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Aluminum Structures

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8.1 Introduction

8.1.1 The Material

Background

Of the structural materials used in construction, aluminum was the latest to be introduced into the market place even though it is the most abundant of all metals, making up about 1/12 of the earth's crust. The commercial process was invented simultaneously in the U.S. and Europe in 1886. Commercial production of the metal started thereafter using an electrolytic process that economically separated aluminum from its oxides. Prior to this time aluminum was a precious metal. The initial uses of aluminum were for cooking utensils and electrical cables. The earliest significant structural use of aluminum was for the skins and members of a dirigible called the *Shenendoah* completed in 1923. The first structural design handbook was developed in 1930 and the first specification was issued by the industry in 1932 [4].

Product Forms

Aluminum is available in all the common product forms: flat-rolled, extruded, cast, and forged. Fasteners such as bolts, rivets, screws, and nails are also manufactured. The available thicknesses of flat-rolled products range from 0.006 in. or less for foil to 7.0 in. or more for plate. Widths to 17 ft are possible. Shapes in aluminum are extruded. Some presses can extrude sections up to 31 in. wide. The extrusion process allows the material to be placed in areas that maximize structural properties and joining ease. Because the cost of extrusion dies is relatively low, most extruded shapes are designed for specific applications. Castings of various types and forgings are possibilities for three-dimensional shapes and are used in some structural applications. The design of castings is not covered in detail in structural design books and specifications primarily because there can be a wide range of quality depending on the casting process. The quality of the casting affects structural performance.

Alloy and Temper Designation

The four-digit number used to designate alloys is based on the main alloying ingredients. For example, magnesium is the principal alloying element in alloys whose designation begins with a 5(5083, 5456, 5052, etc.). Cast designations are similar to wrought designations but a decimal is placed between the third and fourth digit(356.0). The second part of the designation is the temper which defines the fabrication process. If the term starts with T, e.g., -T651, the alloy has been subjected to a thermal heat treatment. These alloys are often referred to as heat-treatable alloys. The numbers after the T show the type of treatment and any subsequent mechanical treatment such as a controlled stretch. The temper of alloys that harden with mechanical deformation starts with H, e.g., -H116. These alloys are referred to as non-heat-treatable alloys. The type of treatment is defined by the numbers in the temper designation. A 0 temper is the fully annealed temper. The full designation of an alloy has the two parts that define both chemistry and fabrication history, e.g., 6061-T651.

8.1.2 Alloy Characteristics

Physical Properties

Physical properties usually vary only by a few percent depending on alloy. Some nominal values are given in Table 8.1.

TABLE 8.1 Some Nominal Properties of Aluminum Alloys

Property	Value
Weight	0.1 lb/ in.^{3}
Modulus of elasticity	
Tension and compression	10,000 ksi
Shear	3,750 ksi
Poisson's ratio	1/3
Coefficient of thermal expansion (68 to 212 °F)	0.000013 per °F

Data from Gaylord and Gaylord, *Structural Engineering Handbook*, McGraw-Hill, New York, 1990.

The density of aluminum is low, about 1/3 that of steel, which results in lightweight structures. The modulus of elasticity is also low, about 1/3 of that of steel, which affects design when deflection or buckling controls.

Mechanical Properties

Mechanical properties for a few alloys used in general purpose structures are given in Table 8.2. The stress-strain curves for aluminum alloys do not have an abrupt break when yielding but rather have a gradual bend (see Figure 8.1). The yield strength is defined as the stress corresponding to a 0.002 in./in. permanent set. The alloys shown in Table 8.2 have moderate strength, excellent resistance to corrosion in the atmosphere, and are readily joined by mechanical fasteners and welds. These alloys often are employed in outdoor structures without paint or other protection. The higher strength aerospace alloys are not shown. They usually are not used for general purpose structures because they are not as resistant to corrosion and normally are not welded.

TABLE 8.2 Minimum Mechanical Properties

Alloy and temper	Product	Thickness range, in.	Tension		Compression	Shear		Bearing	
			TS	YS	YS	US	YS	US	YS
3003-H14	Sheet and plate	0.009-1.000	20	17	14	12	10	40	25
5456-H116	Sheet and plate	0.188-1.250	46	33	27	27	19	87	56
6061-T6	Sheet and plate	0.010-4.000	42	35	35	27	20	88	58
6061-T6	Shapes	All	38	35	35	24	20	80	56
6063-T5	Shapes	to 0.500	22	16	16	13	9	46	26
6063-T6	Shapes	All	30	25	25	19	14	63	40

Data from The Aluminum Association, *Structural Design Manual,* 1994.
Note: All properties are in ksi. TS is tensile strength, YS is yield strength, and US is ultimate strength.

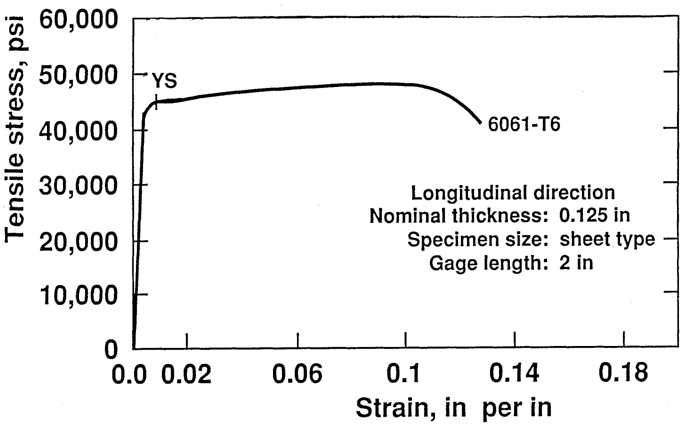

FIGURE 8.1: Stress-strain curve.

Toughness

The accepted measure of toughness of aluminum alloys is fracture toughness. Most high strength aerospace alloys can be evaluated in this manner; however, the moderate strength alloys employed for general purpose structures cannot because they are too tough to get valid results in the test. Aluminum alloys also do not exhibit a transition temperature; their strength and ductility actually increase with decrease in temperature. Some alloys have a high ratio of yield strength to tensile strength (compared to mild steel) and most alloys have a lower elongation than mild steel, perhaps 8 to 10%, both considered to be negative factors for toughness. However, these alloys do have sufficient ductility to redistribute stresses in joints and in sections in bending to achieve full strength of the components. Their successful use in various types of structures (bridges, bridge decks, tractor-trailers, railroad cars, building structures, and automotive frames) has demonstrated that they have adequate toughness. Thus far there has not been a need to modify the design based on toughness of aluminum alloys.

8.1.3 Codes and Specifications

Allowable stress design (ASD) for building, bridge, and other structures that need the same factor of safety, and Load and Resistance Factor Design (LRFD)for building and similar type structures have been published by the Aluminum Association [1]. These specifications are included in a design manual that also has design guidelines, section properties of shapes, design examples, and numerous other aids for the designer.

The American Association of State Highway and Transportation Officials has published LRFD Specifications that cover bridges of aluminum and other materials [2]. The equations for strength and behavior of aluminum components are essentially the same in all of these specifications. The margin of safety for design differs depending on the type of specification and the type of structure.

Codes and standards are available for other types of aluminum structures. Lists and summaries are provided elsewhere [1, 3].

8.2 Structural Behavior

8.2.1 General

Compared to Steel

The basic principles of design for aluminum structures are the same as those for other ductile metals such as steel. Equations and analysis techniques for global structural behavior such as load-deflection behavior are the same. Component strength, particularly buckling, post buckling, and fatigue, are defined specifically for aluminum alloys. The behavior of various types of components are provided below. Strength equations are given. The designer needs to incorporate appropriate factors of safety when these equations are used for practical designs.

Safety and Resistance Factors

Table 8.3 gives factors of safety as utilized for allowable stress design.

TABLE 8.3 Factors of Safety for Allowable Stress Design

Component	Failure mode	Buildings and similar type structures	Bridges and similar type structures
Tension	Yielding	1.95	2.20
	Ultimate strength	1.65	1.85
Columns	Yielding (short col.)	1.65	1.85
	Buckling	1.95	2.20
Beams	Tensile yielding	1.65	1.85
	Tensile ultimate	1.95	2.20
	Compressive yielding	1.65	1.85
	Lateral buckling	1.65	1.85
Thin plates in compression	Ultimate in columns	1.95	2.20
	Ultimate in beams	1.65	1.85
Stiffened flat webs in shear	Shear yield	1.65	1.85
	Shear buckling	1.20	1.35
Mechanically fastened joints	Bearing yield	1.65	1.85
	Bearing ultimate	2.34	2.64
	Shear str./rivets, bolts	2.34	2.64
Welded joints	Shear str./fillet welds	2.34	2.64
	Tensile str./butt welds	1.95	2.20
	Tensile yield/ butt welds	1.65	1.85

Data from The Aluminum Association, *Structural Design Manual*, 1994.

The calculated strength of the part is divided by these factors. This allowable stress must be less than the stress calculated using the total load applied to the part. In LRFD, the calculated strength of the part is multiplied by the resistance factors given in Table 8.4. This calculated stress must be less than that calculated using factored loads. Equations for determining the factored loads are given in the appropriate specifications discussed previously.

TABLE 8.4 Resistance Factors for LRFD

Component	Limit state	Buildings	Bridges
Tension	Yielding	0.95	0.90
	Ultimate strength	0.85	0.75
Columns	Buckling	Varies with slenderness ratio	Varies with slenderness ratio
Beams	Tensile yielding	0.95	0.90
	Tensile ultimate	0.85	0.80
	Compressive yielding	0.95	0.90
	Lateral buckling	0.85	0.80
Thin plates in compression	Yielding	0.95	0.90
	Ultimate strength	0.85	0.80
Stiffened flat webs in shear	Yielding	0.95	0.90
	Buckling	0.90	0.80

Buildings data from The Aluminum Association, *Structural Design Manual*, 1994. Bridges data from American Association of State Highway and Transportation Officials, *AASHTO LRFD Bridge Design Specifications*, 1994.

Buckling Curves for Alloys

The equations for the behavior of aluminum components apply to all thicknesses of material and to all aluminum alloys. Equations for buckling in the elastic and inelastic range are provided. Figure 8.2 shows the format generally used for both component and element behavior. Strength of the component is normally considered to be limited by the yield strength of the material. For buckling behavior, coefficients are defined for two classes of alloys, those that are heat treated with temper designations -T5 or higher and those that are not heat treated or are heat treated with temper designations -T4 or lower. Different coefficients are needed because of the differences in the shapes of the stress-strain curves for the two classes of alloys.

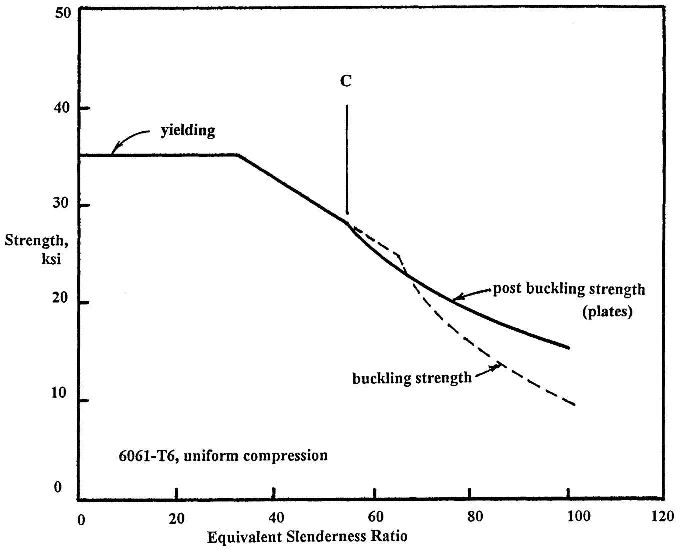

FIGURE 8.2: Buckling of components.

Effects of Welding

In most applications some efficiency is obtained by using alloys that have been thermally treated or strain hardened to achieve higher strength. The alloys are readily welded. However, welding partially anneals a narrow band of material (about 1.0 in. on either side of the weld) and thus this *heat affected* material has a lower strength than the rest of the member. The lower strength is accounted for in the design equations presented later.

If the strength of the heat affected material is less than the yield strength of the parent material, the plastic deformation of the component at failure loads will be confined to that narrow band of lower strength material. In this case the component fails with only a small total deformation, thus exhibiting low structural toughness. For good structural toughness the strength of the heat-affected material should be well above the yield strength of the parent material. In the case of liquid natural gas containers, an annealed temper of the plate, 5083-0, has been employed to achieve maximum toughness. The strength of the welded material is the same as that of the parent material and there is essentially no effect of welding on structural behavior.

Effects of Temperature

All of the properties important to structural behavior (static strength, elongation, fracture toughness, and fatigue strength) increase with decrease in temperature. Elongation increases but static and fatigue strength decrease at elevated temperatures. Alloys behave differently but significant changes in mechanical properties can occur at temperatures over 300°F.

Effects of Strain Rate

Aluminum alloys are relatively insensitive to strain rate. There is some increase in mechanical properties at high strain rates. Thus, published strength data based on conventional tests are normally used for calculations for cases of rapidly applied loads.

8.2.2 Component Behavior

This section presents equations and discussion for determining the strength of various types of aluminum components. These equations are consistent with those employed in current specifications and publications for aluminum structures.

Members in Tension

Because various alloys have different amounts of strain hardening both yielding and fracture strength of members should be checked. The net section of the member is used in the calculation. The calculated net section stress is compared to the yield strength and tensile strength of the alloy as given in Table 8.2. Larger factors of safety are applied for ultimate rather than yield strength in both ASD and LRFD specifications as noted in Tables 8.3 and 8.4.

The strengths across a groove weld are given for some alloys in Table 8.5. These properties are used for the design of tension members with transverse welds that affect the entire cross-section. For members with longitudinal welds in which only part of the cross-section is affected by welds, the tensile or yield strength may be calculated using the following equation:

$$F_{pw} = F_n - \frac{A_w}{A}(F_n - F_w) \qquad (8.1)$$

where

F_{pw} = strength of member with a portion of cross-section affected by welding

F_n = strength of unaffected parent metal

TABLE 8.5 Minimum Strengths of Groove Welds

Parent material	Filler metal	Tension		Compression	Shear
		TS[a]	YS[b]	YS[b]	US
3003-H14	1100	14	7	7	10
5456-H116	5556	42	26	24	25
6061-T6	5356	24	20	20	15
6061-T6	4043	24	15	15	15
6063-T5,-T6	4043	17	11	11	11

Data from The Aluminum Association, *Structural Design Manual*, 1994.
Note: All strengths are in ksi. TS is tensile strength, YS is yield strength, and US is ultimate strength.
[a] ASME weld-qualification values. The design strength is considered to be 90% of these values.
[b] Corresponds to a 0.2% set on a 10-in. gage length.

F_w = strength of material affected by welding
A = area of cross-section
A_w = area that lies within 1 in. of a weld

Columns Under Flexural Buckling

The Euler column formula is employed for the elastic region and straight line equations in the inelastic region. The straight line equations are a close approximation to the tangent modulus column curve. The equations for column strength are as follows:

$$F_c = B_c - D_c \frac{KL}{r} \qquad \frac{KL}{r} \le C_c \tag{8.2}$$

$$F_c = \frac{\pi^2 E}{(KL/r)^2} \qquad \frac{KL}{r} > C_c \tag{8.3}$$

where
F_c = column strength, ksi
L = unsupported length of column, in.
r = radius of gyration, in.
K = effective-length factor
E = modulus of elasticity, ksi
B_c, D_c, C_c = constants depending on mechanical properties (see below)

For wrought products with tempers starting with -O, -H, -T1, -T2, -T3, and -T4, and cast products,

$$B_c = F_{cy}\left[1 + \left(\frac{F_{cy}}{1000}\right)^{1/2}\right] \tag{8.4}$$

$$D_c = \frac{B_c}{20}\left(\frac{6B_c}{E}\right)^{1/2} \tag{8.5}$$

$$C_c = \frac{2B_c}{3D_c} \tag{8.6}$$

For wrought products with tempers starting with -T5, -T6, -T7, -T8, and -T9,

$$B_c = F_{cy}\left[1 + \left(\frac{F_{cy}}{2250}\right)^{1/2}\right] \tag{8.7}$$

$$D_c = \frac{B_c}{10}\left(\frac{B_c}{E}\right)^{1/2} \tag{8.8}$$

$$C_c = 0.41\frac{B_c}{D_c} \tag{8.9}$$

where F_{cy} = compressive yield strength, ksi

The column strength of a welded member is generally less than that of a member with the same cross-section but without welds. If the welds are longitudinal and affect part of the cross-section, the column strength is given by Equation 8.1. The strengths in this case are column buckling values assuming all parent metal and all heat-affected metal. If the member has transverse welds that affect the entire cross-section, and occur away from the ends, the strength of the column is calculated assuming that the entire column is heat-affected material. Note that the constants for the heat-affected material are given by Equations 8.4, 8.5, and 8.6. If transverse welds occur only at the ends, then the equations for parent metal are used but the strength is limited to the yield strength across the groove weld.

Columns Under Flexural-Torsional Buckling

Thin, open sections that are unsymmetrical about one or both principal axes may fail by combined torsion and flexure. This strength may be estimated using a previously developed equation that relates the combined effects to pure flexural and pure torsional buckling of the section. The equation below is in the form of effective and equivalent slenderness ratios and is in good agreement with test data [3]. The equation must be solved by trial for the general case.

$$\begin{aligned}&\left[1-\left(\frac{\lambda_c}{\lambda_y}\right)^2\right]\left[1-\left(\frac{\lambda_c}{\lambda_x}\right)^2\right]\left[1-\left(\frac{\lambda_c}{\lambda_\Phi}\right)^2\right]\\&\qquad-\left(\frac{y_o}{r_o}\right)^2\left[1-\left(\frac{\lambda_c}{\lambda_x}\right)^2\right]-\left(\frac{x_o}{r_o}\right)^2\left[1-\left(\frac{\lambda_c}{\lambda_y}\right)^2\right]=0\end{aligned} \tag{8.10}$$

where

λ_c = equivalent slenderness ratio for flexural-torsional buckling

λ_x, λ_y = slenderness ratios for flexural buckling in the x and y directions, respectively

x_o, y_o = distances between centroid and shear center, parallel to principal axes

r_o = $[(I_{xo}+I_{yo})/A]^{1/2}$

I_{xo}, I_{yo} = moments of inertia about axes through shear center

λ_Φ = equivalent slenderness ratio for torsional buckling

$$\lambda_\phi = \sqrt{\frac{I_x+I_y}{\frac{3J}{8\pi^2}+\frac{C_w}{(K_\Phi L)^2}}} \tag{8.11}$$

where

J = torsion constant

C_w = warping constant

K_ϕ = effective length coefficient for torsional buckling

L = length of column

I_x, I_y = moments of inertia about the centroid (principal axes)

Beams

Beams that are supported against lateral-torsional buckling fail by excessive yielding or fracture of the tension flange at bending strengths above that corresponding to stresses reaching the tensile or yield strength at the extreme fiber. This additional strength may be accounted for by applying a shape factor to the tensile or yield strength of the alloy. Nominal shape factors for some aluminum shapes are given in Table 8.6. These factors vary slightly with alloy because they are affected by the shape of the stress-strain curve but the values shown are reasonable for all aluminum alloys.

This higher bending strength can be developed provided that the cross-section is compact enough so that local buckling does not occur at a lower stress. Limitations on various types of elements are given in Table 8.7. The bending moment for compact sections is as follows.

$$M = ZSF \tag{8.12}$$

where

M = moment corresponding to yield or ultimate strength of the beam
S = section modulus of the section
F = yield or tensile strength of the alloy
Z = shape factor

TABLE 8.6 Shape Factors for Aluminum Beams

Cross-section	Yielding, K_y	Ultimate, K_u
I and channel (major axis)	1.07	1.16
I (minor axis)	1.30	1.42
Rectangular tube	1.10	1.22
Round tube	1.17	1.24
Solid rectangle	1.30	1.42
Solid round	1.42	1.70

Data from Gaylord and Gaylord, *Structural Engineering Handbook*, McGraw-Hill, New York, 1990, and The Aluminum Association, *Structural Design Manual*, 1994.

TABLE 8.7 Limiting Ratios of Elements for Plastic Bending

Element	Limiting ratio
Outstanding flange of I or channel	$b/t \leq 0.30(E/F_{cy})^{1/2}$
Lateral buckling of I or channel	
Uniform moment	$L/r_y \leq 1.2(E/F_{cy})^{1/2}$
Moment gradient	$L/r_y \leq 2.2(E/F_{cy})^{1/2}$
Web of I or rectangular tube	$b/t \leq 0.45(E/F_{cy})^{1/2}$
Flange of rectangular tube	$b/t \leq 1.13(E/F_{cy})^{1/2}$
Round tube	$D/t \leq 2.0(E/F_{cy})^{1/2}$

Data from Gaylord and Gaylord, *Structural Engineering Handbook*, McGraw-Hill, New York, 1990.

Effects of Joining

If there are holes in the tension flange, the net section should be used for calculating the section modulus. Welding affects beam strength in the same way as it does tensile strength. The groove weld strength is used when the entire cross-section is affected by welds. Beams may not develop the bending strength as given by Equation 8.12 at the locations of the transverse welds. In these locations it is reasonable to use a shape factor equal to 1.0. If only part of the section is affected by welds, Equation 8.1 is used to calculate strength and compact sections can develop the moment as given by Equation 8.12. In the calculation the flange is considered to be the area that lies farther than 2/3 of the distance between the neutral axis and the extreme fiber.

Lateral Buckling

Beams that do not have continuous support for the compression flange may fail by lateral buckling. For aluminum beams an equivalent slenderness is defined and substituted in column formulas in place of KL/r. The slenderness ratios for buckling of I-sections, WF-shapes, and channels are as follows.

For beams with end moments only or transverse loads applied at the neutral axis:

$$\lambda_b = 1.4 \frac{L_b}{\sqrt{\frac{I_y d C_b}{S_c} \sqrt{1.0 + 0.152 \frac{J}{I_y} \left(\frac{L_b}{d}\right)^2}}} \tag{8.13}$$

For beams with loads applied to top and bottom flanges where the load is free to move laterally with the beam:

$$\lambda_b = 1.4 \frac{L_b}{\sqrt{\frac{I_y d C_b}{S_c} \left[\pm 0.5 + \sqrt{1.25 + 0.152 \frac{J}{I_y} \left(\frac{L_b}{d}\right)^2}\right]}} \tag{8.14}$$

where

λ_b = equivalent slenderness ratio for beam buckling (to be used in place of KL/r in the column formula)

C_b = coefficient depending on loading and beam supports $= 12.5M_{\max}/(2.5M_{\max} + 3M_A + 4M_B + 3M_C)$ for simple supports

$M_{\max}$ = absolute value of maximum moment in the unbraced beam segment

M_A = absolute value of moment at quarter-point of the unbraced beam segment

M_B = absolute value of moment at midpoint of the unbraced beam segment

M_C = absolute value of moment at three-quarter-point of the unbraced beam segment

d = depth of beam

I_y = moment of inertia about axis parallel to web

S_c = section modulus for compression flange

J = torsion constant

The plus sign is to be used in Equation 8.14 if the load acts on the bottom (tension) flange, the minus sign if it acts on the top (compression) flange.

Equations 8.13 and 8.14 may also be used for cantilever beams of the specified cross-section by the use of the appropriate factor C_b. For a concentrated load at the end, the factor is 1.28 and for a uniform lateral load, the factor is 2.04.

These equations also may be applied to I-sections in which the tension and compression flanges are of somewhat different size. In this case the beam properties are calculated as though the tension flange is the same size as the compression flange. The depth of the section is maintained.

Lateral buckling strengths of welded beams are affected similarly to that of flexural buckling of columns. For cases in which part of the compression flange has heat-affected material, Equation 8.1 is used. The total flange area is that farther than 2/3 the distance from the neutral axis to the extreme fiber. If the beam has transverse welds away from the supports, the strength of the beam is calculated as though the entire beam is of heat-affected material.

For other types of cross-sections and loadings not provided for above, and for cases in which the loads cause torsional stresses in the beam, other equations and analysis are needed. Some cases are covered elsewhere [1, 3].

Members Under Combined Bending and Axial Loads

The same interaction equations may be used for aluminum as for steel members. The following equations are for bending in one direction. Both formulas must be checked.

$$\frac{f_a}{F_{ao}} + \frac{f_b}{F_b} \leq 1.0 \tag{8.15}$$

$$\frac{f_a}{F_a} + \frac{C_b f_b}{F_b(1.0 - f_a/F_e)} \leq 1.0 \tag{8.16}$$

where

f_a = average compressive stress from axial load
f_b = maximum compressive bending stress
F_a = strength of member as a column
F_b = strength of member as a beam
F_{ao} = strength of member as a short column
F_e = $\pi^2 E/(KL/r)^2$

Buckling of Thin, Flat Elements of Columns and Beams Under Uniform Compression

The elastic buckling of plates is calculated using classical plate buckling theory. For inelastic stresses, straight line formulas that approximate a secant-tangent modulus combination are used. These straight line formulas give higher stresses than those for columns that use tangent modulus, and they are in close agreement with test data. An equivalent slenderness ratio, $K_p b/t$, is utilized in the equations.

$$F_p = B_p - \frac{D_p K_p b}{t} \qquad \frac{K_p b}{t} \leq C_p \tag{8.17}$$

$$F_p = \frac{\pi^2 E}{(K_p b/t)^2} \qquad K_p \frac{b}{t} > C_p \tag{8.18}$$

where

F_p = buckling stress of plate, ksi
b = clear width of plate
t = thickness of plate
K_p = coefficient depending on conditions of edge restraint of plate (see Table 8.8)
B_p, D_p, C_p = alloy constants defined below

TABLE 8.8 Values of K_p for Plate Elements

Type of member	Stress distribution	Edge support	K_p
Column	Uniform compression	One edge free, one edge supported	5.1
		Both edges supported	1.6
Beam (flange)	Uniform compression	One edge free, one edge supported	5.1
		Both edges supported	1.6
Beam (web)	Varying from compression on one edge to tension on the other edge	Compression edge free, tension edge with partial restraint	3.5
		Both edges supported	0.67

Data from Gaylord and Gaylord, *Structural Engineering Handbook*, MacGraw-Hill, New York, 1990.

For wrought products with tempers starting with -0, -H, -T1, -T2, -T3, and -T4, and cast products,

$$B_p = F_{cy}\left[1+\frac{(F_{cy})^{1/3}}{7.6}\right] \tag{8.19}$$

$$D_p = \frac{B_p}{20}\left(\frac{6B_p}{E}\right)^{1/2} \tag{8.20}$$

$$C_p = \frac{2B_p}{3D_p} \tag{8.21}$$

For wrought products with tempers starting with -T5, -T6, -T7, -T8, and -T9,

$$B_p = F_{cy}\left[1+\frac{(F_{cy})^{1/3}}{11.4}\right] \tag{8.22}$$

$$D_p = \frac{B_p}{10}\left(\frac{B_p}{E}\right)^{1/2} \tag{8.23}$$

$$C_p = 0.41\frac{B_p}{D_p} \tag{8.24}$$

Buckling of Thin, Flat Elements of Beams Under Bending

For webs under bending loads, Equations 8.17 and 8.18 apply for buckling in the inelastic and elastic ranges. C_p is given by Equation 8.21. However, the values of B_p and D_p are higher than those of elements under uniform compression because they include a shape factor effect, the same as that defined for beams. The constants for the straight-line equation are as follows. They apply to all alloys and tempers.

$$B_p = 1.3F_{cy}\left[1+\frac{(F_{cy})^{1/3}}{7}\right] \tag{8.25}$$

$$D_p = \frac{B_p}{20}\left(\frac{6B_p}{E}\right)^{1/2} \tag{8.26}$$

Post-Buckling Strength of Thin Elements of Columns and Beams

Most thin elements can develop strengths much higher than the elastic buckling strength as given by Equation 8.18. This higher strength is used in design. Elements of angle, cruciform, and channel (flexural buckling about the weak axis) columns may not develop post-buckling strength. Thus, the buckling strength should be used for these cases. For other cases, the post-buckling strength (in the elastic buckling region) is given as follows:

$$F_{cr} = k_2\frac{\sqrt{B_pE}}{K_pb/t} \quad \text{for} \quad b/t > \frac{k_1B_p}{K_pD_p} \tag{8.27}$$

where

F_{cr} = ultimate strength of plate in compression, ksi

B_p, D_p = coefficients defined in Equations 8.19 through 8.26

k_1, k_2 = coefficients. $k_1 = 0.5$ and $k_2 = 2.04$ for wrought products whose temper starts with -0, -H.-T1, -T2, -T3, and -T4, and castings. $k_1 = 0.35$ and $k_2 = 2.27$ for wrought products whose temper starts with -T5, -T6, -T7, -T8 and -T9

Weighted Average Strength of Thin Sections

In many cases a component will have elements with different calculated buckling strengths. An estimate of the component strength is obtained by equating the ultimate strength of the section multiplied by the total area to the sum of the strength of each element times its area, and solving for the ultimate strength. This weighted average approach gives a close estimate of strength for columns and for beam flanges.

Effect of Local Buckling on Column and Beam Strength

If local buckling occurs at a stress below that for overall buckling of a column or beam, the strength of the component will be reduced. Thus, the elements should be proportioned such that they are stable at column or beam buckling strengths. There are methods for taking into account local buckling on column or beam strength provided elsewhere [1, 3].

Shear Buckling of Plates

The same equations apply to stiffened and unstiffened webs. Equivalent slenderness ratios are defined for each case. Straight line equations are employed in the inelastic range and the Euler formula in the elastic range. The equations are as follows:

$$F_s = B_s - D_s\lambda_s \qquad \lambda_s \leq C_s \tag{8.28}$$

$$F_s = \frac{\pi^2 E}{\lambda_s^2} \qquad \lambda_s > C_s \tag{8.29}$$

For tempers -0, -H, -T1, -T2, -T3, and -T4

$$B_s = F_{sy}\left(1 + \frac{F_{sy}^{1/3}}{6.2}\right) \tag{8.30}$$

$$D_s = \frac{B_s}{20}\left(\frac{6B_s}{E}\right)^{1/2} \tag{8.31}$$

$$C_s = \frac{2B_s}{3D_s} \tag{8.32}$$

For tempers -T5, -T6, -T7, -T8, and -T9

$$B_s = F_{sy}\left(1 + \frac{F_{sy}^{1/3}}{9.3}\right) \tag{8.33}$$

$$D_s = \frac{B_s}{10}\left(\frac{B_s}{E}\right)^{1/2} \tag{8.34}$$

$$C_s = 0.41\frac{B_s}{D_s} \tag{8.35}$$

where
F_{sy} = shear yield strength, ksi
λ_s = $1.25h/t$ for unstiffened webs
= $1.25a_1/t[1 + 0.7(a_1/a_2)^2]^{1/2}$ for stiffened webs
h = clear depth of web
t = web thickness
a_1 = smallest dimension of shear panel
a_2 = largest dimension of shear panel

Web Crushing

One of the design limitations of formed sheet members in bending and thin-webbed beams is local failure of the web under concentrated loads. Also, there is interaction between the effects of the concentrated load and the bending strength of the web.

For interior loads

$$P = \frac{t^2(N + 5.4)(\sin\Theta)(0.46F_{cy} + 0.02\sqrt{EF_{cy}})}{0.4 + r(1 - \cos\Theta)} \tag{8.36}$$

where
P = maximum load on one web, kips
N = length of load, in.
F_{cy} = compressive yield strength, ksi
E = modulus of elasticity, ksi
r = radius between web and top flange, in.
t = thickness, in.
Θ = angle between plane of web and plane of loading (flange)

For loads at the end of the beam

$$P = \frac{1.2t^2(N + 1.3)(\sin\Theta)(0.46F_{cy} + 0.02\sqrt{EF_{cy}}}{0.4 + r(1 - \cos\Theta)} \tag{8.37}$$

If there is significant bending stresses at the point of the concentrated load, the interaction may be calculated using the following equation:

$$\left(\frac{M}{M_u}\right)^{1.5} + \left(\frac{P}{P_u}\right)^{1.5} \leq 1.0 \tag{8.38}$$

where
M = applied moment, in.-kips
P = applied concentrated load, kips
M_u = maximum moment in bending, in.-kip
P_u = web crippling load, kips

Stiffeners for Flat Plates

The addition of stiffeners to thin elements greatly improves efficiency of material. This is especially important for aluminum components because there usually is no need for a minimum thickness based on corrosion, and thus parts can be thin compared to those of steel, for example.

Stiffening Lips for Flanges

The buckling strength of the combined lip and flange is calculated using the equations for column buckling given previously and the following equivalent slenderness ratio that replaces the effective slenderness ratio. Element buckling of the flange plate and lip must also be considered.

$$\lambda = \pi\sqrt{\frac{I_p}{3/8J + 2\sqrt{C_w K_\phi / E}}} \tag{8.39}$$

where
λ = equivalent slenderness ratio (to be used in the column buckling equations)
I_p = $I_{xo} + I_{yo}$ = polar moment of inertia of lip and flange about center of rotation, in.^{4}
I_{xo}, I_{yo} = moments of inertia of lip and flange about center of rotation, in.^{4}
K_ϕ = elastic restraint factor (the torsional restraint against rotation as calculated from the application of unit outward forces at the centroid of the combined lip and flange of a one unit long strip of the section), in.-lb/in.
J = torsion constant, in.^{4}

C_w = $b^2(I_{yc} - bt^3/12)$ = warping term for lipped flange about center of rotation, in.^{6}
I_{yc} = moment of inertia of flange and lip about their combined centroidal axis (the flange is considered to be parallel to the y-axis), in.^{4}
E = modulus of elasticity, ksi
b = flange width, in.
t = flange thickness, in.

Intermediate Stiffeners for Plates in Compression

Longitudinal stiffeners (oriented parallel to the direction of the compressive stress) are often used to stabilize the compression flanges of formed sheet products and can be effective for any thin element of a column or the compression flange of a beam. The buckling strength of a plate supported on both edges with intermediate stiffeners is calculated using the column buckling equations and an equivalent slenderness ratio. The strength of the individual elements, plate between stiffeners and stiffener elements, also must be evaluated.

$$\lambda = \frac{4Nb}{\sqrt{3}t}\sqrt{\frac{1 + A_s/bt}{1 + \sqrt{1 + 32I_e/3t^3b}}} \tag{8.40}$$

where
λ = equivalent slenderness ratio for stiffener that replaces the effective slenderness ratio in the column formulas
N = total number of panels into which the longitudinal stiffeners divide the plate, in.
b = stiffener spacing, in.
t = thickness of plate, in.
I_e = moment of inertia of plate-stiffener combination about neutral axis using an effective width of plate equal to b, in.^{4}
A_s = area of stiffener (not including any of the plate), in.^{2}

Intermediate Stiffeners for Plates in Shear (Girder Webs)

Transverse stiffeners on girder webs must be stiff enough so that they remain straight during buckling of the plate between stiffeners. The following equations are proposed for design.

For $s/h \leq 0.4$

$$I_s = \frac{0.46Vh^2}{E}(s/h) \tag{8.41}$$

For $s/h > 0.4$

$$I_s = \frac{0.073Vh^2}{E}(h/s) \tag{8.42}$$

where
I_s = moment of inertia of stiffener (about face of web plate for stiffeners on one side of web only), in.^{4}
s = stiffener spacing, in.
h = clear height of web, in.
V = shear force on web at stiffener location, kips
E = modulus of elasticity, ksi

Corrugated Webs

Corrugated sheet is highly efficient in carrying shear loads. Webs of girders and roofs and side walls of buildings are practical applications. The behavior of these panels, particularly the shear stiffness, is dependant not only on the type and size of corrugation but also on the manner in which it is attached to edge members. Test information and design suggestions are published elsewhere [3]. Some of the failure modes to consider are as follows.

1. Overall shear buckling. Primarily this is a function of the size of corrugations, the length of the panel parallel to the corrugations, the attachment, and the alloy.
2. Local buckling. Individual flat or curved elements of the corrugations must be checked for buckling strength.
3. Failure of corrugations and/or fastening at the attachment to the edge framing. If not completely attached at the ends, the corrugation may roll or collapse at the supports or fastening may fail.
4. Excessive deformation. This characteristic is difficult to calculate and the best guidelines are based on test data. The shear deformation can be many times that of flat webs particularly for those cases in which the fastening at the supports is not continuous.

Local Buckling of Tubes and Curved Panels

The strength of these members for each type of loading is defined by an equation for elastic buckling that applies to all alloys and two equations for the inelastic region which are dependent on alloy and temper. The members also need to be checked for overall buckling.

Round Tubes Under Uniform Compression

The local buckling strength is given by the following equations.

$$F_t = B_t - D_t\sqrt{\frac{R}{t}} \qquad \frac{R}{t} \leq C_t \tag{8.43}$$

$$F_t = \frac{\pi^2 E}{16(R/t)\left(1+\frac{\sqrt{R/t}}{35}\right)^2} \qquad \frac{R}{t} > C_t \tag{8.44}$$

where

F_t = buckling stress for round tube in end compression, ksi
R = mean radius of tube, in.
t = thickness of tube, in.
C_t = intersection of equations for elastic and inelastic buckling (determined by charting or trial and error)

The values of the constants, B_t and D_t, are given by the following formulas.

For wrought products with tempers starting with -O, -H, -T1, -T2, -T3, and -T4, and cast products,

$$B_t = F_{cy}\left(1+\frac{F_{cy}^{1/5}}{5.8}\right) \tag{8.45}$$

$$D_t = \frac{B_t}{3.7}\left(\frac{B_t}{E}\right)^{1/3} \tag{8.46}$$

For wrought products with tempers starting with -T5, -T6, -T7, -T8, and -T9,

$$B_t = F_{cy}\left(1+\frac{F_{cy}^{1/5}}{8.7}\right) \tag{8.47}$$

$$D_t = \frac{B_t}{4.5}\left(\frac{B_t}{E}\right)^{1/3} \tag{8.48}$$

where

F_{cy} = compressive yield strength, ksi

For welded tubes, Equations 8.45 and 8.46 are used along with the yield strength for welded material. The accuracy of these equations has been verified for tubes with circumferential welds and R/t ratios equal to or less than 20. For tubes with much thinner walls, limited tests show that much lower buckling strengths may occur [3].

Round Tubes and Curved Panels Under Bending

For curved elements of panels under bending, such as corrugated sheet, the local buckling strength of the compression flange may be determined using the same equations as given in the preceding section for tubes under uniform compression.

In the case of round tubes under bending a higher compressive buckling strength is available for low R/t ratios due to the shape factor effect. (Tests have indicated that this higher strength is not developed in curved panels.) The equations for tubes in bending for low R/t are given later. Note that the buckling of tubes in bending is provided by two equations in the inelastic region, that defined below and that for intermediate R/t ratios, which is the same as that for uniform compression, and the equation for elastic behavior, which also is the same as that for tubes under uniform compression.

$$F_{tb} = B_{tb} - D_{tb}\sqrt{R/t} \qquad R/t \leq C_{tb} \tag{8.49}$$

where

F_{tb} = buckling stress for round tube in bending, ksi

R = mean radius of tube, in.

t = thickness of tube, in.

C_{tb} = $[(B_{tb} - B_t)/(D_{tb} - D_t)]^2$, intersection of curves, Equations 8.43 and 8.49

The values of the constants, B_{tb} and D_{tb}, are given by the following formulas.

For wrought products with tempers starting with -0, -H, -T1, -T2, -T3, and -T4, and cast products,

$$B_{tb} = 1.5F_y\left(1 + \frac{F_y^{1/5}}{5.8}\right) \tag{8.50}$$

$$D_{tb} = \frac{B_{tb}}{2.7}\left(\frac{B_{tb}}{E}\right)^{1/3} \tag{8.51}$$

For wrought products with tempers starting with -T5, -T6, -T7, -T8, and -T9,

$$B_{tb} = 1.5F_y\left(1 + \frac{F_y^{1/5}}{8.7}\right) \tag{8.52}$$

$$D_{tb} = \frac{B_{tb}}{2.7}\left(\frac{B_{tb}}{E}\right)^{1/3} \tag{8.53}$$

where

F_y = tensile or compressive yield strength, whichever is lower, ksi

Round Tubes and Curved Panels Under Torsion and Shear

Thin walled curved members can buckle under torsion. Long tubes are covered in specifications [1] and provisions for stiffened and unstiffened cases are provided elsewhere [3].

8.2.3 Joints

Mechanical Connections

Aluminum components are joined by aluminum rivets, aluminum and steel (galvanized, aluminized, or stainless) bolts, and clinches. The joints are normally designed as bearing-type connections because the as-received surfaces of aluminum products have a low coefficient of friction and slip often occurs at working loads. Some information has been developed for the amount of roughening of the surfaces and the limiting thicknesses of material for designing a friction-type joint, although current U.S. specifications do not cover this type of design.

Table 8.9 presents strength data for a few of the rivet and bolt alloys available. Rivets are not recommended for applications that introduce large tensile forces on the fastener. The joints are proportioned based on the shear strength of the fastener and the bearing strength of the elements being joined. The bearing strengths apply to edge distances equal to at least twice the fastener diameter, otherwise reduced values apply. Steel bolts are often employed in aluminum structures. They are generally stronger than the aluminum bolts, and may be required for pulling together parts during assembly. They also have high fatigue strength, which is important in applications in which the fastener is subject to cyclic tension. The steel bolts must be properly coated or be of the 300 series stainless to avoid galvanic corrosion between the aluminum elements and the fastener.

TABLE 8.9 Strengths of Aluminum Bolts and Rivets

	Minimum expected strength, ksi	
Alloy and temper	Shear	Tension on net area
	Rivets	
6053-T61	20	—
6061-T6	25	—
	Bolts	
2024-T4	37	62
6061-T6	25	42
7075-T73	41	68

Data from The Aluminum Association, *Structural Design Manual,* 1994.

Thin aluminum roofing and siding products are commonly used in the building industry. One failure mode is the pulling of the sheathing off of the fastener due to uplift forces from wind. The pull-through strength is a function of the strength of the sheet, the geometry of the product, the location of the fastener, the hole diameter, and the size of the head of the fastener [3].

Welded Connections

The aluminum alloys employed in most nonaerospace applications are readily welded, and many structures are fabricated with this method of joining. Transverse groove weld strengths and appropriate filler alloys for a few of the alloys are given in Table 8.5. Because the weld strengths are usually less than those of the base material, the design of aluminum welded structures is somewhat different from that of steel structures. Techniques for designing aluminum components with longitudinal and transverse welds are provided in the preceding section. If the welds are inclined to the direction of stress, neither purely longitudinal or transverse, the strength of the connection more closely approximates that of the transversely welded case.

Fillet weld strengths are given in Table 8.10. Two categories are defined, longitudinal and transverse. These strengths are based on tests of specimens in which the welds were symmetrically placed and had no large bending component. In the case of longitudinal fillets, the welds were subjected to primarily shear stresses. The transverse fillet welds carried part of the load in tension. The difference in stress states accounts for the higher strengths for transverse welds. Aluminum specifications utilize the values for longitudinal welds for all orientations of welds because many types of transverse fillet welds cannot develop the strengths shown due to having a more severe stress state than the test specimens, e.g., more bending stress. Proportioning of complex fillet weld configurations is done using structural analysis techniques appropriate for steel and other metals.

TABLE 8.10 Minimum Shear Strengths of Fillet Welds

	Shear strength, ksi	
Filler alloy	Longitudinal	Transverse
4043[a]	11.5	15
5356	17	26
5554	17	23
5556	20	30

[a] Naturally aged (2 to 3 months)

Data from Sharp, *Behavior and Design of Aluminum Structures,* McGraw-Hill, New York, 1993.

Adhesive Bonded Connections

Adhesive bonding is not used as the only joining method for main structural components of nonaerospace applications. It is employed in combination with other joining methods and for secondary members. Although there are many potential advantages in the performance of adhesive joints compared to those for mechanical and welded joints, particularly in fatigue, there are too many uncertainties in design to use them in primary structures. Some of the problems in design are as follows.

1. There are no specific adhesives identified for general structures. The designer needs to work with adhesive experts to select the proper one for the application.
2. In order to achieve long-term durability proper pretreatment of the metal is required. There are little data available for long-term behavior, so the designer should supplement the design with durability tests.
3. There is no way to inspect for the quality of the joint. Proper quality control of the joining process should result in good joints. However, a mistake can result in very low strengths, and the bad joint cannot be detected by inspection.
4. There are calculation procedures for proportioning simple joints in thin materials. Techniques for designing complex joints of thicker elements are under development, but are not adequate for design at this time.

8.2.4 Fatigue

Fatigue is a major design consideration for many aluminum applications, e.g., aircraft, cars, trucks, railcars, bridges, and bridge decks. Most field failures of metal structures are by fatigue. The current design method used for all specifications, aluminum and steel structures, is to define categories of details that have essentially the same fatigue strength and fatigue curves for each of these categories. Smooth components, bolted and riveted joints, and welded joints are covered in the categories. For a new detail the designer must select the category that has a similar local stress. Chapter 24 of this Handbook provides details of this method of design.

Many of the unique characteristics related to the fatigue behavior of aluminum components have been summarized [5]. Some general comments from this reference follow.

1. Some cyclic loads, such as wind induced vibration and dynamic effects in forced vibration, are nearly impossible to design for because stresses are high and the number of cycles build up quickly. These loads must be reduced or eliminated by design.
2. Good practice to eliminate known features of structures causing fatigue, such as sharp notches and high local stresses due to concentrated loads, should be employed in all cases. In some applications the load spectrum is not known, e.g., light poles, and fatigue resistant joints must be employed.
3. The fatigue strength of aluminum parts is higher at low temperature and lower at elevated temperature compared to that at room temperature.
4. Corrosion generally does not have a large effect on the fatigue strength of welded and mechanically fastened joints but considerably lowers that of smooth components. Protective measures, such as paint, improve fatigue strength in most cases.
5. Many of the joints for aluminum structures are unusual in that they are quite different from those of the fatigue categories provided in the specifications. Stress analysis to define the critical local stress is useful in these cases. Test verification is desirable if practical.

8.3 Design

Aluminum should be considered for applications in which life cycle costs are favorable compared to competing materials. The costs include:

1. Acquisition, refining, and manufacture of the metal
2. Fabrication of the metal into a useful configuration
3. Assembly and erection of the components in the final structure
4. Maintenance and operation of the structure over its useful life
5. Disposal after the useful life

The present markets for aluminum have developed because of life cycle considerations. Transportation vehicles, one of the largest markets, with aerospace applications, aircraft, trucks, cars, and railcars, are light weight thus saving fuel costs and are corrosion resistant thus minimizing maintenance costs. Packaging, another large market, makes use of close loop recycling that returns used cans to rolling mills that produce sheet for new cans. Building and infrastructure uses were developed because of the durability of aluminum in the atmosphere without the need for painting, thus saving maintenance costs.

8.3.1 General Considerations

Product Selection

Most aluminum structures are constructed of flat rolled products, sheet and plate, and extrusions because they provide the least cost solution. The properties and quality of these products are guaranteed by producers. The flat rolled products may be bent or formed into shapes and joined to make the final structure. Extrusions should be considered for all applications requiring constant section members. Most extruders can supply shapes whose cross-section fits within a 10-in. circle. Larger shapes are made by a more limited number of manufacturers and are more costly. Extrusions are attractive for use because the designer can incorporate special features to facilitate joining, place material in the section to optimize efficiency, and consolidate number of parts (compared with fabricated sheet parts). Because die costs are low the designer should develop unique shapes for most applications.

Forgings are generally more expensive than extrusions and plate, and are employed in aerospace applications and wheels, where the three-dimensional shape and high performance and quality are essential. Castings are also used for three-dimensional shapes, but the designer must work with the supplier for design assistance.

Alloy Selection

For extrusions alloy 6061 is best for higher strength applications and 6063 is preferred if the strength requirements are less. 5XXX alloys have been extruded and have higher as-welded strength and ductility in structures but they are generally much more expensive to manufacture, compared to the 6XXX alloys.

6061 sheet and plate are also available and are used for many applications. For the highest as-welded strength, the 5XXX alloys are employed.

Table 8.11 shows alloys that have been employed in some applications. Choice of specific alloy depends on cost, strength, formability, weldability, and finishing characteristics.

TABLE 8.11 Selection of Alloy

Application	Specific use	Alloys
Architecture Sheet	Curtain walls, roofing and siding, mobile homes	3003, 3004, 3105
extrusions	Window frames, railings, building frames	6061, 6063
Highway Plate	Signs, bridge decks	5086, 5456, 6061
extrusions	Sign supports, lighting standards, bridge railings	6061, 6063
Industrial Plate	Tanks, pressure vessels, pipe	3003, 3004, 5083, 5086, 5456, 6061
Transportation		
Sheet/plate extrusions	Automobiles, trailers, railcars, shipping containers, boats	5052, 5083, 5086, 6061, 6009
	Stiffeners/framing	6061
Miscellaneous extrusions	Scaffolding, towers, ladders	6061, 6063

Data from Gaylord and Gaylord, *Structural Engineering Handbook*, McGraw-Hill, New York, 1990.

Corrosion Resistance

Alloys shown in Table 8.11, 3XXX, 5XXX, and 6XXX, have high resistance to general atmospheric corrosion and can be employed without painting. Tests of small, thin specimens of these alloys in a seacoast or industrial environment for over 50 years of exposure have shown that the depth of attack is small and self-limiting. A hard oxide layer forms on the surface of the component, which prevents significant additional corrosion.

If aluminum components are attached to steel components, protective measures must be employed to prevent galvanic corrosion. These measures include painting the steel components and placing a sealant in the joint. Stainless steel or galvanized fasteners are also required.

Some of the 5XXX alloys with magnesium content over about 3% may be sensitized by sustained elevated temperatures and lose their resistance to corrosion. For these applications alloys 5052 and 5454 may be used.

Metal Working

All of the usual fabrication processes can be used with aluminum. Forming capabilities vary with alloy. Special alloys are available for automotive applications in which high formability is required. Aluminum parts may be machined, cut, or drilled and the operations are much easier to accomplish compared to steel parts.

Finishing

Aluminum structures may be painted or anodized to achieve a color of choice. These finishes have excellent long-term durability. Bright surfaces also may be accomplished by mechanical polishing and buffing.

8.3.2 Design Studies

Some specific design examples follow in which product form, alloy selection, and joining method are discussed. The Aluminum Association Specifications are used for calculations of component strength.

EXAMPLE 8.1: Lighting Standard

Design Requirements

1. Withstand wind loads for area
2. Fatigue and vibration resistant
3. Heat treatable after welding to achieve higher strength
4. Base that breaks away under vehicle impact

Alloy and Product

Round, extruded tubes of 6063-T4 are selected for the shaft. This alloy is easily extruded and has low cost and excellent corrosion resistance. The -T4 temper is required so that the pole can be tapered by a spinning operation, and so that the structure can be heat treated and aged after welding. A permanent mold casting of 356-T6 is selected for the base. The shaft extends through the base. This base may be acceptable for break away characteristics. If not, a break away device must be employed.

Joining

MIG circumferential welds are made at the top and bottom of the base using filler alloy 4043. This filler alloy must be employed because of the heat treat operation after welding. The corrosion resistance of a 5XXX filler alloy may be lowered by the heat treatment and aging.

Design Considerations

Wind induced vibration occasionally can be a problem. The vibration involves both the standard and luminare. Currently there is no accurate way to predict whether or not these structures will vibrate. Light pole manufacturers have dampers that they can use if necessary.

Calculation Example-Bending of Welded Tube

Determine the bending strength of a 8 in. diameter(outside) X 0.313 in. wall tube of 6063-T4, heat treated and aged after welding using ASD. Factors of safety corresponding to building type structures apply.

For this special case of fabrication, the specifications allow the use of allowable stresses for the welded construction equal to 0.85 times those for 6063-T6. Also, the allowable stresses can be increased 1/3 for wind loading.

1. The allowable tensile stress (tensile properties are given in Table 8.2, shape factors in Table 8.6, and factors of safety in Table 8.3) is as follows.
   Tensile strength: $F_{tu} = 0.85(1.24)(1.33)(30)/(1.95) = 21.6$ ksi
   Yield strength: $F_{ty} = 0.85(1.17)(1.33)(25)/(1.65) = 20.0$ ksi
2. The allowable compressive strength is given by Equations 8.43 to 8.53.
   $R/t = (4.0 - 0.313)/(0.313) = 11.8$. Equation 8.49 applies because R/t is less than $69.6(C_b t)$. Constants are determined from Equations 8.52 and 8.53.
   $F_{tb} = (0.85)(1.33)(45.7 - 2.8\sqrt{(R/t)})/1.65 = 24.7$ ksi
3. The lower of the three values, 20.0 ksi is used for design. This bending stress must be less than that calculated from all loads.

EXAMPLE 8.2: Overhead Sign Truss

Design Requirements

1. Withstand wind loads for locality (signs and truss are considered).
2. Prevent wind induced vibration of truss and members.
3. Provide structure that does not need painting.

Alloy and Product

Extruded tubes of 6061-T651 are selected for the truss and end supports. This alloy is readily welded and has excellent corrosion resistance. It also is one of the lower cost extrusion alloys.

Joining

The individual members will be machined at the ends to fit closely with other parts and welded together using the MIG process. 5356 filler wire is specified to provide higher fillet weld strength compared to that for 4043 filler.

Design Considerations

Wind induced vibration must be prevented in these structures. The trusses are particularly susceptible to the wind when they do not have signs installed. Vibration of the entire truss can be controlled by the addition of a suitable damper (at midspan) and individual members must be designed to prevent vibration by limiting their slenderness ratio [3].

Calculation Example-Buckling of a Tubular Column with Welds at Ends

The diagonal member of the truss is a 4-in. diameter tube (outside diameter) of 6061-T651 with a wall thickness of 0.125 in. The radius of gyration is 1.37. Its length is 48 in. and it is welded at each end to chords using filler 5356. Use ASD factors of safety corresponding to bridge structures (Table 8.3). Assume that the effective length factor is 1.0. Allow 1/3 increase in stress because of wind loading.

$$KL/r = (1.0)(48)/1.37 = 35.0$$

For column buckling, Equation 8.2 applies ($KL/r \leq C_c$). The constants are calculated from Equations 8.7, 8.8, and 8.9 and parent metal properties (Table 8.2).

$$F_c = (1.33)(39.4 - 0.246(35.0))/2.20 = 18.6 \quad \text{ksi}$$

For yielding at the welds (the entire cross-section is affected at the ends), the properties in Table 8.5 are employed.

$$F_c = (1.33)(20)/1.85) = 14.4 \quad \text{ksi}$$

The allowable stress is the lower of these values, 14.4 ksi.

Calculation Example-Tubular Column with Welds at Ends and Midlength

This is the same construction as described above, except that the designer has specified that a bracket be circumferentially welded to the tube at midlength. This weld lowers the column buckling strength. The column is now designed as though all the material is heat-affected. Equation 8.2 still applies but constants are now calculated using Equations 8.4, 8.5, and 8.6 and properties from Table 8.5.

$$F_c = (1.33)[22.8 - (1.0)(35.0)(0.133)]/2.20 = 11.0 \quad \text{ksi}$$

This stress is less than that calculated previously for yielding(14.4 ksi) and now governs. This stress must be higher than that calculated using the total load on the structure.

EXAMPLE 8.3: Built-Up Highway Girder

Design Requirements

The loads to be used for static and fatigue strength calculations are provided in AASHTO specifications. Long time maintenance-free construction is also specified. The size of the girder is larger than the largest extrudable section.

Riveted Construction

Alloy 6061-T6 is selected for the web plate, flanges, and web stiffeners. This alloy has excellent corrosion resistance, is readily available, and has the highest strength for mechanical joining. Rivets of 6061-T6 are used for the joining because they are a good match for the parts of the girder from strength and corrosion considerations. The extrusions for the flanges and stiffeners are special sections designed to facilitate fabrication and to achieve maximum efficiency of material. A sealant is placed in the faying surfaces to enhance fatigue strength and to prevent ingress of detrimental substances.

Welded Construction

Alloy 5456-H116 is selected for the web plate and flange plate. This alloy has high as-welded strength compared to 6061-T6 and excellent corrosion resistance. Alloys 5083 and 5086 would also be satisfactory selections. The filler wire selected for MIG welding is 5556, to have high fillet weld strength.

Calculation Example: Strength of Riveted Joint

The 6061-T6 parts are assembled as received from the supplier, so that the joint must be designed as a bearing connection. Use ASD for design. The thickness of the web plate is 1/2 in. and it is attached to the legs of angle flanges (two angles) that are 3/4 in. thick. Rivets 1 in. in diameter (area is 0.785 in.^{2}) are used.

Allowable bearing load on the web (bearing area is $0.50 \times 1.0 = 0.50$ in.^{2}) for one fastener is (see Tables 8.2 and 8.3):

Based on yielding: $P = (58)(0.50)/1.85 = 15.7$ kips

Based on ultimate: $P = (88)(0.50)/2.64 = 16.7$ kips

Allowable shear load on one rivet with double shear:

Based on ultimate (see Tables 8.3 and 8.9):

$$P = (2)(.785)(25)/2.64 = 14.9 \text{ kips}$$

The allowable load per rivet is the smaller of the three values or 14.9 kips.

Calculation Example: Fatigue Life of Welded Girder with Longitudinal Fillet Welds

The allowable tensile strength for a 5456-H116 girder is (see Tables 8.2 and 8.3):

Based on yield: $F = 33/1.85 = 17.8$ ksi (governs)

Based on ultimate: $F = 46/2.2 = 20.9$ ksi

Calculate the number of cycles that the girder can sustain at a stress range corresponding to a stress of 1/2 the static design value (8.9 ksi). Category B applies to a connection with the fillet weld parallel to the direction of stress. For this category, the fatigue strength is:

The stress range: $S = 130N^{-.207} = 8.9$ ksi

The number of cycles: $N = 423{,}000$ cycles

(Fatigue equations from [1].)

Calculation Example: Intermediate Stiffeners

Stiffeners on girder webs must be of sufficient size to remain straight when the web buckles. Stiffener sizes are given by Equations 8.41 and 8.42.

EXAMPLE 8.4: Roofing or Siding for a Building

Design Requirements

1. Withstand wind loads(uplift as well as downward pressure)
2. Withstand concentrated loads from foot pressure or from reactions at supports
3. Corrosion resistant so that painting is not needed

Alloy and Product

Sheet of alloy 3004-H14 is selected. This alloy and temper have sufficient formability to roll-form the trapezoidal shape desired. They also have excellent corrosion and reasonable strength. Other 3XXX alloys would also be good choices.

Design Considerations

Attachment of the sheet panels to the supporting structure must be strong enough to resist uplift forces. The pull through strength of the sheet product as well as the fastener strength are considered. Sufficient overlap of panels and fasteners at laps are needed for watertightness.

Calculation Example: Web Crushing Load at an Intermediate Support

Consider the shape shown in Figure 8.3. The bearing length is 2 in. (width of flange of support). Use LRFD specifications for buildings. The material properties for 3004-H14 are given in Table 8.2

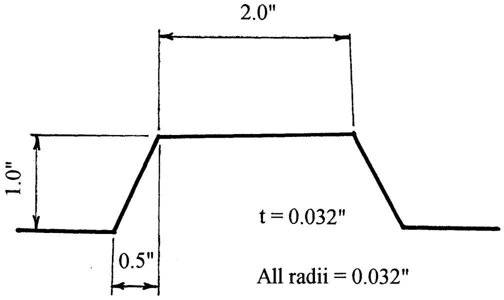

FIGURE 8.3: Example 8.4.

and the resistance factors are in Table 8.4. For an interior load use Equation 8.36. $\phi = 0.90$ for this case, the same as that for web buckling.

$$\begin{aligned}\phi P &= \frac{(0.90)(0.032)^2(2.0+5.4)(0.866)(0.46\times 14.0+0.02(10100\times 14.0)^{1/2})}{0.4+0.032(1-0.5)} \\ &= 0.198 \quad \text{kips per web}\end{aligned}$$

This load must be higher than that calculated using the factored loads. (Equations for factored loads are given in the [1].)

Calculation Example: Bending Strength of Section

To calculate the section strength, the strength of the flange under uniform compression and the strength of the web under bending are calculated separately, and then combined using a weighted average calculation. The area of the web used in the calculation is that area beyond 2/3 of the distance from the neutral axis. The resistance factor for the strength calculations from Table 8.4 is 0.85. The radii are neglected in subsequent calculations so that plate widths are to the intersection point of elements. The width to points of tangency of the corner radii is more accurate.

Strength of Flange

Equation 8.27 governs because the b/t ratio (62.5) is larger than the b/t limit given for that equation. Values for B_p and D_p are given by Equations 8.19 and 8.20; the value of K_p is in Table 8.8.

$$\phi F_{cr} = (0.85)(2.04)(18.4\times 10100)^{1/2}/(1.6)(62.5) = 7.5 \quad \text{ksi}$$

Strength of Web

The web is in bending and has a h/t ratio of 35 so Equation 8.17 governs. Values for B_p and D_p are given by Equations 8.25 and 8.26, and the value of K_p is in Table 8.8.

$$\phi F_p = (0.85)(24.5-(0.67)(.147)(35)) = 17.9 \quad \text{ksi}$$

Strength of Section

The bending strength of the section is between that calculated for the flange and web. An accurate estimate of the strength is obtained from a weighted average calculation, which depends on the areas of the elements and the strength of each element. The area of the webs is that portion further than 2/3 of the distance from the neutral axis.

$$\phi F = [(2.0)t(7.5) + (2)(1.12)t(0.187)(17.9)]/(2.0 + 0.374)t = 9.5 \quad \text{ksi}$$

This stress must be higher than that calculated using factored loads.

Calculation Example: Intermediate Stiffener

The bending strength of the section in Figure 8.3 can be increased significantly, with a small increase in material, by the addition of a formed stiffener at midwidth as illustrated in Figure 8.4. The strength of the stiffened panel is calculated using an equivalent slenderness ratio as given by Equation 8.40 and column buckling equations. The addition of a few percent more material as illustrated in Figure 8.4 can increase section strength by over 25%.

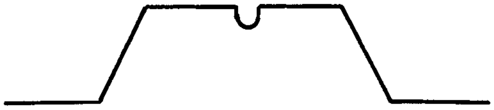

FIGURE 8.4: Example 8.4.

Calculation Example: Combined Bending and Concentration Loads

The formed sheet product can experience high longitudinal compressive stresses and a high normal concentrated load at the same location such as an intermediate support. These stresses interact and must be limited as defined by Equation 8.38.

EXAMPLE 8.5: Orthotropic Bridge Deck

Design Requirements

1. Withstand the static and impact loads as provided in an appropriate bridge design specification.
2. Withstand the cyclic loads provided in the specifications.
3. Fabricated by the use of welding.
4. Corrosion resistant so that painting is not needed.
5. Large prefabricated panels to shorten erection time.

Alloy and Product

The selection depends on the type of construction desired. Figure 8.5 is a plate reinforced by an extruded closed stiffener. This construction has been used successfully. The plate is 5456-H116, chosen because of it's high as-welded strength. The extrusion is of 6061-T651 which has high strength and reasonable cost. The extrusion is designed to accommodate welding and attachment to supports to minimize fabrication costs. Both alloys have excellent corrosion resistance and will not need to be painted.

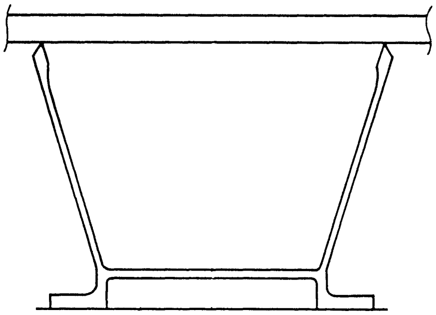

FIGURE 8.5: Example 8.5.

All extruded decks with segments either bolted or welded together, to achieve a shape similar to that in Figure 8.5, have also been used. 6061-T651 extrusions for all the segments are the choice in this case.

Joining

MIG welding with filler alloy 5556 is selected for attaching the extrusions to the plate. Fixturing is required to control the final shape of the panel.

Design Considerations

Large panels, 11 ft × 28 ft or larger, complete with wearing surface have been fabricated. The panels must be attached tightly to the supporting structure to avoid fatigue failures of the fasteners. Galvanized A356 bolts are suggested for the attachment to obtain high static and fatigue strengths.

Calculation Example: Bending Stresses in Plate and Section

Fatigue is the major design concern in a metal bridge deck. Wheel pressures cause bending stresses in the deck plate transverse to the direction of the stiffeners. These loads also cause longitudinal bending stresses in the stiffened panel. Fatigue evaluations are needed for both stresses. Deflection and static strength requirements of specifications also must be met.

EXAMPLE 8.6: Ship Hull

Design Requirements

1. Withstand pressures from operation in seas, including dynamic pressures from storms.
2. Withstand stresses from bending and twisting of entire hull from storm conditions.
3. Hull is of welded construction.
4. Hull must plastically deform without fracture when impacting with another object.
5. Employ joints that are proven to be fatigue resistant in other metal ship structures.
6. Corrosion resistant so that painting is not required even for salt water exposure.

Alloy and Product

The hull is constructed of stiffened plate. Alloy 5456-H116 plate and 5456-H111 extruded stiffeners are selected. Main girders are fabricated using 5456-H116 plate. Other lower strength 5XXX alloys are also suitable choices. This alloy is readily welded and has high as-welded strength.

The 5456-H111 extrusions are more costly than those of 6061-T6 but the welded 5XXX construction is much tougher using 5XXX stiffening, and thus would better accommodate damage without failure. This alloy has excellent resistance to corrosion in a salt water environment.

Joining

MIG welding using 5556 filler is specified. This is a high strength filler and is appropriate for joining parts of this high strength alloy.

Design Considerations

Loadings for hull or component design are difficult to obtain. The American Bureau of Shipping has requirements for the size of some of the components. Fireproofing is required in some areas.

Calculation Example: Buckling of Stiffened Panel

For a longitudinally framed vessel, the hull plate and stiffeners will be under compression from bending of the ship. The stiffened panel must be checked for column buckling between major transverse members using Equations 8.2 and 8.3. For hull construction that is subjected to normal pressures, the stiffened panel will have lateral bending as well as longitudinal compression. Equations 8.15 and 8.16 are needed in this case.

Elements of the stiffened panel must be checked for strength under the compression loads. In addition, an angle or T stiffener can fail by a torsion about an enforced axis of rotation, the point of attachment of the stiffener to the plate. Equation 8.39 may be used for the calculation.

EXAMPLE 8.7: Latticed Tower or Space Frame

Design Requirements

1. Withstand wind, earthquake, and other imposed loads.
2. Corrosion resistant so that painting is not required.
3. Prevent wind induced vibration.

Alloy and Product

Extrusions of 6061-T651 are selected for the members because of their corrosion resistance, strength, and economy. 6063 extrusions can be more economical if the higher strength of 6061 is not needed. The designer should make full use of the extrusion process by designing features in the cross-section that will facilitate joining and erection, and that will result in optimal use of the material.

Joining

Mechanical fasteners are selected. Galvanized A325 or stainless steel fasteners are best for major structures because of their higher strength compared to those of aluminum.

Design Considerations

Overall buckling of the system as well as the buckling of components must be considered. The manner in which the members are attached at their ends can affect both component and overall strength.

Special extrusions in the form of angles, Y-sections and hat-sections have been used in these structures. Some of these sections can fail by flexural-torsional buckling under compressive loads.

Equation 8.10 covers this case. These sections, because they are relatively flexible in torsion, can vibrate in the wind in torsion as well as flexure.

8.4 Economics of Design

There are two considerations that can affect the economy of aluminum structures: efficiency of design and life cycle costs. These considerations will be summarized briefly here.

Most structural designers are schooled in and are comfortable with design in steel. Although the design of aluminum structures is very similar to that in steel, there are differences in their basic characteristics that should be recognized.

1. The density of aluminum alloys is about 1/3 that of steel. Efficiently designed aluminum structures will weigh about 1/3 to 1/2 of those of efficiently designed steel structures, depending on failure mode. The lighter structures are governed by tensile or yield strength of the material and the heavier ones by fatigue, deflection, or buckling.
2. Modulus of elasticity of aluminum alloys is about 1/3 that of steel. The size/shape of efficient aluminum components will need to be larger for aluminum structures as compared to those of steel, for the same performance.
3. The fatigue strength of a joint of aluminum is 1/3 to 1/2 that of steel, with identical geometry. The size/shape of the aluminum component will need to be larger than that of steel to have the same performance.
4. The resistance to corrosion from the atmosphere of aluminum is much higher than that of steel. The thickness of aluminum parts can be much thinner than those of steel and painting is not needed for most aluminum structures.
5. Extrusions are used for aluminum shapes, not rolled sections as used for steel. The designer has much flexibility in the design to (1) consolidate parts, (2) include features for welding to eliminate machining, (3) include features to snap together parts or to accommodate mechanical fasteners, and (4) to include stiffeners, nonuniform thickness, and other features to provide the most efficient placement of metal. Because die costs are low, most extrusions are uniquely designed for the application.

Aluminum applications are economical generally because of life cycle considerations. In some cases, e.g., castings, aluminum can be competitive on a first cost basis compared to steel. Light weight and corrosion resistance are important in transportation applications. In this case the higher initial cost of the aluminum structure is more than offset by lower fuel costs and higher pay loads. Closed loop recycling is possible for aluminum and scrap has high value. The used beverage can is converted into sheet to make additional cans with no deterioration of properties.

8.5 Defining Terms

Alloy: Aluminum in which a small percentage of one or more other elements have been added primarily to improve strength.

Foil: Flat-rolled product that is less than 0.006 in. thick.

Heat-affected zone: Reduced strength material from welding measured 1 in. from centerline of groove weld or 1 in. from toe or heel of fillet weld.

Plate: Flat-rolled product that is greater than 0.25 in. thick.

Sheet: Flat-rolled product between 0.006 in. and 0.25 in. thick.

Temper: The measure of the characteristic of the alloy as established by the fabrication process.

References

[1] Aluminum Association. 1994. *Aluminum Design Manual,* Washington D.C.

[2] American Association of State Highway and Transportation Officials. 1994. *AASHTO LRFD Bridge Design Specifications,* Washington D.C.

[3] Sharp, M. L. 1993. *Behavior and Design of Aluminum Structures,* McGraw-Hill, New York.

[4] Sharp, M. L. 1994. Development of Aluminum Structural Technology in the United States, *Proceedings, 50th Anniversary Conference,* Structural Stability Research Council, Bethlehem, PA, 21-22 June 1994.

[5] Sharp, M. L., Nordmark, G. E., and Menzemer, C. C. 1996. *Fatigue Design of Aluminum Components and Structures,* McGraw-Hill, New York.

Further Reading

[1] Aluminum Association. 1987. *The Aluminum Extrusion Manual*, Washington D.C.

[2] American Bureau of Shipping. 1975. *Rules for Building and Classing Aluminum Vessels,* New York.

[3] American Welding Society. 1990. *ANSI/AWS D1.2-90 Structural Welding Code Aluminum*, Miami, FL.

[4] Gaylord and Gaylord. 1990. *Structural Engineering Handbook*, McGraw-Hill, New York.

[5] Kissell, J. R. and Ferry, R. L. 1995. *Aluminum Structures, A Guide to Their Specifications and Design,* John Wiley & Sons, New York.