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Tabbing Guide for Composite Test Specimens

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16. Abstract

This document provides guidelines for selecting suitable tabbing configurations for composite material test specimens. Additionally, a practical methodology is detailed for preparing and applying tabs to composite test specimens. This document is based on research performed within the Mechanical Engineering Department at the University of Utah and previously by the Composite Materials Research Group (CMRG) at the University of Wyoming, both sponsored by the Federal Aviation Administration.

The use of composite materials as a material of choice for structural applications has seen tremendous growth over the last several decades. This growth has resulted in a proliferation of both commercial and in-house composite material testing facilities. A reoccurring problem in the process of materials testing is the proper selection of tabbing configuration and the proper bonding of end tabs onto test specimens. This is a fundamental and a critical step in the testing process since the tabs protect the specimen as well as introduce the load into the specimen. Those who perform composite material testing on a routine basis have presumably developed tabbed specimen configurations and tabbing procedures that provide accurate and repeatable results. The suggested procedures offered here can be compared with those already being used. For those users who do material testing less frequently, this Guide should be especially useful.

The first section provides an introduction to the preparation and testing of tabbed composite specimens and overviews the need for tabs on composite specimens. Section 2 discusses factors affecting the selection of tabbing materials and adhesives. Common choices for tabbing materials and methods for determining adhesive properties are described. Data relating to the performance of typical adhesives is given. Section 3 presents considerations involved in the design of a tabbing configuration. Additionally, a finite element-based design methodology for minimizing stress concentrations in the tab region is presented. Section 4 presents results from finite element analyses of tab configurations under tensile loading. Tab configuration design variables are investigated individually, and recommendations for each design variable are presented. Similar finite element results and design variable recommendations for compression testing are presented in Section 5. Section 6 presents a step-by-step procedure for specimen tabbing. The procedure details the preparation of the tabbing material and test panel, proper alignment and adhesive bonding of the tabs, and curing of the adhesive.

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EXECUTIVE SUMMARY

This document provides guidelines for selecting suitable tabbing configurations for composite material test specimens. Additionally, a practical methodology is detailed for preparing and applying tabs to composite test specimens. This document is based on research performed within the Mechanical Engineering Department at the University of Utah and previously by the Composite Materials Research Group (CMRG) at the University of Wyoming, both sponsored by the Federal Aviation Administration.

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1. TABBING OF COMPOSITE TEST SPECIMENS: AN OVERVIEW.

In contrast to metallic specimens, the testing of composite materials reinforced with high strength and/or high modulus fibers is not straightforward. Valid axial tension and compression testing of very strong and/or very stiff unidirectional composite materials remains a challenge. Since a unidirectional composite is the basic building block in structural composite laminates, its properties must be well characterized for use in lamination analyses. Thus, in this document considerable attention is given to the testing of unidirectional composites. The goal is to produce a valid failure mode within the central gage section of the specimen. For an acceptable gage section failure to occur, the magnitude of the desired uniform stress state present in the gage section must be higher than the stress state elsewhere in the specimen, including in the gripping region. While the axial strength of most unidirectional composites is high, their transverse normal and shear strengths are relatively low. As a result, unidirectional composite specimens may fail in transverse normal and/or shear failure modes even when these induced stresses are low relative to the applied axial normal stress.

For both tension and compression testing, the required axial load may be introduced into the composite specimen through shear forces applied along the specimen surfaces. In practice, shear forces are applied using some form of grips, which clamp the specimen surfaces at each end and apply a shear force through friction. Smooth, flat grip surfaces apply a uniform shear force to the specimen surfaces while producing minimal surface damage. Because smooth grip surfaces result in relatively low coefficients of friction between the grips and the specimen, relatively high clamping forces are required to prevent grip slipping. Because the transverse compressive strength of a typical unidirectional composite is relatively low, high clamping forces can result in significant through-thickness compressive stresses, and crushing of the specimen in the gripped regions. Thus, grip surface roughness must be increased so sufficiently reduced clamping pressures may be used. Since coarser grip faces tend to damage the surface of the test specimen and produce premature failure in the gripped region, protective tabs are bonded onto the faces of the specimen in the grip regions. When this is done, aggressive grip faces may be used which "bite" into the surfaces of the tabs. Thus, specimen tabs permit the use of coarse grip surfaces and corresponding low grip pressures while preventing surface damage to the specimen. Additionally, specimen tabs serve to reduce induced stress concentrations at the ends of the wedges.

Tabbing of composite test specimens may also be considered as a means of effectively thickness-tapering the test specimen so that the central gage section has a reduced cross-sectional area compared to the tabbed specimen ends. Another concept for reducing the cross-sectional area of the gage section is to use width-tapered specimens. Unlike metallic specimens, premature unidirectional composites often experience longitudinal splitting failures in the tapered region of a width-tapered specimen. This is typically due to the relatively low shear strength of the material. Thus, achieving a reduced cross-sectional area of the gage section using width-tapered specimens generally is not acceptable for unidirectional composite materials. Consequently, unidirectional composite tension and compression specimens typically achieve thickness-tapering through the use of adhesively bonded tabs.

Although tabbing of unidirectional composite specimens addresses problems with gripping-induced damage to the surfaces of the specimen, the tabs themselves can result in stress

concentrations, particularly at tab terminations adjacent to the specimen gage section. To reduce these stress concentrations, tabs are often tapered at the gage section ends. However, some stress concentration generally remains. Tabbed tension and compression specimens often fail in the vicinity of this tab termination region, either at the tab ends or slightly inside the tabs. While specimen tabbing is advantageous in terms of minimizing the detrimental effects of gripping, the tab configuration must be designed to minimize additional induced stress concentrations so that tab region failures do not precede gage section failures. These stress concentrations may be minimized through the proper selection of tabbing material, adhesive, and tab taper geometry.

For compression testing, a second option for introducing load into the specimen is through end loading. However, the direct application of compressive forces at the specimen ends may result in localized crushing of the composite. Such specimen end crushing is often attributed to the difficulty of introducing the compressive force uniformly across the specimen ends. Nonuniform end loading produces localized stress concentrations that leads to premature failure. Such failures are often characterized as brooming or crushing at the specimen ends. One method of preventing end failures is to adhesively bond tabs on opposing faces at each end of the specimen. The tabs increase the total surface area over which the end loading is applied, thus reducing the stresses in the composite at the specimen ends. Note that any force applied at the end of a tab must be transferred through shear into the composite specimen over the length of the tab. Thus, an end-loaded compression specimen is effectively loaded by a combination of end loading and shear loading.

In summary, specimen tabs typically are used for end loading and shear loading of high-strength composite specimens. Specimen tabs are used to facilitate load introduction into the test specimen without producing premature failure due to an undesired failure mode. As a result, the specimen tabs and adhesive use to bond the tabs to the specimen must be able to transmit the required loading into the specimen through shear. Additionally, the tabbing geometry, tabbing material, and adhesive should be selected to minimize stress concentrations in the specimen in the vicinity of the tab ends. Tabbing designs are discussed in the following sections of this document.

Since unidirectional specimens are also very sensitive to misalignment of the applied loading, care must be taken during tabbing and specimen cutting to ensure that the fiber orientation is coincident with the loading direction. In-plane misalignment produced in the tabbing and specimen cutting operations results in a reduced number of continuous fibers through the gage section of the specimen and reduced failure loads. Additionally, out-of-plane fiber misalignment may be produced during the tabbing process by variations in the specimen, tabs, and/or adhesive bond line thickness. Such misalignment causes eccentric loading, leading to bending of the specimen and higher interlaminar stresses under the tabs. Thus, in addition to selecting the proper tabbing configuration, a proper tab bonding procedure should be followed to produce good fiber alignment. Suggested tab bonding procedures, suitable for use with both paste adhesives and film adhesives, are detailed in section 6.

2. MATERIAL SELECTION FOR SPECIMEN TABBING.

An important step in successful tabbing is the selection of the tabbing material and adhesive. Both the tabbing material and the adhesive must be able to transmit the required shear load into

the composite specimen during testing. Additionally, these materials should minimize stress concentrations in the vicinity of the tab ends. Other factors that must be considered include the type of testing (tension, compression, or shear), the testing temperature, the composite material to be tested, and the test fixture or loading grips to be used.

2.1 TABBING MATERIAL SELECTION.

The tabbing material must be capable of transmitting adequate load into the composite specimen to produce the desired specimen failure prior to a shear or compressive failure of the tab material itself. Additionally, the tabbing material must be suitable for use at the required test temperature. Another desirable feature is the selection of relatively low cost materials that may be machined using the same techniques to be used to machine the composite material. Several materials that are commonly used for tabbing composite test specimens are described below.

2.1.1 Glass Fabric/Epoxy Laminated Circuit Board.

Laminated circuit board materials incorporating various polymer matrices are commonly available at relatively low cost. A glass fabric/epoxy laminated circuit board is an excellent choice for tabbing material for testing at temperatures up to 177°C (350°F). For short-time use up to 177°C, the readily available NEMA Grade G-10 glass fabric/epoxy is commonly used for tabbing. Since the mechanical properties of the G-10 material are significantly reduced as the test temperature approaches 177°C, NEMA Grade G-11 glass fabric/epoxy is often used for elevated temperature testing. The G-11 material is suitable for short-time use up to 204°C (400°F). Both of these glass fabric/epoxy materials require minimal surface preparation and may be machined after being bonded to the composite test panel. In addition to using commercially available laminated circuit board, glass/epoxy tabs may be fabricated using either unidirectional or woven fabric prepreg.

2.1.2 Carbon/Epoxy Tabs.

Another potential tabbing material, particularly for use with carbon/epoxy composite test specimens, is carbon/epoxy. Such tabs can be applied in a cocuring step during panel fabrication, or in a separate tabbing procedure. However, cocuring the tabs with the test specimen panel requires specialized tooling and technology. Additionally, carbon/epoxy is a relatively expensive tabbing material, and may not be appropriate for routine testing applications. Some controversy exists as to the optimal layup and fiber orientation within the carbon/epoxy tabs, e.g., unidirectional, cross-ply, ±45° angle ply, or woven fabric.

2.1.3 Metallic Tabs.

Low carbon steel and aluminum tabs have long been used for tabbing composite specimens and are readily available at relatively low cost. One disadvantage of using steel tabs, because of the high relative stiffness of steel, is the difficulty encountered when cutting the tabbed panel into individual specimens. The cutting tool can easily catch an edge of a steel tab, popping it off of the composite panel. A disadvantage of using aluminum tabs is the difficulty associated with adhesive bonding to the composite specimen. Due to the oxide layer that forms rapidly on the

just-cleaned surface of aluminum, extra steps may be required to ensure proper surface preparation of the aluminum tabs.

2.1.4 Unbonded Tabs.

Using unbonded friction tabs that are compressed by the grips is an option as well. Friction tabs such as abrasive wire mesh are placed against the surface of the specimen. Plastic tab inserts (such as butyrate plastic) are used as an interface between the aggressive grip faces and the abrasive wire mesh. When placed into the grips and compressed, the coarse surfaces of the grips bite into the plastic tab inserts. The high-friction coefficient of the abrasive wire mesh allows load to be transferred via shear between the plastic tab inserts and the composite test specimen. Although unbonded friction tabs eliminate the need for an adhesive, and thus the problems associated with tab debonding, high-shear stresses remain. Thus, relatively high-gripping pressures generally are needed to avoid slippage. Such high-gripping pressures can cause the wire mesh to disintegrate or crush the composite specimen. As a result, unbonded friction tabs generally are not recommended as an alternative to bonded tabs for testing high-strength unidirectional composites. However, it may be acceptable to use unbonded friction tabs with lower strength composites, including cross-ply laminates, notched laminates, short fiber composites, and textile composites.

2.1.5 Untabbed Specimens.

Using untabbed specimens may be attractive as a low-cost option, in conjunction with less coarse gripping surfaces, especially when testing lower strength composites. Wedge grips are available with less severe surface texture (e.g., tungsten carbide particle-coated surfaces) and have been suggested for use with untabbed specimens [1]. In composite specimens with load bearing 0° plies on the outer surfaces of the specimen, fiber damage often occurs in the grip regions when tabs are not used, resulting in tab region failures. The current ASTM Standard D 3039 [2], which applies to straight-sided tensile test specimens (with or without tabs), suggests that no failure should occur within one specimen width of each tab or grip. As a result, untabbed specimens generally are not acceptable for unidirectional composites. For lower strength composites such as cross-ply laminates (with 90° plies on the outer surfaces), textile composites, and similar lower strength materials, untabbed specimens may produce acceptable gage section failures.

2.2 ADHESIVE SELECTION.

Adhesive selection is no less important than tabbing material selection. The adhesive must be able to transmit the required load into the test specimen through shear and must withstand the compressive force applied by the grips. Further, the adhesive must be suitable for use at the desired test temperature, and the required cure temperature of the adhesive must not exceed the acceptable exposure temperature for both the test panel and the tabbing material. The adhesive layer may be designed to further minimize stress concentrations at the tab terminations. Other desirable features include workability, storage requirements (out-time), and be readily available at a reasonable cost.

2.2.1 Adhesives Availability.

Adhesives are available in a wide variety of forms and require widely differing application techniques. When classified by their mode of processing or cure, some common adhesive groupings are two-part cure, film, solvent-based, water-based, contact, pressure-sensitive, and hot-melt. Of these groupings, the most commonly used adhesives for tab bonding are two-part cure and film adhesives. Two-part curing adhesives commonly used for tab bonding are comprised of an adhesive and a catalyst to initiate the cure process. The two parts are mixed together immediately prior to application. A pot life, i.e., the length of working time once the adhesive is mixed, of at least 30 minutes is generally required for tab bonding. Film adhesives are supplied in a one-part, precatalyzed form. The adhesive is supplied as a partially cured (B-staged) thin film, spread on a backing sheet, often wrapped onto a spool, and stored frozen to inhibit further curing.

Hundreds of candidate adhesives are commercially available from U.S. and foreign suppliers. While there is considerable overlap between many of the adhesives produced, there is also a great diversity in properties, handling characteristics, curing conditions, temperatures of application and use, and environmental conditions for which they are intended. Because adhesion is a system phenomenon, the strength of the adhesive bond obtained using a specific adhesive involves many different factors, including type of test specimen and tab material, surface preparation, testing temperature, and loading rate. Nonetheless, most test laboratories commonly use one or two preferred adhesives for most of their tab bonding applications. However, the preferred adhesives tend to differ from one testing laboratory to another.

2.2.2 Strength Data for Commonly Used Adhesives.

Two types of adhesives data are desirable for tab bonding applications. First, in situ or thin film tests may be conducted to assess the adhesive performance in a specific tabbed specimen configuration. Such tests are useful for qualitative comparisons between candidate adhesives for specific tabbing and testing applications. Secondly, the modulus and strength of an adhesive may be determined using bulk adhesive tests performed on specimens produced from the adhesive. Although no specific ASTM standard tests exist for bulk adhesive testing, many existing standards for plastics and rubbers can be adapted to test the properties of bulk adhesives, e.g., ASTM D 638 [3]. Bulk adhesive tensile specimens, either straight-sided or tapered, may be molded to final dimensions or machined from plates. Shear strength and shear modulus of the bulk adhesive may be obtained from solid rod torsion testing, or by using the V-notched (Iosipescu) shear test method commonly used for composite materials (ASTM D 5379 [4]). Bulk adhesive properties determined from these quantitative tests are useful when designing tabbing configurations to minimize stress concentrations, as will be demonstrated in section 3.

2.2.2.1 In Situ Adhesive Test Results.

To assess the in situ strength of candidate adhesives for tab bonding, tension testing was performed using Hexcel AS4/3501-6 carbon/epoxy specimens tabbed with G-10 glass fabric/epoxy tabs. To ensure adhesive failure of the tabs, the tests were performed with short tab lengths that were approximately 20 mm (0.75 in.). Using mechanical wedge grips, these specimens were tested in tension until adhesive failure resulted in debonding of the short tabs.

The in situ adhesive shear strength, $\tau_{in\ situ}$, was determined by dividing the failure load, $P_{failure}$ by twice the bonded area of a tab, A_{tab}

$$\tau_{in\,situ} = \frac{P_{failure}}{2(A_{tab})}$$

Three adhesives were evaluated for in situ shear strength in tabbing configurations.

- Techkits A-12 epoxy
- 3M AF191 epoxy
- Hysol EA 9689 epoxy

Techkits A-12 epoxy adhesive [5] has been used extensively as a tab-bonding adhesive for testing from room temperature up to 121°C (250°F). This room-temperature cure, two-part paste adhesive is especially well suited for test materials that have low-cure temperatures and, thus, cannot have tabs cured at significantly elevated temperatures. The normal cure cycle for Techkits A-12 is either room temperature for 24 hours or 65°C (150°F) for 1 hour. Both 3M AF191 epoxy [6] and Hysol EA 9689 epoxy [7] are film adhesives that are cured at a temperature of 350°F. Both have been used for elevated temperature testing up to 177°C (350°F). These adhesives are cured in a vacuum bag using a procedure described in section 6. The use of a vacuum bag resulted in a pressure of approximately 69 KPa (10 psi) being applied to the adhesive bond, which has been found to be adequate for this application.

Results from the in situ testing of these three tabbing adhesives are shown in table 1. Testing was performed at room temperature and at 121°C (250°F). The Techkits A-12 epoxy paste adhesive and the 3M AF191 epoxy film adhesive performed well at room temperature. However, the Hysol EA 9689 epoxy film adhesive performed the best of the three adhesives at 121°C. Note that the in situ adhesive strengths obtained from these qualitative tests are not suitable for general use as a true adhesive strength since the adhesive is subjected to shear and compressive stresses during testing that vary along the length of the bond line. However, these in situ strengths provide a useful comparison between candidate adhesives for use in specimen tabbing.

TABLE 1. IN SITU ADHESIVE SHEAR STRENGTH FOR GLASS/EPOXY TABS BONDED TO AS4/3501-6 CARBON/EPOXY COMPOSITE MATERIAL

Adhesive	Test Condition	In Situ Adhesive Strength	
		MPa	(Ksi)
Techkits A-12 Epoxy Paste Adhesive	Room Temperature	125	(18.2)
	121°C (250°F)	24.1	(3.5)
3M AF191 Epoxy Film Adhesive	Room Temperature	121	(17.6)
	121°C (250°F)	52.4	(7.6)
Hysol EA 9689 Epoxy Film Adhesive	Room Temperature	78.6	(11.4)
	121°C (250°F)	72.4	(10.5)

2.2.2.2 Bulk Adhesive Test Results.

Bulk adhesive testing was performed on two epoxy adhesives: Hysol 907 and 3M AF163-2K. Hysol 907 epoxy adhesive [8] is a room-temperature cure, two-part paste adhesive that is well suited for room temperature testing. Hysol 907 does not require an elevated temperature postcure cycle but does require three days at room temperature to fully cure. Alternatively, full cure may be accelerated by heating for two hours at 60°C (140°F) or 1 hour at 82°C (180°F). 3M AF163-2K epoxy film adhesive [9] is a structural adhesive film with a nylon knit supporting carrier. This adhesive is cured under vacuum for 90 minutes at 107°C (225°F) or for 60 minutes at 121°C (250°F). The nominal thickness of the adhesive film is 0.24 mm (0.0095 in.), and multiple layers of the film adhesive can be used to create the desired thickness.

Two types of bulk adhesive testing were performed. Tension testing was performed on straight-sided tensile specimens molded from the bulk adhesive. Additionally, shear testing was performed on 76- x 12.7- (3-in. x 0.5-in.) bulk adhesive specimens using the V-notched (Iosipescu) shear test. From tension testing, the tensile strength, tensile modulus, and Poisson's ratio were obtained. From shear testing, the shear strength and shear modulus were determined. All testing was performed at room temperature. Bulk adhesive test results from the Hysol 907 epoxy adhesive and the 3M AF-163-2K epoxy film adhesives are shown in table 2. For comparison, adhesive material property data provided by the adhesive manufacturers are also listed in table 2. For both adhesives, moduli and strength values obtained from bulk adhesive testing were considerably different than those listed by the manufacturer. Representative stress versus strain plots obtained from tension testing of the two adhesives are shown in figure 1a. The Hysol 907 epoxy adhesive exhibits a relatively linear stress versus strain response. The 3M AF163-2K epoxy adhesive exhibits a higher tensile strength and significant material nonlinearity prior to failure. Representative stress versus strain plots obtained from shear testing of the two adhesives are shown in figure 1b. Similar to results from tensile testing, the Hysol 907 epoxy adhesive exhibits a relatively linear stress versus strain response, whereas the 3M AF163-2K epoxy adhesive exhibits significant material nonlinearity.

TABLE 2. MATERIAL PROPERTIES OF ADHESIVES AND COMPARISONS WITH MANUFACTURER'S DATA

Adhesive Type	Source of Data	Tensile Modulus GPa (Ksi)	Tensile Strength MPa (Ksi)	Poisson's Ratio	Shear Modulus MPa (Ksi)	Shear Strength MPa (Ksi)
Hysol 907 Epoxy	Lab Tests	3.17 (460)	37.9 (5.5)	0.33	1154 (167)	11.2 (1.62)
	Manufacturer [8]	1.69 (245)	21.4 (3.1)	0.35	627 (91)	2.8 - 22.1 (0.4 - 3.2)
AF163-2K Epoxy	Lab Tests [10]	2.53 (367)	44.1 (6.4)	0.37	931 (135)	38.6 (5.6)
	Manufacturer [9]	1.11 (161)	48.3 (7.0)	0.34	413 (60)	--

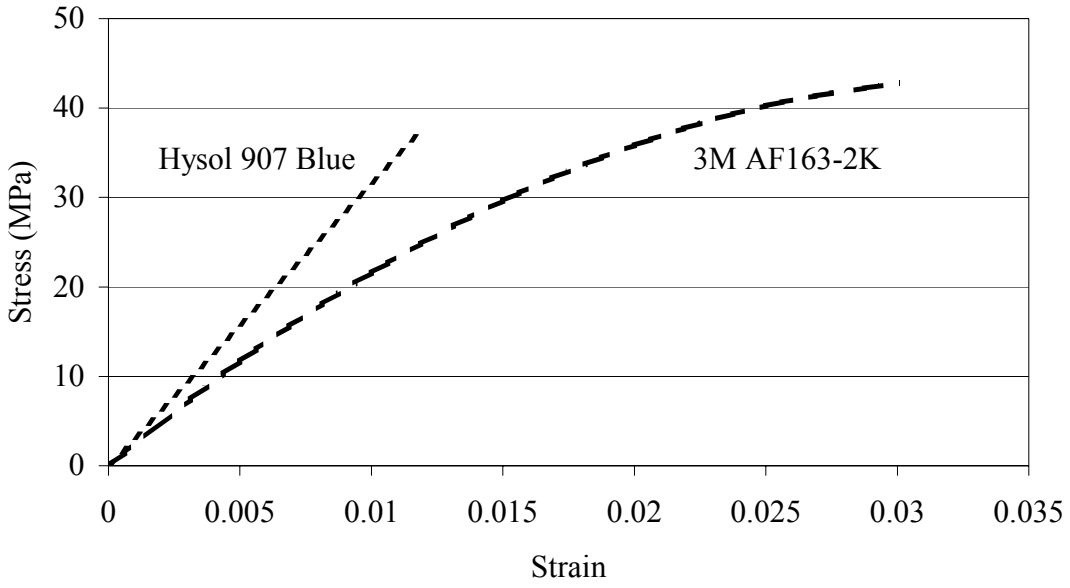

FIGURE 1a. TENSILE STRESS-STRAIN CURVES OF 3M AF163-2K EPOXY FILM ADHESIVE AND HYSOL 907 EPOXY ADHESIVE

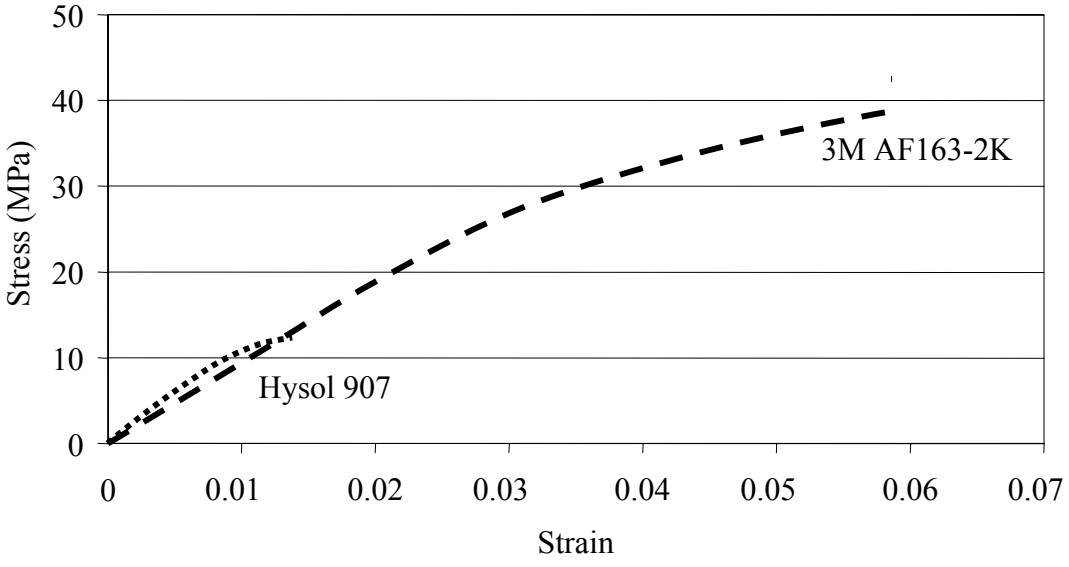

FIGURE 1b. SHEAR STRESS-STRAIN CURVES OF 3M AF163-2K EPOXY FILM ADHESIVE AND HYSOL 907 EPOXY ADHESIVE

3. TAB CONFIGURATION DESIGN AND SELECTION.

The purpose of tabbing a composite specimen is to introduce load into the test specimen without producing premature failure in an undesired failure mode. Thus, a successful tab configuration design is one that produces a valid failure mode within the central gage section of the specimen.

For this to occur, the uniform stress state in the gage section must be of greater severity than the stress state elsewhere in the specimen, including the gripping region. Thus, a main focus when designing a tab configuration is to minimize stress concentrations within the tab region of the specimen. Other considerations include the ability of the tab material and adhesive to transmit the required load into the composite specimen during testing and their ability to withstand the environment used to fabricate and test the specimens.

Figure 2 shows a typical tabbed specimen configuration for tension testing. The three components of the specimen are the composite material, the tab material, and the adhesive. The central region of the specimen, or gage section, is the region in which a uniform state of stress is required and a suitable failure mode is desired. The tab regions are composed of tabs that are adhesively bonded to the ends of the composite. The tab termination regions, or transition regions between the tab region and gage sections, are of particular interest in the design process due to the stress concentrations present.

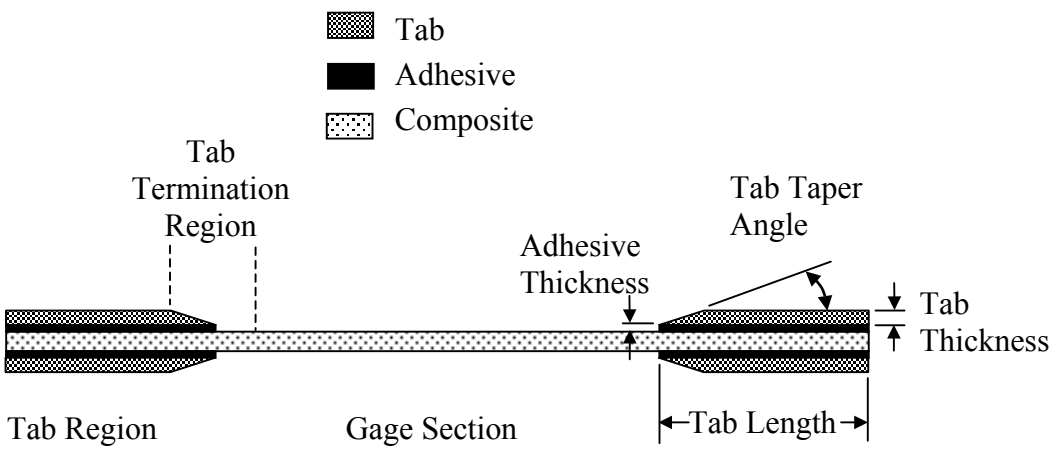

FIGURE 2. TYPICAL TABBED COMPOSITE TENSION SPECIMEN

3.1 TAB CONFIGURATION DESIGN VARIABLES.

The design of a tabbed specimen configuration involves all three components of the tabbed specimen: the composite material, the tab material, and the adhesive. Table 3 lists the available design variables associated with each component of a tabbed composite specimen. Properties of the composite material that affect the design of a tabbing configuration include its material stiffnesses and material strengths. Generally, however, these properties are not available as design variables since they are fixed for the composite material being tested. The thickness of the composite material to be tested may be an available variable, if the test program permits it. Note that the design of a suitable tab configuration primarily involves material selection and geometric design associated with the tabs and the adhesive. Each of the variables listed may affect the magnitude of the stress concentration in the tab termination regions and should be chosen so the overall stress concentrations are minimized. It should be noted that these design variables are dependent on each other and that minimizing stress concentrations is not the only requirement of the design process. However, understanding the role of each design variable in minimizing the tab termination region stress concentrations is important for designing a tabbing

configuration that will result in acceptable gage section failures. Thus, the stress concentrations associated with each design variable will be investigated in detail.

TABLE 3. DESIGN VARIABLES FOR A TABBED COMPOSITE SPECIMEN

	Components of Tabbed Specimen		
	Composite Material	Tab Material	Adhesive
Design Variables	Geometric design • Laminate thickness	Material selection • Tab material stiffness • Tab material strength Geometric design • Tab thickness • Tab length • Tab taper angle	Material selection • Adhesive stiffness • Adhesive strength Geometric design • Adhesive thickness

The stress state in the tab region of a specimen is complex due to the geometric discontinuity at the tab termination and the difference in material properties of the adhesive, the tabs, and the test specimen. As a result, computational analysis techniques such as the finite element method are required to analyze the tab region stress state and design a suitable tab configuration. Finite element modeling is used here to investigate the effect of each design variable on the tab termination region stress concentrations. Using finite element modeling to analyze candidate tab configurations is detailed in the following section.

3.2 FINITE ELEMENT ANALYSIS OF TAB CONFIGURATIONS.

The finite method is a useful tool for analyzing the state of stress in candidate tab configurations. By modeling a series of tabbing configurations, best-suited designs may be identified. Additionally, the sensitivity of the tab termination region stress concentration to an individual design variable can be determined. In this Guide, finite element analysis is used to investigate several tab configuration design variables. An overview of the methodology followed for performing finite element analysis is presented in the following sections.

3.2.1 Modeling of Tabbed Composite Specimens.

For straight-sided composite test specimens (i.e., no width tapering), the geometry of the specimen does not vary across the specimen width. As a result, the three-dimensional (3-D) test specimen may be analyzed using a two-dimensional (2-D) model as shown in figure 3. Generally, either a plane strain assumption ($\varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0$) or plane stress assumption ($\sigma_z = \tau_{xz} = \tau_{yz} = 0$) is used to account for the out-of-plane (z) direction of the model. The use of a plane strain assumption better approximates the interior regions of the specimen, whereas a plane stress approximation better approximates the edge surface of the specimen. A plane strain assumption is generally recommended, since it represents the majority of the specimen volume. It should be noted that free-edge effects are possible in the composite specimen, producing free-edge stresses that are not accounted for in a 2-D model. To investigate such stress variations in the out-of-plane direction of the model, a 3-D analysis is required.

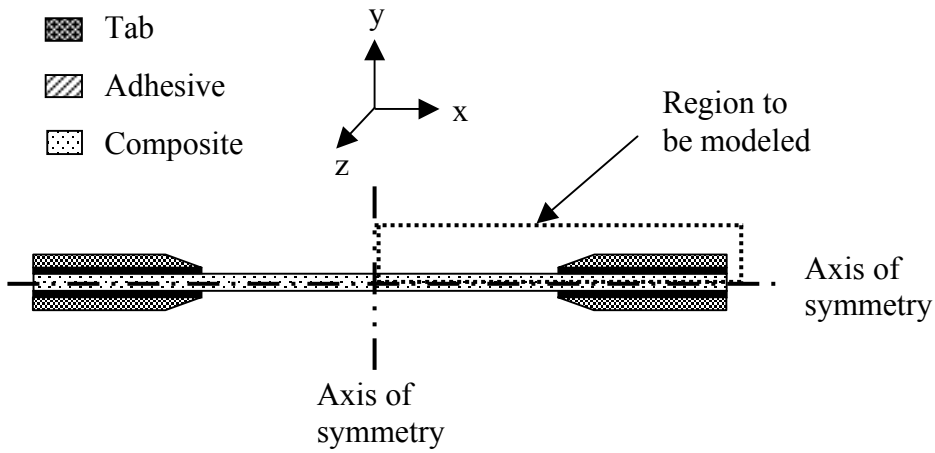

FIGURE 3. CROSS-SECTION OF SPECIMEN TO BE MODELED

Note that the global coordinate system in figure 3 is selected such that the 2-D model is oriented in the x-y plane. This orientation of coordinate system favors finite element modeling, since many commercial finite element codes use the x-y plane as the default for 2-D modeling. However, this selection of coordinate system results in the composite laminate being in the x-z plane. In laminated plate analysis, it is common to orient the laminate with the x-y plane. As a result, care must be taken when inputting material properties of the composite into the finite element analysis to assure that the correct orientation is obtained.

A tabbed composite specimen has two perpendicular planes of symmetry, as shown in figure 3. As a result, only one-fourth of the specimen cross-section must be modeled. Along the lines of symmetry, displacement boundary conditions are applied as shown in figure 4a for tension loading. Loading conditions are applied to the outer surface of the tab to simulate the actual loading configuration produced by the grips. Note that for tapered tabs, these tractions are applied only along the untapered length of the tabs, as shown in figure 4b.

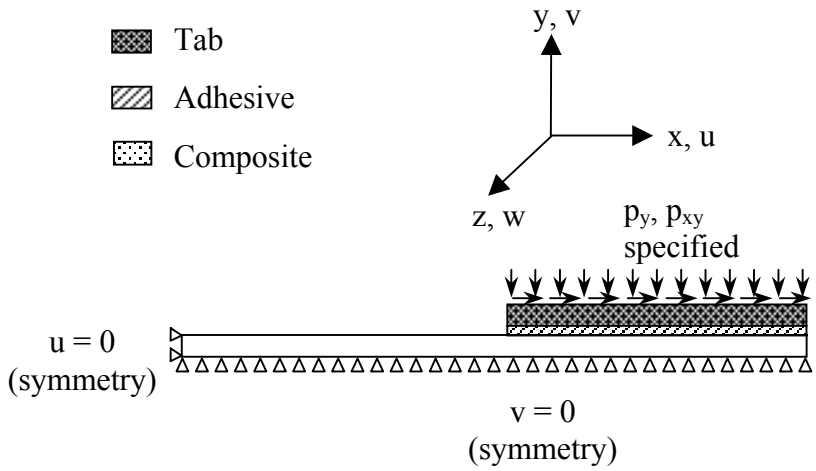

FIGURE 4a. MODELED REGION OF TENSION TEST SPECIMEN WITH UNTAPERED TABS

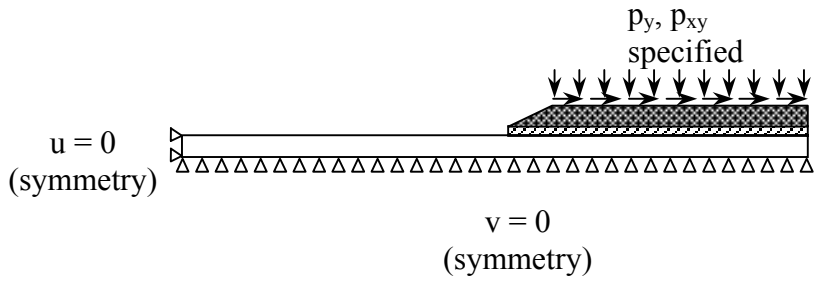

FIGURE 4b. MODELED REGION OF TENSION TEST SPECIMEN WITH TAPERED TABS

When simulating wedge grips, the gripping traction, p_y (force/unit area), increases in proportion to the load applied to the specimen, P. Thus, to correctly simulate the wedge grip, both the normal loading (p_y) and shear loading (p_{xy}) of the tab surfaces must be included. The ratio of the shear traction p_{xy} to the normal traction p_y may be expressed as

$$\frac{p_{xy}}{p_y} = \frac{\dfrac{F_{xy}}{A_{tab}}}{\dfrac{F_y}{A_{tab}}} = \frac{F_{xy}}{F_y} = \tan\left(\tan^{-1}(\mu) + \phi\right),$$

where:

p_{xy} = shear traction (force/unit area) applied to tab surface
p_y = normal traction (force/unit area) applied to tab surface
F_{xy} = shear force applied by grip
F_y = normal force applied by grip
μ = static coefficient of friction between the grip and wedge
ϕ = taper angle of the grip.

For the case where $\mu = 0.06$ (lubricated steel on steel) [11] and $\phi = 15°$, this ratio becomes

$$\frac{p_{xy}}{p_y} = 0.33$$

For these conditions, the shear traction applied to the tab surface should be 0.33 times the magnitude of the normal traction applied to the same surface. Note that the direction of p_{xy} reverses from that shown in figure 4a and 4b for the case of compressive loading.

Linear elastic finite element analysis generally is recommended for analyzing candidate tabbing configurations. In such analyses, the resulting stresses are proportional to the applied load, such that results may be scaled to represent any applied load level. However, some adhesives exhibit appreciable nonlinear stress versus strain behavior under the applied loading. For cases where such adhesives are to be modeled and where the magnitude of the adhesive stresses are well above the linear region of the stress versus strain curve, a material nonlinear finite element

analysis may be required for accurate determination of the stress distributions in the tab region. In general, material nonlinear finite element analysis is more difficult and requires more material property inputs than linear analysis. Unless otherwise mentioned, the finite element analyses performed here to investigate the tab configuration design variables were linear elastic analyses.

3.2.2 Material Property Input.

As input to linear elastic finite element analyses, elastic properties (elastic modulus, shear modulus, and Poisson's ratio) are required for the test conditions to be analyzed. Generally, good estimates of the required elastic properties are available for the tab material and the composite material to be tested. However, obtaining accurate elastic properties of adhesives is often more difficult, since many adhesive manufacturers do not publish such properties.

The composite material and the tabbing material may be orthotropic, such that elastic properties for different material directions must be input. Most commercial finite element software packages allow for the modeling of orthotropic materials. Care should be taken to ensure that the orthotropic material properties are inputted correctly, such that the material properties are oriented properly with respect to the model. Composite material properties are commonly referred to using a 1-2-3 material coordinate system. For example, the 0° fiber direction is referred to as the 1-direction in a material coordinate system. Commercial finite element codes often require material properties to be input using the global x-y-z coordinate system of the model. Depending on the orientation of the orthotropic material with respect to the global coordinates, the two coordinate systems may not be aligned such that 1 = x, 2 = y, and 3 = z. In such cases, special care must be taken to input the material properties correctly in the global x-y-z coordinate system, especially the Poisson's ratio terms.

3.2.3 Meshing of the Modeled Region.

The modeled region of the tabbed specimen shown in figure 4 is meshed using 2-D finite elements. Within the meshed region, the primary region of interest for investigating stress concentrations is the tab termination region. Since there may be large stress gradients in this region, smaller finite elements should be used than in other regions of the specimen. Figure 5 shows acceptable finite element meshes used in the tab termination region for a tapered tab (figure 5a) and an untapered tab (figure 5b). Eight-node quadrilateral elements were used in these meshes. Within this region of interest, the adhesive layer was meshed using two layers of elements through the thickness. Care was taken to ensure that the aspect ratio of the elements within this region of high stress gradients did not exceed 2:1. In general, high element aspect ratios may produce errors in regions of high stress gradients, and are not recommended.

3.2.4 Analysis of Tab Configuration Design Variables.

The design of a suitable tab configuration primarily involves determining the design variables associated with the tabs and the adhesive. Although each design variable may affect the magnitude of the stress concentrations in the tab termination regions, they cannot be considered independently when designing a suitable tab configuration. However, it is important to understand the role of each design variable in minimizing the tab termination stress

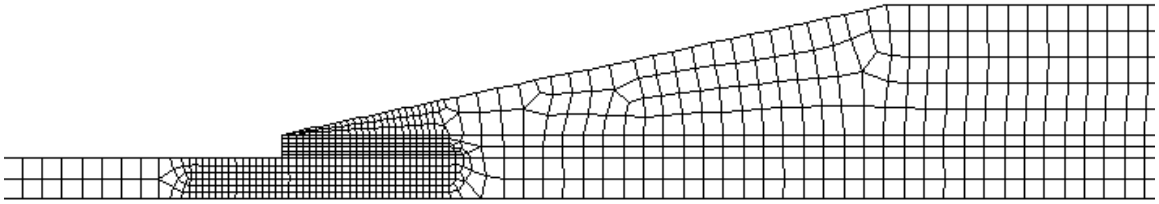

FIGURE 5a. FINITE ELEMENT MESH IN THE TAB TERMINATION REGION, TAPERED TAB

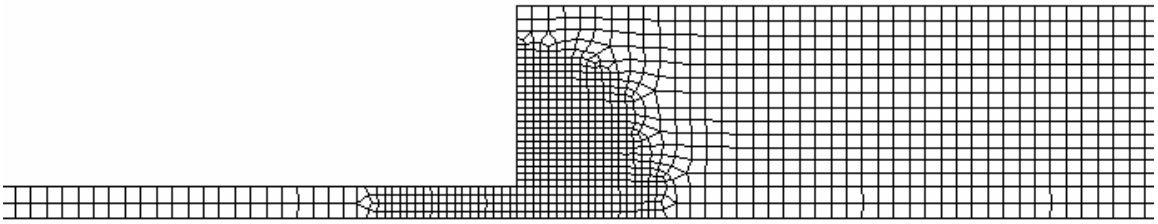

FIGURE 5b. FINITE ELEMENT MESH IN THE TAB TERMINATION REGION, UNTAPERED TAB

concentrations. Stress concentrations associated with each design variable will be investigated in detail in the following sections for both tension and compression loading. Finite element analyses are performed using two baseline tab configurations. Based on the results of these analyses, general guidelines for selecting each design variable are presented. At a minimum, these recommendations will minimize the amount of testing required to arrive at a suitable tabbing configuration.

4. EVALUATION OF DESIGN VARIABLES FOR TENSION TESTING.

As previously discussed, the design of a suitable tab configuration primarily involves design variables associated with the tabs and the adhesive. Each design variable may affect the magnitude of the stress concentrations in the tab termination regions. Although the design variables are not independent, they are investigated individually to provide an understanding of their role in minimizing the tab termination region stress concentrations. Finite element analysis is performed on baseline tab configurations for both tension and compression specimens. Based on these results, general guidelines for selecting each design variable are presented.

The two baseline tab configurations investigated are shown in figure 6. Both tab configurations were based on a unidirectional carbon/epoxy tension specimen with glass fabric/epoxy tabs. One tab configuration, referred to as the thin adhesive and tapered tab, (figure 6a) had a 0.25-mm (0.010-in.) -thick adhesive bond line and a 12° tab taper angle. The second configuration,

referred to as the thick adhesive and untapered tab, (figure 6b) had a 1.27-mm (0.05-in.) adhesive bond line thickness and a 90° tab taper angle. Dimensions of these two tab configurations are shown in figure 6. Baseline properties used in the finite element analyses are listed in table 4. (Note that all parameters are referred to the global x-y-z coordinate system of the model shown in figure 4.)

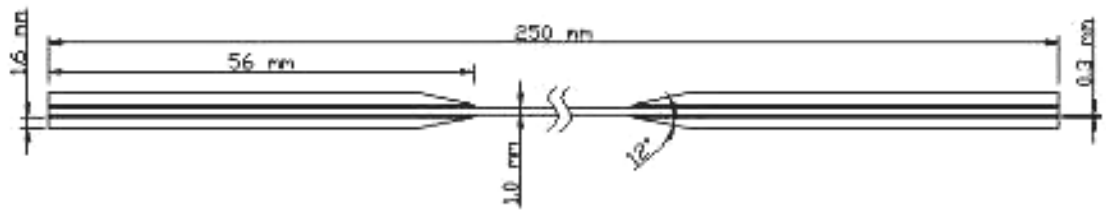

FIGURE 6a. THIN ADHESIVE AND TAPERED TAB, BASELINE TAB CONFIGURATION

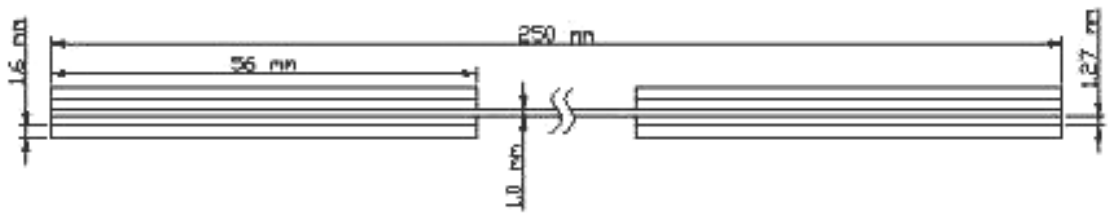

FIGURE 6b. THICK ADHESIVE AND UNTAPERED TAB, BASELINE TAB CONFIGURATION

Stress concentrations produced in the composite specimen were calculated using the two baseline tab configurations shown in figure 6 and described in table 4. All three in-plane stress components were investigated within the composite specimen; the axial stress σ_x, the interlaminar normal stress σ_y, and the interlaminar shear stress τ_{xy}. Figure 7 illustrates the location of the peak stresses within the composite specimen. Note that the peak values of all three stress components occurred within two elements adjacent to the tab termination. The average value of each stress component within the element was used for calculating stress concentrations. The peak values of all three stress components are normalized by dividing by the far-field axial stress $\overline{\sigma}_x$ taken from an element in the gage section of the specimen, as shown in figure 7.

TABLE 4. BASELINE TAB CONFIGURATION PROPERTIES FOR TENSION SPECIMEN FINITE ELEMENT ANALYSIS

Property	Baseline Value
Composite Material	Unidirectional carbon/epoxy
Longitudinal modulus, E_x	142 GPa (20.6 Msi)
Transverse modulus, $E_y = E_z$	9.2 GPa (1.33 Msi)
Poisson's ratio, ν_{xy}	0.25
Poisson's ratio, ν_{xz}	0.29
Laminate thickness	1.0 mm (0.039 in.)
Tab Material	G-10 glass fabric/epoxy
In-plane modulus, E_x	32.6 GPa (4.7 Msi)
Transverse modulus, E_y	6.9 GPa (1.0 Msi)
Poisson's ratio, ν_{xy}	0.06
Poisson's ratio, ν_{xz}	0.08
Tab thickness	1.57 mm (0.062 in.)
Tab length	56 mm (2.2 in.)
Tab taper angle	
Thin adhesive/tapered tab	12°
Thick adhesive/untapered	90°
Adhesive	Hysol 907 two-part paste adhesive
Modulus	3.17 GPa (0.46 Msi)
Poisson's ratio	0.31
Thickness	
Thin adhesive/tapered tab	0.26 mm (0.010 in.)
Thick adhesive/untapered	1.27 mm (0.050 in.)

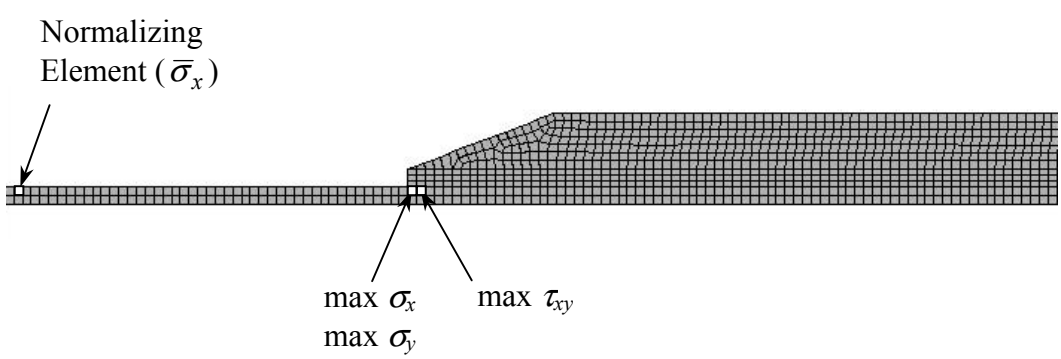

FIGURE 7. LOCATION OF PEAK VALUES OF STRESS COMPONENTS

Finite element analyses were performed to investigate the tab termination stress concentrations associated with each of the tab configuration design variables listed in table 3. The two baseline tab configurations shown in figure 6 were used for these analyses. To investigate each design variable, variations in the value of that specific parameter from the baseline value shown in table 4 were analyzed. Normalized peak values for the three in-plane stress components within the composite are plotted for the values of each design variable modeled. For each design variable, a summary of the results from finite element analysis is given and a recommendation is made.

4.1 SELECTION OF TABBING MATERIAL FOR TENSION TESTING.

- SUMMARY. The selected tabbing material must have adequate strength to transmit the required load into the specimen, while being as compliant (low stiffness) as possible to minimize stress concentrations. Other desirable features include a relatively low-cost material that may be machined in the same manner as the composite material being tested.

- RECOMMENDATION. Glass fabric/epoxy laminated circuit board is recommended for general use as a tabbing material for tension testing.

- RATIONALE. Of the commonly used tabbing materials for composite specimens (described in section 2.1), glass fabric/epoxy laminated circuit board is recommended for general use. This tabbing material is readily available in multiple thicknesses and at relatively low cost. The material has adequate shear strength to permit the required load transfer into most composite specimens, and yet is soft enough to enable the grips to bite into the tab surfaces. The relatively low stiffness of the glass fabric/composite is also advantageous for minimizing tab termination stress concentrations. Finally, glass fabric/epoxy tabbing material can be used for elevated temperature testing (350°F maximum for NEMA Grade G-10 and 400°F maximum for NEMA Grade G-11). Both of these glass fabric/epoxy materials require minimal surface preparation. As a rule, glass fabric/epoxy should be considered as a tabbing material unless there is a clear reason why another material is preferred.

  Finite element analyses were performed on the two baseline tab configurations, shown in figure 6, with varying stiffnesses of the tab material. Five different tab material stiffnesses were analyzed, ranging from 15 GPa to 240 GPa (0.22 Msi to 3.48 Msi). The stress concentrations produced in the composite specimen are shown in figures 8 and 9 for the tapered tab-thin adhesive and untapered tab-thick adhesive configurations, respectively. For both configurations, results show that the stress concentrations in the composite specimen decrease as the stiffness of the tab material decreases. For the range of tab material stiffnesses considered, the stress concentration in the two normal stresses varied by nearly 5% as compared to 3% for the shear stress. Although these differences are not large, they suggest that a relatively compliant tab material such as glass fabric/epoxy should reduce the likelihood of tab region failures from occurring.

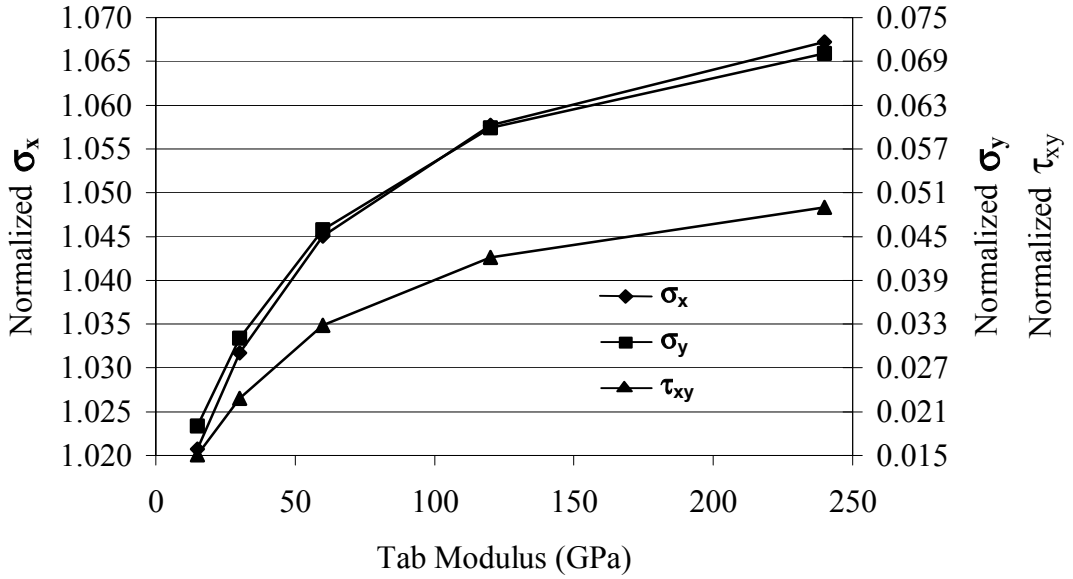

FIGURE 8. EFFECT OF TAB STIFFNESS ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, TAPERED TAB-THIN ADHESIVE CONFIGURATION

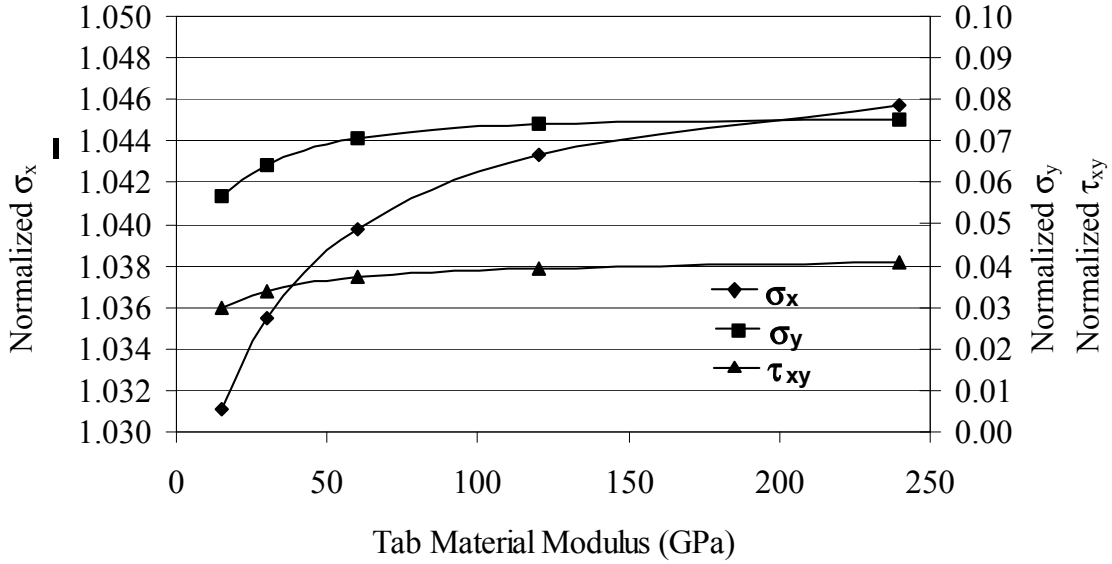

FIGURE 9. EFFECT OF TAB STIFFNESS ON STRESS CONCENTRATIONS IN COMPOSITE SPECIMEN, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

Table 5 shows the normalized stress concentration factors produced using the two baseline tab configurations for three common tabbing materials: glass fabric/epoxy, carbon/epoxy, and steel. For both baseline tab configurations, the glass fabric/epoxy tabs produce the lowest stress concentrations. Note that carbon/epoxy tabbing material, with a

stiffness equal to that of the carbon/epoxy composite specimen (142 GPa), does not minimize the tab region stress concentrations.

TABLE 5. STRESS CONCENTRATIONS PRODUCED FOR SELECTED TABBING MATERIALS, TENSION SPECIMEN

	Tapered Tab, Thin Adhesive			Untapered Tab, Thick Adhesive		
Tab Type	$\sigma_x/\bar{\sigma}_x$	$\sigma_y/\bar{\sigma}_x$	$\tau_{xy}/\bar{\sigma}_x$	$\sigma_x/\bar{\sigma}_x$	$\sigma_y/\bar{\sigma}_x$	$\tau_{xy}/\bar{\sigma}_x$
G-10 glass fabric/epoxy E = 32.6 GPA (4.7 Msi)	1.025	0.0138	0.0187	1.036	0.0303	0.0342
Unidirectional carbon/epoxy E = 142 GPa (20.6 Msi)	1.054	0.0307	0.0414	1.040	0.0334	0.0398
Steel E = 200 GPa (29 Msi)	1.057	0.0314	0.0428	1.043	0.0354	0.0402

4.2 SELECTION OF TAB THICKNESS FOR TENSION TESTING.

- SUMMARY. The tabbing material must be of adequate thickness to protect the composite material from surface damage during gripping. The tab thickness does not have a significant effect on the tab termination stress concentrations.

- RECOMMENDATION. A tab thickness of approximately 1-2 mm (0.04-0.08 in.) is recommended for general use in tensile testing. Any commonly available thickness of the selected tabbing material within this general range is acceptable. Note that G-10 glass fabric/epoxy laminated circuit board is commonly available in 1.6 mm (0.062 in.) thickness.

- RATIONALE. The thickness of the tabs must be sufficient to protect the composite test specimen from damage due to the grips biting into the surface. Since the damage produced by the grips is often limited to the outermost region of the tab surface (~0.5 mm), a minimal tab thickness satisfies this requirement. The common range of selected tab thicknesses is 1 to 4 times the thickness of the test specimen. Note that the recommended tabbing material, G-10 and G-11 glass fabric/epoxy laminated circuit board, is readily available in 1.6 mm (0.062 in.) and 3.2 mm (0.125 in.) thicknesses, either of which are acceptable choices for testing most unidirectional composite materials.

  Finite element analyses were performed on the two baseline tab configurations, shown in figure 6, with varying thickness of glass fabric/epoxy tabs. Five different tab thicknesses were analyzed, ranging from 0.5 mm (0.020 in.) to 4.0 mm (0.16 in.). Note that for the baseline composite specimen thickness of 1.0 mm (0.039 in.), this range of tab thicknesses represents 0.5 to 4.0 times the specimen thickness. The stress concentrations produced in the composite specimen are shown in figures 10 and 11 for the tapered tab-thin adhesive and untapered tab-thick adhesive configurations, respectively. Results show that the tab termination region stress concentration factors decrease slightly as the tab thickness decreases. However, this decrease in stress concentrations is relatively

insignificant, especially for tab thickness of 1.0 mm (0.039 in.) and greater. Thus, the selection of the tab thickness does not have a significant effect on the tab termination stress concentrations.

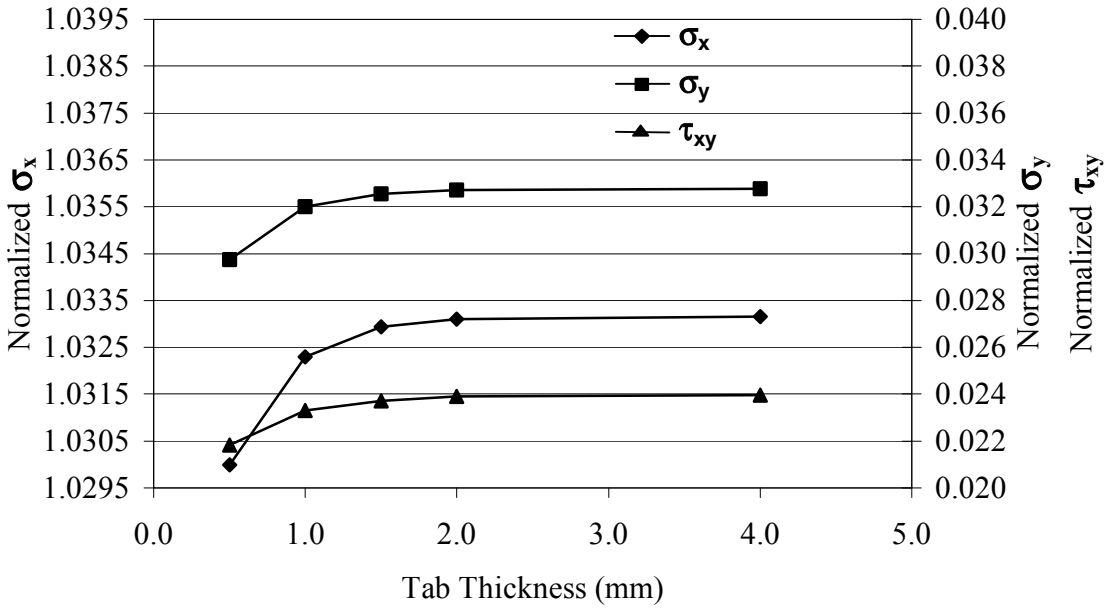

FIGURE 10. EFFECT OF TAB THICKNESS ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, TAPERED TAB-THIN ADHESIVE CONFIGURATION

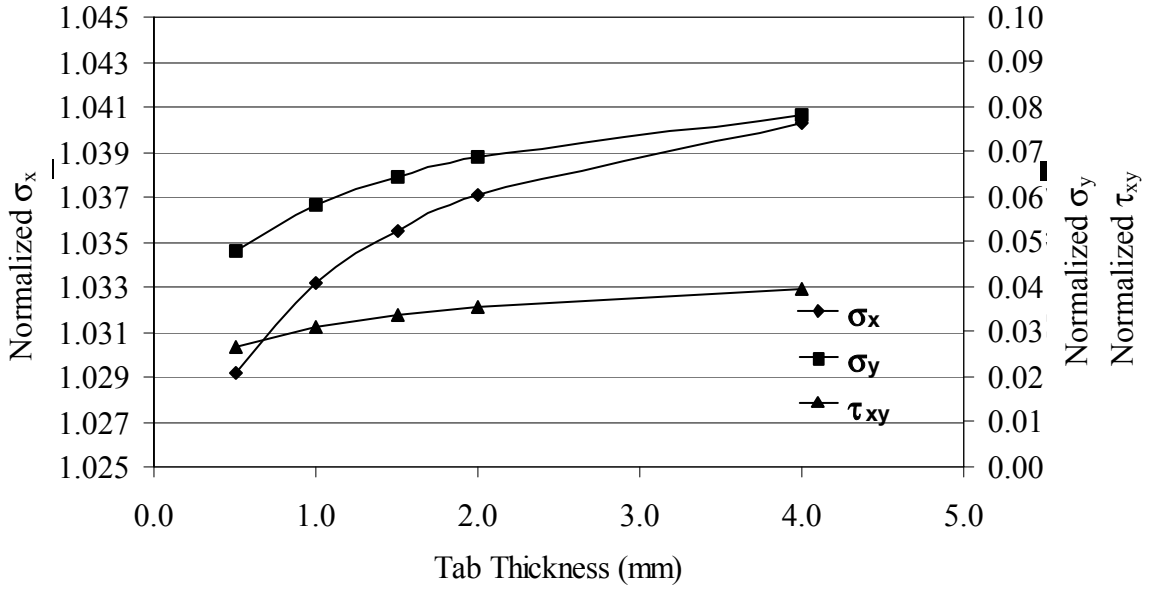

FIGURE 11. EFFECT OF TAB THICKNESS ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

4.3 SELECTION OF TAB LENGTH FOR TENSION TESTING.

- SUMMARY. A suitable tab length is established by both the strength of the tab material and adhesive as well as the practical length limitations of the grips used. A longer tab length serves to slightly reduce the tab termination stress concentrations.

- RECOMMENDATION. A tab length of at least 40 mm (~1.5 in.) is desirable for most tension testing. In general, it is recommended to use the longest tab length permitted by the test grips.

- RATIONALE. The minimum required length of the tabs is dependant on both the load required to fail the specimen and the shear strength of the adhesive. Since the entire untapered length of the tab should be gripped during tension testing, the length of the grips determines the maximum length of the tabs. This practical tab length limit set by the grips should be selected unless material supply or test panel size is a limiting factor. Typical tab lengths for unidirectional composite materials testing range between 40 mm and 90 mm (1.5 and 3.5 in.), primarily since common specimen grips have lengths in this same range.

  Finite element analyses were performed on the two baseline configurations, shown in figure 6, with varying tab lengths. Five different tab lengths were analyzed, ranging from 10 mm to 160 mm (0.39 to 6.29 in.). The stress concentrations produced in the composite specimen are shown in figures 12 and 13 for the tapered tab-thin adhesive and untapered tab-thick adhesive configurations, respectively. Finite element results for both tab configurations suggest that a longer tab length reduces the stress concentrations at the tab termination region, although such reductions are diminished as the tab length increases. Beyond a tab length of approximately 40 mm, the reduction in stress concentrations is minimal. Based on these results, a tab length of at least 40 mm (~1.5 in.) is recommended.

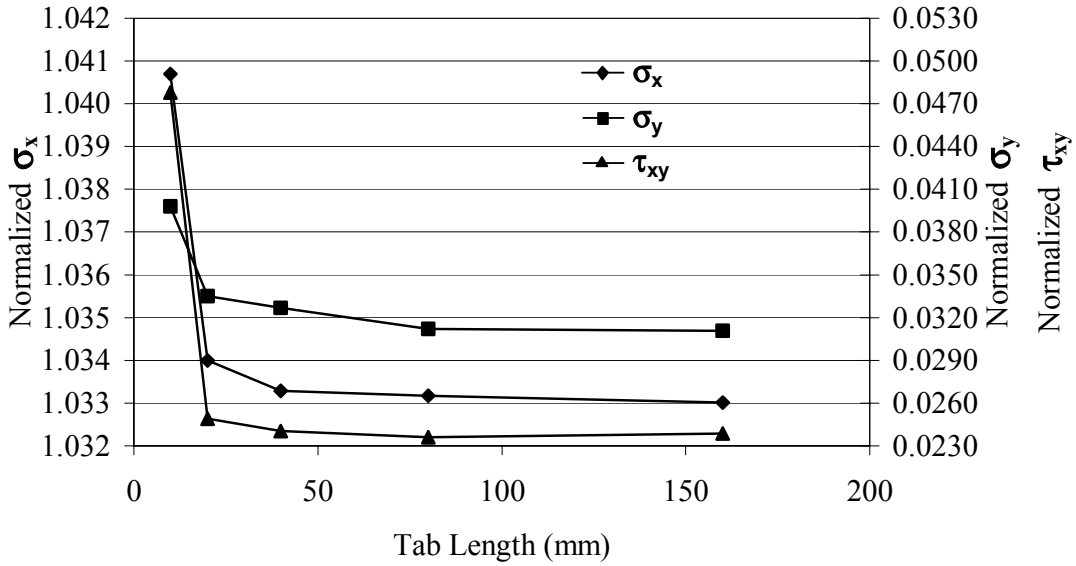

FIGURE 12. EFFECT OF TAB LENGTH ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, TAPERED TAB-THIN ADHESIVE CONFIGURATION

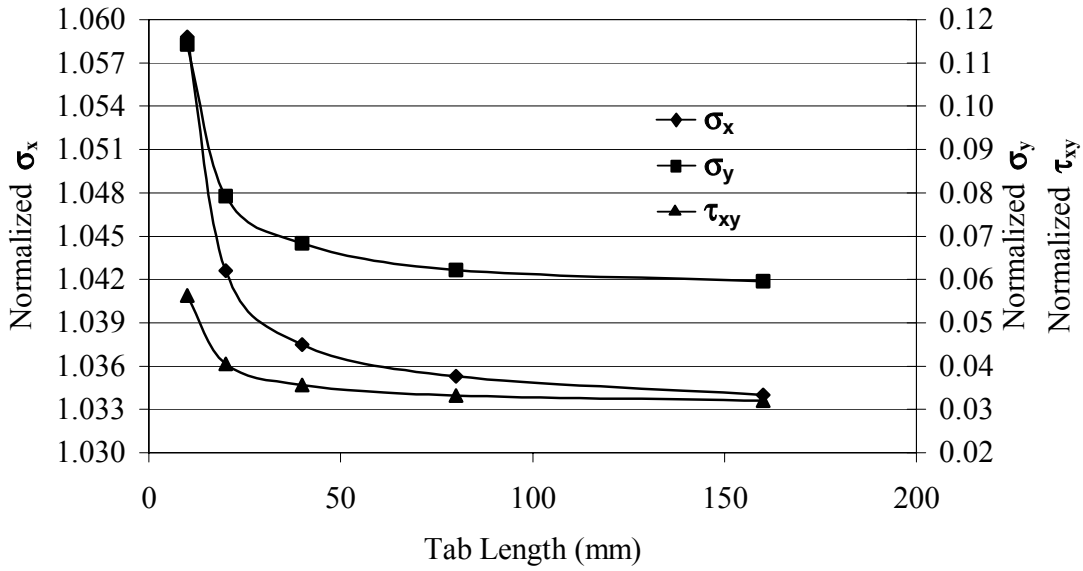

FIGURE 13. EFFECT OF TAB LENGTH ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

4.4 SELECTION OF TAB TAPER ANGLE FOR TENSION TESTING.

- SUMMARY. Although a highly tapered tab is desired to minimize tab termination stress concentrations, ease of fabrication and maintaining bond line uniformity need to be considered. Thus, a compromise must be made when selecting a suitable tab taper angle.

- RECOMMENDATION. A tab taper angle between 10° and 15° is recommended for general tension testing.

- RATIONALE. One of the most important considerations in designing a tab configuration is selecting the taper or bevel angle at the gage section ends of the tabs. A primary design goal when selecting the tab taper angle is to minimize the stress concentration at the tab termination. A larger taper angle serves to feather the tab region into the untabbed gage region, minimizing the geometric discontinuity and the corresponding stress concentrations. However, another important design consideration is to keep the tensile normal stress in the adhesive, or peel stress, below the point at which adhesive failure will occur. Note that clamping pressure cannot be exerted over the tapered region of the tabs. As the tab taper angle is decreased, tensile σ_y stresses are produced in the adhesive in addition to shear stresses τ_{xy} over a larger area of the tabbed area. Together, these stresses can produce adhesive failure and subsequent tab debonding when significant tab tapering is present.

  Finite element analyses were performed on the two baseline tab configurations with varying tab taper angles. Five different tab taper angles were analyzed, ranging from 5° to 90°. Note that the tab taper angle is defined as the angle between the tapered portion of the tab and the surface of the tab (figure 2), such that a highly tapered tab results in a small tab taper angle. For all configurations analyzed, a constant overall tab length of 56 mm (2.2 in.) was used. Thus, the portion of the tab length over which gripping occurred varied for the tapered tab configuration. Stress concentrations produced in the composite specimen versus tab taper angle are shown in figures 14 and 15 for the thin adhesive and thick adhesive configurations, respectively. As expected, the stress concentrations in both specimen configurations decrease as the tab taper angle decreases. For both adhesive thicknesses, the stress concentration factors remain virtually constant for tab taper angles from 90° to 45° and decrease slightly as the taper angle is further reduced to 30°. However, a majority of the reduction in stress concentration factors occurs for tab taper angles between 15° and 5°. The difference in stress concentrations for the tab taper angles modeled was larger for the thin adhesive configuration (2.0 to 3.5 percent) than for the thick adhesive configuration (0.3 to 1.2 percent). Based solely on the magnitudes of the stress concentrations, the results suggest that the smallest possible tab taper angle should be used, especially when a relatively thin adhesive layer (0.26 mm) is used.

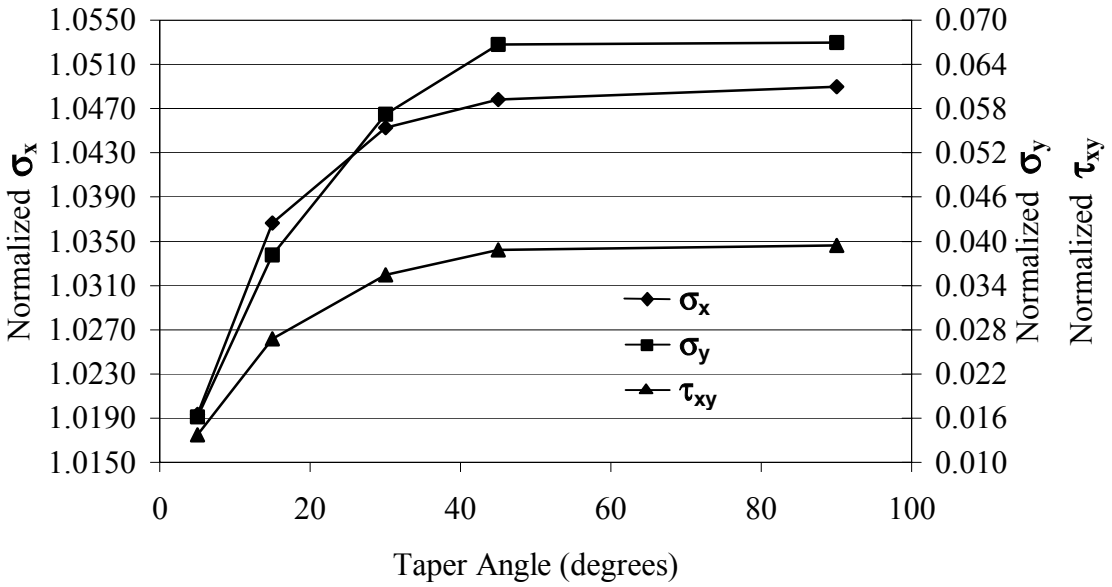

FIGURE 14. EFFECT OF TAB TAPER ANGLE ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, THIN ADHESIVE CONFIGURATION

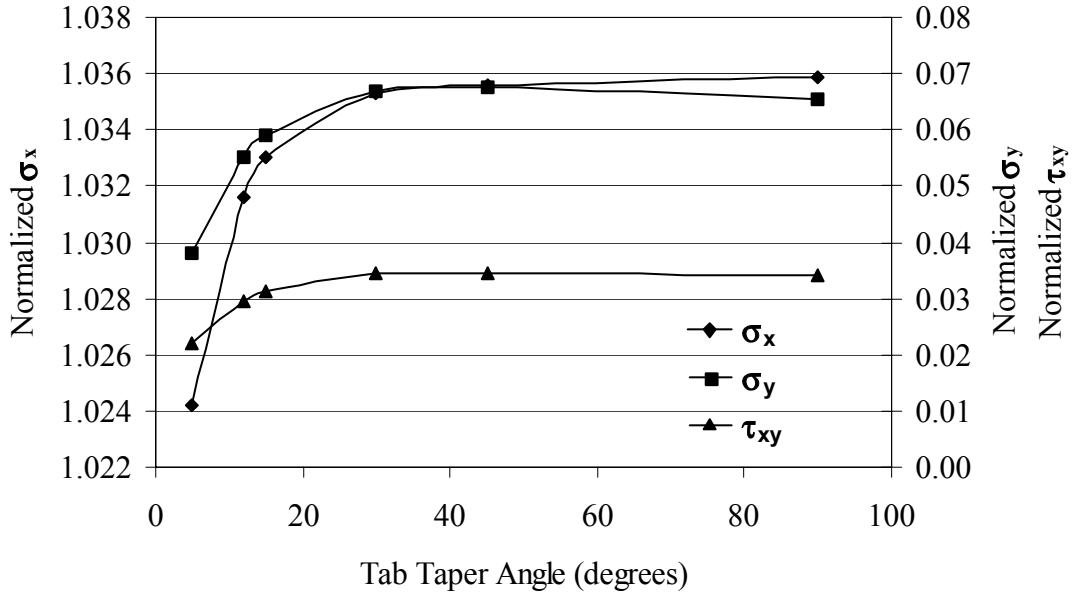

FIGURE 15. EFFECT OF TAB TAPER ANGLE ON STRESS CONCENTRATIONS IN THE COMPOSITE SPECIMEN, THICK ADHESIVE CONFIGURATION

A second design consideration when selecting a suitable tab taper angle is the stress state produced in the adhesive bond line near the end of the tapered tab. Of interest are the magnitudes of the peel stress σ_y and the shear stress τ_{xy}, since adhesive failure and subsequent tab debonding may occur if these stresses become excessive. These stresses are plotted along the length of the adhesive bond line in figures 16 and 17 for the thin and thick adhesive layer configurations, respectively. All stresses are normalized by the far-field axial stress $\overline{\sigma}_x$ in the specimen gage section. The distributions of the peel stress σ_y produced in the adhesive layer are plotted for a series of tab taper angles in figure 16a and 17a for the thin and thick adhesive configurations, respectively. The peel stress σ_y is shown to remain tensile for a greater length along the tab as the taper angle decreases. Note that the peel stresses are shown to decrease significantly as the adhesive layer thickness is increased from 0.26 mm (figure 16a) to 1.27 mm (figure 17a). The τ_{xy} shear stress distributions produced in the adhesive bond line are shown in figures 16b and 17b for the thin and thick adhesive configurations, respectively. The bond line shear stresses are shown to decrease as the adhesive thickness increases.

Based on the finite element results shown in figures 14 through 17, the tab taper angle should be selected to be the smallest practical value. However, the length of the tapered section of the tab begins to increase dramatically as the taper angle becomes less than 10. Additionally, manufacturing difficulties arise as the tab taper angle becomes small. Based on these practical considerations, a tab taper angle between 10° and 15° is recommended for general tension testing.

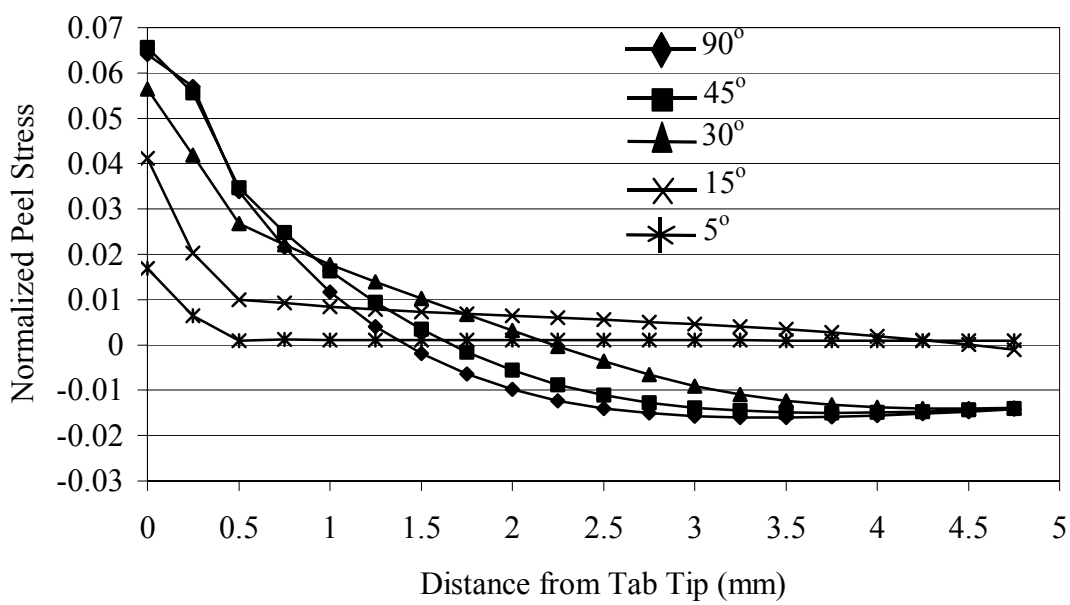

FIGURE 16a. EFFECT OF TAB TAPER ANGLE ON NORMALIZED PEEL STRESS DISTRIBUTION IN ADHESIVE BOND LINE, THIN ADHESIVE CONFIGURATION

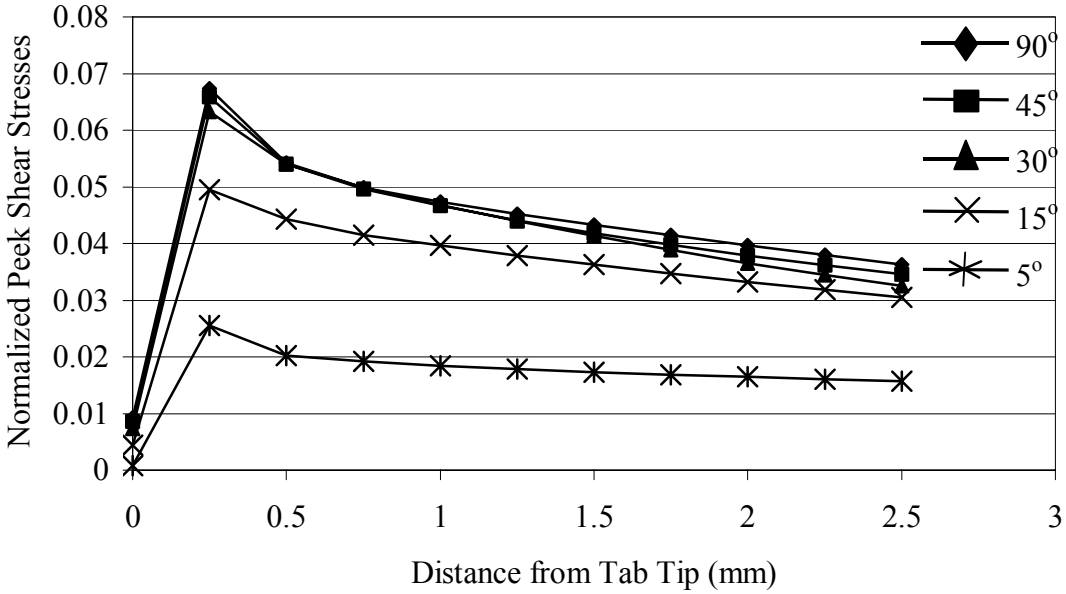

FIGURE 16b. EFFECT OF TAB TAPER ANGLE ON NORMALIZED SHEAR STRESS DISTRIBUTION IN ADHESIVE BOND LINE, THIN ADHESIVE CONFIGURATION

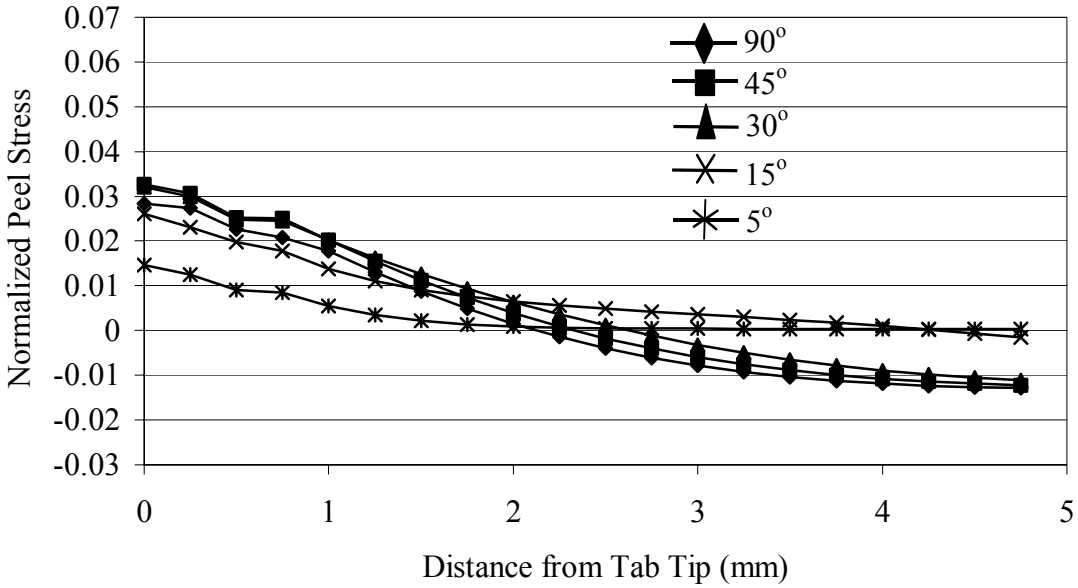

FIGURE 17a. EFFECT OF TAB TAPER ANGLE ON NORMALIZED PEEL STRESS DISTRIBUTION IN ADHESIVE BOND LINE, THICK ADHESIVE CONFIGURATION

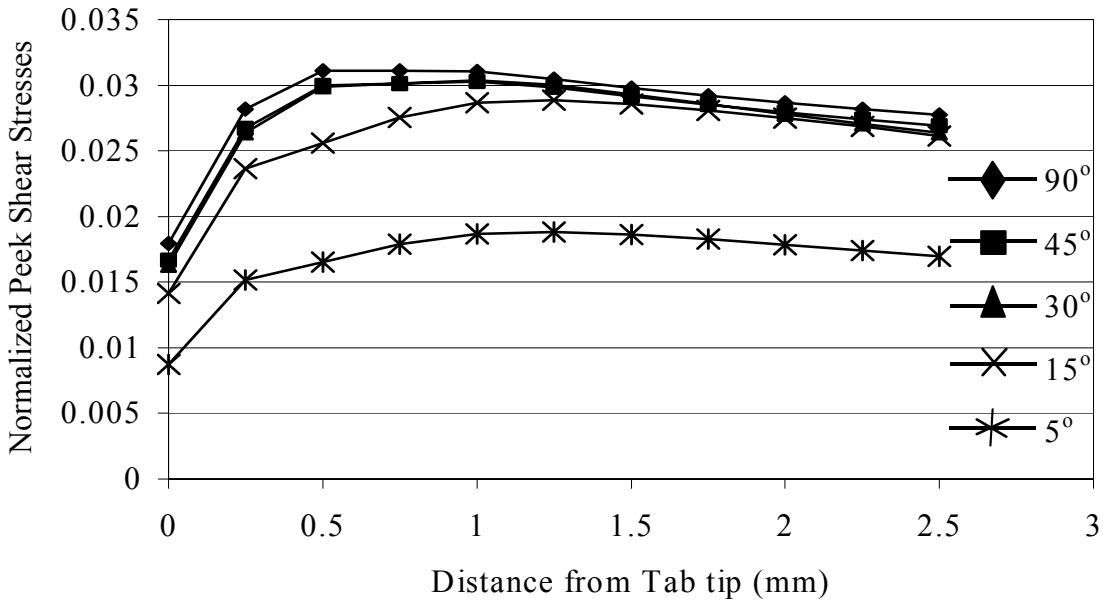

FIGURE 17b. EFFECT OF TAB TAPER ANGLE ON NORMALIZED SHEAR STRESS DISTRIBUTION IN ADHESIVE BOND LINE, THICK ADHESIVE CONFIGURATION

4.5 SELECTION OF ADHESIVE FOR TENSION TESTING.

- SUMMARY. Strength is the primary consideration for adhesive selection. The modulus of elasticity has a minor effect on the magnitude of the stress concentrations in the composite. Although a lower stiffness adhesive produces slightly reduced stress concentrations, the modulus of elasticity is not an important design variable when selecting a suitable adhesive.

- RECOMMENDATION. Adhesive selection should be based on strength properties, ease of application, availability, and cost rather than modulus of elasticity.

- RATIONALE. The primary considerations when selecting a suitable adhesive are its ability to transmit the required load into the test specimen through shear as well as withstanding the compressive loads produced by gripping and the peel stress resulting from tapered tabs. Since many commonly available adhesives may satisfy the above requirements, a secondary consideration in the adhesive selection is minimizing the stress concentration at the tab termination. Since the adhesive is usually more compliant (lower modulus of elasticity) than the tabbing material, the adhesive layer may be used to further reduce stress concentrations in the tab termination region.

  Finite element analyses were performed on the two baseline tab configurations with varying moduli values for the adhesive. Five different adhesive moduli were analyzed, ranging from E = 2.76 to 3.45 GPa (400 to 500 Ksi). This range of adhesive moduli is believed to represent the variation found in candidate adhesives for tab bonding. The

value of Poisson's ratio used for the adhesive, $\nu = 0.31$, was held constant. The resulting shear modulus varied for the different moduli values according to the relation

$$G = \frac{E}{2\,(1+\nu)}$$

Stress concentrations produced in the composite specimen versus adhesive moduli are shown in figures 18 and 19 for the tapered tab-thin adhesive and untapered tab-thick adhesive configurations, respectively. Results show that for both tab configurations, decreasing the adhesive modulus reduces the stress concentrations at the tab termination region, especially for the axial stress component σ_x. Note, however, that the difference in stress concentrations for the range of adhesive moduli investigated is relatively small. Thus, the modulus of the adhesive does not have a major effect on tab termination stress concentrations.

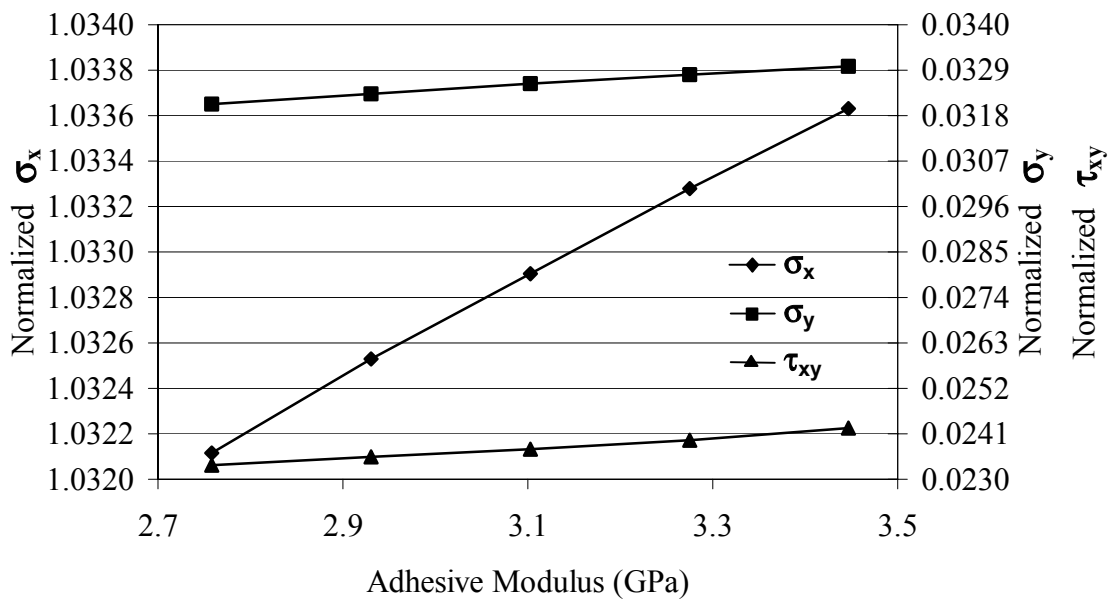

FIGURE 18. EFFECT OF ADHESIVE MODULUS ON STRESS CONCENTRATIONS IN COMPOSITE SPECIMEN, TAPERED TAB-THIN ADHESIVE CONFIGURATION

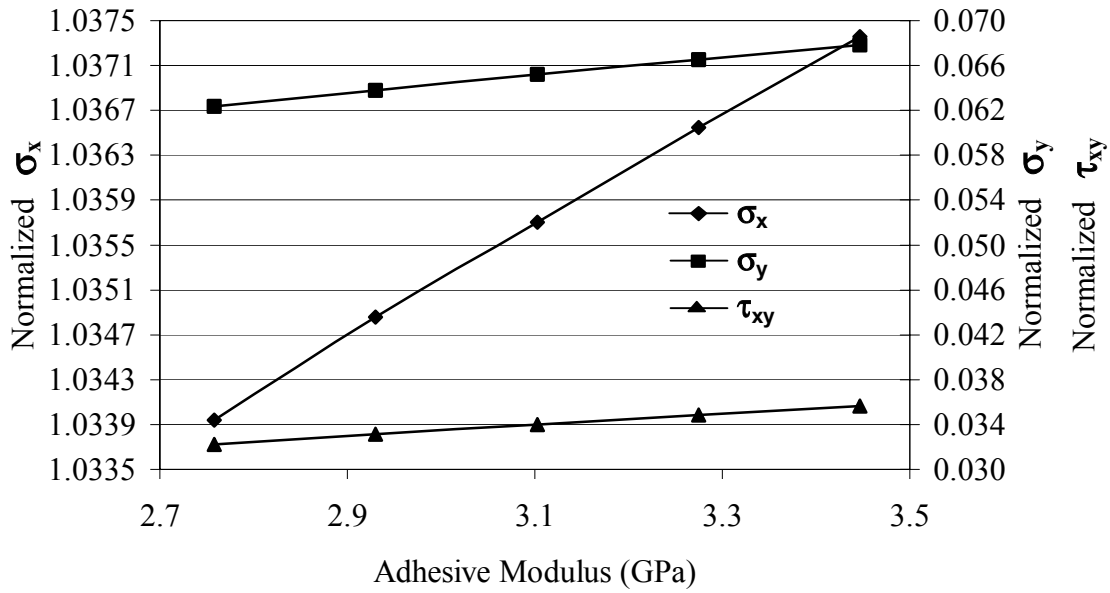

FIGURE 19. EFFECT OF ADHESIVE MODULUS ON STRESS CONCENTRATIONS IN COMPOSITE SPECIMEN, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

4.6 SELECTION OF ADHESIVE THICKNESS FOR TENSION TESTING.

- SUMMARY. Since commonly used adhesives are more compliant than the tab and composite material, a thicker adhesive bond line will further reduce tab termination stress concentrations. The magnitude of stress reduction is greater for untapered tabs than for tapered tabs.

- RECOMMENDATION. For tapered tabs, the adhesive thickness does not have a significant effect on the tab termination stress concentrations. However, a thicker adhesive layer (1.3 mm) is recommended when using untapered tabs.

- RATIONALE. Traditionally, a thin adhesive bond line has been preferred for tab bonding due to strength concerns with increasing bond line thickness. However, many high-strength adhesives are currently available which yield excellent strengths when used in thicker bond lines. Thus, the thickness of the adhesive bond line may be considered to be a design variable when attempting to minimize stress concentrations in tabbing configurations.

  Since most adhesives used are more compliant than the tab and composite material, a thicker adhesive bond line may serve to further reduce stress concentrations. Linear elastic finite element analyses were performed on the two baseline specimen configurations with varying adhesive bond line thickness. Five different adhesive thicknesses were investigated ranging from 0.3 to 2.0 mm (0.012 to 0.079 in.). The stress concentrations produced in the composite specimen are shown in figures 20 and 21 for

the tapered tab and untapered tab configurations, respectively. For the tapered tab configuration (figure 20), the peak axial stress σ_x decreases as the adhesive thickness is increased. However, the normal stress σ_y and shear stress τ_{xy} are shown to increase as the adhesive thickness is increased. Note that the variations in all three-stress components are relatively small for the range of adhesive thicknesses considered. For the untapered tab configuration (figure 21), neither the normal stress σ_y nor the shear stress τ_{xy} are affected significantly by the adhesive thickness. However, the peak axial stress σ_x drops significantly as the adhesive thickness increases. Comparing the results for the two configurations, note that the σ_x and τ_{xy} stress concentrations for the untapered tab with a thick adhesive layer are approximately equal to the stress concentrations in the tapered tab configuration.

Based on these results for a linear elastic adhesive, the thickness of the adhesive bond line may be selected to reduce stress concentrations in the tab termination regions. For a tapered tab configuration, the bond line thickness has a minimal effect on the tab termination stress concentrations. For an untapered tab configuration, however, increasing the bond line thickness significantly reduces the stress concentrations. An adhesive thickness of approximately 1.3 mm (0.05 in.) is suggested for untapered tab configurations. It remains important to keep the bond line thickness uniform so that the overall thickness of the tabbed specimens remains constant. This will eliminate bending in the specimen during gripping and subsequent testing. The difficulty of maintaining a uniform bond line increases as the desired bond line thickness increases.

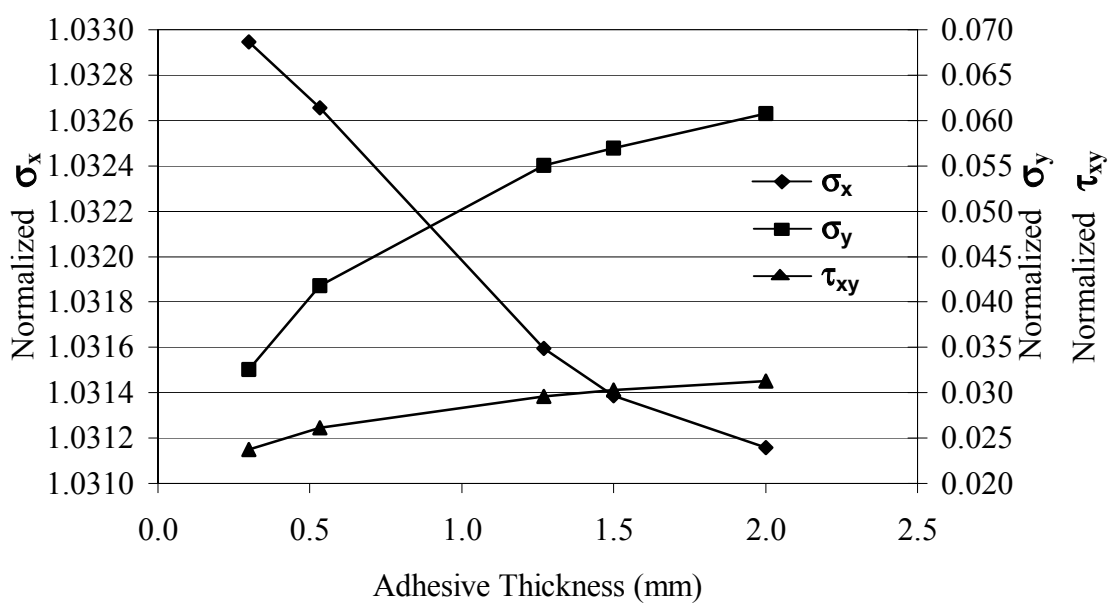

FIGURE 20. EFFECT OF ADHESIVE THICKNESS ON STRESS CONCENTRATIONS IN COMPOSITE SPECIMEN, TAPERED TAB CONFIGURATION

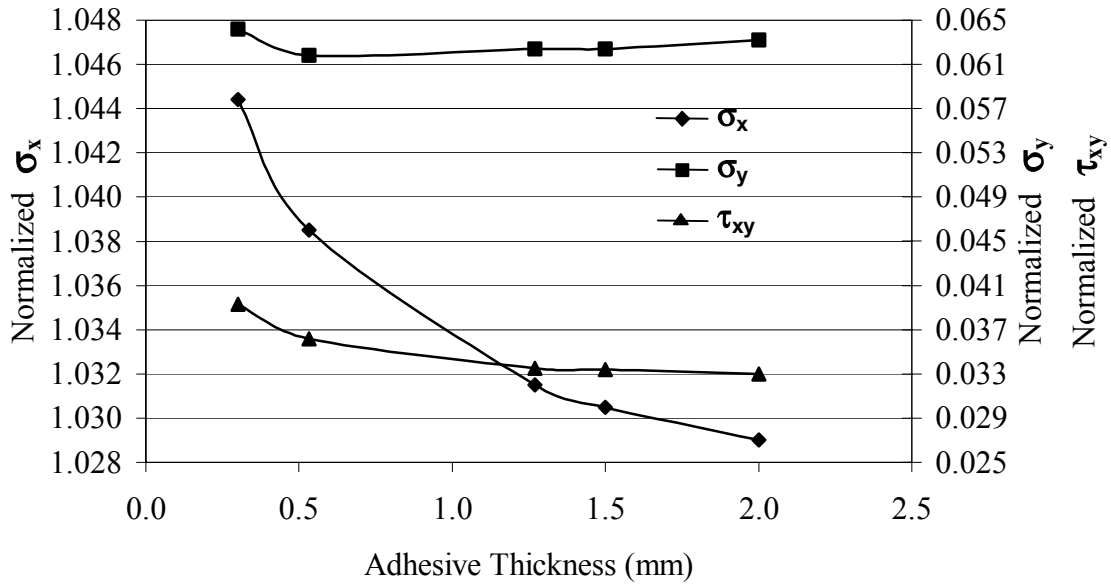

FIGURE 21. EFFECT OF ADHESIVE THICKNESS ON STRESS CONCENTRATIONS IN COMPOSITE SPECIMEN, UNTAPERED TAB CONFIGURATION

4.7 EXPERIMENTAL RESULTS FROM TENSION TESTING.

Experimental testing was performed to verify the results of the finite element analysis and justify the recommendations made. Testing was performed using the two baseline configurations, shown in figure 6. The composite material tested was unidirectional AS4/3501-6 carbon/epoxy. The tab material used was 1.57-mm (0.062-in.) -thick G10 glass fabric/epoxy laminated circuit board. Two tab taper angles were investigated: 90° (untapered) and 12° (tapered). For each taper angle, two adhesives were used; Hysol 907 two-part paste adhesive [8] and 3M AF163-2K film adhesive [9]. As shown previously in figure 1, the 3M film adhesive is more compliant than the Hysol 907 adhesive. Three adhesive thicknesses were investigated: 0.3 mm (0.012 in.), 0.5 mm (0.021 in.), and 1.3 mm (0.050 in.). Testing was performed in accordance with ASTM standard D 3039 [2]. A total of seven specimens were tested for each configuration investigated.

Figure 22 compares the tensile strengths for the different untapered 90° tab configuration and tapered 12° tab configuration with three different Hysol 907 adhesive thicknesses, where *A* is the average and *S* is the standard deviation of the specimen sets. The average failure tensile stress and the scatter from the seven specimens tested for each configuration is shown above the individual specimen data bars. When untapered tab specimens were bonded using the Hysol 907 adhesive (modeled in finite element analysis), the tensile stress increased significantly when the adhesive thickness increased from 0.3 to 1.3 mm, in agreement with finite element results. Likewise, the finite element results and tension test results for the tapered tab specimens bonded with the Hysol 907 showed the same trend as the untapered specimens but with less significant variation in magnitude.

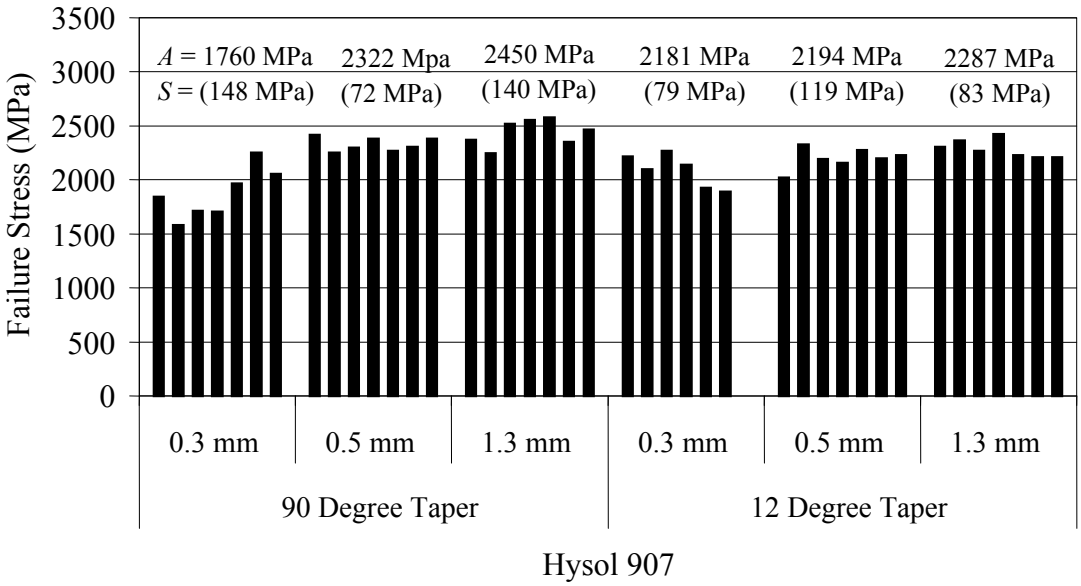

FIGURE 22. TENSILE TEST RESULTS FOR SPECIMENS USING HYSOL 907 ADHESIVE

However, as shown in figure 23, using the more ductile than the Hysol 907 adhesive 3M AF163-2K adhesive, the variation in tensile stress with increasing adhesive thicknesses was reduced. Figure 23 compares the tensile stress for the different untapered 90° tab configuration and tapered 12° tab configuration with three different AF163-2K adhesive thicknesses ranging from 0.3 to 1.3 mm. Curiously, the highest tensile strength obtained from the more ductile 3M AF163-2K adhesive was for the thinnest adhesive bond line thickness.

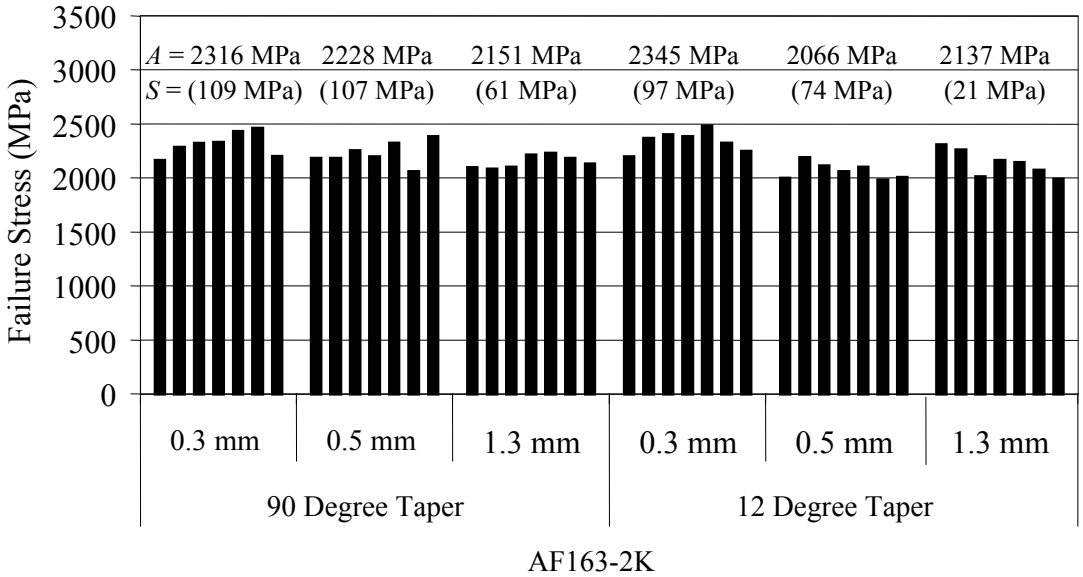

FIGURE 23. TENSILE TEST RESULTS FOR SPECIMENS USING
3M AF163-2K ADHESIVE

No significant variations or clear trends in tensile stress are seen when comparing the two adhesives and the different adhesive thicknesses. These results suggest that the reduction in stress concentration due to the tapered tab is of greater significance than the thickness or ductility of the adhesive.

In summary, the experimental results indicate that the measured tensile stress can be affected significantly, depending on which tabbing configuration is used. In general, good results were obtained using a more ductile adhesive, especially for thinner adhesive bond line thicknesses. However, a less ductile, stiffer adhesive can produce comparable tensile stresses when the adhesive bond line thickness is made larger. The experimental results show that the need for a tapered tab or thick adhesive layer decreases as the ductility of the adhesive increases. Since the ductility or modulus of an adhesive may not be known, it is recommended that a tapered tab, a thick adhesive layer, or both be used to minimize tab termination stress concentrations.

5. EVALUATION OF DESIGN VARIABLES FOR COMPRESSION TESTING.

For compression testing, load may be introduced into the specimen via shear loading of the tab surfaces, through end loading of the tabbed specimen, or from a combination of both methods. Thus, the investigation of suitable tabbing configurations for compression specimens requires that the method of load introduction be considered. Note that the detailed stress analyses of tensile specimens presented in section 4 were the specimens shear loaded on the tab surfaces. Although some differences in recommended specimen thicknesses and gage section lengths exist between shear-loaded tension and shear-loaded compression specimens, many of the results for the shear-loaded tensile specimens in section 4 may be used to understand shear-loaded compression specimens in this section. To supplement these previous results, additional analyses performed for compression loading will focus on stress concentrations produced under a combination of shear loading and end loading.

Two-dimensional plane-stress finite element analyses were performed to investigate the effect of individual design variables on the stress concentrations at the tab termination region and at the specimen ends. The two baseline tab configurations used to investigate effects of individual design variables are shown in figure 24. Both tab configurations were based on a unidirectional carbon/epoxy compression specimen with glass fabric/epoxy tabs. Material properties and geometric parameters for the two baseline compression configurations were similar to those from the baseline tension configurations (table 4). The specimen thickness was increased from 1 to 2.5 mm and the gage section length was reduced to 13 mm. Additionally, for the thin adhesive/tapered tab case, the tab taper angle was taken to be 30°.

The modeled regions and boundary conditions for the two baseline compression configurations are shown in figure 25. Boundary conditions are shown for the case of the ASTM Standard D 6641 Combined Loading Compression (CLC) test method [12]. The CLC test was developed by the Composite Materials Research Group at the University of Wyoming to generate compressive properties of straight-sided, untabbed, cross-ply composite specimens as well as tabbed, unidirectional composite specimens [13]. The CLC fixture applies the loads to the specimen by the simultaneous combination of shear and axial loading. The fractions of the axial load transmitted into the specimen through the tab surfaces and through the ends of the specimen may be varied. For these analyses, 2/3 of the total applied axial load was assumed to be

transferred into the specimen through shear-loading the surfaces of the tabs and 1/3 through end loading of the tabbed specimen. Following the research performed by Xie and Adams, the ratio of shear load to normal load applied to the tab surface was taken as 0.84 [14]. The end load was applied simultaneously with the shear and normal loads on the tab surface.

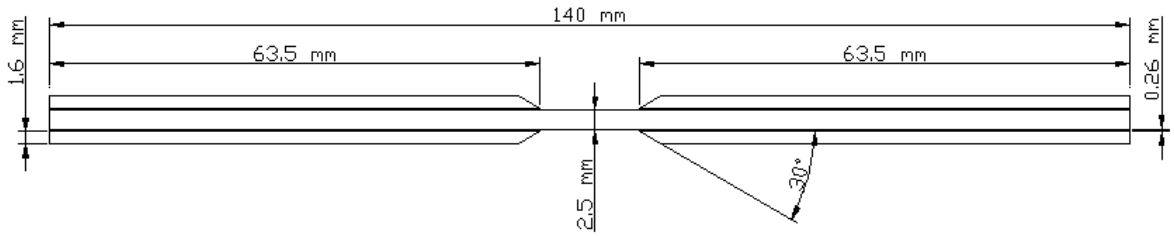

FIGURE 24a. THIN ADHESIVE AND TAPERED TAB, BASELINE TAB CONFIGURATION

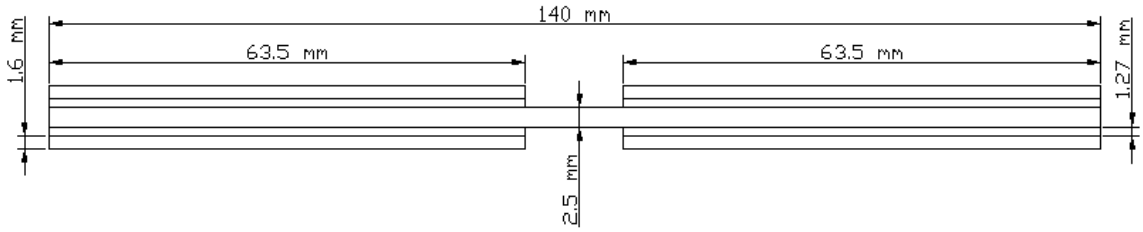

FIGURE 24b. THICK ADHESIVE AND UNTAPERED TAB, BASELINE TAB CONFIGURATION

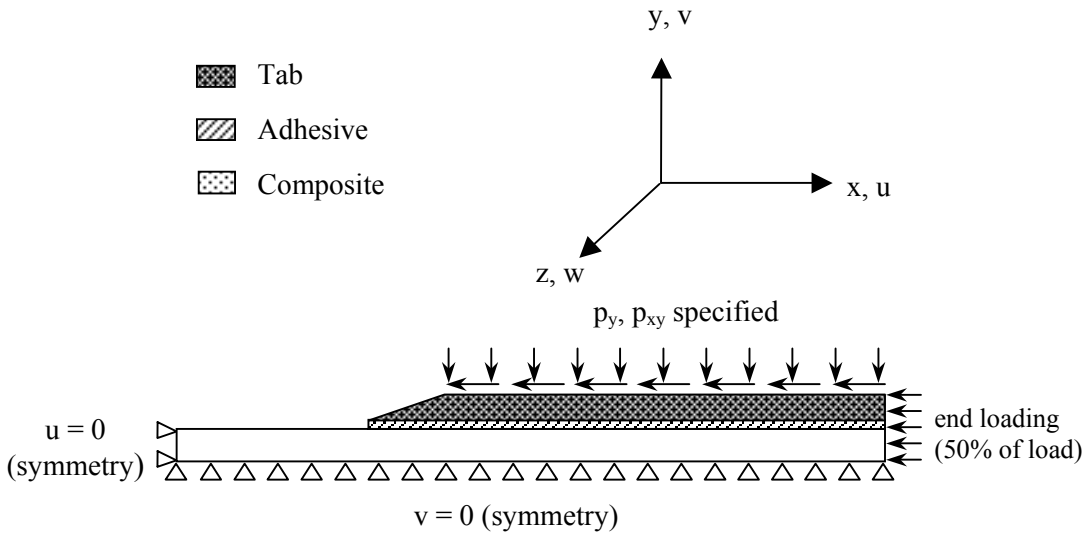

FIGURE 25a. MODELED REGION OF COMPRESSION TEST SPECIMEN WITH TAPERED TABS

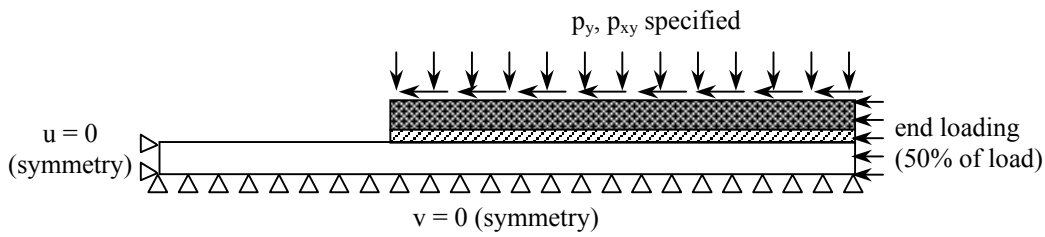

FIGURE 25b. MODELED REGION OF COMPRESSION TEST SPECIMEN WITH UNTAPERED TABS

Finite element analyses were performed to investigate the tab termination stress concentrations associated with each of the tab configuration design variables listed in table 3. The two baseline tab configurations shown in figure 24 were used for these analyses. To investigate each design variable, variations from the baseline value were analyzed. All three in-plane stress components were investigated: the axial stress σ_x, the interlaminar normal stress σ_y, and the interlaminar shear stress τ_{xy}. The peak values of all three stress components are normalized by dividing by the far-field axial stress $\bar{\sigma}_x$ taken from an element at the center of the gage section. The locations of the peak stresses, axial, normal, and shear were determined to be at or near the tab termination and adjacent to the adhesive layer. A localized maximum shear stress was also seen at the tab end where the end loading was being applied.

5.1 SELECTION OF TABBING MATERIAL FOR COMPRESSION TESTING.

- SUMMARY. In general, the tabbing material must have adequate strength to transmit the required load into the specimen through any combination of shear loading and end loading. A lower stiffness tabbing material reduces the tab termination stress concentration. However, overly compliant tab materials produce higher shear stress concentrations at the specimen ends due to end loading.

- RECOMMENDATION. Glass fabric/epoxy laminated circuit board is recommended for general use as a tabbing material for compression testing.

- RATIONALE. The finite element analyses was performed on the two baseline tab configurations shown in figure 24. The range (15 GPa to 240 GPa (0.22 Msi to 3.48 Msi)) of tab material stiffnesses was the same as was used for tension testing analysis. Stress concentrations were examined at both the tab termination region (adjacent to the gage section) and the specimen ends. In general, the variation in stress concentrations at the tab termination for all three stress components (σ_x, σ_y, and τ_{xy}) were similar to those predicted under tensile load, as shown previously in figures 8 and 9. The shear stress concentrations produced in the combined loading compression specimen are shown in figure 26 for the untapered tab-thick adhesive configuration. As was observed for tension loading, the shear stress concentration at the tab termination increases as the stiffness of the tabbing material increases. At the specimen ends, however, the shear stress concentration decreases as the stiffness of the tabbing material increases. Similar results were observed for the tapered tab-thin adhesive configuration.

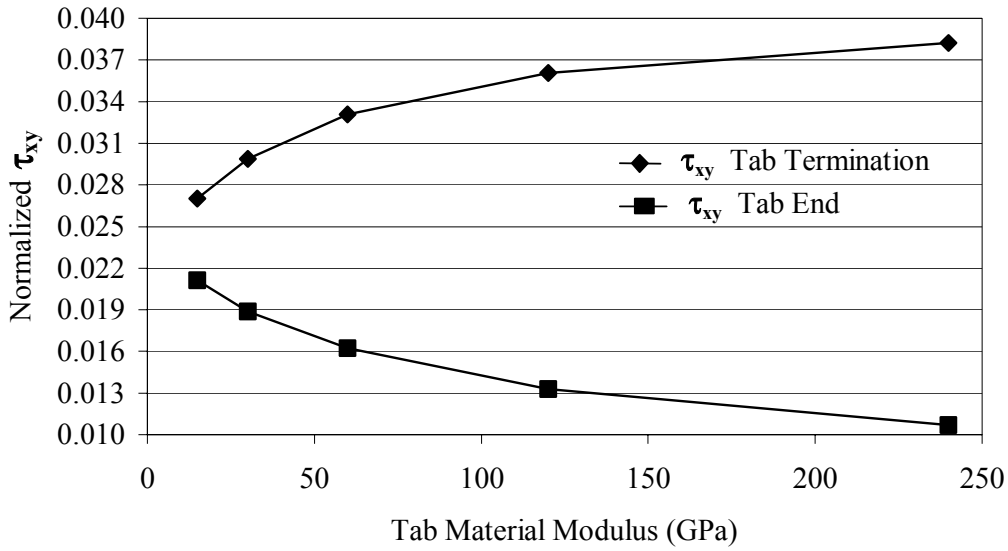

FIGURE 26. EFFECT OF TAB MODULUS ON THE SHEAR STRESS AT TAB TERMINATION AND TAB END, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

To minimize shear stresses at the tab termination and at the tab end, a compromise in the tabbing material stiffness is desirable. A lower stiffness tabbing material, such as glass fabric/epoxy, reduces the tab termination stress concentrations. However, more compliant tab materials produce higher shear stress concentrations at the specimen ends due to end loading. Such high shear stresses at the loaded specimen ends can lead to end-brooming and subsequent end-crushing. Glass/fabric/epoxy tabs, with a modulus of 32.6 GPa (4.7 Msi) are a good compromise when attempting to minimize both regions of stress concentrations. Additionally, this relatively low cost and commonly available tabbing material may be machined in the same manner as the composite material being tested.

5.2 SELECTION OF TAB THICKNESS FOR COMPRESSION TESTING.

- SUMMARY. The tabbing material must be of adequate thickness to protect the composite material from surface damage during gripping. When end loading, the tabbing material must be of adequate thickness to reduce the stresses at the end of the composite specimen and prevent premature end-crushing or brooming failures. The tab thickness does not have a significant effect on the tab termination stress concentrations.

- RECOMMENDATION. A tab thickness of approximately 1-2 mm (0.04-0.08 in.) is recommended for general use in compression testing, including both shear loading and combined loading compression test methods. Note that G-10 glass fabric/epoxy laminated circuit board is available in 1.6 mm (0.062 in.) thickness. For testing thicker specimens, a greater tab thickness may be desired. For such cases, 3.2-mm (0.125-in.)-thick G-10 glass fabric/epoxy is available for use.

- RATIONALE. The tab thickness effects discussed in section 4.2 for tension loading apply for shear-loaded compression testing. For both loadings, the tabbing material must be of adequate thickness to protect the composite material from surface damage during gripping. However, the tab thickness does not have a significant effect on the tab termination stress concentrations. Under combined shear loading and end loading, however, the thickness of the tabs affects the end loading capability of the specimen. When a significant percentage of the applied load is reacted through the specimen ends, the added cross-sectional area due to the tabs serves to reduce the compressive stress at the end of the composite specimen.

  To investigate the effects of tab thickness on stress concentrations at the specimen ends, finite element analyses were performed on the two baseline tab configurations (shown in figure 24) with varying thickness of glass fabric/epoxy tabs. Five different tab thicknesses were analyzed, ranging from 0.5 mm (0.02 in.) to 4.0 mm (0.16 in.). Stress concentrations produced at the tab end are shown in figures 27 and 28 for the untapered tab-thick adhesive and tapered tab-thin adhesive configurations, respectively. For both tab configurations, all three stress components decrease as the tab thickness increases. This result is expected, since increasing the tab thickness increases the cross-sectional area over which the end load is applied. For general purpose compression testing, a tab thickness of 1-2 mm (0.04-0.08 in.) is adequate to reduce the compressive axial stress such that premature end-crushing or brooming failures does not occur. For composite specimens that are significantly thicker than 2.5 mm, however, an increased tab thickness of 2-4 mm may be required. For such cases, 3.2-mm (0.125-in.) -thick G-10 glass fabric/epoxy is available for use.

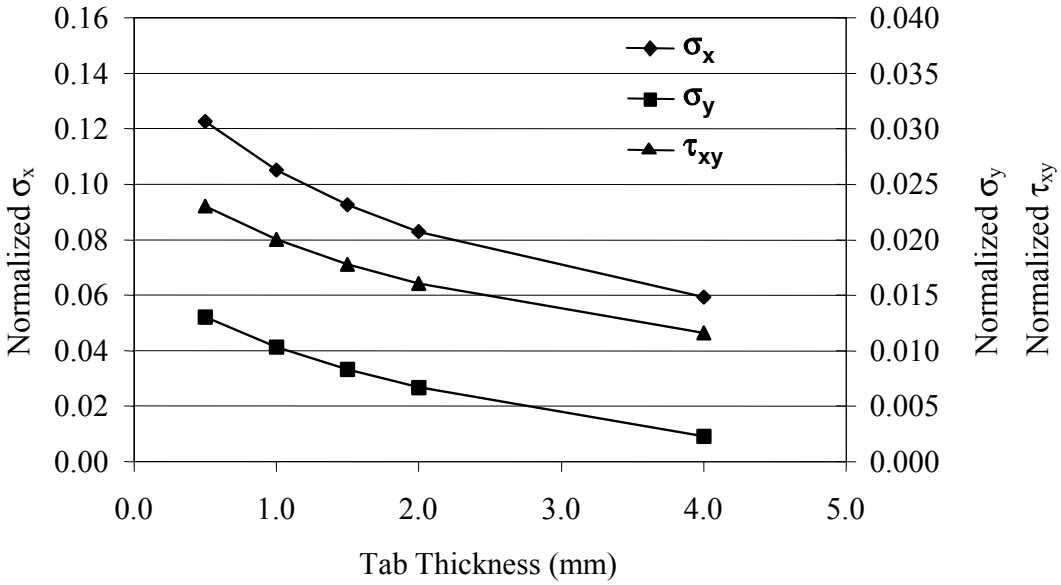

FIGURE 27. EFFECT OF TAB THICKNESS ON STRESS CONCENTRATIONS AT TAB END OF UNTAPERED TAB, THICK ADHESIVE LAYER

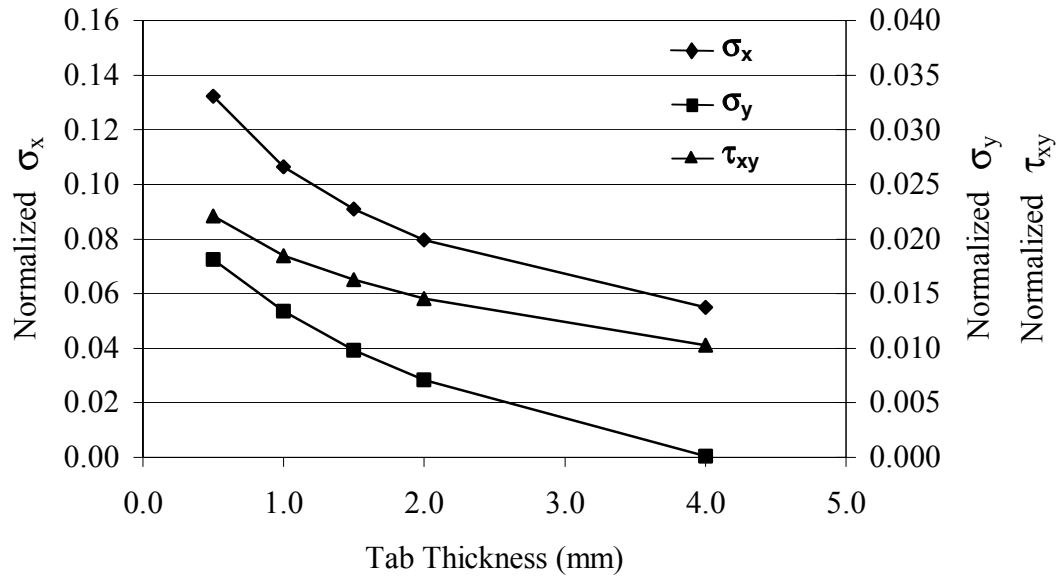

FIGURE 28. EFFECT OF TAB THICKNESS ON STRESS CONCENTRATIONS AT TAB END OF UNTAPERED TAB, THIN ADHESIVE LAYER

5.3 SELECTION OF TAB LENGTH FOR COMPRESSION TESTING.

- SUMMARY. A proper tab length is established by both the strength of the tab material and the adhesive as well as the practical length limitations of the grips used. At the tab termination, the results for compression are similar to those obtained for tension loading: beyond a tab length of approximately 40 mm, the reduction in stress concentrations is minimal. Under combined compression loading, the tab length has no effect on end-crushing when greater than approximately 40 mm.

- RECOMMENDATION. A tab length of at least 40 mm (~1.5 in.) is desirable for most compression testing. In general, it is recommended to use the longest tab length permitted by the test fixture used.

- RATIONALE. The recommended length of the specimen tab on a compression specimen can be established by investigating the stress concentrations at the tab termination and the state of stress at the specimen end. Stress concentrations produced at the tab termination versus tab length are shown in figures 29 and 30 for the untapered tab-thick adhesive and tapered tab-thin adhesive configurations, respectively. As predicted under tension loading, minimal reductions in tab termination stress concentrations are predicted for tab lengths greater than 40 mm. At the ends of the tabbed compression specimen, similar results were obtained: the state of stress at the end of the specimen was not affected as the length of the tab increased beyond approximately 40 mm. These results suggest that a minimum tab length of approximately 40 mm (~1.5 in.) is desirable for most compression testing.

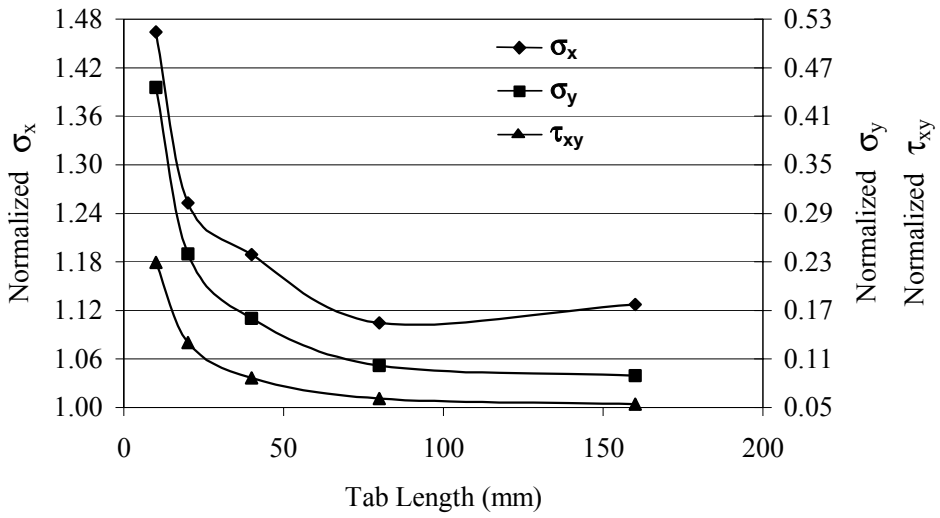

FIGURE 29. EFFECT OF TAB LENGTH ON STRESS CONCENTRATIONS IN THE COMPOSITE COMPRESSION SPECIMEN, UNTAPERED TAB–THICK ADHESIVE CONFIGURATION

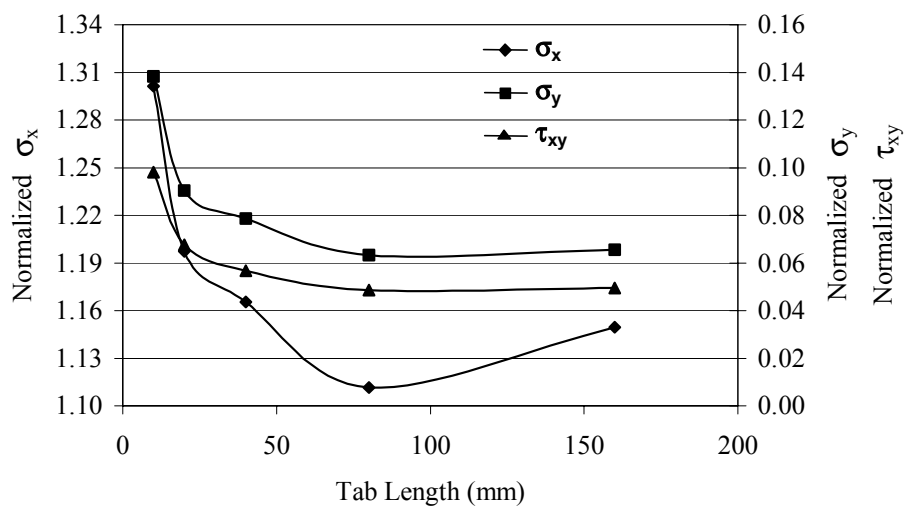

FIGURE 30. EFFECT OF TAB LENGTH ON STRESS CONCENTRATIONS IN THE COMPOSITE COMPRESSION SPECIMEN, TAPERED TAB-THIN ADHESIVE CONFIGURATION

The tab length for compression specimens is dependant on the test fixture being used. The ASTM Standard D 6641 Combined Loading Compression Test Fixture [12] allows a maximum gripping length of approximately 63.5 mm (2.5 in.). The grip length on the shear-loaded IITRI compression test fixture, part of ASTM Standard D 3410 [15], is approximately 63.5 mm (2.5 in.) long. The modified ASTM D 695 compression test fixture [16 and 17] provides end loading on 81-mm-long specimens with 38-mm-long tabs.

5.4 SELECTION OF TAB TAPER ANGLE FOR COMPRESSION TESTING.

- SUMMARY. Although a highly tapered tab is desired to minimize tab termination stress concentrations, tapering the tab increases the unsupported gage length and drastically lowers the applied stress at which specimen buckling occurs.

- RECOMMENDATION. The use of untapered tabs (a tab taper angle of 90°) is recommended for general compression testing.

- RATIONALE. An important design consideration when selecting the tab taper angle is to minimize the stress concentration at the tab termination. Finite element analyses performed for compression specimens with varying tab taper angles provided results similar to those presented in figures 14 and 15 for tension loading. Although the tab termination stress concentrations decrease as the tab taper angle decreases, only slight decreases are predicted as the taper angle is decreased from 90° to 30°. A majority of the reduction in stress concentration factors occurs for tab taper angles less than 15°. Thus, a significant tapering of the tabs is required to produce a significant reduction in the tab termination stress concentration.

  Another important design consideration when selecting the tab taper angle is to prevent specimen buckling from occurring within the unsupported gage section of the specimen. While a small taper angle may be desirable for reducing the tab termination stress concentrations, a small taper angle increases the unsupported gage length of the specimen, thus reducing the applied stress at which the buckling failure occurs within the compression specimen. From trigonometry, the increase in the unsupported gage length due to tab tapering is given by $2t\cos\theta/\sin\theta$, where t is the thickness of the tab and θ is the tab taper angle. For a 30° tab taper angle, a value that produced only slight reductions in stress concentrations, the increase in unsupported gage length for a 1.6-mm-thick tab is 5.5 mm. For a 15° tab taper angle, an 11.9 mm increase in unsupported gage length is produced for a 1.6-mm-thick tab. Thus, a large increase in unsupported gage length is required to produce a significant reduction in tab termination stress concentrations.

  To estimate the applied stress at which buckling occurs in a composite specimen, the well-known Euler buckling equation for a linearly elastic, isotropic column with pinned ends may be modified to account for the orthotropy of the composite material. The critical value of applied stress is given by the relation [18]

$$\sigma_{cr} = \frac{\pi^2 E_x^b I}{l^2 A + 1.2\pi^2 \dfrac{E_x^b I}{G_{xz}}}$$

  where

  E_x^b = Bending modulus of the composite laminate
  I = cross-sectional moment of inertia
  l = specimen gage length
  G_{xz} = through-the-thickness shear modulus

Using this relation, the reduction in buckling stress due to the tab taper angle may be estimated. Calculations were performed for the unidirectional carbon/epoxy specimen shown in figure 24 using material properties provided in table 4. The assumption was made that the tapered length of the tab provided no lateral support and, thus, was added to the total specimen gage length. Based on the buckling equation provided above, a 30° tab taper angle is predicted to reduce the critical buckling stress by 44%. A 15° tab taper angle reduces the predicted buckling stress by 67%. Thus, providing an adequate tab taper to significantly reduce stress concentrations at the tab termination drastically reduces the applied stress at which specimen buckling is predicted to occur. Based on these considerations, the use of untapered tabs is recommended for compression testing of unidirectional composites.

5.5 SELECTION OF ADHESIVE FOR COMPRESSION TESTING.

- SUMMARY. Although strength is the primary consideration for adhesive selection, the modulus of elasticity has a minor effect on the magnitude of the stress concentrations in the composite. Thus, the modulus of elasticity may be considered as a secondary design variable when selecting a suitable adhesive.

- RECOMMENDATION. Adhesive selection should be based on strength properties, ease of application, availability, and cost, rather than modulus of elasticity.

- RATIONALE. As in tension testing, the primary consideration when selecting a suitable adhesive for bonding tabs onto compression specimens is the ability to transmit the required load into the test specimen. The adhesive must also withstand the compressive stresses produced by gripping and the shear stresses resulting from end loading. A secondary consideration is minimizing the stress concentration at the tab termination.

  Finite element analyses were performed on the two baseline tab configurations with adhesive moduli values ranging from E = 2.76 to E = 3.45 GPa (400-500 Ksi). Stress concentrations produced in the composite specimen versus adhesive moduli are shown in figures 31 and 32 for the untapered tab-thick adhesive and tapered tab-thin adhesive configurations, respectively. For both tab configurations, these results indicate that decreasing the adhesive modulus produces relatively small reductions in the stress concentrations at the tab termination region. Thus, the modulus of the adhesive does not have a major effect on tab termination stress concentrations.

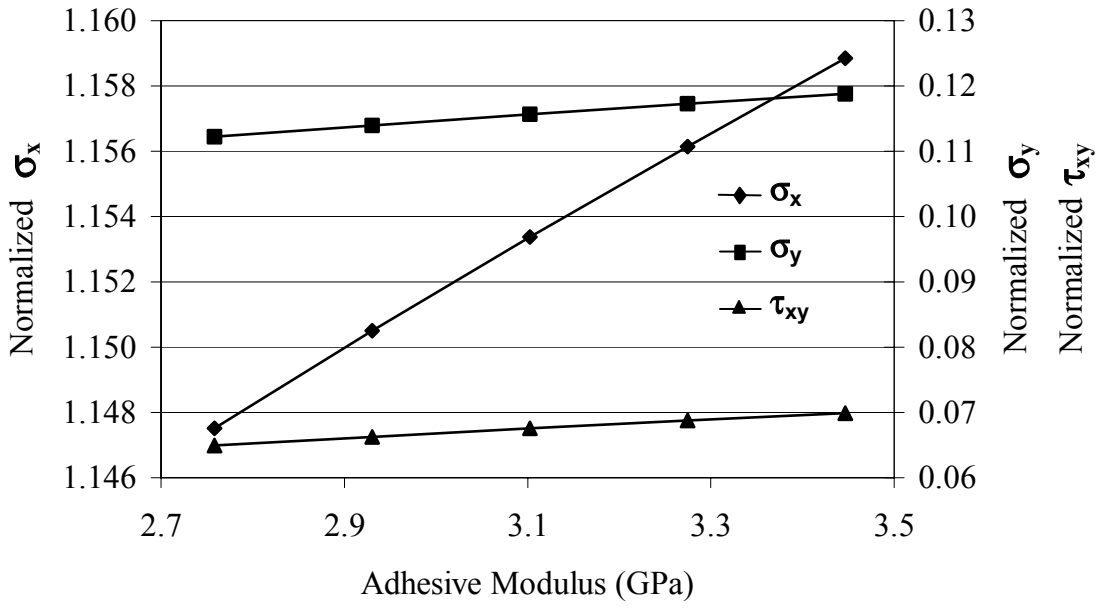

FIGURE 31. EFFECT OF ADHESIVE MODULUS ON STRESS CONCENTRATIONS IN COMPOSITE COMPRESSION SPECIMENS, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

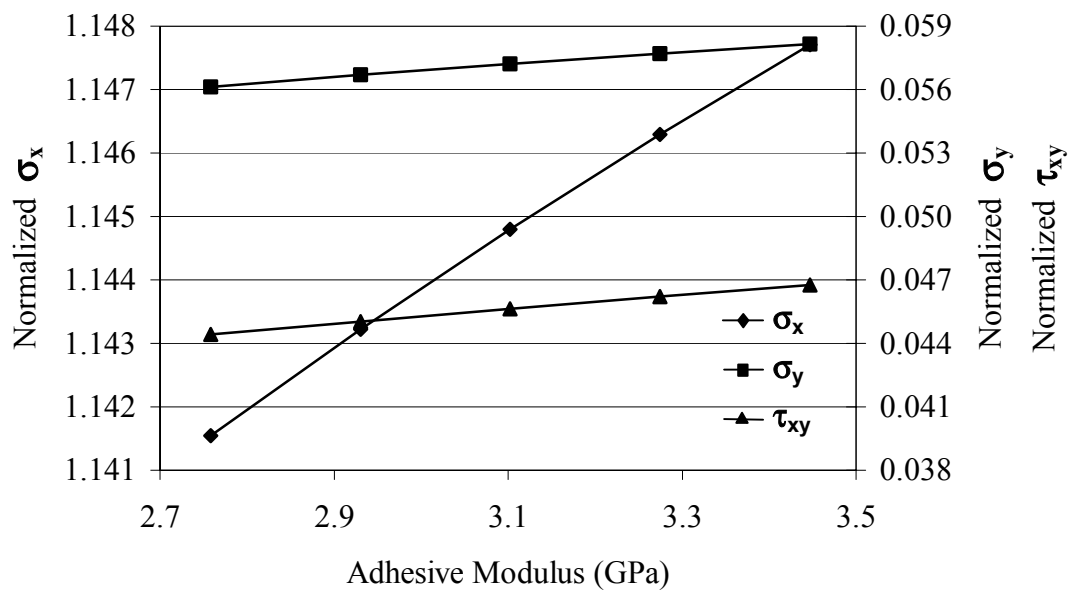

FIGURE 32. EFFECT OF ADHESIVE MODULUS ON STRESS CONCENTRATIONS IN COMPOSITE COMPRESSION SPECIMENS, TAPERED TAB-THIN ADHESIVE CONFIGURATION

5.6 SELECTION OF ADHESIVE THICKNESS FOR COMPRESSION SPECIMENS.

- SUMMARY. Since highly tapered tabs are not recommended for compression testing, a thicker adhesive bond line is useful in reducing tab termination stress concentrations. The magnitude of stress reduction depends on whether the tab is tapered or untapered.

- RECOMMENDATION. An adhesive layer thickness of approximately 1.3 mm (0.05 in.) is suitable with many commonly used adhesives and is recommended for general compression testing.

- RATIONALE. The issues involved in selecting a suitable adhesive thickness for compression specimens are similar to those discussed in section 4.6 for tension specimens. Since most adhesives used are more compliant than the tab and composite material, a thicker adhesive bond line may serve to reduce stress concentrations at the tab terminations. Since highly tapered tabs are not recommended for compression testing, the use of a thicker adhesive bond line is the primary means for reducing stress concentrations.

  Finite element analysis was performed using three different adhesive thicknesses, ranging from 0.3 to 1.3 mm. The results for the untapered tab configurations are shown in figures 33 and 34 for the untapered tab-thick adhesive and tapered tab-thin adhesive configurations, respectively. As for tension loading, the peak normal stress σ_y and shear stress τ_{xy} increase slightly as the adhesive thickness is increased. The peak axial stress σ_x decreases significantly as the adhesive thickness increases. Based on these results, a thicker adhesive bond line of approximately 1.3 mm is recommended for general compression testing.

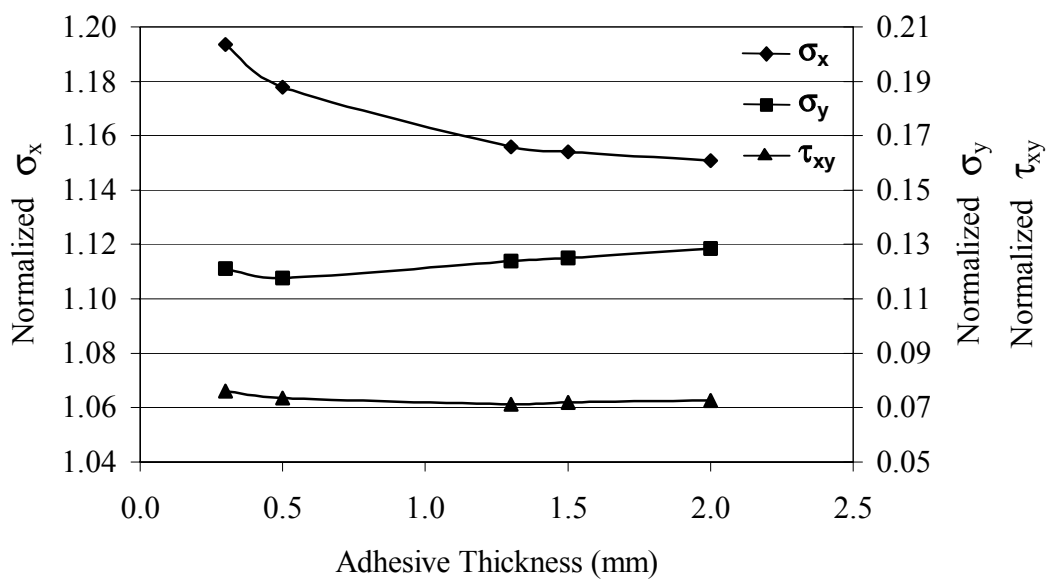

FIGURE 33. EFFECT OF ADHESIVE THICKNESS ON STRESS CONCENTRATIONS IN COMPOSITE COMPRESSION SPECIMENS, UNTAPERED TAB-THICK ADHESIVE CONFIGURATION

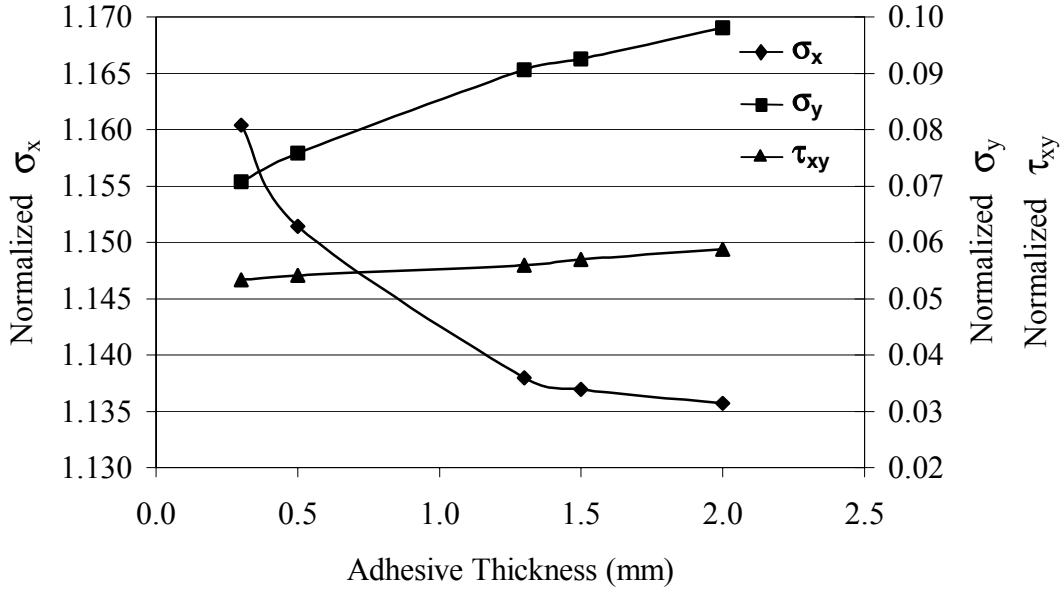

FIGURE 34. EFFECT OF ADHESIVE THICKNESS ON STRESS CONCENTRATIONS IN COMPOSITE COMPRESSION SPECIMENS, TAPERED TAB-THIN ADHESIVE CONFIGURATION

5.7 EXPERIMENTAL RESULTS FROM COMPRESSION TESTING.

Compression testing was performed using the ASTM Standard D 6641 Combined Loading Compression Test Fixture [12]. Unidirectional AS4/3501-6 carbon/epoxy laminates were tabbed using 1.6-mm (0.062-in.) -thick G10 glass fabric/epoxy laminated circuit board. Two tab taper angles were investigated, i.e., 90° (untapered) and 30° (tapered). Two adhesive thicknesses were investigated, i.e., 0.3 mm (0.012 in.) using the 3M AF163-2K adhesive and 1.3 mm (0.050 in.) using the Hysol 907 adhesive. A total of six specimens were tested for each configuration investigated.

Figure 35 compares the compressive strengths obtained from the four different tabbing configurations tested. Additionally, compression strengths obtained from specimens tested without tabs are shown for comparison. The average values and standard deviations of the specimen sets are designated by *A* and *S* respectively. For the tabbed specimens bonded using the Hysol 907 adhesive (modeled in the finite element analyses), the compressive strength increased as the degree of tab tapering increased from 90° (untapered) to 30°. The level of strength increase, due to tapering, was not expected, since finite element results predicted minimal reductions in tab termination stress concentrations when decreasing the tab taper angle from 90° to 30°. For the specimens bonded using the thinner (0.3 mm) 3M AF163-2K adhesive, there was no significant change in compressive strength obtained with tab taper angles of 90° and 30°. Curiously, the highest compressive strength was obtained using the more ductile 3M AF163-2K adhesive with a thin adhesive bond line thickness. Note, however, that the nonlinear stress versus strain behavior of this adhesive was not accounted for in the finite element analyses. For comparison, compressive strengths of specimens tested without tabs are included in

figure 35. The resulting compressive strengths were significantly lower than from any of the tabbed specimen configurations.

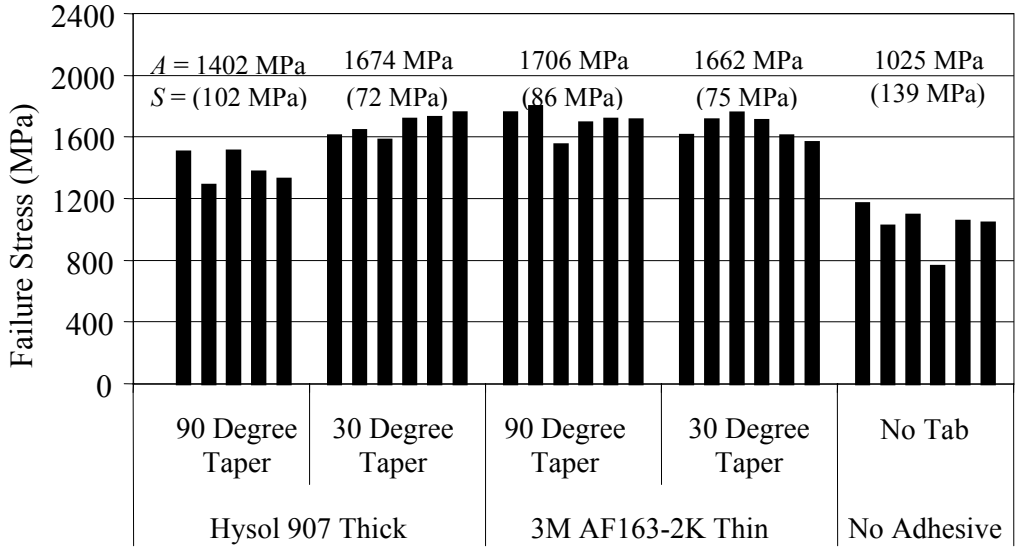

FIGURE 35. COMPRESSION TEST RESULTS FOR SPECIMENS USING COMBINED LOADING COMPRESSION TEST FIXTURE

Adams and Odom [19] performed an experimental investigation of the effects of specimen tab configurations on the compressive strength of unidirectional AS4/3501-6 carbon/epoxy laminates. Testing was performed using a standard IITRI compression test fixture [15] that shear loads the tab surfaces. Two types of tabbing materials were investigated, i.e., glass fabric/epoxy (G10) and low carbon steel. For each tabbing material, both 90° (untapered) and 30° taper angles were used. Average compressive strengths obtained for each tabbing configuration are listed in table 6. The 30° tapered steel tab configuration produced a slightly higher compressive strength than the untapered (90°) configuration. Of the two glass fabric/epoxy tab configurations, the untapered (90°) configuration produced the highest compressive strength, comparable with the strength values obtained using the steel tab configurations. The 30° tapered glass fabric/epoxy tab configuration produced a significantly lower compressive strength than the other configurations. Adams and Odom [19] explained that the tapered tab increased the effective gage length sufficiently to produce specimen buckling.

TABLE 6. EFFECTS OF TAB CONFIGURATION ON COMPRESSIVE STRENGTH OF AS4/3501-6 CARBON/EPOXY USING IITRI TEST FIXTURE [19]

Tab Configuration	Average Compressive Strength (MPa)
Steel tab, 30° taper	1572
Steel tab, 90° taper (untapered)	1517
Glass fabric/epoxy tab, 30° taper	1517
Glass fabric/epoxy tab, 90° taper (untapered)	1255

In summary, experimental results suggest that the use of a tapered tab can provide a beneficial effect by reducing the tab termination stress concentrations. However, tapering the tabs increases the unsupported length of specimen in the vicinity of the gage length and may lead to premature specimen buckling. As a result, tapering of the tabs is not recommended for general compression testing.

6. COMPOSITE SPECIMEN TABBING PROCEDURE.

A detailed, step-by-step procedure for specimen tabbing is presented. This procedure is intended for those who are relatively new to mechanical testing of composite materials and those who perform testing less frequently and, thus, have not developed their own proven procedures. Additionally, the procedures outlined in this Guide are intended to assist those who are having problems with the preparation or testing of tabbed composite specimens. It is important to note that individual testing laboratories will eventually develop their own procedures; thus, the procedures detailed in this Guide can be viewed as suggestions for getting started. These procedures can be altered as required to address specific testing requirements. Careful attention to detail and increasing experience will yield acceptable results in most cases.

6.1 SUBPANEL PREPARATION.

From the composite panel to be tested, cut a subpanel to the proper dimensions to produce the desired number of test specimens (see figure 36).

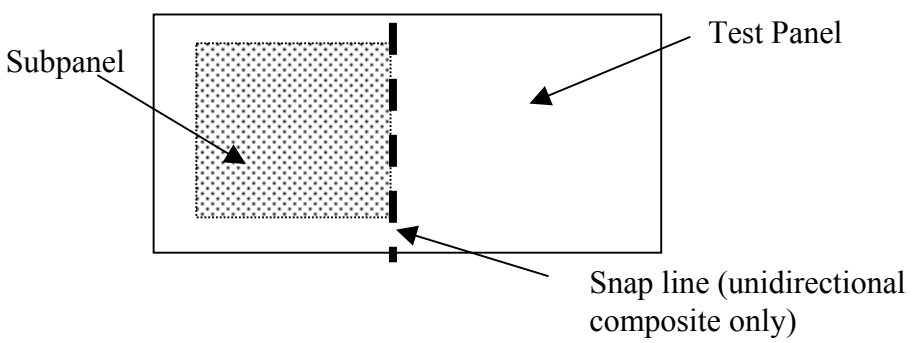

FIGURE 36. LAYOUT OF THE SUBPANEL

6.1.1 Subpanel Sizing.

Obtain the required specimen dimensions from the appropriate test standard for the required specimen dimensions. It will be necessary to oversize the dimensions of the subpanel for both cutting individual specimens and to provide extra specimens as spares. For example, if seven specimens of dimensions 250 mm long by 12.7 mm wide were to be tested, a subpanel at least 270 mm long by 150 mm wide would be required to account for material lost (cutting kerf) due to cutting the individual specimens. If end grinding of the specimens is required (as for end-loaded compression specimens), the subpanel length should be extended by another 10 mm or more. Since additional specimens may be needed after testing is underway, it is recommended to

prepare a subpanel of extra width to accommodate additional specimens. Thus, a subpanel of dimensions 300 mm long by 150 mm wide would be required to produce up to eight test specimens of dimensions 250 mm long by 12.7 mm wide, when five actual tests are planned.

6.1.2 Subpanel Placement.

Orient the subpanel at least 10 mm from the edges of the test panel. A 25-mm edge spacing is preferred if the test panel size permits. This edge spacing is used to eliminate any variations in test panel properties caused by thickness variations or fiber misorientations near the panel edges.

It is important that the fiber orientation is determined and maintained when cutting the subpanel from the composite test panel. Loss of fiber orientation through the tabbing process may result in fiber misorientation in the test specimens and incorrect test results. One method to determine the fiber orientation in a unidirectional composite panel is to snap or break off an edge of the panel by bending it perpendicular to the assumed fiber direction. Using a table or other flat surface with a sharp, straight edge, the panel is held so that a portion of the panel overlaps the edge of the surface, with the assumed fiber direction parallel to the table edge, as shown in figure 37. Holding the panel firmly against the surface, the overhanging portion is pressed down over the sharp edge, breaking the unidirectional composite panel parallel to the fibers at the table edge, as shown in figure 37.

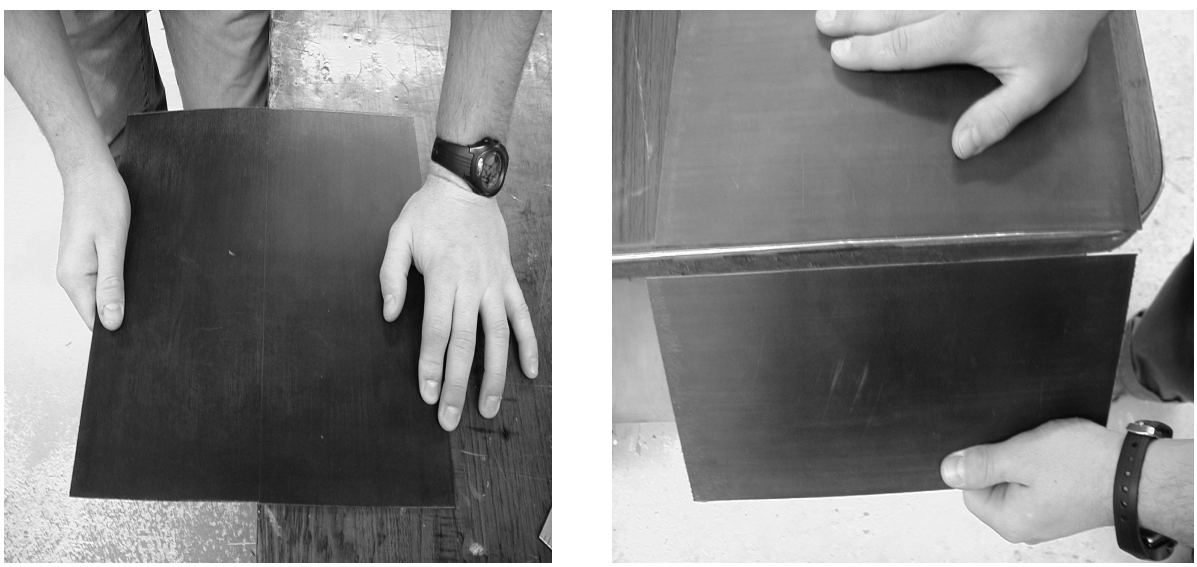

FIGURE 37. DETERMINING FIBER ORIENTATION BY SNAPPING TEST PANEL

Determining where the test panel should be snapped depends on the desired size and the number of subpanels to be produced. Figure 36 shows the preferred location to snap the test panel if a single subpanel is desired from one side of a larger test panel. Note that the panel is snapped along the inward edge of the subpanel. As a result, the fiber orientation is based on a more central location of the test panel (further away from the edge) than if the test panel had been snapped along the outer edge of the subpanel.

This failed or snapped edge will be used as a fiber orientation reference when orienting the tabs onto the subpanel and when cutting the subpanel into test specimens. Following snapping, the failed edges should be inspected for straightness by placing the snapped edge along a flat surface.

If the snapped edge of the panel is not straight, the fibers in the vicinity of this edge will be curved, resulting in fiber misalignment in the test specimen. While a small degree of fiber misalignment may be permissible in the tabbed region of the subpanel, it is important to achieve straight, aligned fibers in the central region between the tabs. Thus, snapped subpanels exhibiting noticeable fiber curvature between the regions to be tabbed should not be used for subsequent testing.

6.1.3 Marking the Gage Section.

Using the reference edge of the subpanel obtained in the previous step, draw lines on the subpanel marking the ends of the gage section. A standard no. 2 pencil and a 90° triangle or framing square are suggested for drawing these lines on the subpanel, as shown figure 38. This step produces two lines oriented perpendicular to the reference edge of the subpanel.

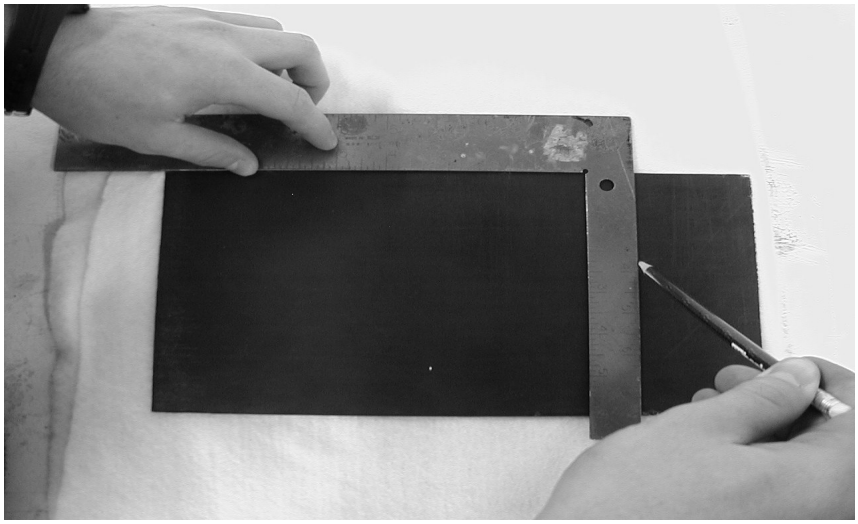

FIGURE 38. MARKING ENDS OF GAGE SECTION ON SUBPANEL

6.1.4 Making Gage Section Spacers.

When tabbing subpanels, it is convenient to make a set of two identical spacers to be placed onto the gage section of the subpanel during tab bonding. These spacers are secured to the gage section of the subpanel to maintain proper tab alignment during adhesive curing. Additionally, the spacers prevent excess adhesive from flowing onto the gage section of the subpanel. Figure 39 shows spacers being positioned on a subpanel prior to tab bonding. Although these spacers are reusable on other subpanels, multiple sets of spacers are desirable if multiple subpanels are to be tabbed at the same time.

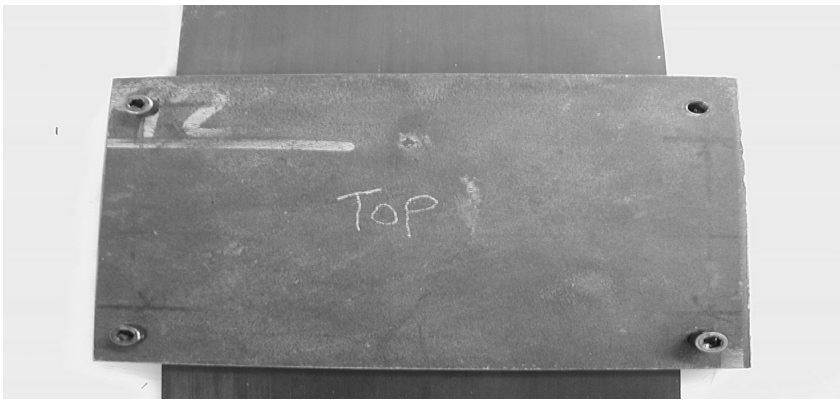

FIGURE 39. SPACERS PLACED ONTO SUBPANEL

The spacers may be made of the same material as the tabs or a different material that is able to withstand the curing process of the adhesive. Steel or aluminum are good choices for spacer materials. The thickness of the spacers is not critical. Six-mm-thick steel spacers are a good choice. The length of the rectangular spacers must be machined to be desired length of the specimen gage section (distance between tabs). The width of the spacers should be at least 25 mm greater than the width of the subpanels to be tabbed, allowing the spacer to overlap on either side of the subpanel, as shown in figure 37. This overlap will be used to connect the top and bottom spacer together on the subpanel gage section without producing damage.

The spacers may be attached to the subpanel using either adhesive tape or fasteners. Using fasteners is a good choice for repetitive use, but requires drilling holes in the spacers; however, adhesive tape is a simple solution for one-time use. If fasteners are to be used for connecting and aligning, drill holes in the top and bottom spacers in the overlap region. Stack and align the two spacers when drilling the four holes. Two holes should be drilled in the overlap region on each side of the spacers, as shown in figure 39. Although the exact location of the holes is not critical, a location roughly 10 mm from the corners of the spacers is suitable. It is important that the four holes line up when the spacers are aligned, thus, the recommendation is to drill both spacers while they are stacked.

The diameter of the holes should be chosen to accommodate a selected fastener arrangement. The easiest arrangement is to use bolts with nuts, such that the hole diameter in both spacers need to be slightly oversized with respect to the bolt. For example, if 6-mm-diameter bolts are to be used, a slightly larger hole diameter (perhaps 7 mm) should be used in both spacers. Another suitable arrangement is to thread the holes in the bottom spacer to accommodate a cap screw and oversize the top spacer holes. By threading the cap screw into the bottom spacers, the fasteners do not protrude through bottom spacer and the assembly sets flush against the table, as shown in figure 40.

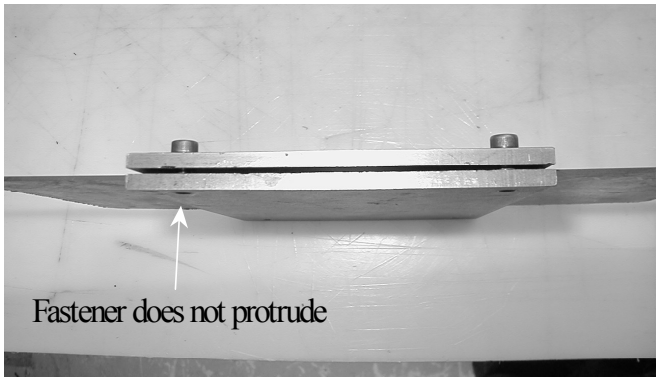

FIGURE 40. SIDE VIEW OF SPACERS ATTACHED TO SUBPANEL

6.1.5 Preparation of Spacers.

Carefully coat the spacers with a mold release agent and let air-dry. Of particular attention are the edges of the spacers placed adjacent to the tabs. The application of release agent facilitates removing the spacers after the cure cycle. Take precautions not to contaminate the tab material with the release agent.

If the spacers are to be secured to the subpanel using adhesive tapes (no fastener option), adhere two strips of double-backed (e.g., carpet) tape to each spacer. The strips of tape should be placed adjacent to the gage section edges of the spacers. This tape can often be used even for elevated temperature adhesive curing, since the degraded tape adhesive will still adhere sufficiently to prevent the flow of adhesive into the gage section. Leave the protective covering on one side of the tape until the spacer is placed on the subpanel.

6.1.6 Surface Preparation of Subpanel.

Grit blast or sand the tab regions of the subpanel to provide a suitable surface roughness and to remove any surface contaminants prior to adhesive bonding. Contaminants such as wax and release agent may be transferred to the composite test panel from the mold or tool during panel curing. Such contaminants may be removed by abrading the surface of the panel over the entire tab region. In general, it is desirable to remove as much of the thin resin-rich layer on the surface of the panel as needed to abrade the entire surface of the tab region. However, care should be taken to minimize abrasion to the fibers immediately below. The desired thickness of the material to be removed is dependent on the surface finish of the panel, the thickness of the outer resin-rich layer, and the method of abrasion. Regardless of these factors, the desired end result is an abraded surface finish across the entire tabbing area with minimal abrasion to the fibers below. Note that the completeness of abrasion across the tabbing area can be inspected visually after rinsing the panel in water and allowing it to dry. Additionally, abrasion of the fibers often can be detected visually while the panel surface is wet.

Grit blasting is a suitable technique for virtually any subpanel surface finish or texture. Sanding may be used when the surface of the subpanel is sufficiently flat and smooth such that the entire surface may be completely sanded without removing excessive material (and abrading fibers) in high spots. Some textile composite panels contain visible surface relief due to the fiber

architecture and are not suitable for sanding, since excessive material removal is required to produce a completely sanded surface.

6.1.6.1 Grit Blasting.

Cover the gage section of the surfaces of the subpanel with heavy tape or other masking material. Grit blast the exposed ends of the subpanel for sufficient duration to remove the exterior surface as uniformly as possible. Some experimentation and practice may be required to obtain the desired results. The air pressures and abrasive grit to be used is dependant on a particular grit blaster used. As general guidelines, air pressures of 275 to 4141 KPa (40 to 60 psi) and abrasive particle sizes between 180 and 300 grit are known to have been successful for carbon/epoxy and glass/epoxy panels. Before grit blasting the subpanel, practice with a scrap panel section if possible. Keep the grit blast nozzle perpendicular to the panel and at the same distance (approximately 6 inches) from the surface of the panel. Make a series of passes over the exposed area, moving at a slow, steady rate (a few inches per second). The removal rate of material may be monitored by performing thickness measurements of the subpanel at specified intervals.

6.1.6.2 Sanding.

If the surface of the panel is sufficiently flat and smooth, sanding may be used rather than grit blasting. Sanding may be performed by hand or by using a hand-held oscillating sander, as shown in figure 41. The use of belt sanders is strongly discouraged, since the material removal rate is difficult to control. Sand only in the tab regions of the subpanel. Masking of the gage section using adhesive tape (such as common masking tape) is recommended, since the lines drawn to mark the ends of the gage section (described in section 6.1.3) may become difficult to see.

FIGURE 41. SANDING THE SUBPANEL

Good results have been obtained by sanding using 220-grit silicon carbide paper. Wet sanding (using water) is recommended to control dust. When sanding, the objective is to remove a uniform thickness of material throughout the tab regions. Often it is possible to determine whether the entire tabbing region has been sanded by rinsing the panel in water and allowing it to dry. Generally, the sanded surface has a noticeably different appearance than the unsanded panel. Visually determining the depth to which the surface has been sanded is difficult. Further, it is very time consuming to monitor sanding depth through a series of thickness measurements. Thus, efforts should be made to sand the entire surface of the tab region uniformly, such that minimal thickness measurements are needed.

6.1.6.3 Subpanel Cleaning and Final Preparation.

Following grit blasting or sanding, remove the masking protecting the gage section. The subpanel should be thoroughly scrubbed in water using a Scotch-Brite pad. Soap is generally not needed, since a final surface cleaning and preparation step will be performed. After washing, the subpanel should be air-dried. It is recommended that the tabbing region of the subpanel not be touched with ungloved hands hereafter, since body oils can cause areas of poor bonding. If needed, remark the gage section using the reference edge of the subpanel as described in section 6.1.3.

The final cleaning step involves wiping the tabbing areas of the subpanel with a lint-free towel wetted with acetone or isopropyl alcohol and air-drying. Apply new masking to both the top and bottom surfaces of the gage section as shown in figure 42. This masking is used to prevent the adhesive from getting on the gage section surfaces of the subpanel during the tab bonding process. Masking tape is generally suitable for this purpose.

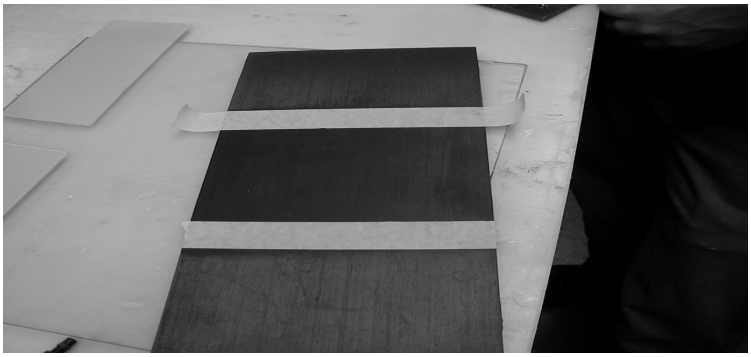

FIGURE 42. RE-MARKED AND TAPED SUBPANEL

6.1.7 Attachment of Spacers Onto Subpanel.

Attach the spacers that were previously prepared to the gage section of the subpanel. As described in section 6.1.5, the spacers may be designed to attach to the subpanel using either adhesive tape or fasteners. If adhesive tape is used, remove the protective covering from the tape that was placed onto the spacers previously. Working with one spacer at a time, align the spacer over the gage section of the subpanel. Firmly press the adhesive tape strips on the spacer against the masking covering the gage section of the subpanel. Turn the subpanel over and repeat the procedure on the other surface.

If the spacers are designed to attach to the subpanel using fasteners, position the two fasteners on either side of the subpanel over the gage section. Connect the spacers together using the four corner fasteners, as shown in figure 43, but do not tighten the fasteners beyond finger tight. Align the two spacers with the masked gage section then tighten the fasteners. Tightening slightly beyond finger tight is required to prevent slippage. However, do not excessively tighten the fasteners because it may damage the subpanel.

FIGURE 43. ATTACHING THE SPACERS TO SUBPANEL

6.2 TAB PREPARATION.

6.2.1 Selection of Tabbing Material.

The tabbing material should be selected based on several factors, including the type of test (tension, compression, or shear), the testing temperature, the composite material to be tested, and the test fixture or loading grips to be used in the testing. Candidate tabbing materials are discussed in section 2.1. Note that a tabbing configuration may be designed using finite element analysis to minimize the stress concentrations associated with the tab terminations. In addition to the tabbing material, other tab considerations include the tab thickness and the tab taper angle.

6.2.2 Preparation of Specimen Tabs.

Cut strips of tabbing material 1/8 inch longer and wider than the specified tabbing area. The excess length will be used to machine a straight edge that will serve as the tab termination edge adjacent to the gage section. The excess width is simply used to ensure that the tabbing material will extend beyond the width of the subpanel. Four tabbing strips will be required for each subpanel to be tabbed.

The straight edge required along one edge of each tabbing material can be obtained using a belt sander. However, the belt sander used must accommodate the entire length of the tab edge being sanded, as shown in figure 44. Note that only the edge of the tab adjacent to the specimen gage section is required to be straight. The other edges will be trimmed when cutting the individual specimens from the subpanel.

Grit blast or sand (figure 45) the surface of the tab strips to be bonded to the subpanel. Details of the grit blasting or sanding procedure are dependent on the tabbing material to be used. The objective of these operations is to remove surface contaminants and provide suitable surface roughness prior to adhesive bonding. Section 6.1.6 details the grit blasting and sanding procedures that are applicable to G-10 and G-11 glass fabric/epoxy tabbing materials.

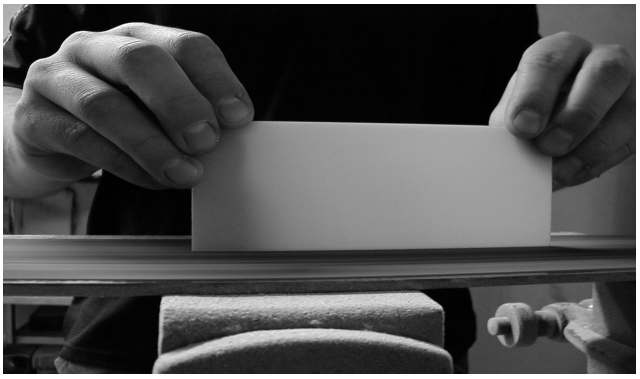

FIGURE 44. PREPARING STRAIGHT EDGE ON TABBING STRIP

FIGURE 45. SANDING OF TABBING STRIPS

Following grit blasting or sanding, the tabbing strips should be thoroughly scrubbed in water using a Scotch-Brite pad and air-dried. The bond surface of the tabbing strips should not be touched with ungloved hands hereafter, since body oils can cause areas of poor bonding. Wipe the bonding surface of the tabbing strips with a lint-free towel wetted with acetone or isopropyl alcohol and air-dry.

6.2.3 Tapering of Tabs (Optional).

As discussed in section 4.4, tapering of the specimen tabs adjacent to the gage section is often desirable for minimizing stress concentrations. There are several methods that may be used to produce a taper angle on a tabbing strip. One method is to place the tabbing strip on a belt sander at the desired angle and sand away the edge of the tabbing material. An angle guide may be used to hold the tabbing strip in the proper orientation when sanding. Another method involves using the same saw used for cutting the tabbing strips. To obtain a proper taper angle when cutting tabbing strips, wedge supports are used. The tabbing strip is clamped or adhered (using double-backed carpet tape) as shown in figure 46.

A third method involves using a surface grinder. Once again, the tabbing strip is secured to a wedge support, as shown in figure 46. The wedge support is secured to the magnetic table of the surface grinder such that the tab edge is aligned parallel to the path of the grinding wheel, as shown in figure 47. The grinding wheel is then passed over the tab edge to produce the desired taper, as shown in figure 48.

FIGURE 46. WEDGE SUPPORT FOR TAPERING TABS

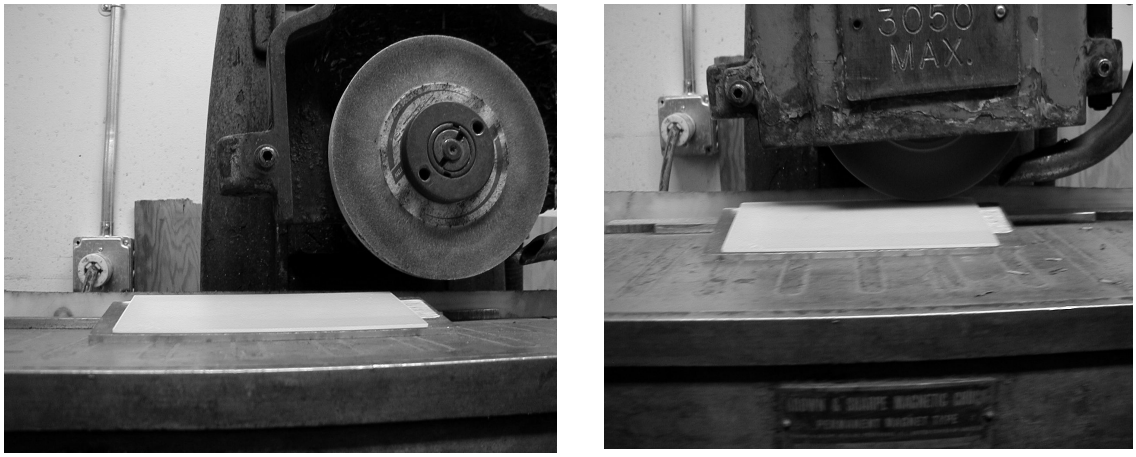

FIGURE 47. TAPERING THE TAB USING A SURFACE GRINDER

FIGURE 48. TAPER PRODUCED IN TABBING STRIP

6.2.4 Application of Wire Bond Line Spacers (Optional).

To control the adhesive thickness when using a paste adhesive, wire spacers may be used. The diameter of the wire placed between the tabbing strip and subpanel will determine the thickness of the adhesive when cured. To accommodate the wire spacers while keeping the tab edge flush with the gage section spacer, small notches are cut into the tab edge, as shown in figure 49. The notches are placed near the outer edges of the tab strip so that the wire spacers will rest near the outer edges of the subpanel where they will be trimmed away during specimen cutting. A small file or hand saw may be used to cut the small notches in the tabbing strips. The wire spacers are placed along the bonding surface of the tabbing strip and bent upward and through the notches, as shown in figure 50. As a result of the notches in the tabbing strips, the tab edge may be placed flush against the gage section spacer without the wire spacers causing any interference.

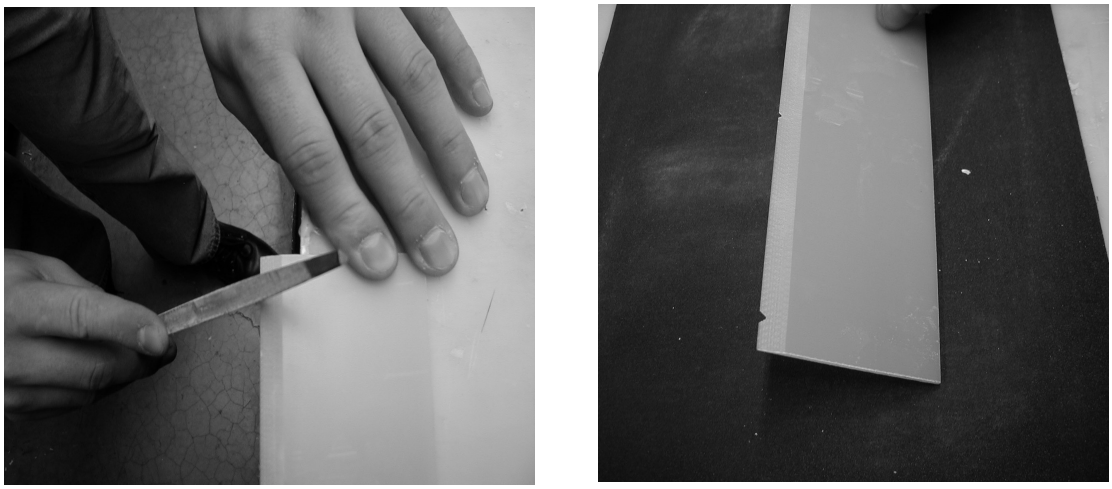

FIGURE 49. NOTCHING OF THE TABBING STRIPS FOR WIRE SPACERS

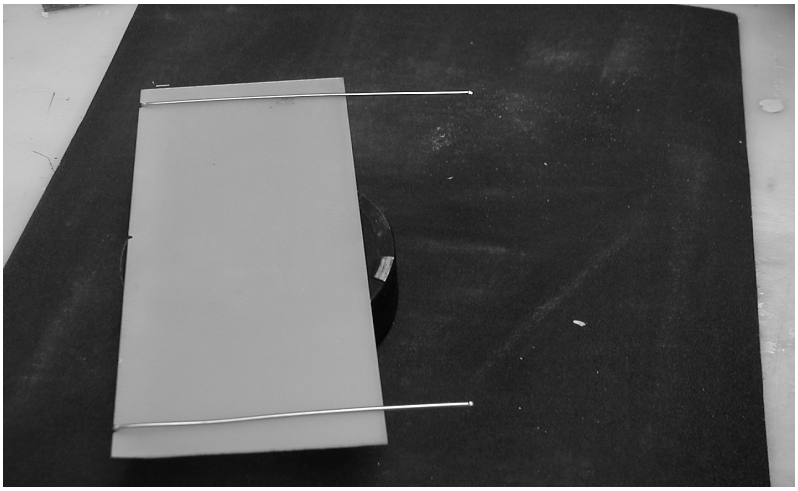

FIGURE 50. PLACEMENT OF WIRE SPACERS IN NOTCHED TABBING STRIPS

6.3 ADHESIVE APPLICATION.

6.3.1 Selection of Adhesive.

As discussed in section 4.6, the selection of the adhesive bond line thickness is a consideration in minimizing the stress concentration in the vicinity of the tab termination. Other considerations when selecting an adhesive include adequate strength and suitability for use at the desired test temperature. The reader is encouraged to refer to section 2.2 for a discussion of adhesive selection considerations.

Two categories of adhesives are commonly used for tab bonding: paste and film adhesives. These two types of adhesives are described in section 2.2. Since the tab bonding process differs significantly using these two types of adhesive, the procedure used for each category of adhesive will be discussed separately when necessary.

6.3.2 Controlling Bond Line Thickness.

When a specified thickness of the adhesive is desired, efforts must be taken to control the bond line thickness. Techniques to achieve a uniform adhesive layer of a desired thickness vary between film and paste adhesives. Thus, these techniques are presented separately.

6.3.2.1 Controlling Film Adhesive Thickness.

When using a film adhesive, the desired thickness is varied by stacking layers of film adhesive between the subpanel and the tab. For a thin bond line, generally only one layer of film adhesive is needed. For thicker bond lines, multiple layers of film adhesive are used. Wire bond line spacers, discussed in section 6.2.4, are generally not used with film adhesives.

6.3.2.2 Controlling Paste Adhesive Thickness.

To achieve the desired bond line thickness when using a paste adhesive, wire spacers may be used as discussed in section 6.2.4. The spacer wires are placed near the ends of the tabbing strips oriented lengthwise with respect to the specimens such that they will be trimmed from the tabbed subpanel and not be present in the test specimens. Small tabbing notches, discussed in section 6.2.4, prevent the wire spacers from being washed out during adhesive bonding while allowing the tabs to be placed flush against the gage section spacer, as shown in figure 51.

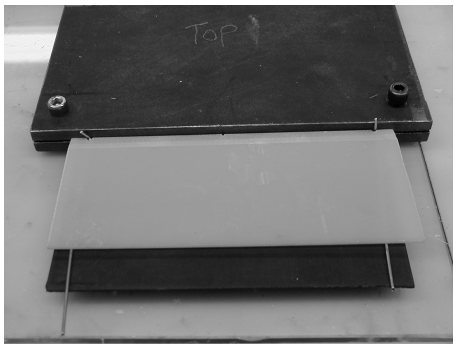

FIGURE 51. TAB WITH WIRE SPACERS PLACED FLUSH AGAINST SPACER

6.3.3 Preparation of Adhesive.

Prepare the adhesive per the manufacturer's directions. For film adhesives, strips of adhesive must be cut to the size of the tabbing strips. Remember that there are a total of four tabbing strips to be applied for each subpanel. For paste adhesives, mix an adequate supply of adhesive to adhere all four tabbing strips at one time.

6.3.4 Application of Adhesive.

Apply the adhesive to the tab region. Since adhesive application techniques differ between film and paste adhesives, they are presented separately.

6.3.4.1 Application of Film Adhesive.

If using film adhesive, remove one backing sheet (exposing only one surface of the film adhesive). Align the piece of film adhesive over the tabbing region of the subpanel, making sure that the edge of the film adhesive is against the gage section spacer. Gently press the exposed surface of the film adhesive against the subpanel surface. Once the film adhesive has been pressed against the subpanel over the entire tabbing region, remove the remaining backing sheet from the film adhesive. Continue to add additional layers of film adhesive to achieve the desired adhesive layer thickness, stacking the adhesive layers on top of the subpanel. Once the desired number of film adhesive layers have been applied, align the tabbing strip with the edge of the gage section spacer and lower onto the film adhesive. Gently press the tabbing strip into the adhesive to achieve good contact. Generally, the tackiness of the film adhesive at room temperature will be sufficient to keep the tabbing strip in place during subsequent handling. However, small pieces of adhesive tape along the edges of the subpanel to secure the tabbing strips will be used if needed. Repeat this procedure for all tabbing strips.

6.3.4.2 Application of Paste Adhesive.

If using a paste adhesive, apply a thin, uniform coat of adhesive to the tabbed regions of the subpanel and the bonding surface of the tabbing strips. The amount of adhesive needed will be dependant on the desired bond line thickness. Applying excessive quantities of adhesive will cause additional adhesive to spew from the edges of the tabbed region, requiring additional cleanup. If extra adhesive is available, place a small quantity onto a piece of release film to monitor the curing of the mixed batch.

Align the tabbing strip (with wire spacers attached, if desired) with the edge of the gage section spacer and lower onto the adhesive covered subpanel. Gently press the tabbing strip into the adhesive to achieve good contact. Although the tackiness of the paste adhesive at room temperature may keep the tabbing strip attached, it is recommended that the edge of the tabbing strip be taped to the gage section spacer to prevent the tabbing strip from shifting during the application of the other tabbing strips and subsequent handling. Repeat this procedure for all tabbing strips.

6.4 CURING OF ADHESIVE.

Once the adhesive has been applied and the tabbing strips attached to the subpanel, the adhesive must be cured. Film adhesive curing often involves the application of both pressure and temperature. However, many paste adhesives may be cured at room temperature. Techniques used to cure a film adhesive at elevated temperature and a paste adhesive at room temperature are presented separately.

6.4.1 Curing of Film Adhesive.

The procedure presented for curing the film adhesive bonded tabs involves the placement of the subpanel assembly into a vacuum bag, placing the vacuum bag into a convection oven, and curing the panel under vacuum-induced pressure and elevated temperature.

6.4.1.1 Preparation of Vacuum Bag Assembly.

The vacuum bag assembly is similar to that used when autoclave curing composite laminates. First, cut a piece of release ply large enough to wrap around the entire subpanel. Porous teflon-coated glass-fabric release ply is suitable. Wrap the subpanel in the release ply and secure with adhesive tape. This release ply will keep the subpanel assembly from becoming adhesively bonded to the vacuum bag or other layers if extra adhesive bleeds during curing. Next, cut a piece of breather cloth large enough to wrap completely around the release-plied subpanel once and to extend outward from the subpanel about 300 mm. The extra length of breather will reach from the panel to the edge of the vacuum bag where the vacuum hose will be inserted. Wrap the breather cloth around the subpanel assembly once, leaving the extra length of cloth free.

Prepare an appropriate-sized vacuum bag that will endure the cure temperature of the adhesive, as illustrated in figures 52a through 52e. For low temperature cures up to 65°C (up to 150°F), reclosable zippered-top polyester bags work well. For higher cure temperatures, prepare a nylon vacuum bag. Place the entire wrapped panel assembly (subpanel with adhered tabs, release ply, and breather) into the vacuum bag, taking precautions to not puncture the bag. Seal the edges of the bag except in the areas where the vacuum hose is to be inserted. The vacuum bag can be sealed by melting the edges together using a freezer bag sealer or vacuum sealant tape. To accommodate the vacuum hose, place a strip of vacuum sealant tape along the entire bottom edge of the remaining opening. Place the end of the vacuum hose into the vacuum bag so that it touches the outer reach of the breather cloth. Press the vacuum hose into the vacuum sealant halfway between the two corners. Cut a 100-mm piece of sealant tape to form around the top of the vacuum hose. Seal the opening of the bag by pressing the top and bottom edges together. Take special care around the perimeter of the vacuum hose to ensure a tight seal.

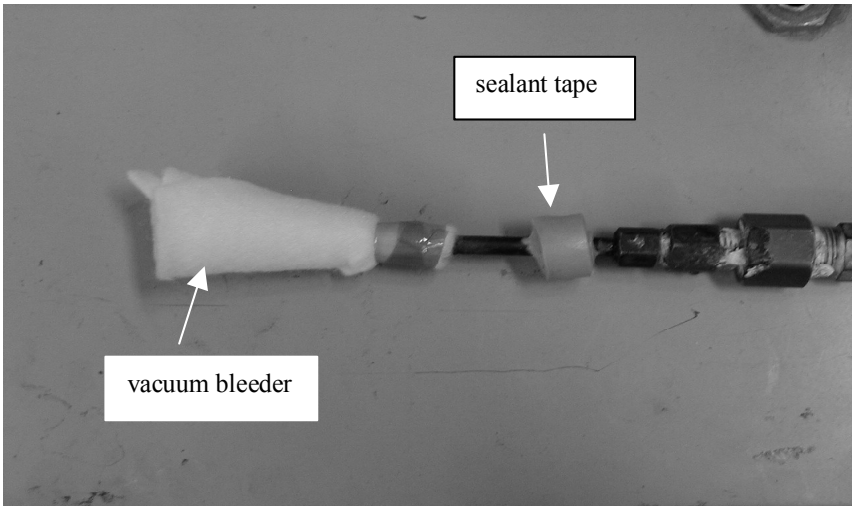

FIGURE 52a. VACUUM HOSE WITH BLEEDER MATERIAL AND VACUUM SEALANT TAPE

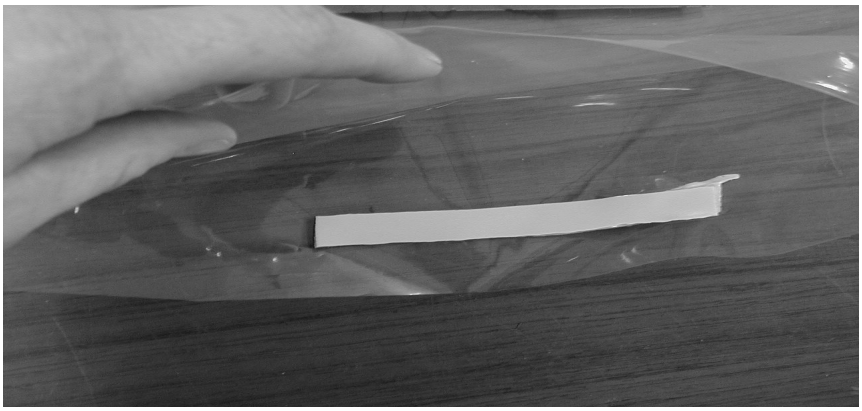

FIGURE 52b. VACUUM SEALANT TAPE PLACED AT BAG OPENING

FIGURE 52c. VACUUM HOSE INSERTED INTO BAG

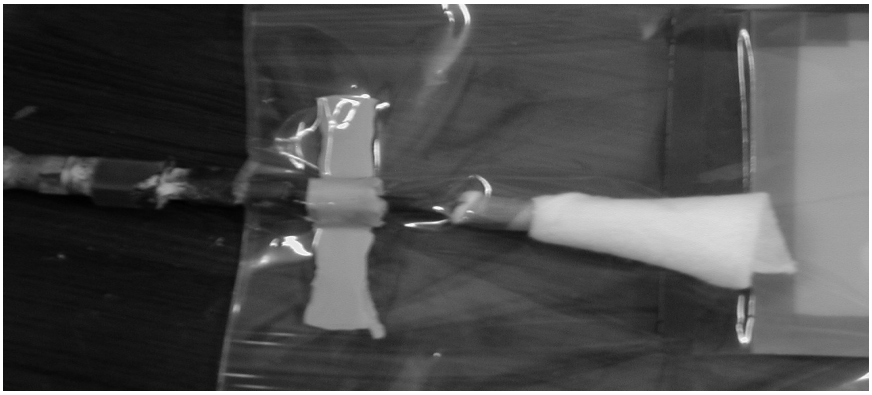

FIGURE 52d. SEALED VACUUM BAG

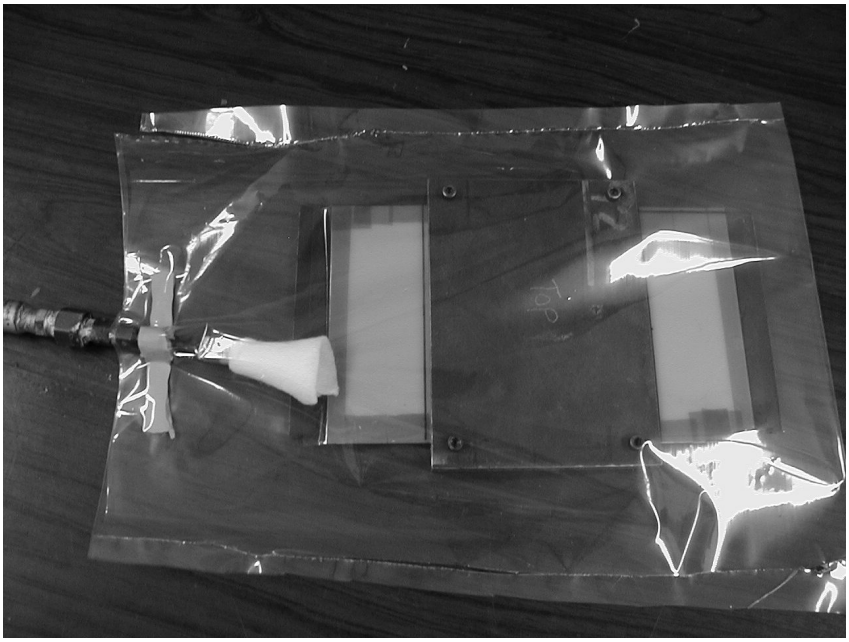

FIGURE 52e. VACUUM-BAGGED PANEL

6.4.1.2 Application of Vacuum and Curing.

Once the vacuum bag has been sealed, place the vacuum-bagged panel into a convection oven for elevated temperature cure. Pass the vacuum hose out of the oven through an oven port and hook up to a vacuum pump. Turn the pump on and pull a vacuum in the bag. The maximum obtainable vacuum is dependant on the pump being used. However, a vacuum of 20 in. Hg is generally obtainable using commonly available vacuum pumps. If the level of vacuum is not as high as desired, check the vacuum bag for leaks, particularly around the perimeter of the vacuum hose. Turn on the convective oven and set the temperature according to the adhesive manufacturer's recommendations. For most film adhesives, leave the vacuum at its highest setting throughout the duration of the cure. When the cure cycle is completed, turn off the vacuum. Once cooled, remove the panel from the vacuum bag.

6.4.2 Curing of Paste Adhesive.

The procedure presented for curing the paste adhesive differs from the film adhesive in that the adhesive is cured at room temperature without a vacuum bag. Although paste adhesives may be cured at an elevated temperature with a vacuum bag, the following procedure is detailed to provide a simpler alternative to that presented in section 6.4.1.

Once the adhesive-coated tabbing strips have been applied to the adhesive-coated subpanel and taped to the gage section spacer, place the assembly onto a flat, level surface. The surface should be covered by a nonporous release film in the event that excess adhesive is released. Place weights on top of the upper tabbing strips, taking precautions to keep them away from the edges where excess adhesive is being squeezed out. The required weight is dependent on the viscosity of the paste adhesive. As a general guide, a pressure of 1 to 3 KPa (0.15 to 0.6 psi) is sufficient for many paste adhesives. Once the weights have been applied, check to see that the tabbing strips have not shifted relative to the subpanel. Excess adhesive that spews out from the junction of the tabbing strip and the gage section spacer should be cleaned away. Additionally, excess adhesive along the reference edge of the subpanel should be removed since this edge will be used as a reference when cutting individual specimens. Excess adhesive emerging from the remaining edges of the tabbing strips is less critical, since these edges will be trimmed when cutting the individual specimens.

Continue to monitor the placement of the tabbing strips until no further adhesive spews from the edges. Leave the weights on the top of the subpanel assembly until the adhesive is fully cured. If a sample of adhesive was retained (section 6.3.4.2), the cure of the adhesive may be monitored by probing this sample without disturbing the tabbed subpanel. Once the adhesive is fully cured, remove the weights from the tabbing strips and separate the tabbed subpanel from the release film below.

6.5 SPECIMEN PREPARATION.

Following curing, remove the gage section spacers from the tabbed subpanel. To prevent damage to the tabs, two small C-clamps can be attached to the tabs on either side of the spacer edge. Using a razor blade or thin knife blade, gently pry the edge of the spacer and lift it off the subpanel. If any excess adhesive is present on the edge of the tabbing strips, use a putty knife or knife blade to chip or scrape it away. Use caution to not scratch or damage the gage section while removing excess adhesive. If C-clamps were used, remove the C-clamps and the masking covering the gage section. A clean surface of the subpanel should be visible.

Visually inspect the adhesive bond line quality around the edges of the tabbing strips. Particular attention should be given to the bond line quality at the tab termination (adjacent to the gage section). No gaps or voids should be present in the adhesive layer along this tab edge. If any excess adhesive exists along the reference edge of the panel, carefully remove the adhesive using a knife or sandpaper.

The tabbed subpanel is now ready for cutting into appropriate sized specimens. Use the reference edge of the subpanel to determine the fiber orientation when cutting specimens.

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