Period #7 Notes: Aluminum as a Structural Material

A. A QUICK LOOK AT ALUMINUM

1. Overview

The amount of aluminum produced annually worldwide is second only to that of steel.

While aluminum is widely used in airframe structures and increasingly being used in automotive frames to decrease weight and improve fuel efficiency, it is not widely used as a civil structural material.

- In 1994, of the approximately 600,000 bridges in the U.S., only nine had primary structural elements of aluminum.

- There are a few landmark building structures that use aluminum as a primary structural material. Key examples are the John Hancock Center Tower in Chicago (Fig. 7.1a) whose exterior bracing system is made of black anodized aluminum alloy, and the ALCOA building in San Francisco (Fig. 7.1b).

Fig. 7.1a

Fig. 7.1b

To better understand aluminum, it is helpful to compare its properties and costs to those of steel:

Table 7.1. Comparative properties and costs of structural steel and aluminum.

	Mass density (g/cm^3)	Youngs Modulus E (GPa) and (Msi)	Yield Str.	Ult. Str.	Melting temp. T_m	Coef. Thermal Expansion α	Cost♦
Steel	7.9	200 (29)	210-1000 MPa (30-150 ksi)	400-1250 MPa (58-180 ksi)	1146ºC (2095ºF)	$12*10^{-6}$ per ºC	$545-$774/ton
Aluminum	2.7	69 (9.9)	28-503 MPa (4-73 ksi)	69-572 MPa (10-83 ksi)	660ºC (1220ºF)	$24*10^{-6}$ per ºC	$2000/ton

♦costs are current as of Feb. 2006. Steel costs are for carbon and alloy steels. Stainless steel costs are substantially higher at $2700-$4800/ton.

From the comparison provided in Table 7.1 a number of observations can be made:

1. Aluminum is only about one third as heavy as steel.
2. Aluminum is only about one third as stiff as steel.
3. The specific stiffnesses of steel and aluminum are very close. Specific stiffness is typically quantified by the ratio of Young’s modulus to mass density.

$$\left(\frac{E}{\rho}\right)_{steel} = 2.53*10^{7}(m\cdot s^{-1})^{2}; \qquad \left(\frac{E}{\rho}\right)_{\text{aluminum}} = 2.55*10^{7}(m\cdot s^{-1})^{2}$$

4. For both steel and aluminum, there is a very significant range of yield and tensile strengths. There is some overlap in the ranges, so that <u>the stronger grades of aluminum are stronger than the weaker grades of structural steel</u>.

5. Normalized for mass densities the specific strengths of steel and aluminum are provided below. The highest specific strength of aluminum exceeds that of steel.

$$\left(\frac{\sigma_{ult}}{\rho}\right)_{steel} = 0.51 - 1.58*10^5 (m \cdot s^{-1})^2; \qquad \left(\frac{\sigma_{ult}}{\rho}\right)_{\text{aluminum}} = 0.25 - 2.12*10^5 (m \cdot s^{-1})^2$$

6. Aluminum is a much lower temperature metal than steel. (This could be an issue in high-rise buildings, since during fires it is critical that the structural material retain its integrity long enough for people to evacuate the building.)

7. The CTE of aluminum is twice that of steel.

8. The cost of aluminum per unit weight is 3-4 times that of carbon and alloy steels. (Costs of stainless steels, however, are greater than those of aluminum.)

Based on these observations it is clear that aluminum can be cost-competitive with steel for weight-critical applications (as in airplanes and automobiles). In applications where weight is not critical, though, steel will generally provide higher stiffness and strength at a much lower cost.

For civil infrastructure applications, weight is typically not a critical issue. Thus, there is relatively little benefit to paying the higher material costs for aluminum.

B. ALUMINUM ALLOYS

Pure aluminum is actually quite weak, having strengths only about one tenth those of low-carbon steels ($\sigma_y \cong$ 4ksi (28 MPa) and $\sigma_{ult} \cong$ 6ksi (42 MPa).

To bring its strength up to acceptable levels, aluminum is usually alloyed with other metals.

Therefore, when specifying aluminum for a particular application, it is important to select the proper alloy.

The AISI system specifies aluminum alloys using a four-digit sequence. The alloys are divided into two major groups: (1) wrought alloys; and (2) cast alloys. The wrought alloys are designated by four digits WXYZ whereas the cast alloys are designated with four digits and a decimal point WXY.Z The wrought alloys are good for structural members that are either extruded, rolled or forged. The cast alloys are suitable for aluminum parts and members that are cast using molds. For civil infrastructure applications, wrought aluminum alloys are most applicable.

Table 7.2. The AISI designation system for aluminum alloys.

Wrought alloys		Cast alloys	
Series	Major alloy	Series	Major alloy
1XYZ	99% pure aluminum	1XY.Z	99% pure aluminum
2XYZ	Copper (Cu)	2XY.Z	Copper (Cu)
3XYZ	Manganese (Mn)	3XY.Z	Si and (Cu or Mg)
4XYZ	Silicon (Si)	4XY.Z	Silicon (Si)
5XYZ	Magnesium (Mg)	5XY.Z	Magnesium (Mg)
6XYZ	Mg and Si	6XY.Z	Unused
7XYZ	Zinc (Zn)	7XY.Z	Zinc (Zn)
8XYZ	Other	8XY.Z	Tin
9XYZ	Unused	9XY.Z	Other

In the designation system for wrought alloys, the digits after the first have special meaning:

- 2nd digit → indicates whether or not the basic alloy is modified (0 if not, >0 if modified)
- 3rd and 4th digits → indicate the amount of aluminum or the primary alloy

In the designation system for cast alloys, the digits after the first have special meaning:

- 2nd and 3rd digits → indicate the amount of aluminum or the primary alloy
- 4th digit → indicates if the alloy composition if for a final casting (0) or an ingot (1 or 2) that will be further processed.

The wrought alloys can be subdivided into those that are *heat-treatable* and those that are *strain-hardenable*.

- The heat-treatable wrought alloys are 2XYZ, 6XYZ, 7XYZ.
- The strain-hardenable wrought alloys are 1XYZ, 3XYZ, 5XYZ.

In the designation for the heat-treatable alloys, an appended two- or three-digit descriptor T1-T10 is commonly provided to describe which of ten different heat treatments were used to achieve the final product.

In the designation for the strain-hardenable alloys, a three-digit descriptor HXY. The first digit H indicates the alloy has been strain hardened. The second digit X →1 for pure strain hardening; X →2 for strain hardening and partial annealing; and X →3 for strain hardening and stabilization. The third digit Y indicates the degree of strain hardening of the material, with 1 being the lowest degree, and 9 being the highest.

For both heat-treatable and strain-hardenable alloys, the single digit descriptor O indicates that the metal has been annealed. Thus any strain-hardening or quenching effects have been eliminated.

Table 7.3. Properties for a few selected strain-hardenable wrought aluminum alloys.

Alloy		Yield strength		Tensile strength		Elongation (%)		composition (%)
		ksi	MPa	ksi	MPa	1/16"	1/2"	
1060	O	4	28	10	69	43		99.6 Al
	H-12	11	76	12	83	16		
	H-14	13	90	14	97	12		
	H-16	15	103	16	110	5		
	H-18	18	124	19	131	6		
3003	O	6	41	16	110	30	40	1.2 Mn
	H-12	18	124	19	131	10	20	
	H-14	21	145	22	152	8	16	
	H-16	25	172	26	179	5	14	
	H-18	27	186	29	200	4	10	
5005	O	6	41	18	124	25		0.8 Mg
	H14	22	152	23	159	6		
	H34	20	138	23	159	8		
	H18	28	193	29	200	4		
	H38	27	186	29	200	5		
5456	O	23	159	45	310	20	24	5.1 Mg 0.7 Mn 0.12 Cr
	H-111	33	228	47	324		18	
	H-112	34	235	45	310		22	
	H-116	37	255	51	352		16	

Table 7.4. Properties for a few selected heat treatable wrought aluminum alloys.

Alloy		Yield strength		Tensile strength		Elongation (%)		composition (%)
		ksi	MPa	ksi	MPa	1/16”	1/2”	
2014	O	14	97	27	186		18	4.5 Cu 0.8 Mn 0.8 Si
	T4/T451	42	290	62	427		15	
	T6/T651	60	414	70	483		13	
6061	O	8	55	18	124	25	30	1.0 Mg 0.6 Si, 0.25 Cu, 0.25 Cr
	T4/T451	21	145	35	241	22	25	
	T6/T651	40	276	45	310	12	17	
7178	O	15	103	33	228	15	16	6.8 Zn, 2.0 Cu, 2.7 Mg, 0.3 Mn
	T6/T651	78	538	88	607	10	11	
	T76/T765	73	503	83	572		11	

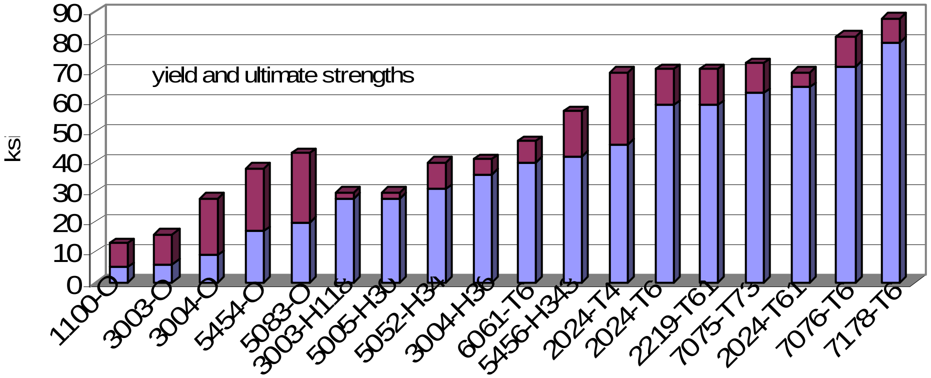

Fig. 7.2. Yield and tensile strengths of selected grades of wrought aluminum alloys.

General observations:

- For the work hardening alloys, strength increases with degree of hardening, with a corresponding decrease in ductility.
- partial annealing or tempering of the work hardening alloys (i.e. H2X, H3X) improves the ductility somewhat.
- For the heat-treating alloys, similar trends hold.
- The strongest wrought aluminum alloys are generally the 2XYZ (copper) and 7XYZ (zinc) series.

C. CORROSION CHARACTERISTICS

1. Dry Corrosion: Like iron and steel, aluminum does corrode. However the oxide product adheres well to the parent metal and provides a barrier that inhibits further dry corrosion.

   The dry-corrosion resistance of pure aluminum is the highest. When aluminum is alloyed to increase its strength, the corrosion resistance suffers somewhat.

2. Wet Corrosion:

   Since aluminum has a relatively low electrode potential of -1.70, it is anodic to most other metals except magnesium, sodium, potassium, and lithium. Thus, it will corrode when immersed in an electrolyte with steel and zinc. Although quite a few ocean-going boats are made with aluminum hulls, they must be carefully monitored to avoid galvanic corrosion.

   If galvanic corrosion of aluminum can be avoided, by avoiding usage of more cathodic metals, then aluminum can be quit durable in water.

The aluminum alloys having the best wet corrosion resistance are those in the 3xxx, 5xxx, and 6xxx series (Table 7.6).

Nevertheless, pure aluminum has better corrosion resistance than any of these alloys. For this reason, aluminum alloys deployed in water are often clad with a thin skin of pure aluminum. Aluminum alloys with this thin coating of pure aluminum are generally called "Alclad" alloys.

Table 7.6. A to E grading of aluminum alloy characteristics, with A being excellent and E being inferior. [adapted from Mech. Engineers' Handbook, 2nd Ed., Kutz, M. (Ed.), John-Wiley Interscience, 1998]

Alloy	Corrosion resistance	Workability	Machinability	Brazeability	Weldability (Arc)
1100	A	A-C	E-D	A	A
2024	D	C-D	B	D	B-C
3003	A	A-C	E-D	A	A
3004	A	A-C	D-C	B	A
5005	A	A-C	E-D	B	A
5052	A	A-C	D-C	C	A
5456	A	B-C	D-C	D	A
6061	B	A-C	D-C	A	A
7075	C	D	B	D	C

D.SUMMARY

When all factors are considered, the 5XYZ and 6XYZ series aluminum alloys are most attractive for potential usage in civil infrastructure applications.