Designation: D7616/D7616M – 11

Standard Test Method for Determining Apparent Overlap Splice Shear Strength Properties of Wet Lay-Up Fiber-Reinforced Polymer Matrix Composites Used for Strengthening Civil Structures [1]

This standard is issued under the fixed designation D7616/D7616M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes the requirements for sample preparation and tensile testing of single-lap shear splices formed with fiber-reinforced polymer (FRP) composite materials commonly used for strengthening of structures made of materials such as metals, timber, masonry, and reinforced concrete. The objective of this method is to determine the apparent shear strength of an overlap splice joint through the application of a far-field tensile force. The method applies to wet lay-up FRP material systems fabricated on site or in a laboratory setting. The FRP composite may be of either unidirectional (0°) or cross-ply (0/90 type) reinforcement. For cross-ply laminates, the construction may be achieved using multiple-layers of unidirectional fibers at either 0 or 90°, or one or more layers of stitched or woven 0/90 fabrics. The composite material forms are limited to continuous fiber or discontinuous fiber-reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. The method is often used to determine the length of the overlap splice needed to ensure that a tension failure occurs in the material away from the splice rather than the splice connection itself.

1.2 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.2.1 Within the text, the inch-pound units are shown in brackets.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D883 Terminology Relating to Plastics

D3039/D3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials

D3878 Terminology for Composite Materials

D4896 Guide for Use of Adhesive-Bonded Single Lap-Joint Specimen Test Results

D5229/D5229M Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

D5687/D5687M Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation

D7565/D7565M Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures

E6 Terminology Relating to Methods of Mechanical Testing

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E456 Terminology Relating to Quality and Statistics

2.2 *Other Standards:*[3]

DOT/FAA/AR-01/33 Investigation of Thick Bondline Adhesive Joints, June 2001

DOT/FAA/AR-02/97 Shear Stress-Strain Data for Structural Adhesives, November 2002

3. Terminology

3.1 *Definitions*—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. Terminology E6 defines

[1] This test method is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available at the Federal Aviation Administration William J. Hughes Technical Center Full-Text Technical Reports page: http://207.67.203.68/F10011.

terms relating to mechanical testing. Terminology E456 and Practice E177 define terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other standards.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *nominal value, n*—a value, existing in name only, assigned to a measurable property for the purpose of convenient designation. Tolerances may be applied to a nominal value to define an acceptable range for the property.

3.2.2 *screed, v*—to move a flat rule along the top of a saturated laminate to level the top of the laminate and simultaneously remove excess resin.

3.2.3 *wet lay-up FRP composite, n*—an FRP composite material fabricated by manually impregnating dry fibers with a matrix of polymeric resin. Semi-automated processes such as machine-aided wetting of fabrics before placement or vacuum aided impregnation of laminates after placement are considered part of wet lay-up FRP. For civil infrastructure strengthening applications, the degree of control over the volume fractions of fibers, matrix, and voids as well as the overall cross-sectional geometry in wet lay-up FRP composites may be less than that for shop manufactured FRP composites on account of the manual process. For strengthening applications, wet lay-up FRP composites are typically applied to the substrate at the same time the dry fiber is impregnated. The impregnating resin may act as the saturant for the FRP composite as well as the bonding agent between the composite reinforcement and the substrate. Wet lay-up specimens may be fabricated in either a field or a laboratory setting.

3.3 *Symbols:*

3.3.1 F^*—strength of FRP laminate per unit width.

3.3.2 h_1—laminate thickness measured outside of the overlap splice on the bottom (flat) laminate.

3.3.3 h_2—laminate thickness measured outside of the overlap splice on the top (kinked) laminate.

3.3.4 h_3—laminate thickness measured within the overlap splice region.

3.3.5 h' —the reference thickness of a fiber, fabric or preform layer without resin, measured outside of the overlap splice.

3.3.6 L—entire length of the overlap splice specimen including the portion dedicated to gripping.

3.3.7 L'—length of the overlap splice region

3.3.8 n—number of specimens.

3.3.9 P—force carried by test specimen.

3.3.10 P^{max}—maximum tensile force.

3.3.11 w—coupon width.

3.3.12 V^*—apparent shear strength of the overlap splice per unit width for the L' under consideration.

4. Summary of Test Method

4.1 Overlap splice specimens are prepared using a wet lay-up procedure. Wet lay-up material may be prepared in a laboratory or field setting, as the testing objectives dictate. For testing in single shear, two thin, flat strips of material having a nominally constant cross section are joined together with a specified overlap and allowed to cure. The cured specimen is mounted in the grips of a mechanical testing machine and monotonically loaded in tension while force is recorded. The following items are reported for each specimen: ultimate force at failure, failure mode, and the apparent shear strength per unit width at failure.

5. Significance and Use

5.1 Overlap splices are used in field applications of FRP composites when site conditions prohibit continuous access to a structural element or when the specified length of the FRP composite is such that saturation and placement of the entire length would be cumbersome. This method can be used as a quality control mechanism for ensuring that overlap splices constructed under field conditions meet or exceed the requirements established by the design engineer or FRP system manufacturer. Both the saturant mixing and fiber saturation method can be verified for wet-layup FRP systems.

5.2 Caution is recommended when interpreting apparent shear strength results obtained from this method. Single shear lap splices develop non-uniform shear stress distributions within the overlap splice region during testing. Additional guidance on the interpretation and use of results obtained from lap shear testing is found in D4896.

5.3 This test method focuses on the FRP material itself, irrespective of gripping method. Therefore, strengths resulting from failure or pullout at either grip are disregarded. The strength measurements are based solely on test specimens that fail in the gage section (away from the grips) or at the splice.

6. Interferences

6.1 A summary of the interferences, specifically material and specimen preparation, gripping, system alignment, and edge effects in cross-ply laminates, are presented in D3039/D3039M.

6.2 Additional interferences may arise from lack of control in wet lay-up specimen preparation procedures outlined in 8.3.1. Specimen variations in resin content, ply thickness, void content and degree of cure may contribute to variability in test results.

6.3 Construction of single lap-splice samples using wet-lay FRP will result in kinked fibers for the top laminate (see Fig. 1). The effects of this kink on lap shear results will be magnified as the thickness, h_1 and h_2, of the FRP increases. This kink may also result in laminate failure outside the region of the bondline and the severity of the kink can impart moment loading to the bonded joint.

6.4 Overlap splice length, L', is identified in D4896, section 5.3.2 as a geometric parameter which affects apparent shear strength properties obtained from overlap splice tests. The results obtained using this test method are valid exclusively for the overlap splice length under consideration.

6.5 If a supplementary adhesive material (e.g., thickened epoxy tack coat) is used to promote bond between composite

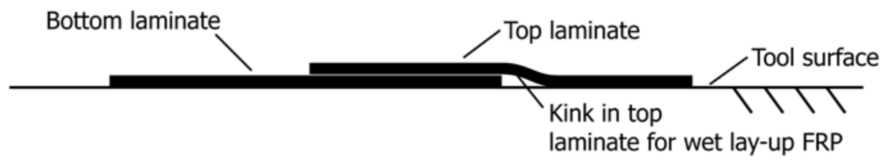

FIG. 1 Interference in Wet-Lay FRP Sample due to Kink in Top Laminate

layers within the overlap splice region, it should be noted that variations in the bond-line thickness may result in different apparent shear strength values or different failure modes. The typically observed trend is that increasing bondline thickness results in decreased apparent shear strength (DOT/FAA/AR-01/33 and DOT/FAA/AR-02/97).

6.6 The fiber/ply orientation within the overlap splice region has also been shown to influence the apparent shear strength or failure mode, or both, in lap shear specimens (DOT/FAA/AR-02/97).

6.7 The temperature and moisture conditions experienced by a specimen during curing and load testing can affect the apparent shear strength of an overlap splice joint. Additional guidance is provided in D3039/D3039M, section 11.4.

7. Apparatus

7.1 Requirements for testing machines and instrumentation are the same as those given in D3039/D3039M, Section 7.

8. Sampling and Test Specimens

8.1 *Sampling*—Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens, such as in the case of a designed experiment. For statistically significant data, the procedures outlined in Practice E122 shall be consulted. Report the method of sampling.

NOTE 1—If specimens are to undergo environmental conditioning to equilibrium, and are of such type or geometry that the weight change of the material cannot be properly measured by weighing the specimen itself (such as a tabbed mechanical coupon), then use another traveler coupon of the same nominal thickness and appropriate size (but without tabs) to determine when equilibrium has been reached for the specimens being conditioned.

8.2 *Geometry*—Recommended geometries for single shear specimens are provided in Fig. 2.

8.2.1 *Splice Length*—The desired overlap splice length shall be specified. A designed experiment may involve the testing of groups of specimens with varying overlap splice lengths. See Table 1 for recommended overall specimen lengths for varying overlap splice lengths. Variation in the overlap splice length as measured along both edges of the specimen shall be no greater than ± 5 %.

TABLE 1 Overall Specimen Length, *L*, as a Function of Overlap Splice Length, *L′*

Overlap length (L') mm^A (in)^B	Minimum Specimen length (L) mm^A (in)^B
25.0 (1.00)	230.0 (9.00)
50.0 (2.00)	260.0 (10.00)
76.0 (3.00)	280.0 (11.00)
100.0 (4.00)	305.0 (12.00)
150.0 (6.00)	360.0 (14.00)
200.0 (8.00)	410.0 (16.00)

^A Tolerances for millimeter dimensions are +/- 1.0 mm.
^B Tolerances for inch dimensions are +/- 0.04 in.

8.2.2 *Specimen Width*—Minimum specimen width for unidirectional wet lay-up FRP specimens shall be 25 mm [1.0 in.]. Minimum width for cross-ply specimens shall be 38 mm [1.5 in.] for wet lay-up composites. Variation in specimen width shall be no greater than ± 1 %.

8.3 *Specimen Preparation:*

8.3.1 *Wet Lay-up FRP*—Make field-prepared specimens in a manner similar to the actual field installation of the material. A polymer release film, typically 600 × 600 mm [24 × 24 in.] is placed on a smooth, flat horizontal surface. The release film shall be at least 0.076 mm [0.003 in.] thick and made of a polymer that will not adhere to the resin used to impregnate the fibers. Usually, acetate and nylon are acceptable. Resin is first applied to the release film. The dimensions of each ply should be no less than 150 × 300 mm [6 × 12 in.] (or longer as required by the specimen size, see Fig. 2). In order to facilitate the construction of the overlap splice joint and to ensure the desired overlap splice length, *L′*, is obtained, the width of the bottom laminate may be slightly larger (5 – 10 mm) than the width of the top laminate. Any excess material present in the bottom laminate shall be removed and discarded during the specimen machining process described in 8.3.4. The dry fibers

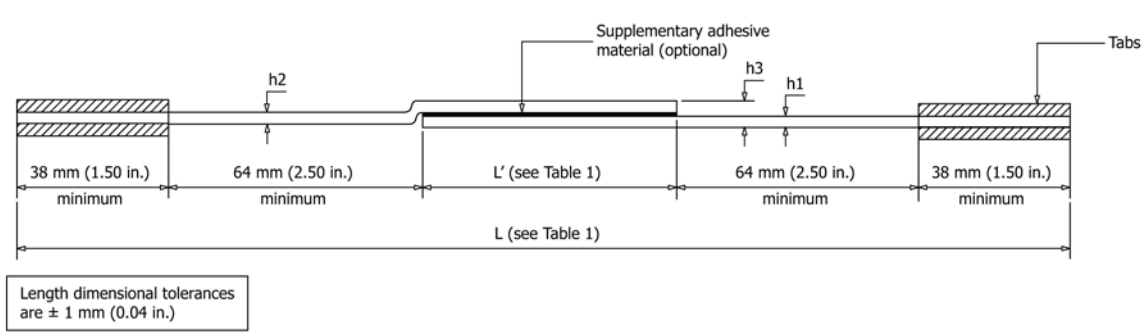

FIG. 2 Dimensions for Single-Shear Wet Lay-Up FRP Specimens

are saturated or coated with the specified amount of resin and placed on the release film. This can be done using a properly calibrated saturator machine or using a manufacturer-specified fiber to resin weight ratio. The specified number of plies at the specified angles (0 or 90°) for the bottom laminate of the single lap splice are sequentially impregnated with resin and stacked onto the release film using the specified amount of resin per ply per unit area as in the actual installation. Using the flat edge of a small hand tool or a grooved roller, air bubbles are worked out of the material. The bubbles shall be worked out in the direction of the primary fibers to ensure that no damage is caused to the fibers. At this point the specified number of plies for the top laminate of the lap splice are sequentially impregnated with resin and stacked onto a second piece of release film. If a supplementary adhesive material is specified, it shall be applied uniformly to both saturated laminates in the region of the overlap splice as in the actual installation. One of the saturated laminates is then placed on top of the other overlapping the bottom portion by the specified overlap splice distance, L'. If the release film on the top laminate does not extend past the entire length of the bottom laminate, the release film on the top laminate shall be removed and replaced with a longer piece such that the entire specimen is protected. An alternative method to eliminate air bubbles is to use the flat edge of a small paddle on the outer side of the upper release film to force the entrapped air out of the material with a screeding action in the primary fiber direction.

NOTE 2—The final fiber, resin, and void content of the material will depend on the method of rolling or screeding the material during fabrication. If the aim of testing is to evaluate FRP material representative of the installed strengthening material, rolling and screeding procedures used to prepare specimens shall resemble those used for the installed strengthening material.

In order to ensure a smooth top surface of the FRP material for gripping, two rigid flat plates shall be placed on top of the top layer of release film outside of the overlap splice region while the resin cures. A third plate may be placed over the overlap splice region if specified. The laminate shall be placed in an area of the job site so as to not interfere with the installation and allowed to cure according to the manufacturer's recommendation (see 8.3.2). After the specified curing procedure is complete, the release films are removed from the panel. Specimens may be cut and tabbed after the curing procedure.

NOTE 3—D5687/D5687M provides guidelines for strictly controlling the preparation of composite test specimens in the laboratory. Laboratory preparation of wet lay-up FRP shall follow these guidelines to the extent that they are compatible with the intended cure and laminate consolidation regimes as used in the field. The lay-up and laminate consolidation steps presented in D5687/D5687M are of particular relevance to this standard.

8.3.2 *Curing*—A cure history representative of a field application is typically used for laboratory-prepared wet lay-up FRP material. Elevated temperature curing beyond that provided for in field applications shall not be used in laboratory preparation of wet lay-up specimens.

8.3.3 *Bonded Tabs*—Follow procedures detailed in D3039/D3039M for information on the use and preparation of bonded tabs.

8.3.4 *Machining Methods*—Specimen preparation is extremely important for this test method. If specimens are cut from plates, take precautions to avoid notches, undercuts, rough or uneven surfaces, or delaminations caused by inappropriate machining methods. Obtain final dimensions by water-lubricated precision sawing, milling, or grinding. The use of diamond tooling has been found to be extremely effective for many material systems. Edges shall be flat and parallel within the tolerances specified in section 8.2. See Appendix X3 of D5687/D5687M for specific recommendations on specimen machining methods.

8.3.5 *Labeling*—Label the specimens so that they will be distinct from each other and traceable back to the raw material. Labeling must be unaffected by the test and must not affect the outcome of the test.

9. Calibration

9.1 The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

10. Conditioning

10.1 The recommended pre-test condition is effective moisture equilibrium at a specific relative humidity as established by Test Method D5229/D5229M; however, if the test requestor does not explicitly specify a pre-test conditioning environment, no conditioning is required and the specimens may be tested as prepared.

10.2 The pre-test specimen conditioning process, to include specified environmental exposure levels and resulting moisture content, shall be reported with the test data.

10.3 If no explicit conditioning process is performed, the specimen conditioning process shall be reported as "unconditioned" and the moisture content as "unknown."

NOTE 4—The term moisture, as used in Test Method D5229/D5229M, includes not only the vapor of a liquid and its condensate, but the liquid itself in large quantities, as for immersion.

11. Procedure

11.1 Measure the width and length of the overlap joint.

11.2 Measure and record the thickness of the overlap joint, h_3, at the center of the joint. Measure and record the thickness of each laminate, h_1 and h_2, outside of the overlap splice region.

NOTE 5—The thickness of the each laminate and the thickness of the lap joint are not required for subsequent calculations. The measurements may be helpful in assessing the overall thickness of the bonding layer between the two laminates and in determining the cause of bond line failures.

11.3 Follow procedures detailed in D3039/D3039M sections 11.3, Speed of Testing, 11.4, Test Environment, 11.5, Specimen Insertion, 11.7, Loading, 11.8, Data Recording, and 11.10, Tab Failures for testing the specimens.

11.4 Record the maximum force sustained by the specimen during the test and the failure mode of the specimen according to the following definitions.

11.4.1 *Overlap Splice Joint Failure*—For failures that occur within the overlap splice region, the primary modes of failure are:

11.4.1.1 *Delamination*—A clean separation between FRP layers that results from shear failure along the bondline. This failure mode is typically reserved for splice joints that do not include a supplementary adhesive material. The remaining failure modes are intended to address splice joints that do include a supplementary adhesive material.

11.4.1.2 *Adhesive failure*—The adhesive makes a clean separation from the FRP substrate.

11.4.1.3 *Cohesive failure*—The adhesive fails in shear along the mid-plane of the bondline.

11.4.1.4 *Thin-layer cohesive failure*—Adhesive fails in shear and a thin layer of adhesive remains attached to the FRP substrate.

11.4.1.5 *Fiber-tear failure*—A shear failure exclusively in the FRP substrate along the length of the bond-line in which reinforcing fibers appear on both sides of the ruptured surface.

11.4.1.6 *Light fiber-tear failure*—Similar to 11.4.1.4 except only a thin layer of the FRP matrix is attached to the adhesive with few or no fibers appearing on the adhesive side of the ruptured surface.

11.4.1.7 Combination of these failure modes.

11.4.1.8 See Fig. 3 for sketches of these potential failure modes.

11.4.2 *Failure Away from Splice*—The primary types of failures away from the overlap splice region are:

11.4.2.1 *Net Section Failure*—longitudinal fiber rupture occurs outside of the overlap region, away from the kink, and a minimum distance w from the grips.

11.4.2.2 *Longitudinal Splitting*—specimen fails along entire length in shear, leaving portions of the overlap splice intact. The shear failure may occur along a plane (A) parallel or (B) perpendicular to the plane of the specimen. This failure mode may also be accompanied by some degree of longitudinal fiber rupture (brooming).

11.4.2.3 *Net Section Failure Due to Kink*—the failure occurs in the FRP laminate in close proximity to the kink induced by formation of the overlap splice.

11.4.2.4 See Fig. 4 for sketches of these potential failure modes.

11.4.3 *Tab Failure*—A significant proportion of failures within one specimen width of the tab should be cause to re-examine the tab material and configuration, gripping method and adhesive, and to make necessary adjustments to promote failure within gauge length of specimen.

12. Calculations

12.1 *Apparent Shear Strength*—For specimens failing in accordance with 11.4.1, calculate the shear strength per unit width of the overlap splice joint using the following equation and report results to three significant figures:

$$V^* = \frac{P^{max}}{w}$$

where:

P^{max} = maximum tensile force before failure, N [lbf];
w = coupon width, mm [in.] measured in accordance with 11.2.3 in D3039/D3039M.

12.2 *Tensile Strength for Net Section Failures*—for specimens clearly demonstrating net section failures away from the lap splice and away from the grips, but including kink-induced net section failures, calculate the maximum tensile force per unit width using Eq 1 and report results to three significant figures.

$$F^* = \frac{P^{max}}{w} \quad (1)$$

where:

F^* = maximum tensile force per unit width, N/mm [lbf/in.];
P^{max} = maximum tensile force before failure, N [lbf];
w = width of the specimen, mm [in.].

NOTE 6—The calculation of tensile strength as outlined below is not intended to provide material tensile strength for design and shall not be used to replace the determination of tensile strength according to D7565/D7565M. These calculations may be of use when used in comparison with tensile strengths calculated according to D7565/D7565M, to assess the potential strength loss due to the presence of splices.

12.3 *Statistics*—For each series of tests, calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = \left(\sum_{i=1}^{n} x_i\right)/n \quad (2)$$

$$S_{n-1} = \sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right)/(n-1)} \quad (3)$$

$$CV = 100 \times S_{n-1}/\bar{x} \quad (4)$$

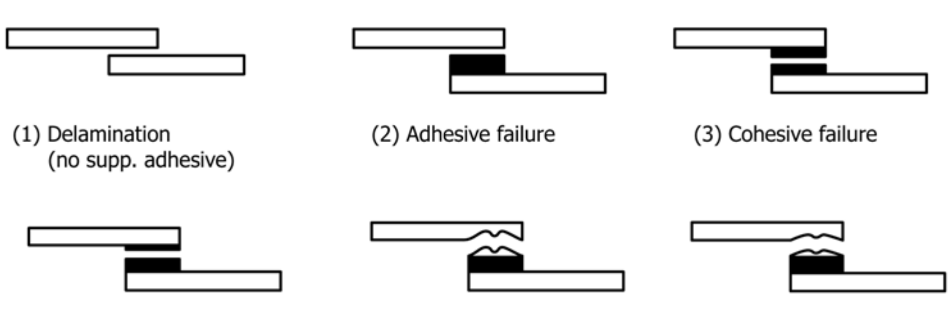

FIG. 3 Overlap Splice Joint Failure Modes for Lap Shear Specimens

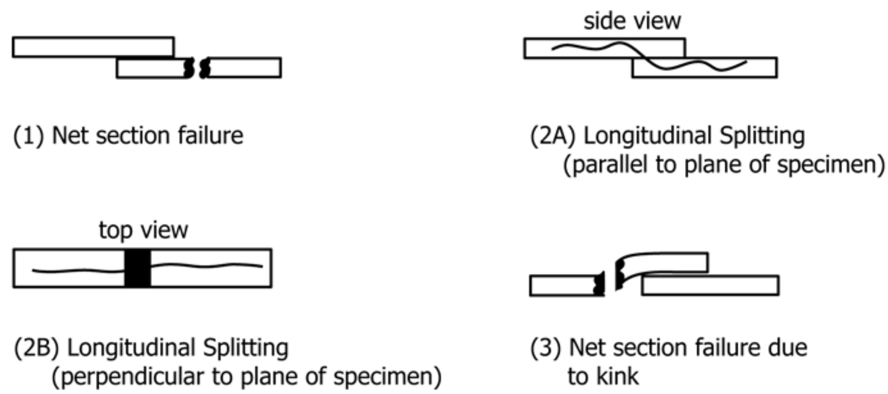

FIG. 4 Other Failure Modes for Lap Shear Specimens

where:

$\bar{x}$ = sample mean (average),
S_{n-1} = sample standard deviation,
CV = sample coefficient of variation, %,
n = number of specimens, and
x_i = measured or derived property.

13. Validation

13.1 Values for ultimate properties shall not be calculated for any specimen that breaks at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

13.2 A significant fraction of failures in a sample population occurring within one specimen width of the tab or grip shall be cause to re-examine the means of force introduction into the material. Factors considered should include the grip pressure, grip alignment, and specimen thickness taper.

14. Report

14.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable (reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requestor):

14.1.1 The revision level or date of issue of this test method.

14.1.2 The date(s) and location(s) of the test.

14.1.3 The name(s) of the test operator(s).

14.1.4 Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.

14.1.5 Identification of the material tested including: material specification, material type, material designation, manufacturer, manufacturer's lot or batch number, source (if not from manufacturer), date of certification, expiration of certification, filament diameter, tow or yarn filament count and twist, sizing, form or weave, fiber areal weight, matrix type, prepreg matrix content, and prepreg volatiles content.

14.1.6 Description of the fabrication steps used to prepare the laminate including: fabrication start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.

14.1.7 Ply orientation stacking sequence of the laminate.

14.1.8 If requested, report density, volume percent reinforcement, and void content test methods, specimen sampling method and geometries, test parameters, and test results.

14.1.9 Average ply thickness of the material. Include the reference thickness, h', provided by the FRP system manufacturer if provided.

14.1.10 Material type and dimensions of rigid flat plates used during curing.

14.1.11 Results of any nondestructive evaluation tests.

14.1.12 Method of preparing the test specimen, including specimen labeling scheme and method, specimen geometry, sampling method, coupon cutting method, identification of tab geometry, tab material, and tab adhesive used.

14.1.13 Calibration dates and methods for all measurement and test equipment.

14.1.14 Type of test machine, grips, jaws, grip pressure, alignment results, and data acquisition sampling rate and equipment type.

14.1.15 Results of system alignment evaluations (if performed).

14.1.16 Dimensions of each test specimen including the overlap splice length, L', the thickness of the overlap joint, h_3, at the center of the joint, and the thickness of each laminate, h_1 and h_2, outside of the overlap splice region.

14.1.17 Conditioning parameters and results, use of travelers and traveler geometry, and the procedure used if other than that specified in the test method.

14.1.18 Relative humidity and temperature of the testing laboratory.

14.1.19 Environment of the test machine environmental chamber (if used) and soak time in the environment.

14.1.20 Number of specimens tested.

14.1.21 Speed of testing.

14.1.22 Individual force per unit width, apparent shear strengths, and corresponding lap splice lengths, and strengths (V^* for shear failures and F^* for net section failures, if calculated), average value, standard deviation, and coefficient of variation (in percent) for the population. Note if the failure force was less than the maximum force before failure.

14.1.23 Failure mode and location of failure for each specimen. See section 11.4.