Dr. Seshu Adluri

ENG 7704
Structural Steel Design

Introduction

Assignments	**10%**
Labs	**5%**
Mid term test	**25%**
Final Examination	**60%**

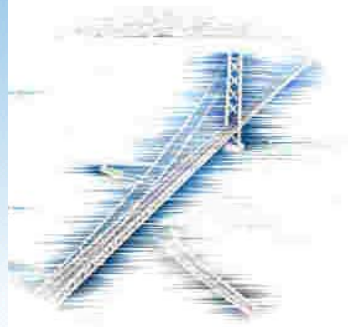
http://www.engr.mun.ca/~adluri/courses/steel/outline.htm

Contact: 12:00-2:00 p.m.
Monday (EN 3044)

MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

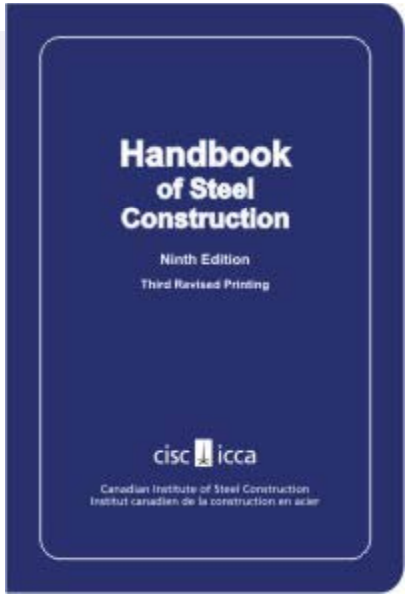
Brute Strength To Amazing Grace

- In structural steelwork, grace, art and function can come together in almost limitless ways; it offers new solutions and opportunities, allowing us to stretch our imagination and actually create some of the most challenging structures.
- Structural steel's low cost, strength, durability, design flexibility, adaptability and recyclability make it the material of choice in North American building construction.
- Steel provides not only strength to structures, but also beauty and drama. It can be combined with other materials to blend the individual advantages to produce an even more inspiring structure.
- Advanced steel fabrication technology has unfolded great opportunities to design spectacular structures with steel.

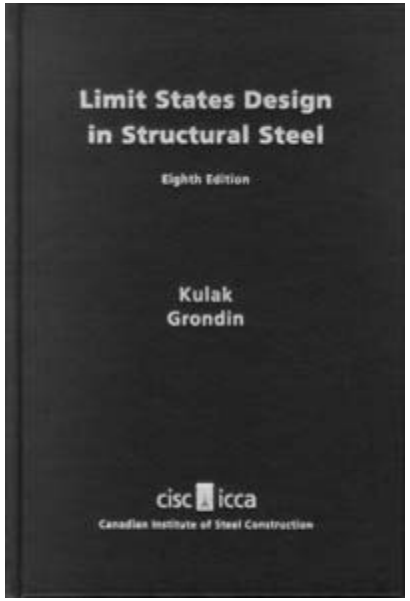


Materials for ENG 7704 Structural Steel Design

- Steel Design Handbook – **CISC**
- **Limit States Design for Steel – CISC Textbook**
- **It's important you have access to the handbook because:**
  - You will have to use the book in the exams
  - The book has the steel code (CSA-S16), properties of steel sections, several useful tables and examples
- Hand written notes in the handbook
  - Simple notes to aid the quick understanding are O.K. But no detailed calculations



cisc icca



MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

Materials for ENG 7704 Structural Steel Design

- Important:
  - Ask questions!
  - If you don't, I will have no choice but to assume that you understood (either that, or that you don't care)!

"I appreciate you taking me under your wing, Dr. Adluri .... I hope to learn a lot."

Additional resources

- **Companion Website — This website from CISC provides other online resources. Visit http://www.cisc-icca.ca/**
- **Also visit AISC website and a number of other sites for steel structures to get information on famous structures, history, economics and technical details**

Course Topics

- **Introduction**
- **Design of Members and Connections**
  - Tension Members –yielding, rupture, shear lag, design
  - Bolted Joints –failure modes, limit strength, design for different configurations, shear and moment, eccentric connections, etc.
  - Welded Joints -types, failure modes, direct load, eccentric connections, etc.
  - Compression Members – Effective Length, Torsional-flexural buckling, built-up members, local buckling
  - Compression member design
  - Flexural Members – Beams, failure modes, classification, lateral-torsional buckling, bracing
  - Beam design for shear and moment
  - Beam-Columns -different checks for design
  - Plate Girder Design
  - Composite Construction –composite beams, failure modes, design
- **Serviceability**: Introductions to Deflections, etc.

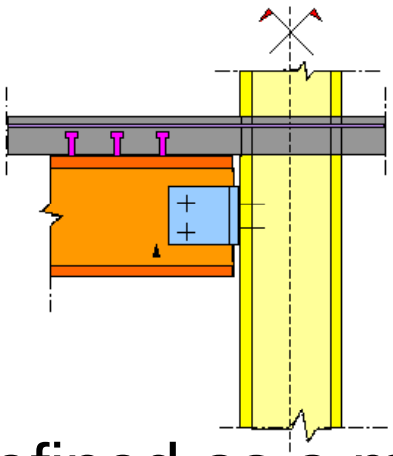
Labs

- Computer Lab
  - S-Frame, finite element, design, design check

- Structures Lab -only if resources permit :-)

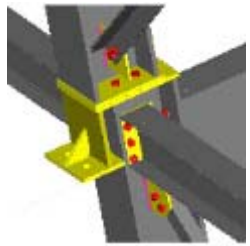
MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

Introduction



Structural design may be defined as a mixture of art and science combining the intuitive feeling for the behaviour of a structure with rational principles of mechanics (statics, solid mechanics, dynamics, etc.) and structural analysis to produce a safe and economical structure to serve its intended purposes.

Steel is one of the most important building materials in the modern era. It is used solely or in combination with other materials such as concrete, timber, composites, etc., for a variety of purposes.



Advantages of Steel

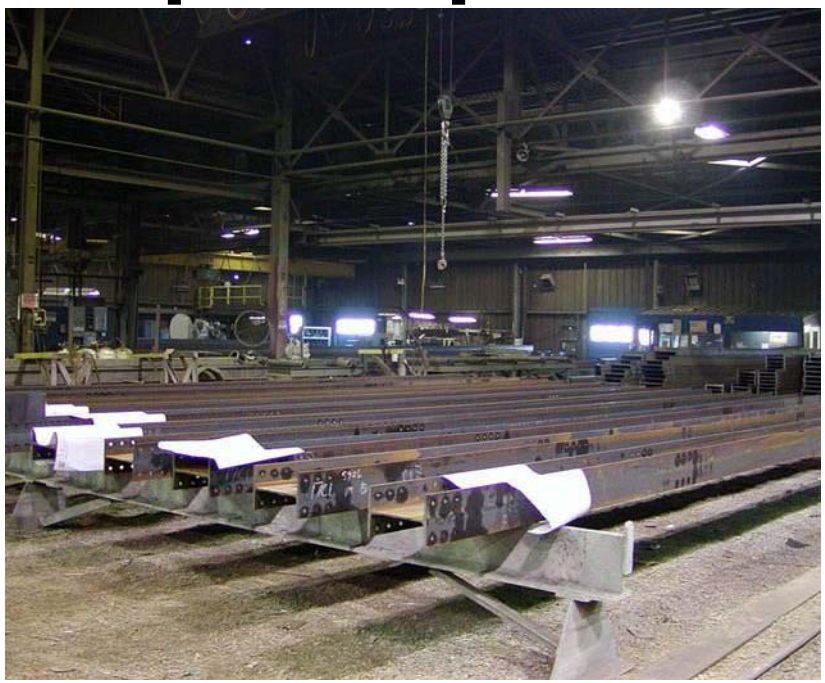
- Economy
- Durability
- Design flexibility
- Simplicity
- All weather construction
- Easy repair
- Recyclable -100% any number of times

Benefits of Structural Steel

Some benefits associated with use of structural steel for owners are:

- Steel allows for reduced frame construction time and the ability to construct in all seasons
- Steel makes large spans and bay sizes possible, providing more flexibility for owners
- Steel is easier to modify and reinforce if architectural changes are made to a facility over its life
- Steel is lightweight and can reduce foundation costs (AISC 1999)
- Steel is durable, long-lasting and recyclable

Unique Aspects of Steel Construction



Procurement and management of structural steel is similar to other materials, but there are some unique aspects to steel construction:

- Steel is fabricated off-site (above left)
- On-site erection is a rapid process (above right)
- This gives use of structural steel some scheduling advantages
- Coordination of all parties is essential for achieving potential advantages

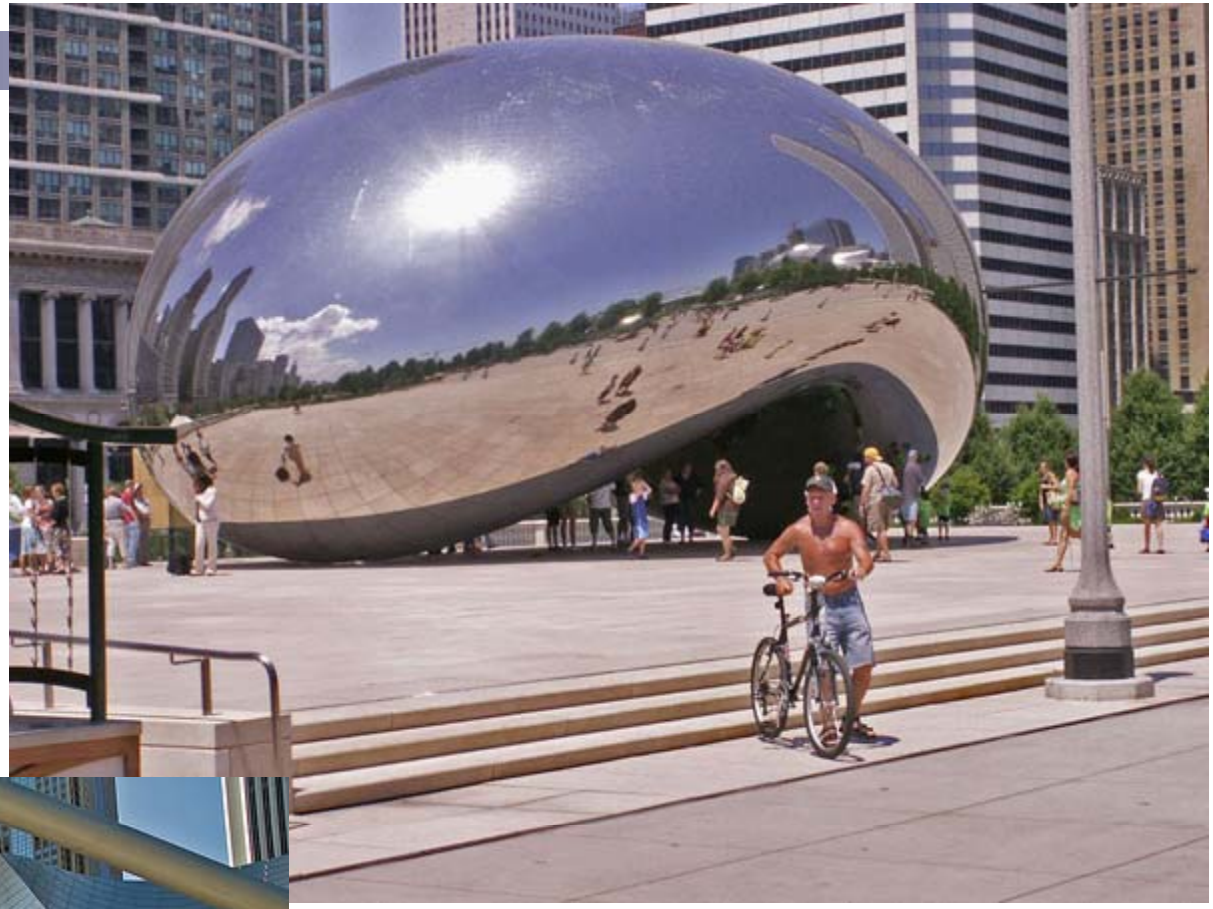
(AISC 1999)

Just couldn’t resist!

Moon Light, Maritimes and Steel tower!

Wow!

- Steel is not just for structures



Chicago's Millennium Park has the modern art sculpture officially titled Cloud Gate, although locals quickly dubbed it -the Bean. Designed by Canadian Frank Gehry. See also Chicago's Millennium Park pavilion with the curved steel elements.

History

- **Wootz** is a steel developed in India around 300 BC. The word *wootz* is a mistranscription of *ukku*, the word for steel in telugu.
- The pillar is fabricated in 310 A.D. in India. It has all along been outside as an astronomical observatory aid. It never rusted.
- 7.21 m (incl. buried), 41 cm diam., 6 tons
- Made by forge welding!

http://www.dedroidify.com/pillar.htm

History

- **Damascus steel** is a hot-forged steel used in Middle Eastern sword making from about 1100 to 1700 AD.
- Damascus swords were of legendary sharpness and strength, and were apocryphally claimed to be able to cut through lesser quality European swords and even rock.
- The foundation for Damascus Steel is Wootz Steel, which originated in India and later spread to Persia.

Pattern welded "Damascened steel" pocket knife

History

- **Japanese sword making from special steel forging is legendary.**
- **It is still practiced with very labour intensive process.**

- **China also has had a very ancient steel industry for sword making, guns and other weaponry.**

Engraving of the Edo era depicting forge scenes

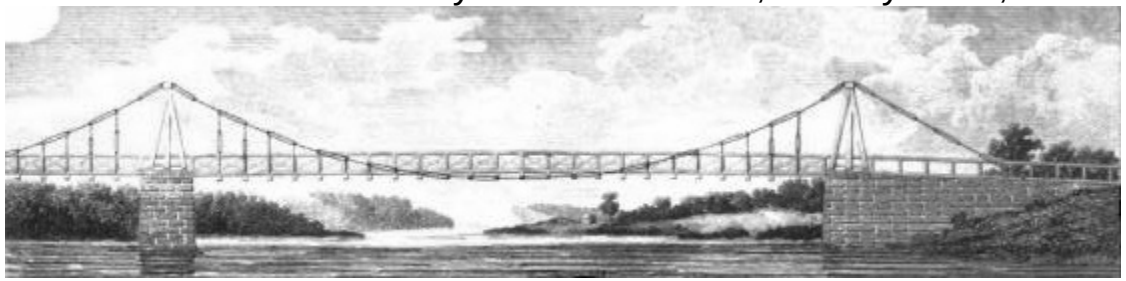
History

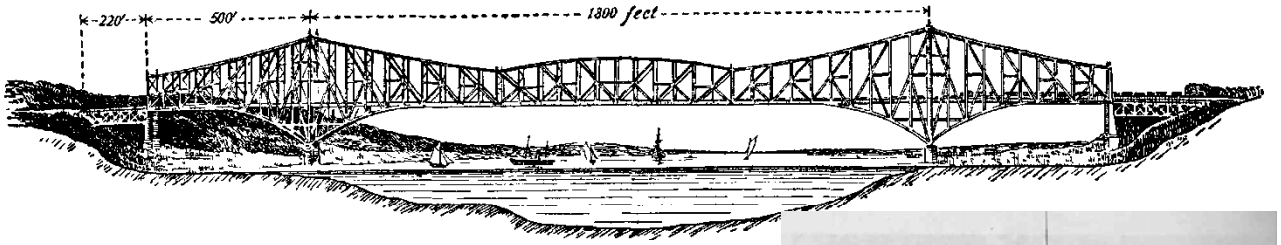
Thomas Telford

Iron bridge-Coalbrookdale, UK, 1789

- Ancient Use:
  - Beginning 5th Cent. B.C., Weaponry, Ornamentals and Bridge construction in India (small suspension bridges), Middle East and China
- Early Use:
  - 1777-79 First Cast iron bridge in England
- 1780-1820 Several bridges all over Europe, preliminary rolled shapes manufactured
  - 1820 -Rails manufactured
  - 1840 -advent of wrought iron

First modern suspension bridge -James Finley's -Jacob's Creek, Pennsylvania, 1801





History …

- Bessemer Process invented in 1855. Bessemer converter introduced in 1870. STEEL INTRODUCED
- 1890 Steel replaces all other forms.

Home Insurance bldg, 1885-1931

- Early Structures:
  - 1870s Brooklyn Bridge
  - 1880s Eiffel Tower (330 m), steel bridges in Pittsburgh, several steel buildings in Chicago (rebuilt after the great fire)
  - 1890sSeveral steel buildings in NY and Europe

- 1907 Quebec Bridge followed by several bridges in North America

History...

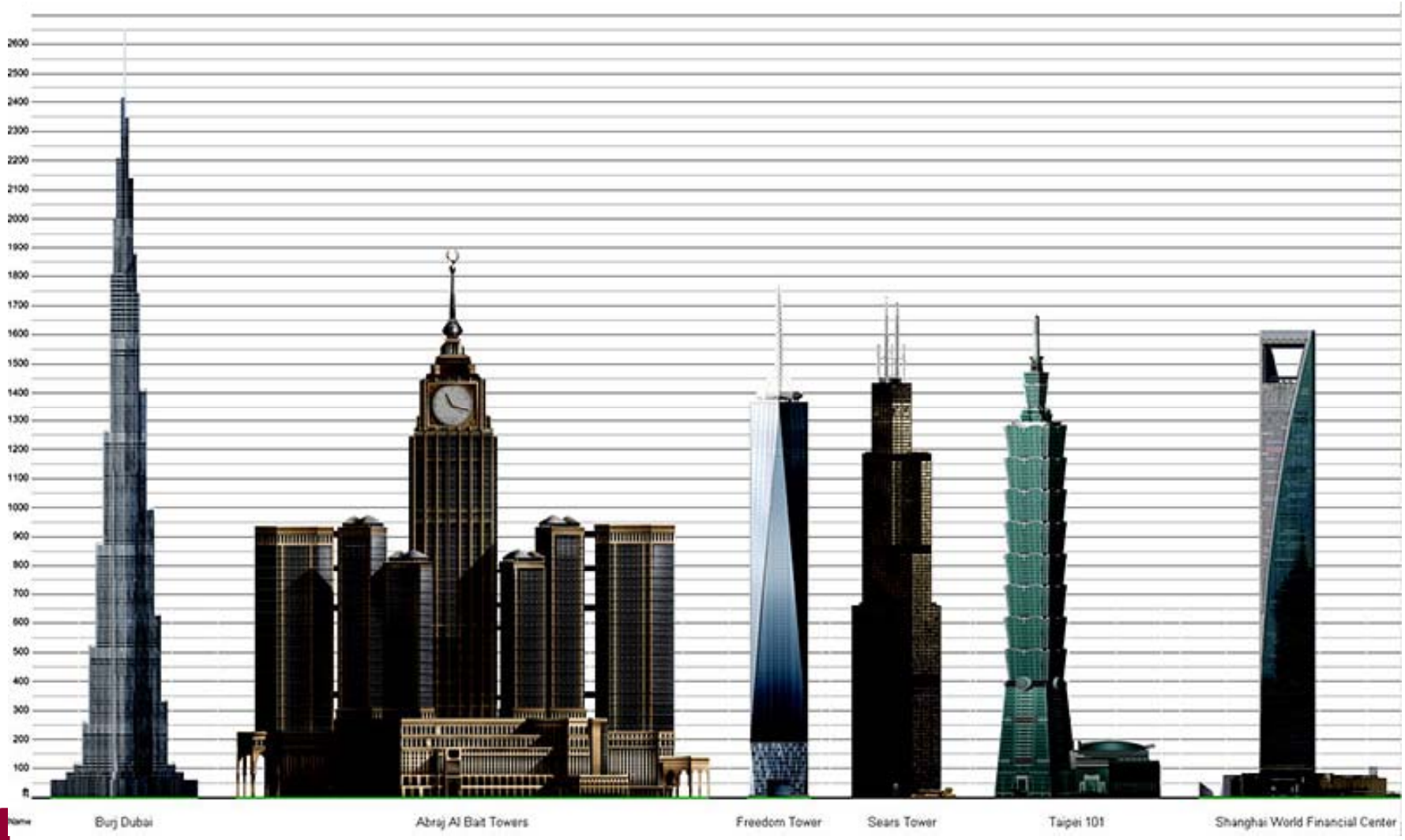
- Modern Structures:
  - 1930s Golden Gate bridge, Empire State Building, etc.
  - 1960s Sears Tower
  - Extensive use of steel for medium to high rise buildings and long span bridges.
  - Equally extensive use of steel in industrial structures, airports, etc.

Now….

- Major construction in Asia
  - Steel-concrete composites, competing business & national interests

Burj Khalifa,
820m, 160 floors

Now….

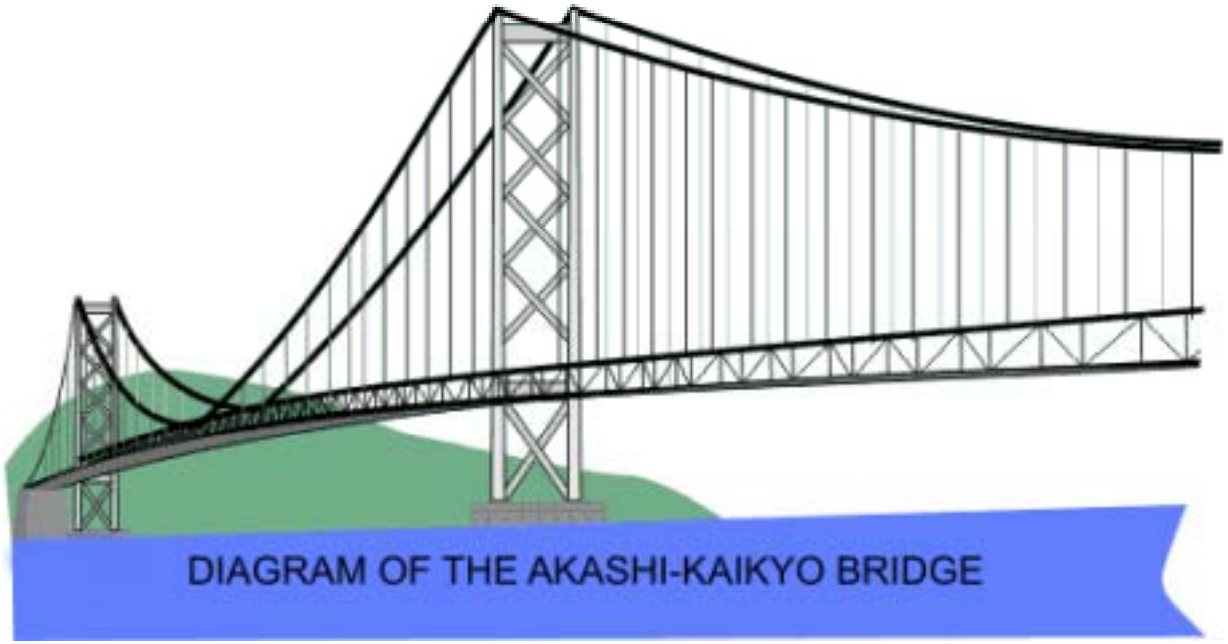

2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
ft
Burj Dubai
Abraj Al Bait Towers
Freedom Tower
Sears Tower
Taipei 101
Shanghai World Financial Center

Future...

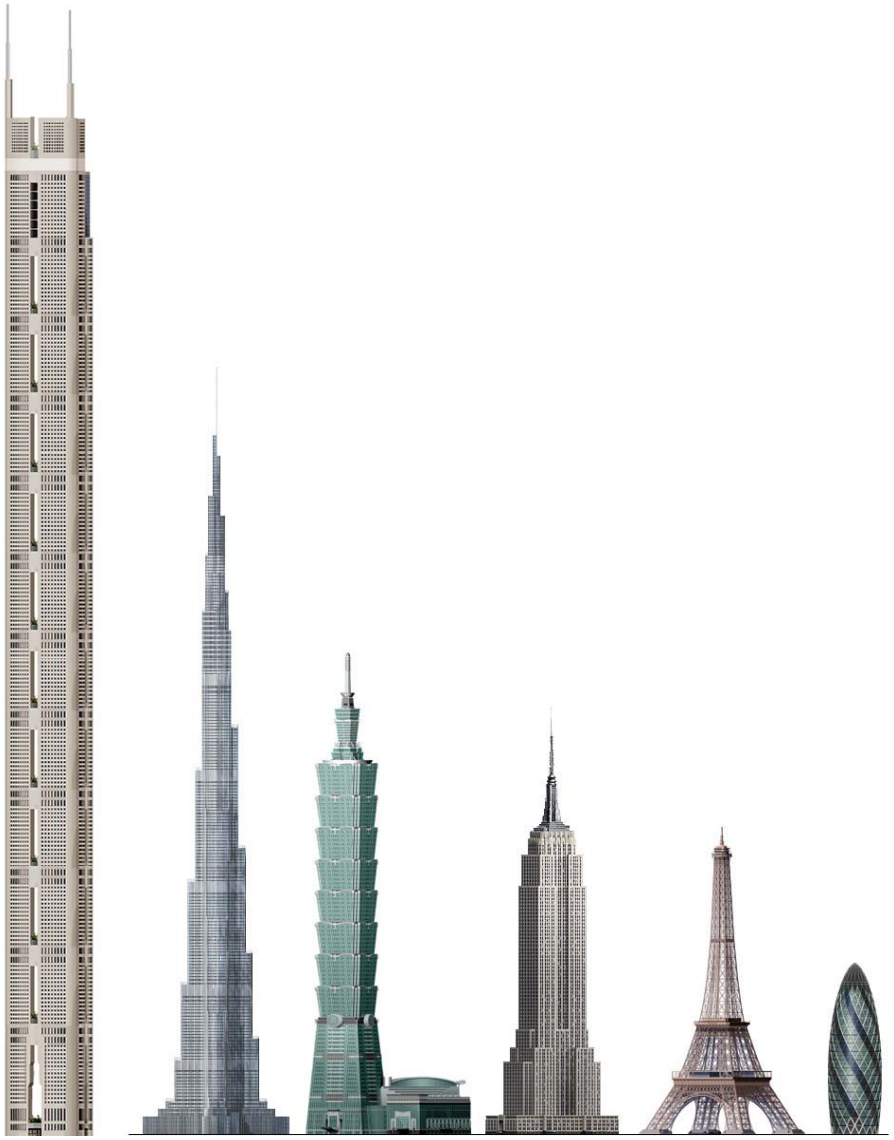
- There is major drop in North America s
  - Asia is booming, Africa and South America might catch-up
  - Millennium Tower in Japan and other futuristic projects are possible (the tower was meant to be about 840 m high, stand alone in Tokyo Bay, isolated, a city of its own population up to 50 000), to be reached by causeway and boats. Never made it since the late 1980s)

Bionic Tower, 1228m

Shanghai -proposed



Future...



A comparison of the Burj Khalifa
and the proposed Nakheel Tower

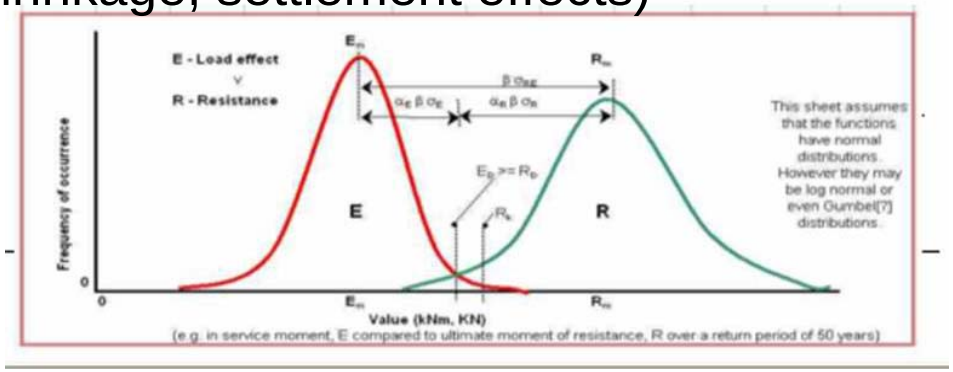
Steel Design

- Structures or structural components primarily made of steel members attached to each other appropriately.
- Steel is excellent in both tension and compression.
- Since steel is primarily made of thin plate like elements, they are susceptible to buckling (local and overall).
- Connections in steel are considerably different from those in concrete. In steel, the members are ‘discrete’ or rolled (fabricated) separately and are attached to each other using appropriate connections.

Shanghai world finance centre

Limit States Design $\phi R \geq \alpha_i S_i$

- Ultimate Limit States - usually means that structural safety has been compromised in a certain way - ultimate load capacity, stability (e.g., local or over all buckling, or overturning), sliding, fracture (due to fatigue), etc.
- Serviceability Limit States - usually means that the functionality of the structure is effected in some way, i.e., it is rendered unsatisfactory in terms of operating conditions - Excessive deflection (could be vertical, horizontal, or skew), vibration, permanent deformation, etc.
- We deal mainly with ultimate strength limit states in this course.
- Clause 7 (CSA-S16), Table 13
- Statistically, ϕ = resistance factor, α = load factor
- D, L, S, W, T = Effects of dead live, snow, and wind loads (also temperature, creep, relaxation, shrinkage, settlement effects)



For more info' refer to the textbook

Degree of Precision

- The accuracy of engineering data is less than ¼ percent (20.5 kN, not 20.55 kN or worse, 20.55125 kN).
- Represent final solution values numerically to an accuracy of three significant digits.
  - If the number begins with 1, then use four significant digits.
  - Examples: 4.78, 728, 1.724, 0.1781, 32.1, 88300, 0.00968, 1056.
- Intermediate values are computed to five significant digits to avoid rounding errors.

For more info', refer to http://en.wikipedia.org/wiki/Significant_figures

Steel | The Material Facts

- Modern steel was first produced in 1738 in Sheffield, England, know as “crucible steel” in was very pure, but difficult and expensive to produce.
  - British Inventor Henry Bessemer produced the first economical steel in 1856.
  - Today steel is produced in over 50 countries all across the world.
  - To every ton of Portland Cement produced, 3 tons of wood and 10 tons of steel are produced.
  - In 2003, China was the first country to produce more than 200 million tons of crude steel in a year (more than 20% of the world’s steel is produced in China).
  - China is the world’s largest consumer of steel (cars, general industry, construction…)
  - The United States and China are the largest importers of steel.
  - Japan is the largest exporter of steel.
  - Steel is the world’s most recycled material. Steel is recycled mostly from junk cars (3-400,000 cars per year per steel mill; 27 cars / minute in North America).
  - More than 60% of the steel produced annually is from recycled steel.
  - Properties of steel are not altered by how many times it is recycled.
  - Per pound of material, steel is the most efficient of all building materials.
  - A small amount of steel can do load-carrying tasks with a fraction of the material needed from other materials such as concrete or wood.
  - Steel is the densest of structural materials and therefore handles longer spans, and produces lighter structures with the greatest economy.
  - Steel can be found in fasteners (nails…), structural components, rebar, sheet-metal, appliances, cars, ships, …

Steel | Chemical Composition

Wrought Iron

< 0.2 % Carbon

Soft & Malleable

Steel

0.2 - 2 % Carbon

+

Controlled amounts of:
Manganese, Phosphorous
Silicon, Sulfur, Oxygen

Cast Iron

< 3 - 4 % Carbon

Hard & Brittle

Carbon Steel

Mild Steel

0.2 - 0.25 % Carbon

Medium Steel

0.25 - 0.45 % Carbon

Hard Steel

0.45 - 0.85 % Carbon

Spring Steel

0.85 - 1.85 % Carbon

+

Combinations of:
Chromium, Cobalt, Copper,
Molybdenum, Nickel,
Tungsten, Vanadium

Alloy Steel

Stainless Steel

Weathering Steel

Steel | Chemical Composition

Cor-Ten Steel Sculpture
By Richard Serra
Museum of Modern Art
Fort Worth, TX

- Steel is an alloy of Iron, Carbon (<2%), and Manganese (<1%). It also contains small amounts of Phosphorous, Silicon, Sulfur and Oxygen

- **Carbon Steel** these chemical elements are controlled to provide consistent quality and grade of steel

  Carbon content greatly affects the properties of steel
  - More Carbon increases : strength, hardness, corrosion-resistance
  - More Carbon decreases : malleability, ductility, and weldability
  - The amount of Carbon does NOT affect the Modulus of Elasticity (E) of the Steel

- **Alloy Steel** is Carbon Steel to which one or more chemical elements have been added to achieve certain physical or chemical properties

  Stainless Steel

  Adding 15-18% Chromium and 7-8% Nickel produces corrosion-resistant steel

  Weathering Steel (Cor-Ten Steel)

  Adding Copper and Phosphorous creates a steel that forms an oxide coating, rust, that adheres to the base metal and prevents further corrosion

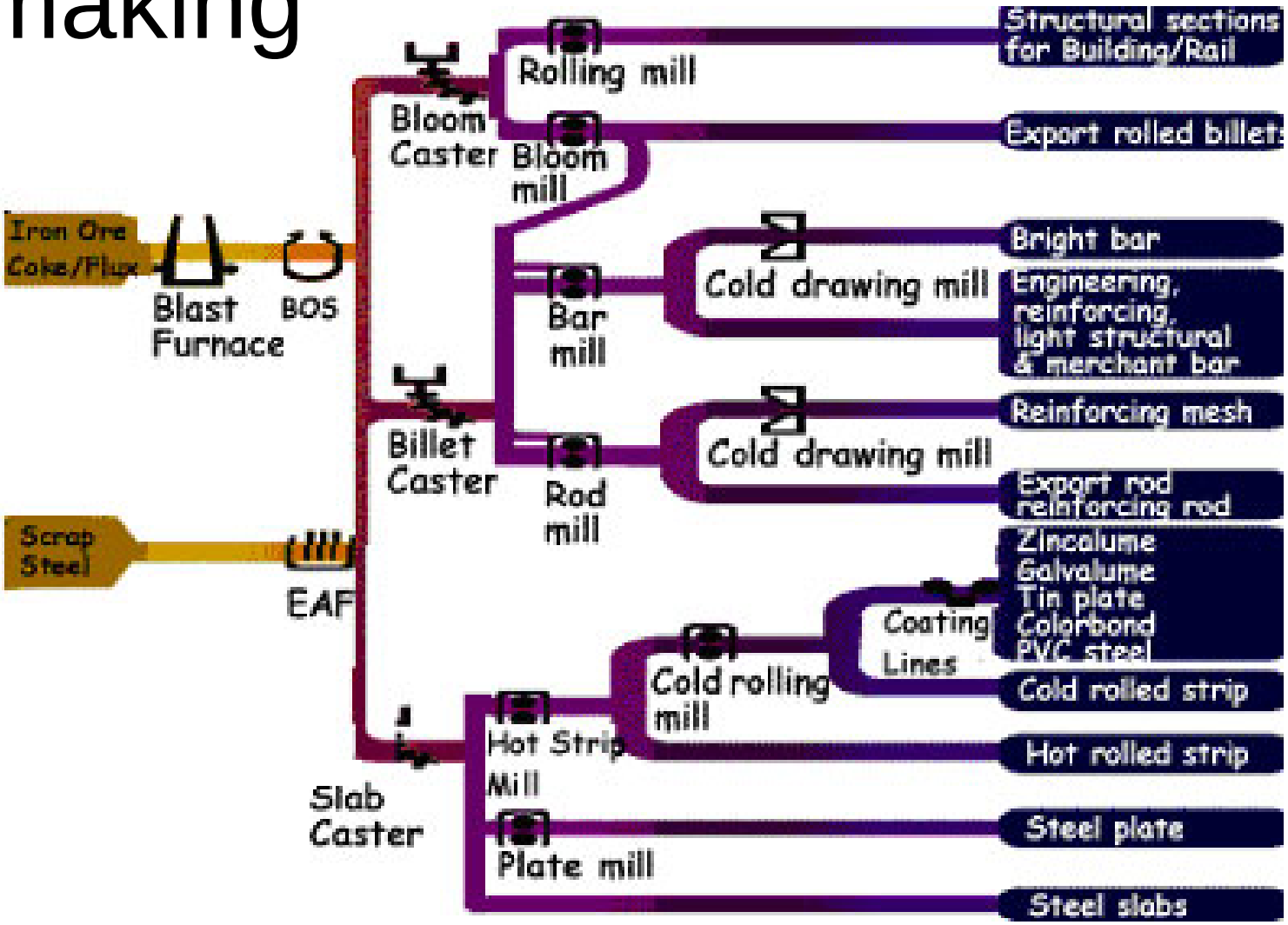
Steel | Production

- Iron ore constitutes 5% of earth's crust, 70% of earth's core is iron.
- U.S. has roughly 25% of world coal supply.
- Steel is heated to molten state to remove oxides
- Three Types of Production Furnaces:
  - Open Hearth Furnace (OHF)
  - Basic Oxygen Furnace (BOF)
  - Electric Arc Furnace (EAF)
- Whether BOF or EAF all steel is recycled back into steel, so although BOF has a lower % of recycled steel, it is still as environmentally friendly.
- Refining is the addition of alloys to obtain certain characteristics in the steel:
  - Molybdenum- strength.
  - Manganese- resistance to abrasion and impact.
  - Vanadium- strength and toughness.
  - Nickel and chromium- toughness, stiffness and corrosion resistance.
- Electric Arc Furnace (EAF) process is environmentally safer.
- Casting: Liquid steel is cast into semi-finished products; billet, blooms
- By 1980s computer controls were prevalent in steel mills.

Open Hearth Furnace (OHF):

- Discontinued in USA due to OSHA and EPA regulations, it wasted energy and manpower.
- Last Open Hearth Furnace in U.S. was closed down in 1980s.
- Extreme heat burned out impurities in iron.
- Accepts variable amounts of scraps (20-80%) .
- 3000°F minimum temperature required, 10 hours to accomplish.
- Worldwide, 3.6% of steel produced in 2003 was OHF.

Steel making



Steel making

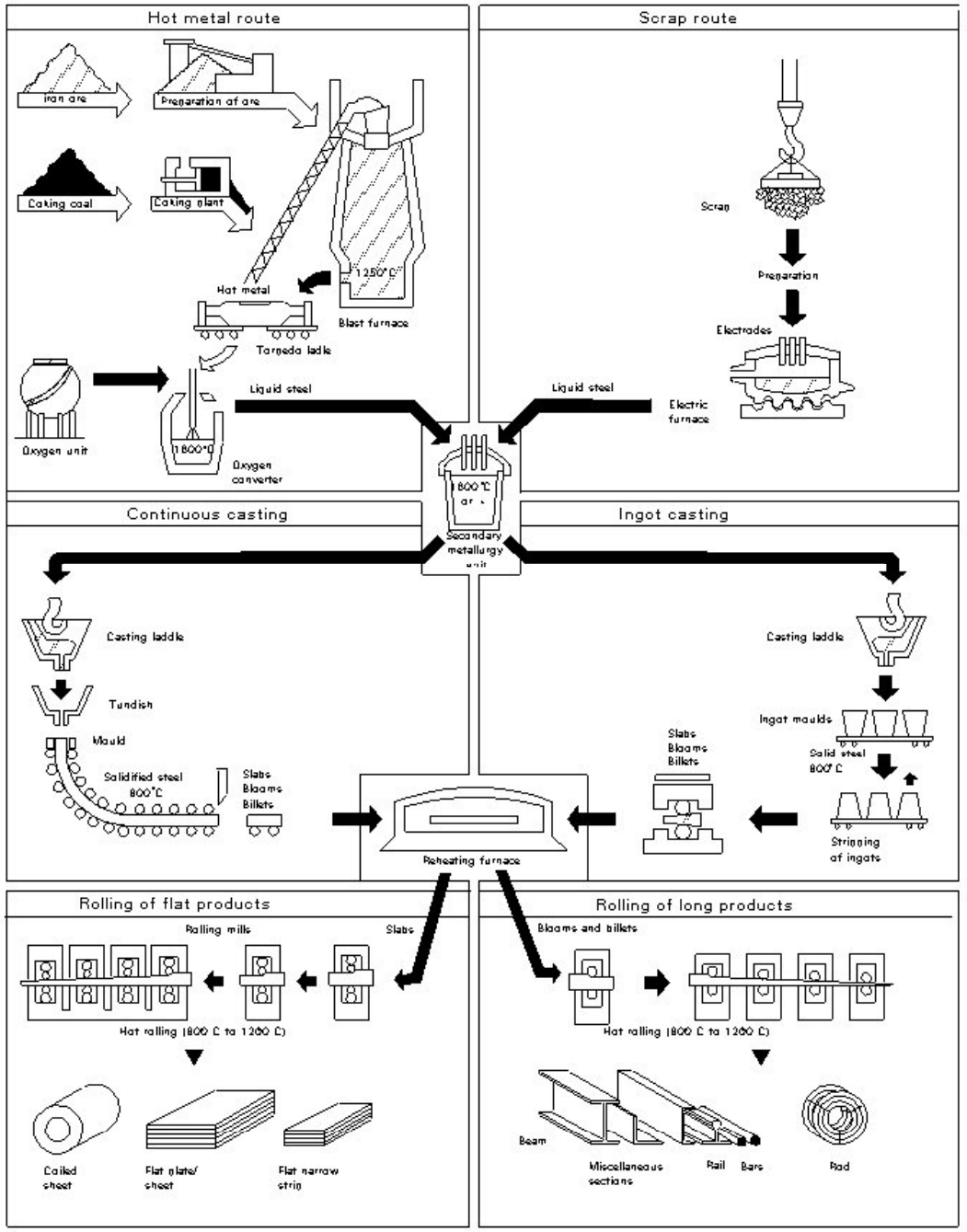


Figure 1 Steel production processes

ESDEP

Steel making

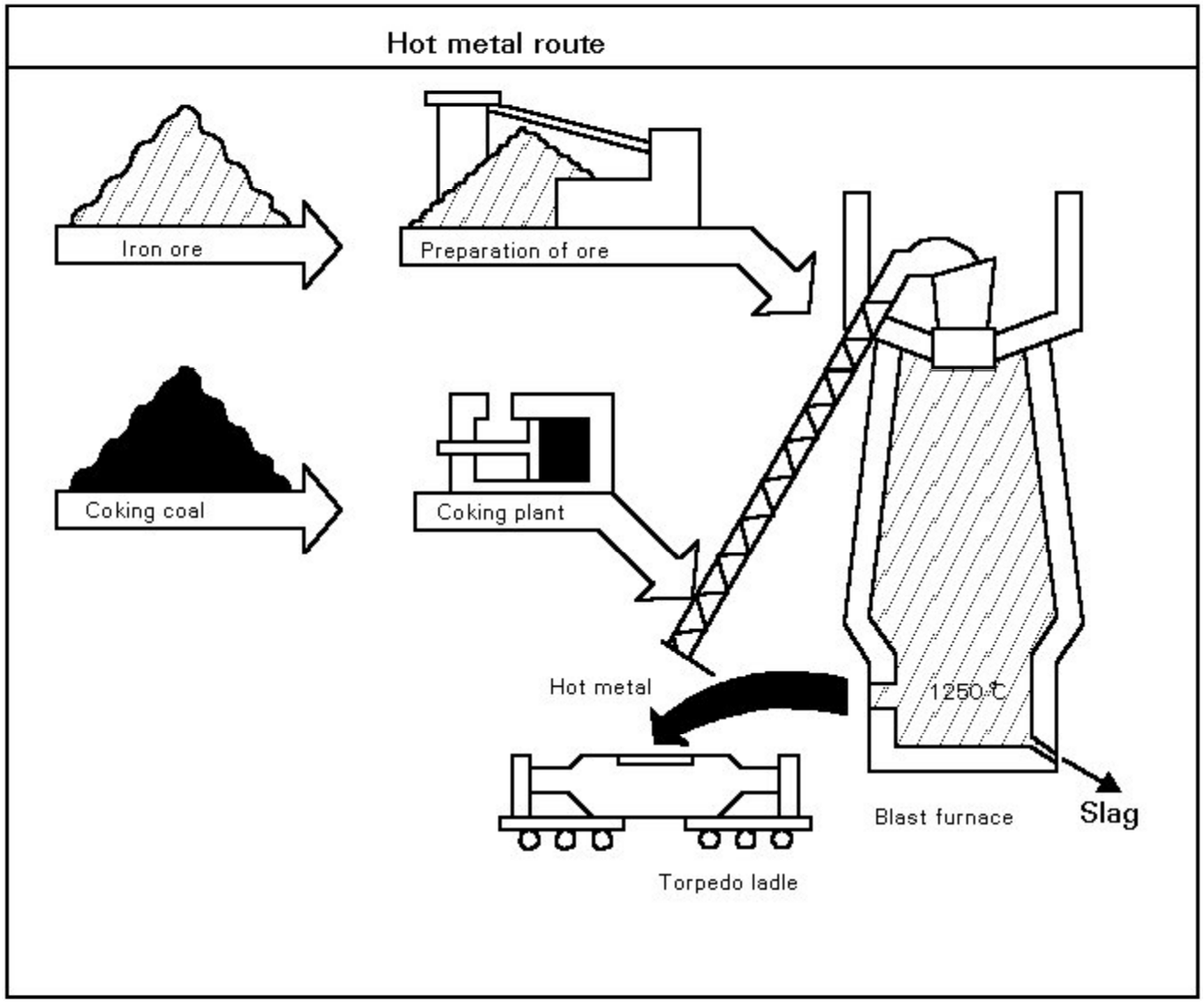


Figure 2 Blast-furnace process

Steel making

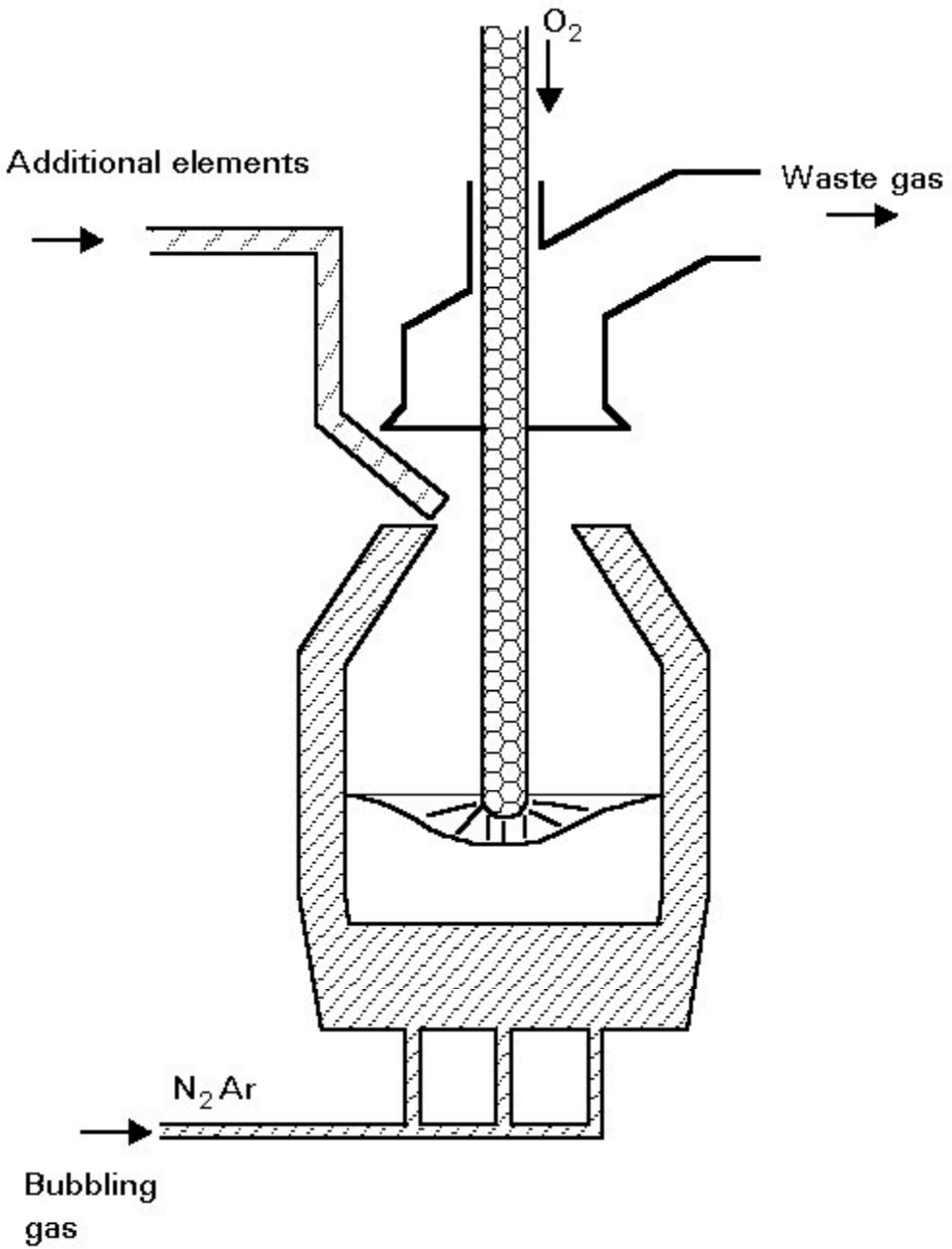


Figure 3 Basic oxygen converter

Steel making

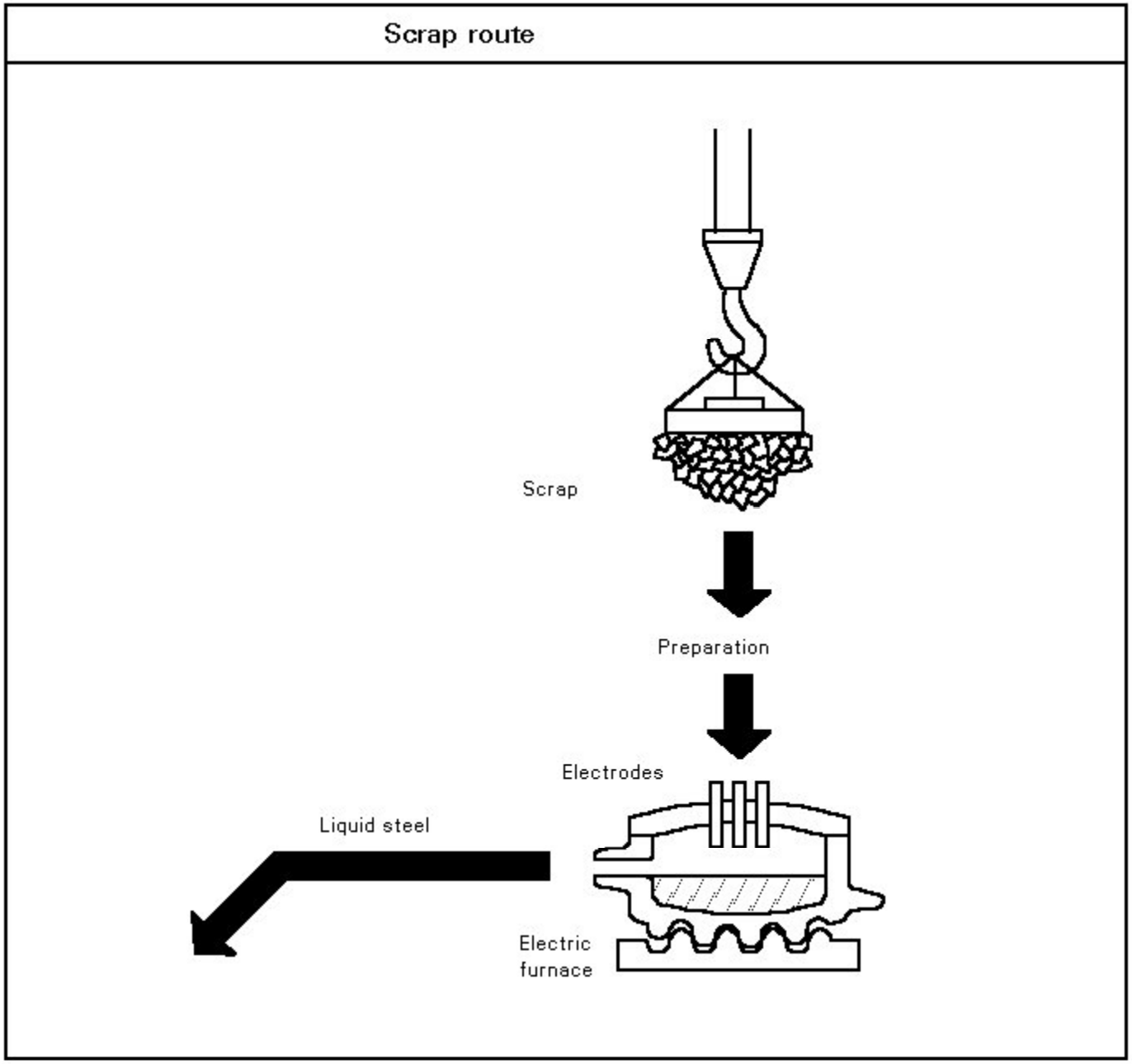
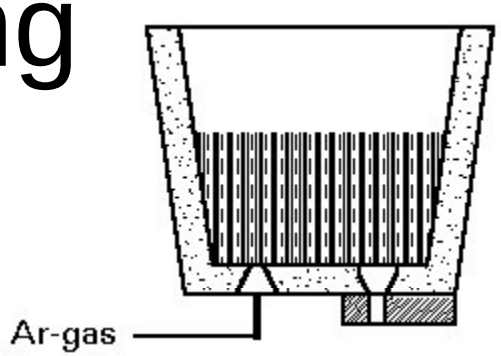


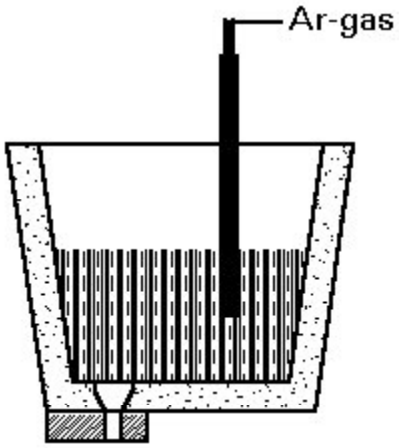
Figure 4 Electric arc furnace

Steel making

Mixing

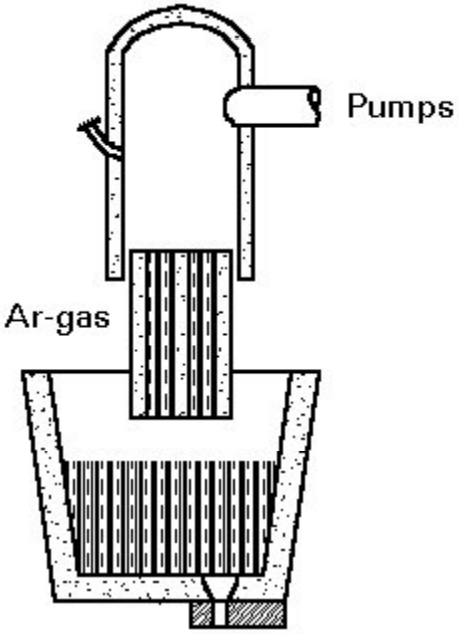


Bottom stirring

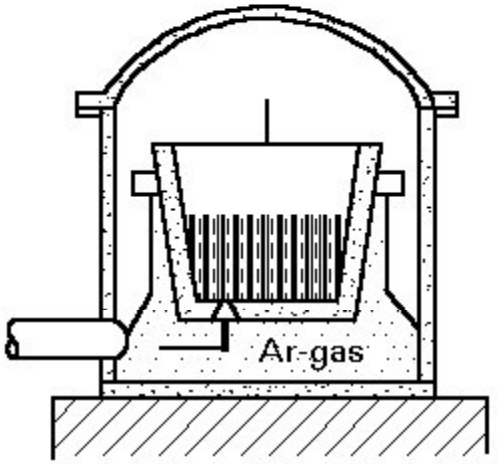


Lance stirring
and injection

Vacuum
treatment



Rh-degasser



Tank - Degasser

Figure 5 Ladle steelmaking process

Steel making

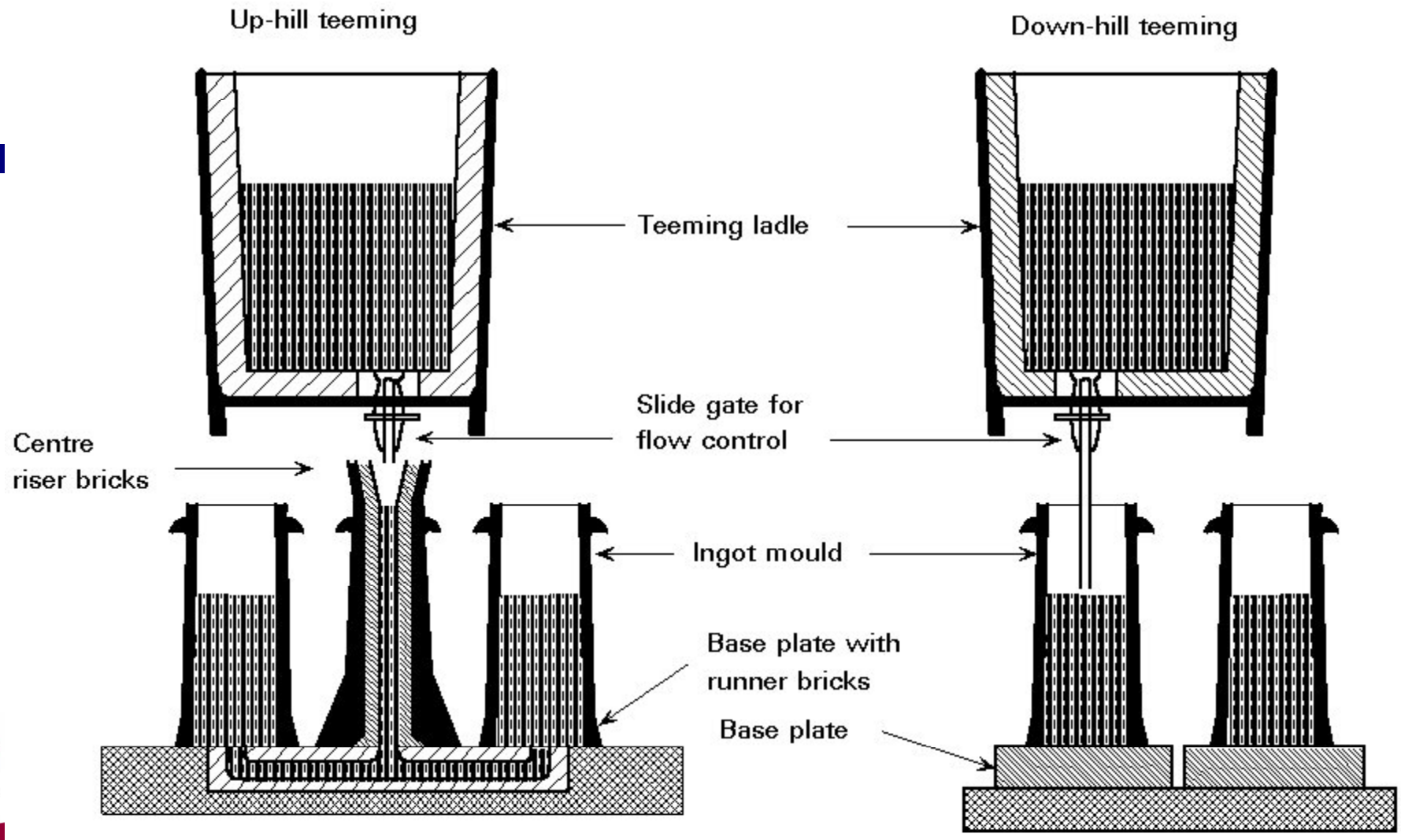


Figure 6 Ingot casting

Steel making

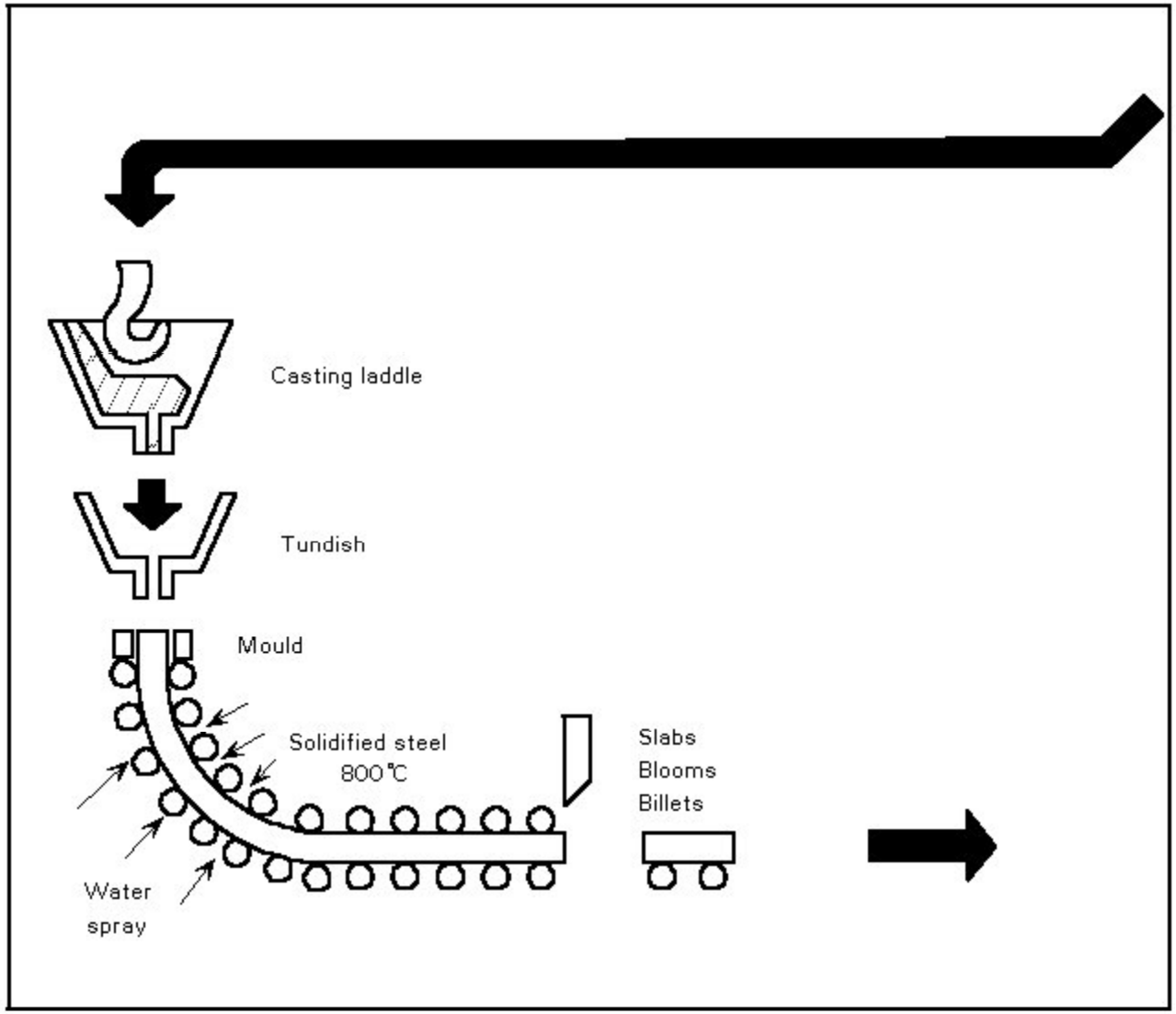
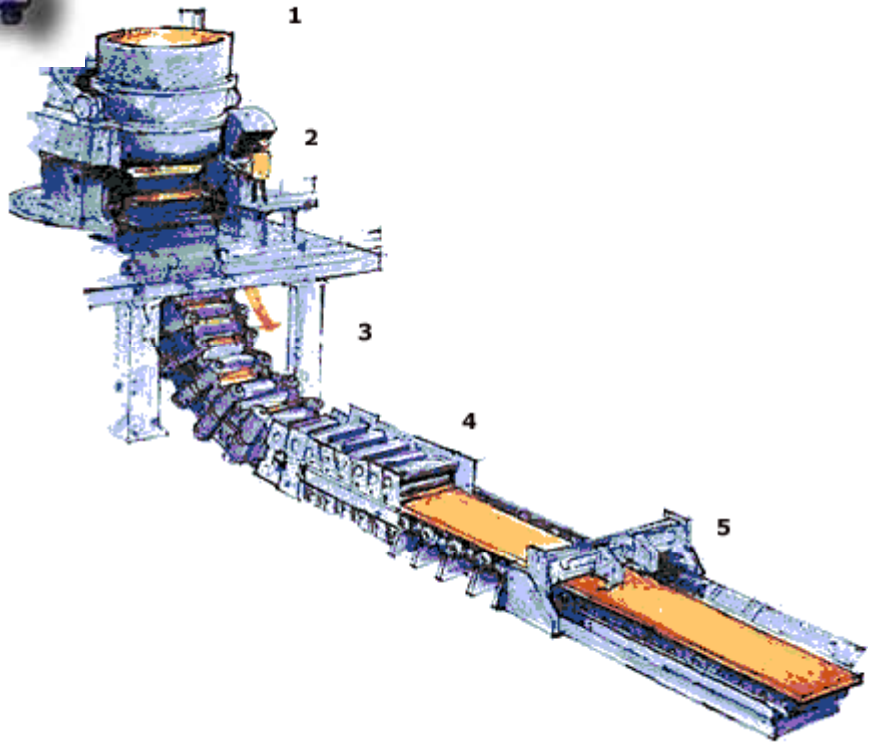


Figure 7 Continuous casting

Steel making

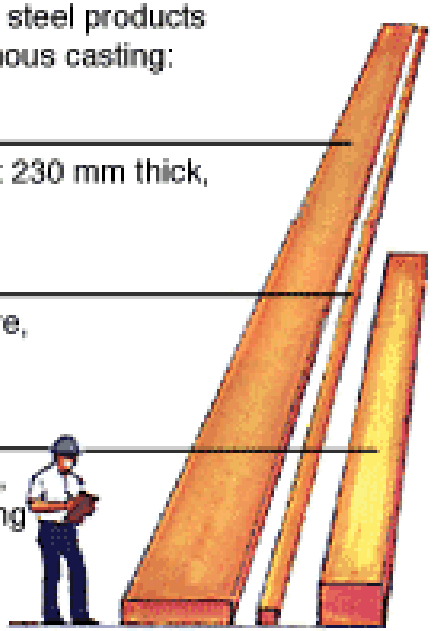


Relative of the raw steel products produced by continous casting:

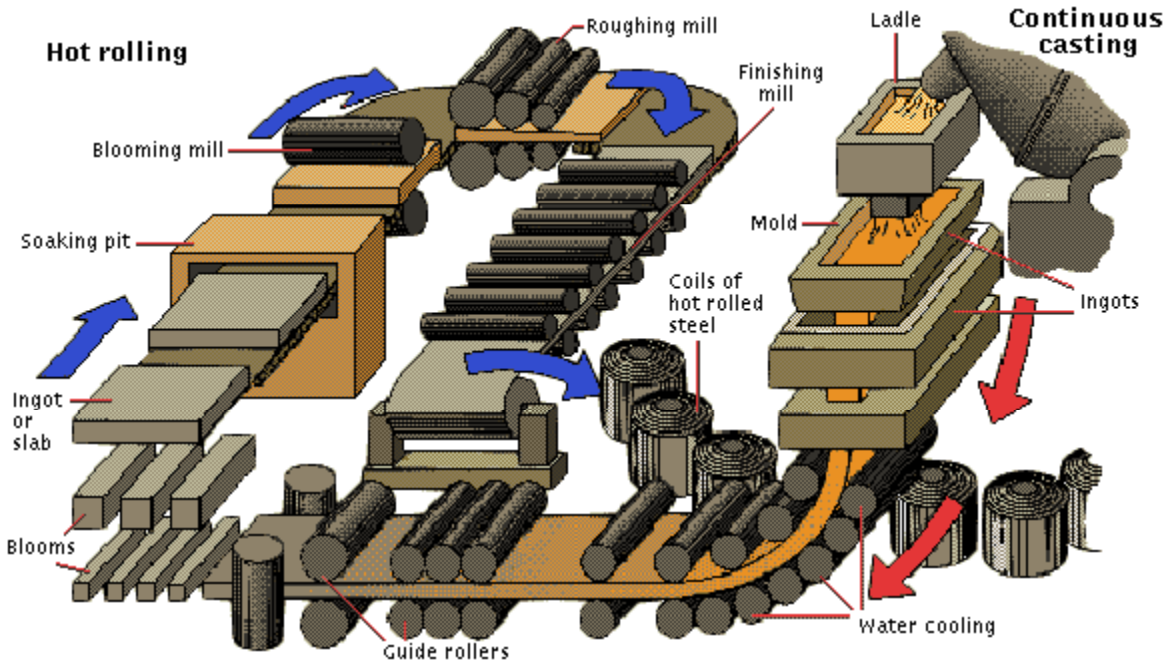
Slabs
1.25 metres wide x 230 mm thick,
12 metres long

Billets
90 - 160 mm square,
12 metres long

Blooms
630 mm x 400 mm,
5.0 - 6.0 metres long



Hot-rolling & Continuous casting



- Continuous casting (*right, red arrows*) is a method of working steel that conveys steel from its molten state to blooms, ingots, or slabs. The white-hot metal is poured into open-ended moulds and continues on through rollers cooled by water. A series of guide rollers further shapes the steel into the desired form.
- However, hot rolling (*left, blue arrows*) is still the primary means of milling steel. This process begins with pre-shaped steel slabs, which are reheated in a soaking pit. The steel passes through a series of mills: the blooming mill, the roughing mill, and the finishing mill, which make it progressively thinner.
- Finally, the steel is wound into coils and transported elsewhere for further processing.

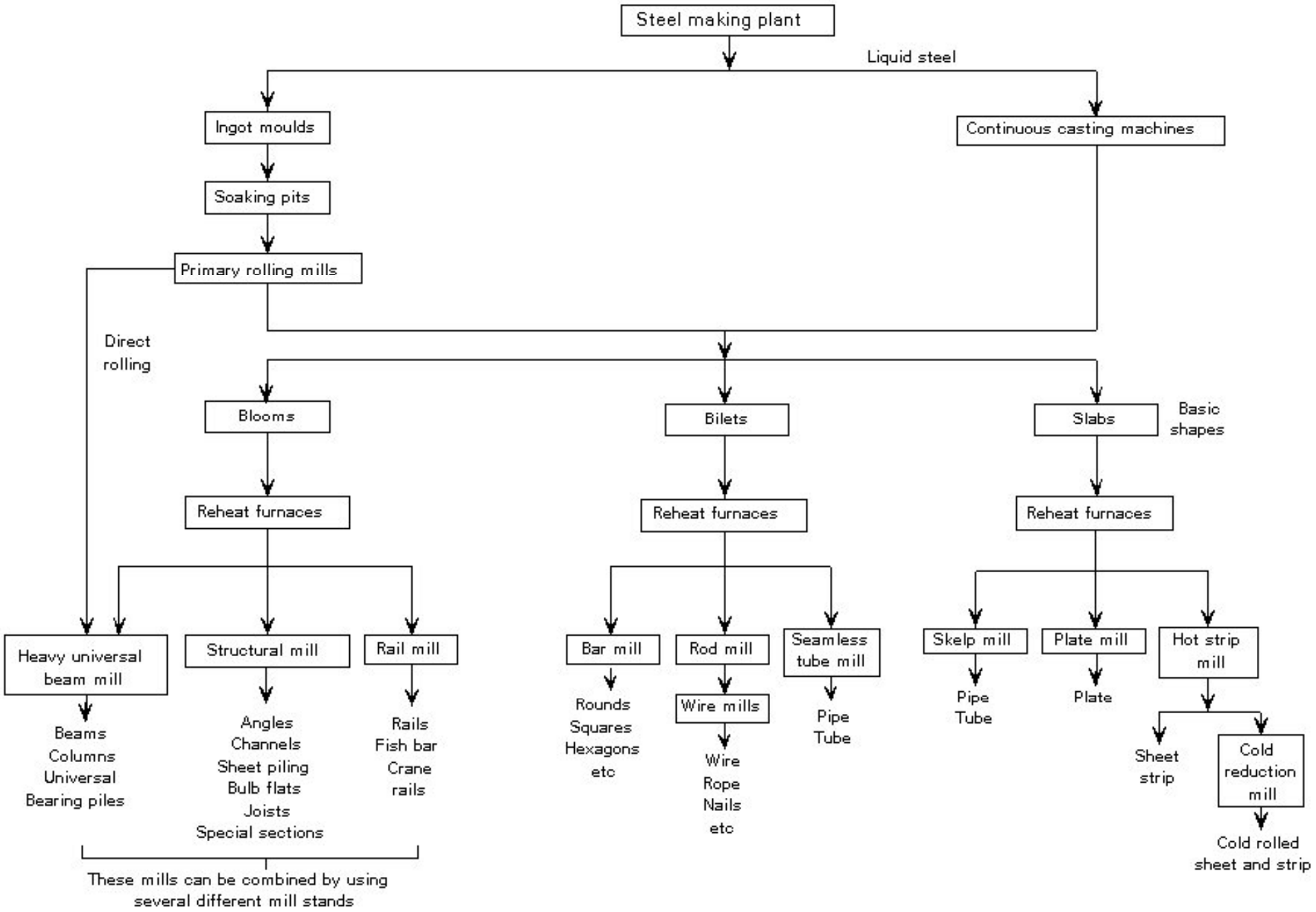


Figure 9 Principal product routes

Steel making

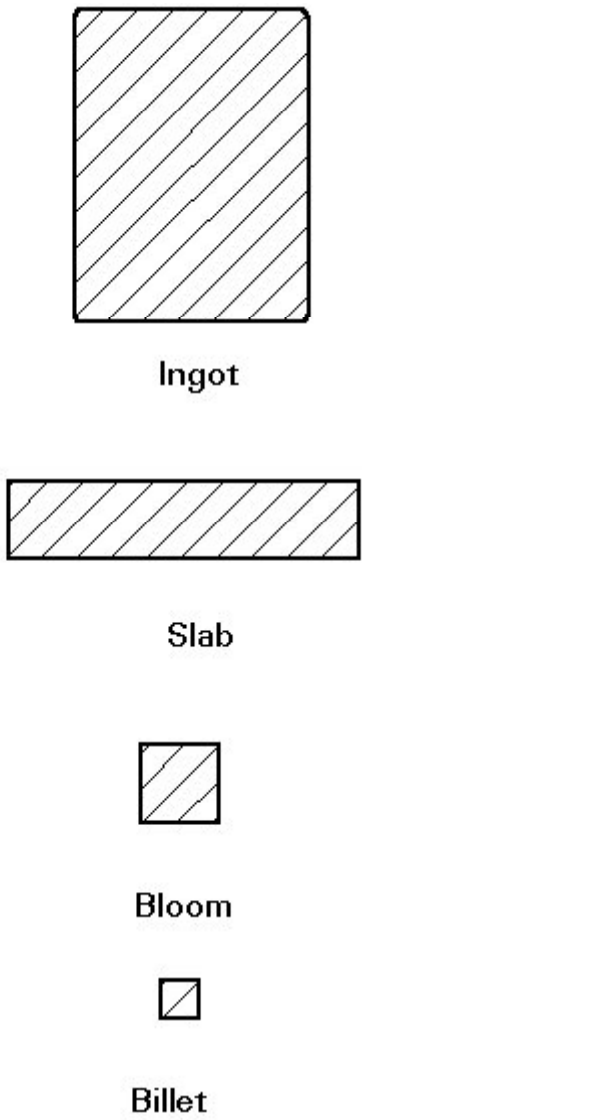


Figure 10 Basic shapes in relative proportion

Steel making

MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

http://www.stahlseite.de/index.htm

Steel making

- Continuous caster

Newfoundland & Labrador, Canada

http://www.stahlseite.de/index.htm

Steel making

- Forging press

http://www.stahlseite.de/index.htm

Steel making

- Precision Forging m/c

MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

http://www.stahlseite.de/index.htm

Steel making

- Bar mill

Newfoundland & Labrador, Canada

http://www.stahlseite.de/index.htm

Steel making

- Coil box

http://www.stahlseite.de/index.htm

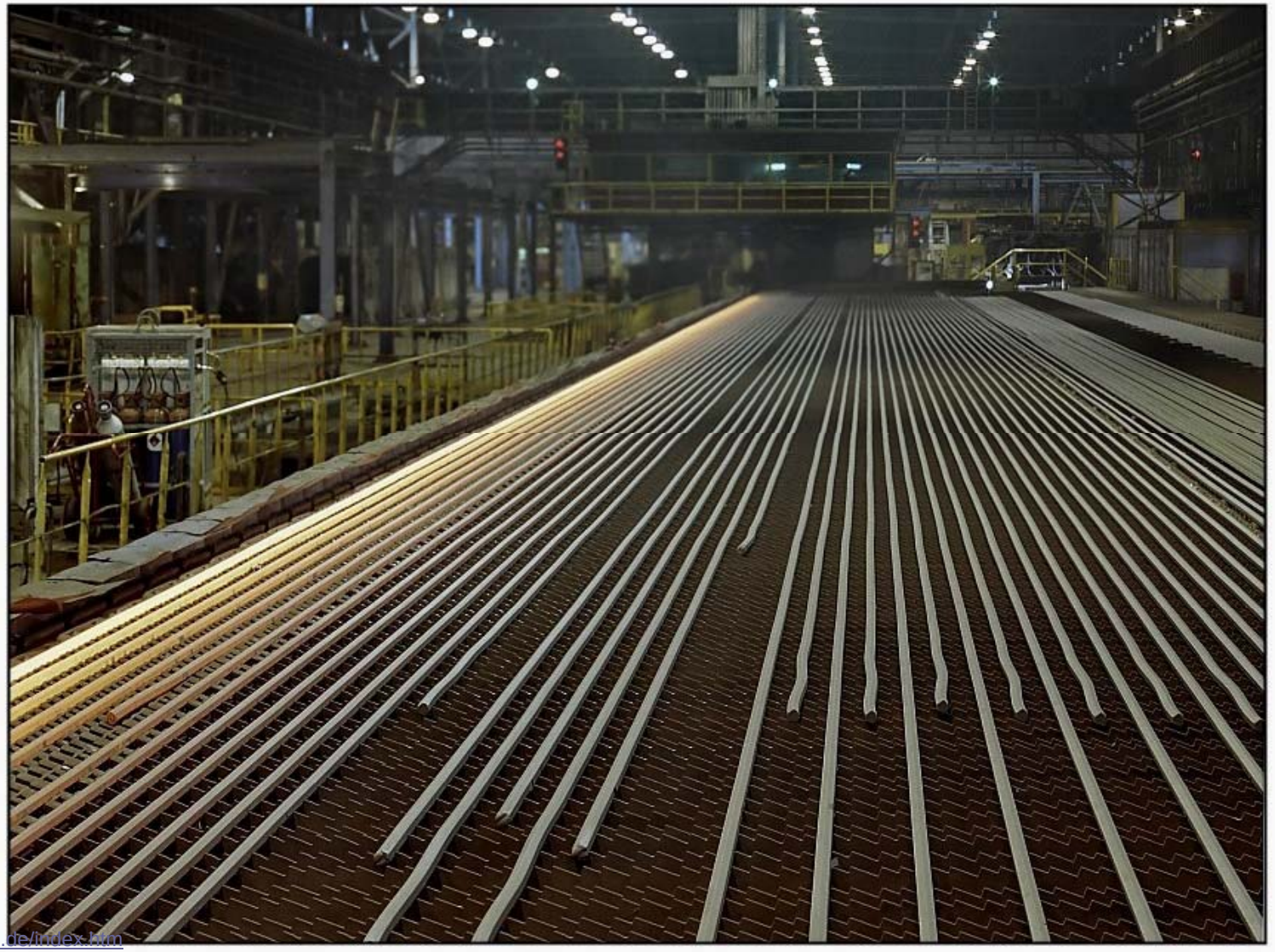
Steel making

- Cooling beds

http://www.stahlseite.de/index.htm

Steel making

- Cooling beds



http://www.stahlseite.de/index.htm

Steel making

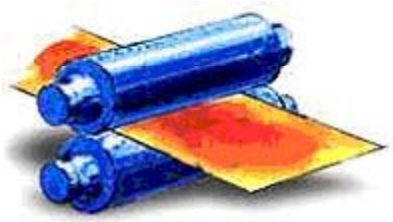
- Heat treatment

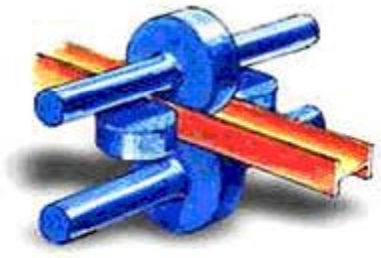
http://www.stahlseite.de/index.htm

Steel Rolling

- Cast steel is a relatively weak mass of coarse, uneven metal crystals, or 'grains'. Rolling causes this coarse grain structure to re-crystallize into a much finer grain structure, giving greater toughness, shock resistance and tensile (stress) strength.
- Rolling is the main method used to shape steel into different products after it has been cast. There are two types of rolling - hot and cold.
- The rolling process (for both hot and cold) consists of passing the steel between two rolls revolving at the same speed but in opposite directions. The gap between the rolls is smaller than the steel being rolled, so that the steel is reduced in thickness and at the same time lengthened
- One set of rollers is called a stand, and in any one mill there can be a number of stands. One length of steel can pass through a stand a number of times so that it is gradually reduced in size and progressively rolled to the desired shape. A slab 230mm thick can end up only 1.5mm thick, but many times longer, after the hot rolling process

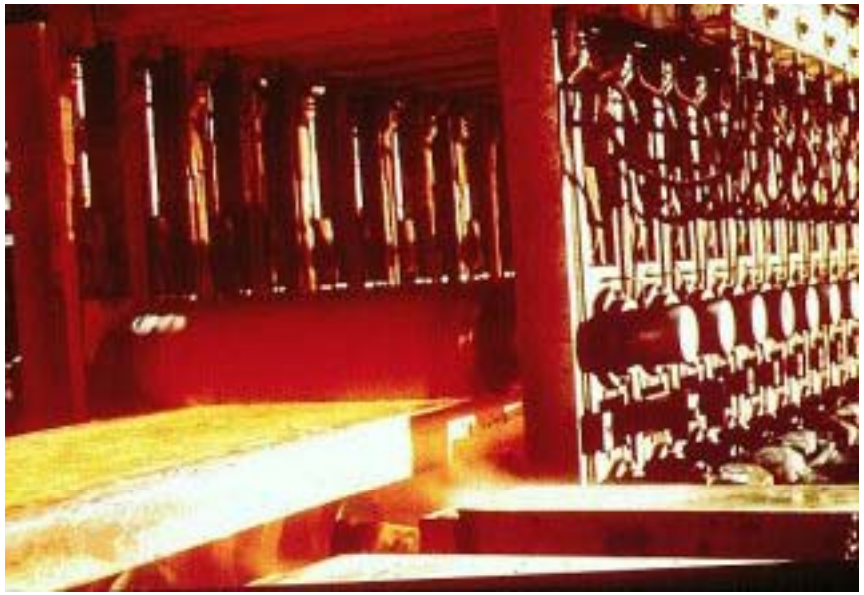
Steel Rolling





- **Hot Rolling**
- Before hot rolling, slabs, blooms and billets are heated in a furnace to about 1200°C. This makes it easier to roll the steel and removes the rough, flaky surface, or scale.
- **Cold Rolling**
- Certain types of steel are also cold rolled after hot rolling. Before cold rolling the steel is cleaned with acid (pickled) to remove the scale.
- Cold rolling is carried out at room temperature and is rolled at very fast speeds using lubricants to reduce friction. Cold rolling increases strength, makes steel thinner and produces a bright smooth surface.

Steel making



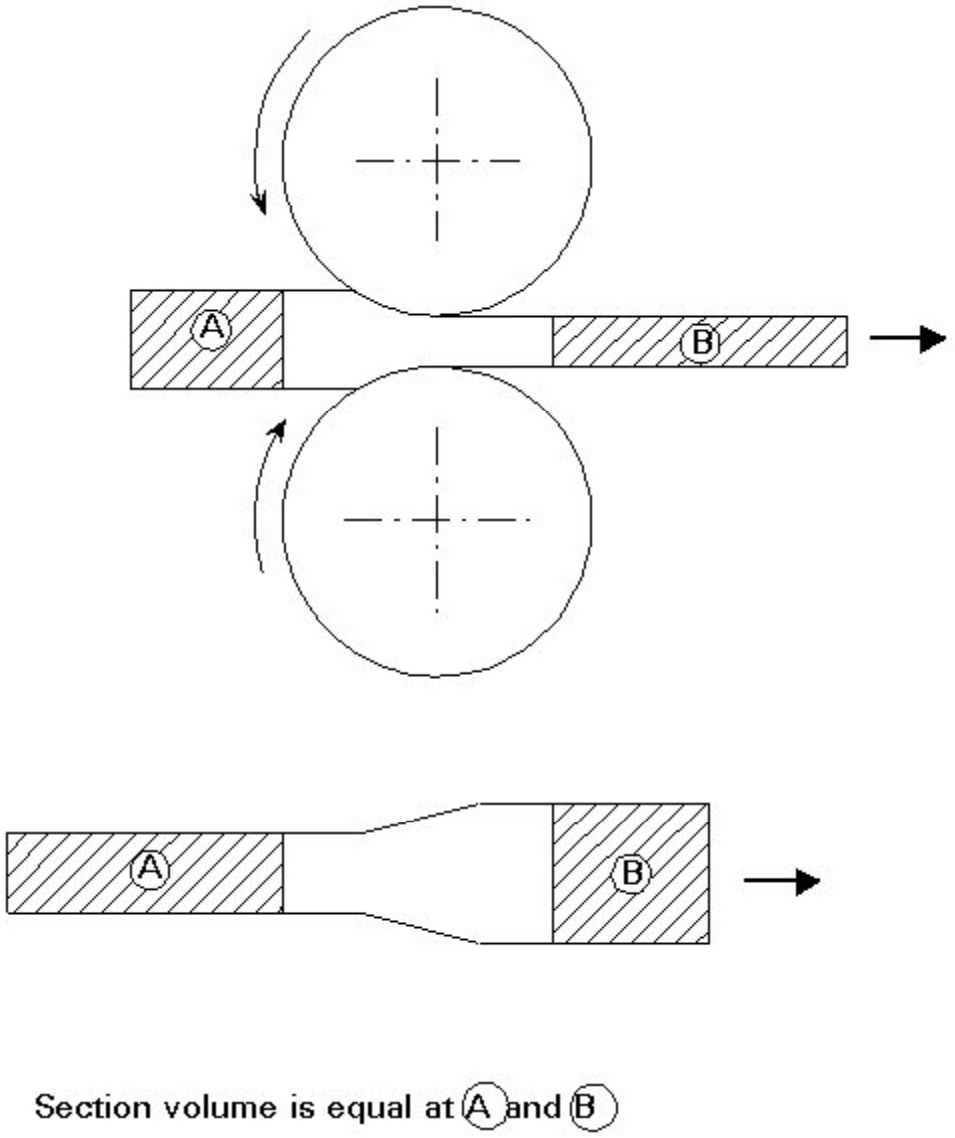


Figure 8 Hot rolling process (Schematic)

Steel making

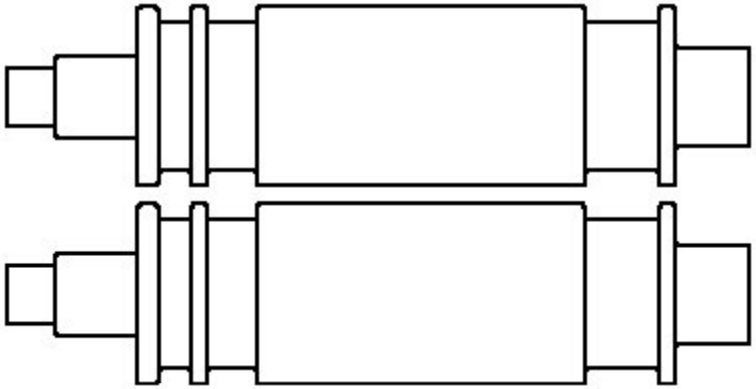
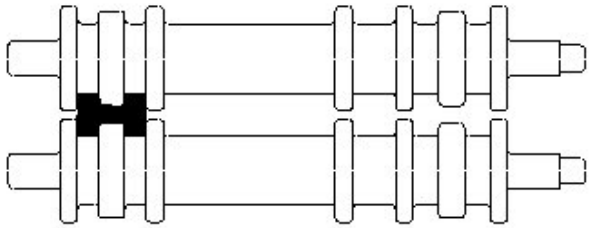
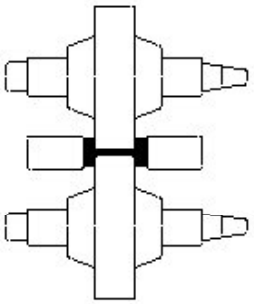


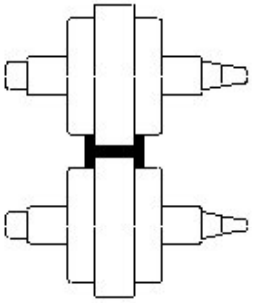
Figure 11 Primary mill rolls for slabs and blooms



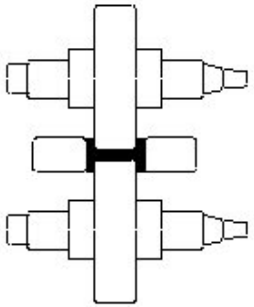
Primary rolls



Horizontal and vertical roughing rolls



Edging rolls



Horizontal and vertical finishing rolls

Figure 13 Sequence of operations for universal beams

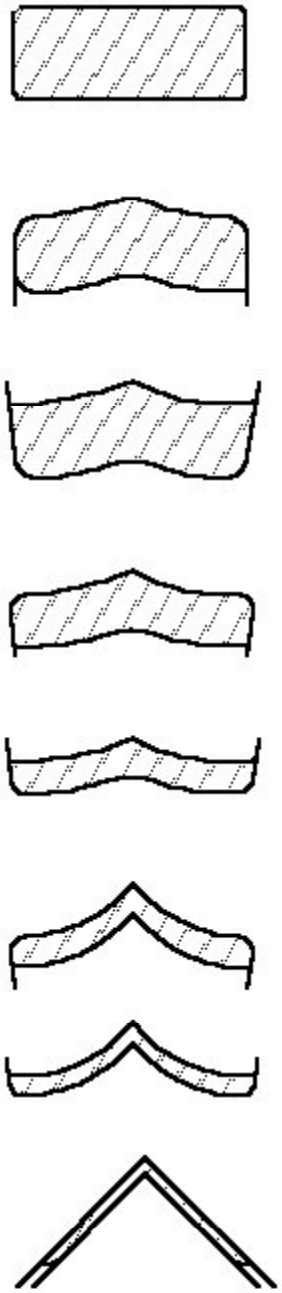
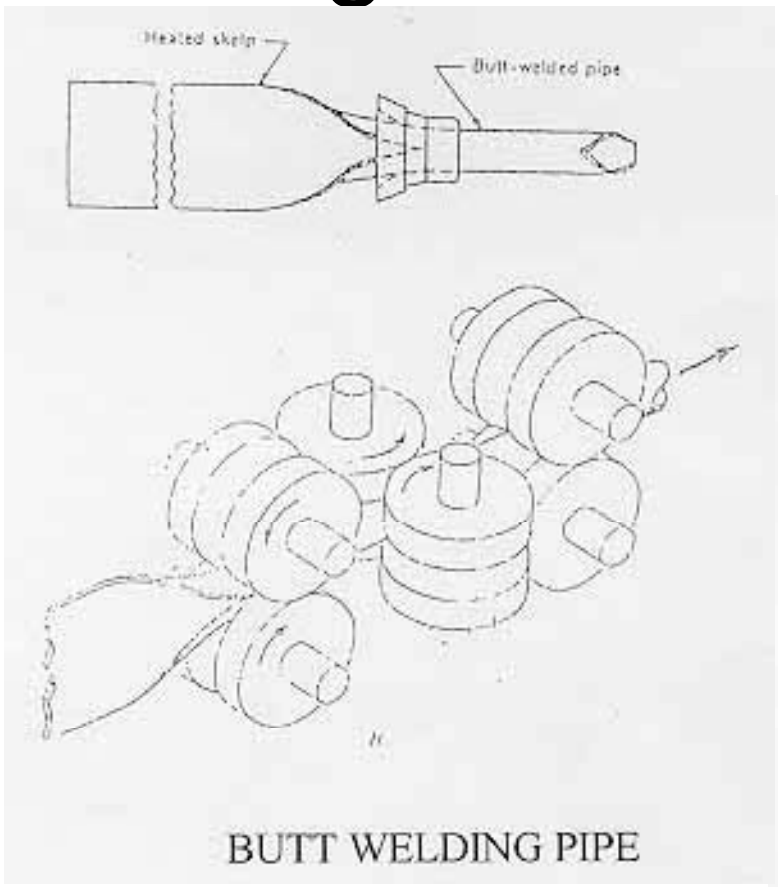


Figure 12 Pass sequence for angles

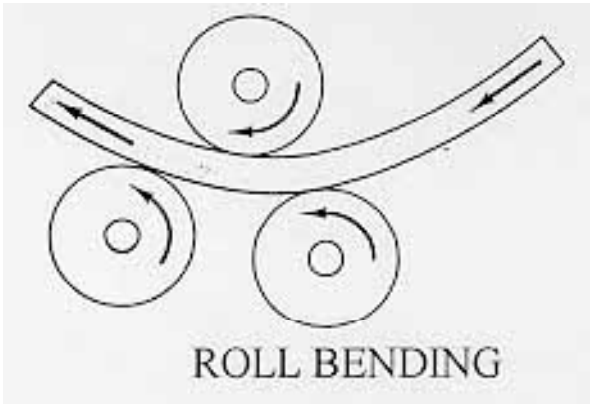
Cold-rolling after hot-rolling

- **Cold Rolling is undertaken to :-**
  - **Reduce the thickness**
  - **Improve the surface finish**
  - **Improve the thickness tolerances**
  - **To offer a range of "tempers"**
  - **As a preparation for surface coating**

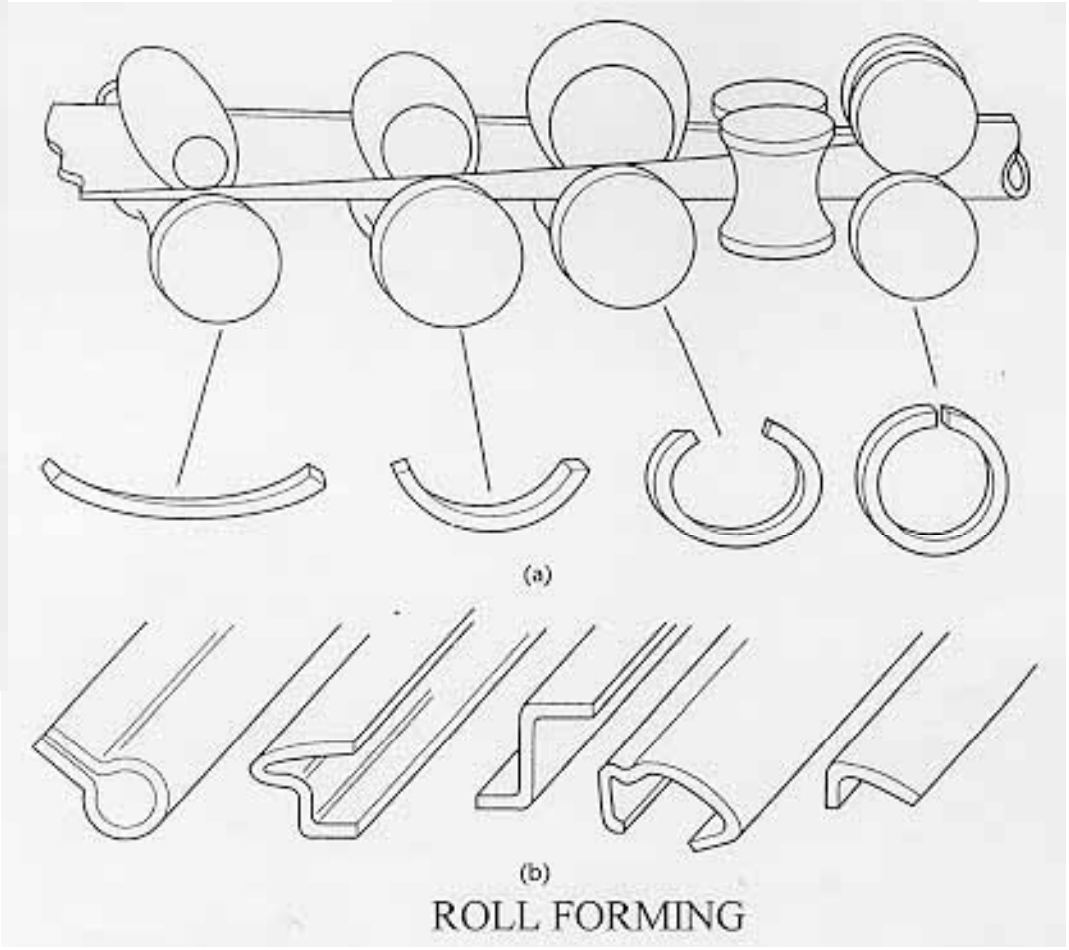
Rolling and forming



BUTT WELDING PIPE



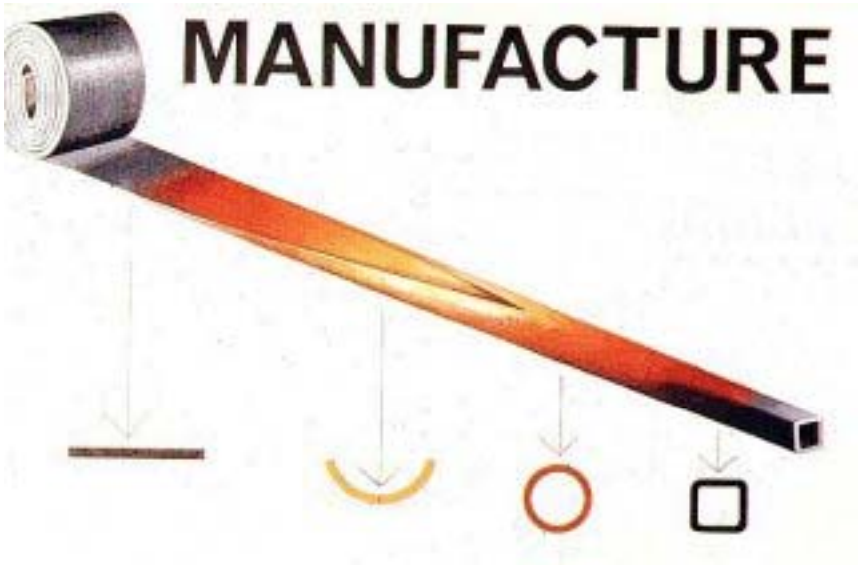
ROLL BENDING

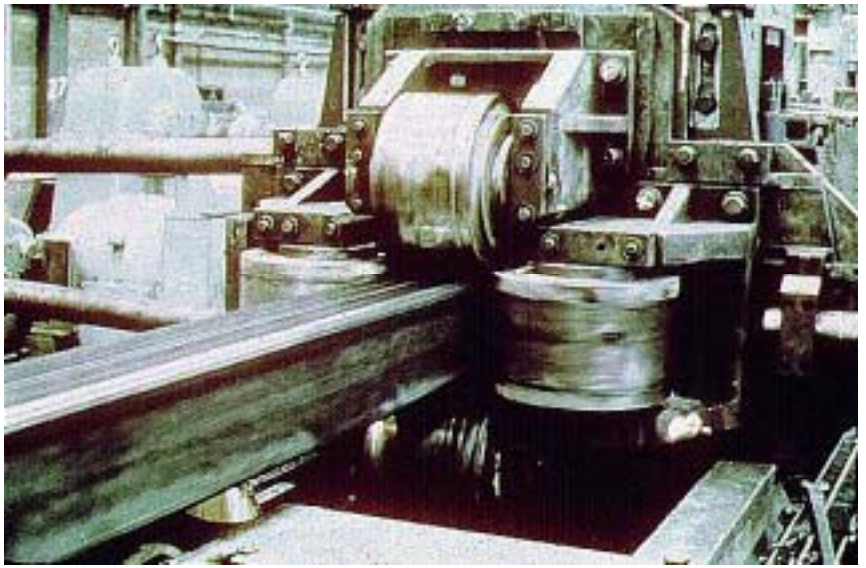


ROLL FORMING

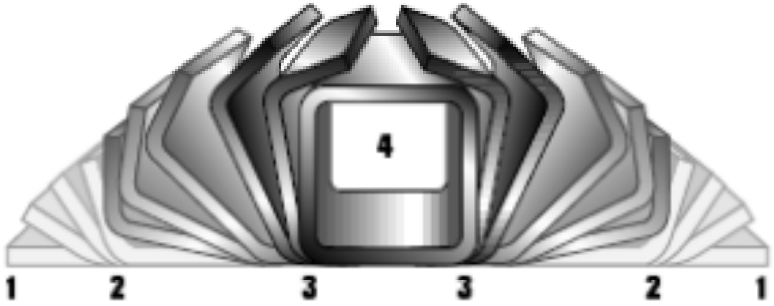
Rolling and forming

Rolling and forming

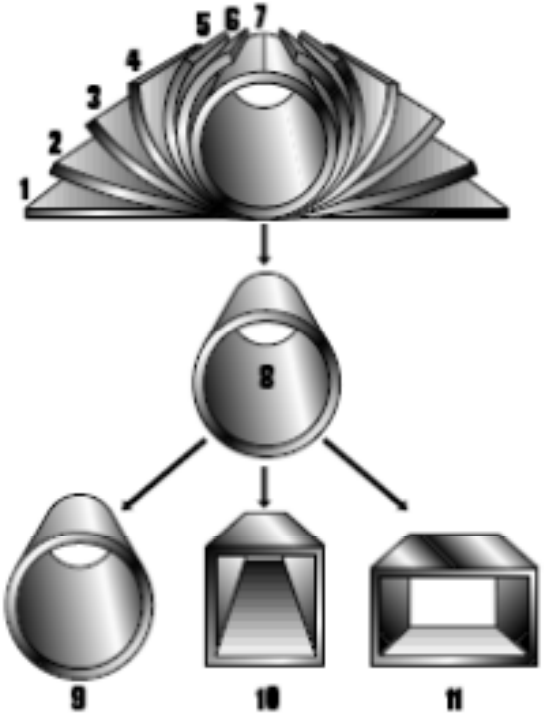




HSS forming



Form-Square Weld-Square (ERW) Process



Electric Resistance Welding (ERW) Process

Submerged Arc Weld (SAW) Process

The Steel Tube Institute of North America http://www.steeltubeinstitute.org/pdf/brochures/dimension_brochure.pdf

Steel structure erection

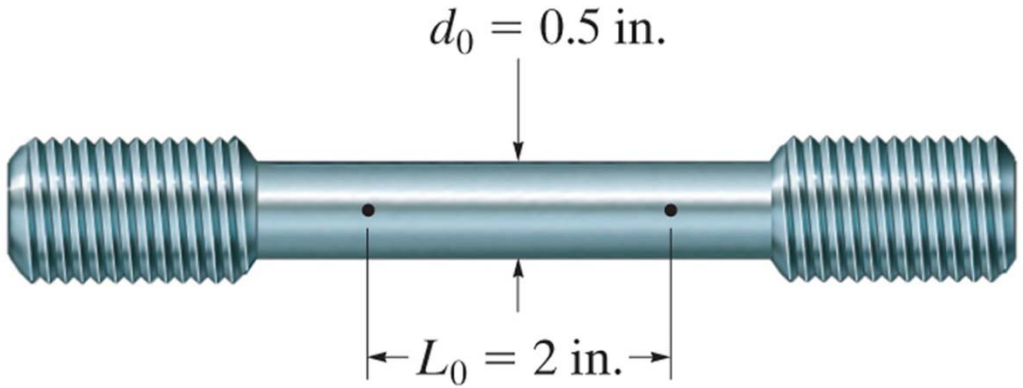
Its cheesy cartoon time! ☺

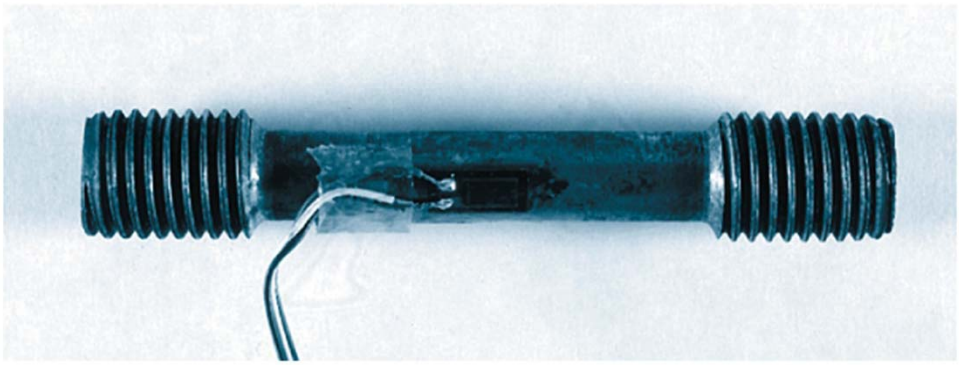
Steel

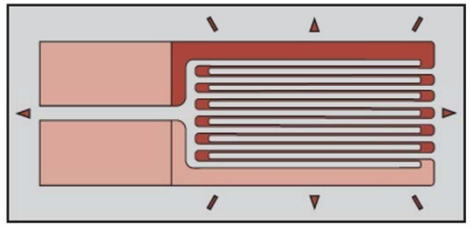
- Steel
  - Not just for structures
  - It makes cartoon people too!

Man and Lady of steel! - ☺

Material behaviour



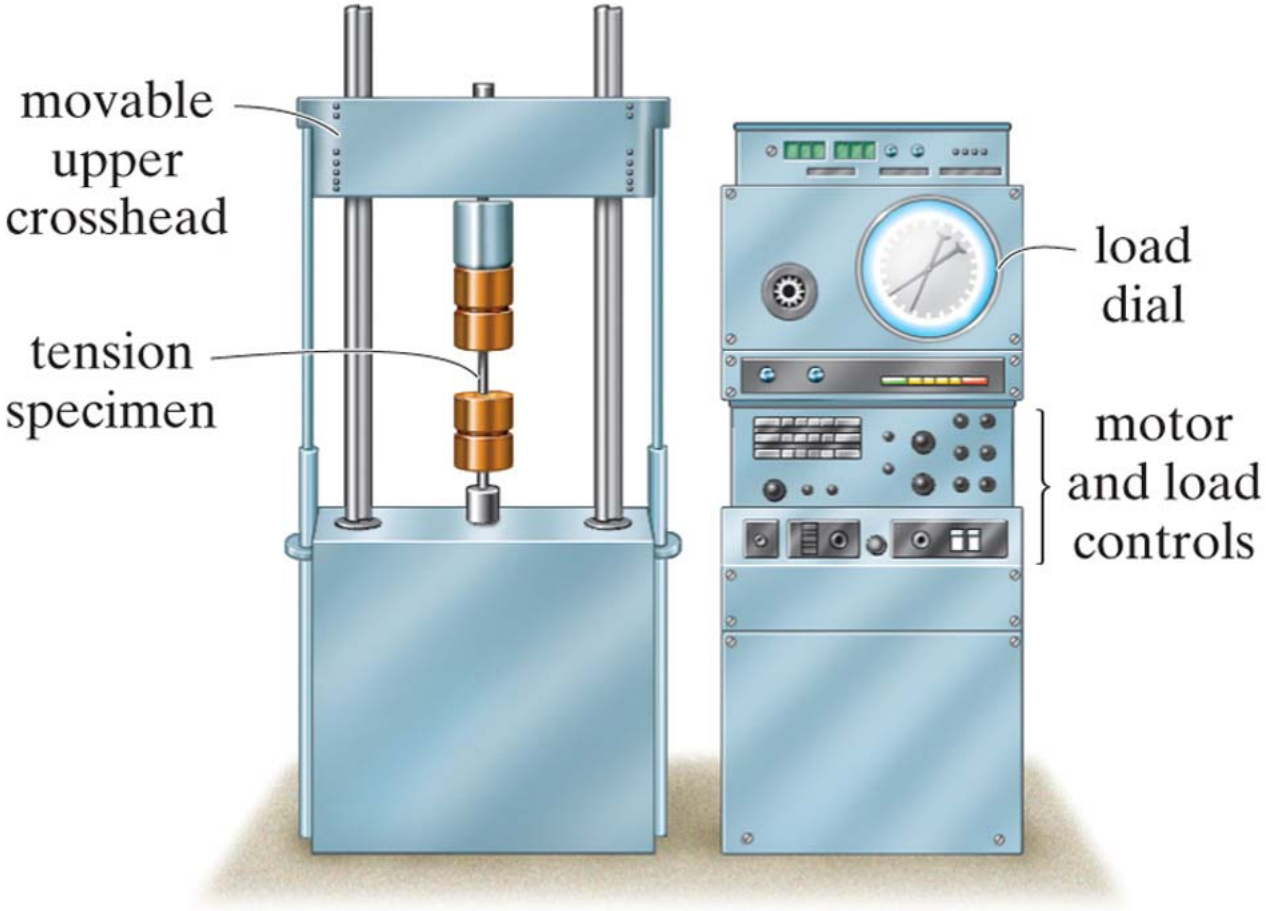




Electrical–resistance strain gauge

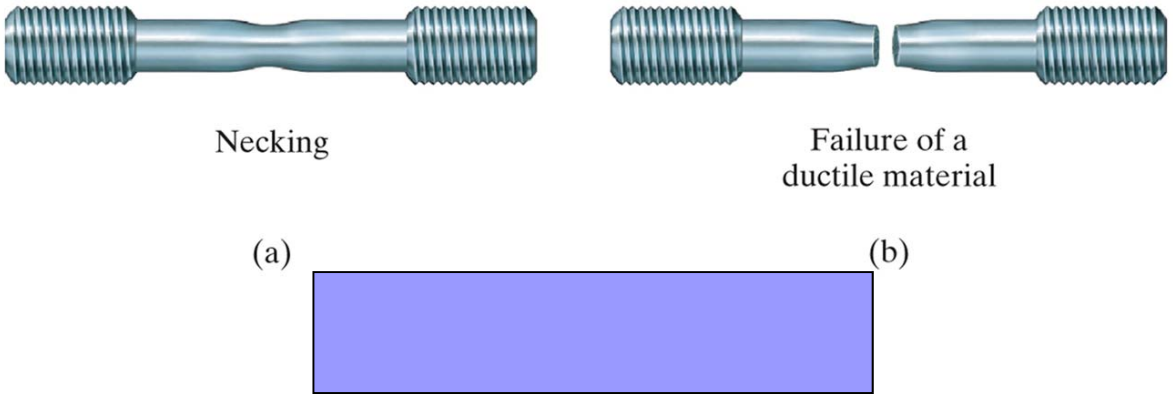
Material behaviour

Burj Dubai



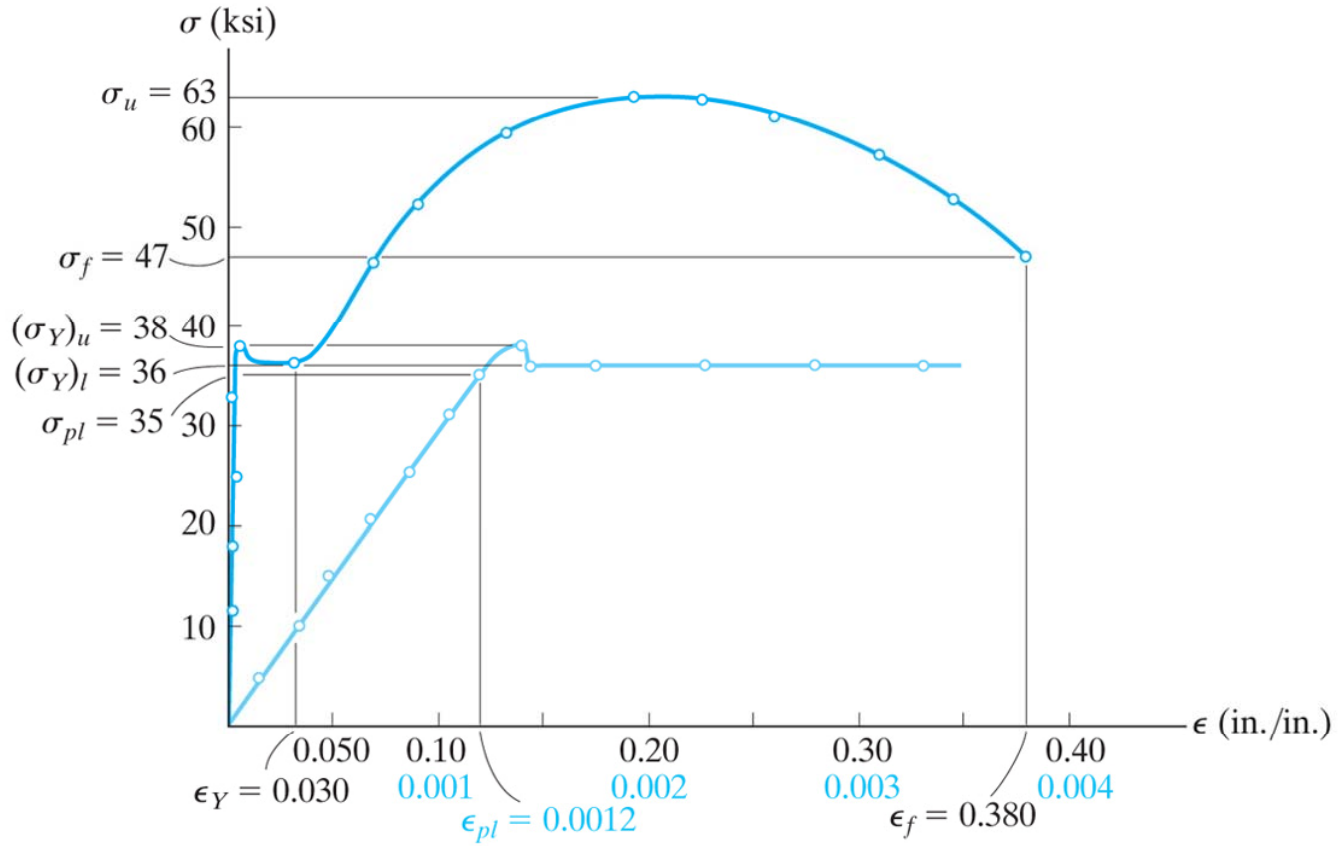
R.C. Hibbeler, Mechanics of Materials, 7th Ed, Prentice Hall

Material behaviour



Material behaviour

Taipei 101

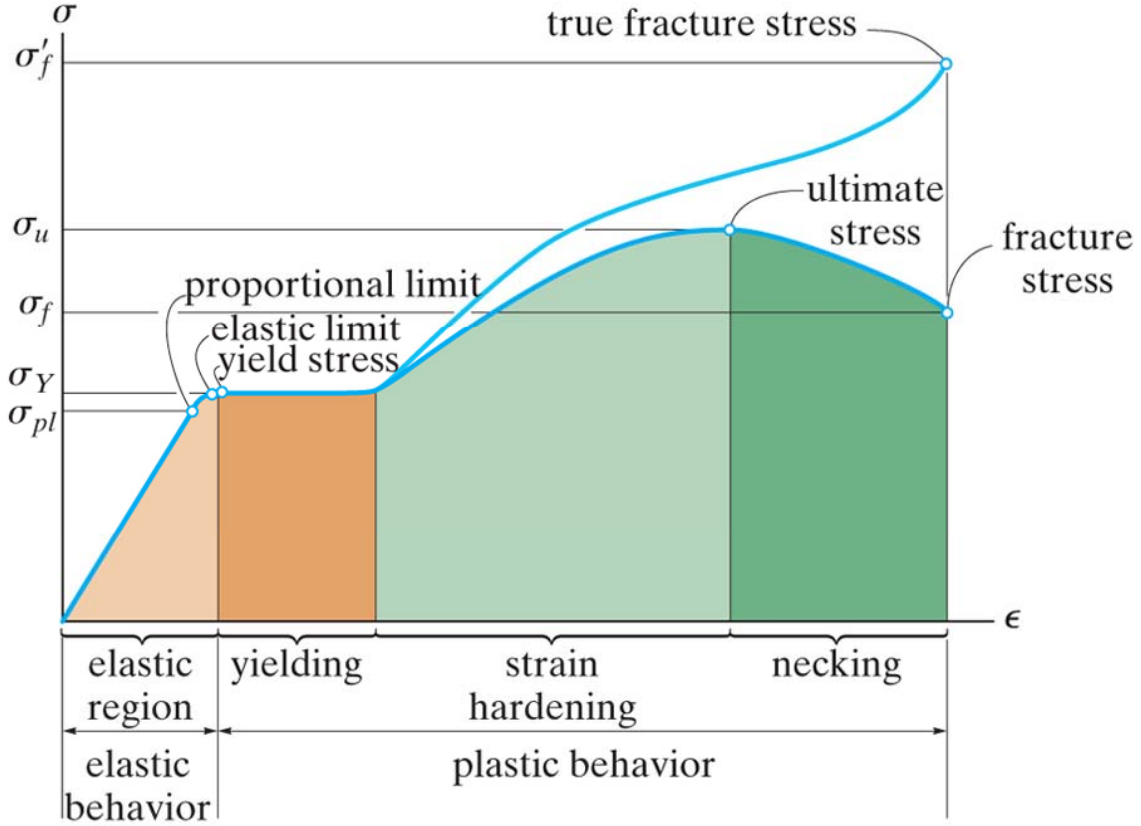


Stress-strain diagram for mild steel

R.C. Hibbeler, Mechanics of Materials, 7th Ed, Prentice Hall

Material behaviour

New York Freedom tower (proposed)



Conventional and true stress-strain diagrams for ductile material (steel) (not to scale)

Material behaviour

- **Temperature effects on material properties**

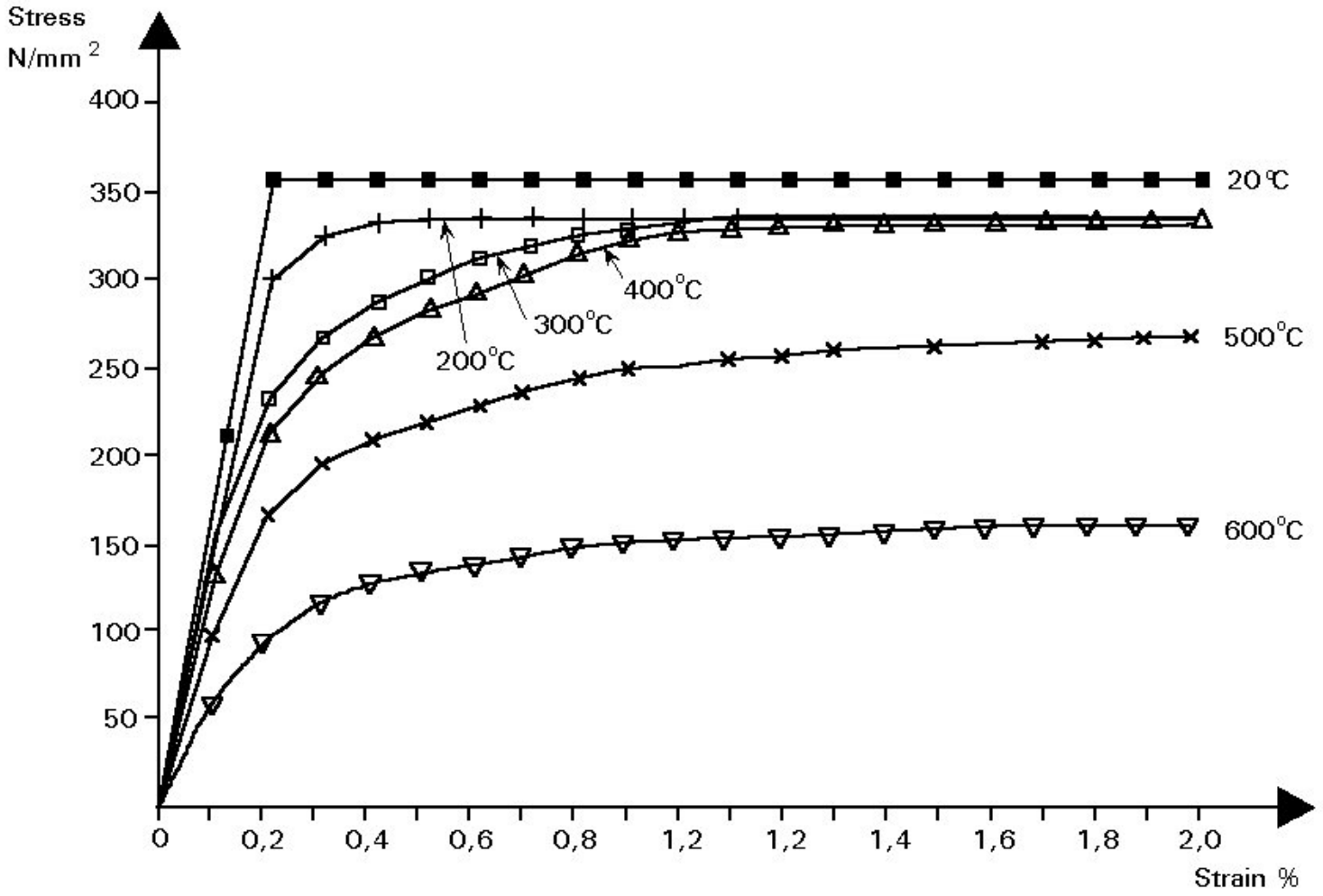
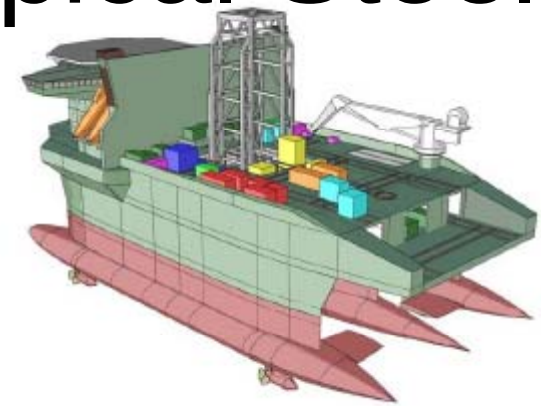
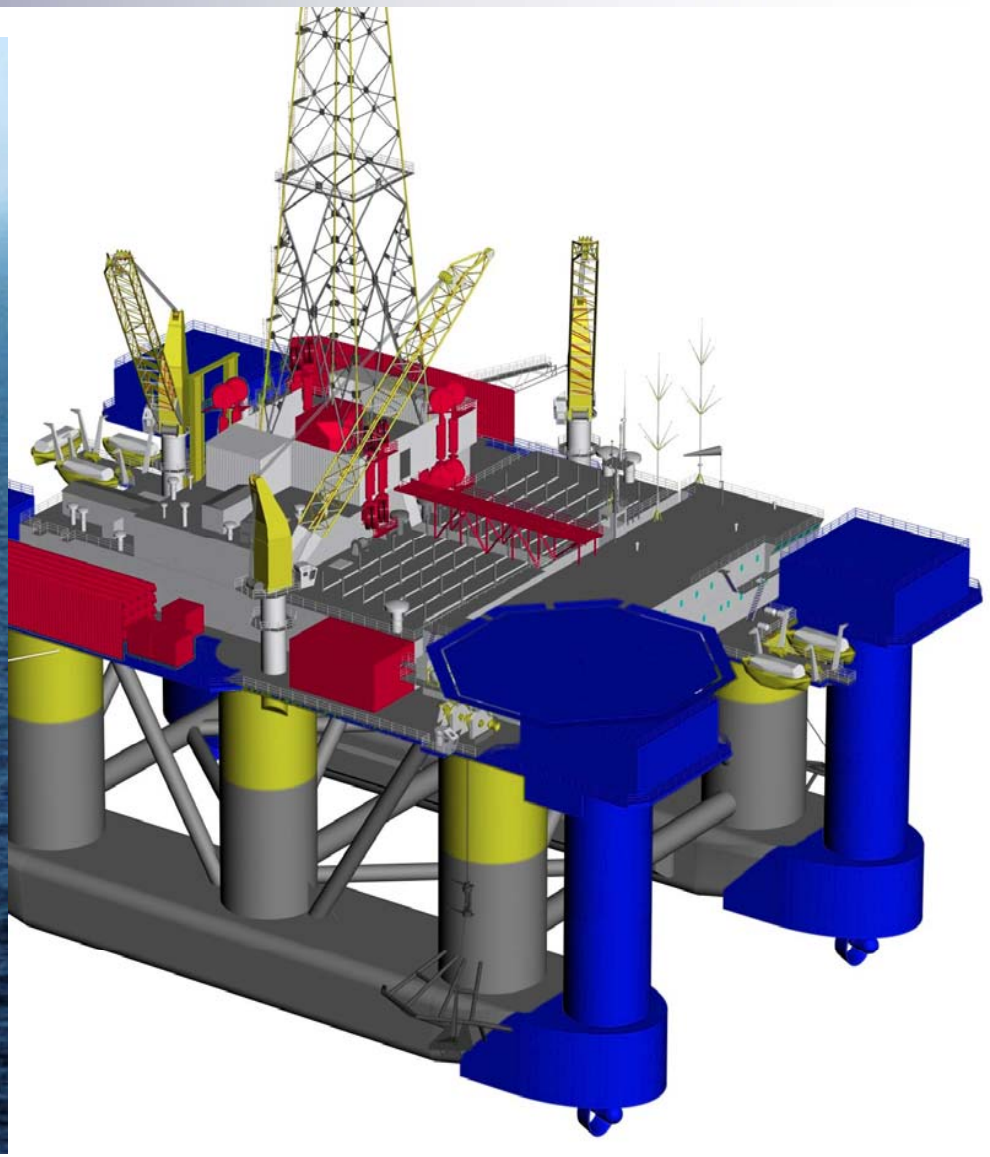


Figure 12 Influence of temperature on the mechanical properties of structural steel (Example shown is Fe490)

Typical Steel Use



Hybernia platform (Grand banks, NL)
topsides are steel



Typical Steel Use

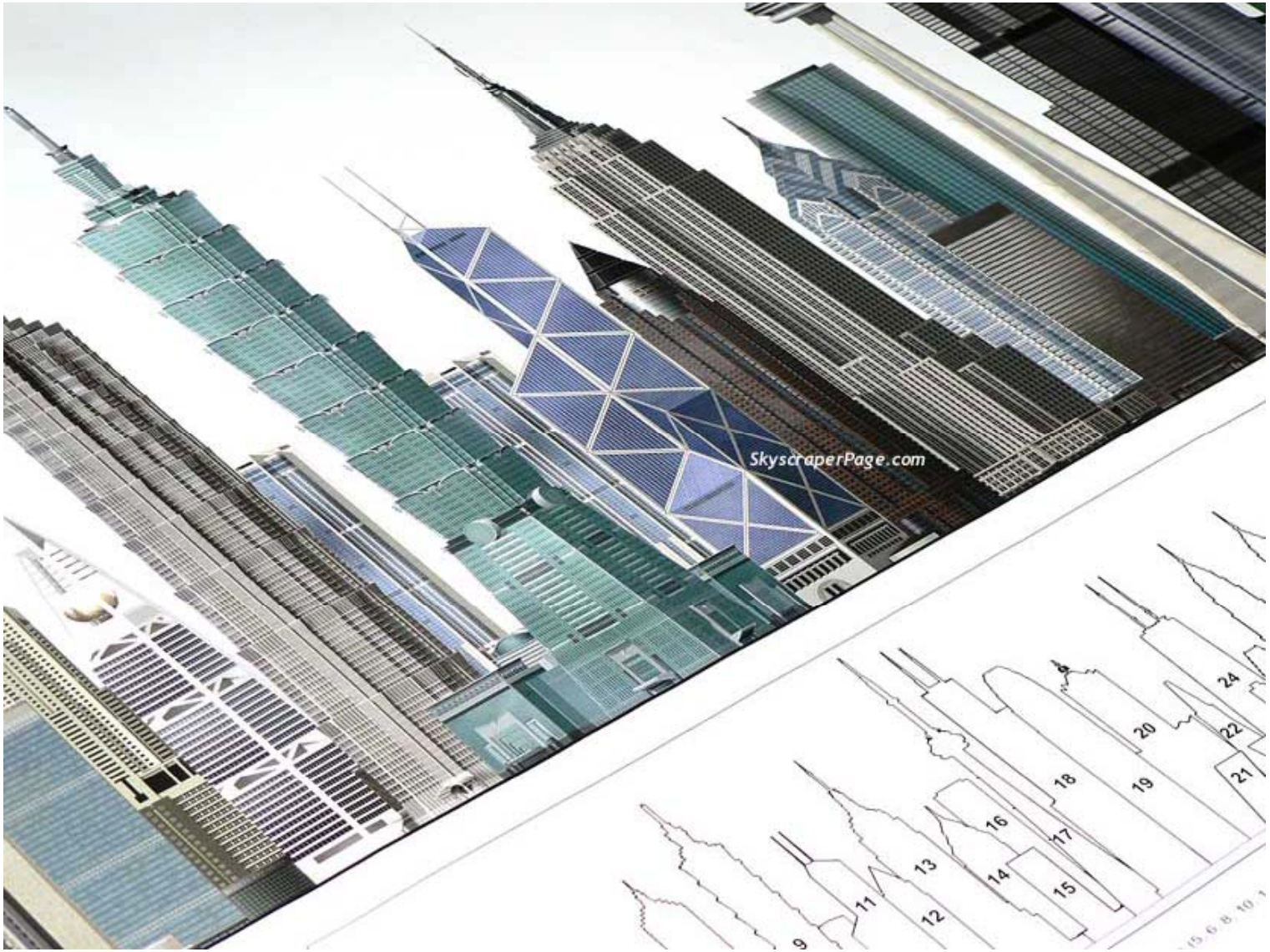
R.C. Hibbeler, Mechanics of Materials, 7th Ed, Prentice Hall

Typical Steel Frame Structure

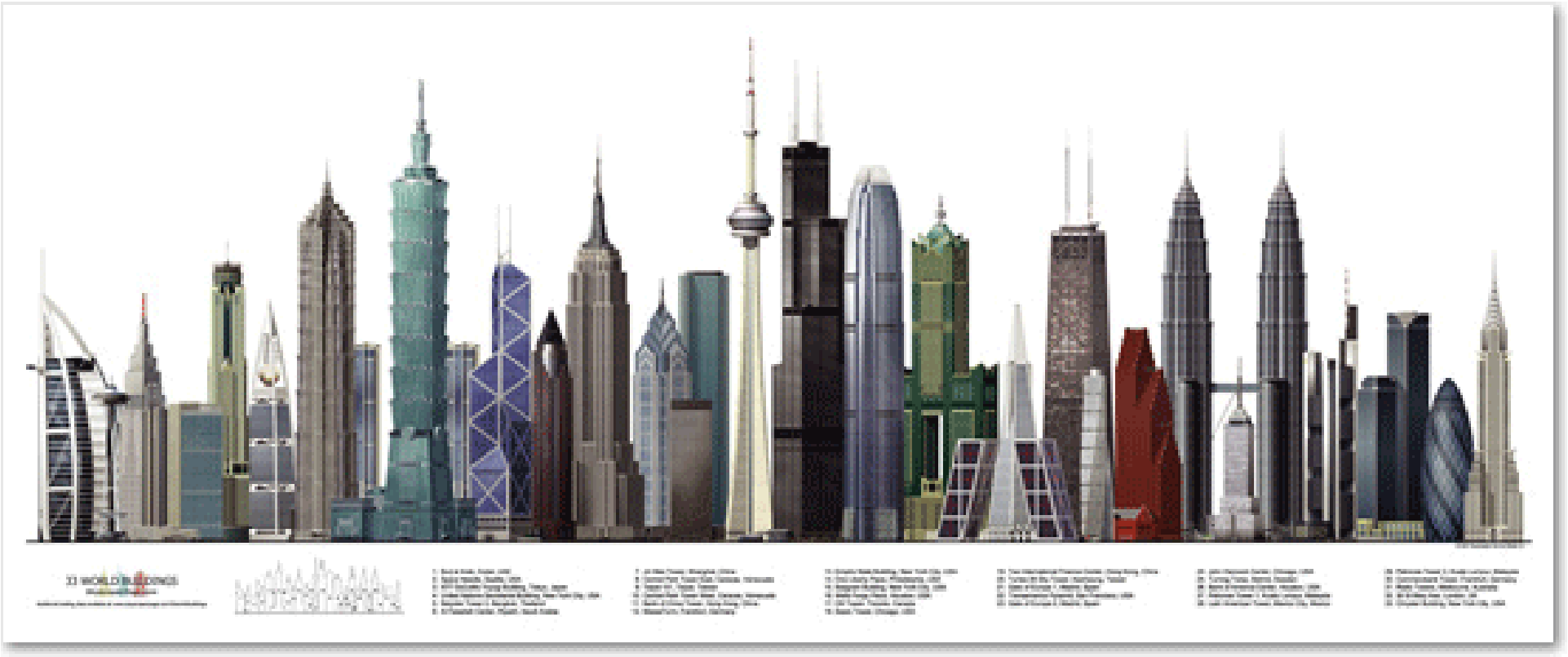
Typical Steel Frame Structure

Chhatrapati Shivaji International Airport, Mumbai, India

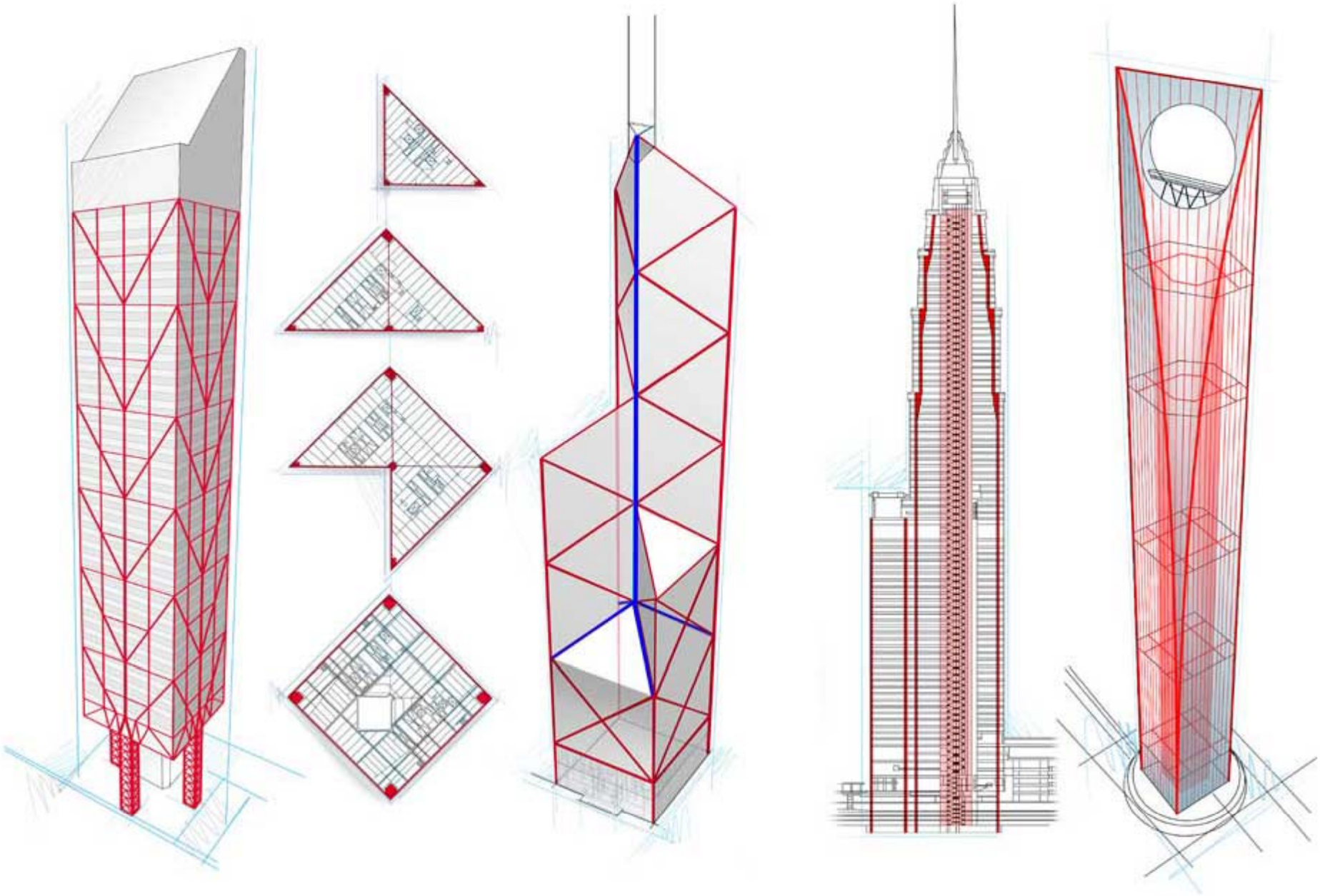
Structures



Structures…..



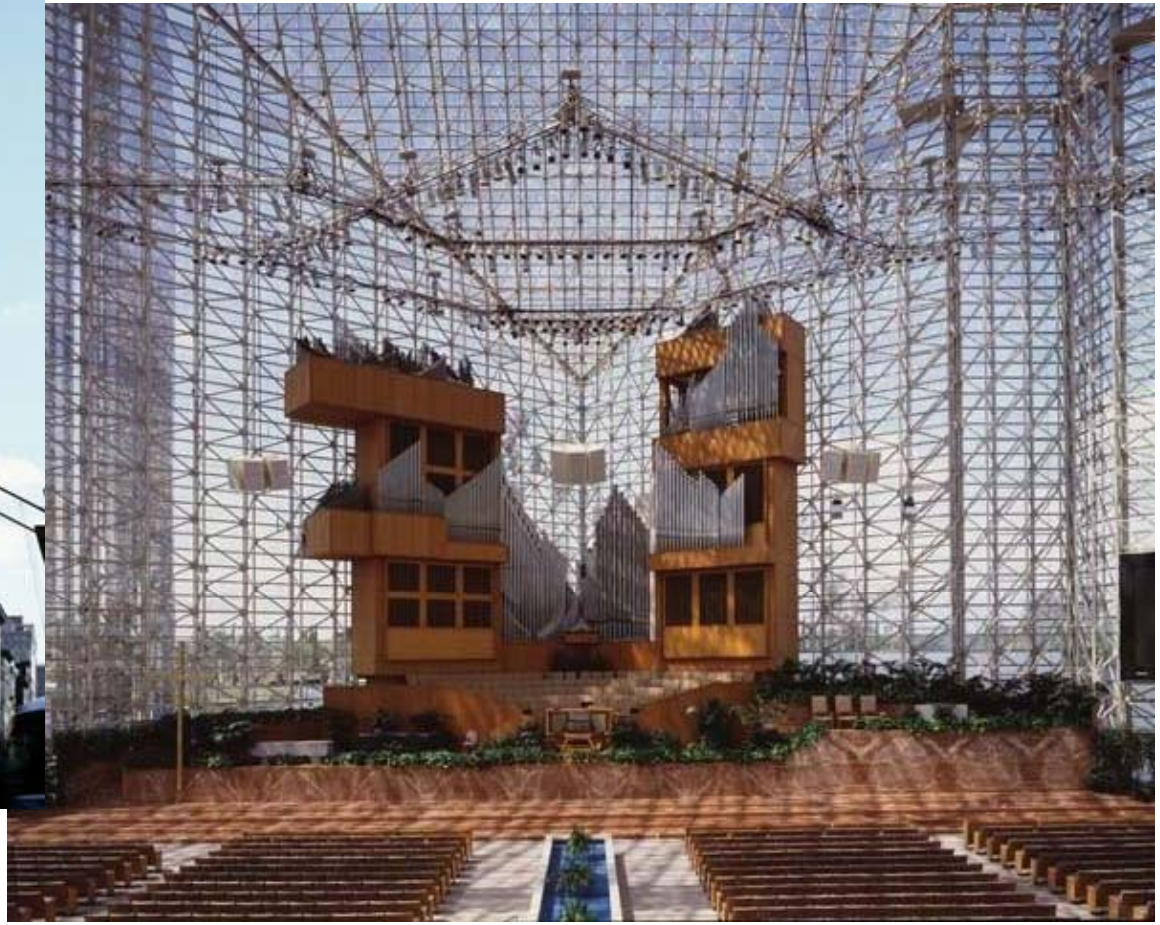
Structures….



Structures …..

Flatiron Building
(Fuller Building) (1903)

Crystal Cathedral (1980) - Garden Grove, CA



Structures….

Walt Disney Concert Hall (2003) - Los Angeles, CA; Frank Gehry

Time Warner Center (2003) - New York

Structures….

Seattle Public Library (2004)

St. Louis Arch, 192mx192m

Bridges

Glen canyon, Colorado

Bridges

New River Gorge Bridge the largest single span steel arch bridge in the western hemisphere. It measures 876 ft. from the bridge to the bottom of the gorge

Old Nanpu Bridge (double loop ramp), Shanghai,

Bridges

Bridges in San Francisco
http://www.wunderground.com/blog/ozcazz/comment.html?entrynum=11&tstamp=200611

Steel gives the flexibility to create the desired aesthetic effect using the structural members

Orient railway station, Lisbon, Portugal Architect: Santiago Calatrava

Exposed steel will require special processing that will impact the cost and schedule

Airport terminal, Lyon, France Architect: Santiago Calatrava

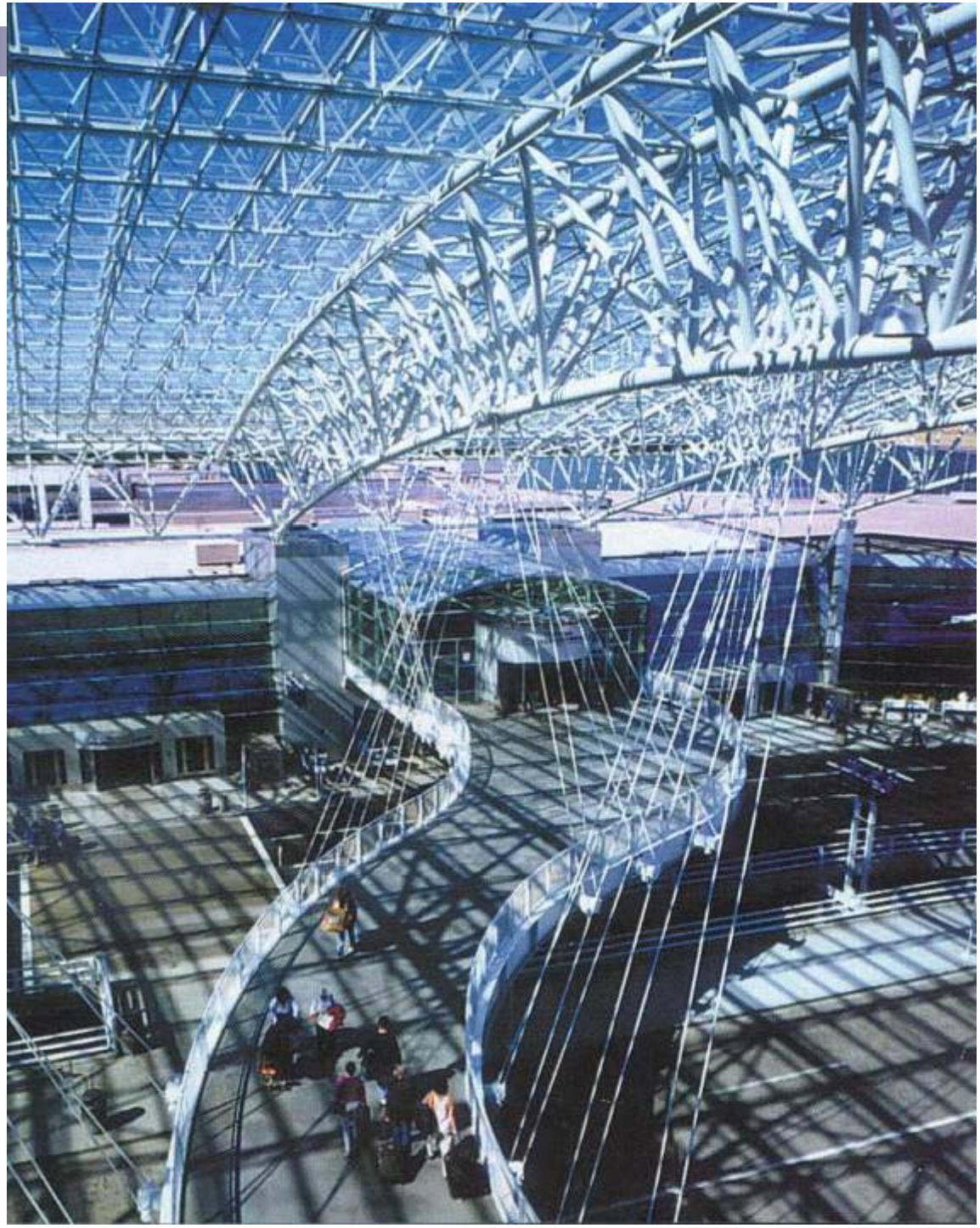
Architecturally Exposed Structural Steel - AESS

Roof of the Santa Fe Opera Theatre, Santa Fe, New Mexico Architects: Polshek Partnership, LLP

Typical Applications

- The entire structure or key portions may use AESS
- Popular applications include
  - Hanging walkways
  - Framing in atriums and lobbies
  - Office interiors
  - Canopies
  - Airport terminals

AESS Canopy and Hanging Walkway



Portland International Airport (PDX) Roadway Canopy and Pedestrian Bridges, Portland, Oregon, Architects: Zimmer Gunsul Frasca Partnership

MEMORIAL UNIVERSITY
Newfoundland & Labrador, Canada

AWSS Atriums and Lobbies

Gaylord Opryland Hotel Texas, Lake Grapevine near Dallas, TX Architects: Hnedak Bobo Group, Memphis, TN, Photo by Glen Patterson

AESS Office Interiors

Lindhout Associates Headquarters, Brighton, MI

Herman Miller Marketplace, Zeeland, MI Architects: Integrated Architecture, Grand Rapids, MI

AESS Airport Terminals

The United Airlines Terminal, Chicago, IL Architects: Murphy/Jahn and A. Epstein & Sons Int'l

AESS Open Web Beams

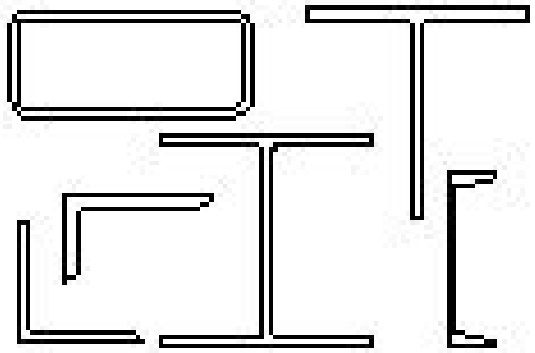
Open web beams are lighter and aesthetically attractive.

Computer-controlled cutters provide design flexibility.

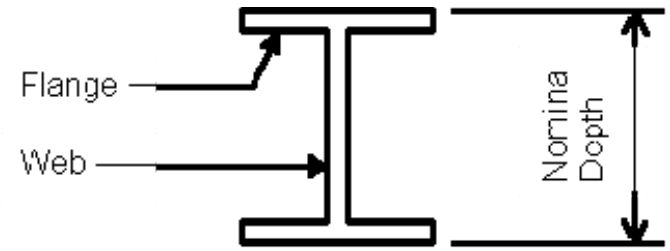
Typical Steel-Concrete Structure

Structural Steel shapes

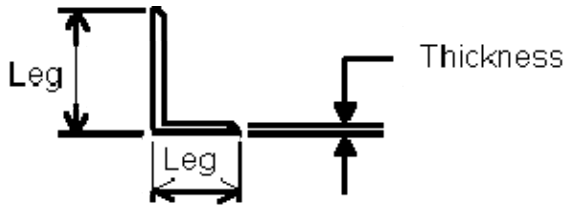
- Hot Rolled shapes –Section 6, CISC Handbook
  - (W) W-shapes (Wide Flange)
  - (S) Sections
  - (L) Angles
  - (C) Channels
  - (WT) Structural Tees
  - HSS
  - Plates, ……
- Built-up members



Structural Steel shapes

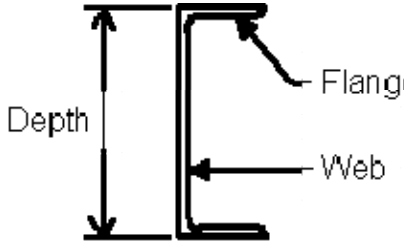


Wide Flange Beam

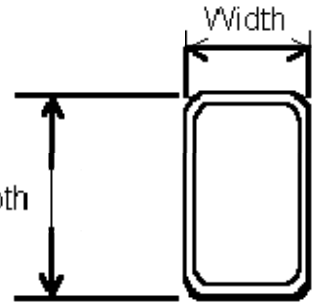


Steel Angle

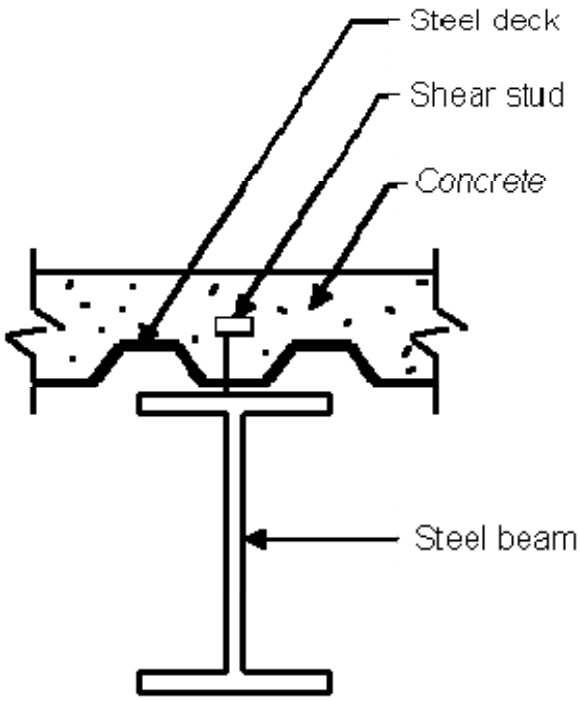
Steel Pipe



Steel Channel



Tube Steel



Composite Steel Beam/Deck Detail

Structural Steel shapes

Fabrication facilities

Fabrication bay

Cambering machine

Fabrication facilities

Residual stresses

- Stresses can be left behind in steel shapes after certain events
  - Hot-rolling (due to differential cooling)
  - Welding (due to differential cooling)
  - Cold-forming (due to plastic deformation)
  - Excessive deformation
  - Etc.

Residual stresses

- Welding residual stresses

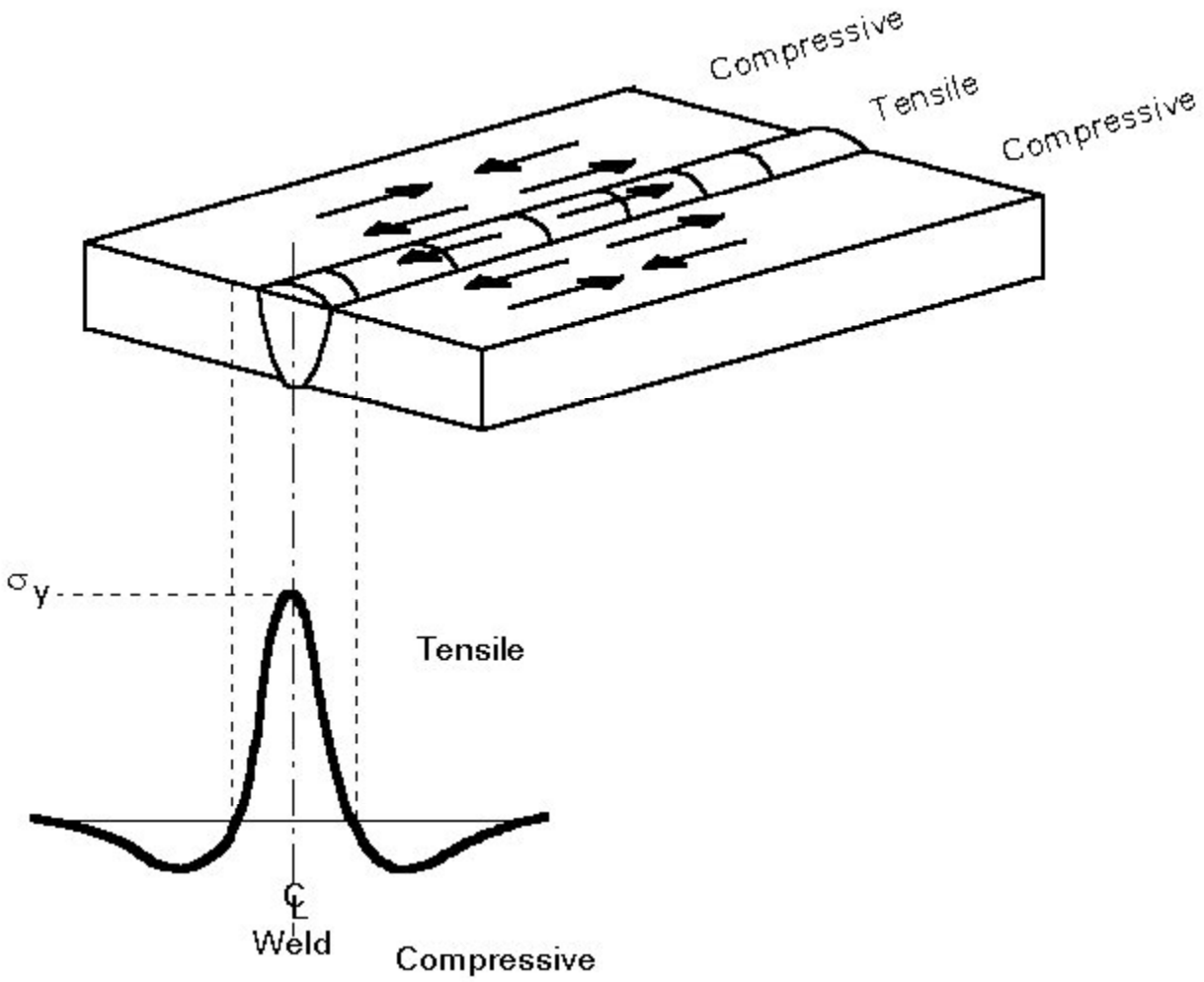


Figure 15 Residual stress

Residual stresses

- Hot-rolled stress contours

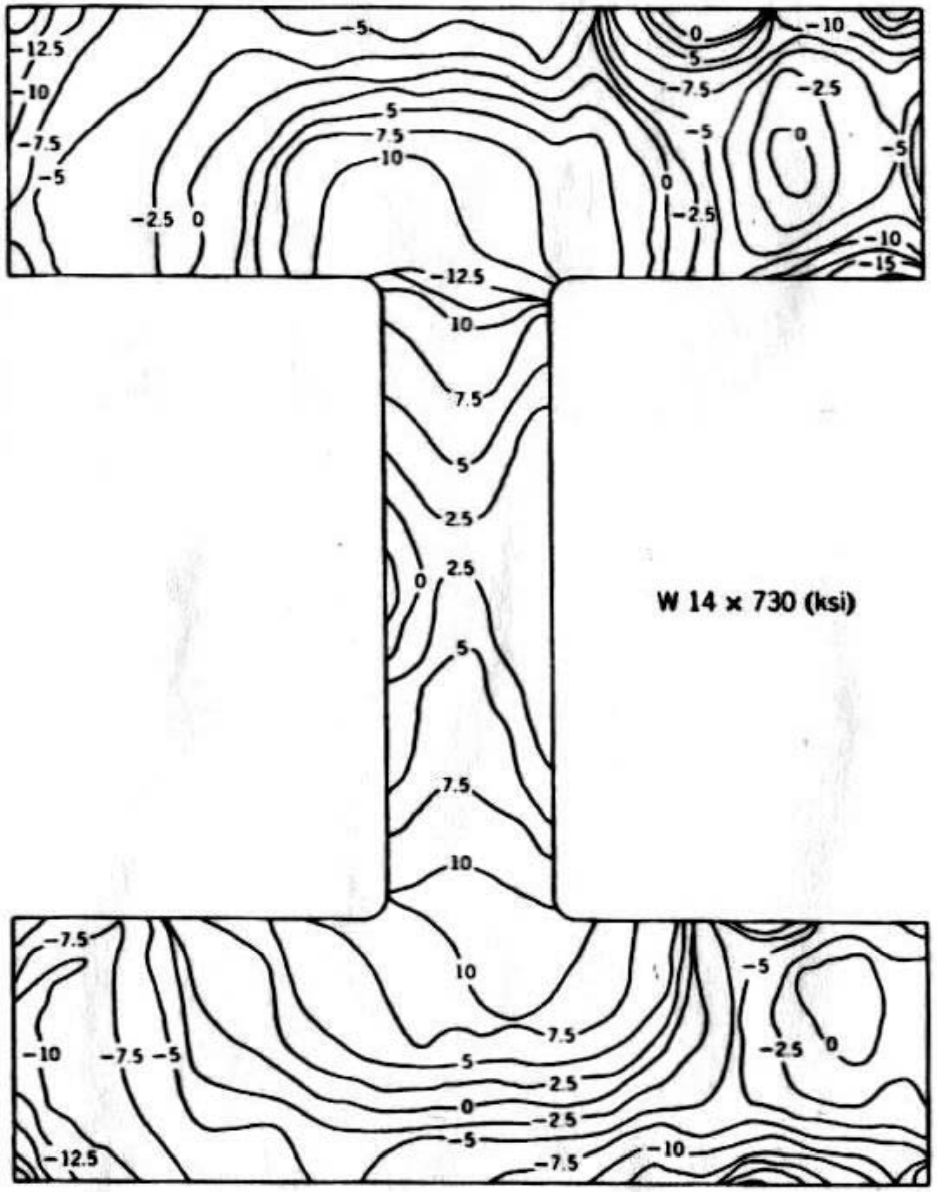
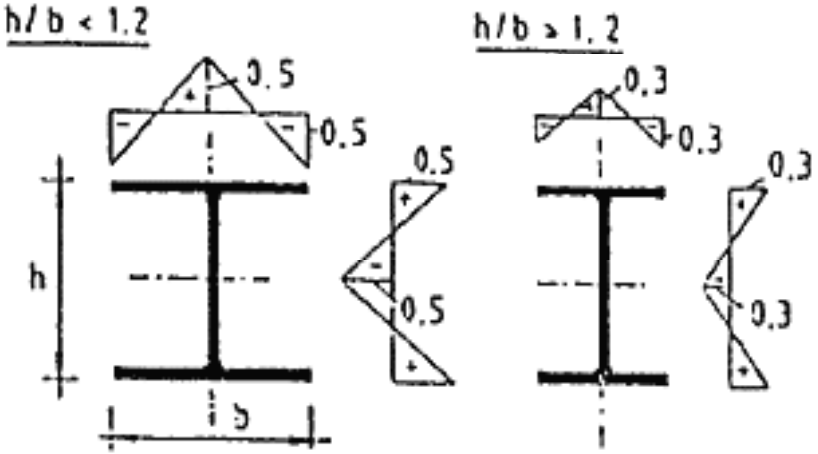


Fig. 3.4 Residual-stress distribution in W14 × 730 shape.

Residual stresses

- Idealized residual stresses in Hot-rolled shapes



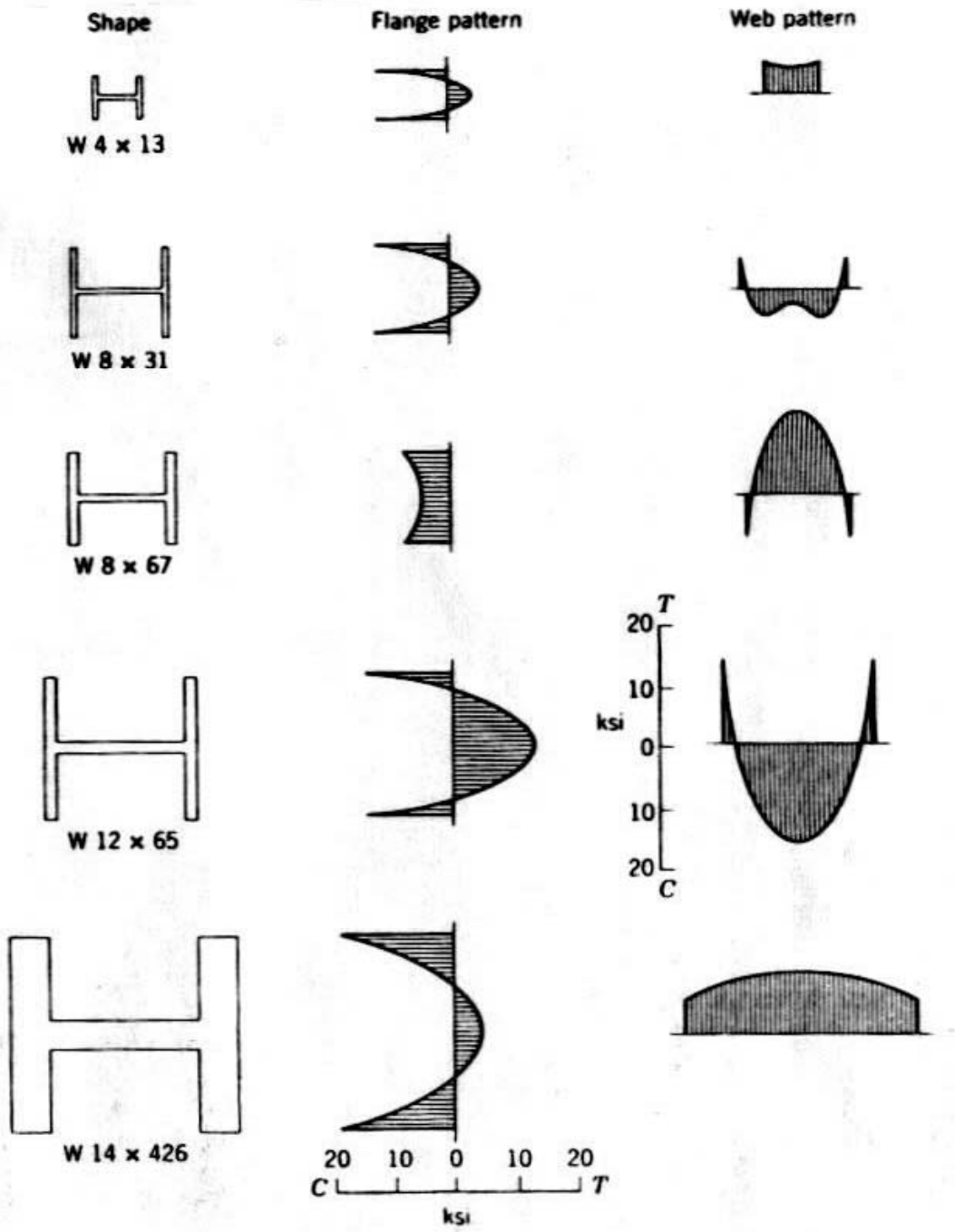


Fig. 3.3 Residual-stress distribution in rolled wide-flange shapes.

References

- Many pictures in this file are taken from various sources such as CISC, AISC, etc. The copyrights for those materials are with the original sources. No copyright is claimed or implied by Dr. Seshu Adluri for things that are already under copyright protection. This file is for teaching purposes only.