Designation: D8511/D8511M – 23

Standard Guide for
Design and Analysis of Local Buckling and Crippling Test Specimens[1]

This standard is issued under the fixed designation D8511/D8511M; 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 guide covers designing local buckling and crippling test specimens to obtain empirical strength data for one-edge-free and no-edge-free cross section configurations using solid laminate composite material construction. This guide also discusses data analysis procedures for these test specimens. Test procedures for local buckling and crippling specimens are covered in Test Method D8510/D8510M. This guide is intended to be used by persons requesting these test types.

1.2 Local buckling and crippling tests require careful specimen design, instrumentation, data measurement and data analysis. Test requestors designing these specimen need to be familiar with Test Method D8510/D8510M, CMH-17 Volume 3 Chapter 9 (**1**)[2], and the stress analysis methods that will use the resulting local buckling and crippling design data.

1.3 *Units*—The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

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

1.4 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]
D883 Terminology Relating to Plastics
D3878 Terminology for Composite Materials
D8510/D8510M

3. Terminology

3.1 *Definitions:*

3.1.1 Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. In the event of a conflict between terms, Terminology D3878 shall have precedence.

NOTE 1—If the term represents a physical quantity, its analytical dimensions are stated immediately following the term (or letter symbol) in fundamental dimension form, using the following ASTM standard symbology for fundamental dimensions, shown within square brackets: [M] for mass, [L] for length, [T] for time, [θ] for thermodynamic temperature, and [nd] for non-dimensional quantities. Use of these symbols is restricted to analytical dimensions when used with square brackets, as the symbols may have other definitions when used without the brackets.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *crippling force, P^{cc} [MLT^{-2}], n*—the applied compressive force at or above the local buckling force at which specimen failure occurs.

3.2.2 *crippling stress, F^{cc} [$ML^{-1}T^{-2}$], n*—the average stress in the test specimen cross-section at failure.

3.2.3 *local buckling force, P^{lcr} [MLT^{-2}], n*—the applied compressive force at which buckling initiates.

3.2.4 *local buckling stress, F^{lcr} [$ML^{-1}T^{-2}$], n*—the average stress in the test specimen cross-section at which buckling of a compression element within the cross-section initiates.

3.2.5 *slenderness ratio, L'/ρ [nd], n*—the ratio of the specimen length adjusted for end boundary condition effects divided by the minimum radius of gyration of the specimen cross-section.

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[1] This guide is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.05 on Structural Test Methods.

Current edition approved Sept. 1, 2023. Published September 2023. DOI: 10.1520/D8511_D8511M-23.

[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

[3] 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.

3.2.6 *width to thickness ratio, b/t [nd], n*—the ratio of the width of the buckling critical section of the specimen cross-section to the specimen thickness.

3.2.6.1 *Discussion*—The width to thickness ratio may be either a nominal value determined from nominal thickness or an actual value determined from measured thickness.

3.3 *Symbols:*

3.3.1 A—cross-sectional area, mm^2 [in.^{2}].

3.3.2 b—width of buckling critical segment of specimen cross-section, relative to laminate centerline, mm [in.].

3.3.3 c—specimen end boundary condition factor (= 1.0 for both ends pinned; = 4 for both ends fully fixed).

3.3.4 F^{lcr}—local buckling stress, MPa [psi].

3.3.5 F^{cc}—crippling stress, MPa [psi].

3.3.6 $L1$—specimen length between end potting or fixture inner surfaces, mm [in.].

3.3.7 $L2$—total specimen length, mm [in.].

3.3.8 L' —specimen length adjusted for end boundary condition (= $L/\sqrt{c}$), mm [in.].

3.3.9 P—total compressive force applied to specimen, N [lbf].

3.3.10 P^{lcr}—applied compressive force at which buckling initiates, N [lbf].

3.3.11 P^{cc}—maximum applied compressive force, N [lbf].

3.3.12 ρ—minimum cross-section radius of gyration.

3.3.13 t—specimen thickness (nominal or actual, as specified), mm [in.].

3.3.14 w—overall width of buckling critical segment of specimen cross-section, mm [in.].

4. Summary of Guide

4.1 This guide provides information for designing test specimens to determine the local instability (buckling) force in one or more cross-section segments and the maximum post-buckled force sustained by a composite specimen. The test involves applying an axial compressive force to an unsupported specimen until local buckling and subsequent catastrophic failure (“crippling”) occurs. Users of this guide should be familiar with the stress analysis methods that will use the resulting local buckling and crippling design data. The following references discuss these methods and associated test data for metallic and composite structures:

4.1.1 CMH-17, Volume 3 Chapter 9 (**1**),

4.1.2 Esp, Chapter 17 (**2**),

4.1.3 Peery, Chapter 14 (**3**),

4.1.4 Peery and Azar, Chapter 11 (**4**),

4.1.5 Niu, Chapter 10 (**5**), and

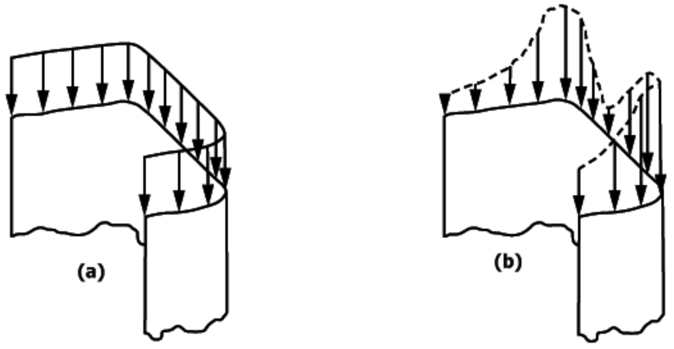
4.1.6 Ziemian (**6**).

5. Background

5.1 When beams or stiffened panels are loaded in compression, force is shared between skin and stiffener cross section elements in proportion to their respective stiffnesses. After initial buckling of an element of the cross section, the effective tangent stiffness of the buckled element is reduced sharply; the unbuckled elements will carry additional force as the overall structural force is increased.

5.2 Prior to any buckling, an axially loaded stiffener or structural member will have a uniformly distributed compressive stress as shown in Fig. 1(a). At some force one or more flat elements of the section begin to buckle, with additional force carried by unbuckled portions (for example, corners, Fig. 1(b)). Metallic structures can exhibit local yielding in the buckled cross-section prior to reaching maximum force (“crippling” failure). In composite structure sections the onset of local failure occurring anywhere in the cross-section typically results in complete section failure. The failure onset can occur in compression in the unbuckled areas or in bending in the buckled areas. In some cases ultimate failure may be preceded by delaminations induced by the post-buckled deformations. This ultimate failure mode is also referred to as “crippling” (or sometimes as “post-buckling failure”) even though the failure mechanisms are different from those of metallic structure. Similar to metals, composite crippling failure stress can be significantly higher than the initial local buckling stress.

5.3 The analysis of sections or stiffened panels loaded in the post-buckling range becomes a geometrically nonlinear problem and, therefore, "conventional" plate buckling linear analysis cannot be used to estimate the crippling strength of



Prior to Local Buckling

After Local Buckling

FIG. 1 Typical Stiffener Stress Distribution Prior and After Local Buckling

composite plates. The analysis of laminated plates is further complicated by high interlaminar stresses in the corners or at the free edge of the plate may trigger a premature failure. Non-linear finite element methods have been used to predict the strength of post-buckled stiffened panels, but typically require some degree of test data for analysis calibration and validation. Empirical crippling curves are therefore typically used for laminated composite stiffener design.

5.4 Classical local buckling and crippling stress analysis of plate segment structural members is based on dividing the section into individual plate elements having various boundary conditions (for example, free edges and no free edges, as shown in Figs. 2-4).

6. Test Specimen Design

6.1 *General:*

6.1.1 Compressive loading of composite column type specimens may exhibit one of four modes: *(1)* a compression material strength failure, *(2)* an overall column flexural, torsional, and or flexural-torsional instability, *(3)* a local instability followed by a continued post-buckled force carrying capability which eventually results in a material strength failure, or *(4)* a combination of local and overall instability followed by post-buckling failure. The first two modes are outside the scope of Test Method D8510/D8510M. The latter two modes are categorized as crippling failure and is the purpose of this guide and Test Method D8510/D8510M. Note that a combined local and global instability in a test specimen is not a desired response as it can produce conservative crippling results.

6.1.2 The standard generic configurations for this testing, Fig. 5, provide data for the two types of cross-section segments: one-edge-free and no-edge-free. Typical no-edge-free and one-edge-free tests in progress with the specimens in the postbuckling range are shown in CMH-17 (**1**). Typical load-displacement curves of no-edge-free and one-edge-free tests are shown in CMH-17 (**1**).

6.1.3 General factors that influence the mechanical response of composite laminates and should therefore be reported include the following: material, methods of material preparation and lay-up, specimen stacking sequence, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, time held at test temperature, void content, and volume percent reinforcement.

6.1.4 Test Method D8510/D8510M does not provide an explicit specimen geometry or data reduction methodology beyond calculation of local buckling and crippling stresses. The discussions below provide guidance on designing specimen geometry to produce the required design data. The following three test procedures are covered in the test standard, Fig. 5.

6.1.4.1 *Procedure A – One Edge Free (OEF)*—The test specimen consists of a straight, constant cross-section, symmetric L-section with potted ends. Both segments of the L-section are intended to buckle at the same applied force. When one leg buckles inward and the other leg buckles outward, the instability mode is a combined flexural-torsional buckling mode which produces lower bound OEF results (**7, 8**). In rare cases both legs buckle the same direction, either inwards or outwards and the torsional mode is not present.

6.1.4.2 *Procedure B – No Edge Free (NEF)*—The test specimen consists of a straight, constant cross-section, symmetric C-section with potted ends. The center "web" segment of the C-channel is intended to buckle while the edge segments are intended to remain unbuckled up to the specimen failure force.

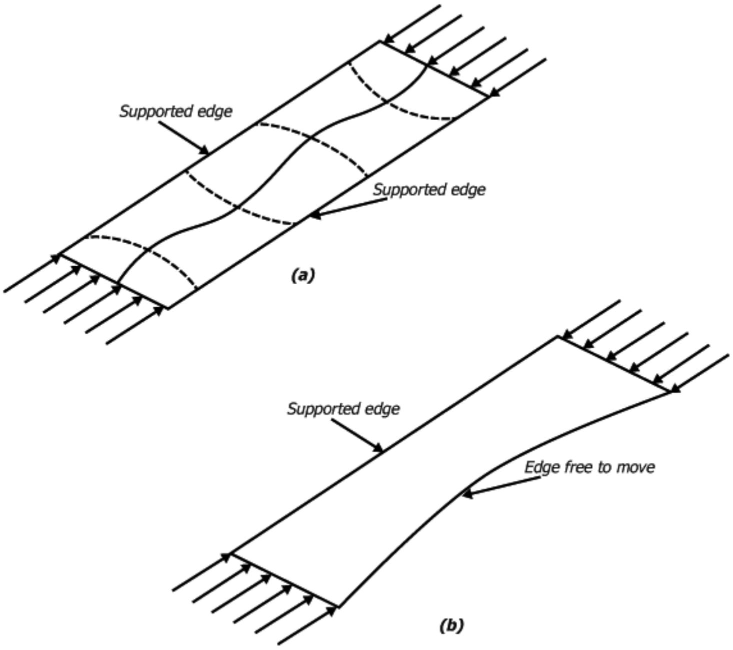


FIG. 2 Plate Buckling *(a)* 4 Edges Supported (No Edge Free Condition) *(b)* 3 Edges Supported (One Edge Free Condition)

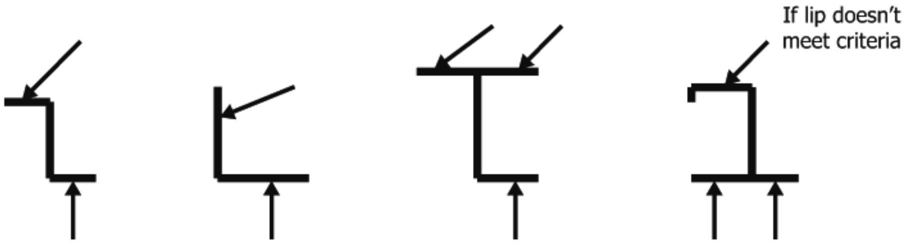


FIG. 3 Example One-Edge-Free Elements in Structural Stiffener Shapes

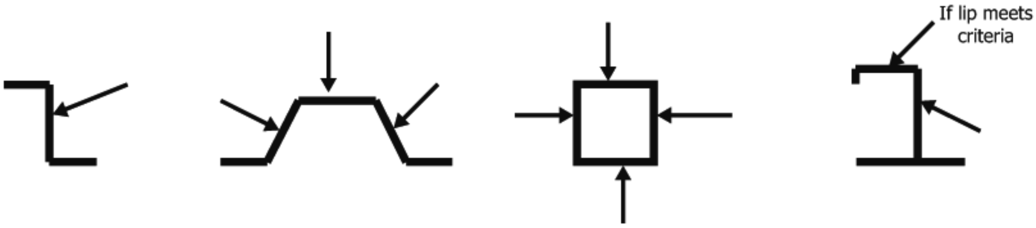
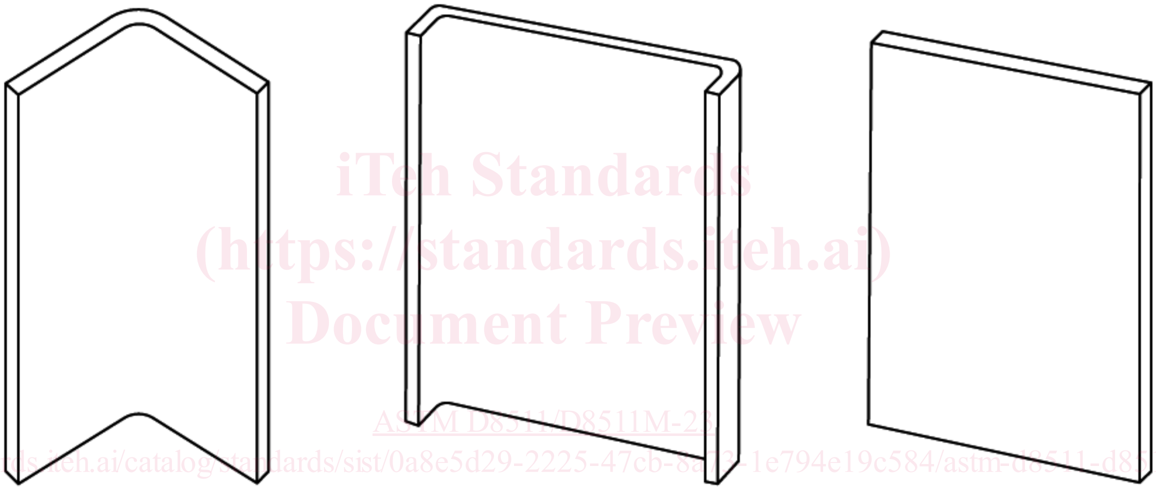


FIG. 4 Example No-Edge-Free Elements in Structural Stiffener Shapes



Procedure A **Procedure B** **Procedure C**

FIG. 5 Specimen Types

6.1.4.3 *Procedure C – No Edge Free (NEF)*—The test specimen consists of a flat laminate specimen that is supported on the unloaded edges by V-groove fixture restraints and loaded with a clamping fixture on each end.

6.1.5 The initial local buckling behavior of composite plates can be predicted fairly reliably with analytical or finite element methods; refer to (**1**) or (**2**). However, since local buckling stresses are obtained from the same test specimens used to generate crippling stresses, these empirical buckling results are often also used to generate design curves.

6.1.6 Tests have been conducted over the decades by a number of companies and research organizations using relatively narrow plates, with one supported and one free unloaded edges ("one-edge-free", OEF) or with two supported unloaded edges ("no-edge-free", NEF).

6.1.7 As discussed in 5.3, the post-buckling behavior of composite plates is derived from empirical test data. This data is often graphed on a log-log plot as F^{cc} vs b/t, similar to what is done for metal section F^{cc} data. Example data plots for both local buckling and crippling are provided in CMH-17 (**1**), and Fig. 6. Data is also sometimes plotted in normalized forms, such as Fcc/Fcu vs b/t, or nondimensional form based on laminate stiffness parameters, as discussed in CMH-17 (**1**).

6.2 *One-Edge Free (OEF) Specimen Design:*

6.2.1 At least five types of specimens have been previously used for OEF crippling tests (Fig. 7):

6.2.1.1 Flat plates with V-groove fixture on one edge,

6.2.1.2 Symmetric L-angle sections (with two "legs" being OEF),

6.2.1.3 Cruciform ("+") sections (with four "legs" being OEF),

6.2.1.4 Z-shaped sections (with two flanges being OEF), and

6.2.1.5 C-channel sections (with two flanges being OEF).

6.2.2 Some of the empirical OEF test data shown in CMH-17 comes from flat plate tests. However, these specimens have a tendency to slip out of the fixture V-groove on the

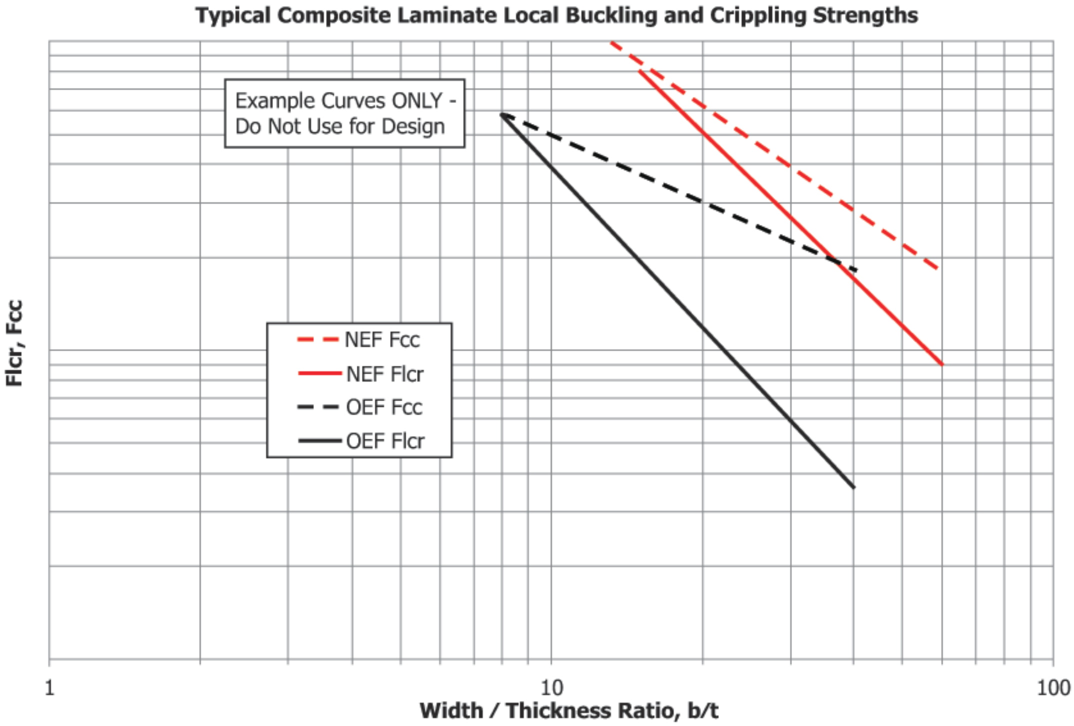


FIG. 6 Typical Composite Laminate F^{lcr} and F^{cc} Curves vs b/t Ratio

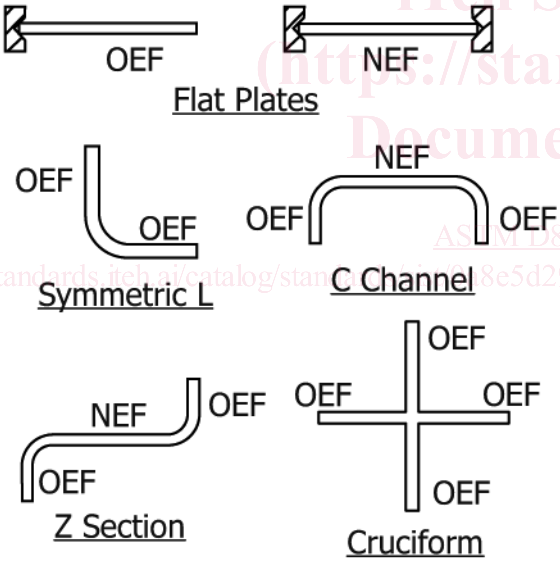


FIG. 7 Historical Crippling Specimen Cross-Sections

one unloaded edge after buckling. Also, this test configuration does not adequately represent the unbuckled corners of actual stiffener sections (results can be too conservative). Cruciform sections are difficult to fabricate with composites and are not fully representative of actual stiffener sections. Z- and C-channel sections are more typically used for NEF tests as they are more expensive to fabricate than simple L-angles. Also, if both the flanges and webs of a Z- or C-section are allowed to buckle, then analysis of the test data becomes complicated. The symmetric L-angle sections are relatively simple to fabricate with most composite materials. Therefore, most proprietary industry OEF tests have been done with symmetric L-angle sections, and this is the only test configuration included in Test Method D8510/D8510M.

6.2.2.1 As stated in 6.1.4.1, buckling of a symmetric L-angle specimen involves either a local flexural or flexural-torsional instability mode.

6.2.3 As shown in Fig. 6, OEF data is typically obtained for width-to-thickness (b/t) ratios between 8 and 40. With a b/t less than ~ 8, depending on the material and layup, buckling does not occur before ultimate compressive failure (as shown by convergence of the F^{lcr} and F^{cc} lines in the plot. Most stiffener geometries do not have b/t ratios above 20, so test data may not be needed for design purposes above that value.

6.2.4 The number of tests to conduct at different b/t values is a function of the intended stiffener design space, which includes the ranges of thicknesses, laminate layups, and b/t values. The test matrix should consider at least the minimum and maximum thickness values along with at least two or three layups (covering the range of axial stiffnesses) over the b/t range anticipated for structural design. Also, tests at different environmental conditions may be necessary. Since there can be a large number of unique configurations tested and the specimens relatively expensive, typically only small numbers of replicates (3-5) are tested. In general the laminate layup and thickness should be constant throughout the specimen.

6.3 *No-Edge Free (NEF) Specimen Design:*

6.3.1 At least three types of specimens have been previously used for NEF crippling tests (Fig. 7):

6.3.1.1 Flat plates with V-groove fixtures on two edge,

6.3.1.2 Z-shaped sections (with center web being NEF), and

6.3.1.3 C-channel sections (with center web being NEF).

6.3.2 The empirical NEF test data shown in CMH-17 comes from a mixture of flat plate, Z- and C-channel tests. The flat