Introduction to Aluminum as a Structural Material

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Learning Outcomes

- Know the major aluminum alloy groups and their uses
- Know the principal structural properties of aluminum
- Become proficient in designing aluminum structural members and connections

Course Outline

- 1 Overview
- 2 Alloys and tempers
- 3 Products
- 4 Material properties
- 5 Structural design overview

1. Overview

- Examples of aluminum structures
- Aluminum’s main attributes
- Sources of information

Examples of Aluminum Structures

- Curtain walls and storefronts
- Roofing and canopies
- Space frames
- Tanks and vessels (corrosive & cryogenic)
- Portable structures (scaffolding, ladders)
- Highway products (signs, light poles, bridge rail)

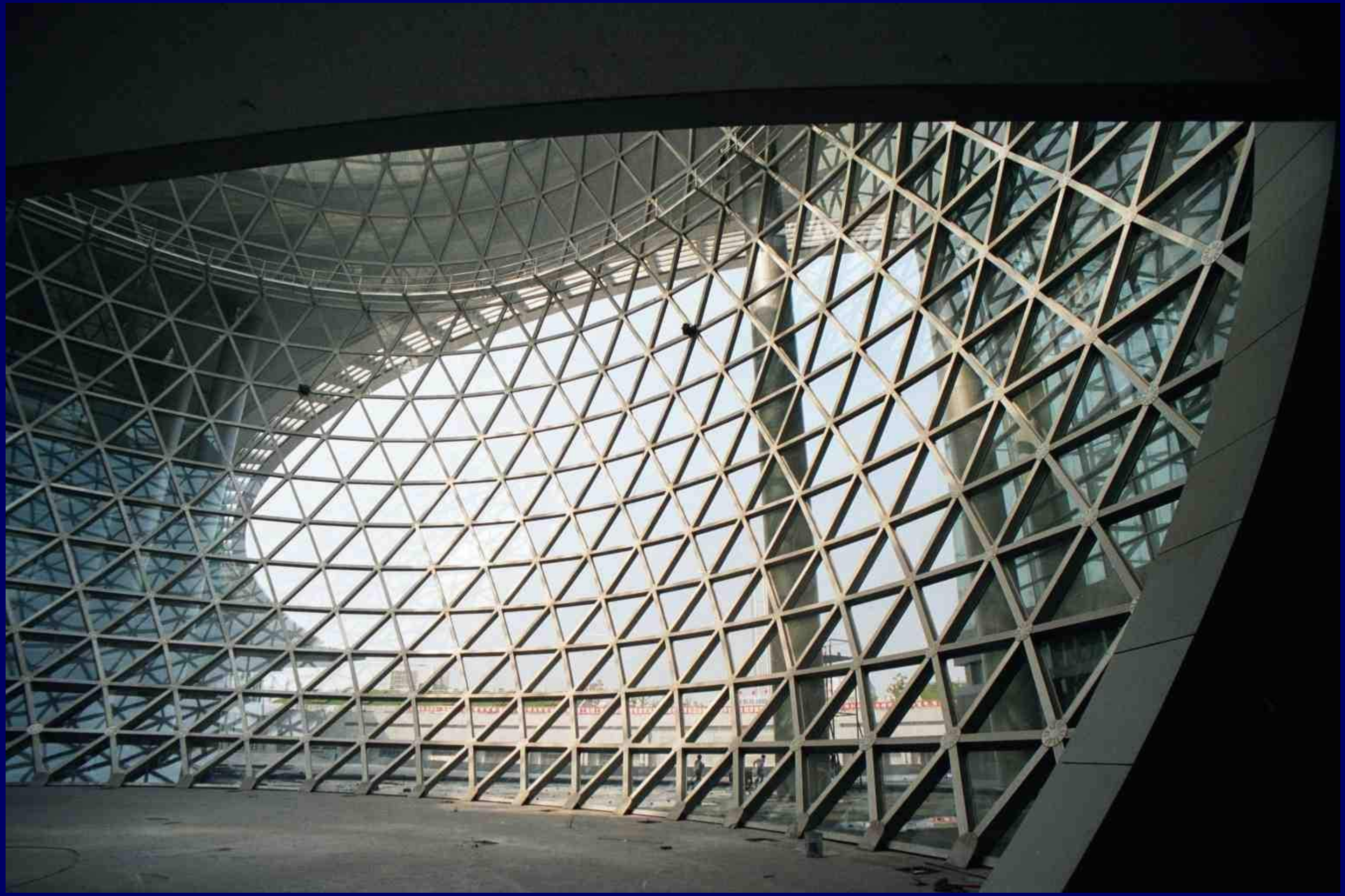
Cira Center Curtain Wall

courtesy of Larson Engr.

Science Land Egg (164’ wide)

courtesy of Temcor

Science Land Egg



courtesy of Temcor

Aluminum's Main Attributes

- Formability
- High strength-to-weight ratio
- Corrosion resistance
- Better strength, ductility at low temperature
- Low modulus of elasticity (10,000 ksi)
- High electrical and thermal conductivity
- Low melting point (1200^{o}F)

Low Melting Point

Where Aluminum Structures Make Sense

- Members with complex cross sections
- Long clear spans
- Portable or moving structures
- Retrofitting existing structures
- Structures in cryogenic environments
- Structures in corrosive environments
- Structures in seismically active zones

- Founded in 1933, its 120 members include the major US producers
- AA writes most standards on aluminum; has worldwide influence
- Contact: www.aluminum.org

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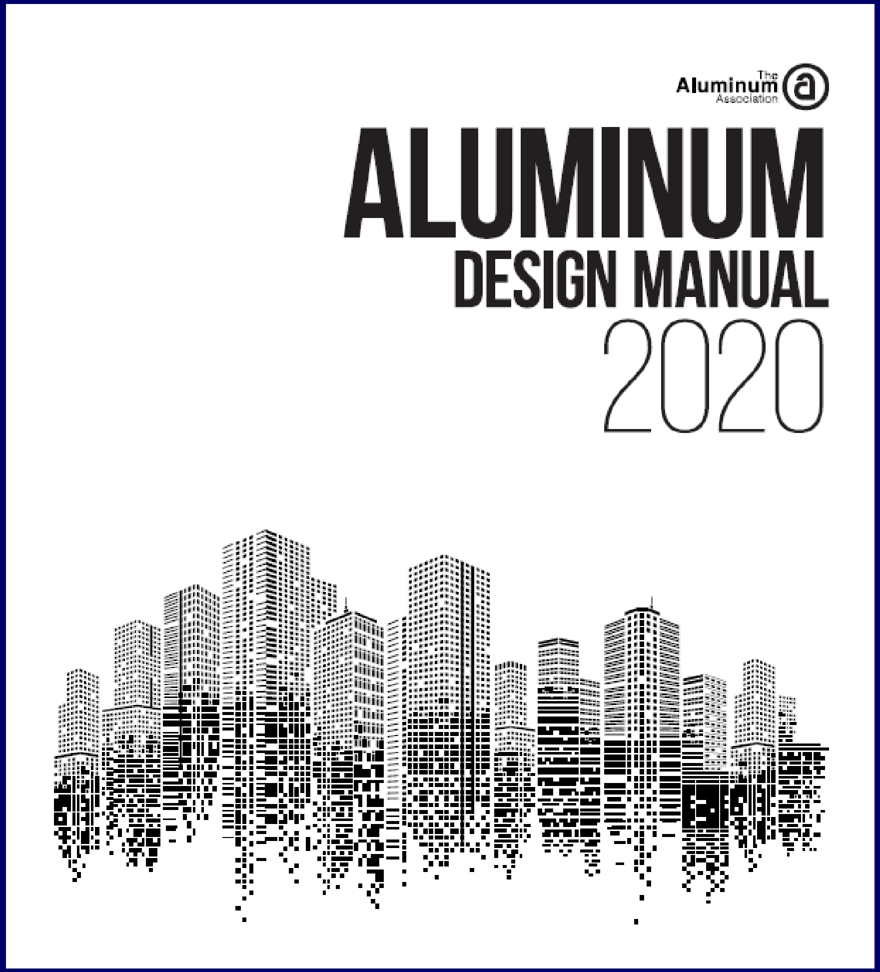
  Arlington, VA 22202

  703-358-2960; pubs 480-779-6259

The *Aluminum Design Manual*



Aluminum Design Manual (ADM)

- Issued every 5 years; latest is 2020
- Prior editions: 1994, 2000, 2005, 2010, 2015
- 1st ed (1994) was compilation of several AA pubs previously issued separately; most importantly, the *Specification for Aluminum Structures* (SAS)
- Errata: http://aluminum.org/resources/industry-standards

Aluminum Design Manual Contents

- The *Aluminum Design Manual* (ADM)
  - Part I – *Specification for Aluminum Structures*
  - Part II – Commentary
  - Part III – Design Guide
  - Part IV – Material Properties
  - Part V – Section Properties

Aluminum Design Manual Contents

- The *Aluminum Design Manual* (ADM)
  - Part VI – Design Aids
  - Part VII – Illustrative Examples
  - Part VIII – Guidelines for Aluminum Sheet Metal Work in Building Construction
  - Part IX – Code of Standard Practice for Fabricating and Erecting Structural Aluminum

Specification for Aluminum Structures (SAS)

- The *Specification for Aluminum Structures* is Part I of the *Aluminum Design Manual*
- SAS is also called “the Aluminum *Specification*”
- Adopted in IBC (and previously by BOCA, UBC, SBC)
- It’s the source of all aluminum structural design requirements in the US

Specification for Aluminum Structures (SAS)

- 2010 edition was a major rewrite
- It's a unified Specification, with both:
  - Allowable Strength Design (ASD)
    - For buildings and bridges
  - Load and Resistance Factor Design (LRFD)
    - For buildings only
    - Load factors from ASCE 7 (= 1.2*D* + 1.6*L* …)
    - Every edition since 1994 has had LFRD

2020 Specification for Aluminum Structures (SAS)

- A. General Provisions
- B. Design Requirements
- C. Design for Stability*
- D. Design of Members for Tension
- E. Design of Members for Compression
- F. Design of Members for Flexure
- G. Design of Members for Shear
- H. Design of Members for Combined Forces and Torsion
- J. Design of Connections

2020 Specification for Aluminum Structures (SAS)

- L. Design for Serviceability*
- M. Fabrication and Erection
- N. Quality Control and Quality Assurance**

Appendices

- 1. Testing
- 3. Design for Fatigue
- 4. Design for Fire Conditions*
- 5. Evaluation of Existing Structures*
- 6. Member Stability Bracing*

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*New in 2010; **New in 2015

2. Alloys and Tempers

- Wrought alloy designation system
- Aluminum temper designation system
- Material specifications

Aluminum Isn't Just One Thing

- Like other metals, aluminum comes in many alloys
- Alloy = material with metallic properties, composed of 2 or more elements, of which at least one is a metal
- Different aluminum alloys can have very different properties
- Alloying elements are usually < 5%

Wrought Alloy Designation System

Number	Main Alloy	Strength	Corrosion
1xxx	$\geq$ 99% Al	Fair	Excellent
2xxx	Cu	High	Fair
3xxx	Mn	Fair	Good
4xxx	Si	Good	Good
5xxx	Mg	Good	Good
6xxx	Mg Si	Good	Good
7xxx	Zn	High	Fair
8xxx	others		

Wrought Alloy Key

- 1st digit denotes main alloying element
- 3rd and 4th digits are sequentially assigned
- 2nd digit denotes a modification
- Example:
  - 2319 = AlCu alloy (2xxx) modification on 2219
  - 2319 composition is identical to 2219 except slightly more Ti (grain refiner to improve weld strength); both have 6.3% Cu

1xxx Alloys (pure Al)

- Common uses:
  - Electrical conductors
  - Corrosive environments
- Examples
  - 1060 (99.60% aluminum)
  - 1100 (99.00% aluminum)
- Pro: corrosion resistant, good conductors
- Con: Not very strong

2xxx Alloys (Al-Cu)

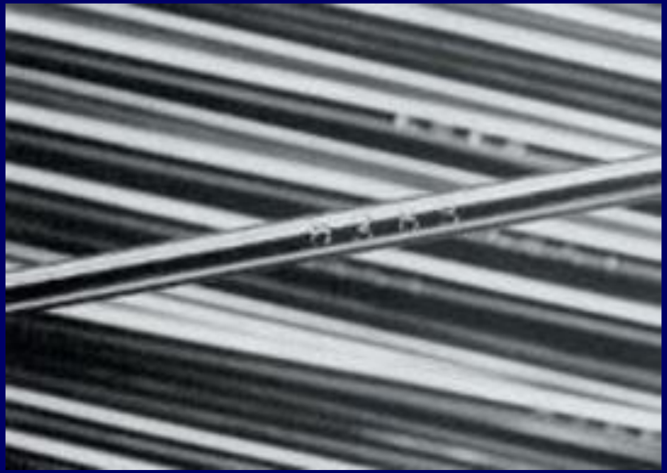
- Common Uses
  - Aircraft parts, skins
  - Fasteners
- Example
  - 2024
- Pro: Strong
- Con: Not very corrosion resistant; hard to weld when Cu is about 1 to 5%

3xxx Alloys (Al-Mn)

- Common Uses
  - Roofing and siding
  - Gutters and downspouts
- Examples
  - 3003, 3004, 3105
- Pro: Formable, good corrosion resistance
- Con: Not that strong

4xxx Alloys (Al-Si)

- Common Uses
  - Welding and brazing filler metal
- Example
  - 4043
- Pro: Flows well
- Con: Lower ductility

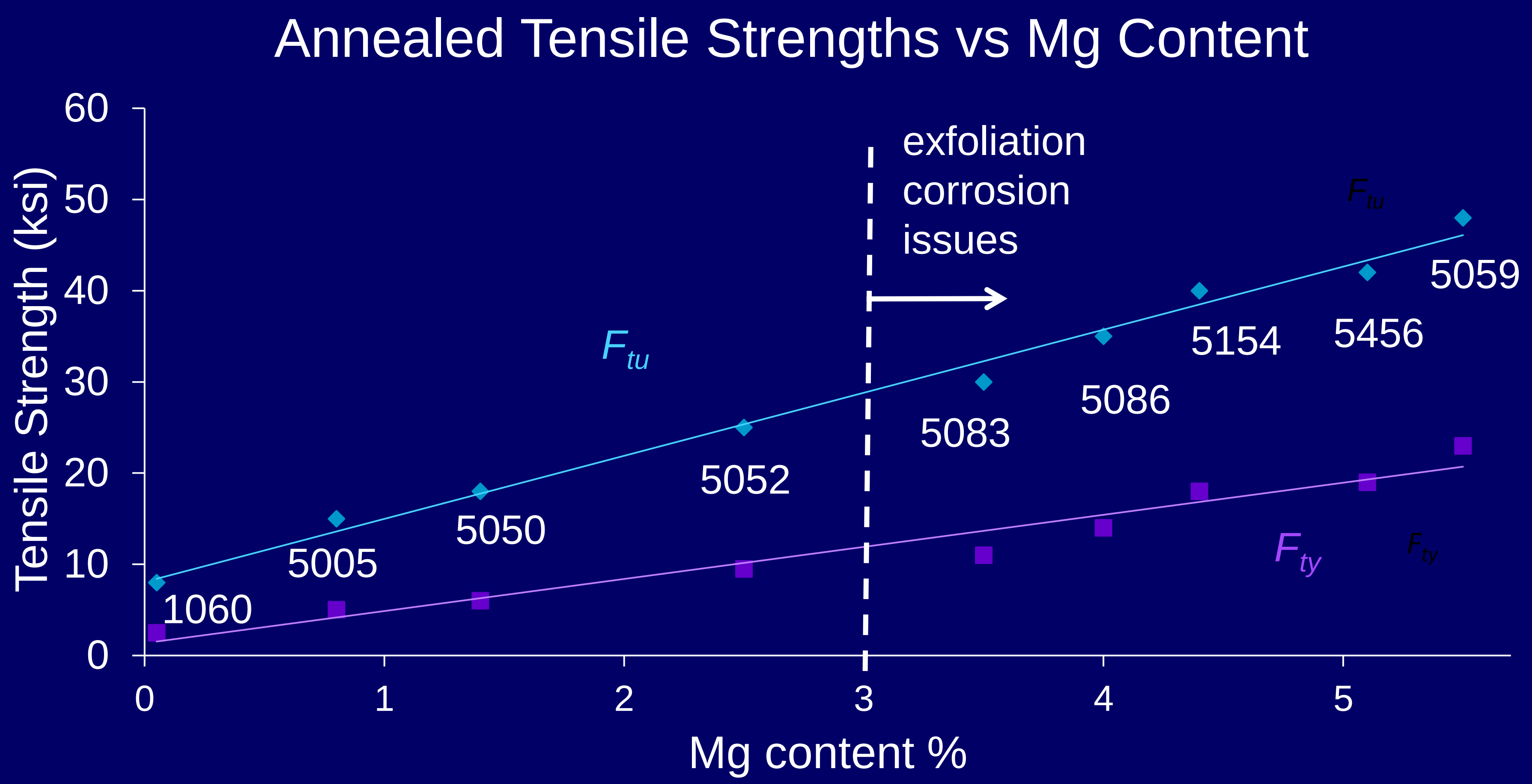


5xxx Alloys (Al-Mg)

- Common Uses
  - Marine applications
  - Welded plate structures
- Examples
  - 5052, 5083

- Pro: Strong, even when welded
- Con: Hard to extrude; those with 3%+ Mg can have corrosion resistance issues

5xxx Alloys


Annealed Tensile Strengths vs Mg Content
Tensile Strength (ksi)
60
50
40
30
20
10
0
0
1
2
3
4
5
Mg content %
exfoliation
corrosion
issues
Ftu
Fty
1060
5005
5050
5052
5083
5086
5154
5456
5059

6xxx Alloys (Al-Mg_2Si)

- Common Uses
  - Structural shapes
  - Pipe
- Examples
  - 6061, 6063
- Pro: Good combination of strength and corrosion resistance, very extrudable
- Con: Lose considerable strength when welded

7xxx Alloys (Al-Zn)

- Common Uses
  - Aircraft parts
- Two classes
  - With copper (example: 7075)
  - Without copper (example: 7005)
- Pro: Very strong (7075-T6 F_{tu} = 80 ksi)
- Con: Not very corrosion resistant;
  hard to arc weld (except those w/ no Cu)

How Alloys are Strengthened

- Alloying elements (Mg is good example)
- Tempering:
  - Strain hardening (cold working)
  - Heat treatment
- Heat treatable: 2xxx, 6xxx, 7xxx
- Non-heat treatable: 1xxx, 3xxx, 5xxx

Annealed Condition

- Before tempering, alloys start in the annealed condition (-O suffix)
- Annealed condition is weakest but most ductile
- Tempering increases strength, but decreases ductility
- Most alloys are annealed by heating to 650ºF (melting point is about 1100ºF)

Strain Hardening

- Mechanical deformation at ambient temps
- For sheet and plate, deformation is by rolling to reduce the thickness
- Some non-heat treatable alloys undergo a stabilization heat treatment
  - Purpose: to prevent age softening
  - Only used for some Al-Mg (5xxx) alloys

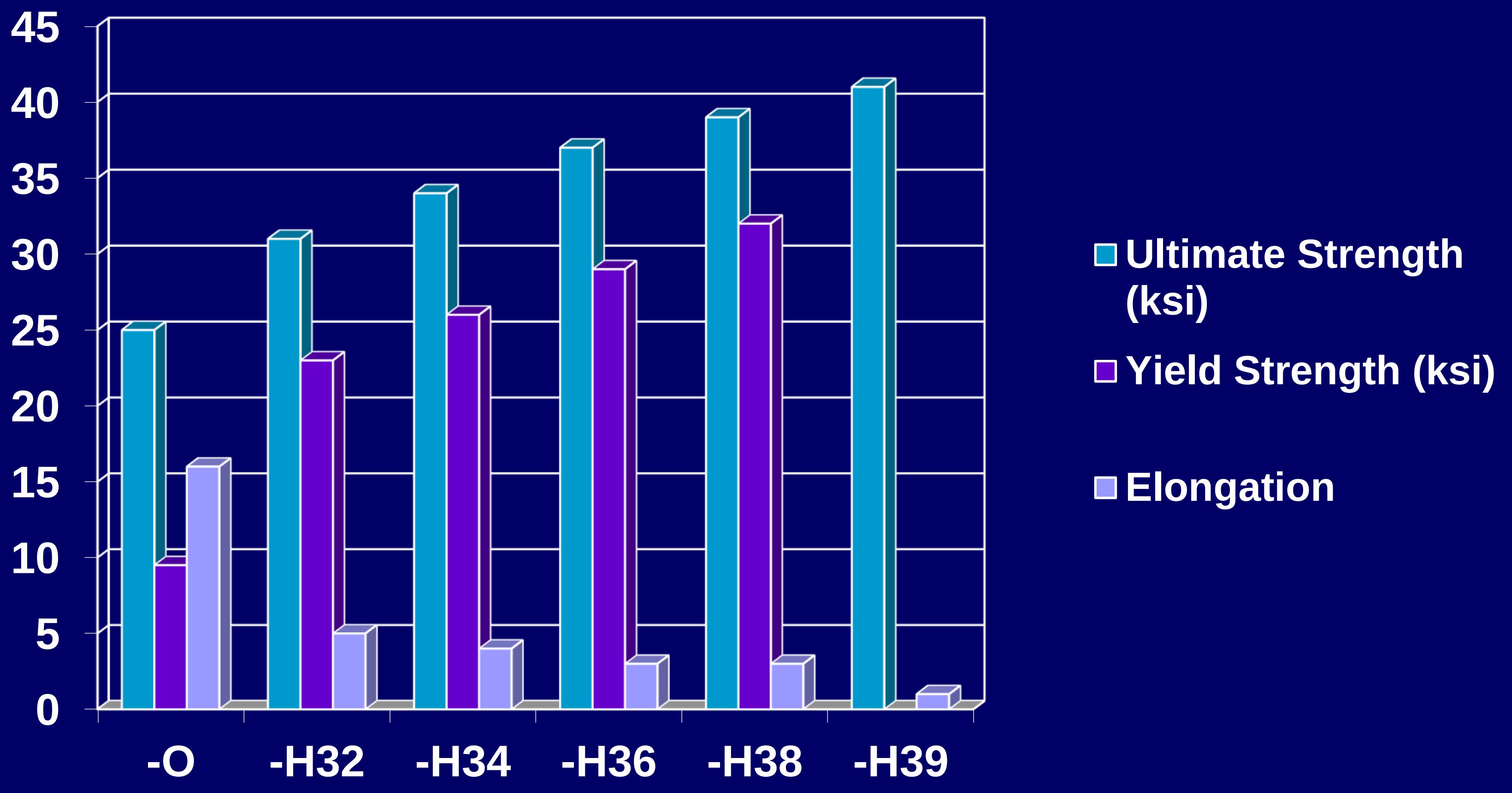
Strain Hardened Tempers

- H1x – Strain hardened only (1100-H14)
- H2x – Strain hardened & partially annealed (3005-H25)
- H3x – Strain hardened & stabilized (5005- H34)
- H4x – Strain hardened and lacquered or painted and thermally cured

Strain Hardened Tempers

Temper	F_{tu} (ksi)	Description
5052-O	25	Annealed
5052-H32	31	¼ hard
5052-H34	34	½ hard
5052-H36	37	¾ hard
5052-H38	39	Full hard
5052-H39	41	*Really* hard

Effect of Strain Hardening 5052



Heat Treating

- Solution heat treatment
  - Annealed material (6061-O) is heated to 990°F, then quenched
  - Resulting temper is 6061-T4
- Precipitation heat treatment (artificial aging)
  - Solution heat treated material (6061-T4) is heated to 350°F and held for 8 hrs
  - Resulting temper is 6061-T6

Tempers Summarized

- -H is for strain hardened tempers
  - 1xxx, 3xxx, 5xxx alloys
  - Higher 2nd digit: stronger, less ductile
- -T is for heat treated tempers
  - 2xxx, 6xxx, 7xxx alloys
  - T4 = solution heat treated
  - T5 and greater = precipitation heat treated

ASTM Aluminum Specifications Typically Include:

- Minimum mechanical properties:

  F_{ty}, F_{tu}, elongation e
- Dimensional tolerances (ANSI H35.2)
- Chemical composition limits
- Identification marking requirements
- Sometimes, other requirements like bendability, corrosion resistance.

ASTM Wrought Aluminum Specifications

- B209 Sheet and Plate
- B210 Drawn Seamless Tubes
- B211 Bar, Rod, and Wire
- B221 Extruded Bars, Rods, Wire, Profiles and Tubes
- B241 Seamless Pipe and Seamless Extruded Tube
- B247 Die Forgings, Hand Forgings, Rolled Ring Forgings

ASTM Wrought Aluminum Specifications

- B308 Standard Structural Profiles
- B316 Rivet and Cold Heading Wire and Rod
- B429 Extruded Structural Pipe and Tube
- B632 Rolled Tread Plate
- B928 High Magnesium Aluminum Alloy Sheet and Plate for Marine and Similar Service (has corrosion resistance reqs)
- There are others not included in SAS

3. Aluminum Product Forms

- Wrought products
  - Made by mechanically working the metal
  - Example: rolling to produce sheet
  - Tolerances are in ANSI H35.2 or *AS&D*
- Castings
  - Made by pouring molten metal into a mold
  - Example: sand casting
  - Tolerances are up to you

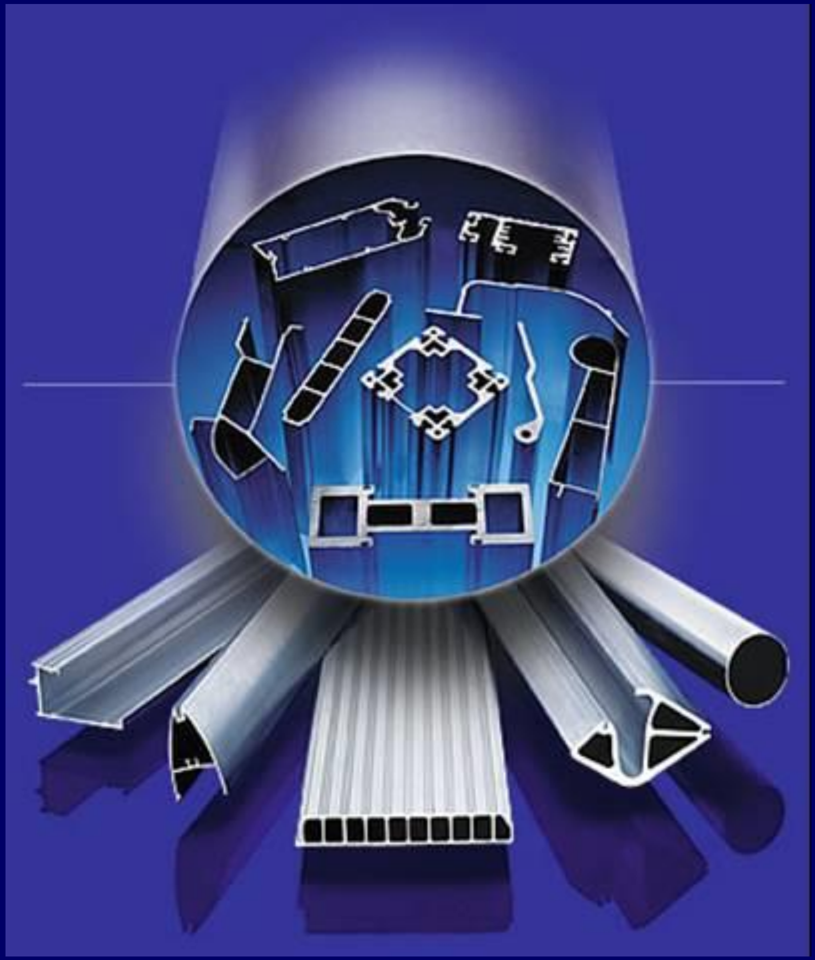
Sheet and Plate

- Rolled product with slit, sheared, or sawed edges
- Sheet: 0.006” $\leq$ t < 0.25”
  - t < 0.006” is foil
  - $t \geq$ 0.020” for most construction applications
  - IBC specifies 0.024” min t for roofing
- Plate: $t \geq$ 0.25”
  - t up to 8” available in some alloys, strength is slightly less in thicker plates

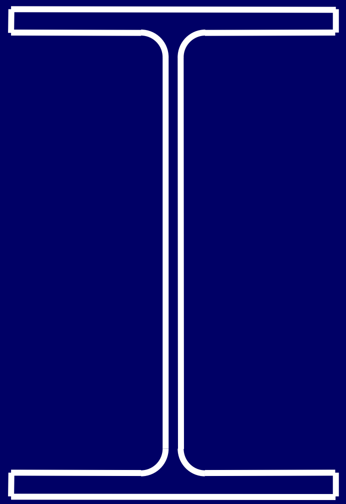
Extrusions

- Made by pushing solid material through an opening called a die
- Offers great flexibility to designers
- Solid and hollow shapes can be extruded
- Some alloys are easier to extrude
- Maximum circle size
  - for common products ≈ 19”
  - for special products ≈ 30”

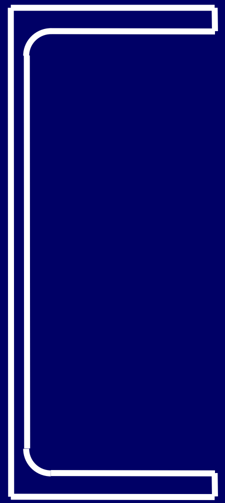
Extruded Shapes



Aluminum Association Standard I-beams and Channels



15 I-Beams

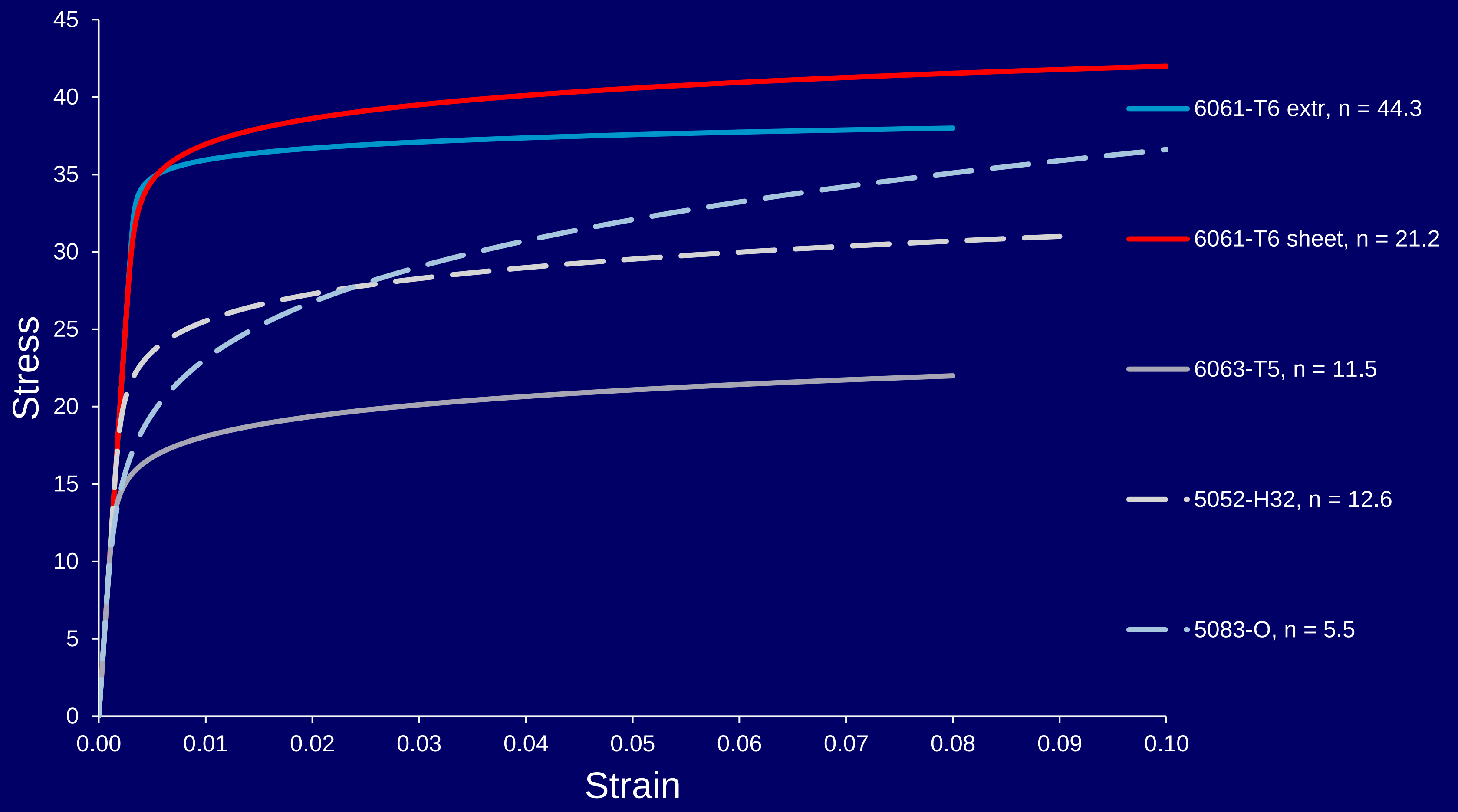


20 Channels

4. Aluminum Material Properties

- Strengths
- Modulus of Elasticity, Poisson’s Ratio
- Ductility
- Effect of Welding on Properties
- Effect of Temperature on Properties
- Physical Properties

Stress-Strain for Several Alloys



Types of Strengths

Type of Stress	Yield	Ultimate
Tension	F_{ty}	F_{tu}
Compression		
H temper:	$F_{cy} = 0.9F_{ty}$	–
other tempers:	$F_{cy} = 1.0\ F_{ty}$	
Shear	$F_{sy} = 0.6F_{ty}$	$F_{su} = 0.6F_{tu}$

Some Aluminum Alloy Strengths

Alloy-temper, product	F_{ty} ksi	F_{tu} ksi
5052-H32 sheet & plate	23	31
5083-H116 plate $\leq$ 1.5” thick	31	44
6061-T6 extrusions	35	38
6063-T5 extrusions $\leq$ 0.5” thick	16	22

Modulus of Elasticity, Poisson's Ratio

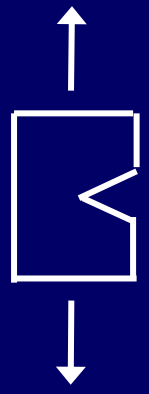
- Modulus of Elasticity (Young's Modulus) E
  - Measures stiffness and buckling strength
  - Compressive E = 1.02(Tensile E)
  - Varies by alloy; E_c = 10,100 to 10,900 ksi for SAS alloys, but use 10,100 ksi for all
  - Compares to 29,000 ksi for steel
- Poisson's ratio ν
  - Average value = 0.33
- Shear Modulus G = 3,800 ksi = $E/[2(1+\nu)]$

Ductility

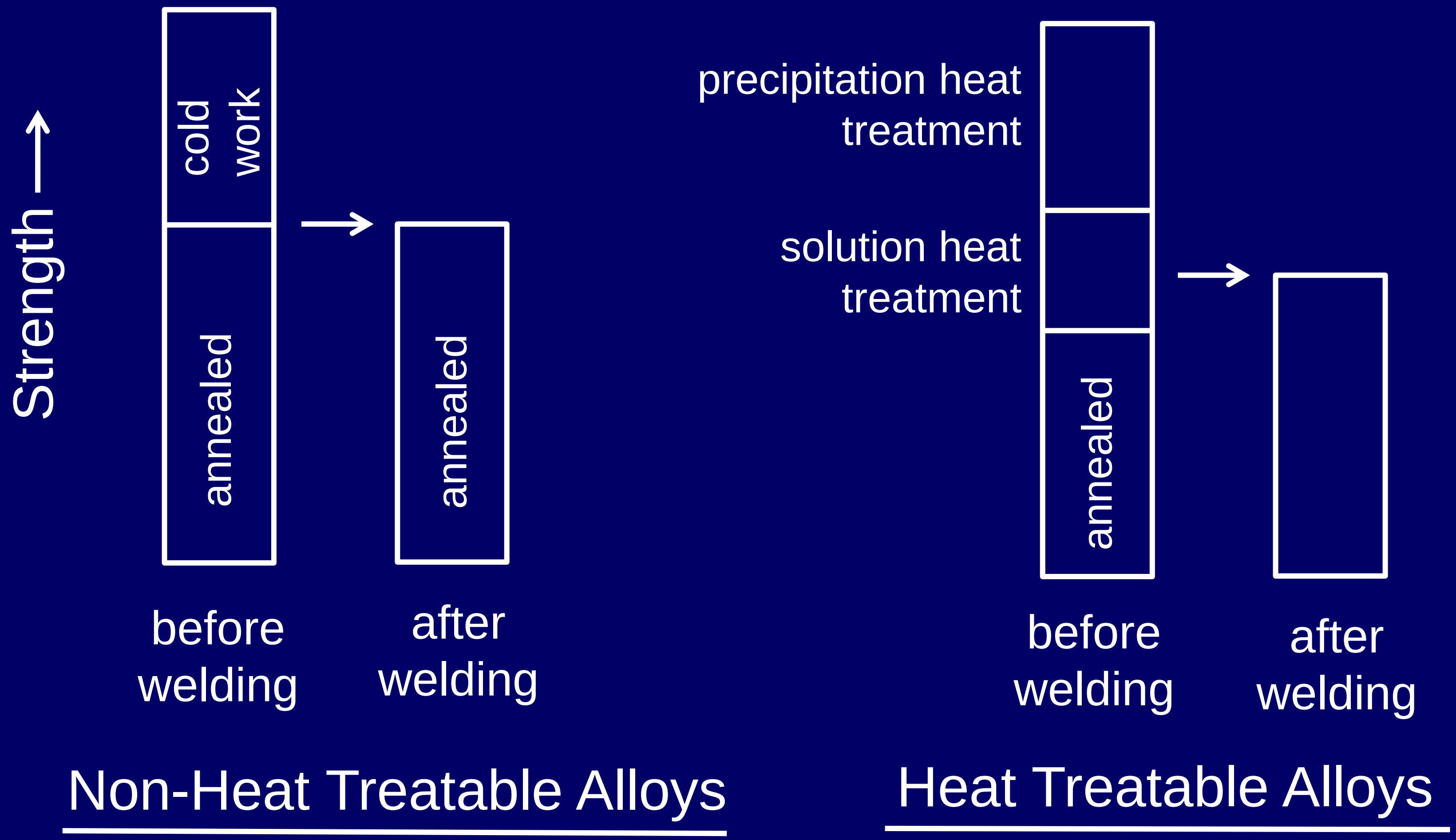
- Ductility: the ability of a material to withstand plastic strain before rupture
- Fracture Toughness: Aluminum doesn't have a transition temperature like steel
- Elongation e
- ASTM E292 Notch-Yield Ratio =

  (F_{tu} of standard notched specimen)/F_{ty}

  If notch-yield ratio > 1, not brittle



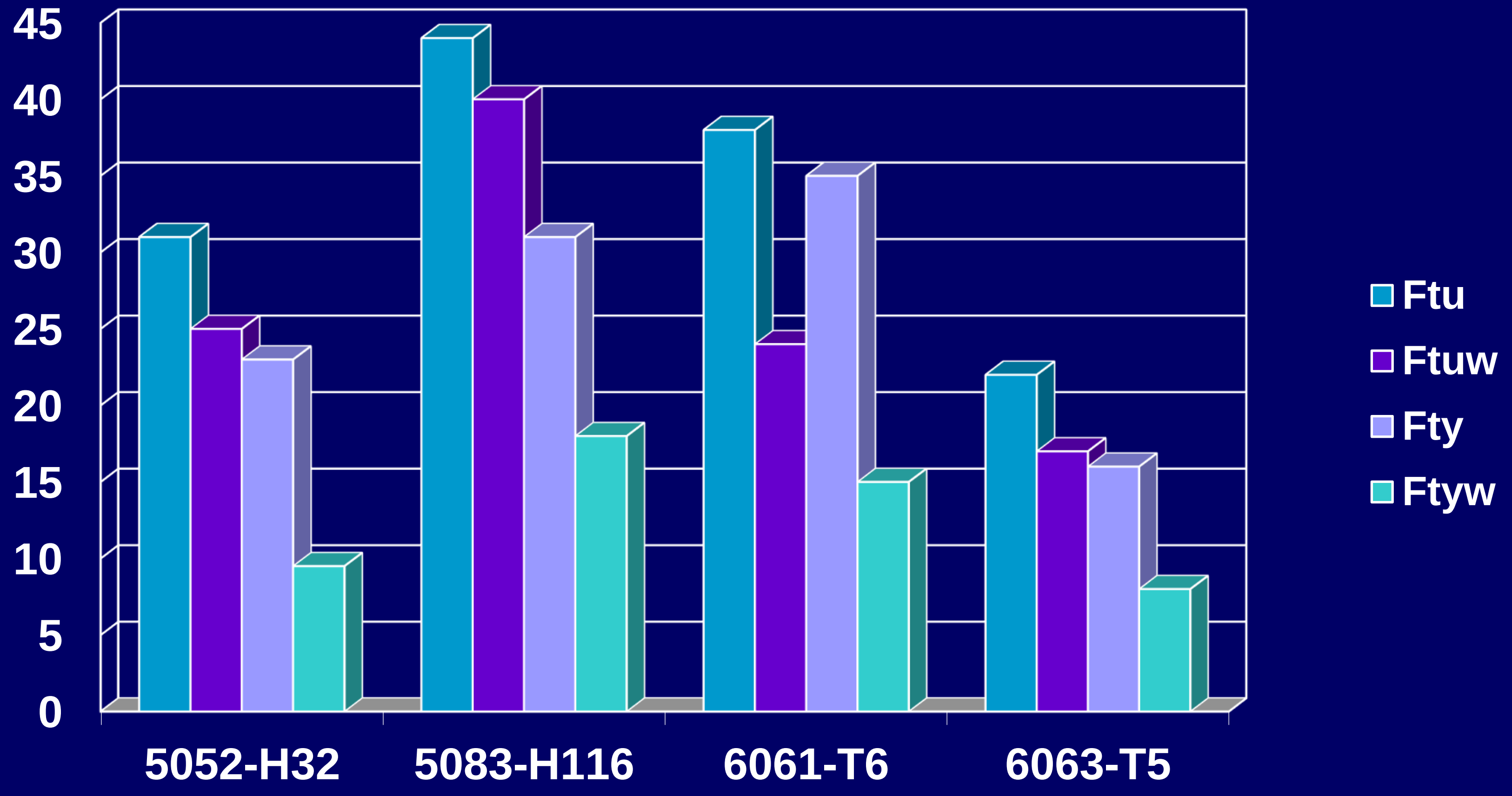
Effect of Welding



Welded Strengths

- Welded strengths are in SAS Table A.4.3
- Notation: add *w* to subscript
  - F_{tuw} = welded F_{tu}
- AWS D1.2 Table 3.2 gives same F_{tuw} as SAS Table A.4.3
  - To qualify groove weld procedures in D1.2, F_{tuw} must be achieved
- Beware: SAS F_{tyw}'s decreased in 1994

Effect of Welding on Strength



Effect of Temperature

- Below room temperature:
  - Elongation and strengths increase
  - Risk of brittle fracture does not increase
- Above about 150^{o}F:
  - Elongation increases
  - Strengths and modulus of elasticity decrease
  - Aluminum is pretty worthless (structurally) above about 450^{o}F

Physical Properties

- Density γ
  - Average value = 0.1 lb/in^3
  - Varies by alloy; for alloys in *ASD*, +3%, -5%
  - Example: 6061-T6 density = 0.098 lb/in^3
- Coefficient of Thermal Expansion α
  - Average value = 13 x $10^{-6}/^oF$
  - Varies slightly by alloy and temperature
  - Lengths over 30 ft: consider expansion joints

5. Structural Design Overview

- Types of structures
- Limit states
- Strength limit state design methods:
  - Allowable Strength Design (ASD)
  - Load and Resistance Factor Design (LRFD)
- Determining required forces

Types of Structures

- Building-type structure: a structure of the type addressed by a building code
- Bridge-type structure: a structure not addressed by building codes and designed for highway, pedestrian, or rail traffic
- Other structures: everything else (for example, lifting equipment)
- Required reliability depends on structure type

Limit States

- A structural engineer considers limit states
  - Static strength
    - available strength $\geq$ required strength
  - Serviceability (deflection, vibration, etc.)
  - Fatigue
    - allowable stress range $\geq$ applied stress range

ENGINEER

What my friends think I do

What my mother thinks I do

What my wife thinks I do

What society thinks I do

What I think I do

What I really do

What a Structural Engineer Does

- *Analysis:* determine forces, moments in the structure (required strength)
  - Use the same methods for all materials
  - But beware: since aluminum is more flexible than steel, 2nd order effects may be more significant
- *Design:* proportion the aluminum structure to safely resist the loads (provide available strength)

ASD vs. LRFD

- Allowable Strength Design (ASD):
  - (strength)/(safety factor) $\geq$ load effect
  - allowable strength $\geq$ load effect
- Load & Resistance Factor Design (LRFD):
  - (strength)(resistance factor) $\geq$ (load factor)(load effect)
  - design strength $\geq$ (load factor)(load effect)
- In both, available strength $\geq$ req'd strength
- The difference is load factors

Aluminum ASD vs. LRFD

- Since dead load is a small part of the load in most aluminum structures, LRFD isn't as significant for aluminum:
  - If $D = 0.05L$, LRFD is $1.2D + 1.6L = 1.66L$
  - w/ same load factors, $1.6D + 1.6L = 1.68L$
- Also, many aluminum structures are designed for a single load (e.g., curtain walls are designed for wind only)

Safety/Resistance Factors for Aluminum Building Structures

Limit State	Safety Factor Ω	Resistance Factor ϕ
Yield	$\Omega_y = 1.65$	$\phi_y = 0.90$ (was 0.95)
Rupture	$\Omega_u = 1.95$	$\phi_u = 0.75$ (was 0.85)
Fastener Rupture	$\Omega_f = 2.34$	$\phi_f = 0.65$

Safety Factors Ω for Aluminum Building Structures

Stress type	yielding	buckling or rupture
Axial tension	1.65	1.95
Bending tension	1.65	1.95
Axial compression	1.65	1.65 (was 1.95)
Bending compression	1.65	1.65
Shear	1.65	1.95

SAS Section C.2: Analysis Must Account for:

- Axial, flexural, and shear deformations
- Second-order effects (P-Δ and P-δ)
- Geometric imperfections (use construction and fabrication tolerances)
- Effect of inelasticity on flexural stiffness (use $\tau_b I$ in place of I)
- Uncertainty in stiffness and strength (use $0.8E$ in place of E, i.e. 8,000 ksi)

Thank You

- Please contact me with questions
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