. The bearing tests to be used in conjunction with the test matrix are the ASTM D 5961 Procedure A, if the joints used in the application are in double shear, or ASTM D 5961 Procedure B two bolt specimen, if the joints are in single shear.

7.5.2.2 Double shear bearing tests

The two tests described in this section introduce the bearing load in a double shear configuration. In actual applications, load transfer in a single shear configuration is more commonplace, resulting in larger stress concentrations in the thickness direction, and lowering the realizable bearing strength; these single-shear tests are discussed in Section 7.5.2.3. In other words, the bearing strength values measured by the double-shear tests cannot be applied to single shear joints.

The main difference between the two test standards described below is how the bearing load is applied. ASTM D 953 uses a pin, where ASTM D 5961, Procedure A uses a bolt with torque. As the clamp-up force is a significant factor for increasing the bearing strength, ASTM D 953 provides a lower bound on the bearing strength for the double shear configuration. Furthermore, as the pin is not representative of a bolted joint, the results of this test are usually not used for design but as a material property for comparison purposes of different materials.

7.5.2.2.1 ASTM D 953 bearing strength of plastics

This test method (Reference 7.5.2.2.1) is the oldest method to measure the bearing response of a composite material. It is the only method available to measure pure bearing strength of a material without the intrusion of bolt influences, such as clamping and washer. As such it is useful for comparison of bearing properties of different materials. The test can obtain bearing strength under tension and compression loading.

Limitations of this test are:

Pin Loading – Introduction of bearing load by a pin is not representative of most structural joints.

Fixturing – The test apparatus is unnecessarily complicated. ASTM D 5961 has a much simpler arrangement.

Specimen Geometry – The geometry of the specimen is inconsistent in e/D and W/D ratios for the two specimen thicknesses specified. As these ratios have a significant influence on bearing strength, a user may find differences in bearing strength for the two thickness where such difference does not exist in the material.

Specimen Configuration – The lay-up of the specimen is not specified and may lead users to test unidirectional material with disastrous results.

Data Reduction – The data reduction mandated by the standard is specifically tied to a parabolic shape that does not reflect actual load-displacement curves. The use of template is antiquated in this computer age. The data reduction method of ASTM D 5961 is more general and useful.

In summary, this test is useful to differentiate between materials as to their bearing strength, but the bearing properties, ultimate strength, yield strength, and the load-displacement response do not relate to the bearing properties of an actual double shear joint. Bearing strength, as measured by the test in this section, is considered a material property for relative evaluation and design. Furthermore D 5961 allows use of pins and hence can be used instead of D 953 and take advantage of simpler fixturing. In realistic structural joints, factors like geometry, fastener type, and load eccentricity will significantly influence the realizable fraction of the bearing strength measured in the proposed test. Bearing strength tests more appropriate in design of joints are discussed in Sections 7.5.2.2.2 and 7.5.2.3.

7.5.2.2.2 ASTM D 5961, Procedure A

This recently developed standard has addressed all of the deficiencies of ASTM D 953 while still permitting a test with a load introduction by a close tolerance pin. ASTM is a standardized adaptation of, and taken in large part from previous MIL-HDBK-17 work. The flexibility built-in in the ASTM D 5961 allows for testing to a standard configuration or to a variation that may be representative of the particular user's application. The loading clevice is simple to make and the test procedures and data requirements are clearly described. Only a tensile loading condition is proposed for evaluating bearing failures; under compression, the larger edge distance ($e>>3D$) should only influence the bearing stress at failure minimally unless a shear-out mode of failure is possible (e.g., a laminate with a large percent of 0° plies). The data generated by this standard is acceptable to be included in MIL-HDBK-17. Bearing and joint strength values are reported in MIL-HDBK-17 as typical or average values. Therefore, bearing and joint strength values that are available for each specific condition should be analyzed to produce typical property values as described in Chapter 8. Test data must include the data documentation required by Table 2.5.6 and will be published in property tables per Volume 2, Section 1.4.2. Bearing data developed at a specific fiber volume may not be applicable for fiber volumes that are much different because of failure mode changes.

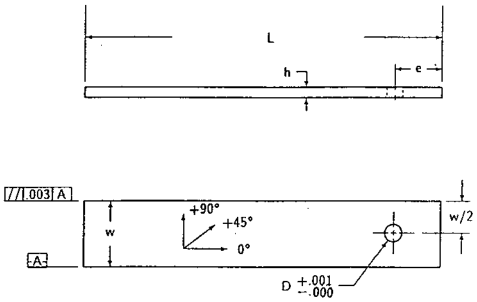
The standard test specimen and the fixture assembly are reproduced here from ASTM D 5961 as Figures 7.5.2.2.2(a) and (b). For the standard test, bearing load is applied by the lightly torqued bolt. In this test it is mandatory to measure average displacement across the loaded hole as the function of load. An example of the resulting bearing stress/bearing strain curve is shown in Figure 7.5.2.2.2(c). The bearing strain was obtained by normalizing by bolt diameter. Thus, the 2% offset measurement, which is the default in this standard, is in actuality 2% of the bolt diameter. There is no general consensus as to what the value of the offset should be. The usage in the aerospace industry varies from 1%D, for stiff double shear joints to 4%D for single shear joints, the latter being a standard for metal bearing tests in MIL-HDBK-5. Before selecting an offset measurement, for both aerospace and non-aerospace applications, the user should decide how it would be used. If the goal is to use it to represent bearing yield strength, the offset value should be close to $0.67F^{bru}$, relating to the aircraft industry's safety factor of 1.5. Another measure of the offset value could be the amount of deformation a given design was limited to.

D 5961/D 5961M

DRAWING NOTES:
1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING:
2. ALL DIMENSIONS IN INCHES WITH DECIMAL TOLERANCES AS FOLLOWS:

.X	.XX	.XXX
± .1	± .03	± .01

3. ALL ANGLES HAVE TOLERANCE OF ± .5°.
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO -A- IS RECOMMENDED TO BE WITHIN ± .5°. (See Section 6.1.)
5. FINISH ON MACHINED EDGES NOT TO EXCEED 64√ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROINCHES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO -A-, OVERALL LENGTH, HOLE DIAMETER, AND COUPON THICKNESS.



Parameter	Standard Dimension, in.
fastener or pin diameter, d	0.250 +0.000/−0.001
hole diameter, D	0.250 +0.001/−0.000
thickness range, h	0.125-0.208
length, L	5.5
width, w	1.5 ±0.03
edge distance, e	0.75 ±0.03
countersink	none

FIGURE 7.5.2.2.2(a) *Double-shear test specimen drawing (inch-pound).*

D 5961/D 5961M

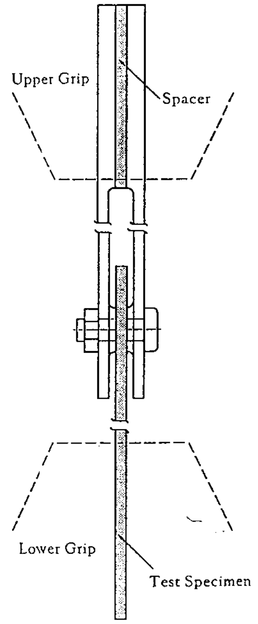


FIGURE 7.5.2.2.2(b) *Fixture assembly for procedure A.*

It should be noted that in laboratory practice, the bearing response is usually recorded in terms of bolt load versus average displacement and not as shown in Figure 7.5.2.2.2(c).

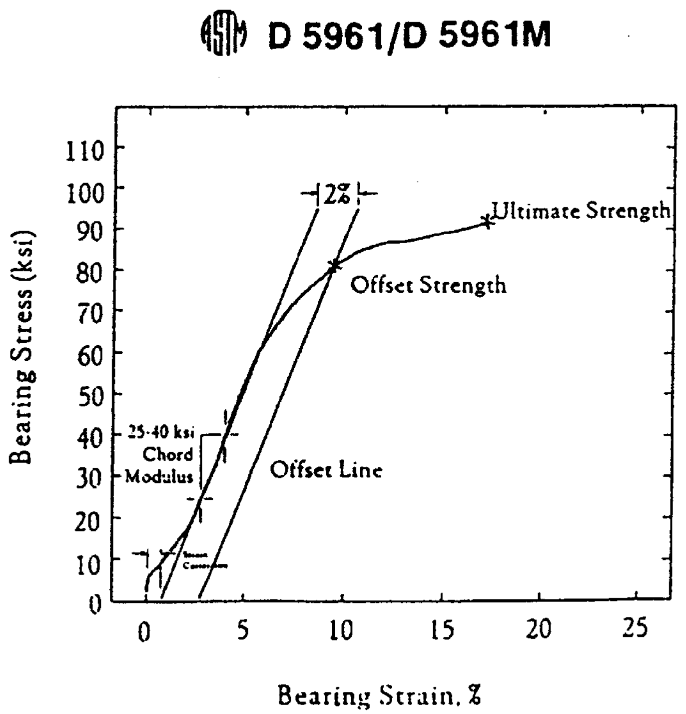


FIGURE 7.5.2.2.2(c) *Example of bearing stress/bearing strain curve.*

7.5.2.3 Single shear bearing tests

7.5.2.3.1 Overview

The single shear bearing test configuration is more representative of most aircraft bolted joint applications than the double shear tests described in Section 7.5.2.2. The single lap induces both bending and shear loads on the fastener, while the double lap induces mostly shear loads. Two types of single shear specimens are used, one with one bolt and the second with two bolts. The latter being closer to replicating a multi-fastener joint. Both specimens need to be tabbed to assure the load line alignment at the faying surface of the two joining plates. As such the specimens are somewhat more complex than for the double shear configuration. On the other hand, there is no need to fabricate a clevice.

7.5.2.3.2 ASTM D 5961, Procedure B

By developing Procedure B of ASTM D 5961, ASTM recognized the need for a bearing test that is representative of single lap joints found in realistic structures. Single bolt and two bolt configurations are allowed by the standard.

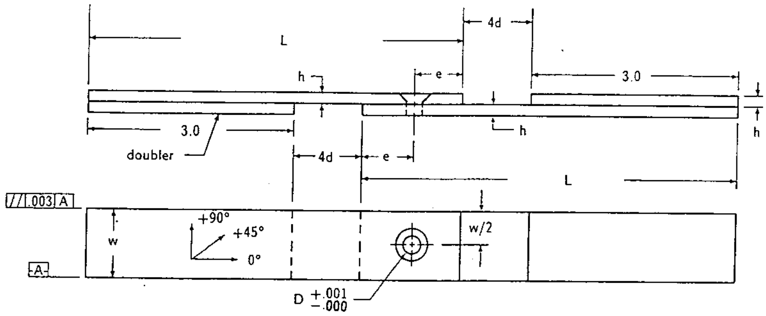
The recommended single fastener joint configuration is shown in Figure 7.5.2.3.2(a). This is the same specimen specified in MIL-STD-1312-X (Reference 7.5.2.3.2). It should be recognized that this joint configuration is subject to high bending due to the load eccentricity transmitted through the bolt. The bending can be reduced by increasing the stiffness of the two laps, either through increased thickness, and/or material stiffness. It should also be noted that the single fastener joint is generally not representative of multi-fastener joint applications because of excessive joint rotation and deflection. Therefore, it is generally used for screening purposes or for fastener development.

D 5961/D 5961M

DRAWING NOTES:
1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING:
2. ALL DIMENSIONS IN INCHES WITH DECIMAL TOLERANCES AS FOLLOWS:

.X	.XX	.XXX
± .1	± .03	± .01

3. ALL ANGLES HAVE TOLERANCE OF ± .5°.
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO [-A-] WITHIN ± .5°.
5. FINISH ON MACHINED EDGES NOT TO EXCEED 64√ (SYMBOLOGY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROINCHES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO [-A-], OVERALL LENGTH, HOLE DIAMETER, COUNTERSINK DETAILS, COUPON THICKNESS, DOUBLER MATERIAL, DOUBLER ADHESIVE.



Parameter	Standard Dimension, in.
fastener diameter, d	0.250 +0.000/−0.001
hole diameter, D	0.250 +0.001/−0.000
thickness range, h	0.125-0.208
length, L	5.5
width, w	1.5 ±0.03
edge distance, e	0.75 ±0.03
countersink	none (optional)

FIGURE 7.5.2.3.2(a) *Single-shear test specimen drawing (inch-pound) (see Figure 7.5.2.3.2(b) for details of double-fastener version).*

The two bolt lap configuration shown in Figure 7.5.2.3.2(b) may be used to generate both design and fastener screening data. When tested, the specimen geometry shown in Figure 7.5.2.3.2(b) is intended to result in composite bearing failures (as opposed to tension or cleavage failures). It should be noted that this specimen configuration is not pure bearing but has a by-pass load resulting in tensile strain in the two laps. The tensile bypass strain level will be low for the configuration specified in the standard, however, any configuration variations should be checked to make sure that the by-pass strain is not greater than 0.2% to prevent tensile failure of the laps. Fastener pull-thru's and fastener failures, although not acceptable as a measure of composite bearing strength, do provide a measure of joint strength for a particular fastener type.

Both the single bolt specimen, Figure 7.5.2.3.2(a), and the two bolt specimen, Figure 7.5.2.3.2(b), can be adopted to test metal to composite joints. A one-piece metal tongue can be machined for one lap or the tab can be bonded to a metal strip with dimensions so as to align the load path along the interface between the two laps.

Limitations of the test(s) are

Shim Allowance – The standard does not discuss the use of shims between the composite laps to simulate mating gaps occurring in actual joints. The thickness of the shim has a large influence on the bearing strength as discussed in Section 7.5.2.5. A common aerospace practice is to place an unbonded aluminum shim between laps of the thickness equivalent to the allowable liquid shim dimension, 0.03 in. for aircraft structures.

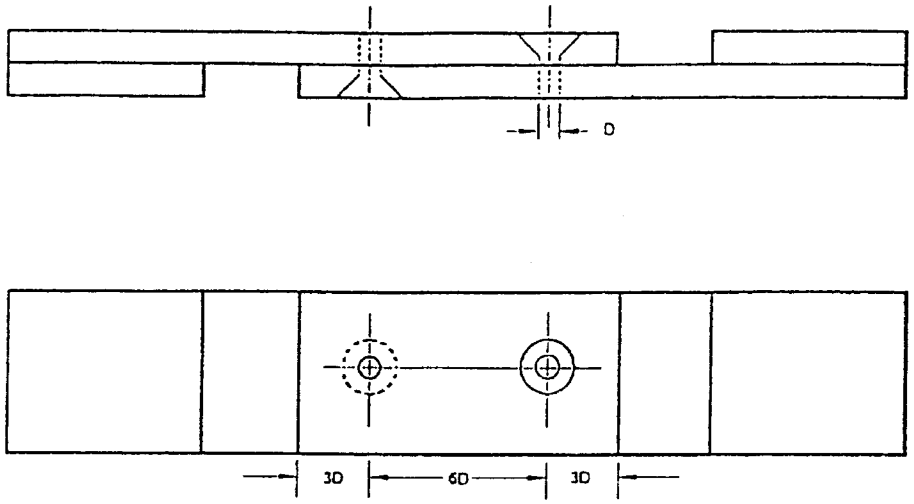


FIGURE 7.5.2.3.2(b) *Single-shear, double-fastener test specimen schematic.*

7.5.2.4 Suggested joint bearing test matrices

This section describes test matrices required to obtain design values for the bearing strength of single or double lap joints. Imbedded in the test matrices are smaller matrices, whose resulting test data can be applicable for the selection and screening of fasteners. The recommended test methods and specimens are the ASTM D 5961 Procedure A if the actual joint configuration is in double shear, and the two bolt test specimen and procedure of ASTM D 5961 Procedure B for single shear.

Bearing strength is a function of joint geometry and stiffness of the members and the fastener. It should be noted that for a 0/±45/90 family of laminates with 20-40% of 0° plies and 40-60% of ±45° plies, the bearing strength is essentially constant. In addition, fastener characteristics such as clamp-up force, and head and tail configuration have a significant effect. However, for a specific laminate family, a specific fastener, and equal thickness lamina joining members, the parameter with the greatest influence is t/D. This was recognized by the aircraft designers and all the bearing data for metals is presented in MIL-HDBK-5 (Reference 7.5.2.4) in terms of the t/D parameter, Figure 7.5.2.4. The slope of this non-dimensional curve is the bearing strength which decreases with increased t/D until for sufficiently thick laminates shear failure occurs in the bolt. The data generated using the recommended test specimens, procedures, and test matrices will produce equivalent data for composite joints.

In the design process there may be instances where the joint configuration may not correspond to the test configurations recommended here, i.e., unequal joining members, gaps, solid shims, fuel sealing provisions. These effects on bearing strengths should be evaluated by modifying the specimen geometry as needed. The test procedures presented here are still applicable.

For composite-to-composite bolted joints, the recommended test matrix for single shear bearing strength testing is given in Table 7.5.2.4(a) and the associated test specimen configuration is given in Figure 7.5.2.3.2(b).

The test data generated from the full test matrix of Table 7.5.2.4(a) will be sufficient to design composite-to-composite mechanical joints against bearing failure for one material and one fastener type. For other fasteners, the tests with note (1) should be sufficient to provide correction factors that would be applicable to all other not-tested conditions. These are labeled as fastener supplier tests or screening tests. For screening tests, in addition to t2 thickness, a third thickness specimen (t3) is shown so that sufficient test data would be generated to construct Figure 7.5.2.4. For composites, this type of normalized plot is only valid for bearing data on a specific laminate.

TABLE 7.5.2.4(a) *Composite-to-composite mechanically fastened joint test matrix for bearing strength.*

GEOMETRY	SKIN MEMBER THICKNESS in. (mm)	LAY-UP	BOLT DIAMETER in. (mm)	ENVIRONMENT (TEMP/% MOIST)	NUMBER OF TESTS
COMPOSITE TO COMPOSITE	0.2 (5)	25/50/25	0.25 (6.4) D2	RT/ambient RT/ambient	10[1,2] 5[1]
	0.2 (5)	50/40/10	0.25 (6.4) D2	RT/ambient RT/ambient	5 5
	t2	25/50/25	0.25 (6.4) D2	RT/ambient RT/ambient	5[1] 5[1]
	t2	50/40/10	0.25 (6.4) D2	RT/ambient RT/ambient	5 5
	t3	25/50/25	0.25 (6.4) D2	RT/ambient RT/ambient	5[1] only 5[1] only
COMPOSITE TO COMPOSITE	0.2 (5)	25/50/25	0.25 (6.4) D2	hot/wet hot/wet	5 5
	0.2 (5)	50/40/10	0.25 (6.4) D2	hot/wet hot/wet	5 5
	t2	25/50/25	0.25 (6.4) D2	hot/wet hot/wet	5 5
	t2	50/40/10	0.25 (6.4) D2	hot/wet hot/wet	5 5

Notes:
[1] Supplier fastener screening tests
[2] Contains additional 5 specimens with 0.03 ± 0.003 in. (0.76 ±0.08 mm) liquid shim gap between members (optional)
Single shear configuration per Figure 7.5.2.3.2(b) or double shear configuration per Figure 7.5.2.2.2(a).

Tests should be conducted at room temperature ambient conditions, and one hot, wet condition. The hot, wet test should be conducted on specimens after they are preconditioned to equilibrium level moisture content (see Section 2.2.7.2). The recommended temperature for the hot, wet test is T_g - 50F° (T_g - 28C°), based on the wet glass transition temperature. Hot/wet tests are conducted after specimens have been preconditioned.

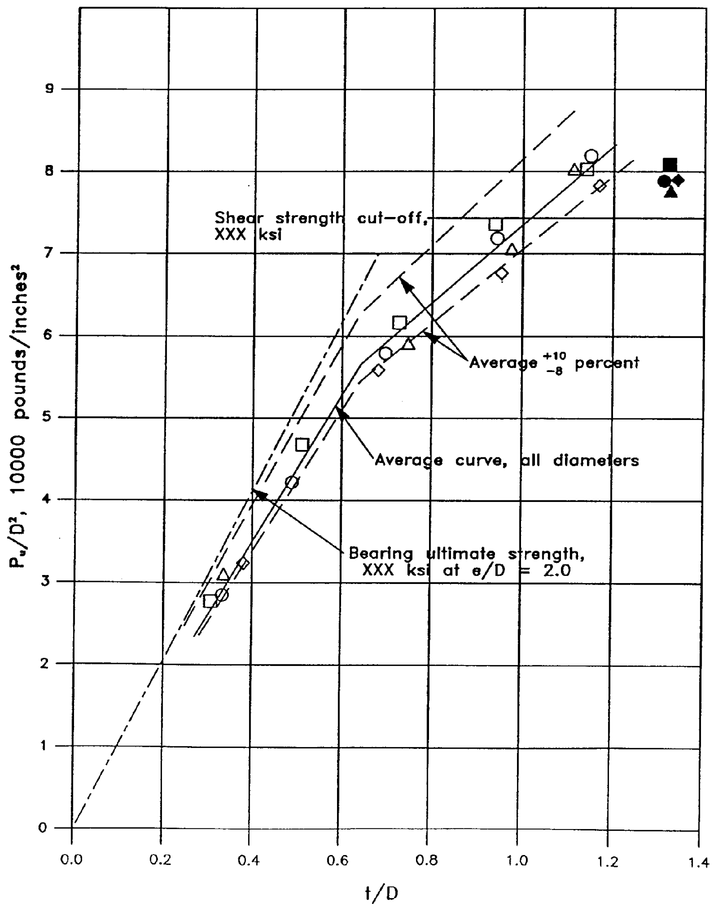


FIGURE 7.5.2.4 *Average ultimate-load strength curve.*

In the design test matrix two different composite lay-ups are shown at each thickness. The lay-up varies from quasi-isotropic $(45/0\text{-}45/90)_{ns}$ to an orthotropic lay-up of 50% 0° plies in the load direction $(45/0/\text{-}45/90/0_2/45/0/\text{-}45/0)_{ns}$. For a fabric material, the lay-up percentages for the latter laminate have been modified to (40/20/40). One other thickness (t2) and bolt diameter (D2) are left unspecified; their choice should be dependent on the application. Two environments should be tested, room temperature as received and hot/wet. The selection of hot/wet temperature and moisture content should be guided by Section 2.2.8.

The baseline 0.2 inch (5 mm) thick quasi-isotropic lay-up with the 0.25 inch (6.4 mm) bolt diameter could be used to evaluate the effect of a 0.03 inch (0.8 mm) thick or thicker liquid shim gap between the two members (option Note (2); also see Section 7.2.5.1). A metal spacer can be used instead of the liquid shim if the spacer is unbonded to the composite.

For composite-to-metal bolted joints, the recommended test matrix for single shear bearing strength testing is given in Table 7.5.2.4(b). The general comments from the composite-to-composite bolted joints section also apply to the composite-to-metal bolted joints since the test matrices are the same. The composite-to-composite configuration is more critical than the composite-to-metal joint with respect to the design of the fastener tail; therefore, the composite-to-composite test specimen is more useful for the evaluation of fasteners by the fastener supplier. Because of the above reason, note (1) in Table 7.5.2.4(b) has been designated as tests required for a different fastener.

TABLE 7.5.2.4(b) *Composite-to-metal mechanically fastened joint test matrix for bearing strength.*

GEOMETRY	SKIN MEMBER THICKNESS in. (mm)	LAY-UP	BOLT DIAMETER in. (mm)	ENVIRONMENT (TEMP/% MOIST)	NUMBER OF TESTS
COMPOSITE TO METAL	0.2 (5)	25/50/25	0.25 (6.4) D2	RT/ambient RT/ambient	10[1,2] 5[1]
	0.2 (5)	50/40/10	0.25 (6.4) D2	RT/ambient RT/ambient	5 5
	t2	25/50/25	0.25 (6.4) D2	RT/ambient RT/ambient	5[1] 5[1]
	t2	50/40/10	0.25 (6.4) D2	RT/ambient RT/ambient	5 5
COMPOSITE TO METAL	0.2 (5)	25/50/25	0.25 (6.4) D2	hot/wet hot/wet	5 5
	0.2 (5)	50/40/10	0.25 (6.4) D2	hot/wet hot/wet	5 5
	t2	25/50/25	0.25 (6.4) D2	hot/wet hot/wet	5 5
	t2	50/40/10	0.25 (6.4) D2	hot/wet hot/wet	5 5

Notes: [1] Alternate fastener tests
[2] Contains additional 5 specimens with 0.03 ± 0.003 liquid shim gap required between members (optional)
Single shear configuration per Figure 7.5.2.3.2(b).

The recommended fatigue matrix is given in Table 7.5.2.4(c). Constant amplitude fatigue is suggested with a stress ratio of R = -0.2 (compressive load is 20 percent of tensile load). Frequency of loading should be selected so as to avoid excessive heating at the joint area of the specimen. For current material systems this translates to 5 Hz. This test matrix should be repeated for each fastener under consideration. The fifteen replicates per test will allow three replicates at each of the five stress levels. A load level of half the static strength is a good starting point. All tests should be conducted at room temperature/ambient environment.

The specimens with specified thickness and bolt diameter (t = 0.2 in. (5 mm) and D = 0.25 in. (6.4 mm)) have been sized to fail in bearing. Specimens should be selected based on assuring bearing failure and avoiding bolt shearing, or net tension failures either in composite or metal members.

TABLE 7. 5.2.4(c) *Mechanically fastened joint fatigue test matrix for bearing fatigue.*

GEOMETRY	THICKNESS	LAY-UP	TOTAL NUMBER OF TESTS
COMPOSITE TO COMPOSITE	t1	25/50/25	15[1]
	t1	50/40/10	15
COMPOSITE TO COMPOSITE	t1	25/50/25	15[1]
	t1	50/40/10	15

Notes: [1] Supplier fastener screening tests
[2] Constant amplitude fatigue (R=-0.2) to 4% hole elongation measured across a single hole
Specimen geometry is the same as for static tests.

7.5.2.5 Effects of thickness/gaps/shimming

Although in most composite applications, the use of bonded joints appears more weight-efficient, bolted joints still predominate due to their higher joint reliability and the need to disassemble some joints. In the assembly of composite structure, gaps between mating surfaces will occur and the disposition of these gaps is required prior to clamp-up of the fastener. Closing excessive unshimmed gaps when installing fasteners can cause delaminations in the composite structure, however, residual gaps of any size may reduce joint performance.

Test data show that the strength of bolted composite joints depends partially on bolt diameter, composite thickness, shimmed gap thickness, and the type of shimming material used. Examples of strength reduction curves are shown in Figures 7.5.2.5(a) and (b) for the diameter to thickness ratio and shimmed gap effects for a single shear composite joint in a multiple bolt splice. These are not generic curves and generation of similar data would be required for specific user application. The reduction factors are then used to reduce the nominal allowable bearing stress. The nominal bearing allowable for a particular material system would be obtained using tests with configurations minimizing bolt bending to obtain uniformity of stress through the thickness (a large diameter to thickness ratio clevis or multi-fastener test) and using all pertinent statistical and environmental knockdowns. Joint strength reduction factors are greater for joints using liquid shims for filling the gaps than joints using metal or composite solid shims.

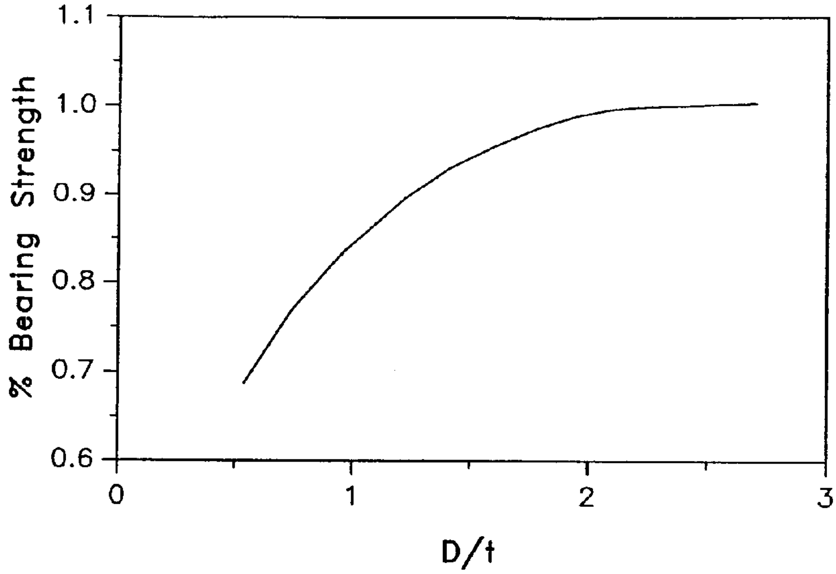


FIGURE 7.5.2.5(a) *Bearing strength reduction vs D/t.*

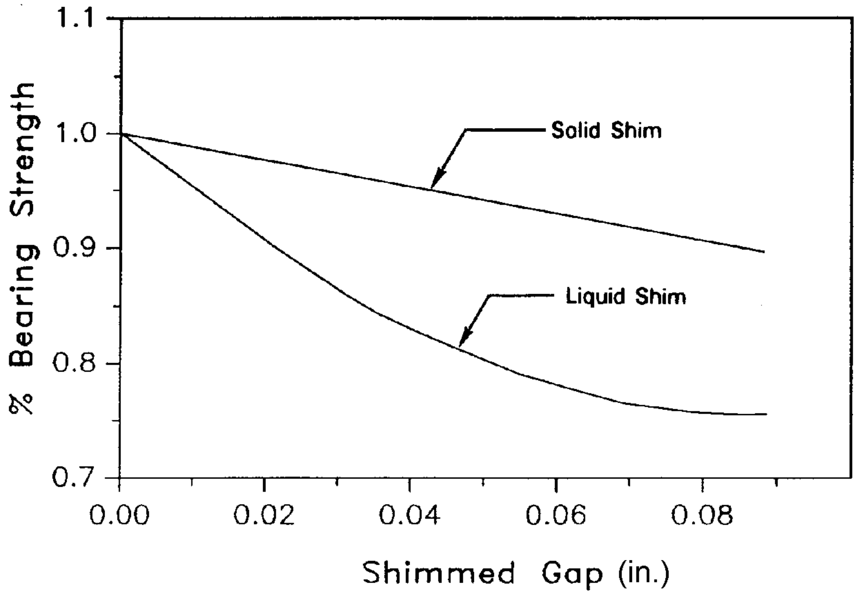


FIGURE 7.5.2.5(b) *Bearing strength reduction vs shimmed gap.*

7.5.2.6 Failure modes

Descriptions for failure modes are provided in Figures 7.5.2.6(a) - (d).

<u>Laminate Failures</u>

L-NT:	Laminate Net Section Tensile Failure
L-NC:	Laminate Net Section Compressive Failure
L-OC:	Laminate Off-Set Compressive Failure
L-BR:	Laminate Bearing Failure
L-SO:	Laminate Shear-Out Failure
L-MM:	Mixed Mode Failure
L-PT:	(Laminate allowing) Fastener Pull-Through Failure

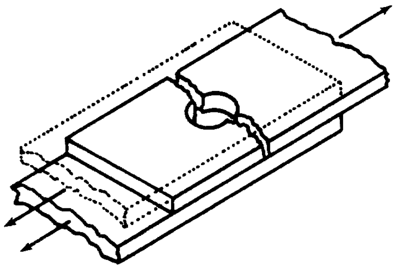
<u>Fastener Head/Collar Failures</u>

F-HD:	Fastener Head Dished
F-FS:	Fastener Flange Shear Failure
F-HS:	Fastener Head, Blind or Formed Head Shear Failure
F-BH:	Fastener Blind Head Deformed
F-NF:	Fastener Collar Fracture Failure
F-NS:	Fastener Collar Stripped

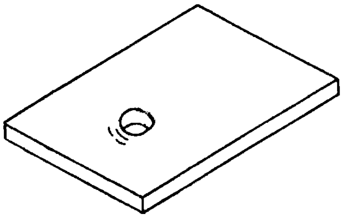
<u>Fastener Shank Failures</u>

F-STH:	Fastener Shank Tensile Failure at Shank/Head or Formed Head Junction
F-STT:	Fastener Shank Tensile Failure in Threads
F-ST:	Fastener Shank Tensile Failure
F-SST:	Fastener Sleeve or Stem Tensile Failure
F-SSH:	Fastener Shank Shear Failure at Shank/Head Junction
F-SS:	Fastener Shank Shear Failure

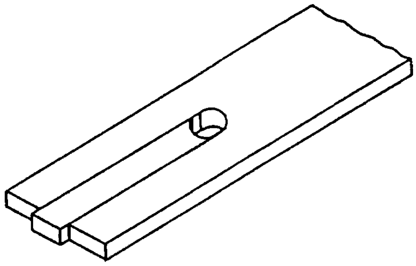
FIGURE 7.5.2.6(a) *Failure mode descriptions for mechanical fastened joints.*



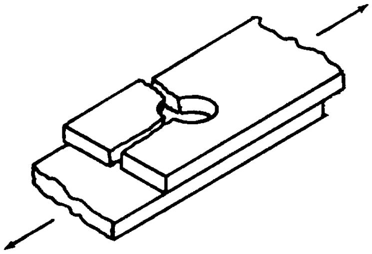
L-NT, L-NC: Laminate Net Section Tension (or Compression) Failure



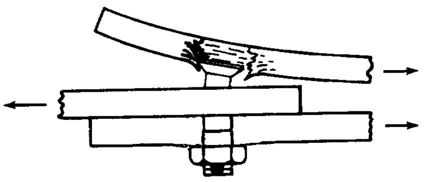
L-BR: Laminate Bearing Failure



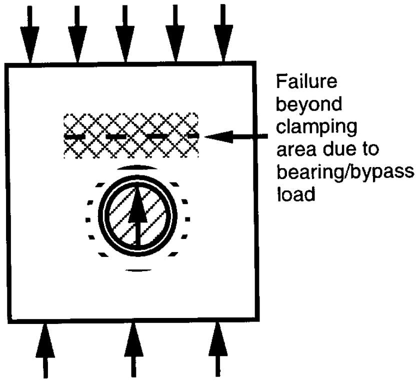
L-SO: Laminate Shear-out Failure



L-MM: Mixed Mode Failure
(unsuitable for data generation)



L-PT: Fastener Pull-Through (or Partial Pull-Through) Failure



L-OC: Laminate Off-Set Compression Failure

FIGURE 7.5.2.6(b) *Failure mode descriptions for mechanically fastened joints.*

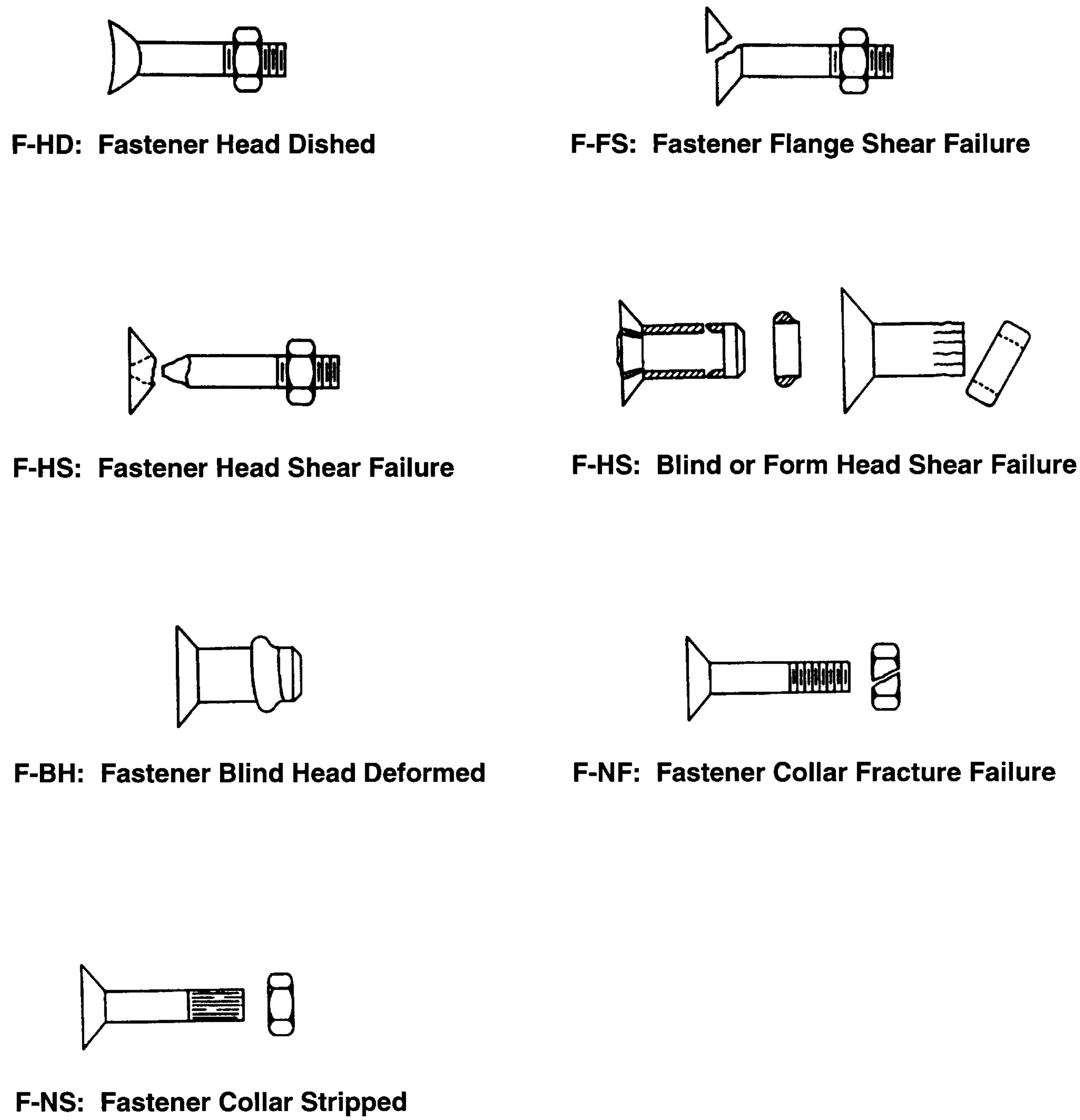


FIGURE 7.5.2.6(c) *Failure mode descriptions for mechanically fastened joints .*

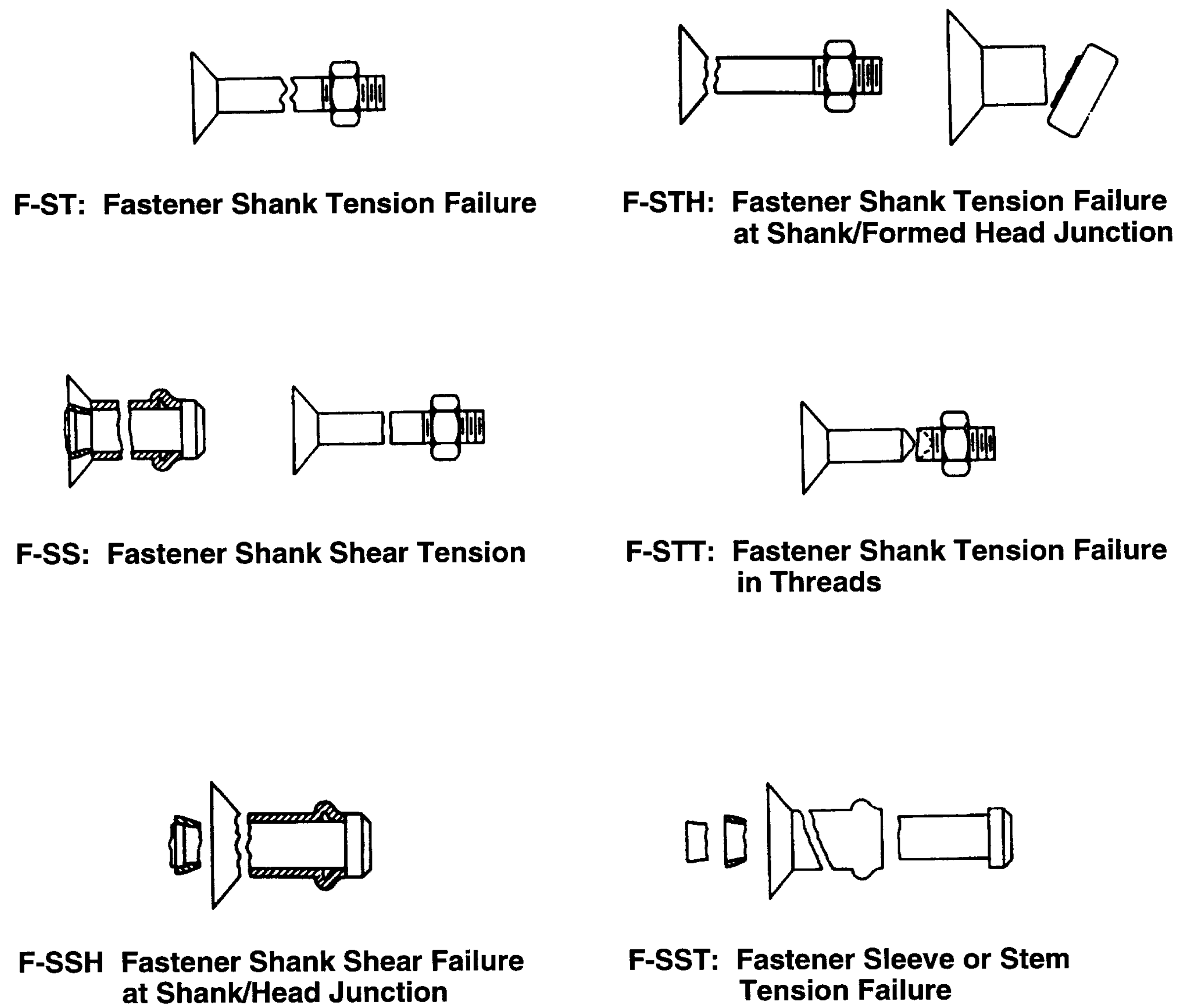


FIGURE 7.5.2.6(d) *Failure mode descriptions for mechanically fastened joints.*

7.5.3 Bearing/by-pass evaluation

7.5.3.1 Overview and rationale

Designs of composite structure containing bolted joints in which the load transfer is greater than 20% of the total load at an individual bolt may require test substantiation. The purpose of this section is to provide guidance on how to obtain these data. Specifically, this section describes specimen geometries, test procedures, and test matrices to sufficiently define experimental lines AC and EC' in Figure 7.5.1.3 to B-basis significance for the variability and environmental dependence of the material is known *a priori*.

Analytical procedures, *e.g.*, see Reference 7.5.3.1, are being developed to reduce testing requirements. Progress has been made in the net tension/by-pass quadrant (line AC) for the failure mode characterized as net tension. For this failure mode, a good correlation was obtained using linear interaction for combined bearing/by-pass loading.

7.5.3.2 Specimen design and testing

Various specimens and text fixtures have been utilized by the aerospace industry to obtain bearing/by-pass strengths. All can be classified into three general categories: (1) passive, (2) independent bolt load, and (3) coupled bolt load/by-pass load. In the passive method, load is transferred through the bolt into an additional strap, as shown in Figure 7.5.3.2(a). The magnitude of the transferred load, and hence the bearing/by-pass ratio, is thus a function of metal strip stiffness and the details of bolt installation. Without a significant amount of strain gauging, it is difficult to establish how much bearing load will be transferred. This method/specimen is not recommended without experimental verification of load transfer parameters. Because of geometrical limitations, this method is most applicable with low load transfer usually not greater than 40%, which may not be where significant interaction effects occur. The major advantage of the passive method is that it does not need special fixturing. The testing itself is equivalent to a standard tension or in-plane stabilized compression test.

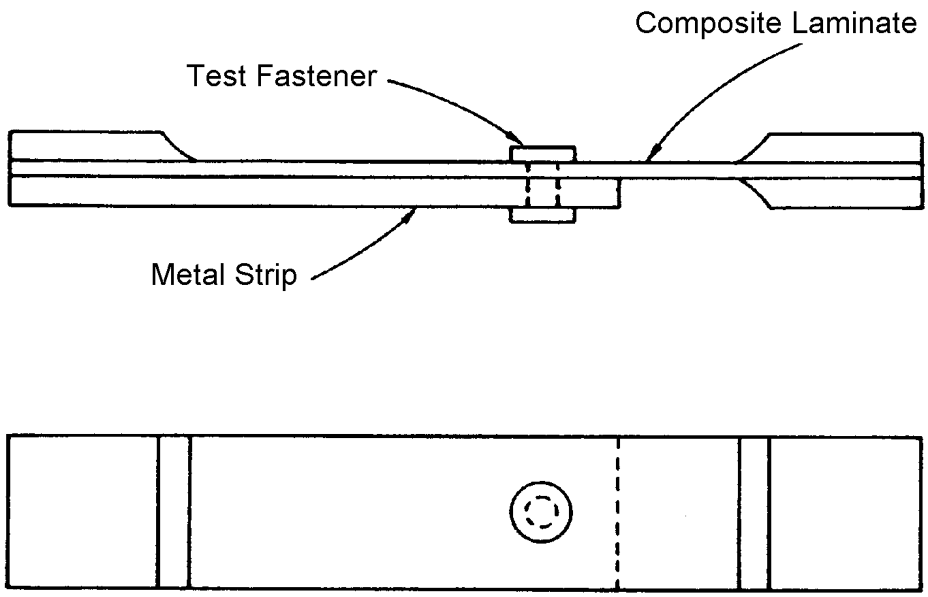


FIGURE 7.5.3.2(a) *Passive by-pass/bearing specimen (single shear).*

In the coupled bolt load/by-pass load method, the bolt is loaded by mechanical linkages attached to the test machine (Figure 7.5.3.2(b)). By locating the vertical link at different locations, different bearing/by-pass ratios can be tested. This ratio will remain constant until failure during each particular test. Because of this constraint and the complexities of test fixturing, this method is also not recommended as the primary method of obtaining bearing/by-pass data.

The recommended test method for bearing/by-pass should load the bolt independently, with the bolt load measured directly, so that the bearing stress can be calculated without resorting to backing out a value from strain gage readings on joining members. Test fixtures to accomplish this require a loading cell(s) separate from the testing machine which complicates the test procedures. Specialized test fixturing has been developed by the industry to synchronize the loading between the bolt and the specimen. One well-documented test system has been developed by the NASA Langley Research Center (Reference 7.5.3.1). Figure 7.5.3.2(c), taken from this reference, illustrates the complexities of the fixturing. The coupon from Reference 7.5.3.1 is shown in Figure 7.5.3.2(d), modified with an additional hole to alert the tester if any shear-out failures occurred. It is typical of all independently loaded test systems in the industry. It should be noted that for compressive loading, the specimen is stabilized to prevent buckling.

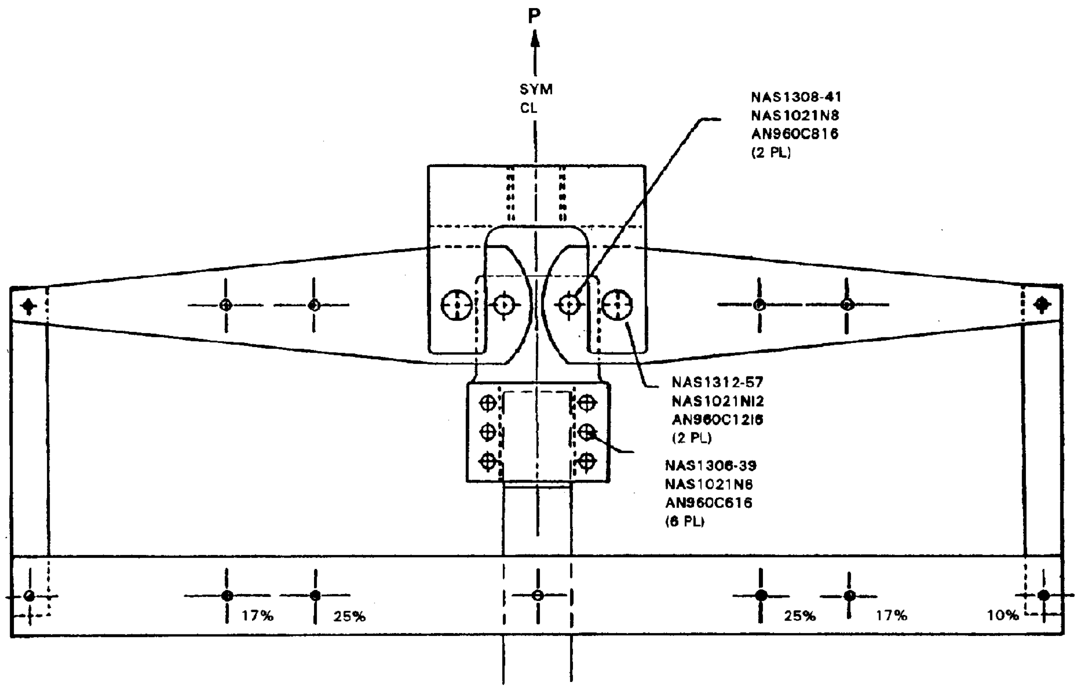


FIGURE 7.5.3.2(b) *Bolt bearing by-pass test fixture.*

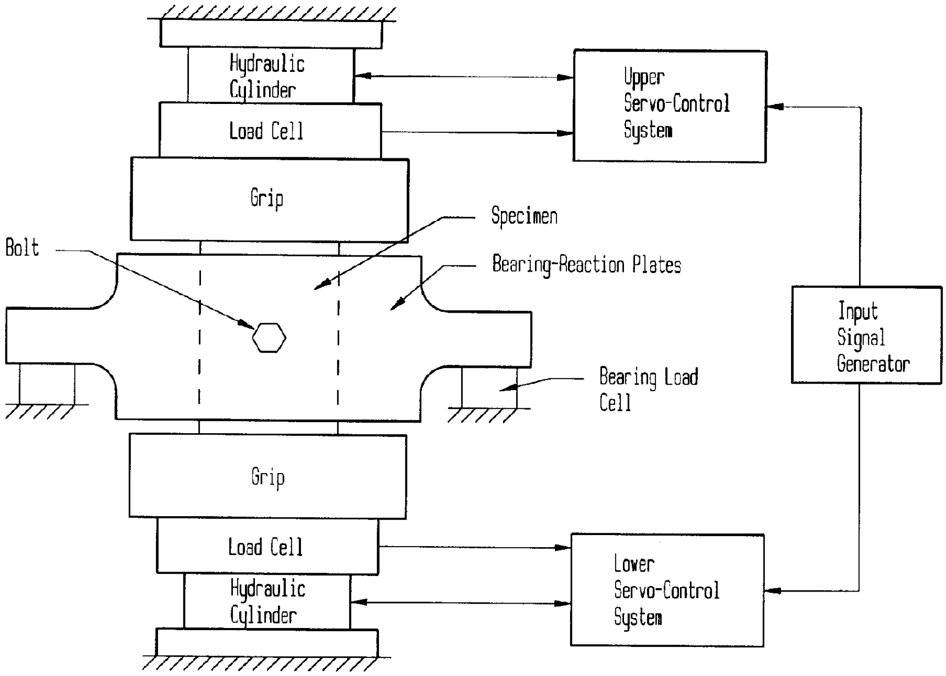


FIGURE 7.5.3.2(c) *Block diagram of the combined bearing by-pass test system (Reference 7.5.3.1).*

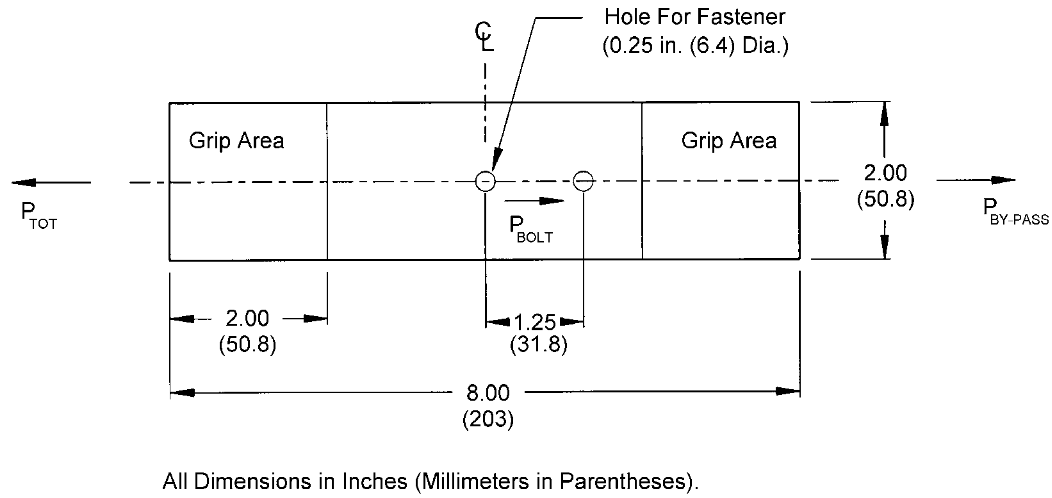


FIGURE 7.5.3.2(d) *Specimen for bearing/by-pass test.*

7.5.3.3 Suggested bearing/bypass test matrix

The minimum testing requirements necessary to construct the bearing/by-pass interaction plot of Figure 7.5.1.3 for a particular polymer matrix composite material are outlined in Table 7.5.3.3. The test matrix assumes that the end points (A and E) have been or will be obtained from no bolt load notch tension/compression tests recommended in Section 7.4. It also assumes that the points C and C_1 are obtained from the bearing strength tests enumerated in Section 7.5.2 for single shear and Section 7.2.4 for double shear. As no environmental tests other than that at room temperature have been specified in Table 7.5.3.3, the environmental effects on the bearing/by-pass strength are to be deduced from the interaction curves' endpoints. The laminate called out are the same as in Section 7.4.2 and 7.43. For completeness, the laminate lay-ups should be as follows: $[+45/0/-45/(\pm45)_3/90]_{ns}$ for 10/80/10, $[+45/0/-45/90]_{ns}$ for 25/50/25, and $[+45/0/-45/90/0_2/+45/0]_{ns}$ for 50/40/10.

The test specimen and procedures to fulfill the test requirements of Table 7.5.3.3 should use an individually loaded bolt method such as described in Reference 7.5.3.1 and shown in Figures 7.5.3.2(c) and (d), or similar. The test matrix can be applied to either a single shear or double shear joint. In the event that both types of joints exist in the structure the test matrix should be repeated.

7.5.3.4 Data reduction

The data reduction procedures of notched tension and bearing tests are applicable to bearing/by-pass tests. The bolt load versus displacement plot should be obtained as for the bearing test. In addition, total of by-pass load must be recorded. Failure mode must also be described.

TABLE 7.5.3.3 *Bearing/by-pass test matrix.*

Lay-up	Environment (Temp/% Moist)	Tension		Compression		Total No. of Tests
		Bearing/By-pass ratio		Bearing/By-pass ratio		
		0.75	0.50	0.75	0.50	
10/80/10	RT/ambient	5	5	5	5	20
25/50/25	RT/ambient	5	5	5	5	20
50/40/10	RT/ambient	5	5	5	5	20
TOTAL		15	15	15	15	60

7.5.4 Shear-out strength

The shear-out strength of a material is its ability to withstand shear-out failure of the type shown in Figure 7.5.1.2. Composite joints are usually designed to avoid this mode of failure. However, by reducing the edge distance from the typical value of three times the fastener diameter ($3D$), the bearing specimens of Sections 7.2.4 and 7.2.5 can be induced to fail by shear-out. Thus these specimens and procedures are used to determine the joint shear-out strength. The shear-out strength is calculated as $P/2et$ based on the gross section. Definitions of e, D, and t are described in Figure 7.5.4(a). The shear-out failure mode in composite bolted joints can be avoided by having sufficient edge distance and interspersed stacking sequence with adequate numbers of ±45° and 90° plies. Indeed, it is virtually impossible to create a design limiting shear-out failure mode at a $3D$ edge distance without clustering together an excessive number of plies of the same direction. On the other hand, in some situations, particularly in rework or repair, short edge distances cannot be avoided. Thus the capability of laminates in shear-out must be known, even when the laminate would not fail by shear-out at the nominal edge distance.

Because a pure bearing test specimen is used to determine the shear-out strength, misinterpretations have occurred in reports that claim that the smaller e/d ratios reduce the bearing strength of the joint. While the shear lap specimens with small e/D ratios do fail at lower joint bearing stresses than the laminate bearing strength, it is because a lower joint failure has occurred in the shear-out failure mode in the shearing surfaces, preempting the bearing mode of failure.

How the failure mode changes as a function of e/D and laminate lay-up is illustrated in Figure 7.5.4(b). In this figure, failure test data for e/D ratios between 1.5 and 2.5 and for different laminates are plotted with bearing stress as the ordinate and shear-out stress as the abscissa. The plotted results show a constant shear-out failure stress irrespective of bearing stress or e/D ratio. For one laminate, even at an e/D ratio of 2.5, sufficiently high joint load was reached to fail the joint by bearing failure. The data of Figure 7.5.4(b) also show a reduction in shear-out strength when the grouping of the same direction plies are doubled from four to eight. Typical failures are shown in Figure 7.5.4(a) where a plug of material is displaced parallel to the fiber direction without any crushing of fibers ahead of the bolt. As this shear-out failure mode is a matrix failure, it is susceptible to degradation with environment.

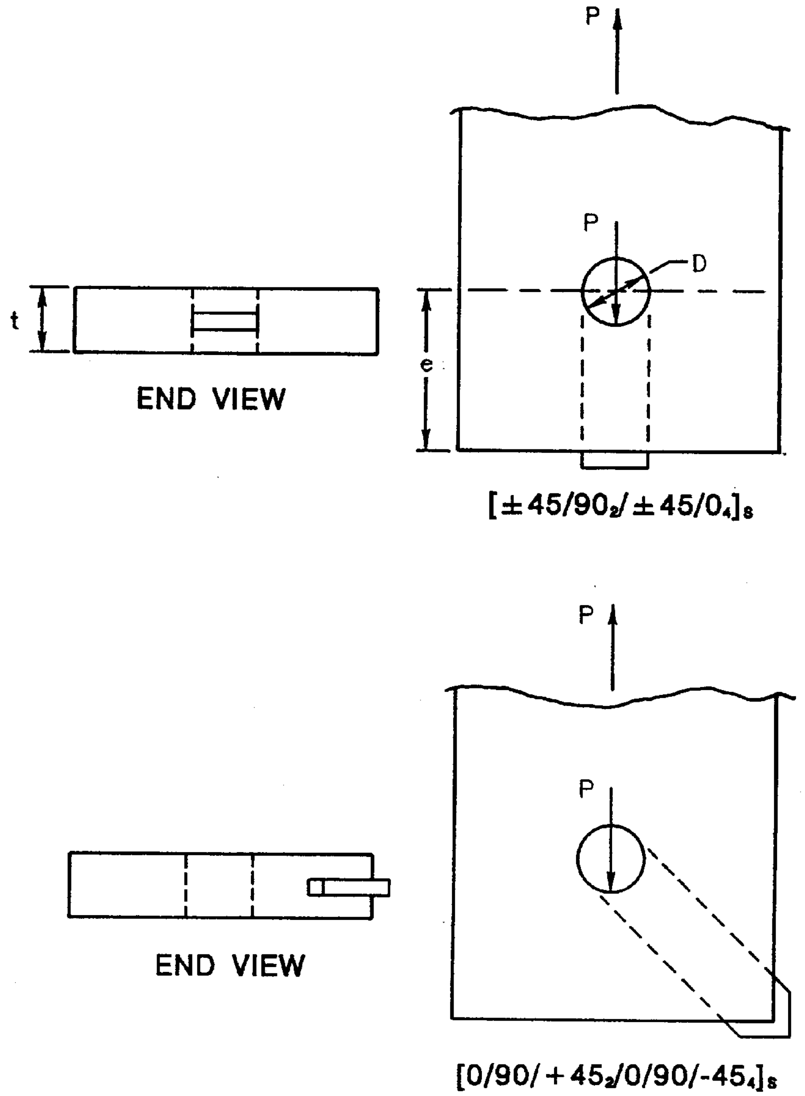


FIGURE 7.5.4(a) *Shear-out failure mode.*

Yet other data, for laminates with fifty percent or more of concentrated plies in the bearing load direction show shear-out failures at the same load irrespective of whether the edge distance (e) is 2D or 8D. So additional edge distance alone cannot be relied upon to enhance shear-out resistance of highly orthotropic laminates. To avoid shear-out failure, one must avoid large concentrations of same direction plies. The conclusion is that the shear-out strength is more dependent on the laminate and stacking order than on the edge distance.

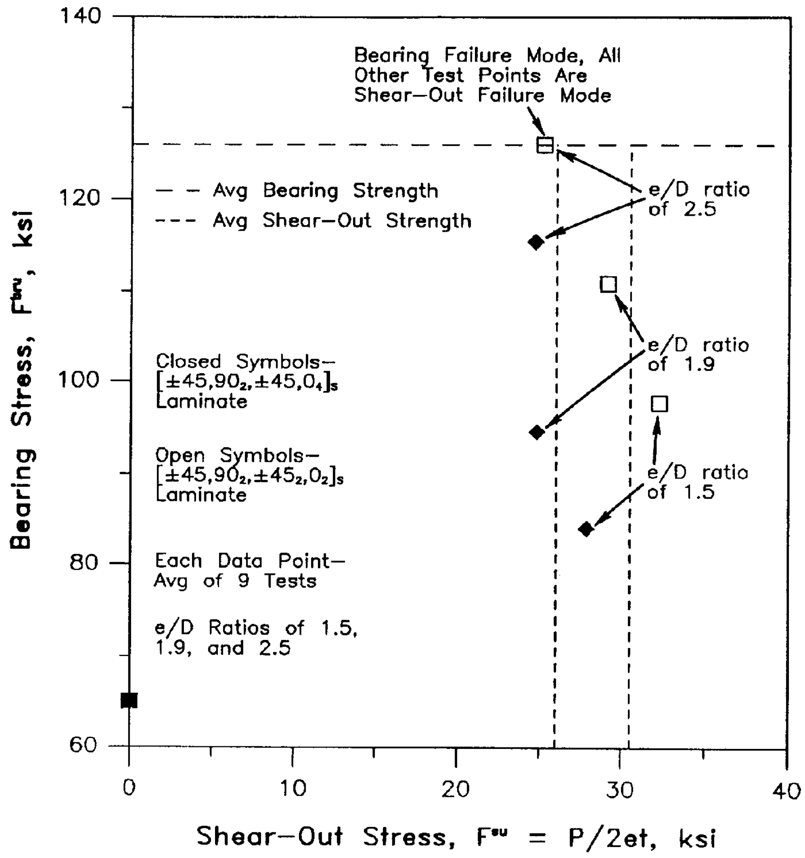


FIGURE 7.5.4(b) *Bearing/shear-out test failure data as a function of bearing and shear-out stresses - AS1/3501-5A, RT, ambient.*

7.5.5 Fastener pull-thru strength (MIL-HDBK-17 test method)

7.5.5.1 Scope

Test procedures for determining the sheet pull-thru characteristics of mechanically fastened composite joints are described in this section. Sheet pull-thru is defined as the load level at which two composite plates attached by a mechanical fastener can no longer support an increase in load when the plates are pulled apart perpendicular to the plates' plane. Two methods are suggested; one method, an adaptation of MIL-STD-1312 Test 8 for Tensile Strength (recently being adopted by AIA Standards Committee as NAS M1312), is described in detail and for the purposes of this handbook will be called Procedure A. This method is suitable for screening and fastener development purposes. The second method, Procedure B, is suitable to establish design values, but as this test is more configuration dependent only a sketch of possible testing configuration is provided. Both methods can be utilized to perform comparative evaluations (with baseline fasteners having established usage) of the candidate fasteners/fastener system designs. It is understood that the specimens described herein may not be representative of actual joints which might contain one or more free edges adjacent to the fastener or contain multi-fasteners that change the actual boundary conditions.

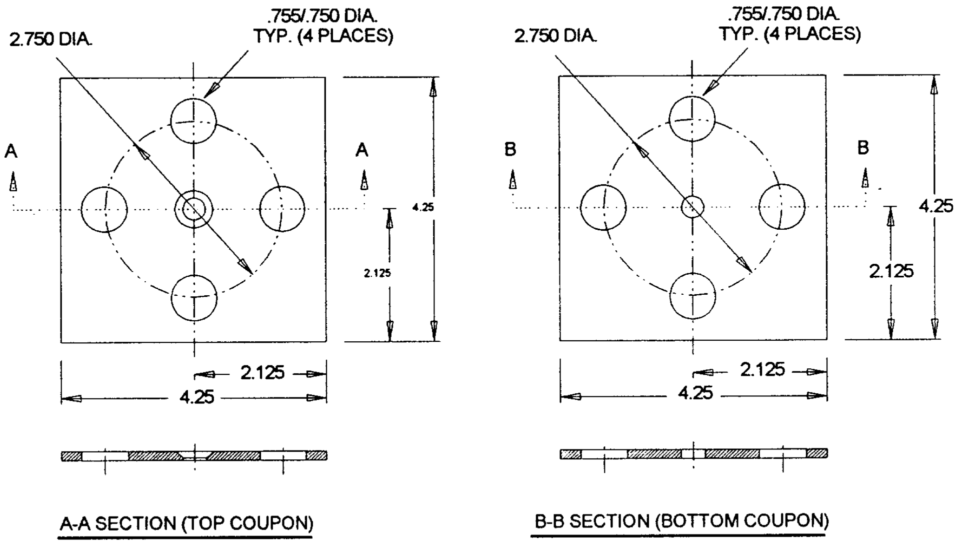
7.5.5.2 Summary of test methods

Both procedures use a flat square specimen with a constant rectangular cross-section. A centrally located hole is used to install a fastener, see Figures 7.5.5.2(a) and (b). For Procedure A additional 4 holes are needed on the periphery of the specimen to accommodate the test fixture, Figure 7.5.5.2(c).

Additionally, as can be seen from Figure 7.5.5.2(a), Procedure A requires two such square plates. The two plates are joined together by the fastener, with one plate being rotated 45° degrees with respect to the second plate, Figure 7.5.5.2(d). These plates are pried apart by compressive loads that are transmitted by the fixture of Figure 7.5.5.2(c) resulting in a tensile load on the fastener and compressive load on the composite plate. For Procedure B one plate is connected to a yoke, Figure 7.5.5.2(e). The yoke loads the fastener in tension creating a pull-thru force on the joint.

Both the applied load and the associated deformation are monitored in both procedures. A typical load deflection curve is shown in Figure 7.5.5.2(f). The deflection can be measured either by the relative cross-head displacement or by an extensometer. The first peak load observed on the load displacement curve defines the structural failure load.

Procedure A test is easily performed as most test laboratories have the fixture shown in Figure 7.5.5.2(c). The only critical point is the correct installation of the test fastener. Additionally the composite plates must be sufficiently stiff to transmit the compressive fixture loading without excessive plate bending or bearing damage.



100° TENSION HEAD

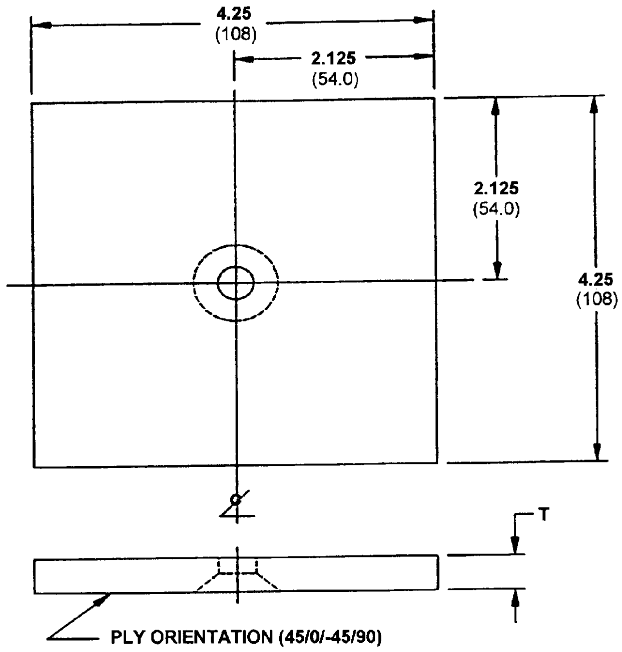
SHANK DIAMETER	T (1)
5/32	.096
3/16	.111
1/4	.150
5/16	.190
3/8	.229

130° SHEAR HEAD

SHANK DIAMETER	T (1)
5/32	.055
3/16	.061
1/4	.080
5/16	.106
3/8	.127

(1) NOTES: "T" IS A SUGGESTED MINIMUM SPECIMEN THICKNESS FOR TENSILE TESTING 100° & 130° FLUSH HEAD FASTENERS. THICKNESS DIMENSIONS REPRESENT STANDARD DESIGN CRITERIA THAT ALLOW THE COUNTERSINK TO PENETRATE A MAXIMUM DEPTH EQUAL TO 70% OF THE SHEET THICKNESS.

FIGURE 7.5.5.2(a) *Fastener pull-thru test plate for Procedure A.*



NOMINAL FASTENER SHANK DIA.	100° (1) TENSION HEAD "T"	130° (1) SHEAR HEAD "T"	CLEARANCE HOLE
5/32	0.096	0.055	1.312
3/16	0.111	0.061	1.500
1/4	0.150	0.080	2.000
5/16	0.190	0.106	2.500
3/8	0.229	0.127	3.000

(1) NOTES: "T" IS A SUGGESTED MINIMUM SPECIMEN THICKNESS FOR TENSILE TESTING 100° & 130° FLUSH HEAD FASTENERS. THICKNESS DIMENSIONS REPRESENT STANDARD DESIGN CRITERIA THAT ALLOW THE COUNTERSINK TO PENETRATE A MAXIMUM DEPTH EQUAL TO 70° OF THE SHEET THICKNESS.

ALL DIMENSIONS IN INCHES (MILLIMETERS)

FIGURE 7.5.5.2(b) *Fastener pull-thru test plate for Procedure B.*

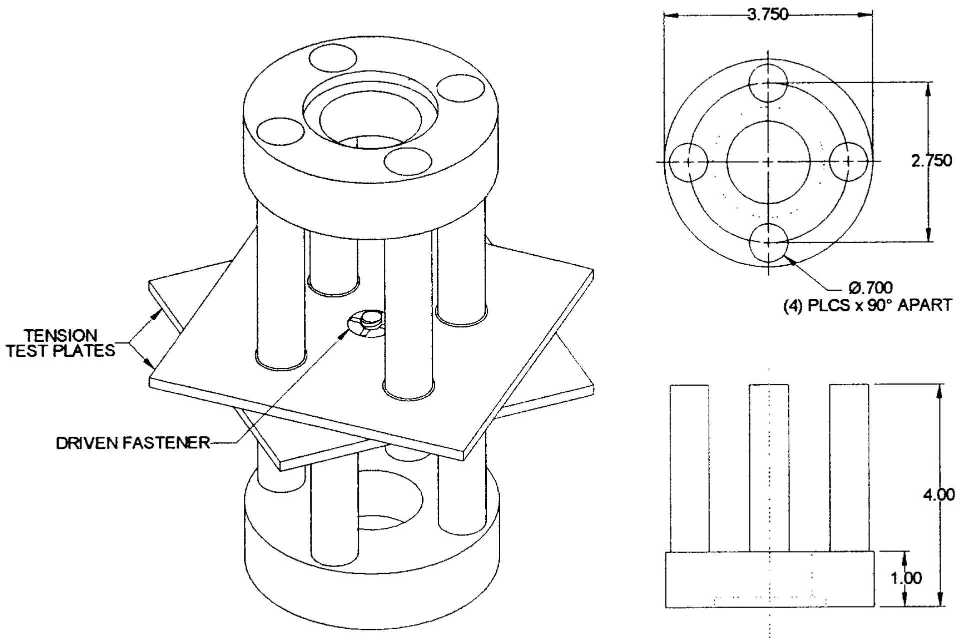


FIGURE 7.5.5.2(c) *Fastener pull-thru test fixture for Procedure A.*

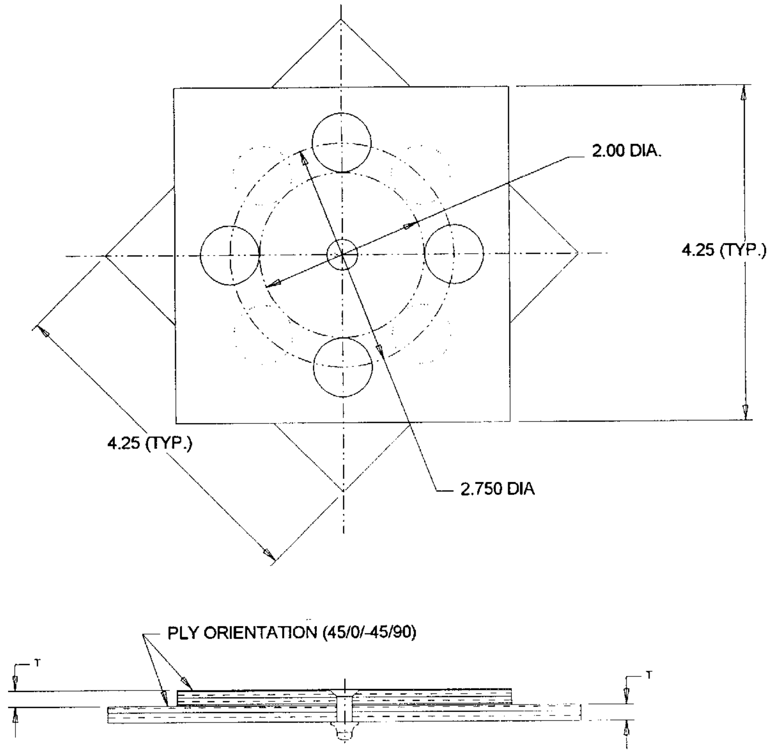


FIGURE 7.5.5.2(d) *Assembled test specimen for Procedure A.*

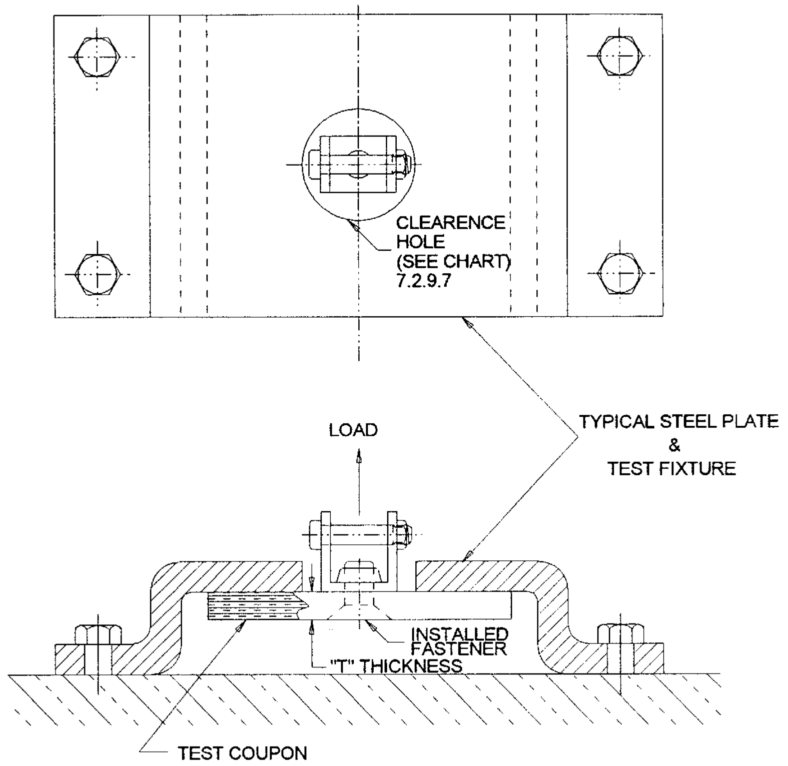


FIGURE 7.5.5.2(e) *Fastener pull-thru test fixture for Procedure B.*

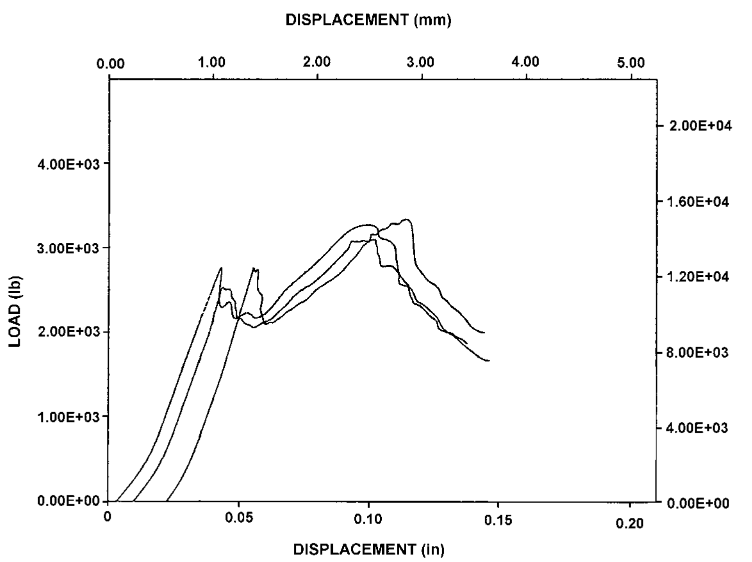


FIGURE 7.5.5.2(f) *Typical load deflection curve.*

7.5.5.3 Significance

Polymeric composites are weak in the transverse direction, therefore, the test to establish pull-thru characteristics has acquired more significance than for metal mechanical joints. Early tests using fasteners common to metal structures led to premature joint failures and resulted in development of fasteners specific for composite applications. These fasteners have larger heads and tails to reduce transverse compression stress on the composite laminate. Determination of the pull-thru strength of a particular composite/fastener joint design has become a normal requirement in the design and verification of a composite structure.

In addition to determining the pull-through strength of a particular composite plate/fastener combination, these procedures can also be utilized for evaluation of different fastener components such as bolt/nuts, pin/collars, or washers to satisfy pull-thru strength requirements.

7.5.5.4 Apparatus

Test Machine - Testing should be conducted using a universal test machine capable of applying tension or compression load at a controlled rate per ASTM E 8 guidelines (Reference 7.5.5.4(a)). The calibration system for the machine should conform to ASTM E 4, its accuracy verified every 12 months by a method complying with ASTM E 4 (Reference 7.5.5.4(b)). The ultimate failing loads of the fasteners/joints should be within the load range of the test machine as defined in ASTM E 4.

Deflection Measurement – Load-deflection response should be recorded autographically. The movement sensor should be installed to measure the relative motion between the movable cross-head and the stationary cross-head. If a measuring device is used it should be an averaging, differential transformer extensometer or equivalent. It should be used in conjunction with an autographic recorder and should have an accuracy of 0.5% of indicated joint deflection at loads equivalent to 70% of the anticipated joint's strength and be calibrated per ASTM E 83 (Reference 7.5.5.4(c)). Load and deflection ranges should be used that give the initial part of the load-extension curve a slope between 45° and 60°. Load and deflection ranges and scales should be held constant for each test group (test group is defined as specimens of the same configuration, fastener type and size and their baseline counterparts).

Test Fixture - The test fixture for the screening test should be as described in Figure 7.5.5.2(c) capable of transmitting compression loads to the test specimen. The fixtures should be parallel within 15 minutes of arc and capable of loading the specimen to fastener failure without experiencing local compressive deformation. The test schematic for a more structure-representative test is shown in Figure 7.5.5.2(e). A load cell capable of applying a tensile load is required.

7.5.5.5 Test specimen

Test specimen configuration should be in accordance with Figure 7.5.5.2(a) for Procedure A or Figure 7.5.5.2(b) for Procedure B. For Procedure A, the composite ply lay up should be similar to Figure 7.5.5.2(d). The ply orientation provides a balanced laminate having a quasi-isotropic (25%, 50%, 25%) distribution. The lay-up for Procedure B has been left open and should closely mimic the actual application.

7.5.5.6 Specimen assembly

Fastener Installation – Fasteners should be installed per the manufacturer’s recommendation or applicable process specification.

Grip Length – Fastener grip lengths should be selected to ensure full shank bearing through the total specimen thickness. Fasteners with load bearing tails that are formed during installation and bear against the composite test surface should be tested in both minimum and maximum grip conditions. This is because the effective bearing area may vary from one grip condition to the other.

Fasteners with manufactured heads used in conjunction with nuts or collars that do not change shape affecting the bearing surface being tested, should be tested in nominal grip condition.

Head Flushness – Unless otherwise specified flush head fasteners should be installed within ±.005 inches (±0.1 mm) from the composite surface.

7.5.5.7 Test matrix

A suggested test matrix to be used for fastener screening or development is shown in Table 7.5.5.7. Procedure A test specimen (Figure 7.5.5.2(d)) is to be used in conjunction with this test matrix that represents the required testing for one fastener configuration. The testing should be performed at room temperature, ambient and hot, wet conditions. The latter is defined as the highest temperature and moisture content for the composite material (see Section 2.2.8). The test matrix is to be repeated for a different fastener, head or tail configuration, and installation hole clearance. As used in Table 7.5.5.7, Class 1 is reserved for interference fit, Class 2 for aircraft quality, usually +0.003 in (+0.08 mm), and Class 3 for clearance fit.

A test matrix similar to Table 7.5.5.7 should be constructed for the Figure 7.5.5.2(e) test (Procedure B). However, as the test is more design-oriented, fewer variables need to be tested. The replication of 5 should be maintained.

7.5.5.8 Report

The test results should be reported in terms of structural failure load, load-deflection curve, and the observed failure mode.

7.5.6 Fastener-in-composite qualification tests

7.5.6.1 Overview

A first step in design of composite bolted joints is the identification of fasteners that are suitable for use with composites. The data generated by tests outlined in this section will provide a realistic basis for selection as the tests will give a good estimate of joint strength. Composites require fasteners with larger tail footprints (than metals), especially for blind fasteners; the tests described here will interrogate this feature. After fastener selection additional test data, enumerated in Sections 7.5.2 and 7.5.6, will be needed to design bolted joints for other laminates and failure modes that are not a function of specific fastener characteristics.

The test requirements and methods have been extracted from Sections 7.5.2 and 7.5.6, thus details of testing procedures can be obtained from those sections. Testing for fastener-in-composite qualification uses only one laminate lay-up (quasi-isotropic), but more than one thickness. Also, the testing is limited to room temperature as the environment is not a driver for fasteners as it is for composites. The test program is based on the assumption that the plates to be joined are both composites. If the particular fastener is also intended for use in metal/composite combinations, testing should be performed for that configuration. The test matrices reflect two properties most affected by fastener properties: joint bearing and pull-thru strengths. It is suggested that pull-thru tests be conducted first to determine the suitability of the fastener for composites. Once that property is satisfactory, the more expensive bearing tests can be undertaken. In aircraft industry, there is also a requirement established by aircraft manufacturers and certifying agencies that 25% of bearing and pull-thru tests be tested by someone other than the manufacturer of the fastener. For inclusion of data in the MIL-HDBK-5, the fastener must be in-use by at least one aircraft manufacturer. For completeness, test requirements for fastener shear and tensile strengths are included here, although these properties are independent of joining members.

TABLE 7.5.5.7 *Fastener pull-thru test matrix*.

GEOMETRY	COMPOSITE SHEET THICKNESS in. (mm)	LAY-UP	FASTENER NOMINAL SHANK DIAMETER in. (mm)	INSTALLATION HOLE CLASS	ENVIRONMENT (TEMP/% MOIST)	NUMBER OF TESTS (1)
COMPOSITE TO COMPOSITE	0.190 (4.83) Head side	25/50/25	0.250 (6.35)	Class 2	RT/ambient hot/wet	5 5
COMPOSITE TO COMPOSITE	0.120 (3.05) Tail side	25/50/25	0.250 (6.35)	Class 2	RT/ambient hot/wet	5 5
COMPOSITE TO METAL (2) (Metal on head side)	0.190 (4.83)	25/50/25	0.250 (6.35)	Class 3	RT/ambient hot/wet	5 5
COMPOSITE TO METAL(2) (Metal on tail or nut side)	0.160 (4.06)	25/50/25	0.250 (6.35)	Class 2	RT/ambient hot/wet	5 5

Notes: (1) Each grip condition where applicable (see Section 7.2.9.4).
(2) Metal thickness can be varied to accommodate fastener grip length.

Fasteners for use with carbon fiber composites should be titanium, A286 CRES or Monel to reduce the potential for galvanic corrosion. In some applications, particularly space applications, galvanic corrosion is not a problem. This limitation does not apply to aramid or fiberglass composites.

The data generated by the test program presented here will not be sufficient by itself to qualify a fastener for use in aircraft structures. Fatigue testing, manufacturing tolerances studies (grip lengths, seating angles, hole diameters) are the other criteria that have to be satisfied to complete fastener qualification requirements.

7.5.6.2 Fastener shear tests

These tests are conducted using steel plates per MIL-STD-1312, Test 13 for double shear and Test 20 for single shear (Reference 7.5.2.3.2). Evidence of previous valid qualification tests could be accepted here.

7.5.6.3 Fastener tension tests

These tests are conducted in steel plates per MIL-STD-1312, Test 8 (Reference 7.5.2.3.2). Evidence of previous valid qualification tests could be accepted here.

7.5.6.4 Fastener Pull-thru tests

Test specimen configuration to determine pull-thru strength should be in accordance with Figures 7.5.5.2(a), (b), and (c). The test procedures are given in Section 7.5.5. The test matrix, Table 7.5.6.4, requires testing for three different diameters representative of the applicability of the fastener. One diameter should be 0.25 in. This may require adjustments in laminate thickness; however, the laminate lay-up must be maintained as $(45/0/-45/90)_{ns}$. The test matrix is to be repeated for each fastener under consideration.

TABLE 7.5.6.4 *Fastener qualification pull-thru test matrix*[1].

Geometry	Composite Sheet Thickness in. (mm)	Lay-Up	Fastener Nominal Shank Diameter in. (mm)	Number of Tests[2]
Composite to Composite	0.190 (4.83)[3] Head Side	25/50/25	0.25 (6.4)	5
	0.120 (4.83)[3] Tail Side	25/50/25	0.25 (6.4)	5
	t2 Head Side	25/50/25	D2	5
	t2 Tail Side	25/50/25	D2	5
	t3 Head Side	25/50/25	D3	5
	t3 Tail Side	25/50/25	D3	5

Notes: [1]All tests to be performed at RT/ambient and with installation hole Class 2.
[2]Each grip condition where applicable (see Section 7.5.5.4).
[3]May be different for other diameters.

7.5.6.5 Bearing tests

The composite-to-composite two bolt bearing specimen geometry shown in Figure 7.5.2.3.2(b) is suggested. This single shear configuration is more representative of multi-fastener joints found in the industry. With an acceptable fastener, composite bearing failure should be achieved, although secondary fastener rotation about its longitudinal axis may be evident. The test matrix for fastener qualification is shown in Table 7.5.6.5. Three different thicknesses of one lay-up $(45/0/-45/90)_{ns}$ and three fastener diameters are suggested. One diameter should be 0.25 in. (6.35 mm) and the other two reflecting the range of available fastener sizes. Selection of additional thicknesses of the composite members should stay within these guidelines to assure maximum usefulness of data: (1) $0.8<D/t<2$ and (2) countersink depth should not exceed 0.67 of total laminate thickness. The goal of the tests is to obtain a family of three curves of bearing stress versus D/t ratio for each diameter tested. There should be 15 data tests for each diameter. The test matrix is to be repeated for each fastener under consideration.

TABLE 7.5.6.5 *Fastener qualification bearing test matrix[1].*

Geometry	Thickness in. (mm)	Lay-Up	Bolt Diameter in. (mm)	Number of Tests
Composite	0.2 (5)	25/50/25	0.25 (6.4)	5
to	0.2 (5)	25/50/25	D2	5
Composite	0.2 (5)	25/50/25	D3	5
Composite	t2	25/50/25	0.25 (6.4)	5
to	t2	25/50/25	D2	5
Composite	t2	25/50/25	D3	5
Composite	t3	25/50/25	0.25 (6.4)	5
to	t3	25/50/25	D2	5
Composite	t3	25/50/25	D3	5

Note: [1] All tests are to be performed at RT, ambient.

7.5.6.6 Data presentation

Data presentation should follow the guidelines of Volume 2, Section 1.4.2. Additionally, bearing data should be presented as plots of bearing strength vs. D/t for each diameter tested.

7.5.7 Bearing/mechanical joint test methods for MIL-HDBK-17 data submittal

For bearing strength, test data obtained from ASTM D 5961 are publishable in MIL-HDBK-17 either as double shear values, Procedure A, or single shear values, Procedure B. For design values the two bolt specimen is more representative of actual joints.

No bearing/by-pass method is recommended, however, a test method that measures the by-pass load directly will produce acceptable data for MIL-HDBK-17.

Shear-out strength values are acceptable for MIL-HDBK if obtained from the bearing tests of ASTM D 5961. The failure mode for these tests must be distinctly observed as shear-out and not bearing.

Pull-thru strength test data from Procedure A of Section 7.5.5 is acceptable for inclusion in MIL-HDBK-17. Data obtained using Procedure B, although acceptable for establishing design values, may be very configuration dependent and hence not usable for others.

7.6 BONDED JOINT TESTS

7.6.1 Overview

In principle, bonded joints are structurally more efficient than those that are mechanically fastened. Bonded joints eliminate hole drilling for fastener installation resulting in a structure without notches that cause stress concentrations. Composite structures can have bonded joints fabricated by three different processes: secondary bonding, co-bonding, and co-curing. Secondary bonding uses a layer of adhesive to bond two pre-cured composite parts. Thus, this type is most similar to metal bonded joints in structural behavior and fabrication method. Co-curing is a process wherein two parts are simultaneously cured. The interface between the two parts may or may not have an adhesive layer. In the co-bonding process one of the detail parts is pre-cured with the mating part being cured simultaneously with the adhesive. Surface preparation is a critical step in any bonded joints and must be clearly defined before any bonding is performed. This is particularly important in secondary and co-bonding processes. More detail on bonded joint fabrication is given in Volume 3, Section 2.9.

The type of bonded joints addressed in this section are secondarily bonded and co-bonded. For these types of joints, knowledge of mechanical properties, particularly stiffness of the adhesive, is a design imperative. Well designed adhesive joints in aircraft structures are not critical in the adhesive layer but in the adherends, whether they be metal or composites, but this does not obviate the need to know the strength capability of the adhesive in shear and tension. The composite adherends are in most instances well constructed laminates with sufficient number of plies in the principal load directions ensuring that the failure mode is fiber dominated. The properly selected adhesives are formulated to be much more ductile than the resins used as matrices in composites as they are not required to provide support to fibers, particularly under compressive loading, thus steering the joint failure to the adherends. The fibers also constrain the resin so that the behavior of the matrix is also more brittle than the resin by itself. This may shift the composite bonded joint failure to a transverse, through the thickness, tensile failure of the composite laminate.

Two distinct type of tests are needed to characterize the behavior of a bonded joint and obtain sufficient mechanical data to perform structural analysis. It is assumed that the mechanical properties of the composite adherends are known. For simplicity and standardization goals, the tests to determine adhesive properties make use of metal adherends. The results of these tests provide properties of adhesive for design and analysis, comparative data, surface preparation effectiveness, but in no way represent the strength of a composite structural bonded joint. This is obtained by testing specimen configurations with composite and/or honeycomb adherends that are more application representative. Both types of testing are discussed in the sections that follow.

7.6.2 Adhesive characterization tests

Adhesive strength and stiffness data is required if successful bonded joints are to be designed. As adhesive behavior is elastic-plastic, it is not sufficient to characterize the adhesive by ultimate strength and initial tangent modulus. The data that are needed include stress-strain curves in shear and tension at the service temperature and humidity environments.

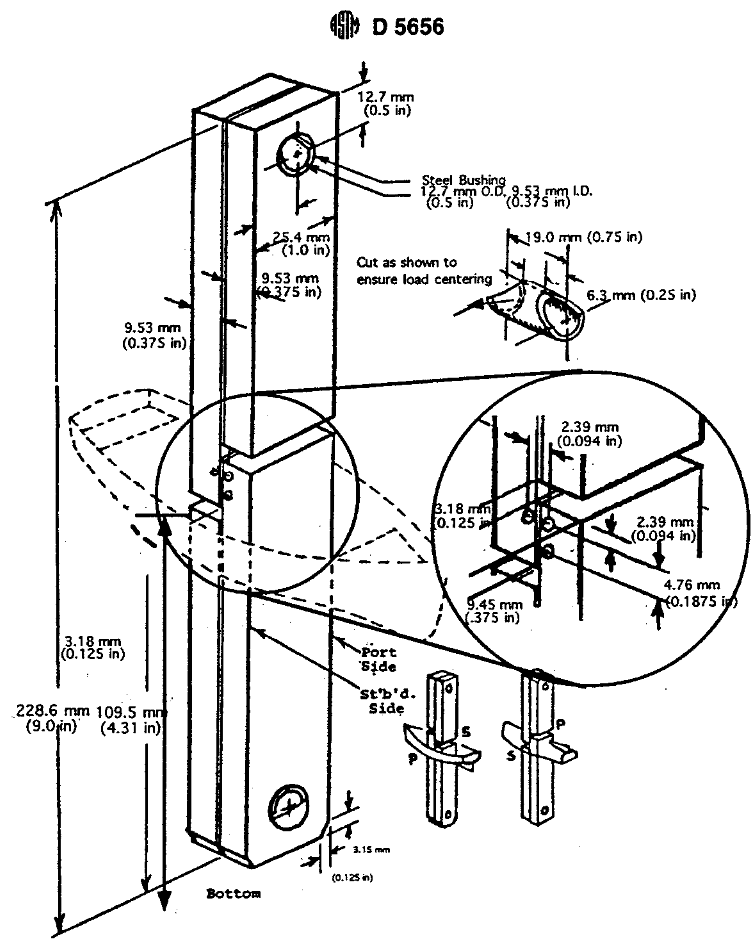
The test methods that are currently favored by the industry to obtain these data are the thick adherend test for the shear properties that was pioneered by Krieger (Reference 7.6.2 (a) and 7.6.2 (b)) and resulted in ASTM D 5656, and the ASTM D 2095 (Reference 7.6.2 (c)) test for the tensile strength by means of bar and rod specimen. None of the tests are completely satisfactory for various reasons. However, as they have gained widespread usage, it is deemed useful to have them referenced in this chapter.

Moisture conditioning of adhesive specimens to equilibrium (uniform moisture content of the entire bondline) before wet testing requires prohibitive duration times - several years. This is because of low values of moisture diffusivity of common adhesives and the use of test specimens with moisture impervious metal adherends for which water can only enter the adhesive through exposed bondline edges. Fortunately, adhesive failures usually initiate at bond edges, due either to shear stress peaking or to peel (tensile) stresses. Thus, as long as a reasonable depth of adhesive near the edges has approached the desired equilibrium moisture level, test results will be representative of a fully equilibrated bondline. The common practice of exposing test specimens to the required relative humidity at reasonably high temperatures (160 to 180°F (71-82°C) for epoxies) for 1000 hours (42 days) achieves this goal. An alternative method to determine the effect of absorbed moisture on adhesives is to use cast adhesive neat resin specimens and perform tension and compression tests. As in this case the entire specimen is exposed, the times to reach equilibrium are significantly less.

7.6.2.1 Shear tests

7.6.2.1.1 ASTM D 5656 (thick adherend specimen)

This test method uses the KGR-1 extensometer that is attached to a specimen of geometry shown in Figure 7.6.2.1.1(a). Typical data obtained by this test is shown in Figure 7.6.2.1.1(b) for one adhesive at different temperatures. Because of KGR-1 design and use of aluminum adherends, the test method is limited to 300°F (150°C). For higher temperature applications titanium adherends have been used to increase the usable temperature of the method.



NOTE—Asymmetry obviates "left-right" covention. Ship terms retain identity of test site when specimen is rotated or inverted.

FIGURE 7.6.2.1.1(a) *Thick adherend specimen (Figure 2 from D 5656).*

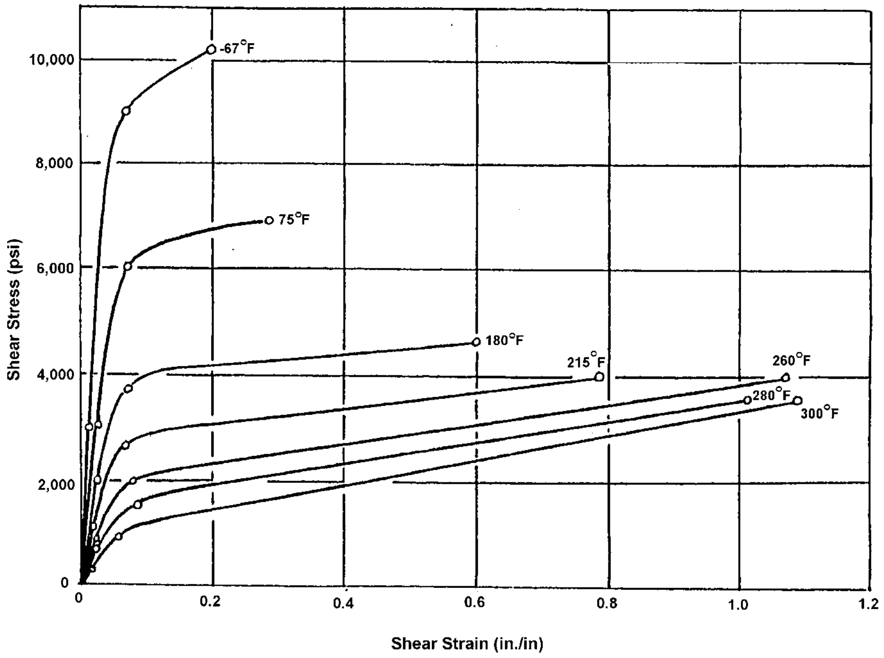


FIGURE 7.6.2.1.1(b) *Shear stress-strain response of FM 300 K adhesive at different temperatures in °F.*

How to interpret the shear stress-strain curves of Figure 7.6.2.1.1(b) in terms of adhesive shear modulus has been a subject of numerous papers. Krieger in Reference 7.6.2(a) states that only a small correction for adherend deformation is needed to obtain adhesive properties and that by characterizing the stress-strain curve using three points, all the necessary information for design of bonded joints with the particular adhesive is determined. These three points are shown in Figure 7.6.2.1.1(c). A more extensive analysis of the test method and the associated measurement device was performed by Kassapoglou and Adelmann in Reference 7.6.2.1.1(a). They found the method to be reasonably accurate for soft adhesives, but suggest some improvements for other situations. However, their conclusions are limited to the elastic range and the method is considered quite adequate for measuring stress-strain response in the plastic (large deformation) region. Reference 7.6.2.1.1(b), using Moire' fringe interferometry, validated Krieger measurements, but found the method susceptible to loading eccentricities which causes early failure and large scatter in modulus measurement. Reference 7.6.2.1.1(b) also suggested using a strain gage at the geometrical center of the bondline instead of the KGR-extensometer if the data of interest is the initial tangent modulus.

For bonded joint stress analysis, the test stress-strain curves of Figure 7.6.2.1.1(b) are sometimes further simplified to a perfect elastic-plastic material response, as described in Reference 7.6.2.1.1(c). Thus, the stress-strain data as obtained by the thick adherend test, although not 100% correct, is of sufficient accuracy for the current design and analysis methodology.

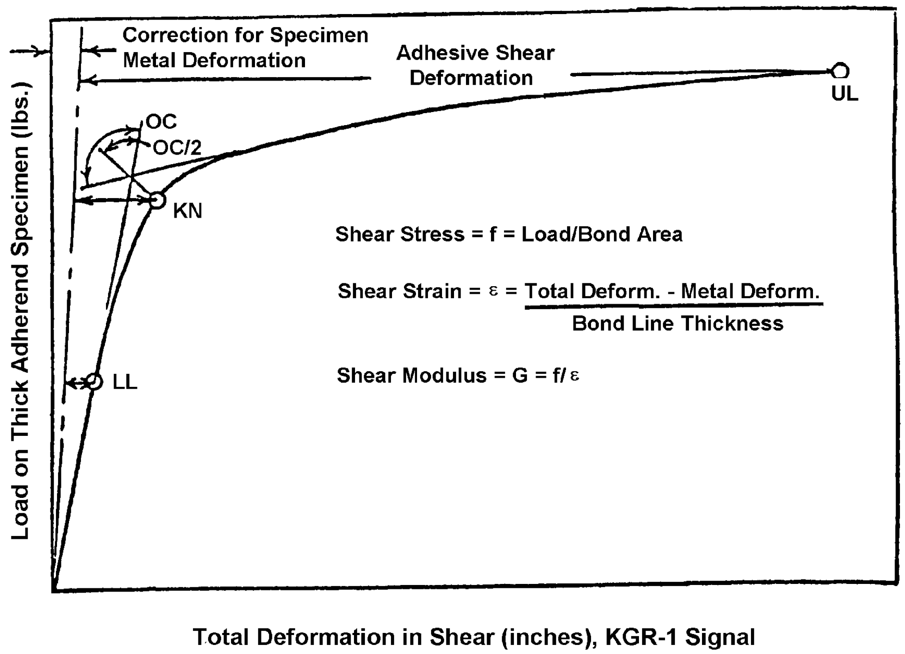


FIGURE 7.6.2.1.1(c) *Load deformation curve with critical points to determine elastic-plastic response.*

7.6.2.1.2 ASTM E 229 (tubular specimen)

An alternate method to obtain shear strength and stiffness is by use of a tubular specimen loaded in torsion. The basis of the test is a narrow, annular ring of adhesive subjected to uniform shear loads around the circumference. Because the thickness of the tube is small compared to its radius, the shear stress across it is considered constant. Although the test provides pure shear distribution, the test apparatus is complex and specialized testing know-how is required which have led to the disuse of this test method. A test method utilizing the tubular specimen is the ASTM E 229 Standard Test Method (Reference 7.6.2.1.2). It uses narrow but large diameter adherend tubes and measures angle of twist by an Amsler Mirror Extensometer. Details of the test are described in the standard.

7.6.2.1.3 ASTM D 1002 (thin single lap spec. - QA test only)

The single lap shear test described in the ASTM D 1002 is a test that is widely used for comparative evaluation of the adhesive and for qualification and incoming inspection purposes. The test is also useful to evaluate surface preparation procedures as this test uses metal adherends. The main attribute of this test is that it is easy to fabricate and test.

Limitations of this test are

Shear Strength – The maximum shear stress obtained from this test (maximum load divided by bond area) has no relation to the adhesive shear strength. The stress field in the adhesive has a large component of peel stress that contributes to the specimen failure. The apparent shear strength will also be a function of the adherend modulus and its thickness. Because the apparent shear strength will vary with adherend modulus and thickness, for comparative purposes, the specimen configuration should be kept constant. ASTM D 4896 should be consulted for interpretation of test results.

Shear Stiffness – The test cannot measure adhesive stiffness because of large bending inherent in the specimen.

Joint Realism – Because the adherends are metal, the test cannot simulate failure modes of a composite to composite bonded joint. Surface preparation and adhesion are completely unrepresentative of a composite to composite bonded joint. Furthermore, as the process to fabricate composite bonded joint will be quite different to the fabrication of this metal to metal lap joint, this specimen cannot be used for in-process control.

To address the problem of joint realism, the ASTM D 1002 has been modified to admit composite adherends. ASTM D 3163 is the resulting standard. This standard, however, has all the other limitations of ASTM D 1002. When using this standard, in addition to thickness, the lay-up of the composite material must approximate the joint laminate as the apparent shear strength will vary with lay-up. For composite applications, the use of this standard is preferable if the properties of the adhesive/adherend interface characterization are of interest. If the primary purpose is adhesive characterization, then ASTM D 5656 should be used.

7.6.2.2 Tension tests

7.6.2.2.1 ASTM D 2095

Tensile strength of the adhesive can be obtained by the ASTM D 2095 method, Figure 7.6.2.2.1 (Reference 7.6.2(c)). Either bar or a rod specimen can be used in this test method. The design of the specimens and specimen preparation is described in ASTM Recommended Practice D 2094 (Reference 7.6.2.2.1(a)). The tensile strengths obtained by this test method should be used with caution as the test specimen is susceptible to peel initiated failure at the specimen edges. The adhesive failure strength can be used in an approximate peel analysis as proposed in Reference 7.6.2.2.1(b). As good bonded joint design practice minimizes peel stresses, the exact knowledge of tensile strength capability is not that critical.

An independent measurement of the Young's modulus of the adhesive is needed as the adhesive often does not obey laws of isotropic materials and can not be obtained from shear modulus measurement, i.e., $G = E/2(1+\nu)$.

7.6.2.3 Fracture mechanics properties

Another approach to determining the behavior of bonded joints is to use fracture mechanics. This analysis and failure criteria requires testing to obtain critical strain energy release rates in modes I and II. The tests to be performed are described in Section 6.8.6.

7.6.2.4 Suggested adhesive characterization test matrix

Tests for adhesive properties should be performed at room temperature, ambient conditions, and at low and high usage temperature extremes as discussed in Section 2.2.8. The replication should be a minimum of five at each test condition.

7.6.3 Bonded joint characterization tests

Tests of bonded joint configurations representative of actual joints must be tested to validate the structural integrity of the joint. As these specimens quickly become point design oriented, it is difficult to standardize. Thus the discussion will be limited to the simplest specimens which contain the important parameters of the bonded composite joint: geometry, composite laminates and/or metal adherends, adhesive, fabrication process, and quality control procedures.

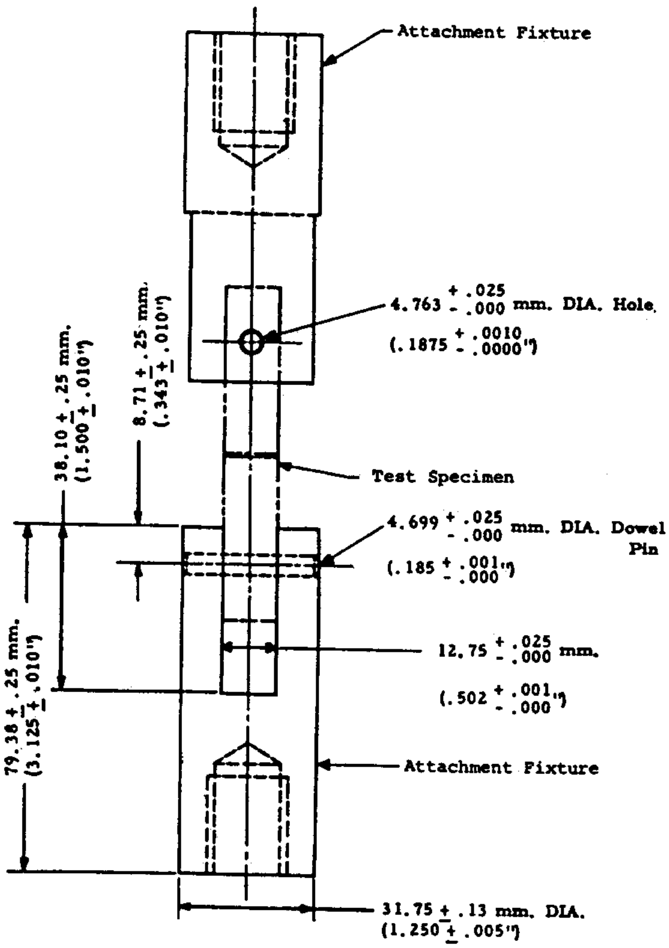


FIGURE 7.6.2.2.1 *Test specimens and attachment fixtures.*

7.6.3.1 Honeycomb to face sheet flatwise tension test (ASTM C 297)

For honeycomb construction there is a need to determine the strength of the bond between the core and the facings of an assembled sandwich panel. ASTM C 297 is the test most commonly used by the industry (Reference 7.6.3.1). The specimen and test assembly is shown in Figure 7.6.3.1. The specimen size is usually 2 by 2 in., but can be round. It is important to use the same processing to fabricate the specimen as for the actual component in order to have meaningful results. This test does not determine adhesive tensile strength, but does give an indication how well the adhesive wets the walls of the honeycomb. The failure mode should be recorded, as for some configurations the bond has a higher tensile strength than the honeycomb itself. In most applications the honeycomb-to-facesheet bond has higher strength than the core, but for this test, to induce bond failures higher strength core should be used. The main difficulties encountered with this specimen are bonding of the fixture to the face sheet, especially at elevated, wet environmental conditions, and maintaining parallelism between the fixtures and the specimen.

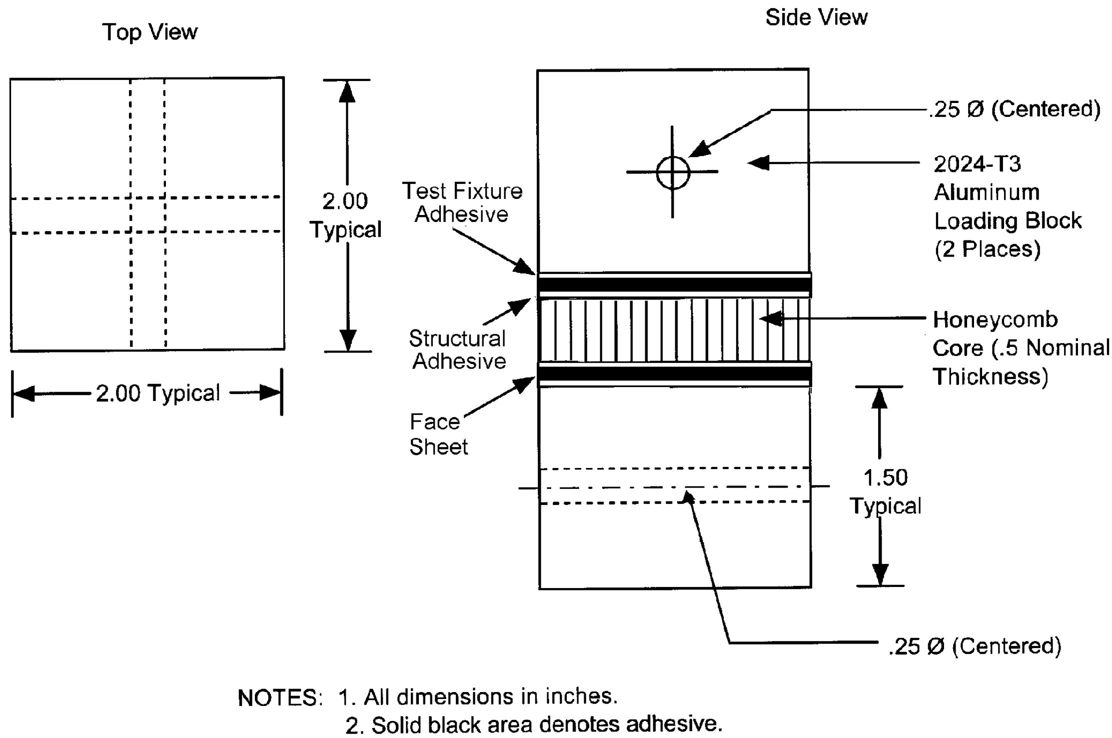


FIGURE 7.6.3.1 *Flatwise tensile loading fixture and specimen.*

7.6.3.2 Skin to stiffener bond tests

To assess the strength of skin-to-stiffener bonded joints in situations where out-of-plane loads are being developed, i.e., fuel pressure, post-buckling, fairly simple tests are being used in the industry. Although these tests cannot completely represent the behavior of the actual structure, they provide design data and early assessment of the adequacy of selected materials and geometry before commitment to large component validation tests. The maximum benefits from these tests are obtained when the specimens represent as closely as possible the geometry and fabrication processes of the simulated component. The schematics of two such tests are presented here. The "T" pull-off test shown in Figure 7.6.3.2(a) is similar to the ASTM C-297 except that only one block is needed. Because the bending of the skin and stiffener flanges are suppressed by the rigid loading block, the disbond failure will generally occur in the heel of the stiffener and not at the flange ends. This is a serious deficiency of the specimen, if in component tests the failure is at flange ends. The location of the failure is strongly dependent on the ratio of stiffener/skin stiffness; the lower the ratio, the more useful is the test.

Using rollers to resist the pull-off load instead of the rigid block, Figure 7.6.3.2(b), can be a better method if the skin is more flexible. There is the problem how far apart to place the rollers to match the skin displacement. The specimen in Figure 7.6.3.2(b) can be used to apply a moment to the bonded joint. This is represented by P1 loads and R1 reactions in Figure 7.6.3.2(b). Post-buckling of shear panels introduces significant twisting moments in the interface and the capability of the joint against them must be determined as part the structural analysis.

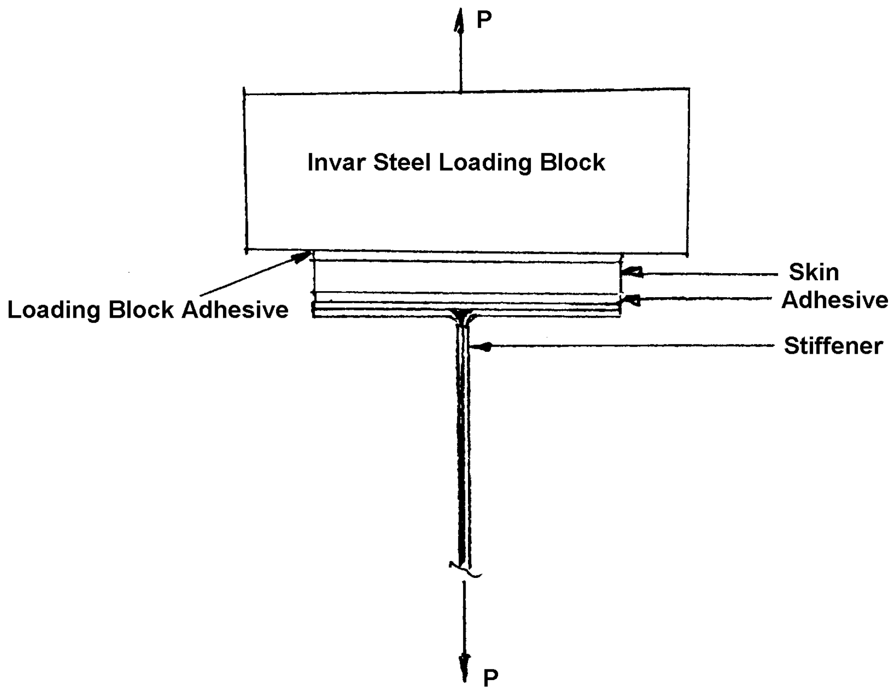


FIGURE 7.6.3.2(a) *"T" pull-off specimen.*

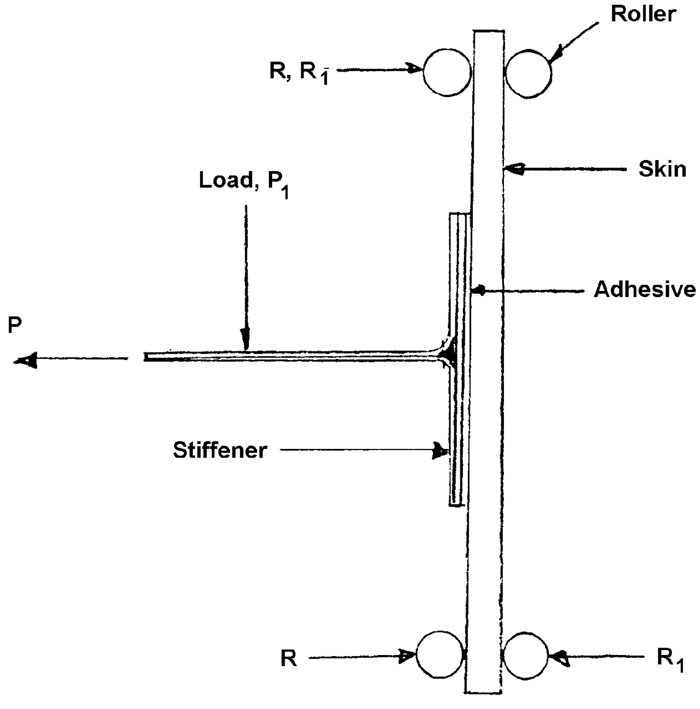


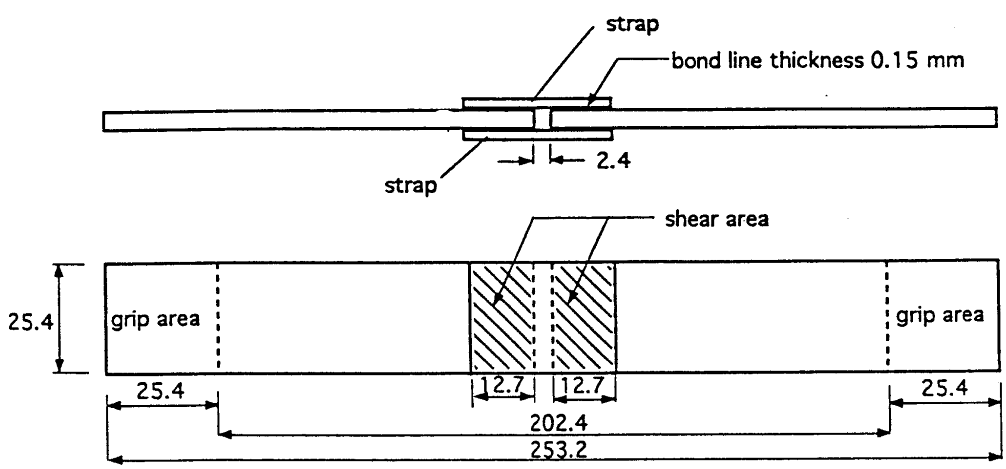
FIGURE 7.6.3.2(b) *"T" twist-off specimen.*

7.6.3.3 Double overlap joint tests

Double overlap specimens range between single step type to ones containing many steps and are usually loaded in tension. The complexity being dependent on what type of data is to be obtained or the structural application. An example of a specimen derived from ASTM D 3528 - 92 (Reference 7.6.3.3) is shown in Figure 7.6.3.3(a). This test specimen is useful for determining adhesive shear strength as the double shear configuration reduces peel stresses. This configuration is not usually used in design, as the load transfer capability can be increased significantly by tapering the outside adherends.

For higher load transfer, double lap joints will contain many steps. To validate such a joint, specimens of a type shown in Figure 7.6.3.3(b) have been used. These type of specimens are quite expensive to fabricate and hence are not replicated in large numbers. As these specimens are to represent a particular design, care must be taken that the specimen is manufactured using the same processes as the actual joint. Another example of a joint verification specimen is shown in Figures 7.6.3.3(c) and (d). It represents a chordwise connection between a composite skin and a titanium spar and is a double lap two-step joint.

The multi-step joint specimen could be converted to scarf joint specimen if that was the actual design.



Adherend:

Carbon/Epoxy [0]16
or Carbon/Epoxy [0/90/-45/45]2s

Strap:

Carbon/Epoxy [0]8
or Carbon/Epoxy [0/90/-45/45]s

All dimensions in mm

FIGURE 7.6.3.3(a) *Geometry and materials of the double-lap test specimens.*

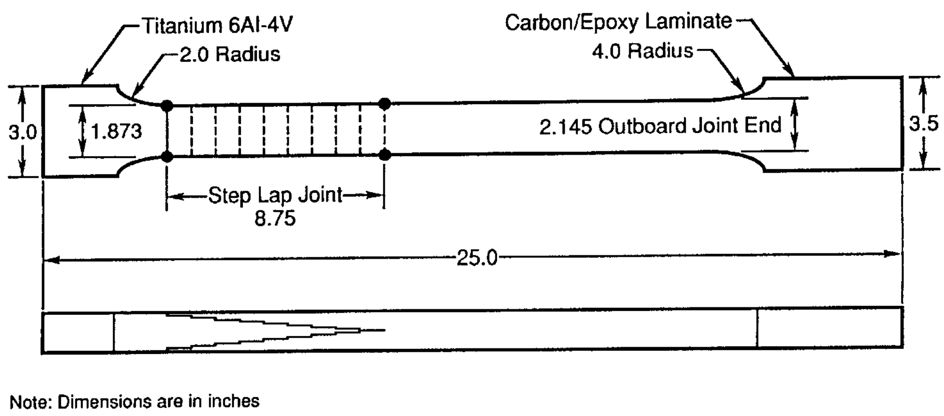


FIGURE 7.6.3.3(b) *Step lap joint specimen example.*

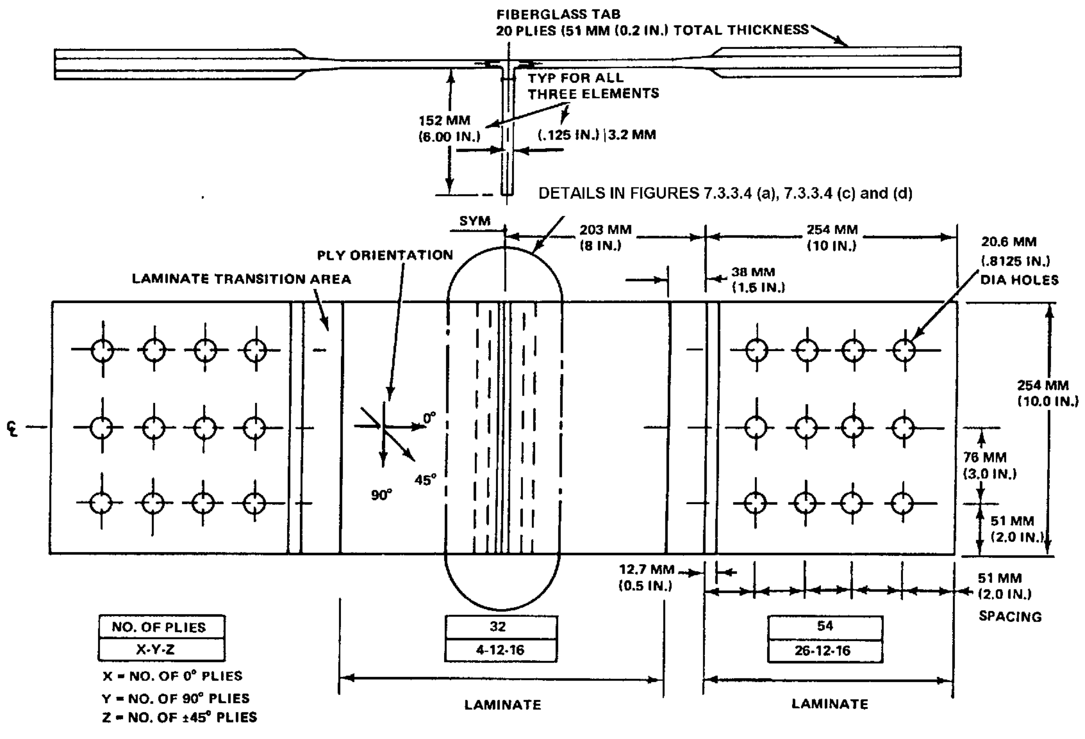


FIGURE 7.6.3.3(c) *Specimen configuration.*

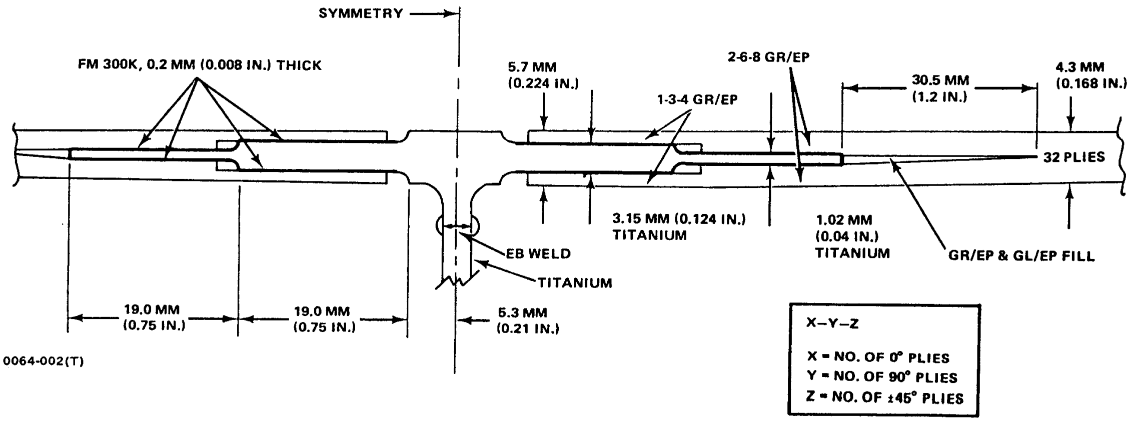


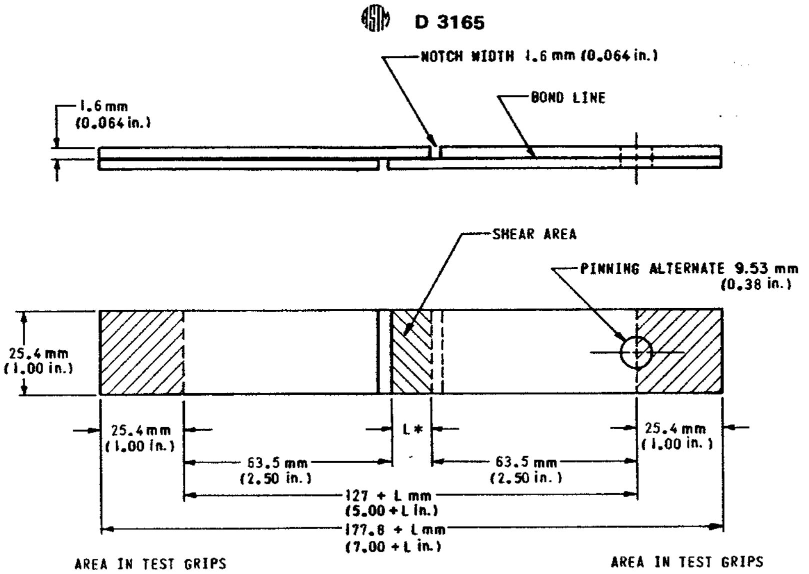
FIGURE 7.6.3.3(d) *Concept A detail, two-side stepped joint.*

7.6.3.4 Single overlap joint tests

Single overlap specimens are similar to those described in the above section. However, because single overlap specimens induce additional peel stresses due to bending, the length of the joint must be longer to minimize that effect. This effectively eliminates usefulness of single step specimens to determine strength property of realistic joints. Single step single overlap joints, however, are used for comparison between different adhesives and for quality control. Two different approaches to minimize peel stresses in single lap test specimen are described in this section. The ASTM D 3165 method minimizes peel by keeping the load line in the adhesive layer similarly to the single shear bearing tests of ASTM D 5961, Procedure B. The second approach, exemplified by European Aircraft Industry Standard prEN 6066, reduces peel stresses by easing the load into the joint by scarfing or by multiple small steps.

7.6.3.4.1 ASTM D 3165

This method measures comparative shear strength of adhesive joint when tested using single lap specimen of Figure 7.6.3.4.1. This specimen is used widely in the industry as an alternative to the ASTM D 1002 or ASTM D 3163 as it reduces the peel stresses in the lap while retaining the interface realism of a composite bonded joint. All the limitations enumerated for ASTM D 1002 in Section 7.6.2.1.3 are applicable here. For composites, there is an additional difficulty in fabricating this type of specimen. The usual procedure of machining the notch can be substituted by placing a spacer in the notch area and laying-up separate laminates. Both manufacturing methods need trained composite engineers and mechanics to establish a manufacturing process that will result in useful specimens.



NOTE—*L = length of test area. Length of test area can be varied. Recommended length of lap is 0.50 ± 0.01 in. (12.7 ± 0.3 mm).

FIG. 1 Form and Dimensions of Test Specimen.

FIGURE 7.6.3.4.1 *Form and dimensions of test specimens.*

7.6.3.4.2 European Aircraft Industry Standard EN 6066

A 1 in. (25 mm) wide multi-step or scarfed specimen has been developed for bonded joint characterization. This specimen, shown in Figure 7.6.3.4.2(a) is referenced in a preliminary European Aircraft Industry Standard EN 6066 (Reference 7.6.3.4.2). This standard also defines types of failures that are possible with such a specimen, Figure 7.6.3.4.2 (b). This testing standard has been called out for obtaining qualification data for a wet lay-up repair material.

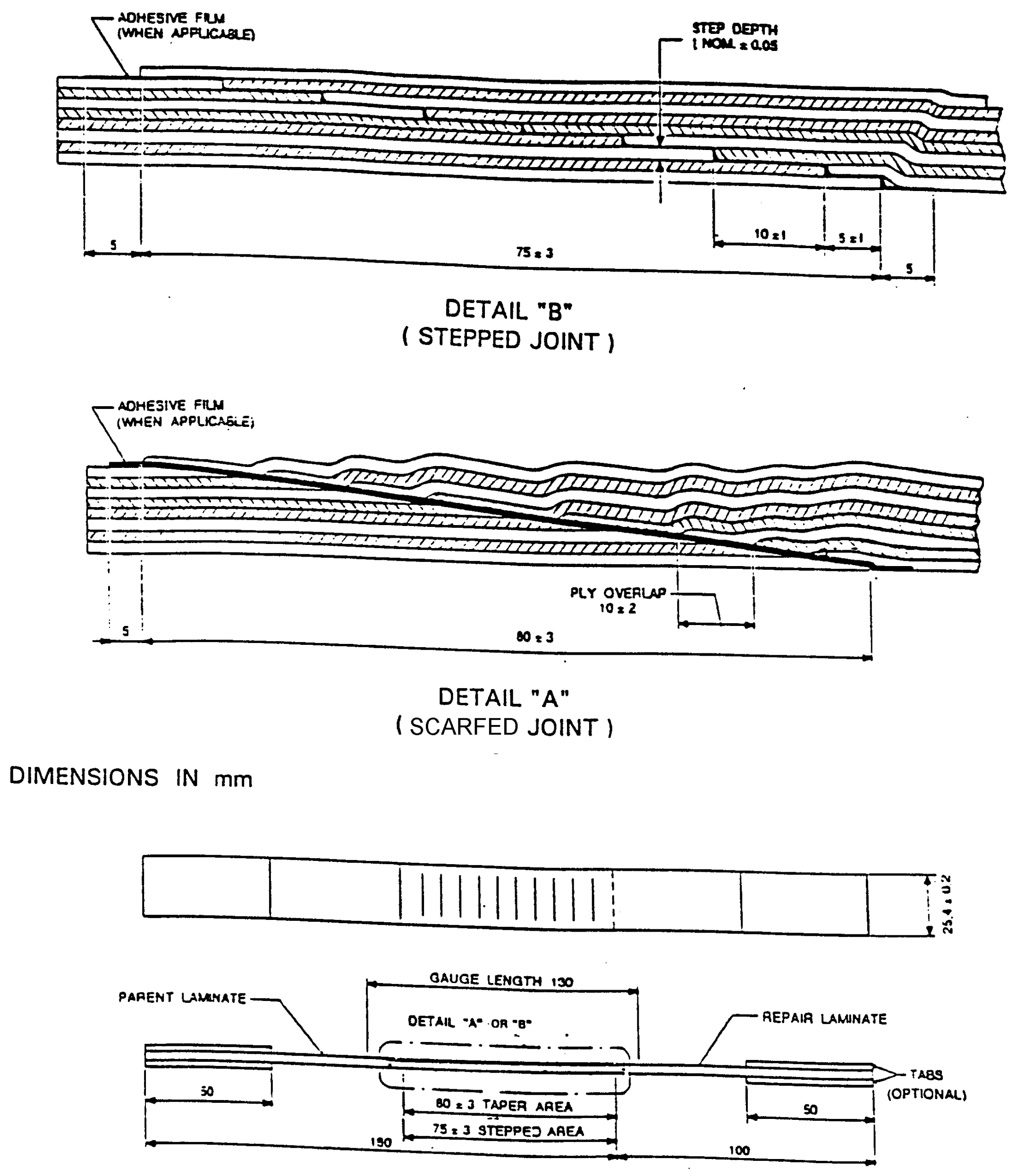


FIGURE 7.6.3.4.2(a) *Scarfed and stepped joint specimens.*

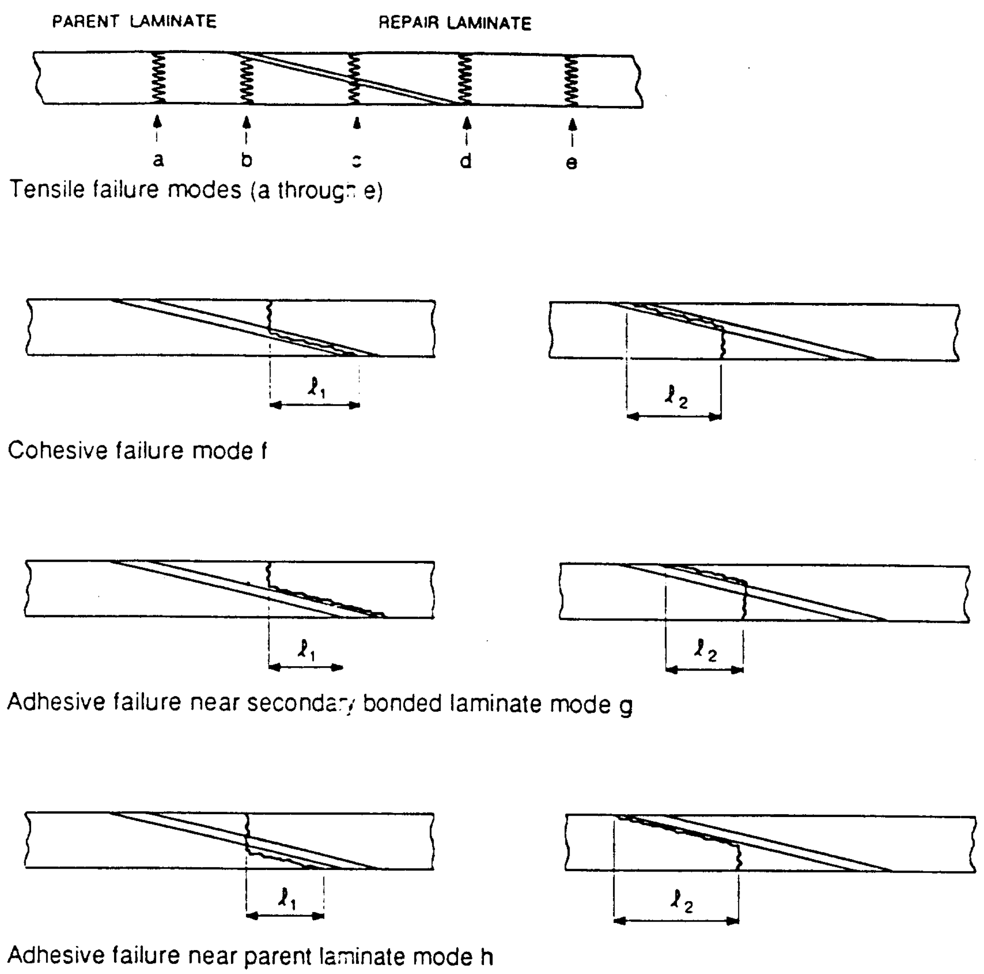


FIGURE 7.6.3.4.2(b) *Determination of failure modes and dimensions for joint specimens (Reference 7.6.3.4.2).*

7.6.3.4.3 Other examples

Two-step and scarfed verification specimens are shown in Figures 7.6.3.4.3(a) and (b) for the same spar to skin joint shown in Figure 7.6.3.3.3(b). Such specimen should be developed to validate any major joint design.

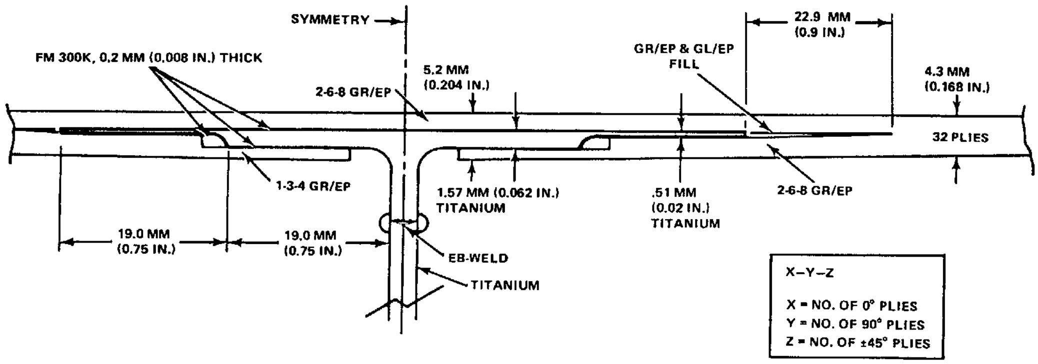


FIGURE 7.6.3.4.3(a) *Concept B detail, one-side stepped joint.*

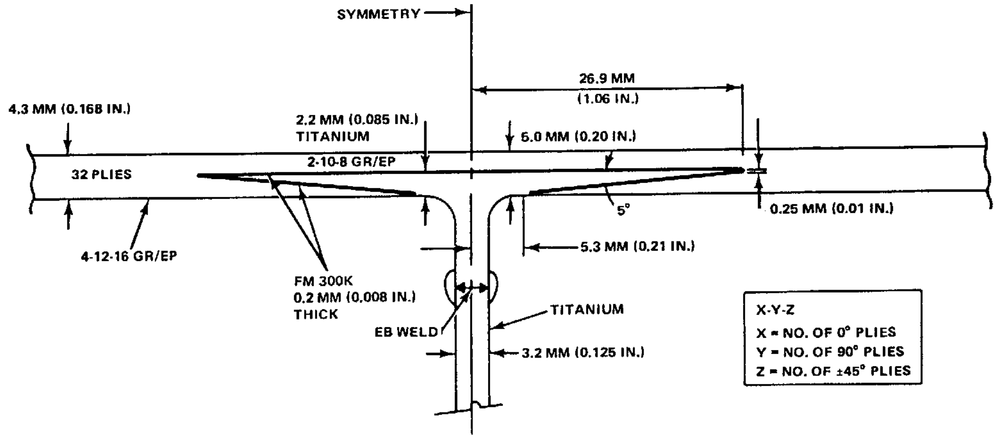


FIGURE 7.6.3.4.3(b) *Concept C detail, scarf joint.*

7.7 DAMAGE CHARACTERIZATION

7.7.1 Overview

Damage characterization is a key parameter in the use of composite materials in aerospace applications. Unlike traditional metallic materials, composites vary in strength depending on direction and lay-up. They can also be relatively brittle. Interlaminar tensile and shear strengths are especially low compared to isotropic metallic materials. Damage such as internal delaminations may not even be visually apparent. This combination of attributes makes consideration of damage characterization a key factor in the use of composite materials. Approaches for consideration of damage in design and certification are found in Section 5.0 of Volume 3.

Damage characterization can be divided into two issues, the resistance of a material to damage from impact (damage resistance), and the ability of a material or structure to perform safely after damage (damage tolerance). Damage can occur while handling during the manufacturing process, while in use or during maintenance procedures. This damage can be the result of manufacturing defects, foreign body impacts such as rocks or ice, or tool drops. This section will outline impact and indentation tests that are commonly performed to evaluate the damage resistance and tolerance of candidate materials. Crack growth, micro-cracking and fatigue tests are discussed elsewhere in this handbook.

7.7.2 Damage resistance

Damage resistance of a material is commonly considered to be the resistance of the material to impact damage in aerospace applications. Impacts may arise from dropped tools, foreign objects such as rocks on runways, from hail and ice, and from ballistics. Impact testing is commonly used to screen materials for damage resistance and tolerance and as a part of larger sub-element and element tests performed during certification.

Simulation of all these conditions may require testing at differing energy levels, velocities, impactor geometries, and support conditions.

7.7.2.1 Falling weight impact

Another common method for investigating impact resistance is the falling weight test. This type of impact is included as a portion of the Compression After Impact (CAI) testing discussed in Section 7.7.3. Generally, a flat panel is impacted normal to its surface. Commonly, 0.5 inch to 1 inch (12.7 to 25.4 mm) diameter hemispherical tups are used. Quasi-isotropic laminates approximately 0.2 to 0.4 inch (5.08 to 10.16 mm) thick are often used to screen materials for aircraft structural applications. The energy of the weight at impact is given by the classical equation.

$$E = \tfrac{1}{2} mv^2 = mgh$$

E = energy
m = mass
v = velocity
g = gravitational constant of 9.8 m/sec^2 or 32 ft/sec^2
h = drop height

Since g is constant, energy levels for the falling weight test are generally given in foot-pounds or foot-pounds per inch of thickness. With variations of velocity of the falling weight, the damage may vary with even constant energy. This phenomenon is related to the type of damage, the rate it propagates in the specimen and the deformation of the specimen during impact.

The falling weight used for CAI testing is generally dropped from a few feet, with a mass of 10 to 20 pounds, and is considered a low velocity impact. Low velocity tests such as a falling weight do not adequately simulate ballistic damage. Occasionally investigators may accelerate the drop with elastic cords to gain a somewhat higher velocity. If very low velocity impacts are to be studied, a long fulcrum pendulum may be used to impact the specimen with a much higher mass.

Following the impact, an assessment of the damage must be performed. Criteria for damage assessment may include measurement of the visually apparent damage area, measurement of dent depth, and non-destructive evaluation, such as C-Scan, for the internal damage area. Following this assessment, additional mechanical tests such as CAI or fatigue may be performed.

Sources of Experimental Error

1. The velocity may be slower than predicted due to friction on the guide rails/tube. To ensure accuracy the actual weight velocity should be measured just prior to impact.

2. Steps should be taken so the weight does not bounce and impact the specimen more than once.

3. The amount of damage will be dependent on the specimen support conditions, such as clamping arrangements. These must be reproduced very carefully. The overall stiffness of the base of the machine and even the flooring under the impactor may influence the test results.

7.7.2.2 Izod and charpy impact

Izod and Charpy impact are common classical tests performed on plastic and metallic materials. These tests are described in ASTM D 256. Within the ASTM standard, five procedures are given. The Izod test is discussed in procedures A, C and D of the standard and uses a notched rectangular bar 2.5" X 0.5" X 0.25" to 0.5" (6.35 cm x 1.27 cm x .635 cm x 1.27 cm) thick. One end of the specimen is held in a vise as a vertical cantilever and impacted on the same face as the notch, at a fixed distance above the notch and vise, by a weighted pendulum. The energy lost by the pendulum during impact is measured and the Izod impact strength is calculated. Procedure C contains a correction factor for the energy required to toss the broken specimen part. This factor is considered significant for materials with Izod impact strengths less than 0.5 ft-lbsf/inch of notch.

The Charpy test was formerly discussed in Procedure B, but has been removed as of 1997 and has been issued as a new standard, ASTM D 6110. It also uses a notched rectangular bar 2.5" X 0.5" X 0.25" to 0.5" (6.35 cm x 1.27 cm x .635 cm x 1.27 cm) thick. In this test the specimen is supported as a horizontal simple beam and is broken by the pendulum with the impact site halfway between the supports and directly opposite the notch.

Procedure D is a variation on the Izod tests, but with differing notch radii. This can give an indication of the notch sensitivity of the material.

Procedure E is a reversed-notched Izod test. It is similar to Procedure A except the specimen is impacted on the face opposite the notch. This procedure gives an indication of the unnotched impact strength of the plastic.

None of the tests in ASTM D 256 are generally appropriate for continuously reinforced composite materials, and data from these tests will not be accepted into MIL-HDBK-17.

7.7.2.3 Quasi-static indentation

Quasi-static indentation tests may be performed by supporting a flat panel in a frame and indenting the center of the panel with a tup attached to a universal-testing machine. This method is described in ASTM D 6264. The most common test specimen is a 6" X 6" (15.24 x 15.24 cm) quasi-isotropic laminate, approximately 0.17" (4.32 mm) thick. The specimen may be simply supported on a frame with a 5-inch diameter cutout, or on a solid, flat, rigid support. Load and cross-head displacement are measured during the test and the resulting curve is reported. A predefined level of damage or cross-head displacement is used to define where to take data during the test and where to stop the test in the case of the rigidly supported configuration. In the case of the simple support configuration, the maximum indentation force is also reported. Dent depth and damage are evaluated after the specimen is unloaded.

7.7.2.4 Other damage resistance tolerance tests

Other impact tests are often included at higher levels of the building block approach. These may include ballistic impact, ice/hail simulation, bird strike simulation and other program specific tests. These are often accomplished through use of an air gun that fires a projectile at the test specimen. Details of these tests have not been standardized, and are not discussed in detail here.

Specialized tests are also performed to evaluate a materials performance and durability in specific applications. These include roller cart and spiked heel resistance tests for flooring.

7.7.3 Damage tolerance tests

7.7.3.1 Compression after impact tests

7.7.3.1.1 Overview

The compression after impact (CAI) test is an empirical evaluation of the degradation of laminate compressive strength due to out-of-plane impact. Investigators use many different impact and damage tolerance tests depending on material form, application and expected damage. Although the CAI tests proposed here were developed by the airframe industry for comparing the damage tolerance of candidate composite materials, they may be generally applicable to other industries. The possible damage scenarios the test was designed to simulate include dropped tools, runway debris kickup, etc. Because the impact is relatively low velocity, the test is not commonly used to assess ballistic damage tolerance.

Several methods are commonly used in the composite industries to determine CAI. Though none are currently ASTM standards all of the methods involve impacting a flat laminate plate. The plate is constrained by a support system with a cutout opposite to the impact site. The impactor is normally a hemispherical tup (falling dart, rod or ball). The most common methods are SACMA SRM 2R-94 (Reference 7.7.3.1.1(a)) and NASA 1092 and 1142, B.11 (References 7.7.3.1.1(b) and (c)).

Sandwich panels are also commonly evaluated for damage tolerance. There are currently no industry wide standards for CAI on sandwich panels. However, for qualification or screening tests, many firms impact a flat sandwich panel under controlled conditions and then perform an evaluation. This evaluation may consist of NDI, water intrusion, residual compressive strength or shear strength testing. A more detailed discussion may be found in Reference 7.7.3.1.1(d).

The impact level is generally selected to cause visual damage to the laminate, but such that the damage is localized at the center of the plate. Other levels of damage such as "barely visible impact damage" (BVID) have been used. If the damage extends to over one half the width of the specimen or if the impactor penetrates through the laminate, the damage level is too large to meaningfully evaluate with a subsequent compression test. Impact levels are specified in the methods but may be varied for experimental purposes.

After impact, the level of damage may be characterized by the apparent damage area (front and back), indentation depth, and nondestructive evaluation by ultrasonic C-Scan or similar techniques. Prior to compression testing, NASA methods require an additional machining step to reduce the specimen size and insure the ends are flat and parallel. Compression testing is then performed in a fixture that stabilizes the specimen near the edges, but does not constrain transverse deformation due to Poisson's effect.

Limitations of CAI testing (all methods) are as follows:

Materials with differing thicknesses or lay-ups should not be directly compared.

Users should be cautioned that damage mechanisms in these test specimens may not scale up to larger parts. This is particularly true with composites made from toughened resin systems.

The level of impact damage is dependent on the rigidity of the specimen support system during impact. Lab to lab variation may be encountered due to differing support systems. Generally less rigid support will result in less impact damage and higher CAI strength.

There may be variation among testers regarding the impact mass used to obtain a given energy level. Data and theoretical models are not sufficient to state the significance of varying mass/velocity at a given energy.

Reliable results are not obtained if the failure is not in the impact area. Soft laminates may fail by buckling above or below the side supports. End brooming is also possible. Both are unacceptable failure modes.

Like most composite tests, proper specimen preparation is critical. End flatness and parallelism are particularly important.

7.7.3.1.2 SACMA SRM 2R-94 "Compression after Impact Properties of Oriented Fiber-Resin Composites"

SACMA SRM 2-88 method was developed from Boeing BSS 7260. The test specimen is a 4"x 6" (100 mm x 150 mm) quasi-isotropic specimen nominally 0.25" (6 mm) thick. If C-Scan will be used after impact, an initial C-Scan should be performed as a baseline. The specimen is clamped to an aluminum support base with a 3"x 5" (76.2 mm x 127 mm) cut out. The specimen is then impacted with an impactor having 0.625" (15.75 mm) diameter hemispherical tup at a height to provide a target impact energy of specimen thickness. The mass of the impactor is not specified but is between 10 and 12 pounds (4.5 and 5.5. kilograms) in normal practice. The impact energy is determined by one of the following methods:

Method 1: Energy = drop weight x drop height/specimen thickness
Method 2: Energy = 1/2 mass $(\text{velocity})^2$ /specimen thickness

The specified impact energy level is 1500 inch-pounds/inch thickness (6.7 Joules/mm thickness). The velocity is measured just prior to impact. The velocity measurement is corrected for any travel between the flag and the specimen. Since Method 2 takes into account friction losses, it is the preferred method.

Rebound impacts of the specimen must be avoided. If instrumentation is used during impacting, the actual impact energy can be calculated, and impact force versus time can be recorded. The impacted specimen is inspected via an ultrasonic scan. The area and the general configuration of the delamination can be recorded.

Specimen testing -- A compressive loading fixture is used to ensure axial loading in the desired plane. The method requires four axial strain gages to be used to measure the strain although the strain gages are not always used in industry practice. The testing speed is 0.05 inches/min (1 mm/min). The output of each gage is plotted individually to check for unusual loading conditions. CAI is calculated as follows:

$$F^{CAI} = \frac{P}{tw} \qquad 7.7.3.1.2$$

where

P = load
t = thickness
w = width

Advantages: Requires much less material than the NASA methods and the elimination of a secondary machining step saves cost.

Disadvantage: There is no machining step after impact to remove possible damage in the clamp areas or ends.

7.7.3.1.3 NASA 1142, B.11 "Compression After Impact Test"

The NASA CAI methods are described in NASA 1092, ST-1 and NASA 1142, B.11

The NASA 1142, B.11 method is a later version of NASA 1092.

The test specimen is 7"x 12" (180 mm x 300 mm) quasi-isotropic composite plate prior to impacting. Thickness is 0.25" (6 mm) in normal practice. Ultrasonic C-Scan should be performed prior to impact for a baseline. The specimen is clamped to a steel support plate with a 5"x 5" (130 mm x 130 mm) cutout opposite to the impact site. The specimen is impacted with an impactor equipped with a 0.5" (13 mm) diameter hemispherical tup. The mass of the impactor is 10 to 12 lbs (4.5-5.5 kg). The required impact energy is 20 foot-pounds (27 Joules).

Following the impact, the specimen is visually examined, ultrasonically inspected and then machined to its final compression test dimensions of 5"x 10" (130 mm x 250 mm). This final machining step eliminates any damage sustained by the specimen in the clamped area during impact and allows for ends to be machined flat after impact.

The specimen is then instrumented with back-to-back axial gages. The gages are used to monitor for unusual loading conditions during the test. The strain gages are not always used in industry practice. CAI is calculated as follows:

$$F^{CAI} = \frac{P}{tw} \tag{7.7.3.1.3}$$

where

P = load
t = thickness
w = width

7.7.3.1.4 Test methods for MIL-HDBK-17 data submittal

Data produced by the following test methods (Table 7.7.3.1.4) are currently being accepted by MIL-HDBK-17 for consideration for inclusion in Volume 2:

TABLE 7.7.3.1.4 *Compression after impact test method for MIL-HDBK-17 data submittal.*

PROPERTY	SYMBOL	ALL DATA TYPES	SCREENING
Compression after impact strength	F^{CAI}		SACMA SRM 2R-94 NASA 1192, B.11

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7.5.5.4(b) ASTM Practice E 4, “Force Verification of Testing Machines,” *Annual Book of ASTM Standards*, Vol. 3.01, American Society for Testing and Materials, West Conshohocken, PA.

7.5.5.4(c) ASTM Practice E 83, “Verification and Classification of Extensometers,” *Annual Book of ASTM Standards*, Vol. 3.01, American Society for Testing and Materials, West Conshohocken, PA.

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7.6.2(c) ASTM Test Method D 2095, “Test Method for Tensile Strength of Adhesives by Means of Bar and Rod Specimens,” *Annual Book of ASTM Standards*, Vol. 15.06, American Society for Testing and Materials, West Conshohocken, PA.

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7.6.3.4.2 European Aircraft Industry Standard EN 6066, “Determination of Tensile Strength of Tapered and Stepped Joints”.

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