

ALUMINUM STRUCTURES

Guide to Their Specifications and Design

- Aluminum Association included by its published book (Aluminum Design Manual) the Specification for Aluminum Structures (hereafter called the Aluminum Specification) 2000 edition. That is mean The Specification for Aluminum Structures is Part I of the Aluminum Design Manual
- Besides discussion of design requirements to the Aluminum Specification In Aluminum *Specification* we compare these design provisions to the more familiar requirements for steel buildings published by the American Institute of Steel Construction (AISC)
- When designing with steel, engineers often restrict their choices to those shapes listed in tables of *compact sections*, where the section properties and dimensions are all provided, and the *slenderness* of the cross-sectional *elements* have already been checked to confirm that they are not governed by *local buckling*.
- While this approach may be safe, it is not very creative. When we create our own shape, however, we assume responsibility for determining its section properties and checking the slenderness of the cross-sectional elements. Furthermore, we may find that our new section is not compact, and we must then determine the local buckling stress limits.
- Aluminum is very competitive with these materials when the application is for a stocky column. Conversely, since aluminum's modulus of elasticity is about one-third that of steel's, aluminum is less likely to be competitive for slender columns.

TABLE 2.1 Properties That Affect Structural Performance of Metals

Structural Performance of	Property
Tensile members	yield strength, ultimate strength, notch sensitivity
Columns (compression members)	yield strength, modulus of elasticity
Beams (bending members)	yield strength, ultimate strength, modulus of elasticity
Fasteners	ultimate strength
Welded connections	ultimate strength of filler alloy; ultimate strength of heat-affected base metal

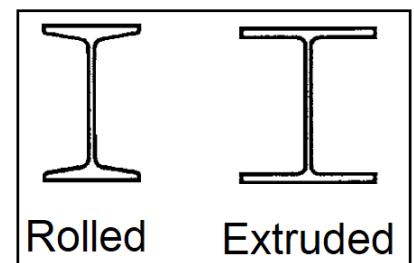
- Aluminum alloys are divided into two categories:
 - Wrought alloys, those that are worked to shape,
 - Cast alloys, those that are poured in a molten state into a mold that determines their shape.
- The Aluminum Association maintains an internationally recognized designation system for each category, described in ANSI H35.1, Alloy and Temper Designation Systems for Aluminum
- Tempering refers to the alteration of the mechanical properties of a metal by means of either a mechanical or thermal treatment.

- I. **Wrought Alloys** : the four-digit number is assigned to each alloy registered with the Association. The first number of the alloy designates the primary alloying element, which produces a group of alloys with similar properties. The second digit denotes a modification of an alloy. For Example :
- a. **6xxx**: Alloys in this group contain magnesium and silicon in proportions that form magnesium silicide (Mg_2Si). These alloys have a good balance of corrosion resistance and strength. 6061 is one of the most popular of all aluminum alloys and has a yield strength comparable to mild carbon steel. The 6xxx series alloys are also very readily extruded, so they constitute the majority of extrusions produced and are used extensively in building, construction, and other structural applications.
- II. **Tempers** Aluminum alloys are tempered by heat treating or strain hardening to further increase strength beyond the strengthening effect of adding alloying elements. Alloys are divided into two groups based on whether or not their strengths can be increased by heat treating. Both *heat treatable* and *non-heat treatable* alloys can be strengthened by strain hardening.

The basic temper designations are:

- F : As fabricated.
- O : Annealed.
- H : Strain-hardened
- W : Solution heat-treated.
- T : Thermally treated to produce stable tempers other than F, O, or H.
- T6 Solution heat-treated and then artificially aged. for example, 6063-T6 extrusions

Standard Extruded Shapes Before World War II, most aluminum shapes were produced by rolling, like steel, and so had cross sections similar to those of steel. Many of these shapes had sloped flanges that facilitated rolling but complicated connection details. Wartime and postwar demand for aluminum products prompted better production techniques, specially extrusions, which eventually displaced much of the rolled production. Since extrusions are not subject to the limitations of the rolling process, the need for sloped flanges was gone



Custom Extruded Shapes Sometimes the Aluminum Association or other standard shapes are impractical or inefficient for a specific application. In these cases, users may design their own shapes. Keep in mind that some limitations exist:

1) Minimum Thickness: The minimum thickness is a function of a number of factors, including the circle size (larger shapes require larger wall thickness) and whether a shape is hollow or solid. Table 3.2 provides approximate guidelines, but actual limits depend on the shape and the extruder. Elongation testing is not performed for shapes less than [1.6 mm] thick.

2) Maximum Length: Extrusions can be produced up to [30 m] long, but [12 m] is generally the practical limit for extrusions shipped by truck. Structural shapes available from metal supply warehouses usually are stocked in [6 m or 7.5 m] maximum lengths.

3) Maximum Circle Size: Extrusions are produced from billets, which are usually cylindrically shaped. Because of this, extrusion cross-section size is usually limited to that which fits within a circle. Larger extrusion presses use larger circle size dies. There are numerous [250 mm] and smaller presses, about a dozen mills with presses larger than 12 in. [300 mm], while the largest in North America is 31 in. [790 mm]. Because of production limitations, an extrusion typically cannot fill the full area of the circle, but rather only part of the circle area (Figure 3.4).

4) Maximum Area: The largest cross-sectional area that can be extruded is about [80,600 mm²].

5) Maximum Weight: The maximum total weight of an extrusion is limited by the weight of a billet to about [2,000 kg].

4.4 FRACTURE PROPERTIES

Ductility is the ability of a material to withstand plastic strain before fracture. Material that is not ductile may fracture at a lower tensile stress than its minimum ultimate tensile strength because it is unable to deform plastically at local stress concentrations that inevitably arise in the real world.

4.7 FIRE RESISTANCE

Because of the relatively low melting point of aluminum alloys (around 1,100F [600C]), however, aluminum is not suitable when exposed to high temperatures, such as in fireplaces, where it quickly turns to mush. In fires, thin-gauge aluminum sheet can melt so fast that it appears to be burning. But in reality, semi-fabricated aluminum products, such as extrusions, sheet, plate, castings, and forgings, are not combustible under ordinary conditions

The coefficient of thermal expansion,

which is the rate at which material expands as its temperature increases, is itself a function of temperature, increasing with increasing temperature. Average values are used for a range of temperatures, usually from room temperature (68F [20C]) to water's boiling temperature (212F [100C]). The coefficient also varies by alloy. The average coefficient is approximately $13 \times 10^{-6}/\text{F}$ [$23 \times 10^{-6}/\text{C}$]. Table 4.4 compares aluminum's coefficient to some other materials

[illegible]

Design strength: the resistance factor multiplied by the nominal strength, ϕR_n .

Design stress: the design strength divided by the appropriate section property, such as section modulus or cross section area.

Design load: the applied load determined in accordance with either LRFD load combinations or ASD load combinations, whichever is applicable.

Nominal strength: strength of a structure or component (without the resistance factor or safety factor applied)

Available strength: for LRFD, design strength;

for ASD, allowable strength.

ASD (Allowable Strength Design): the method of proportioning structural components such that the allowable strength equals or exceeds the required strength of the component under the action of the ASD load combinations. $R_a \leq R_n/\Omega$ (R_n/Ω = allowable strength)

ASD load combination: the load combination in the applicable building code intended for allowable strength design.

LRFD (Load and Resistance Factor Design): a method of proportioning structural components such that the design strength equals or exceeds the required strength of the component under the action of the LRFD load combinations. $R_u \leq \phi R_n$ (ϕR_n = Design strength)

LRFD load combination: a load combination in the applicable building code intended for strength design (load and resistance factor design)

Safety factor Ω : a factor that accounts for deviations of the actual strength from the nominal strength, deviations of the actual load from the nominal load, uncertainties in the analysis that transforms the load into a load effect, and for the manner and consequences of failure.

Resistance factor ϕ : a factor that accounts for unavoidable deviations of the actual strength from the nominal strength and for the manner and consequences of failure.

Beam: a structural member that has the primary function of resisting bending moments.

Column: a structural member that has the primary function of resisting a compressive axial force.

Closed shape: a hollow shape that resists lateral-torsional buckling primarily by torsional resistance rather than warping resistance, that is, for which C_w is much less than $0.038JL^2/b$.

Effective length: the length of an otherwise identical column with the same strength when analyzed with pinned end conditions.

Unbraced length: the length of a member between brace points or between a brace point and a cantilever's free end, measured between the longitudinal centroidal axes of the bracing members.

- For columns, brace points are points at which lateral translation is restrained for flexural buckling or twisting is restrained for torsional buckling.
- For beams, brace points are points at which the compression flange is restrained against lateral deflection or the cross section is restrained against twisting

Effective length factor: ratio between the effective length and the unbraced length of the member.

Effective net area: net area modified to account for the effect of shear lag.

Elastic analysis: structural analysis based on the assumption that the structure returns to its original geometry on removal of the load.

member buckling: flexural, torsional, or flexural-torsional buckling of the overall member.

Local buckling: the limit state of buckling of a compression element within a cross section

Flexural-torsional buckling: a buckling mode in which a compression member bends and twists simultaneously without change in cross-sectional shape.

Lateral-torsional buckling: the buckling mode of a flexural member involving deflection normal to the plane of bending occurring simultaneously with twist about the shear center of the cross-section.

post-buckling strength: the load or force that can be carried by an element, member, or frame after initial elastic buckling has occurred

Stiffener: a structural element attached or integral to a member to distribute load, transfer shear, or prevent buckling

member: an individual, discrete component of a larger structure, such as a beam or column.

net area: gross area reduced to account for removed material.

nominal load: magnitude of the load specified by the applicable building code

longitudinal centroidal axis: axis through the centroid of a member along its length

load factor: a factor that accounts for deviations of the nominal load from the actual load, for uncertainties in the analysis that transforms the load into a load effect and for the probability that more than one extreme load will occur simultaneously.

gage: transverse center-to-center spacing of fasteners.

gauge: a term previously used in referring to the thickness of a wrought product. Thickness is preferred in dimension description.

geometric axis: axis parallel to a web, flange, or angle leg.

grip: thickness of material through which a fastener passes.

limit state: a condition in which a structure or component becomes unfit for service and is judged either to be no longer useful for its intended function (serviceability limit state) or to have reached its ultimate load-carrying capacity (strength limit state).

load effect: forces, stresses, and deformations produced in a structural component by the applied loads.

This Specification includes the symbols, glossary, Chapters A through M, and Appendices 1 through 6

The purchaser shall require the casting producer to report tensile yield strengths.

For sand castings, the purchaser shall require that tensile ultimate and tensile yield strengths of specimens cut from castings shall be at least 75% of the values specified in ASTM B 26

Strengths shall be taken from Table A.3.6 or Table A.3.6M. The compressive yield strength F_{cy} of castings shall be taken as the tensile yield strength F_{ty} . The modulus of elasticity E of castings shall be taken as 10,000 ksi (70,000 MPa).

Table A.3.3
TENSION COEFFICIENT k_t

Alloy and Temper	Unwelded	Weld-Affected Zones
2014-T6, -T651, -T6510, -T6511	1.25	–
Alclad 2014-T6, -T651		
6005-T5, 6105-T5	1.25	–
6066-T6, -T6510, -T6511	1.1	–
6070-T6, -T62	1.1	–
all others listed in Table A.3.4 and Table A.3.6	1.0	1.0

Table A.3.1
GENERAL PROPERTIES

Property	Symbol	Value
Poisson's ratio	ν	0.33
Shear modulus of elasticity	G	$3E/8$
Coefficient of thermal expansion	α	$13 \times 10^{-6}/^{\circ}\text{F} = 23 \times 10^{-6}/^{\circ}\text{C}$
Density	γ	$0.10 \text{ lb/in}^3 = 2.7 \times 10^3 \text{ kg/m}^3$
Shear yield strength	F_{sy}	$0.6 F_{ty}$

Table A.3.4
MECHANICAL PROPERTIES FOR WROUGHT ALUMINUM PRODUCTS (Continued)

ALLOY	TEMPER	PRODUCT	THICKNESS in.	F_{tu} ksi	F_{ty} ksi	F_{cy} ksi	F_{su} ksi	E ksi
6061	-T6, T651	Sheet & Plate	0.010 to 4.000	42	35	35	27	10,100
	-T6, T6510, T6511	Extrusions	All	38	35	35	24	10,100
	-T6, T651	Rod & Bar	up thru 8.000	42	35	35	25	10,100
	-T6	Drawn Tube	0.025 to 0.500	42	35	35	27	10,100
	-T6	Pipe	All	38	35	35	24	10,100
6063	-T5	Extrusions	up thru 0.500	22	16	16	13	10,100
	-T5	Extrusions	0.501 to 1.000	21	15	15	12	10,100
	-T52	Extrusions	up thru 1.000	22	16	16	13	10,100
	-T6	Extrusions & Pipe	All	30	25	25	19	10,100
6066	-T6, T6510, T6511	Extrusions	All	50	45	45	27	10,100

ALLOY	TEMPER	PRODUCT	THICKNESS mm	F_{tu} MPa	F_{ty} MPa	F_{cy} MPa	F_{su} MPa	E MPa
6061	-T6, T651	Sheet & Plate	0.25 to 100.00	290	240	240	185	69,600
	-T6, T6510, T6511	Extrusions	All	260	240	240	165	69,600
	-T6, T651	Rod & Bar	up thru 200	290	240	240	170	69,600
	-T6	Drawn Tube	0.63 to 12.50	290	240	240	185	69,600
	-T6	Pipe	All	260	240	240	165	69,600
6063	-T5	Extrusions	up thru 12.50	150	110	110	90	69,600
	-T52	Extrusions	up thru 25.00	150	110	110	90	69,600
	-T5	Extrusions	12.50 to 25.00	145	105	105	85	69,600
	-T6	Extrusions & Pipe	All	205	170	170	130	69,600
6066	-T6, T6510, T6511	Extrusions	All	345	310	310	185	69,600

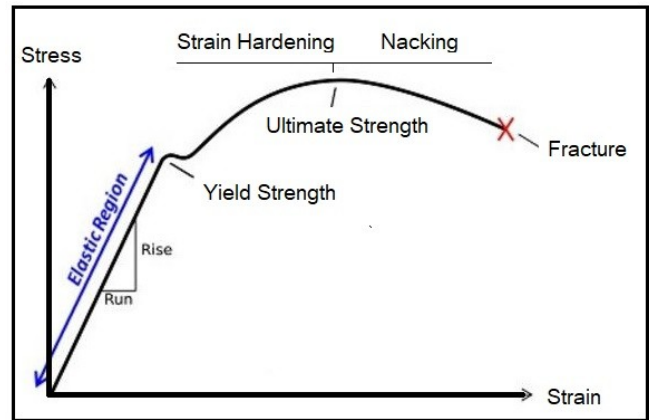
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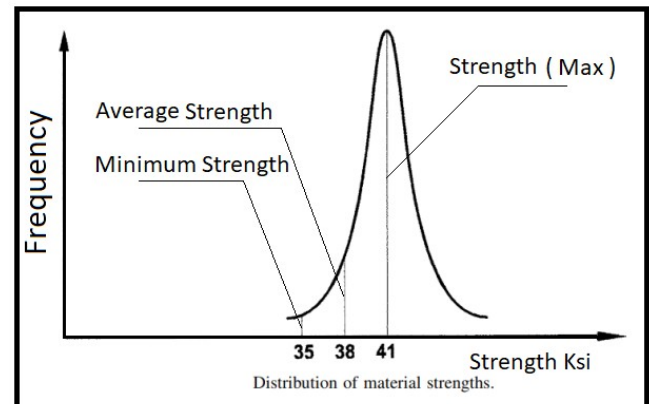
General information

- The Aluminum Specification provides minimum strengths for 22 alloys by temper and product form. The strengths given are:

- tensile yield strength (F_{ty})
- tensile ultimate strength (F_{tu})
- compression yield strength (F_{cy})
- shear yield strength (F_{sy})
- shear ultimate strength (F_{su})



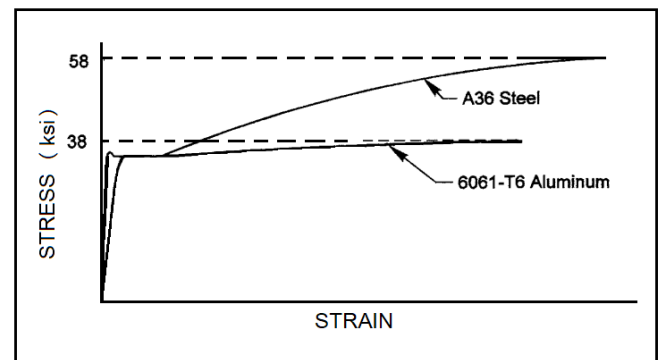
- A material's modulus of elasticity E (also called Young's modulus) is the slope of the elastic portion of the stress-strain curve and is a measure of the material's stiffness and buckling strength
- Typical (average) strengths are given in the Aluminum Design Manual, Part V, but they are not used in structural design. Typical strength values are used instead of minimum strengths,
- However, to calculate the necessary capacity of fabrication equipment, such as punches and shears. Typical strengths are about 15% higher than minimum strengths.



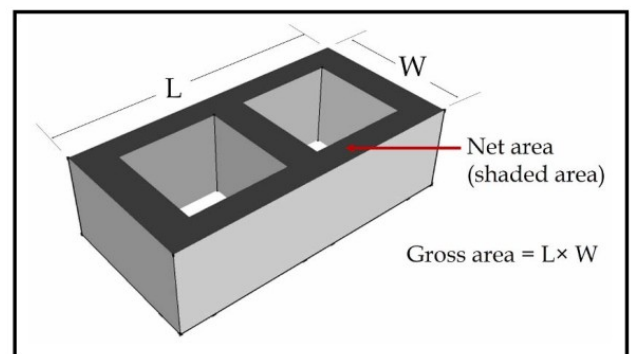
Tension

- 6061-T6 sheet has a minimum tensile ultimate strength of 42 ksi [290 MPa], whereas 6061-T6 extrusions have a minimum tensile ultimate strength of 38 ksi [260 MPa].

- The only minimum strengths that are required in product specifications for most mill products, and, thus, are said to be guaranteed are tensile yield and ultimate strengths. (Wire and rod to be made into fasteners must also meet minimum shear ultimate strength requirements.)
- Since the gross area usually equals or exceeds the net area and k_t is 1 in most cases, fracture will govern the allowable tensile strength if $F_{ty} > 0.85 F_{tu}$
- Aluminum's tensile modulus of elasticity is about 2% less than its compressive modulus. Since bending involves both tensile and compressive stress, bending deflection calculations use an average modulus, found by subtracting 100 ksi [700 MPa] from the compressive modulus.
- Tensile stresses may also cause yielding, but the consequences are, perhaps, not quite as disastrous as fracture.
- At room temperature, not all aluminum alloys exhibit the ability to sustain stresses well above yield, a property some structural designers may take for granted with A36 steel. This is demonstrated by examining their stress-strain curves up to failure. For example, at a minimum, A36 steel yields at 36 ksi [250 MPa] and breaks at 58 ksi [400 MPa], while 6061-T6 extrusion, its aluminum counterpart, yields at 35 ksi [240 MPa] but breaks at 38 ksi [260 MPa]. Consequently, the allowable strength of 6061-T6 members is governed by its ultimate strength, unlike the allowable strength of typical A36 steel members, which is usually governed by its yield strength.
- Yielding on the net section is not considered a limit state because it's assumed that the net section exists over only a small portion of the total length of the member. Therefore, yielding on the net section will result in very little elongation of the member in relation to its overall length
- Since the stress on the gross area is always less than or equal to the stress on the net area and the allowable stress on the gross area is higher than on the net area, the fracture strength on the net area always governs.



Comparison of the stress-strain curves of A36 steel and 6061-T6 aluminum.



Compression

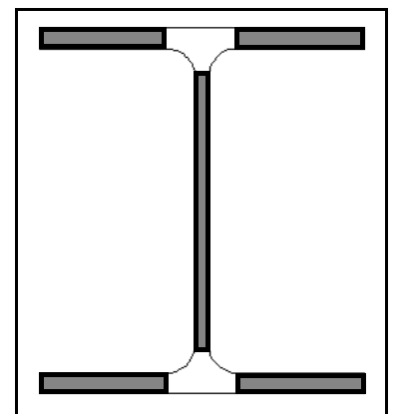
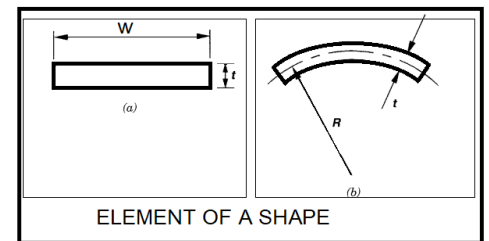
Axial Compression

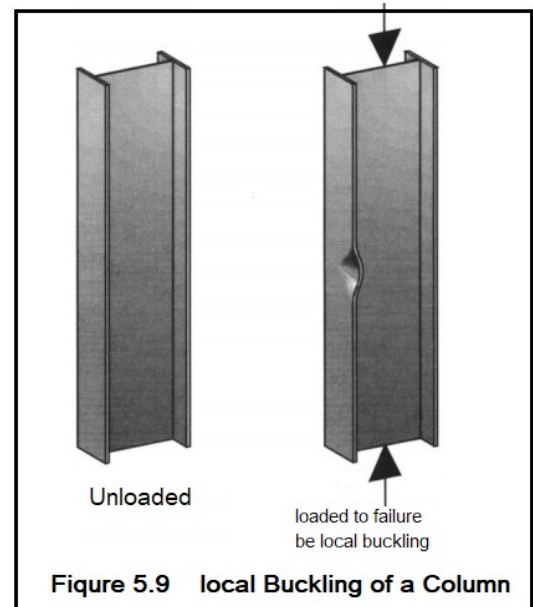
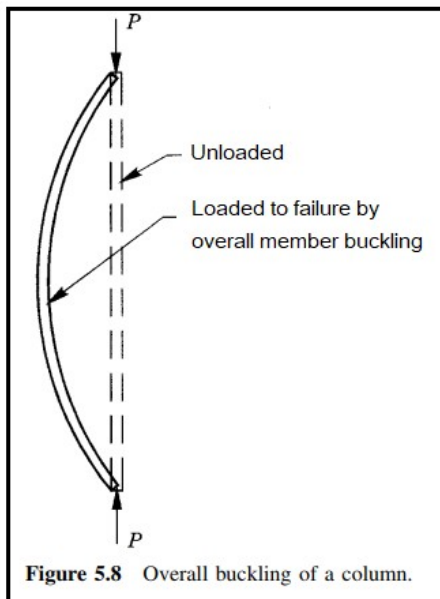
- 1. Member buckling strength (Global buckling • Overall buckling)
 - a. **Types:**
 - i. Flexural Buckling

- ii. Torsional Buckling
 - iii. Combination of Flexural and Torsional Buckling
- II. Local buckling strength
 - a. Stages
 - i. Yielding Strength (Plastic)
 - ii. Inelastic Strength (Intermediate Stage)
 - iii. Elastic Strength
 - iv. Post-Buckling Strength
- III. Interaction between member buckling and local buckling strengths

A. Overall buckling (Flexural Buckling)

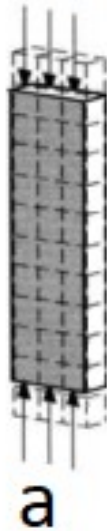
- In this section, we address members in axial compression. The shorthand term in the Aluminum Specification for such members is columns. It rather applies to any member subject to axial compression.
- Compressive ultimate strength is not a measured mechanical property for aluminum alloys. For material as ductile as aluminum, compressive ultimate strength has no meaning; in compressive tests, the metal swells but does not exhibit brittle fracture.
- Each structural shape is considered to consist of one or more elements. (In the Aluminum Specification, elements of shapes are also called components of shapes.)
- Elements are defined as plates either rectangular or curved in cross section and connected only along their edges to other elements. For example, an I-beam consists of five elements: two rectangular plate elements in each of the two flanges, and one rectangular plate element called the web.
- Buckling may be divided into two types: overall buckling, which occurs over the length of the member, and local buckling, which is confined to an element of a cross section over a length about equal to the width of the element.
- An interaction can occur between overall buckling and local buckling, causing overall buckling to occur at a lower load than it would if local buckling were not present. We'll deal with this insidious effect also.
- Local buckling is more likely to limit member strength where slender elements make up the cross section. Designers of hot-rolled steel shapes usually deal with what is called compact sections. These are composed of elements deliberately proportioned, so that overall buckling occurs **before** local buckling.



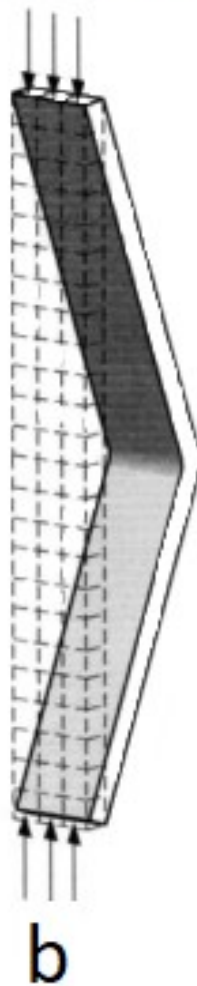


- Slender is not necessarily synonymous with thin gage; a plate element of any thickness can buckle locally before overall buckling occurs if it is wide enough
 - **A Qualitative View**
- Let's examine the general performance of a column as a function of its slenderness. Imagine a very short metal ruler with a rectangular cross section under an axial compressive load. As the load increases, the ruler does not buckle, but it is eventually shortened by yielding of its cross section, as shown in Figure 5-10a.
- Now imagine a longer ruler of the same cross section, again loaded as a column. The load is increased until the ruler buckles laterally. Once buckled, the member cannot support any additional load. When the load is removed, the column remain its deflected shape (see Figure 5-10b). Because of this, the column is said to have undergone inelastic buckling. At the buckle, the metal has been stressed beyond its yield strength, so the buckled shape is permanent.
- Finally, imagine a very long ruler under an axial compression load. As the load increases, this long ruler buckles much sooner than the intermediate length ruler, displacing laterally by a distance that varies along its height. The buckled shape is shown in Figure 5-10c. At the midheight, the lateral displacement is greatest. Once buckled, the member cannot support any additional load. If the ruler is long enough, at no point on the column is exceeded the yield strength when the buckling occurs, so when the load is removed, the ruler springs back to its original straight shape. Because the deflection is not permanent, this behavior is called elastic buckling.

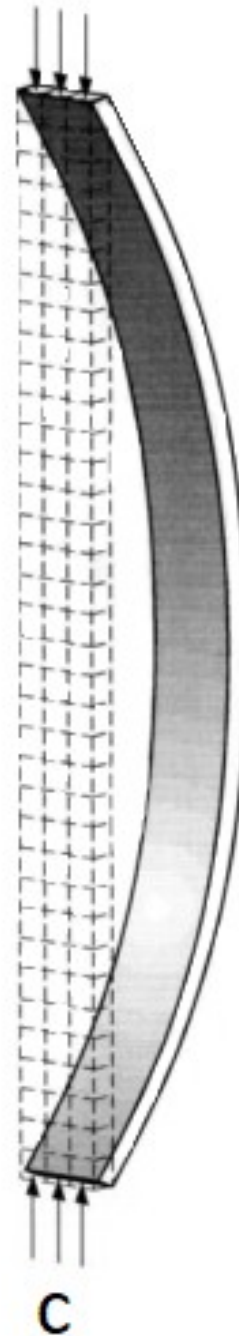
Undergo
Yielding



Intermediate
Slenderness
which undergo
Inelastic Buckling



For slender columns,
which undergo
elastic buckling



Conclusion

The strength of slender columns (those that buckle elastically) was predicted by Leonhard Euler in 1757. His equation is still used today for both steel and aluminum, so the elastic buckling strength is also called the Euler buckling strength of the column and this equation is graphed in Figure 5.13.

$$\text{Elastic buckling Stress} = \frac{\pi^2 E}{\left(\frac{kL}{r}\right)^2}$$

Note that it is independent of the yield or ultimate strength properties of the material

The elastic buckling strength of a column made of 6061-T6 aluminum alloy which has a compressive yield strength of 35 ksi [240 MPa], The only mechanical property that influences the elastic buckling strength is the modulus of elasticity (E)

the slope of the stress-strain curve. In the elastic range, E is constant, so the elastic buckling strength for a given alloy varies only with the slenderness of the column, expressed as the ratio kL/r , discussed further below

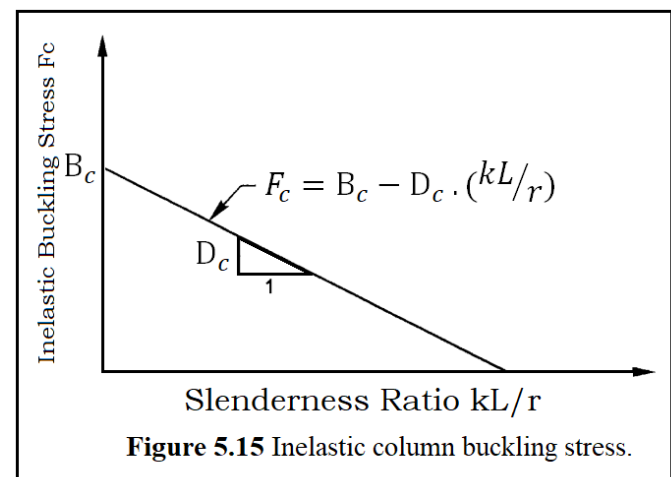
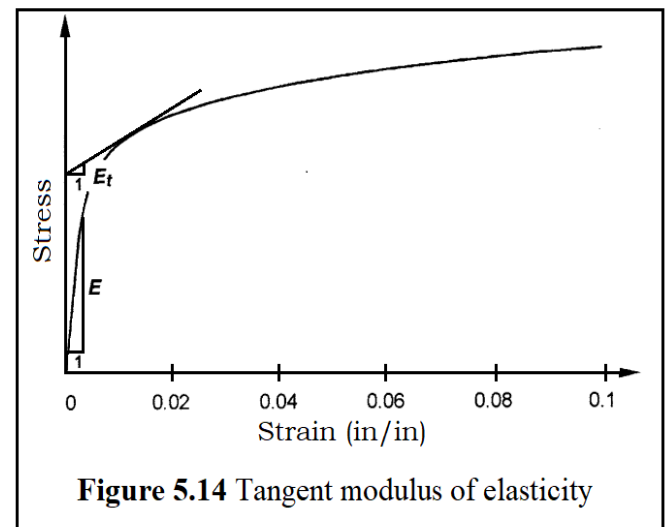
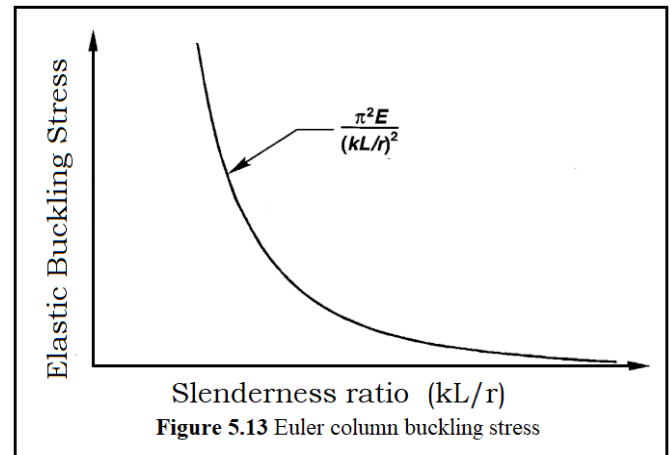
Inelastic buckling occurs when the stress at the buckle is greater than the yield strength, which happens in columns of intermediate slenderness. We can also use the Euler buckling equation to predict buckling strength of such columns. However, at these higher stresses, the modulus of elasticity, or slope of the stress-strain curve, varies depending on the strain, and is called the tangent modulus of elasticity, E_t . (Figure 5.14.) Substituting E_t for E :

$$\text{Inelastic buckling Stress} = \frac{\pi^2 E_t}{\left(\frac{kL}{r}\right)^2}$$

Fortunately, tests have shown that rather than using the tangent modulus, which varies with stress, this equation can be conveniently reduced to a linear function of the slenderness kL/r :

$$\text{Inelastic buckling Strength } F_c = B_c - D_c \cdot \left(\frac{kL}{r}\right)$$

- In this equation, B_c is the stress at which the inelastic buckling strength line intersects the y-axis, and D_c is the slope of the inelastic buckling line (Figure 5.15).
- Formulas for B_c and D_c have been determined for aluminum alloys by test.



- Inelastic buckling strength is graphed with the strengths of the other slenderness regimes in Figure 5-16 with safety factors applied

TABLE 6.1 Safety Margins in the Aluminum Specification

Type of Structure	Yield Strength	Ultimate Strength	
Building Type	1.65	1.95	The slenderness ratio at which the inelastic buckling
Bridge Type	1.85	2.20	

curve (line) intersects the elastic buckling curve is called C_c (as it is for steel). This slenderness (C_c) is called the slenderness limit S_2 because it's the upper limit of applicability of the inelastic buckling equation.

- When the slenderness ratio is above this limit, buckling will be elastic. Collectively, B_c , D_c , and C_c are called buckling formula constants, and they are based on the shape of the stress-strain curve above yield. As we mentioned in Section 2-4, aluminum alloys are divided into two groups: those that are not artificially aged (tempers -O, -H, -T1, -T2, -T3, -T4) and those that are (tempers -T5 - T6- T7- T8 -T9).
- Finally, the strength of columns so stocky that they will not buckle is just the compressive yield strength (F_{cy}): (compressive yield strength = F_{cy})

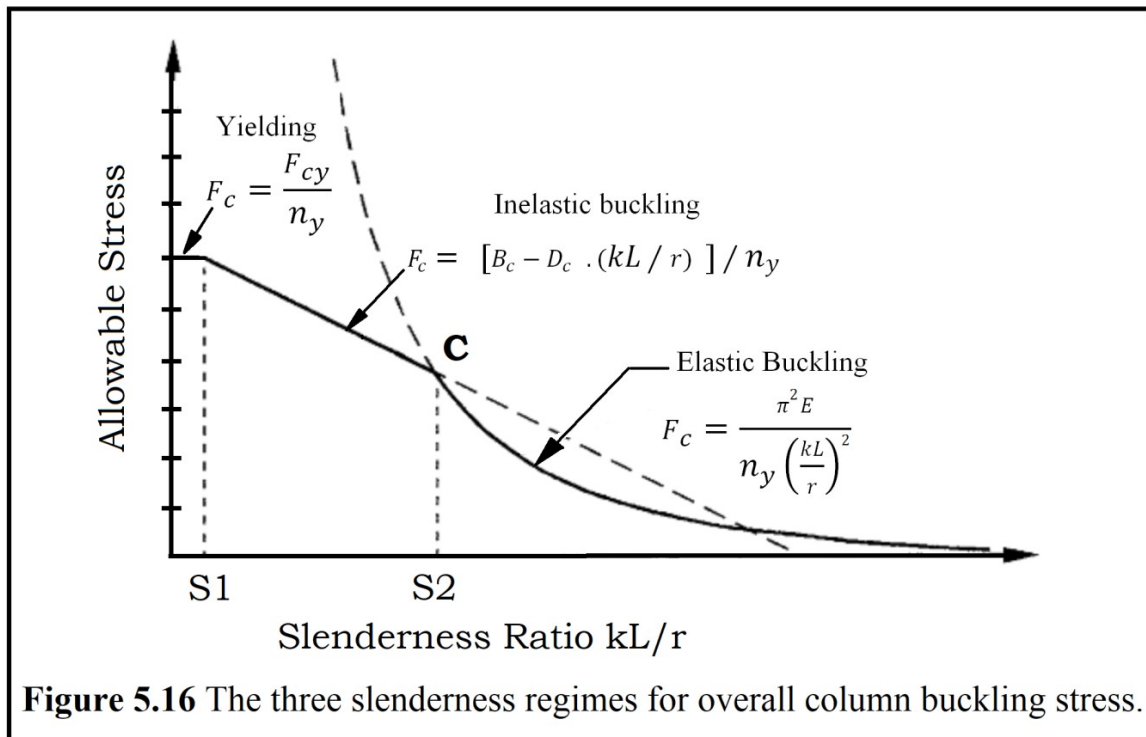
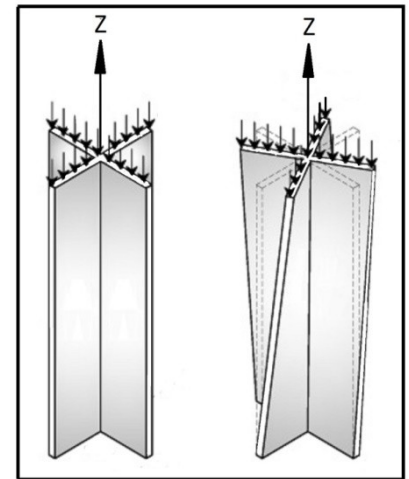


Figure 5.16 The three slenderness regimes for overall column buckling stress.

B. Overall Buckling (torsional buckling)

Another kind of overall buckling is torsional buckling, which is a twisting or corkscrewing of the column. Equal leg cruciform sections, which are point symmetric, tend to buckle this way.

- No lateral displacement takes place along the member length during buckling, *only twisting*.
- The axis of buckling is the longitudinal axis of the member for torsional buckling.



C. Torsional-flexural buckling

- Last, shapes that are not doubly symmetric may buckle in the overall buckling mode called torsional-flexural buckling, a combination of twisting and lateral deflection.
- for both torsional or torsional-flexural buckling for doubly or singly symmetric sections is given in Aluminum Specification Section 3.4.7.2.
- A way to treat these buckling modes involving torsion is to replace kL/r with an "effective" kL/r .
- A method for determining the effective slenderness ratio $(kL/r)_e$
- designers must already know if a shape is subject to torsional or torsional-flexural buckling in order to choose which Aluminum Specification Section (3.4.7.1 or 3.4.7.2) applies.

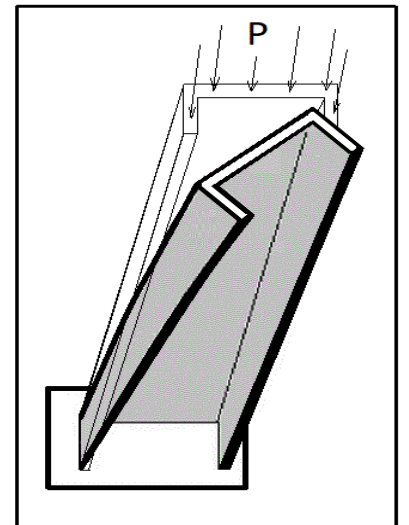
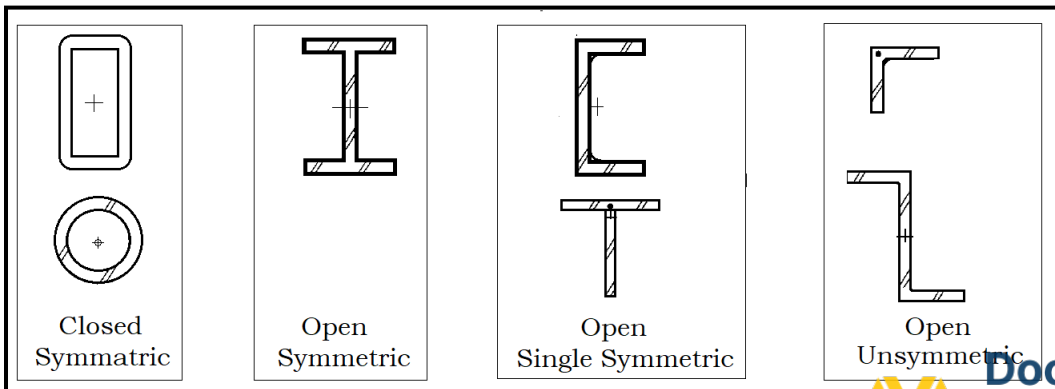


TABLE 5.2 Overall Column Buckling Modes

Shape	Flexural Buckling	Torsional Buckling	Torsional-Flexural Buckling
Closed	Yes	No	No
Open—doubly symmetric	Yes	Yes	No
Open—singly symmetric	Yes	No	Yes
Open—unsymmetric	Yes	No	Yes



Local buckling strength (Component of column)

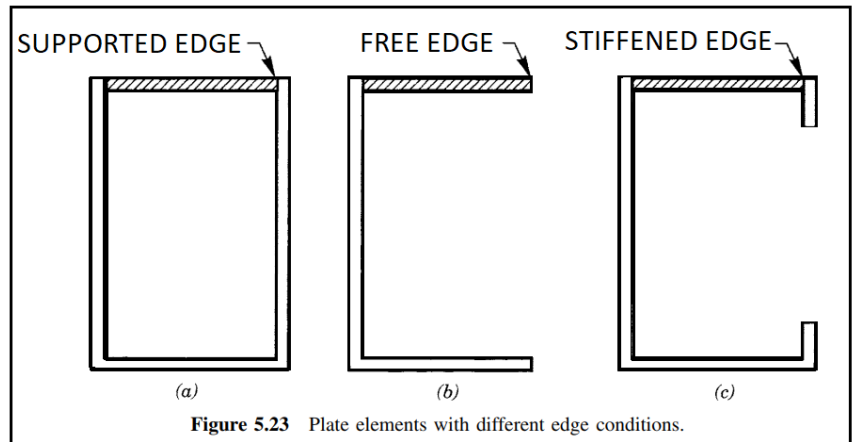
Stages

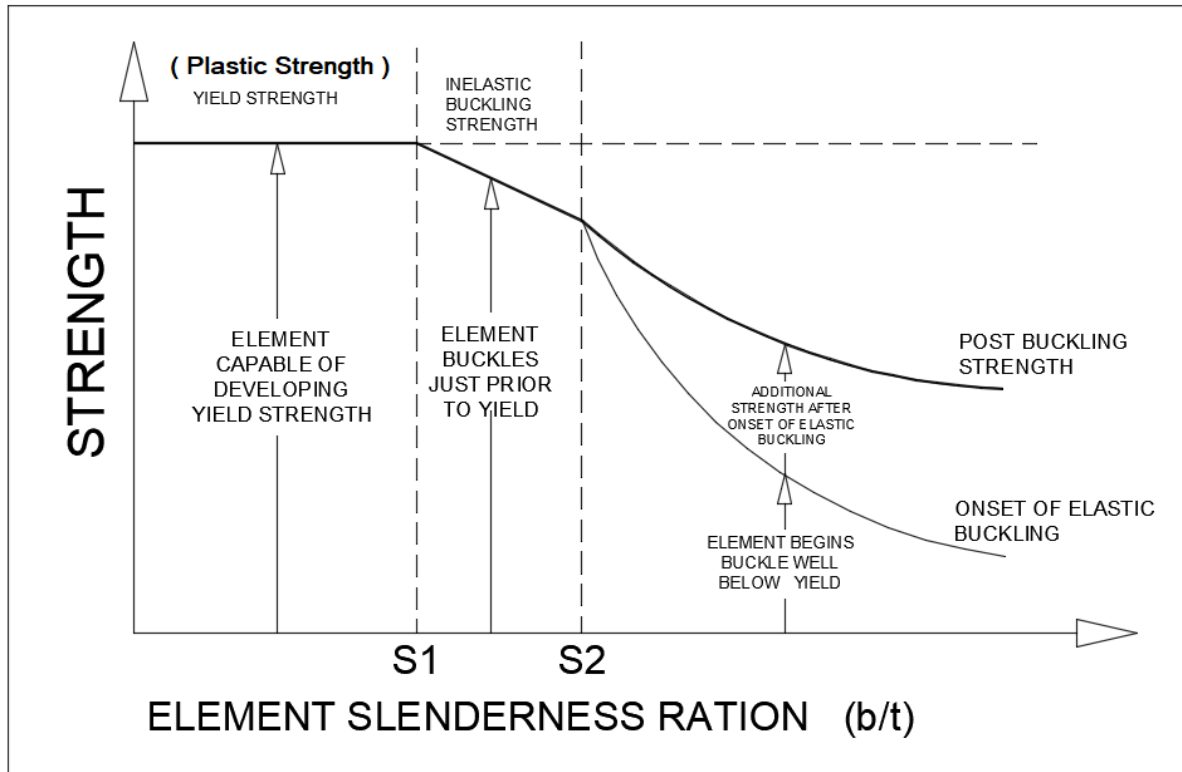
- a. Yielding Strength (Plastic)
- b. Inelastic Strength (Intermediate Stage)
- c. Elastic Strength
- d. Post-Buckling Strength

First let's talk briefly about individual elements, and then we'll discuss how they buckle. Every plate element has four edges, but the important feature of elements is what they are attached to along their two longitudinal edges (i.e., parallel to the direction of the compressive force). Along a longitudinal edge, an element can:

- a) be attached to another element,
- b) have a free edge,
- c) have a stiffener

Once again, the behavior is classified in three regimes of slenderness, but we'll see that slenderness has a completely different meaning when applied to an element than it did for overall buckling.

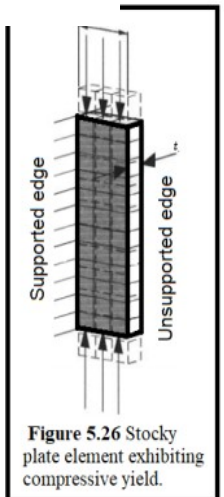




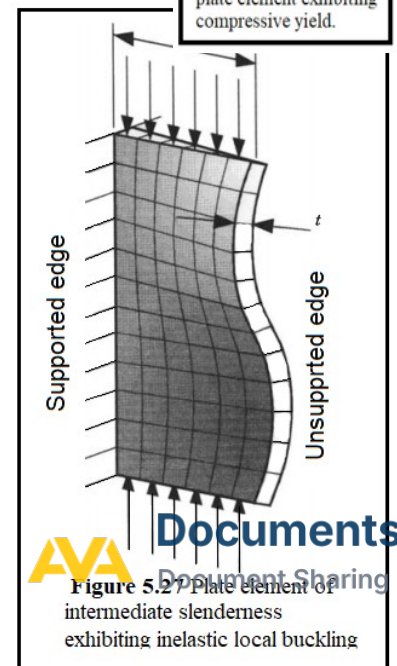
The Three Regimes Of Local Buckling for Elements of Columns

i.

First, imagine a stocky flat plate in axial compression, with a thickness (t) not much less than its width (b), and supported along one longitudinal edge (Figure 5.26). The axial load may be increased until the stress in the plate reaches the compressive yield strength of the material. No buckling occurs because the plate is so stocky. This regime is illustrated by the leftmost portion of the curve in Figure 5.29, where the element's strength is the yield strength of the material.



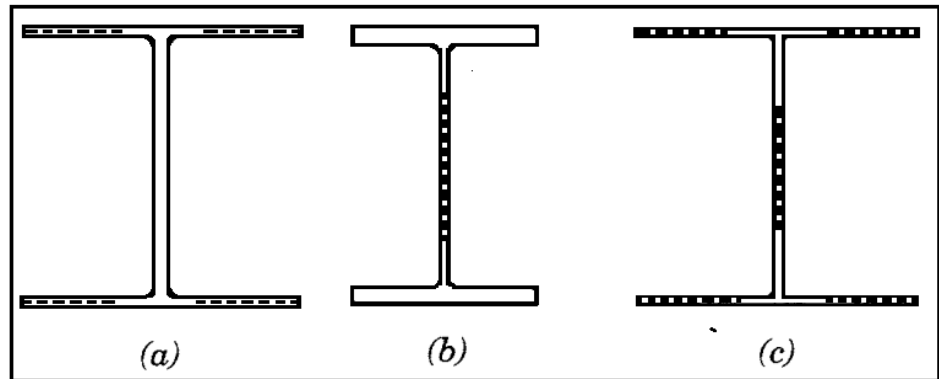
- ii. Next, imagine increasing the width of this plate while its thickness remains the same (Figure 5.27). Again, an axial load is applied, but this time as the load increases, the plate buckles just before the average stress reaches yield. The stress increases at the buckles due to their out-of-plane eccentricity, so Localized yielding occurs, causing the buckles to remain when the load is removed. Thus, this mode of failure is termed inelastic buckling of the element. While the overall buckling we described in Section 5.2.1 was dependent on the length



of the column, this local buckling of an element depends on the ratio of its width to its thickness (b/t) and is independent of its length. The center portion of Figure 5.29 shows the regime in which the onset of inelastic buckling limits the strength of an element.

- iii. Finally, let's increase the plate width further still and once more load the plate in compression (Figure 5.28). Again, waves or buckles appear, but this time the free edge is so flimsy that it buckles well below yield. Near the supported edge, however, the plate is still sufficiently stiff to support the load. Because the stress is in the elastic range, the buckles disappear when the load is removed.

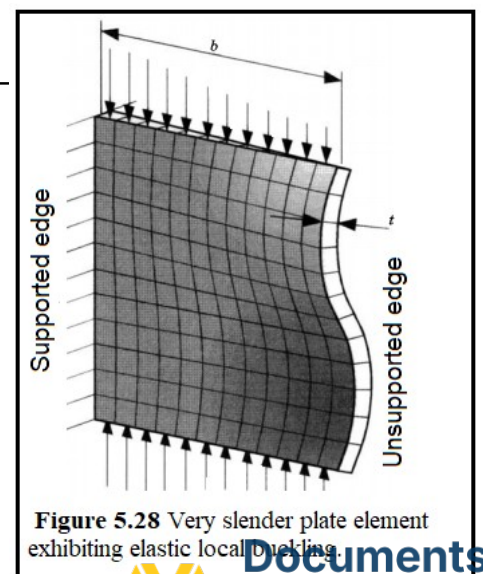
- iv. after the onset of elastic buckling. This capacity is called post buckling strength. When buckling begins, compressive stresses



are redistributed across the width of the plate, with lower stress where buckling has occurred, and higher stresses along the supported longitudinal edge, which is held straight and in place under the load by the edge support. At maximum load, the average stress on the plate cross section is called the crippling stress.

Postbuckling Strength : When designing members with slender elements in compression, you must first reprogram your outlook toward compression behavior. With compact sections, you assume that an axial-compression load results in a uniform compressive stress in the cross section. The stress then,

is: $F = P/A$



In actuality, this is a generalization that is no longer valid if any of the cross sectional elements have buckled.

Slender elements, on the other hand, may vary dramatically in their relative stiffness. Stiffness may also vary significantly across the width of an individual element.

Now let's assemble the cross section of an I-beam by combining several elements, as shown in Figure 5.30a. The web is a flat plate element supported along both edges by the flanges, and each flange consists of two flat plate elements supported along one edge by the web. This shape is drawn with exaggerated proportions so that it is visually evident that some portions have greater stiffness than others.

When a very small load is applied, it is supported by the entire cross section. As the load increases, the flanges begin to buckle along their unsupported edges at a stress level well within the elastic range.

This onset of local elastic buckling, as we saw previously when discussing an individual element, does not limit the load-carrying capacity of the section. It does, however, introduce a change in its behavior.

Once buckled, the wavy edges of the flanges are rendered ineffective, and load is redistributed to the stiffer areas nearer the flange-web junction.

The area of the cross section that is actually carrying load is, thus, reduced. As the load increases, the buckles extend further across the flanges, and the force continues to be redistributed to the shrinking effective area. Eventually, the combination of the reduced effective area supporting an increased load results in failure of the cross section.

Note that the web might experience elastic buckling rather than the flanges as suggested by Figure 5.30b, or all of the elements as shown in Figure 5.30c. It is not a matter of flange behavior versus web behavior, but rather an application of the principle that the regions of greatest stiffness attract more of the load. This redistribution of force has two significant results:

- It allows the member to support additional load beyond the onset of elastic buckling
- It results in a reduced effective section in this post buckled regime.

While taking advantage of the additional load capacity, we must also remember to account for the reduced area. We will see that the reduced effective section in the post buckled condition may require you to recalculate capacities that were based on the full cross-sectional properties, including deflection and overall buckling strength of the column.

Chapter B Design Requirements

B 1 Section properties

Section properties such as cross-sectional area, moment of inertia, section modulus, radius of gyration, and torsion and warping constants shall be determined using nominal dimensions .

B 2 Load and Load Combination

Building type Structure: ASCE 7, Minimum Design Loads for Buildings and Other Structures, shall be used.
Bridge-Type Structures highway bridges shall be designed for the nominal loads and load combinations given in AASHTO's Standard Specifications for Highway Bridges.

B 3 Design Basis

Designs shall be made according to the provisions for Load and Resistance Factor Design (LRFD) or Allowable Strength Design (ASD). LRFD is limited to building-type structures

B 3 .1 Design for Strength Using Load and Resistance Factor Design (LRFD)

Design using the provisions for Load and Resistance Factor Design (LRFD) meets the requirements of this specification when the design strength of each structural component equals or exceeds the required strength determined on the basis of the LRFD load combinations. All provisions of this *Specification* except Section B.3.2.2 shall apply. **Design shall satisfy Equation B.3-1:**

$$R_u \leq \phi R_n \quad (\text{B.3-1})$$

R_u = required strength

ϕR_n = design strength

R_n = nominal strength

ϕ = resistance factor

Resistance factors for building-type structures shall be as given in this Specification.

B3 .2 Design for Strength Using Allowable Strength Design (ASD)

Design using the provisions for Allowable Strength Design (ASD) meets the requirements of this Specification when the allowable strength of each structural component equals or exceeds the required strength determined on the basis of the ASD load combinations. All provisions of this specification except Section B.3.2.1 shall apply.

Design shall satisfy Equation B.3-2:

$$R_a \leq R_n / \Omega \quad (\text{B.3-2})$$

R_a = required strength

R_n = nominal strength

Ω = safety factor

R_n / Ω = allowable strength

Safety factors for building-type structures and bridge type structures shall be as given in this Specification

B.3.3 Design for Stability

Stability of the structure and its components shall be determined in accordance with Chapter C.

B.3.4 Design for Serviceability

Structures and their components shall meet the serviceability requirements given in Chapter L

B.3.5 Design for Fatigue

Structures and their components subjected to repeated loading shall meet the requirements of Appendix 3. Fatigue need not be considered for seismic loads.

B.3.6 Design for Fire Conditions

Design for fire conditions shall meet the requirements of Appendix 4

B.3.7 Design of Braces

B 5 Elements Element

B.5.4 Strength of Elements in **Uniform Compression**

B.5.4.1 Flat Elements Supported On One Edge

B.5.4.2 Flat Elements Supported on Both Edges

B.5.4.3 Flat Elements Supported on One Edge and with a Stiffener on the Other Edge

B.5.4.4 Flat Elements Supported on Both Edges and with an Intermediate Stiffener

B.5.4.5 Curved Elements Supported on Both Edges

B.5.4.6 Flat Elements Alternate Method

B.5.5 Strength of Elements in **Flexure**

B.5.5.1 Flat Elements Supported on Both Edges

B.5.5.2 Flat Elements Supported on Tension Edge, Compression Edge Free

B.5.5.3 Flat Elements Supported on Both Edges and with a Longitudinal Stiffener

B.5.5.4 Flat Elements Alternate Method

Chapter C. Design for Stability

Chapter D. Design of Members for Tension

D 2 Tensile Strength

D 3 Area Determination

Chapter E. Design of Members for Compression

E 2 Effective Length

E 3 Member Buckling

E 4 Local Buckling

E 5 Interaction Between Member Buckling and Local Buckling

Chapter F. Design of Members for Flexure

F1 General Provisions

F2 Open Shapes

F3 Closed Shapes

F4 Rectangular Bars

F6 Pipes and Round Tubes

F7 Rods

F8 Elements of Flexural Members

Chapter G. Design of Members for Shear

G 2 Members with Flat Webs Supported on Both Edges

G 3 Round or Oval Tubes

Chapter H. Design of Members for Combined Forces and Torsion

B.5.4 Strength of Elements in Uniform Compression

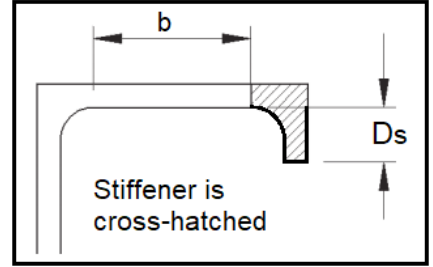
B.5.4.3 Flat Elements Supported on One Edge and with a Stiffener on the Other Edge (Uniform Compression).

First Condition :

- supported on one edge and with a stiffener on the other edge,
- with a stiffener of depth $DS \leq 0.8b$,
- with a thickness no greater than the stiffener's thickness, the stress corresponding to the uniform compression strength is

$$F_c = F_{ut} + (F_{st} - F_{ut}) \cdot \rho_{st}$$

Where :



- F_{UT} is determined using Section B.5.4.1 and neglecting the stiffener
- F_{ST} is determined using Section B.5.4.2 Flat Elements Supported on Both Edges
- ρ_{st} = stiffener effectiveness ratio determined as follows:

Stiffener effectiveness ratio	b/t	Ref.
$\rho_{st} = 1$	$b/t \leq S_e/3$	(B.5-6)
$\rho_{st} = \frac{r_s}{9 \cdot t \left(\frac{b/t}{S_e} - \frac{1}{3} \right)} \leq 1.0$	$S_e/3 < b/t < S_e$	(B.5-7)
$\rho_{st} = \frac{r_s}{1.5 \cdot t \left(\frac{b/t}{S_e} + 3 \right)} \leq 1.0$	$S_e < b/t < 2 \cdot S_e$	(B.5-8)

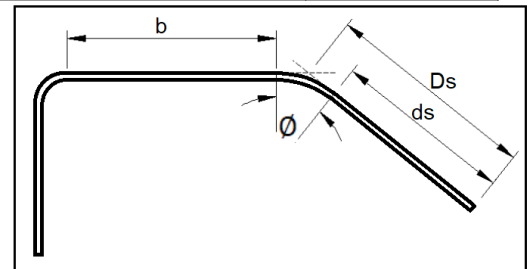
r_s = the stiffener's radius of gyration about the stiffened element's mid-thickness. For straight stiffeners of constant thickness (see Figure B.5.3)

$$r_s = d_s \cdot \frac{\sqrt{3}}{4}$$

where d_s = the stiffener's flat width

θ = the angle between the stiffener and the stiffened element.

$$S_e = 1.28 \cdot \sqrt{\frac{E}{F_{cy}}}$$



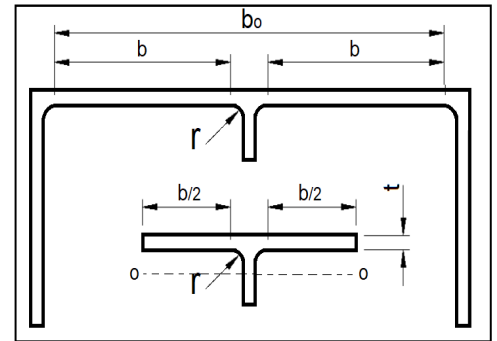
F_c for the stiffened element determined using Section B.5.4.3 shall not exceed F_c for the stiffener determined using Section B.5.4.1.

- For flat elements supported on one edge and with a stiffener on the other edge, and Second Condition :
- with a stiffener of depth $DS > 0.8b$, where DS is defined in Figure B.5.3, or with a thickness greater than the stiffener's thickness, the stress corresponding to the uniform compression strength is $F_c = F_{UT}$.

B.5.4.4 Flat Elements Supported on Both Edges and with an Intermediate Stiffener

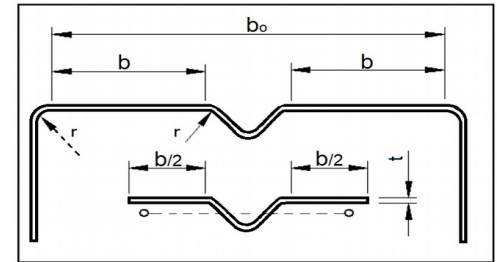
The stress F_c corresponding to the uniform compression strength of flat elements supported on both edges and with an intermediate stiffener is:

Limit State	F_c	λ_s	Slenderness Limit
Yielding	F_{cy}	$\lambda_s \leq S1$	$S1 = \frac{B_c - F_{cy}}{D_c}$
Inelastic buckling	$B_c - (D_c \cdot \lambda_s)$	$S1 < \lambda_s < S2$	
Elastic buckling	$\frac{\pi^2 \cdot E}{\lambda_s^2}$	$\lambda_s \geq S2$	$S2 = C_c$



λ_s slenderness ratio of an element with an intermediate stiffener

$$\lambda_s = 4.62 \cdot \left(\frac{b}{t} \right) \cdot \sqrt{\frac{1 + A_s / (b \cdot t)}{1 + \sqrt{1 + \frac{10.67 I_0}{b \cdot t^3}}}}$$



- A_s area of the stiffener
- Line o-o is the neutral axis of the stiffener and element of width $b/2$ on each side of the stiffener
- I_0 = moment of inertia of a section including the stiffener and one half of the width of the adjacent sub-elements and the transition corners between them taken about the centroidal axis of the section parallel to the stiffened element (Figure B.5.4).
- F_c shall not exceed F_c determined using Section B.5.4.2 for the sub-elements of the stiffened element.
- F_c need not be less than F_c determined using Section B.5.4.2 and neglecting the stiffener.