Designation: D4896 – 01 (Reapproved 2016)

Standard Guide for Use of Adhesive-Bonded Single Lap-Joint Specimen Test Results[1]

This standard is issued under the fixed designation D4896; 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.

INTRODUCTION

The true strength of an adhesive is a material property independent of the joint geometry, adherend properties, and load, and is a good starting point for determining an allowable design stress. Allowable stresses in shear and tension are needed to design safe, efficient, adhesively bonded joints and structures. The true shear strength, however, cannot be easily determined using single-lap specimens.

Many factors affect the apparent shear strength of an adhesive when measured with a small laboratory specimen, and in particular, with a single-lap specimen. For example, the failure of a typical single-lap specimen, is usually controlled by the tensile stress in the adhesive, and not by the shear stress. The factors that control the tensile stress in lap-joint specimen, and thus, the apparent shear strength are the size and shape of the specimen, the properties of the adherends, the presence of internal stresses or flaws, and the changes that take place in the specimen due to adhesive cure and the environment. Similarly these factors affect the apparent tensile strength of an adhesive in butt-joint test specimens.

Due to the effects of these factors, the apparent shear strength obtained through measurements on small laboratory specimens may vary widely from the true shear- or tensile-strength values needed to determine allowable shear and tension design stresses.

The objectives of this guide are: to develop an appreciation of the factors that influence strength and other stress measurements that are made with small laboratory test specimens; to foster the acceptable uses of the widely used thin-adherend single-lap-joint test; and, specifically, to prevent misuse of the test results.

1. Scope

1.1 This guide is directed toward the safe and appropriate use of strength values obtained from test methods using single-lap adhesive joint specimens.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.3 The discussion focuses on shear strength as measured with small thin-adherend, single-lap specimens. Many factors, however, apply to shear modulus, tensile strength, and tensile modulus measured by small laboratory specimens in general. This discussion is limited to single-lap specimens and shear strength only for simplification.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D896 Practice for Resistance of Adhesive Bonds to Chemical Reagents

D906 Test Method for Strength Properties of Adhesives in Plywood Type Construction in Shear by Tension Loading

D907 Terminology of Adhesives

D1002 Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)

D1144 Practice for Determining Strength Development of Adhesive Bonds

D1151 Practice for Effect of Moisture and Temperature on Adhesive Bonds

D1183 Practices for Resistance of Adhesives to Cyclic

[1] This guide is under the jurisdiction of ASTM Committee D14 on Adhesives and is the direct responsibility of Subcommittee D14.80 on Metal Bonding Adhesives.

Current edition approved May 1, 2016. Published May 2016. Originally approved in 1989. Last previous edition approved in 2008 as D4896 – 01 (2008)$^{\varepsilon 1}$. DOI: 10.1520/D4896-01R16.

[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.

Laboratory Aging Conditions
D1780 Practice for Conducting Creep Tests of Metal-to-Metal Adhesives
D2294 Test Method for Creep Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)
D2295 Test Method for Strength Properties of Adhesives in Shear by Tension Loading at Elevated Temperatures (Metal-to-Metal)
D2339 Test Method for Strength Properties of Adhesives in Two-Ply Wood Construction in Shear by Tension Loading
D2919 Test Method for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading
D3163 Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading
D3164 Test Method for Strength Properties of Adhesively Bonded Plastic Lap-Shear Sandwich Joints in Shear by Tension Loading
D3165 Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies
D3166 Test Method for Fatigue Properties of Adhesives in Shear by Tension Loading (Metal/Metal)
D3434 Test Method for Multiple-Cycle Accelerated Aging Test (Automatic Boil Test) for Exterior Wet Use Wood Adhesives
D3528 Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading
D3632 Test Method for Accelerated Aging of Adhesive Joints by the Oxygen-Pressure Method
D3983 Test Method for Measuring Strength and Shear Modulus of Nonrigid Adhesives by the Thick-Adherend Tensile-Lap Specimen
D4027 Test Method for Measuring Shear Properties of Structural Adhesives by the Modified-Rail Test
D4562 Test Method for Shear Strength of Adhesives Using Pin-and-Collar Specimen
D5868 Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding
E6 Terminology Relating to Methods of Mechanical Testing
E229 Test Method for Shear Strength and Shear Modulus of Structural Adhesives (Withdrawn 2003)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 The following terms are defined in accordance with Terminologies D907 and E6.

3.2 *creep*—the time-dependent increase in strain in a solid resulting from force.

3.3 *shear strength*—the maximum shear stress which a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original dimensions of the cross section of the specimen. (See *apparent* and *true shear strength*).

[3] The last approved version of this historical standard is referenced on www.astm.org.

3.4 *strain*—the unit change due to force, in the size or shape of a body referred to its original size or shape. Strain is a nondimensional quantity, but is frequently expressed in inches per inch, centimeters per centimeter, etc. (Refer to Terminology E6 for specific notes.)

3.4.1 *linear (tensile or compressive) strain*—the change per unit length due to force in an original linear dimension.

3.4.2 *shear strain*—the tangent of the angular change, due to force, between two lines originally perpendicular to each other through a point in a body.

3.5 *stress*—the intensity at a point in a body of the internal forces or components of force that act on a given plane through the point. Stress is expressed as force per unit of area (pounds-force per square inch, newtons per square millimetre, etc.).

NOTE 1—As used in tension, compression, or shear tests prescribed in product specifications, stress is calculated on the basis of the original dimensions of the cross section of the specimen.

3.5.1 *normal stress*—the stress component perpendicular to the plane on which the forces act. Normal stress may be either:

3.5.1.1 *compressive stress*—normal stress due to forces directed toward the plane on which they act, or

3.5.1.2 *tensile stress*—normal stress due to forces directed away from the plane on which they act.

3.5.1.2.1 *Discussion*—In single-lap specimen testing, the plane on which the forces act is the bondline. Tensile stress is sometimes used interchangeably, although incorrectly, with peel or cleavage stress. Peel and cleavage involve complex tensile, compressive, and shear stress distributions, not just tensile stress.

3.5.2 *shear stress*—the stress component tangential to the plane on which the forces act.

3.6 *Definitions of Terms Specific to This Standard:*

3.6.1 *allowable design stress*—a stress to which a material can be subjected under service conditions with low probability of mechanical failure within the design lifetime.

3.6.1.1 *Discussion*—Allowable design stress is obtained usually by multiplying the true shear strength of the material (or close approximation thereof) by various adjustment factors for manufacturing quality control, load and environmental effects, and safety.

3.6.2 *apparent shear strength*—(in testing a single-lap specimen) the nominal shear stress at failure without regard for the effects of geometric and material effects on the nominal shear stress. Often called the *lap-shear* or *tensile-shear strength.*

3.6.3 *average stress*—(in adhesive testing) the stress calculated by simple elastic theory as the load applied to the joint divided by the bond area without taking into account the effects on the stress produced by geometric discontinuities such as holes, fillets, grooves, inclusions, etc.

3.6.3.1 *Discussion*—The average shear and tensile stresses are denoted by τ_{avg} and σ_{avg} respectively. (See 5.3.1.) (*Average stress* is the same as the preferred but less common term, *nominal stress*, as defined in Terminology E6.)

3.6.4 *cleavage stress*—(in adhesive testing) a term used to describe the complex distribution of normal and shear stresses present in an adhesive when a prying force is applied at one end of a joint between two rigid adherends.

3.6.5 *peel stress*—(in adhesive testing) a term used to describe the complex distribution of normal and shear stresses present in an adhesive when a flexible adherend is stripped from a rigid adherend or another flexible adherend.

3.6.6 *single-lap specimen*—(in adhesive testing) a specimen made by bonding the overlapped edges of two sheets or strips of material, or by grooving a laminated assembly, as shown in Test Methods D2339 and D3165. In testing, a single-lap specimen is usually loaded in tension at the ends.

NOTE 2—In the past this specimen has been referred to commonly as the tensile-shear- or the lap-shear-specimen. These names imply that this is a shear dominated joint, and that the measured strength is the shear strength of the adhesive. This is not true for most uses of such specimens. (An exception would be where the adhesive being evaluated is so low in strength as not to induce any bending in the adherends.) It is recommended that, henceforth, this specimen be referred to as a single-lap specimen.

3.6.7 *stress concentration*—a localized area of higher than average stress near a geometric discontinuity in a joint or member (such as a notch, hole, void, or crack); or near a material discontinuity (such as a bonded joint or weld) when the joint or member is under load.

3.6.7.1 *Discussion*—In adhesive testing, the most common and important discontinuities are the ends of the bonded adherends and the interfaces between the adhesive and adherends.

3.6.8 *stress concentration factor*—the ratio of the stress at a point in a stress concentration to the average stress.

3.6.9 *thick adherend*—(in adhesive testing) an adherend used in a single-lap specimen that does not bend significantly when a load is applied, resulting in relatively lower tension/normal stress at the ends of the overlap; and, more uniform normal and shear stress distributions in the adhesive compared to a joint made with thin adherends and placed under the same load.

3.6.9.1 *Discussion*—A thick adherend for a typical epoxy adhesive and steel joint is at least 0.25 in. (6.36 mm) thick when the overlap is 0.50 in. (12.7 mm), based on finite element analysis and mechanical tests (**1 and 2**).[4] Objective criteria for determining whether or not an adherend is thick are given in Test Method D3983.

3.6.10 *thin adherend*—(in adhesive testing) an adherend used in a single-lap specimen that bends significantly, causing significant tension/normal stresses in the adhesive at the ends of the overlap and nonuniform shear and normal stress distributions in the adhesive when a load is applied.

3.6.10.1 *Discussion*—The bending of the adherends, the tension-normal stresses, and the nonuniform stress distributions are continuous functions of the adhesive modulus and thickness, the adherend modulus, and the joint overlap length as described more fully in Test Method D3983. An adherend thickness to overlap length ratio of less than 1:5 is a reasonable approximation of a thin adherend for epoxy-steel joints (**1 and 2**).

3.6.11 *true shear strength*—the maximum uniform shear stress which a material is capable of sustaining in the absence of all normal stresses.

4. Significance and Use

4.1 Single-lap specimens are economical, practical, and easy to make. They are the most widely used specimens for development, evaluation, and comparative studies involving adhesives and bonded products, including manufacturing quality control.

4.2 Special specimens and test methods have been developed that yield accurate estimates of the true shear strength of adhesives. These methods eliminate or minimize many of the deficiencies of the thin-adherend single-lap specimens, but are more difficult to make and test. (See Test Methods D3983, D4027, D4562, and E229.)

4.3 The misuse of strength values obtained from such Test Methods or Practices as D906, D1002, D1144, D1151, D1183, D1780, D2294, D2295, D2339, D3163, D3164, D3165, D3434, D3528, D3632, and D5868, as allowable design-stress values for structural joints could lead to product failure, property damage, and human injury.

5. Considerations for the Analysis of Small Single-Lap Specimen Test Results

5.1 The true shear strength of an adhesive can be determined only if normal stresses are entirely absent. These conditions can be approached under special conditions, but not in single-lap specimens made with the thin adherends normally used in manufacturing and in most standard test specimens. In most cases the tensile stress in the adhesive controls joint failure. As a consequence the single-lap specimen strength is unrelated to, and an unreliable measure of, the true shear strength of an adhesive (**1 and 2**).

5.2 Changes in adhesive volume during cure, the size of the joint, the modulus of the adherends, and temperature or moisture shifts after cure, all affect the magnitude of the stresses imposed on an adhesive in service. The thermal conductivity and permeability of the adherends affect the extent of thermal or moisture softening and the rate of chemical degradation of the adhesive in service. Therefore, in addition to the problems stated in 5.1, the average stress at failure of small single-lap specimens after a given exposure is an unreliable measure of an adhesive's environmental resistance in any other joint, especially a much larger structural joint.

5.3 *Factors Affecting Apparent Shear Strength:*

5.3.1 Specimen geometry, material properties, and load are factors affecting *apparent shear strength*. The shear and normal stresses at any point in a single-lap specimen are described mathematically in the classic linear-elastic analysis of Goland and Reissner (**3**). Modern finite element analysis has proven the Goland and Reissner analysis to be accurate except at the very ends of the overlap (**1**). Both the Goland and Reissner and finite element analyses show that both the normal and shear

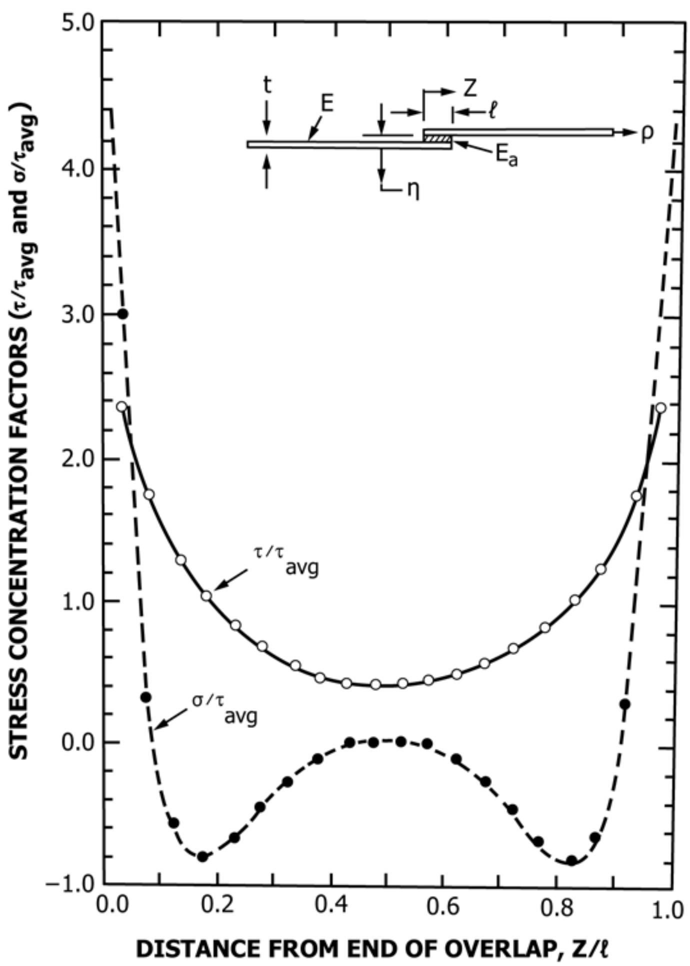
[4] The boldface numbers in parentheses refer to the list of references at the end of this guide.

stress concentration factors increase toward the ends of the overlap (Fig. 1). Usually the tensile stress concentration is higher and is the dominant factor in failure. This means that peak stresses, and in particular the peak tensile stresses cause failure, not the average shear stress across the bonded area. Thus the strength of a single-lap specimen, or the apparent shear strength of the adhesive, is simply the average shear stress that happens to exist in the joint when the stress concentrations reach a critical level and the joint fails. It is not the true shear strength of the adhesive.

5.3.2 In addition to the problem of determining the true shear strength of the adhesive with a single-lap specimen, both shear- and tensile-stress concentrations are controlled by the following geometric-, material-, and load-parameters, as shown by Goland and Reissner (**3**):

5.3.2.1 adhesive shear modulus,
5.3.2.2 adhesive layer thickness,
5.3.2.3 adherend tensile modulus,
5.3.2.4 adherend thickness,
5.3.2.5 adherend Poisson's ratio,
5.3.2.6 overlap (joint) length, and
5.3.2.7 tensile stress in adherends away from the joint.

5.3.2.8 A change in any of these parameters from the values of the test specimen will change the stress concentrations and consequently the average shear stress at failure as described in 5.3.1. The apparent shear strength measured with a single-lap specimen, therefore, cannot be assumed to predict the strength of joints that differ in any way from that specimen.



τ = actual adhesive shear stress at a point
τ_{avg} = average (nominal) adhesive shear stress in the joint
σ = actual adhesive normal stress at a point
E_a = adhesive modulus
E = adherend modulus
η = adhesive layer thickness
t = adherend thickness
υ = adhesive Poisson's ratio
ℓ = overlap length
Z = location of a point along the overlap length
p = tensile stress in the adherends away from the joint

FIG. 1 Variation of the shear and normal stress concentration factors (τ/τ_{avg}, and σ/τ_{avg} respectively) along a single-lap specimen with the parameters that affect their magnitude at a given point. (Adapted from Guess, Allred, and Gerstle, (2))

5.4 *Internal Stresses and Flaws:*

5.4.1 When an adhesive hardens (polymerizes), it shrinks volumetrically through solvent loss or through additional crosslinking. In bonding, the shrinkage is restrained by the adherends causing internal stresses to arise within the adhesive. Internal stress affects the adhesive's resistance to an externally applied stress, and it may reduce the apparent shear strength (**4**). The amount of the apparent shear strength reduction depends on; the amount of internal stress, the bonding conditions, the adhesive layer thickness, and the properties of the adherends. The apparent shear strength of an adhesive obtained from a given small single-lap specimen, therefore, may differ from that obtained from a joint made with different adherends or by a different bonding process.

5.4.2 Bondline flaws are potential sites for crack initiation. The effect of edge flaws vary with joint geometry and the adherend properties (**5**). In short single-lap specimens, as in most small joints, even small flaws are likely to be of a critical size for crack initiation because they are more likely to be present in an area of high stress concentration. On the other hand, longer structural single-lap joints may be quite insensitive to moderate flaws in the lightly stressed center region (**6**). Conclusions about the effects of flaw size and location cannot be drawn from short specimen tests alone.

5.5 *Environmental Effects:*

5.5.1 *Long-term effects:*

5.5.1.1 Bonded joints often fail by chemical degradation of the adhesive or adherends progressing inward from exposed edges (**7**), or by crack growth inward from the edges (**5**, **8**). Short single-lap test specimens and other small joints with a high ratio of bond-edge-to-bond-area are more sensitive to a chemically or physically harsh environment than large joints because the effective bond area diminishes more rapidly than in full-scale joints. Small specimens are particularly sensitive in stressed-durability tests and may give results that are overly conservative.

5.5.1.2 Thermal degradation, as well as hydrolytic degradation are not limited to the joint perimeter, especially if the adherends are porous. In these cases, differences in the properties of the adherends used in small test specimens, and those used in larger structural joints may affect the adhesive's performance. Chemical differences may directly affect the nature or rate of the degradation reaction. Differences in permeability may indirectly affect the reaction by controlling the rate of diffusion of reactants into, or reaction products away from the adhesive layer.

5.5.1.3 In view of the arguments in 5.5.1.1 and 5.5.1.2, small single-lap specimens can be used for rapid, economical comparisons of the relative durability of adhesives and bonding processes provided that the specimen has been properly analyzed and is well understood. Also, if these conditions are met, the single-lap specimen can be quite useful for establishing threshold levels for stress in stressed-durability testing (**7**). Extrapolation of the actual service life of structural joints from short-term accelerated tests of small specimens, however, must be approached very cautiously. The results must be carefully studied to ensure that the degradation mechanism is the same in the small specimen as would be expected in the structural joint.

5.5.2 *Short-Term Effects:*

5.5.2.1 Changes in temperature and moisture directly affect the strength and other mechanical properties of adhesives. When the external environment changes, the thermal conductance, moisture permeability of the adhesive and adherends, the thickness of adherends, and the width of the joint affect how fast the environment changes in the interior of the bondline. Different adherends or joint geometries will result in different amounts of delay, thus producing different apparent shear strengths under otherwise similar environmental conditions.

5.5.2.2 The normal variation of temperature and moisture in the service environment causes the adherends and the adhesive to swell and shrink (**4, 9**). The adherends and adhesive are likely to have different thermal and moisture coefficients of expansion. Even in small specimens, short-term environmental changes can induce internal stresses or chemical changes in the adhesive that permanently affect the apparent shear strength and other mechanical properties of the adhesive (**7, 8**). The problem of predicting joint behavior in a changing environment is even more difficult if a different type of adherend is used in a larger structural joint than was used in the small specimen.

5.5.2.3 For the reasons outlined in 5.5.2.1, and 5.5.2.2, the short-term effects of variation of temperature and moisture on an adhesive's strength determined with small specimens cannot be assumed to directly predict the performance of structural joints bonded with the same adhesive unless those effects can be measured and the results properly interpreted (**7**).

5.6 *Elastic Strain Reserve:*

5.6.1 In short single-lap specimens, the adherends are usually stronger than the adhesive joint, thus causing failure to occur in the adhesive. If the adhesive is not brittle, plastic flow occurs when the stress in an adhesive exceeds the elastic limit. Plastic deformation may occur throughout the adhesive layer in short single-lap specimens at failure. But longer structural joints may be designed to limit plastic flow to the ends of the overlap (**6**). In the center of a structural single-lap joint, the adhesive should be only lightly stressed and still lie within the elastic range. This elastic region in the center of the joint may prevent the accumulation of creep strain which would otherwise lead to creep rupture (**6**) or fatigue failure (**10**).

5.6.2 For the above reasons, conclusions about the dead-load or fatigue resistance of an adhesive derived from short single-lap specimens cannot be assumed to predict the behavior of a longer structural single-lap joint bonded with the same adhesive.

6. Acceptable Uses of Thin-Adherend, Single-Lap Specimen Tests

6.1 Single-lap tests, like those described in Test Methods D906, D1002, D2339, D3163, D3164, D3165, and D3528, are not suitable for determining the true shear strength of an adhesive. The apparent shear strength measured with a single-lap specimen is not suitable for determining allowable design stresses, nor is it suitable for designing structural joints that differ in any manner from the joints tested without thorough analysis and understanding of the joint and adhesive behaviors.

6.2 Single-lap tests may be used for comparing and selecting adhesives or bonding processes for susceptibility to fatigue and environmental changes (**11**), but such comparisons must be made with great caution since different adhesives may respond differently in different joints.

6.3 Single-lap tests can be used in research and development to provide the justification for further, more expensive testing needed to establish the acceptability of an adhesive for structural joints (**11**).

6.4 Single-lap tests can be used to monitor the quality of materials and the control of bonding processes.

7. Tests for Developing Adhesive Design-Shear Stresses

7.1 Allowable design stresses for adhesives in shear should be developed under the supervision of an engineer with knowledge of adhesive behavior, using tests such as Test Method E229, D3983, or D4027, to obtain quantitative data for design. It must be recognized, however, that even these tests suffer unrealistic effects of some of the factors discussed above because they themselves are not realistic configurations of structural joints. Supplementary testing of realistic structural elements or components is required to determine flaw tolerance, fatigue and creep resistance, and environmental effects. In extraordinary circumstances, testing a full-scale bonded structure may be warranted to identify hidden configuration or design faults that would adversely affect long-term performance (**7**), or that might be required for final-design verification and for aircraft certification (**11**).

8. Keywords

8.1 shear strength; single-lap joint; tension loading

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