Fundamentals of Steel

Part A

by

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INTRODUCTION

Steel is a very versatile product and it comes in many shapes and forms. It is used in all walks of life from automobiles to toasters, from buildings to toys. It is everywhere. Steel is used for the columnsand beams of the frames of buildings in the form of rolled shapes, plate girders, and trusses. Steel is used for bridge beams and as reinforcing for concrete. Steel in the form of plates – both stiffened and un-stiffened – is used for the main load carrying elements of ships, aircraft, tanks, tunnels and casings, and shell roofs. Plate type members are also used as bridge decks, folded plates, and deck and wall panels. It is used as interior wall framing, bearing plates for columns, and as metal decking on steel bar joists.

Steel is a man made product. It does not occur naturally in nature. It is an amazingly uniform material andit is a homogeneous and easily shaped and assembled material. Compared to the other common construction materials, steel is also anenvironmentally friendly and stable material. It comes from the manufacturer or fabricator ready to use -it does not need curing time like concrete. It has one coefficient of expansion unlike wood which expands and contracts differently in different directions depending on the humidity. Steel is 100% recyclable – it can be re-used in the manufacturing process with no waste. It is ductile and malleable and can be rolled and welded to form different structural shapes. And, steel has a high strength to weight ratio compared to other construction materials.

Need to hold something up? Need something strong to do it? Steel is the "man among boys" in the strength department. It is by far the strongest material commonly used in buildings and bridges. And it is also among the heaviest at 490 pounds per cubic foot.

Because of so many different kinds of structural steels available today and its wide range of uses, in this *Fundamentals of Steel – Part A* course, we will generally confine our discussion tostructural steels as a material. We will look at the history of steel in the U.S., the codes, governing it, the mechanical properties, and the various shapes commonly used in constructing most buildings and bridges.

Fundamentals of Steel – Part B looks at how steel is used in the field with an emphasis on connections – both welded and bolted. Bar joists are discussed. And, some of the serious weaknesses of steel are discussed.

A BRIEF HISTORY OF STRUCTURAL STEEL

For completeness, a simplified and brief listing of the important events in the history of structural steel is presented. And, obviously, many important dates and events were not included. These, however, highlight the history of structural steel.

The important thing to take away from this list is the length of time it has taken to develop from Hooke's Law to where we were only about 50 years ago. In the past few decades we have developed methods and means of design and fabrication far more accurate and incomprehensibly less time consuming than we knew even 20 to 30 years ago. The development of the computer and other technical advances are changing the way we work with steel. However, the basic product – steel – is relatively unchanged.

Some important dates in the development of steel as a construction material:

- 1676 - Hooke's Law was developed stating that when the level of stress in a material is below the proportional limit, there is a straight line relationship between stress and strain.

- 1744 – L. Euler developed the theory of the buckling of bars - Euler's formula. This and Hooke's Law were the original basis of structural steel design. After these, a conscious effort was made to use the ductile characteristics of steel.

- 1823 – Navier formulated the differential equation for a buckled plate.

- 1856 - Steel first made in the U.S.

- 1873 – First tabulated values of rolled shapes.

- 1877 – First specification in the U.S. (developed by consulting engineers and railroad companies).

- 1908 – First wide flange shapes rolled in the U.S.

- 1914 – American Association of State Highway Officials (AASHO) was organized.

- 1921 –American Institute of Steel construction (AISC)was organized.

- 1923 – First AISC Specifications for Buildings issued.

- 1924 - First*Code of Standard Practice for Steel Buildings and Bridges* published by the AISC.

- 1926 – First AAASHO Specification issued.

- 1946 – First American Iron and Steel Institute (AISI) Specification issued.

STRUCTURAL STEEL CODES

The specifications and codes for structural steel are a set of rules that must be rigorously followed. These specifications and codes govern steel design,construction of structures, the selection of members,fabrication of members,and provide a framework for construction methods.

The "code" for steel design and construction in the United States is recognized to mean the **Code of Standard Practice for Steel Buildings and Bridges**. This code was first published in 1924 by the American Institute of Steel Construction (AISC).

The American Institute of Steel Constructionwas founded in 1921. It is a non-profit organization that specifies the technical information for structural steel. It is also the trade organization for the fabricated structural steel industry in the United States.

The Institute's objectives are to improve and advance the use of fabricated structural steel through research and engineering studies. Its purpose is to develop the most efficient and economical design and fabrication of steel members used in the construction of structures. To accomplish these objectives, the Institute publishes many manuals, textbooks, specifications and technical booklets.

The best known and most widely used publication of the AISC is the **Manual of Steel Construction**. Every serious designer of structural steel has a copy of the Manual on their desk or in a file in their computer. The manual includes information relative to the most common sizes and shapes of steel including their properties; design tables to aid in the selection of beams, columns, and connections; and specifications for the design of structural steel for buildings and bridges. It is the handbook for the everyday design of structural steel – for the most commonly used structural steel members. It does not include ALL structural shapes available – only the most commonly used ones.

The specification chapter of the AISC Manual is the **Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings.**It is a unique publication in that it includes a

commentary section that provides background information on the basis for, and the limitations of, the various sections of the specification.

The 1st Edition of the Specifications was published on June 1, 1923 and has survived to today. This Specification has evolved. It has been revised many times. The intention of the Specification is to cover the many everyday design criteria in routine design office usage. It is not intended to cover the infrequently encountered problems within the full range of structural design practice.

The publications of the AISC include information generated by and obtained from individuals practicing engineering; those in engineering education; other individuals; companies engaged in fabrication and erection of structural steel; and various other trade groups and associations including the American Iron and Steel Institute (AISI), The American Society of Testing and Materials (ASTM), and others.

MANUFACTURE OF STRUCTURAL STEEL

Steel is a man made product. It does not occur naturally in nature. The first steel was actually manufactured in Austria in the 1820's. Today, steel is manufactured in many countries throughout the world including, of course, the United States.

The primary goal of steel manufacturing is to reduce the amount of carbon present in the iron ore. Controlling the amount of carbon as well as controlling the amount of trace elements leads to the manufacture of the structural steel used today.

Heat is required to manufacture steel. Originally in the United States,refined coal was the primary heat source. Today, steel making uses electricity and other means for providing the heat. Following is a description of making steel using refined coal as the heat source.

Steel is manufactured by combining two main raw materials and adding or controlling several trace elements, all in the presence of heat. The raw materials are iron ore and limestone. And some of the trace elements include phosphorous, sulfur, manganese, silicon, copper, nickel, and vanadium. Carbon has the most influence on the properties of steel and leaving just the right amount in the end product is the primary objective of the steel manufacturing process. The structural steels today have between 0.2 and 1.5% carbon and are commonly referred to as structural carbon steels.

When using coal as the heat source, there are actually three raw materials needed to make steel – coal, iron ore, and limestone. The three raw materials are each treated or processed before being combined together.

Coal is changed into coke before being used as the heat source for combing the iron ore with the limestone. The coal is mined, and then crushed and washed. It is then baked in ovens in the absence of air to prevent burning. After baking, the white hot material is quenched to create coke. The coke is then ready to be shipped to the steel mills and combined with the iron ore and limestone in the blast furnace. Coke is the basic fuel in blast furnaces.

Iron ore is mined and processed nearby to remove impurities and non-iron bearing minerals. The iron ore is crushed, subjected to magnetic separation to remove ore particles, rolled into pellets and baked. By doing this part of the processing near the mine, the transportation costs are reduced by not having to transport large quantities of non-iron bearing materials.

Limestone is crushed and washed before being used in the steel making process. Limestone acts as a cleanser in the process by combining with the impurities of the process and forming a slag that is skimmed off the top of the molten steel.

The blast furnace is where the three main ingredients – iron ore, limestone, and coal in the form of coke - are combined to produce pig iron. It is called a blast furnace because of the continuous blast of air necessary to produce the required heat to enable the chemical reactions to occur in the raw materials in the stack. The molten end product of this process is pig iron. The pig iron is then refined into steel in the next step – the steel making furnaces.

The molten pig iron is transferred into the steel making furnaces. These furnaces apply high temperatures to the pig iron. Because structural steel is completely recyclable, scrap steel may also be added to these furnaces. Lime is also added during this process to combine with impurities to form a slag that is removed. Trace elements of other minerals are added here to affect the properties of the final product. Once the chemical composition of the molten steel is correct for the grade and type of steel being produced, it is poured into a ladle and transported to a casting area.

In the casting area, the molten steel is formed into bulk shapes (ingots) of various sizes which are allowed to cool and to solidify. These solid shapes are then rolled into the common shapes we are familiar with – plates, pipes and tubes, structural shapes, rails, rods, and bars.

MECHANICAL PROPERTIES OF STRUCTURAL STEEL

Steel has several important mechanical properties that are crucial when designing, fabricating, and using steel as a construction material. Much is known about the mechanical properties of steel because steel is probably the most studied and defined of the most common structural materials. In this *Fundamentals of Steel* course, we will look at a few of its most significant properties.
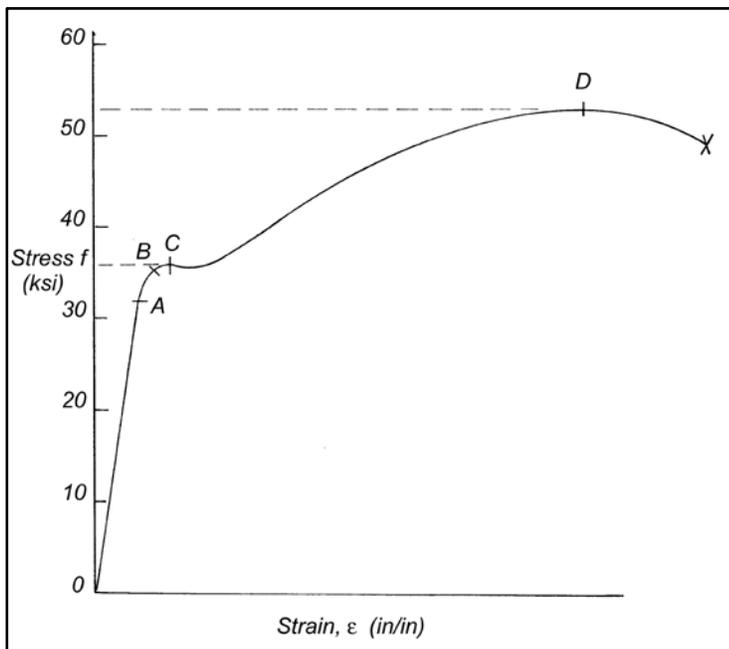
The mechanical behavior of structural steel is represented by the stress-strain diagram. Figure 1 shows a typical stress-strain diagram for steel. This is actually a plot of load versus elongation of a steel sample in tension. The load is converted to stress by dividing it by the original cross sectional area of the test specimen. And the elongation is converted to strain by dividing the increase in length by the original length of the test specimen. This particular curve represents the behavior of a low carbon steel specimen in tension.

Figure 1 - Typical stress - strain diagram for structural carbon steel

When the steel specimen is initially loaded, the plot of the stress versus strain is a straight line. In this straight line section of the diagram, the stress is directly *proportional* to strain. This holds true for stresses up to point "A", the **proportional limit**.
Stresses beyond point A on the diagram produce a curve that is no longer a straight line. As the stresses increase beyond point A, a point called the **elastic limit** is reached. This is point B on

the diagram. At stresses below point B, the steel test specimen will return to its original size and shape when the load is removed. At stresses higher than the elastic limit, the material will be permanently deformed.

The *yield point*, point C on the diagram, is the first stress at which the material will markedly increase in length with no apparent increase in stress. A7 Steel has a yield point of 34,100 psi; A36 has a yield point of 36,000 psi; and A242, A440, and A441 have a yield point of 50 ksi for shapes, plates, and bars ¾" thick and less.

If the load continues to increase above the yield point, the curve will rise again. Continuing to increase the load will cause the curve to continue to rise to a maximum value called the *tensile strength*, point D on the curve. After reaching this peak, the curve will drop somewhat until the steel sample finally breaks. This is the end of the plot of the typical stress-strain diagram. A 7 has a tensile strength of 60 to 75 ksi; A36 has a tensile strength of 60 to 80 ksi; and A242, A440, and A441 have tensile strengths of 63 to 70 ksi (70 ksi for shapes, plates, and bars ¾" thick and less).

The fact that the stress-strain diagram drops after reaching the peak seems to indicate that the stress in the sample decreases. This is not the case. The stress actually continues to rise slightly in the test specimen until the ultimate failure of the material occurs. Keep in mind that the plot is generated by a testing machine that measures actual load versus elongation rather than stress versus strain. The stress (vertical axis) is calculated as the load divided by the *original* cross sectional area of the test specimen. As the test specimen nears failure, it necks down and, as a result, the cross sectional area of the specimen is less than the original. This reduced area requires a lower force to keep stretching, even though the actual stress in material keeps rising. The result is that the curve drops before ultimate failure.

Actual measurements of the amount of necking down and the consequent stresses near failure indicate that the stress remains approximately the same as at the peak of the diagram. The peak of the diagram is accepted as the tensile strength of the material.

Some steels do not exhibit the well defined yield point shown in Figure 1. These steels do, however, deform a sizeable amount before fracture. A typical stress strain diagram for steels without a clearly defined yield point is shown in Figure 2. The curve is smooth. For those steels which do not have a clearly defined yield point, the *yield strength* is a useful measurement. The yield strength is defined as the stress at which the material shows a specific plastic strain –

usually around 0.2% (0.002 in/in). In some cases the yield strength will be defined at a strain of 0.5% (0.005 in/in).

To find the yield strength of a specific grade of steel without a yield point, begin at a 0.2% strain offset and draw a line parallel to the initial portion of the stress strain diagram as shown. Where that line intersects with the stress strain curve, is defined as the yield strength as shown in Figure 2.When the value of the yield strength is used, it should be noted what value of strain was used to determine it.

When designing steel structures, sometimes terms are used interchangeably. For example, yield point and yield strength are often used interchangeably. They are both thought of as the yield point of a particular steel since a specific steel will not have both a yield point AND a yield strength as defined above.

Figure 2 - Typical stress - strain diagram for structural carbon steel without a yield point

Reference data listing the mechanical properties of structural steel will almost always include values for the yield strength and the tensile strength. A comparison of the design stresses in a structure with the yield strength or the tensile strength of the material is the usual criteria for the design of steel structures. This comparison is usually in the form of comparing the design stresses with some fraction of the yield strength and tensile strength.
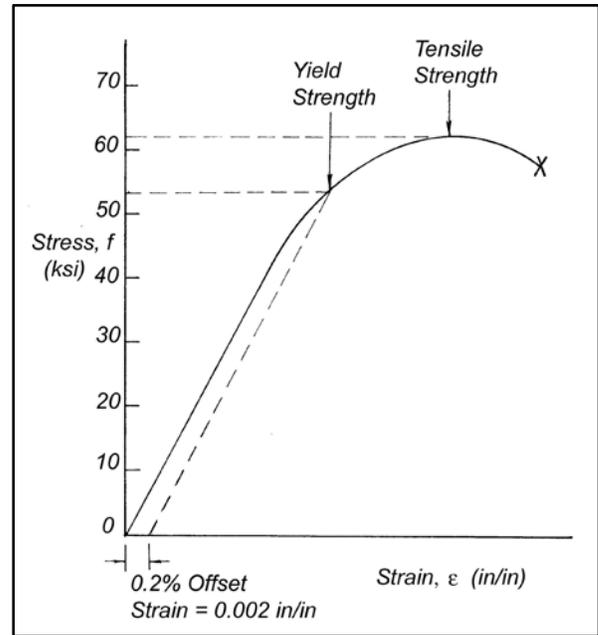
The slope of the straight line portion of the stress strain diagram is the ***modulus of elasticity, E***. Figure 3 shows an enlarged portion of a stress-strain diagram for structural carbon steel. The modulus of elasticity is defined as the ratio of the normal stress to the normal strain in the direction of the applied load.

$$E = \frac{stress}{strain} = \frac{\Delta f}{\Delta \epsilon}$$

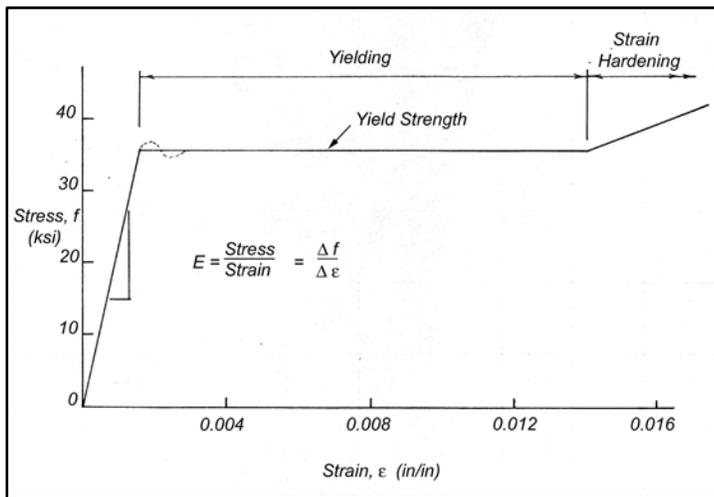The modulus of elasticity is a representation of Hooke's Law (stress is proportional to strain), and applies only to stresses below the proportional limit. When the stress reaches the yield point, large strains occur with no increase in stress. The steel is said to be yielding. After a certain strain is reached, strain hardening of the steel occurs and the steel gains strength.

Figure 3 - Portion of a stress - strain diagram for structural carbon steel

The modulus of elasticity defines the **stiffness** of the material and is one of the most important properties of steel when determining the deflections of beams, local buckling of the web and flange, and buckling of columns. The modulus of elasticity for use in design of structural steels is usually 29,000,000 psi which, written another way is 29 x 10^6psi, which is, of course, equal to 29,000 ksi. This stiffness, which is much higher than that of the other common construction materials, is an important asset of structural steel. (Note that E = 29.6 x 10^6 psi and E = 30 x 10^6 psi are also sometimes used in design calculations.)

Poisson's ratio is the absolute value (always positive) of the ratio of transverse strain to longitudinal strain under axial load. It is represented by the symbol μ. Figure 4 is an illustration of Poisson's ratio for an element in tension. From the illustration;

$$\mu = \frac{transverse\ strain}{longitudinal\ strain} = \frac{lateral\ strain}{axial\ strain} = \frac{-\epsilon_l}{\epsilon_a}$$

The minus sign is added to insure a positive value for Poisson's ratio, μ.

Where:

$$\epsilon_l = lateral\ strain = \frac{h_f - h_0}{h_0}$$

And,

$$\epsilon_a = axial\ strain = \frac{L_f - L_0}{L_0}$$

In the elastic range, Poisson's ratio commonly ranges from 0.25 to 0.33. The approximate value of Poisson's ratio for structural carbon steels is 0.29.

Figure 4 - Illustration of Poisson's ratio for an element in tension

Sample Problem:
A 1.000" thick by 8.000" long bar is stretched to 8.064". μ = 0.29. How thick will the bar be?

Answer:
Axial Strain = (8.000 – 8.064) / 8.000 = - 0.008 in/in
Lateral strain = axial strain x μ
          = -0.008 x 0.29
          = -0.00232 in/in
Change in lateral dimension = Lateral strain x h_o
               = -0.00232 x 1.000"
               = - 0.002"
New thickness = h_o + change in lateral dimension
          = 1.000 + (-0.002)
          = 0.998"

The *shearing modulus of elasticity* of steel is the ratio of the shearing stress to the shearing strain within the elastic range. The shearing modulus of elasticity is denoted by G. Figure 5 showsa stress element subjected to shear. The shearing action on parallel faces of the element tends to deform it angularly, as shown to an exaggerated degree. The angle, γ, is measured in radians. Only very small values of shearing strain are encountered in practical problems. However, it is useful to know that there is deformation due to shear.
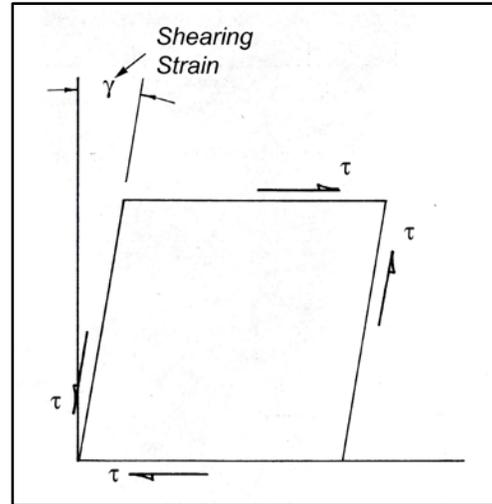

Figure 5 - Illustration of shearing strain on an element

$$G = \frac{shearing\,stress}{shearing\,strain} = \frac{\tau}{\gamma}$$

For structural steel, G is usually in the range of 11.5 x 10^6 psi to 12 x 10^6 psi.

From the theory of elasticity, the shearing modulus of elasticity is related to the modulus of elasticity and Poisson's ratio by the following equation:

$$G = \frac{E}{2(1 + \mu)}$$

The shearing modulus of elasticity, G, is necessary for the calculation of torsional deflections in shafts. Determining any two of the variables by testing allows the determination of the third.

Ductility is the ability of steel to undergo large deformations without fracture. When steel breaks, it can be classified as either ductile or brittle. A ductile material will stretch and yield and reduce in cross sectional area before fracturing. A brittle material will break suddenly with little or no change in cross sectional area or elongation. Ductile steel is preferred for members that carry repeated loadings and impact loads because they are more resistant to fatigue and because they are better at absorbing impact energy. When using the allowable stress design method of designing steel members, some slightly incorrect assumptions are used because of the ductility of mild steels.

The measure for ductility is the percentage of elongation after fracture. A test specimen of

Figure 6 - Illustration of test sample before and after being pulled to failure

known length is pulled to failure in a test machine. After fracture, the pieces are fitted back together and the new length is measured. An illustration of a test specimen before and after being pulled to failure is shown in Figure 6. The percentage elongation is then computed.
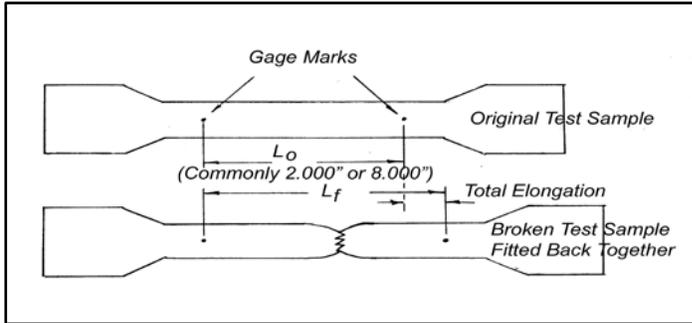
An elongation of greater than 5% is considered a ductile material. A percentage of elongation of less than 5% is considered to be brittle. The percentage elongation for carbon steel is about 21%.

To calculate the percentage of elongation, a test specimen is scribed with gage marks a known distance apart. Common gage distances are 2.000 inches and 8.000 inches. The percentage elongation is the change in length divided by the original length times 100%, as shown.

$$percent\ elongation = \frac{final\ length - gage\ length}{gage\ length} \; x \; 100\%$$

Sample Problem:
A test specimen has gage marks 2.000" apart. After failure in tension, the gage marks are 2.350" apart. What is the percentage of elongation? Is the material brittle or ductile?

Answer:
Percent elongation $= \frac{2.350 - 2.000}{2.000} x \; 100\% = \mathbf{17.5\%}$

17.5% > 5%, therefore the material is **ductile.**

Toughness is the ability of steel to absorb large amounts of energy without failing. A high level of toughness is needed to resist shock or impact loads on a structure. The toughness of steel is related to the total area under the stress strain diagram and is dependent on both strength and ductility.

Fatigue strength is the ability of a material to withstand repeated applications of a load or stress. It is usually expressed as the number of cycles under a given load before failure.

Weldability is the capability of steel to withstand welding without seriously hurting its mechanical properties. Weldability varies considerably for different types of steels and different welding processes.

Notch sensitivity is the tendency toward brittle fracture when notches, holes, or other stress concentrations are introduced into an element.

Generally, the properties of most interest to designers of buildings and bridges are strength and ductility. However, those who design connections for structural steel in buildings and bridges have a keen awareness for the weldability and notch sensitivity of steel.

FACTORS AFFECTING THE MECHANICAL PROPERTIES OF STRUCTURAL STEEL

The properties of steel are affected by many things. It's most significant properties, such as yield point, yield strength, modulus of elasticity, tensile strength, and ductility, are altered by such factors as the manufacturing process;by heat treatment; by mechanical working; and others.

The final mechanical properties of steel are determined by its:
- **Chemical Composition** - the amounts of the trace elements in the product**;**
- **Strain History** - the amount of mechanical working it undergoes during the rolling process**;**
- **Heat Treatment** - the temperatures reached and the time they were maintained during manufacture, and the temperature during rolling; and,
- **Other Factors** - the size and shape of a structural element, its temperature when loaded, and the strain rate.

Chemical Composition

For a given heat of steel, the single most important factor in determining the mechanical properties of steel is the chemical composition. Most structural carbon steels are over 98% iron, roughly ¼ of 1 per cent carbon, and about 1 per cent manganese by weight.

An increase in carbon will increase the hardness and tensile strength of the steel. However, it will also have an adverse effect on the ductility and weldability of the steel. Therefore, the carbon content is usually kept low in structural steel.

The impact strength of steel is reduced as the amount of phosphorous and sulfur increases. Hence, the percentage of these trace elements is also kept low.
Copper used in small amounts will increase corrosion resistance. Small percentages of silicone are used mainly to eliminate unwanted gasses from the molten metal. And, nickel and vanadium have a generally beneficial effect on steel behavior.

Strain History
The strain history of a piece of structural steel is the result of the reduction of cross sectional area of the bulk shape to the final cross section of the end product. This occurs during the normal rolling process – **mechanical working** - that takes place during the manufacturing process of structural steel. Steel shapes are usually hot rolled. Hot rolling occurs when the molten steel is only allowed to cool enough to solidify before it is rolled and shaped. A greater reduction of cross sectional area increases the final yield and tensile strength of the steel. The more severely the steel is worked, the stronger it will be.
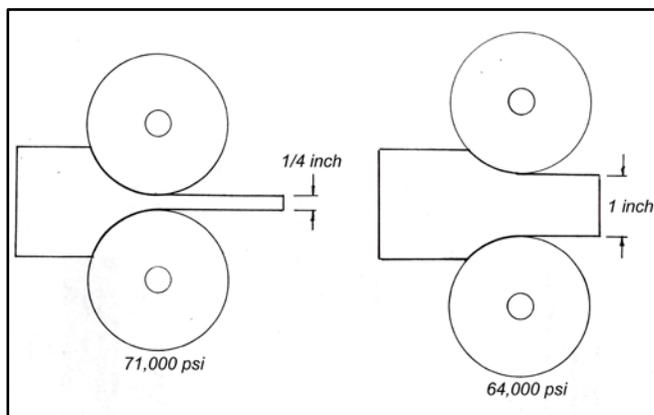

For example, as shown in Figure 7, bars of the exact same steel, both in chemical composition and original size, are rolled to different thicknesses. The bar rolled to a thickness of ¼-inch has a tensile strength of 71,000 psi while the piece rolled to a thickness of 1-inch only has a tensile strength of 64,000 psi.

Figure 7 - Effect of rolling on strength of structural carbon steel

Some steels are cold rolled – **work hardened** - to their final shapes to give them higher strength levels. Cold rolling occurs when the steel has been allowed to cool to approximately room temperature before being rolled to final shape. In concept, cold rolling has the effect of using up or exhausting the first part of the stress-strain diagram. Figure 8 shows the effects of cold rolling on the stress-strain diagram. It is actually more complicated than that though. For example, cold hardening in tension can reduce the yield stress in compression.
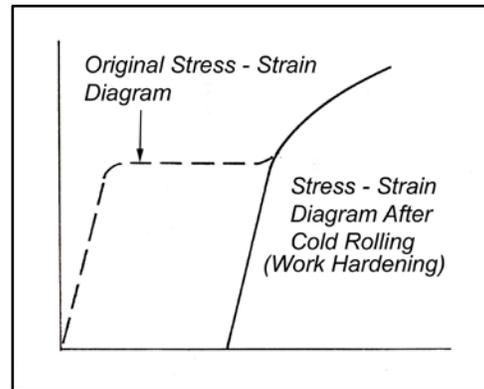

Figure 8 - Effects of cold rolling (work hardening) on the stress-strain diagram for structural carbon steel

Heat Treatment

Heat treatment includes the rate of cooling and the temperature at which the steel is rolled during the manufacturing process. Faster cooling rates and lower rolling temperatures will increase the final yield stress and tensile strength of hot-rolled steel.

When structural shapes are rolled at an elevated temperature – hot rolling – they are generally a relatively soft, low-strength steel which has a very high ductility and is easy to form. Rolling shapes at or near room temperature – cold rolling – produces a higher strength and lower ductility.

Some steels are heat-treated to develop specific properties. Heat-treating steel is accomplished by raising the steel to an elevated temperature – usually above about 1450 to 1650°Fc depending on the alloy – and then cooling it rapidly by quenching it in water or oil. After quenching, the steel has a high strength and hardness but it is often brittle. To regain some of the ductility without losing all of the strength gains, the steel can then be tempered.

Tempering is done by reheating the steel to a temperature in the range of 700 to 1300°F and then cooled. The properties of steel are affected by the tempering temperature – the higher the tempering temperature, the less brittle (or more ductile) the steel.

Other Factors
Other factors that affect the mechanical properties of steel are the size and shape of a structural element, its temperature when loaded, and the strain rate.

The size and shape of a structural element will affect the mechanical properties of the element. In general, smaller elements tend to have higher unit strengths than larger elements especially in fatigue and brittle fracture situations. Notches or other changes in cross section can have a large influence on the strength of an element. Also, the finish of the surface can have an effect on the strength of a structural element. For example, in the case of fatigue, a structural element with a smooth finish will have a higher strength than if it had a rough finish.

Low temperatures and high strain rates tend to increase the yield strength and the tensile strength of steel. However, they also may reduce the ductility. Low temperatures and high strain rates tend to have a greater effect on the yield strength than on the tensile strength. The effect of this is to reduce the margin between the yield and tensile strengths of the steel.

GRADES OF STRUCTURAL STEEL
The grade of structural carbon steel is a designation of the ASTM that identifies the chemical composition and strength characteristics of that structural steel, e.g., ASTM A36, which in this case identifies the steel as having a yield strength of 36,000 pounds per squares inch. The number assigned is the number of the published ASTM standard that defines the required minimum properties for the grade. Different grades have different properties. Not all grade identification numbers refer to the yield strength of the steel. Some of the more common grades are discussed below.

ASTM A36 comes in various shapes and sizes, is weldable, and has a minimum yield strength of 36 ksi. When selecting a type of steel for use, keep in mind that ASTM A36 has been used for a long time and is still the most popular,all-purpose carbon grade steelfor use in today's buildings, bridges, and other engineered structures. The reason for its popularity is that in many applications, the loads and stresses are moderate. Little, if any, savings would result from the use of higher-strength steels. Also, even where stress considerations would favor the use of high-strength steel, other considerations may control. For example, larger members may require an increased stiffness to prevent overall or local instability or excessive deflection. Because

stiffness is a function of the geometric properties of the cross section of the member – not the strength of the steel – no advantage would be gained from using high-strength steel.

ASTM A992 is becoming a popular choice for wide-flange beams used in buildings and industrial structures. It is one of several grades of **high-strength, low alloy (HSLA)** steels. ASTM A992 has a minimum yield strength of 50 ksi. Because of its higher strength, lighter beams can be used when compared to ASTM A36 resulting in potentially significant cost savings. However, because of the lighter sections, it is critical to look carefully at the deflections and the overall and local stability of the member. ASTM A992 is also available as ASTM A992 Grade 60, and ASTM A992 Grade 70, with yield strengths of 60 ksi, and 70 ksi respectively. Another HSLA grade of structural steel that is growing in use is ASTM A913, Grade 65. It has a minimum yield strength of 65 ksi. This steel can produce weight – and therefore, cost – savings when used in large column cross-sections.

ASTM A242 is another high-strength, low-alloy steel. It is often used in locations susceptible to natural weathering conditions. It is referred to as the weathering steel since it has about four times the resistance to corrosion as that of plain carbon steel. Wide-flange beams are available in Grades 42, 46, and 50. Grade 50 is also available in other rolled shapes.

ASTM A572 Grades 42, 50, 55, 60, and 65 are available in shapes and is a general-purpose HSLA structural steel. Some grades are also available in bars and plates.

ASTM A514 is a high-strength low-alloy steel with a yield strength of 90 ksi. Plates and bars made of ASTM A514 can have yield strengths as high as 100 ksi. The steel is heat treated by quenching and tempering. Thicknesses 2.50 inches and less have yield strengths of 100 ksi; greater thicknesses have yield strengths of 90 ksi.

These high strength steels can be an economical choice where lighter members – resulting from the use of higher allowable stresses – are not penalized because of instability, local buckling, deflection, or other similar reasons. And these higher strength steels can be used in tension members, beams in continuous and composite construction where deflections can be minimized, and columns having low slenderness ratios. However, higher strength steels are not to be used indiscriminately. Effective use of all steels depends on a thorough cost and engineering analysis.

STRUCTURAL STEEL SHAPES

Structural steels are produced in a number of forms including plates, bars, rods, sheets, tubing, and shapes including wide-flange beams, I-beams, channels, tee's, and angles.

For any of the structural forms common to the industry, structural carbon steels can be purchased from the place of manufacture – from the steel mills – if the order is large enough. For smaller orders or for smaller members, steel can be purchased from the fabricator. Depending on the equipment of the steel mill, the maximum length of shapes varies widely. Lengths of 60 to 75 feet can be produced by nearly all mills. Lengths of up to 120 feet can be special ordered from some mills.

The most common shapes of structural steel used in buildings and bridges can be either **rolled shapes** or **built-up shapes**. The most common hot rolled shapes are listed in Part 1 of the AISC *Manual of Steel Construction*. Built-up shapes are plates, bars and rods connected by bolts or welds.

The hot rolled shapes are not all manufactured by all manufacturers all the time. Some manufacturers will only produce a certain rolled shape, for example only wide flange beams. Another steel mill may produce angles and channels and a few sizes of I-beams. Another may produce certain sizes of a beam – say, only the very large wide flange beams - for only three months out of the year – the rest of the time being used to produce other sizes or shapes of structural steel.

All of the hot rolled shapes are published in ASTM Specification A6-79b, *Standard Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, And Bars For Structural Use.* The most common shapes included in each edition of the Manual change from edition to edition depending on the listing of shapes included in ASTM Specification A6. It's not unusual to drop many sizes of a class of member from one edition to the next, or to add several different sizes of a class of member. For example, the eighth edition of the Manual dropped 81 W shapes from the previous manual because those 81 shapes were no longer included in ASTM Specification A6. The eighth edition of the AISC Manual also includes six new S shapes which replaced six S shapes included in the previous edition. Also the AISC Manual does not publish all of the shapes included in the ASTM Specification A6. The AISC may choose to not include some shapes in the Manual because they are not "common" sections.

Rolled Shapes

The most common rolled shapes used in buildings and bridges are listed below.

Wide flange shapes (W)are "boxy" beams and are characterized by having essentially parallel flange surfaces. SeeFigure 9. For each specific beam, the surface of the top – or outside - of each flange is parallel with the surface of the bottom – or inside – of that flange. The flange is essentially a constant thickness. The web is also a

Figure 9 - Wide flange shape and additional material for a larger wide flange of same nominal size

constant thickness. The thickness of the web is not equal to the thickness of the flanges. There are many wide flange shapes catalogued in the AISC Manual ranging in size from a small of around 4 inches deep with 4 inch wide flanges weighing around 13 pounds per foot of beam to large 36 inch deep with 16 inchwide flanges weighing around 300 pounds per foot. There are nearly a dozen pages in the AISC Manual containing the various sizes of W-beams. The wide flange beam section of the Manual contains the largest selection of members of any section in the Manual.
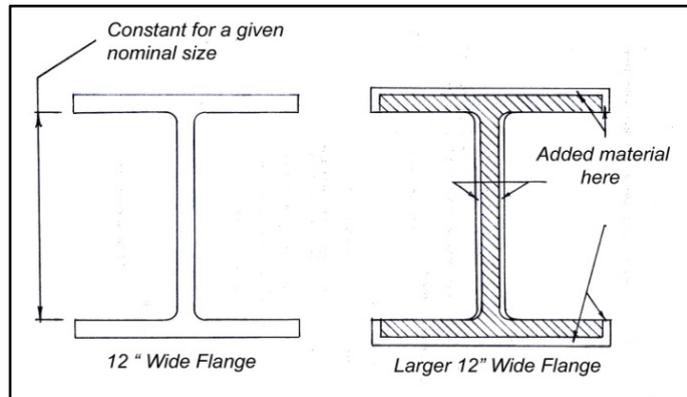
Wide flange beams are identified with the letter "W" followed by two numbers. The first number is the **nominal** depth of the beam and the second number is the weight per foot of the beam. For example, a W 14x132 is a wide flange beam that is nominally 14 inches deep and weighs 132 pounds per foot.

All wide flange beams with the same nominal depth have a fairly wide range of depths and weights per foot with, of course, a corresponding range in properties such as cross sectional area, flange width, section modulus, moment of inertia, etc. For example, there are around 30 different wide flange beams that are nominally 12 inches deep. These 12-inch W-beams range in depth from about 11 $^7/_8$ - inches to nearly 16 $^7/_8$- inches deep and vary in weight from around 14 to around 336 pounds per foot. Other wide flange nominal depths may only have a selection of half-dozen to a dozen, or so, sizes to choose from. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are set up to produce.

To increase the size of a wide flange beam during the manufacturing process, the steel mill will spread its rolls during the hot rolling process. When the rolls are spread, the dimensions of the completed W shape will be different. Within a group of nominally sized W beams, for example, W14's, the dimension between the inside face of the flanges remains constant – in this case about 14 inches. When the rolls are spread to make a different beam of nominal 14 inch depth, the web will increase in thickness in equal amounts on each side of the web, the flanges will get wider equally on each side of the web, and they will also get thicker on the outside, thereby making the total depth of the beam larger. The dimension from inside to inside of the flanges remains constant. By varying the thickness of the web in equal amounts on each side of the centerline of the beam and by expanding the flange in both width and thickness, many more different sizes of each nominal depth can be manufactured. There are more common sizes of wide flange beams than of any other classification.

Bearing pile shapes (HP) are similar in shape to the wide flange in that they also have a "boxy" shape and the flange surfaces are parallel. The web surfaces are also parallel. However, they differ from the wide flange in that the HP shapes have equal flange and web thicknesses. The thickness of the web of a particular HP shape is equal to the thickness of the flange.

Bearing pile shapes are identified with the letters "HP" followed by two numbers. The first number is the nominal depth of the member and the second number is the weight per foot of the structural shape. For example, an HP 13x73 is a bearing pile shape that has a nominal depth of 13-inches and a weight of 73 pounds per lineal foot.

The HP members have relatively few depths and only a few weights within that nominal depth range. The nominal depths range in size from about 8-inches deep to about 14-inches deep. The weights per foot vary from around 30 to 40 pounds per foot to a bit over 100 pounds per foot. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are set up to produce. The total list of available HP sections can usually be listed on a single page in the AISC Manual.
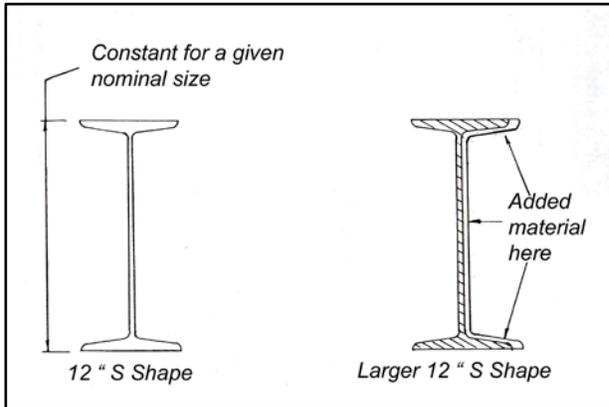
Figure 10 - S Shape and additional material for a larger S Shape of same nominal size

American Standard beams (S) have relatively narrow flanges compared to the depth. They are similar in shape to an "I".See Figure 10.One of the distinguishing features of the S-beam is the sloping inside surface of the flanges. The flanges vary in thickness from a minimum at the ends (or edges) to a maximum at the web. The outside flange surface is square with the web. The inside of the flange slopes at the rate of 2 in 12 inches (about 16 $^2/_3$ %) from the outer edge of the flange to the web. The flange thicknesses listed in the AISC Manual are *average* thicknesses.

American Standard beams are identified with the letter "S" followed by two numbers. The first number indicates the nominal depth of the member and the second number is the weight in pounds per foot. For example, an S 15x42.9 is an American Standard beam that has a nominal depth of 15-inches and weighs 42.9 pounds per foot.

S shapes range from about 3 –inches nominal depth to about 24 inches, and from around 5 pounds per foot for the smaller ones to around 125 pounds per foot for the largest ones. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are set up to produce. The total list of available S sections can usually be listed on a page or two in the AISC Manual.

The nominal dimension for the American Standard beams is the distance from outside to outside of the flanges - not the inside of the flanges as is the case for the wide flange beam. To increase the size of a group of nominally sized S shapes the web thickness and the flange width are changed by an equal amount as shown in Figure 10. For example in an S7, the web is thickened on one side only while allowing the flange on that side to grow a similar amount. The flanges will get wider by the amount that the web thickens. The flange thickness does not change. There are usually only a couple of different sizes of beams of the same nominal size to choose from. For example, there are only two different S15's – the S15 x 50 and the S15 x 42.9.

American Standard channels (C) is an "elongated 'C' section" in shape. The depth of an

American Standard channel is large in proportion to the flange width. See Figure 11. Similar to the S-beam, the channel has a sloping inside face of flange. It too has a slope of approximately 16 ⅔% (2 in 12 inches) on their inner flange surfaces. And the flange varies in thickness from thick at the web to "thin" at the edge. And, again similar to the S-beam, the C-section flange thicknesses listed in the AISC Manual are *average* thicknesses.
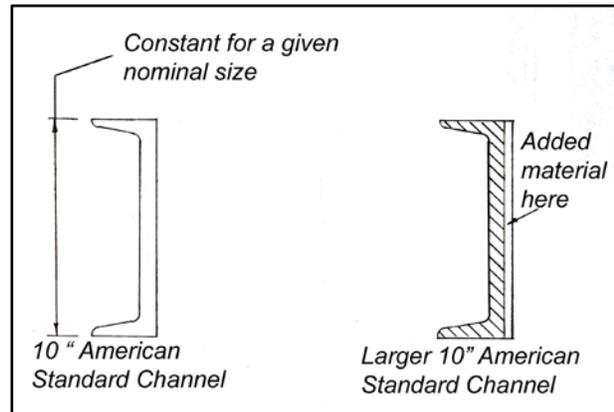

Figure 11 - American Standard Channel and additional material for a larger channel of same nominal size

American Standard channels are identified with the letter "C" followed by two numbers. The first number indicates the nominal depth of the member and the second number is the weight in pounds per foot. In the case of the channel, the nominal depth is the actual depth – an 8" channel is actually 8.00" deep. For example, a C 8x18.75 is an American Standard channel that has a nominal (and actual) depth of 8-inches and weighs 18.75 pounds per foot.

C shapes range from about 3 –inches nominal depth to about 15 inches, and from around 4 pounds per foot for the smaller ones to around 50 pounds per foot for the largest ones. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are set up to produce. The total list of available C sections can usually be listed on a page or two in the AISC Manual.

The nominal size of the American Standard channel is the distance from outside of flange to outside of flange. The different areas and weights within a nominal size channel are created by increasing the thickness of the web and the width of the flanges by the same amount as shown in Figure 11.

M shapes are shapes that cannot be classified as **W**, **HP**, or **S** shapes. Their shape lies somewhere between the W and the S sections. The flange width is somewhat less than the W and somewhat more than the S for similar nominal depths. And the flanges have various slopes

on their inner flange surfaces. The flange thicknesses listed in the AISC Manual are *average* thicknesses.

M shapes are only available from a limited number of producers. And, these steel mills often do not continuously produce each section of their line of products. Sometimes a particular section listed in the AISC Manual is not available. Therefore, they should be checked for availability before specifying these shapes.

M shapes are identified with the letter "M" followed by two numbers. The first number indicates the nominal depth of the member and the second number is the weight in pounds per foot. For example, an M 6x20 is an M shape that has a nominal depth of 6-inches and weighs 20 pounds per foot.

M shapes range from about 4 –inches nominal depth to about 14 inches, and from around 13 pounds per foot for the smaller ones to around 18 pounds per foot for the largest ones. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are set up to produce. The total list of available M sections can usually be listed on a single page in the AISC Manual.

MC shapes are shapes that cannot be classified as **C** shapes and are listed in the AISC Manual as CHANNELS MISCELLANEOUS. Their shape is similar to the American Standard channel – but different. The flanges of the MC shapes have various slopes on their inner flange surfaces. The flange thicknesses listed in the AISC Manual are *average* thicknesses.

Similar to the M shapes, the MC shapes are unique in that they are only available from a limited number of producers. And, these steel mills often do not continuously produce each section of their line of products. Sometimes a particular section listed in the AISC Manual is not available. Therefore, they should be checked for availability before specifying these shapes.

MC shapes are identified with the letter "MC" followed by two numbers. The first number indicates the nominal depth of the member and the second number is the weight in pounds per foot. For example, an MC 13x31.8 is an MC shape that has a nominal depth of 13-inches and weighs 31.8 pounds per foot. And, as it is for the America Standard channel, the nominal depth of the MC shape is the same as the actual depth. A 12-inch nominal MC shape is 12.00 inches deep.

MC shapes range from about 6 –inches nominal depth to about 18 inches, and from around 12 pounds per foot for the smaller ones to around 60 pounds per foot for the largest ones. The sizes and weights vary from time to time depending on ASTM Specification A6 and what the steel mills are tooled to produce. The total list of available MC sections can usually be listed on a page or two in the AISC Manual.

Equal leg and unequal leg angle (L) shapes are structural members with a cross sectional shape that includes a 90° angle. See Figure 12. The two legs of the angle may be equal in length (equal leg angles) or unequal in length (unequal leg angles). The inside surface and the outside surface of the legs are parallel. The profiles of L shapes are essentially identical from the various steel mills except for the size of the fillet between the legs and the shape of the ends of the legs.
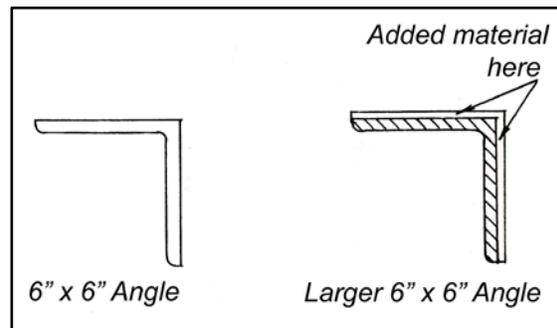
All angles are not always available everywhere all the time. Their availability varies depending on rolling accumulation and geographical location, and for this reason should be checked with material suppliers before specifying.

Figure 12 - Angle and additional material for a larger angle of same nominal size

L shapes are identified with the letter "L" followed by three numbers. The first number is the length of the longer leg of the angle, the second number is the length of the shorter leg of the angle and the third number is the thickness of the legs. If the L shape is an equal leg angle, the first two numbers are the same. For example, an L7 x4 x^5/8 is an unequal leg angle with a long leg equal to 7 - inches, a short leg equal to 4 – inches, and a thickness of both legs equal to ^{5}/8 – inch. An L8 x8 x1 is an angle that is 1 inch thick with the two equal legs of 8 – inches each.

The weight per foot of angles varies as the thickness of the legs for each particular size. For example, an angle with legs of 6 inches and 4 inches can weigh from 10.3 pounds per foot to 27.2 pounds per foot depending on the thickness. In this case the thickness ranges from ^{5}/16 – inch to ^{7}/8 – inch.

Equal leg angles vary in size from 2 x 2 inches to 8 x 8 inches with the smaller angles having a thickness as small as $\frac{1}{8}$ – inch and the larger ones having a thickness as large as 1 $\frac{1}{8}$ inch. Unequal leg angles range in size from 2 ½ x 2 inches to 8 x 6 and 9 x 4 inches. The total list of angles in the AISC Manual takes about half a dozen pages to compile.

To vary the area and weight for a given leg length of angle, the thickness of each leg is changed as shown in Figure 12. Notice that the length of each leg is changed slightly by this procedure.

Angles are often used in pairs, called double angles. This is done so commonly that the AISC Manual has a section listing the properties of sections of double angles. Angle pairs are identical angles meaning that both angles have the same cross section. Pairs of angles can include two angles with equal legs or pairs of angles with unequal legs. The listing of double angles in the AISC Manual considers only that the unequal legs both be either horizontal or vertical, i.e., the long legs back to back, or the short legs back to back. The listing also enumerates properties considering that the back to back angles are touching or that they are separated by a specific distance, often $\frac{3}{8}$" and ¾".

Structural tees (WT, MT, and ST)

Structural tees (WT) are shapes that are made by cutting a W shape in half through the web. A wide flange beam is simple cut in half across the centerline of the beam to make two "T" shaped members - two structural tees. The flanges remain untouched in the cutting operation and the web, after being cut in half, is renamed the **stem**. The shape characteristics of the WT are the same as outlined for the wide flange shapes – namely, constant (but different) thickness of the stem and flanges. There are as many WT structural tees to choose from as there are wide flange beams because of the way they are made – by cutting a W shape in half. Where the smallest wide flange that can be purchased is around 4 – inches deep and 13 pounds per foot, the smallest WT that can be obtained is around 2 – inches deep and weighs about 6.5 pounds per foot – exactly half the size of the original shape. And, similarly, the largest common W shape is a W36 x 300 and, therefore, the largest WT is 18 – inches deep and 150 pounds per foot. And, also like the W shapes, there are nearly a dozen pages in the AISC Manual containing the various sizes of WT shapes.

Structural tees made from cutting W's in half are identified with the letters "WT" followed by two numbers. The first number is the nominal depth of the member and the

second number is the weight per foot of the member. For example, a WT 9 x53 is a structural tee that is nominally 9 inches deep and weighs 53 pounds per foot. This member was manufactured first as a W18x106. Then it was cut in half.

Structural tees (MT) cut from M shapes and structural tees (ST) cut from S shapes are also available. These tees are manufactured in an identical fashion to the WT – namely they are M shapes cut in half and S shapes cut in half. There are an identical number of MT's and ST's as there are M's and S's. And the nominal depths and weights of the MT's and ST's are just half of those of the M and S shapes.

Steel Pipe comes in several nominal diameters ranging from about ½ inch to 12 inches and comes in three grades - Standard Weight steel pipe; Extra Strong steel pipe; and Double-Extra Strong steel pipe. The AISC Manual lists the most common diameters of all three grades. In Standard Weight, sizes range from about ½" in diameter to about 12 inches. The thickness of the wall of the ½" pipe is around $^1/_{10}$ of an inch. The wall thickness of the 12" diameter pipe is about $^3/_8$".

Extra Strong steel pipe has a listing of sizes from about ½" diameter and 0.15 inch thick walls to about 12" diameter with ½ " thick walls.

Double Extra Strong steel pipe has listings for 2" diameter pipe with just over $^4/_{10}$ inch thick walls to 8" diameter with about $^7/_8$" thick walls.

Figure 13 is a graphical representation of the different wall thicknesses for an 8" nominal diameter pipe for the three grades. The nominal diameter is the same for all three pipes as is the outside diameter. But they are not the same. The nominal diameter 8" pipe has an actual outside diameter of 8.625" for all three grades. The nominal diameter of pipes is close to

Figure 13 - Illustration of wall thickness for different classification of steel pipe

the inside diameter – sometimes slightly less and sometimes slightly more – but not the same. Similarly, a nominal 4" diameter pipe has an actual outside diameter or 4.500" for all three grades. They have different wall thicknesses and therefore, different inside diameters.
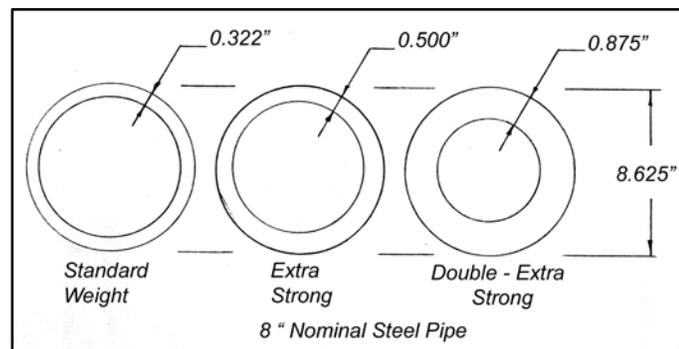
Structural tubing is square and rectangular shaped structural members. The commonly listed square structural tubing in the AISC Manual range in size from about 2" x 2" to about 16" x 16". The rectangular structural tubing listed ranges in size from 3" x 2" to 12" x 20". There are a variety of wall thicknesses to choose from when selecting a particular size of structural tubing.
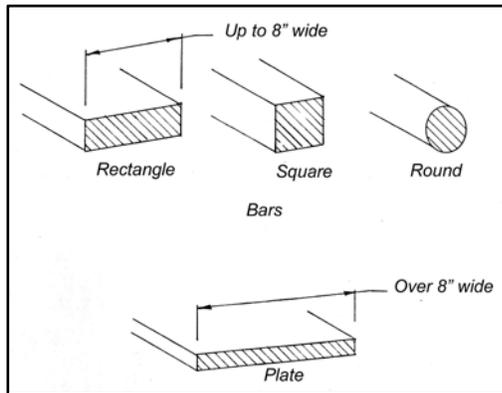

Figure 14 - Bars and Plates

Bars and plates are structural shapes produced by the steel mills. See Figure 14. Square and round bars are just that – bars whose cross sectional shape is either square or round. This size of the common bars range from 1/16" square or round to 12" square or round. The AISC Manual lists the weight of a 12" square bar as 490 pounds per foot. This, of course, makes sense because a piece of steel that is 12" x 12" x 1' long has a volume of 1 cubic foot and steel weighs 490 pounds per cubic foot.

In addition to round and square bars, there are rectangular bars. Pieces of structural carbon steel 8" wide and less are called bars. Pieces of structural carbon steel over 8" wide are called plates. Bars and plates have a specified minimum thickness in their definition of a little less than ¼". Steel that is less than the defined minimum is referred to as sheet steel and not considered here.

Plates are produced to different maximum widths depending on the facilities of the mill. Some mills can produce plates up to 200 inches (16' – 8") wide and several inches thick. Not all mills can produce plates this large.

Built-Up Shapes
Built-up shapes are structural members fabricated from two or more rolled shapes or plates and joined together by welds, bolts, or rivets. Built-up shapes are used where the common rolled shapes do not fit the need. For example, special conditions such as the need for heavier members or for a special geometrical cross section may require the fabrication of a built-up member.

The AISC Manual offers several combinations of built-up members made from common rolled shapes. These are identified in the Manual as **combination sections.** These combination sections are sections that experience has shown to be in popular demand. They combine shapes that are easy to produce and provide an efficient and economical structural member for special

applications. These sections can be useful as struts, lintels, eave struts and light crane and trolley runways.

Some listings in the AISC Manual include attaching a channel to the flange of a wide flange; attaching a channel to an S shape; joining two channels; combining a channel with an angle; and connecting a channel to the web of a wide flange.

Original, or unique, built-up members, of course, must be specifically designed and fabricated to fit the special need. Figure 15 shows various built-up members using angles, channels and plates. Plate girders are also commonly made by attaching a pair of angles as flanges to a plate – the plate functioning as the web.
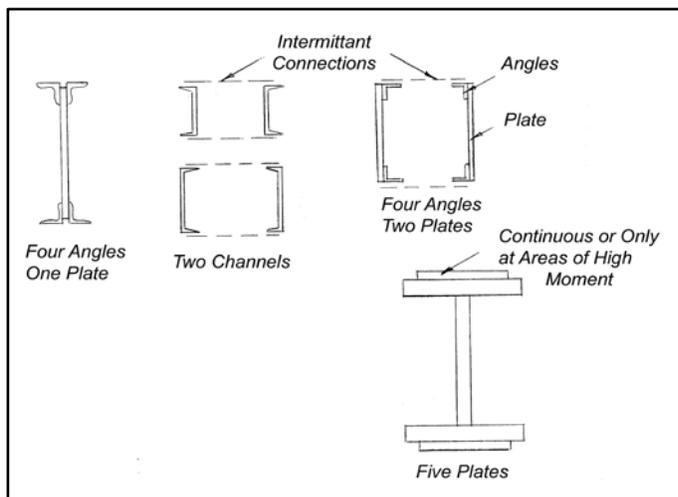

Figure 15 - Various built-up members

A very common, but special and unique, built up member can be seen in many of the overpass bridges crossing the interstate highways. The bridges are often designed using continuous beams. A rolled section can be used as the structural member with plates attached to the flanges in areas of high moments. The plates only run a portion of the length of the beam to provide added moment capacity in the areas of peak moments in the spans.

If the bridge beam were selected based on the maximum moment, a rather large beam would be required in those places where the moment was modest or even zero. However, if plates were welded to the flanges of a smaller beam in the area of the maximum moments, there can be a cost savings because of the lighter beams. The rolled wide flange with plates welded to the flanges is a built-up member.

Another commonly designed built up member is a welded plate girder. This is fabricated by welding three plates together in the shape of a wide flange section. These too are often used in bridges. And, also, often an additional plate or plates are welded the flanges in locations of peak bending moments.

Particularly large plate girders were fabricated and used as the structural frame of the 1,100 foot John Hancock Building in downtown Chicago. Photo No. 1shows the frame on the outside of the building for all to see and admire. The flanges on the larger beams are over 4"thick.

There are almost an unlimited number of different kinds and shapes of built up members that can be fabricated.

Photo No. 1 - John Hancock Building in downtown Chicago

SUMMARY

Steel is one of the most versatile products in the construction industry. It comes in many shapes and forms, it is available anywhere in the country, and it is economical. It is a uniform product that is homogeneous and easily shaped. It is ductile andmalleable and can be rolled and welded to meet almost any need. It is used to frame and structurally support buildings and bridges and it is 100% recyclable.

Fundamentals of Steel – Part A covered steel as a material including its many shapes.

Fundamentals of Steel – Part B will look at how the shapes are used in the field with an emphasis on connections – both bolted and welded. Bar joists - perhaps the most common built-up member - are discussed. Structural carbon steel has some serious weaknesses. These are also discussed including methods of protecting against them.