Week 2: Steel

Mostly an overview of Chapter 3, M&Z

CEE 363 Construction Materials

Steel Topics
- Introduction to iron and steel
- Types of steel used in construction
- Steel production
- Iron-carbon phase diagram
- Heat treatment of steel
- Steel alloys
- Structural steel
- Reinforcing steel
- Mechanical testing of steel
- Steel corrosion
- Astec Industries
- Metals prices

Introduction to Iron and Steel
- A few definitions and general descriptions are in order
  - Iron: Iron is an element and can be pure.
  - Cast iron: Iron that contains about as much carbon as it can hold which is about 4%.
  - Wrought iron: Iron that contains glassy inclusions.
  - Steel: Iron with a bit of carbon in it—generally less than 1%.

A Selection of Mechanical Properties (from Gordon (1979))

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel piano wire</td>
<td>450,000</td>
</tr>
<tr>
<td>Commercial mild steel</td>
<td>60,000</td>
</tr>
<tr>
<td>Cast iron</td>
<td>10,000 to 40,000 and higher</td>
</tr>
<tr>
<td>Wrought iron</td>
<td>20,000 to 40,000</td>
</tr>
</tbody>
</table>

Thermal Expansion of Various Materials (from CISPI (1994))

<table>
<thead>
<tr>
<th>Material</th>
<th>in/in x 10^-6</th>
<th>in/100 ft. of pipe per 100°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron</td>
<td>6.2</td>
<td>0.75</td>
</tr>
<tr>
<td>PCC</td>
<td>5.5</td>
<td>0.66</td>
</tr>
<tr>
<td>Steel (mild)</td>
<td>6.5</td>
<td>0.78</td>
</tr>
<tr>
<td>Steel (stainless)</td>
<td>7.8</td>
<td>0.94</td>
</tr>
<tr>
<td>PVC (high impact)</td>
<td>55.6</td>
<td>6.68</td>
</tr>
<tr>
<td>ABS (Type 1A)</td>
<td>56.2</td>
<td>6.75</td>
</tr>
<tr>
<td>Polyethylene (Type 1)</td>
<td>94.5</td>
<td>11.4</td>
</tr>
</tbody>
</table>
Introduction to Iron and Steel

- A few definitions and general descriptions are in order
  - Alloy steel: A generic term for steels which are alloyed with elements other than carbon. Why alloys? The mechanical behavior iron is changed hugely by the addition of carbon and other additives (or alloys).

Types of steel used in construction

- Structural steel—plates, bars, pipes, structural shapes.
- Reinforcing steel—concrete reinforcement.
- Miscellaneous shapes for applications such as forms.

Types of steel used in manufacturing construction equipment

- A36 plate at Astec Industries, Chattanooga, TN
- A36 plate at Lafarge Cement Plant, Seattle. Part of a new kiln for making clinker (portland cement). Steel is 1.5 in. thick.

Types of steel used in construction

“Civil and construction engineers rarely have the opportunity to formulate steel with specific properties. Rather, they must select existing products from suppliers. Even the shapes for structural elements are generally restricted to those readily available from manufacturers.” M&Z

“Even though civil and construction engineers are not responsible for formulating steel products, they still must understand how steel is manufactured and treated and how it responds to loads and environmental conditions.” M&Z
Example of a local manufacturer
- Nucor Steel Seattle, Inc
- Location: West Seattle
- Nucor acquired assets for Birmingham Steel Dec 9, 2002.
- Annual capacity: 2.2 million tons
- Products
  - Carbon steel angles, channels, flats
  - Reinforcing bar

Typical shapes
- **Angle**
  - Structural steel shape resembling L. May be Equal Leg Angle or Unequal Leg Angle. Used in trusses and built-up girders.
- **Channel**
  - Structural steel shape which has a cross-section resembling [. Used in trusses and built-up girders.

Typical shapes
- **Plate**
  - Sheet steel with a width of more than eight inches, with a thickness ranging from one quarter of an inch to more than one.
- **Flat-rolled steel**
  - Category of steel that includes sheet, strip, and tin plate, among others. Produced by passing ingot/slab through pairs of rolls.
- **Reinforcing Bar (Rebar)**
  - A commodity-grade steel used to strengthen concrete in highway and building construction.

Steel production
- Reduction of iron ore to pig iron.
- Refining pig iron to steel.
- Forming the steel into products.
- Refer to Fig 3.1, M&Z

Steel production (US stats)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Million metric tons (2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig iron production</td>
<td>39.4</td>
</tr>
<tr>
<td>Steel production</td>
<td>91.5</td>
</tr>
<tr>
<td>- Basic oxygen furnaces (%)</td>
<td>48%</td>
</tr>
<tr>
<td>- Electric arc furnaces (%)</td>
<td>52%</td>
</tr>
<tr>
<td>Imports of steel products</td>
<td>21.7</td>
</tr>
<tr>
<td>Exports of steel products</td>
<td>8.2</td>
</tr>
<tr>
<td>Apparent steel consumption</td>
<td>104</td>
</tr>
<tr>
<td>Net import reliance</td>
<td>9%</td>
</tr>
</tbody>
</table>

Import sources: EU—18%, Canada—15%, Mexico—10%, Japan—7%, Other—50%
World steel production

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>91.5</td>
</tr>
<tr>
<td>Brazil</td>
<td>27.5</td>
</tr>
<tr>
<td>China</td>
<td>200</td>
</tr>
<tr>
<td>EU</td>
<td>159</td>
</tr>
<tr>
<td>Japan</td>
<td>110</td>
</tr>
<tr>
<td>Korea</td>
<td>46</td>
</tr>
<tr>
<td>Russia</td>
<td>61.2</td>
</tr>
<tr>
<td>Ukraine</td>
<td>38</td>
</tr>
<tr>
<td>World Total</td>
<td>924</td>
</tr>
</tbody>
</table>

Steel and aluminum recycling

<table>
<thead>
<tr>
<th>Metal</th>
<th>Percentage Recycled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron and steel</td>
<td>55%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>38%</td>
</tr>
</tbody>
</table>

Steel production

- Materials used to produce pig iron
  - Coal—as coke—used to supply carbon. In a blast furnace, ore is heated in the presence of carbon—this allows oxygen in the ore to react with carbon to form gases.
  - Limestone—helps to remove impurities
  - Iron ore—processed ore at the start of the process has about 65% iron.
  - Impurities (slag) float on the top of melt.
- Requires about 3.2 tons of raw materials to produce 1.0 ton of steel.

Steel production

- Three types of furnaces have been used for refining pig iron (or scrap steel) to refined steel
  - Open hearth (no longer used the US)
  - Basic oxygen
  - Electric arc

Iron-carbon phase diagram

- To refine steel from either scrap or pig iron, the amount of carbon must be carefully controlled.
- In M&Z, Fig 3.2 shows a typical iron-carbon diagram. This helps us to understand how this control is done.
- A slightly more colorful version of the iron-carbon phase diagram follows.

Iron-carbon phase diagram--terms

- Ferrite (α): Iron in a BCC structure. Maximum solubility of carbon in ferrite is low (0.02%C).
- Austenite: Iron with a FCC structure. Due to FCC structure, more carbon atoms can be accommodated. Maximum solubility of carbon in austenite is 2.11%.
- Cementite (or iron carbide): This forms when solubility of carbon in solid iron is exceeded. Fe₃C contains 6.67%C. Cementite is present in all commercial steels.
- Pearlite: Lamellar structures of α ferrite and cementite.
Ferrite, pearlite, and iron carbide greatly influence the properties of steel.

- Ferrite has relatively low strength but is very ductile.
- Iron carbide has high strength but little ductility.
- Combining these two in different proportions alters the mechanical properties of steel.
- In general, increasing carbon content increases the strength but reduces ductility.

Iron-carbon phase diagram

- Left side—pure iron (0% carbon) goes through two transformations as temp increases:
  - Pure iron below 912°C has BCC crystalline structure called ferrite.
  - At 912°C, ferrite changes to a FCC structure called austenite (γ).
  - At 1394°C, iron returns to a BCC structure.
  - The high and low ferrites identified as δ and α ferrite.

- Carbon goes into solution with α ferrite at temps between 400°C and 912°C—but solubility limit for carbon is very low—about 0.02% at 727°C.

- At carbon contents less than eutectoid composition, hypoeutectoid (or containing less than 0.77% carbon) alloys are formed. Most structural steels are hypoeutectoid (about 0.1 to 0.3% carbon).

  1. For example, at 0.25% carbon, and above about 810°C, solid austenite exists as grains of uniform material. As the temp drops, α ferrite is formed from 810 to 727°C and accumulates at the grain boundaries of the austenite.
  2. At temps slightly above 727°C, the ferrite will have 0.02% carbon in solution and austenite will have 0.77% carbon.
  3. When temp drops below 727°C, the austenite will transform to pearlite (alternate layers of α ferrite and iron carbide). Pearlite is not a phase but a mixture of two phases. Refer to next image.
Pearlite and Ferrite below 727°C

Iron-carbon phase diagram

The relative amounts of ferrite and austenite are scaled horizontally (refer to blue line). As shown here, there about equal amounts at about 750°C.

Image of pearlite

Light colored material is ferrite and dark material is iron carbide.

Heat treatment of steel

- Properties of steel can be altered by applying a variety of heat treatments.
- **Annealing**: Heat to austenite range (about 10°C above the austenite line) then slowly cool to room temp. Results in softer steel, reduced internal stress, increases ductility and toughness.
- **Normalizing**: Same as annealing but heat to 40°C above the austenite line. Then air cool. Produces a uniform, fine-grained structure. Considered as a corrective treatment and not for strengthening.

Steel alloys

- Alloy agents are added to improve one or more of the following properties
  - Hardness
  - Corrosion resistance
  - Machineability
  - Ductility
  - Strength
- Typical alloys are shown in Table 3.1, M&Z.

Steel alloys

- Structural steels based on composition
  - Carbon or carbon-manganese steels
  - High strength low alloy steels (HSLA)
  - High strength quenched and tempered alloy steels
- Read the content in the pdf file from MIT, Civil and Environmental Engineering Dept, Spring Semester 1999 entitled "Chemical Composition of Structural Steels."
Structural steel

Structural steel grades in the US (but not limited to)
- ASTM A36—be careful, this one is being replaced by ASTM A992. Thus, info in M&Z needs a little updating.
- ASTM A529
- ASTM A572
- ASTM A242
- ASTM A588
- ASTM A514

Refer to additional details in Table 3.2, M&Z.
Be careful—should always obtain information on locally available grades and changing grades.
- ASTM A992
- ASTM A852

Structural steel specifications

City of San Diego—refer to pdf on class website.


Structural steel specifications

Bridges
- American Association of State Highway and Transportation Officials (AASHTO)
- For example, WSDOT Standard Specifications refer to AASHTO M 270. What is this?
  - "Carbon and High-Strength Low-Alloy Structural Steel Shapes, Plates, and Bars and Quenched and Tempered Alloy Structural Steel Plates for Bridges"

Structural steel

Structural steel shapes
- W: Wide-flange
- HP: Wide-flange
- M: Wide-flange
- S: I-beam
- C: Channel
- MC: Channel
- L: Angle
- Refer to Fig 3.5, M&Z.
- Refer to ASTM A6 "Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use."

Structural steel question

Is it always better to specify shapes with the highest possible strength?
Reinforcing steel

- PCC has little tensile strength, thus structural PCC members subjected to tensile and flexural stresses must be reinforced.
- Can be produced in four grades: 40, 50, 60, and 75 ksi.
- Refer to Table 3.3, M&Z.

Reinforcing steel specifications

- WSDOT Standard Specifications, Section 9-07.2 "Deformed Steel Bars"
  - "Deformed steel bars for concrete reinforcement shall conform to the requirements of AASHTO M 31, Grade 60 or ASTM A706.
  - AASHTO M 31 "Deformed and Plain Billet-Steel Bars for Concrete Reinforcement." This specification is the same as ASTM A615.
  - ASTM A706: "Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement"
  - Billet-steel simply refers to a type of section (or block) of steel prior to rolling into a final shape or product.

Reinforcing steel sizes

<table>
<thead>
<tr>
<th>Bar diameter (in.)</th>
<th>US Customary (1/8's of an inch)</th>
<th>Metric (diameter, mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.375</td>
<td>#3</td>
<td>#10</td>
</tr>
<tr>
<td>0.500</td>
<td>#4</td>
<td>#13</td>
</tr>
<tr>
<td>0.625</td>
<td>#5</td>
<td>#16</td>
</tr>
<tr>
<td>0.750</td>
<td>#6</td>
<td>#19</td>
</tr>
<tr>
<td>0.875</td>
<td>#7</td>
<td>#22</td>
</tr>
<tr>
<td>1.000</td>
<td>#8</td>
<td>#25</td>
</tr>
<tr>
<td>1.128</td>
<td>#9</td>
<td>#29</td>
</tr>
<tr>
<td>1.270</td>
<td>#10</td>
<td>#32</td>
</tr>
<tr>
<td>1.410</td>
<td>#11</td>
<td>#36</td>
</tr>
<tr>
<td>1.690</td>
<td>#14</td>
<td>#43</td>
</tr>
<tr>
<td>2.260</td>
<td>#18</td>
<td>#57</td>
</tr>
</tbody>
</table>

Mechanical testing of steel

- The major tests are:
  - Tension test—you will do this one in lab as a group.
  - Torsion test
  - Charpy V Notch Impact Test—a measure of toughness. This will be demonstrated in lab.
  - Bend test
  - Hardness test—this will be demonstrated in lab.

Tension test

- Refer to ASTM E8 "Standard Test Method for Tension Testing of Metallic Materials" (also AASHTO T 68)
- Determine (refer to Figs 3.9—3.10, M&Z)
  - Yield strength
  - Yield point elongation
  - Tensile strength
  - Elongation
  - Reduction of area
- Testing done at room temperature

Tension test in CEE Lab

- Report material property items shown in ASTM E8
  - Yield strength and method used to determine yield strength
  - Yield point elongation
  - Tensile strength
  - Elongation
  - Reduction of area
  - ....and modulus of elasticity.
Impact test

- Also designated AASHTO T 266.
- Used to measure the "toughness" of the material—or more to the point—the energy required to fracture a V-notched simply supported specimen.
- Energy measured in m-N (ft-lb). This value is compared to allowable specification values.
Example—Tanker constructed for WW2

Impact Test Transition Temperature

Example—steel from Titanic

Conversion: joules x 0.74 = ft-lb

Titanic steel plate had a Charpy Value of about 4 ft-lb at 0°C (which was appropriately the water temperature the night of the sinking)

Mechanical properties of Titanic steel from hull

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>28 ksi (193.1 MPa)</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>60 ksi (417.1 MPa)</td>
</tr>
<tr>
<td>Elongation</td>
<td>29%</td>
</tr>
<tr>
<td>Reduction in Area</td>
<td>57.1%</td>
</tr>
</tbody>
</table>

Chemical composition of Titanic steel from hull (%)

<table>
<thead>
<tr>
<th>Source of Steel</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cu</th>
<th>O</th>
<th>N</th>
<th>P2S Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull Plate from Titanic</td>
<td>0.21</td>
<td>0.47</td>
<td>0.049</td>
<td>0.017</td>
<td>0.013</td>
<td>0.011</td>
<td>0.0035</td>
<td>6.8:1</td>
<td></td>
</tr>
<tr>
<td>Sample from Plate—Ship Canal Locks</td>
<td>0.25</td>
<td>0.32</td>
<td>0.012</td>
<td>0.03</td>
<td>--</td>
<td>0.018</td>
<td>0.0035</td>
<td>17.3:1</td>
<td></td>
</tr>
<tr>
<td>A—36</td>
<td>0.20</td>
<td>0.35</td>
<td>0.012</td>
<td>0.027</td>
<td>0.079</td>
<td>0.0035</td>
<td>14.9:1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One of the issues with the steel hull plate from the Titanic is the relatively high amounts of phosphorus and sulfur.

Impact test example specification

- WSDOT Standard Specifications, Section 6-03.2 Materials.
  - “All AASHTO M 270 material used in what the Plans show as main load carrying tension members or as tension components of flexural members shall meet the Charpy V-notch requirements of AASHTO M 270 temperature zone 2. All AASHTO M 270 material used in what the Plans show as fracture critical members shall meet the Charpy V-notch requirements of AASHTO M 270, Fracture Critical Impact Test Requirements, temperature zone 2.”

- So what are the Charpy requirements in AASHTO M 270?
Impact test example specification

- So what are the Charpy requirements in AASHTO M 270?
  - Two tables in AASHTO M 270—non-fracture critical impact test requirements and fracture critical impact test requirements. These are minimum test requirements.
  - Function of steel grade, thickness and joining method and temperature zone (there are three of these).
  - Example for non-fracture critical
    - 36T, Zone 1: 15 ft-lb at 70°F
    - 36T, Zone 2: 15 ft-lb at 40°F
    - 36T, Zone 3: 15 ft-lb at 10°F
  - Example for fracture critical
    - 36F, Zone 1: 25 ft-lb at 70°F
    - 36F, Zone 2: 25 ft-lb at 40°F
    - 36F, Zone 3: 25 ft-lb at 10°F

Note: 36T and 36F refers to a specific grade of steel.

Hardness test

- Often used in specifying machine parts and tools or the effect of heat treatments.
- A frequently used hardness test for steel is the Rockwell Hardness Test.
- ASTM E18 (or AASHTO T 80) “Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials”
- ASTM A370 “Standard Test Methods and definition for Mechanical Testing of Steel Products” contain correlations between Rockwell hardness numbers and approximate tensile strength of the steel.

Steel corrosion

- Corrosion is estimated to cause $276 billion in damage in the US each year. Much of this corrosion is due to iron and steel.
- Some State DOTs, such as the Florida DOT do an extensive amount of corrosion related testing for bridges.

Steel corrosion

- Defined in M&Z as the destruction of a material by electrochemical reaction to the environment.
- Corrosion requires four processes
  - Anode—the corroding metal (steel).
  - Cathode—the reduced metal.
  - Conductor—the steel in this case.
  - Electrolyte—a liquid (or gas) that supports the flow of electrons.
- Corrosion process is analogous to a car battery.
Steel corrosion

Methods for corrosion resistance

- Barrier coatings: Isolate steel from moisture and oxygen. Metallic coatings fit into this category including galvanized coatings such as hot dipped zinc (hot dipped zinc coating is applied to steel at a temperature of about 450°C).
- Inhibitive primer coatings
- Sacrificial primers (cathodic protection): Typically this type of coating is zinc. The zinc becomes an anode and, in effect, “corrodes” in lieu of the steel it is protecting. Thus zinc coatings can protect steel as a sacrificial anode and as a barrier coating.

Steel corrosion

Other preventive measures (some not directly addressed by M&Z):

- Modify the environment
- Modify the properties of a metal
- Install a protective coating over the metals
- Impose an electric current to supply electrons
- Change to non-metallic materials

Supplemental photos—manufacturing of paving equipment

- Photos taken June 2004 at Astec Industries, Chattanooga, TN.
- Astec and Roadtec manufacture heavy equipment for highway construction such as
  - Hot mix plants
  - Milling machines
  - Paving machines

Astec manufacturing site, Chattanooga, TN

Don Brock, CEO, Astec Industries
Roadtec Industries, paving machines

Astec plant located in Alabama

HMA storage silo

Roadtec paving machine and Shuttle Buggy

Steel plate for new paving machine, Roadtec Industries

Plate stock for hot mix plant, Astec Industries
Bending plate, Astec Industries

A different view of bending plate

End result

Hot mix plant being manufactured, Astec Industries

Metals prices

- Steel (hot rolled plate)
  - January 2003: $0.15/lb
  - January 2005: $0.34/lb
- Aluminum alloy
  - April 2005: $0.85/lb
- Titanium
  - April 2005: $4/lb

References