Fundamentals of Steel
Part B

by

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Fundamentals of Steel – Part A discussed steel as a material. Among the topics covered were its history in the U.S., the governing codes, and the manufacturing process. Also covered were the basic properties of steel and a discussion of steel shapes including hot and cold rolled and built-up members. ***Fundamentals of Steel – Part B*** will now look at how steel is used in the field and some of the serious weaknesses of steel.

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 columns and 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. And, structural steel has some very serious weaknesses that must be recognized and properly addresses.

Steel is a man made product. It does not occur naturally in nature. It is an amazingly uniform material and it is a homogeneous and easily shaped and assembled material. Compared to the other common construction materials, steel is also an environmentally 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 B*** course, we will generally confine our discussion to the practical application of structural steels in use in the field.

CONNECTIONS

Once the beams, columns, braces, and other members of a steel structure have been selected, they must be connected together to form a complete and stable load carrying system. The connections must be capable of transferring the loads from one member to another and to making the entire assembly structurally stable. The connections provide the path for transferring forces from one member to another.

There are three common connection mechanisms – welded; bolted; and riveted.

The designs of the main structural members – beams, columns, etc. – are based on formulas that have been developed and refined over the years to provide reliable and safe results. On the other hand, the behavior of a connection is often so complex that it is nearly impossible to describe by a formula. Because of this, there is a specialized group of structural engineers who concentrate on the design of connections. Their main job is to make sure that all the forces and reactions at a joint are properly transferred to the other members as intend during the design by the engineer of record. It is important that the connection designer know not only all of the forces acting on a joint, but also the type of joint that the engineer of record intended at that location – for example is it a pin connection or a moment connection?

There are literally hundreds of different configurations of welded, bolted, and riveted connections used for structural steel today. Many books and other publications are available to fully explain and demonstrate a multitude of joints, their design, and fabrication for use.

Riveted connections are one of the oldest methods of joining materials. They were used back when man first used ductile materials. Today, in the United States, they have been mostly replaced by high strength bolts. The cost of an individual rivet is cheap compared to the cost of a high strength bolt. However, because of the cost of labor, the installed cost of a rivet is more than that of a bolt. It takes a four- or five-man field riveting crew to install the relatively cheap rivets; while a two-man bolting crew can install the relatively more expensive bolts.

For our use, we will look at the basic principles of only the **welded** and **bolted** connections - the two most common methods used in the majority of structural steel connections in the United States today.

Welded Connections

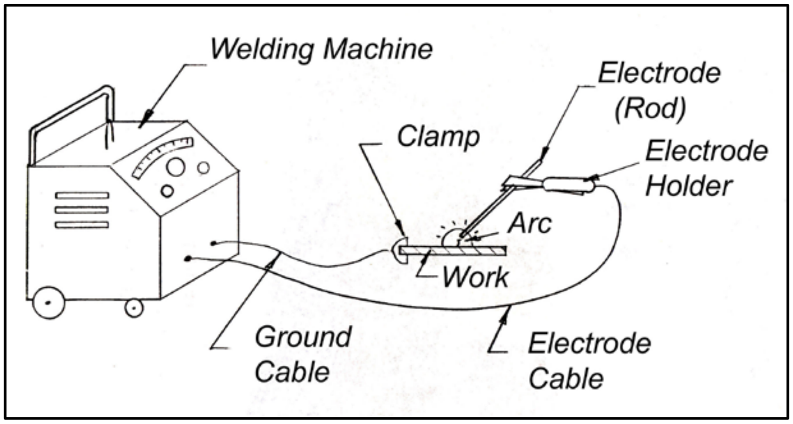

Figure 1 - Depiction of an electric arc welding system

Welding is the act of joining steel pieces using heat and filler metal. Two pieces of steel can be connected together with a weld. A welded connection in structural carbon steel occurs when two pieces of steel are melted at the connection point and weld material is added to the base metal to form the joint. The melting of the base metal and the filler metal is done by the heat generated by an electric arc.

The welding of structural steel is governed by the American Welding Society (AWS) ***Structural Welding Code.***

In electric arc welding a filler rod is used to add metal to the welded zone. As the two parts to be joined are heated to a molten state, the filler metal from the rod combines with the base metal. The filler metal of the rod, or electrode, is higher strength than the base metal. When the molten combination of metals has cooled it is normally stronger than the original base metal. Therefore, when a properly designed and constructed weld has been completed, any failure should be in the base metal, not the weld joint.

Figure 1 is a concept drawing of the electric arc welding system. To create the arc, first an electrical generator creates a high amperage and low voltage electricity. It can be either AC or DC. This power source is connected on one line by the ground cable to the work to be welded. The other line is connected by the electrode cable to the electrode holder and to the electrode. The arc is formed when the electrode is touched to the work, thereby closing the circuit. The arc is maintained by the operator keeping a short distance between the electrode and the base material. The electricity will arc across the gap. To produce a good arc, the distance between the end of the electrode and the base metal must be kept constant. Skilled welders can maintain a steady arc length. Inexperienced welders may lose the arc either by pushing the electrode into the work or by moving the electrode away from the base metal so that the circuit is broken and the arc collapses.

An intense heat is generated by the arc. It is a heat sufficient enough to reduce steel to the molten state. The temperature in the arc itself has been estimated to be as high as 10,000° F. The temperature in the steel near the arc has been measured to be approximately 3,500° F.

During the welding process, it is imperative to keep the arc and the molten metal – both the base metal (the work) and the electrode metal (which is being deposited in the weld) – shielded from the atmosphere. If the molten metal is allowed to contact the oxygen in the atmosphere, it will oxidize and the metal will become porous. The metals will also absorb nitrogen from the atmosphere and lose some of their ductility. Both conditions are bad and must be protected against. The arc must also be shielded from the atmosphere.

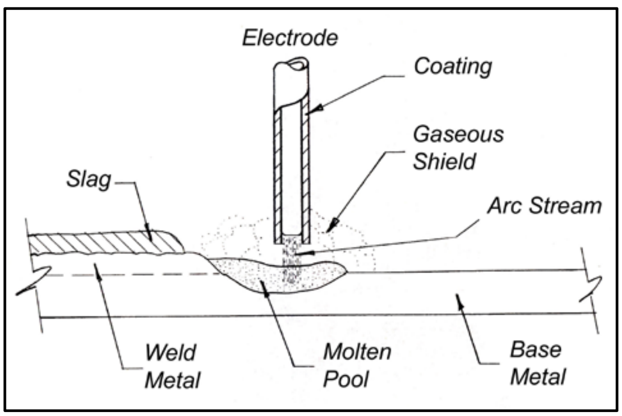

Figure 2 - Shielded arc-welding process

Protecting the metal and arc from the atmosphere is done in different ways. For example, **shielded arc welding** (Figure 2) is when the electrode (the welding rod) is coated with a product that melts at a lower temperature than the metal and creates a gaseous cloud – a shield – around the arc and molten metal. This shield protects the arc and the molten metal from the damaging effects of oxygen and nitrogen from the atmosphere. The coating also contains various chemicals to combine with the impurities in the welding process to create a slag that floats to the top of the weld. This slag must be chipped off the top of the weld after it has cooled. Shielded arc welding is most often used with manual welding.

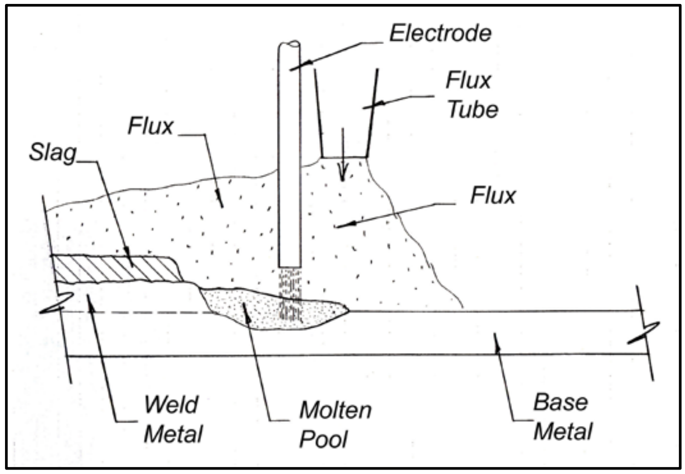

Figure 3 - Submerged arc-welding process

Automatic welding frequently uses a process called **submerged arc welding** (Figure 3). The term "submerged" refers to the fact that the arc is submerged under a mound of powdered flux. The arc is hidden from view. The basic process is similar to the manual shielded arc welding process. The difference is, in automatic welding a motor automatically feeds a bare wire electrode into the weld and a voltage control maintains the proper arc voltage and arc length. The arc is completely and continuously covered by a mound of flux which is deposited from a hopper as the welding progresses along the work. The heat of the arc melts the electrode, a portion of the parent metal, and part of the flux. As is the case of the coating on the rod in shielded arc welding, the flux causes the slag to form and float to the top of the weld. In automatic welding, the slag is usually self cleaning. As the weld cools, the difference in cooling rates between the weld and the slag is high enough to cause the slag to break free from the weld.

There are two main reasons for the coatings on the welding rods used in manual shield arc welding and the flux used in automatic welding. The first is to create a barrier against, or shield from, the atmosphere by creating a gaseous layer around the arc and molten metal. The gaseous cloud is a result of the chemical decomposition of the coating or flux. The second reason for the coatings on the rods or the flux is to act as a mechanism, or stimulus, to cause the impurities of the weld process to float to the top of the molten weld.

There are other welding processes available besides the shielded arc welding and the submerged arc welding processes. However, the thing all structural steel welding processes have in common is that they all involve fusion welding by an electric arc process. They all use the heat of an electric arc to melt an electrode and the base steel at the same time to make a welded connection. The joint is actually formed when the fused material cools and solidifies.

There are many grades of welding rods, each with their own specific material properties. The American Welding Society ***Structural Welding Code – Steel*** specifies the electrode classes and welding processes that can be used with each rod to join the various grades of structural steels. It is imperative to have the final weld material match the base metal in strength, ductility, and other important characteristics.

The different kinds of electrodes are identified by a code beginning with the letter E followed by two or three digits – for example, E60, or E100. The number is the ultimate tensile strength, in ksi, of the weld metal in the rod. For example, an E80 rod would have an ultimate tensile strength of 80,000 psi.

For all the various electrodes and welding processes, almost all welded connections are composed of only two types of welds and five joint types. In the **fillet weld** the weld material is deposited along the edge of members (Fig 4). In the **butt weld** the weld material is deposited through the members (Fig 5). The joint types describe the orientation of the two members that make up the joint. The five types of joints are **tee, corner, butt, lap, and edge** (Fig 6).

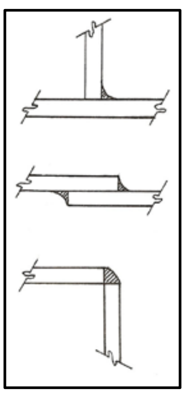

Figure 4 – Fillet Welds

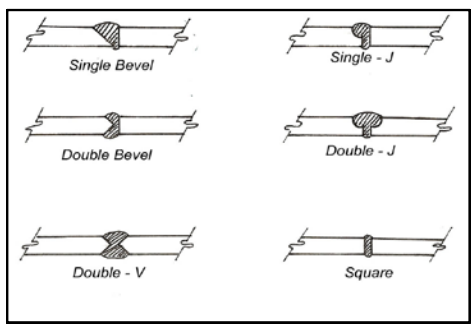

Figure 5- Butt Welds

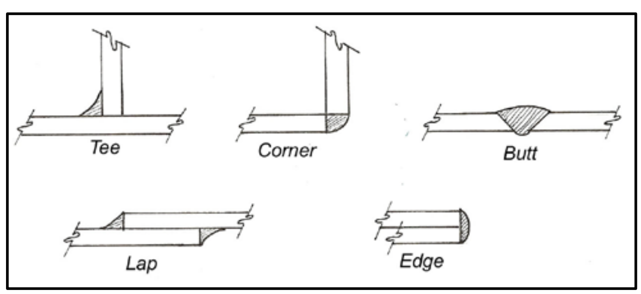

Figure 6 – Weld Joints

The welded joints can be further identified according to the position in which the weld material is deposited.

The four positions are flat, horizontal, vertical, or overhead. (Figure 7). The American Welding Society, AISC, and other welding publications all list and identify the various joints and standard identification nomenclature for the joints.

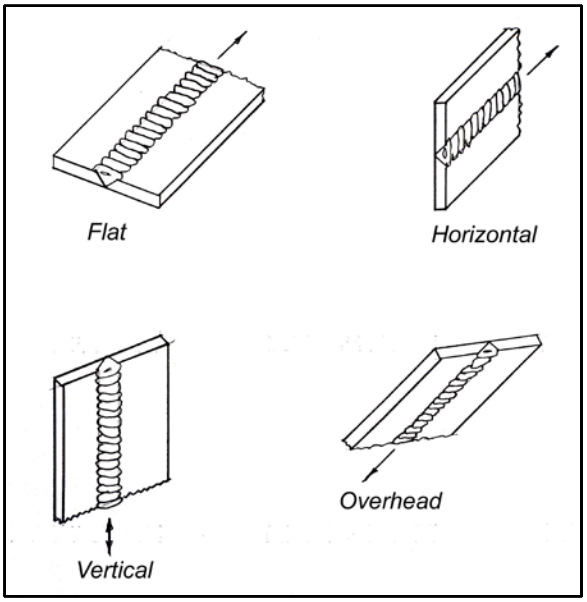

Figure 7 - Weld Positions

The difference between the two types of welds, the butt and the fillet, is the manner in which the stress transfer takes place. In the butt weld the stress transfer is normally in direct tension or direct compression. In its simplest and most common form, the fillet welds are subjected to shear stresses. Fillet welds are nearly all this way because the vast majority of fillet welds are placed to the side of the base material. They are placed in the right angle formed by lapping plates, intersecting plates, or other structural members.

Butt welds are the stronger of the two basic welds. However, most welds are fillet welds because of the less stringent tolerances necessary for the set-up. When using a butt weld to join two pieces of structural steel, the length of the members being joined must be cut to almost exact lengths to join the pieces efficiently and economically. When using a fillet weld, the lapped pieces can be placed with much less precision prior to being welded in place.

An **intermittent weld** is a fillet weld where short lengths of weld are placed along the edge of a joint. An intermittent weld is used where a continuous length of the minimum sized weld would result in a much higher strength than required. In the case of the intermittent weld, only as much weld is used as is needed to develop the required strength in the joint. There is no need to create a weld length that is not needed. Intermittent butt welds are not permitted by the AISC or AASHO/AWS Specifications.

Strength tests have indicated that butt welds of the same thickness as the connected parts are adequate to develop the full capacity of these parts. There is usually no need to calculate stresses in the weld as long as the weld metal matches the plate material in physical properties.

In fillet welds the critical stress is assumed to be a shear stress on the minimum throat area of the weld material regardless of the applied direction of the load. In computing the stress due to direct loads on longitudinal and transverse fillet welds, it is customary to divide the force acting on the weld by its **throat area**. The throat area is taken as the product of the weld length and its theoretical throat T as shown in Figure 8.

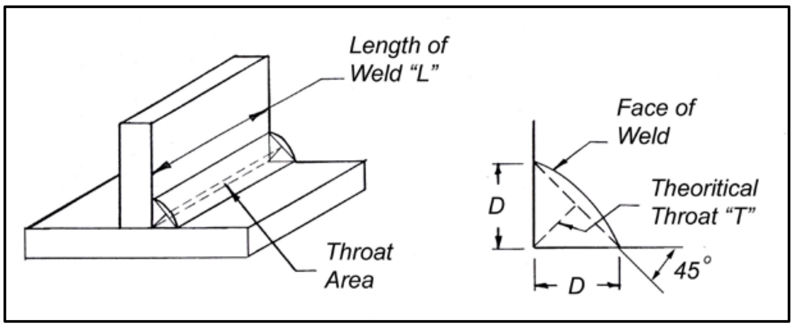

Figure 8 – Area of Throat

The length of the weld throat area is simply the length of the weld. Because the weld size is the same on both legs of the weld material, and it is assumed to be at a 45° angle to the connected pieces, the width of the weld throat, T, is

$$T = \left(\frac{\sqrt{2}}{2}\right) D = .707D$$

Where D is the size of the weld.

<u>Sample Problem:</u>
What is the allowable load on a 6" long by ½" fillet weld if the allowable shear stress of the weld is 22 ksi?

<u>Answer:</u>
A ½ inch fillet weld that is 6 inches long would have a throat area of:

Throat area = length x width = 6" x .707(1/2") = 2.12 sq. in.

And,

Allowable load = Allowable stress x area = 22 ksi x 2.12 sq. in = 46.6 kips

Photo No. 1 - Corner joint in John Hancock Building

Photo No. 2 - Relative size of the welded corner joint for the John Hancock Building

Photo No. 1 shows a corner joint on the John Hancock Building in Chicago. The joint itself was fabricated in a shop offsite and delivered to the building site for installation. The joint is made from 4" thick steel plates welded together to form the corner. The horizontal floor beams and vertical columns were then welded to the corner joint. Bolts were used to connect the diagonal members to the corner joint.

Photo No. 2 shows the relative size of the welded corner joint. This is a massive piece of welded steel plates. Notice the bolted connection of the diagonal members to the welded corner joint.

Bolted Connections

Two or more pieces of steel can be connected together with bolts. The pieces of steel are connected with bolts and nuts to transfer the load from one piece to the other. In a simple lap joint, the load in one plate bears on the side of a bolt which then transfers the force to the other plate producing bearing stresses on the plates at the holes. The opposing bearing stresses tend to shear the bolt and/or crush the plates.

The behavior of bolted connections is very complex. Connections are statically indeterminate, and the distribution of the forces and stresses depends upon the relative deformations of the component parts and the fasteners. Stress concentrations also complicate the situation. Rigorous and exact mathematical calculations are nearly impossible because of the stress redistribution due to ductility of the steel and local yielding of the materials.

Photo No. 3 - Typical 2 span continuous bridge beam

Photo No. 4 - Bolted connection on a steel bridge beam

Bridge beams over highways often have bolted connections. Photo No. 3 is a typical two span continuous beam bridge over an interstate highway. To form one of the beams, three sections of beam are bolted together.

Photo No. 4 is one of the bolted connections of the bridge shown in Photo No. 3. The location of the bolted joint is selected based on the moment diagram of the beam. The joint is placed at a point where the moment is expected to be the smallest – and most certainly away from the point of maximum moment. This joint will carry mostly shear forces of the continuous beam.

Notice the plate connecting the webs of the two pieces of beam. There are three rows of eight bolts in each beam to make the connection – a total of 48 bolts in the web connection. This is the shear portion of the load transfer from beam to beam through the connection. The plate connecting the bottom flange of the beams is the moment transfer between the two beams. It has two long rows of 13 bolts on each beam – a total of 52 bolts in the connection. Those bolts are definitely in single shear. We will do a simple illustration problem with only two bolts to show the methods of failure of a bolted connection in single shear in a bit.

To form a bolted connection, holes are punched and reamed, or drilled in the connecting plates and connection pieces. The holes are usually $^1/_{16}$ inch larger than the diameter of the fasteners. The pieces are then lined up and the bolts inserted. The bolts are then tightened a predetermined amount to provide the completed joint.

A simple lap joint is shown in Figure 9. In this simple joint, the plates have slipped and bear on the bolts tending to either shear the bolts or crush or tear the plates. Figure 9 is an example of single shear in the bolts.

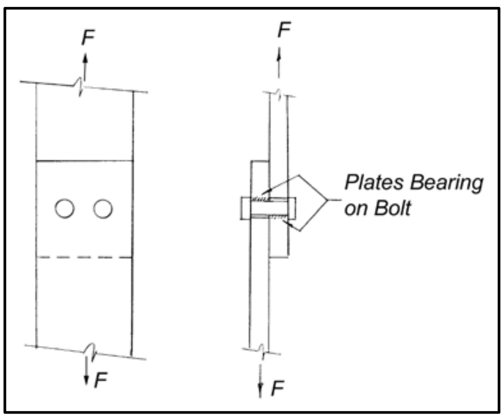

Figure 9 – Bolt Connection-Single Shear

Figure 10 is an example of a bolted connection with the bolts in double shear.

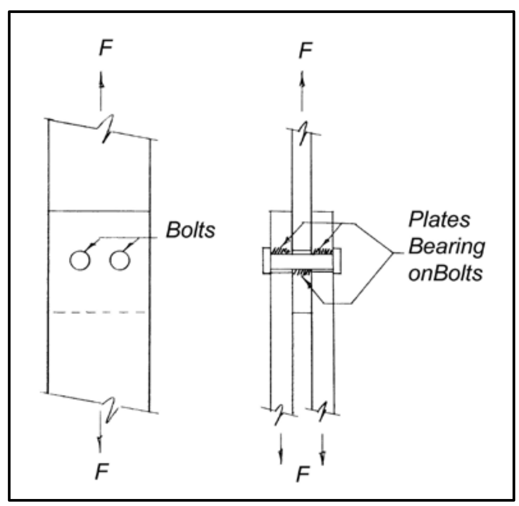

Figure 10 - Bolted Connection - Double Shear

For large joints with a complex arrangement of high strength bolts, it is necessary to think of two methods of load transfer: **friction**, and **bearing**.

Friction

A friction bolted connection is a difficult connection to analyze and design. It is also difficult to construct the joint to function effectively in the field. The plates must be smooth with no defects and match perfectly, and the plates must also be free from all defects including any grease, oil, paint or other contaminants. Joint preparation is critical for a friction joint to be effective. Most bolted joints are bearing type joints.

Bearing

Bearing bolted joints are bolted joints where the plates are allowed to slip and bear on the bolts. The action of two plates in tension bearing on opposite sides of a bolt tends to shear the bolt. This bearing pressure also causes bearing stress on the plate, tending to crush the plates in the areas of the bolts. Because the plates are in tension – the forces pulling the plate while the bolts are resisting the pull – they also have tensile stresses which tend to tear the plate.

Just as the joined steel plates have different strengths, bolts too have different strengths. There are different grades of bolts that can be used for bearing type bolted connections. The AISC Manual lists the most commonly used bolts – the ASTM A307, ASTM A325, and the ASTM A490. Of these three bolts, the A325 is probably the bolt most commonly used for bolted connections. The AISC Manual lists the allowable loads for these bolts.

The allowable shear stress in a bolt and the allowable load per bolt are listed according to the conditions of the joint. The table includes allowable shear loads for including the threads in the shear plane and excluding the threads from the shear plane; whether it is a standard hole ($^1/_{16}$ inch larger than the bolt diameter) or not; the diameter of the bolt; and whether it is in single shear or double shear. For example, a ¾ inch, ASTM A325 bolt used in bearing, single shear with the threads excluded from the shear plane has an allowable load of 13.3 kips.

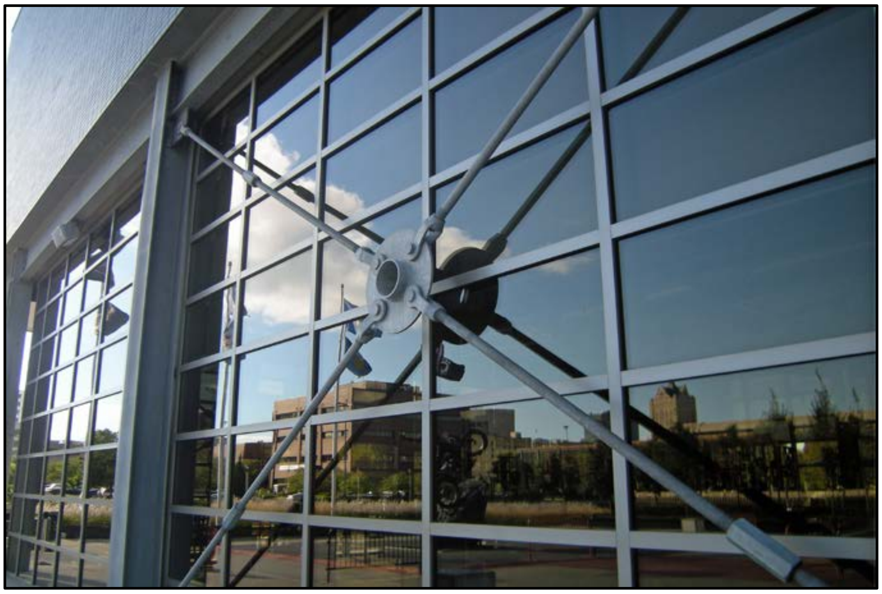

Photo No. 5 - Round bars bolted to center connection plate

Photo No. 5 is a nifty little bolted connection used to attach round bars to a flat, round plate. The bars act as cross bracing for the frame of a building at the Harley Davidson Museum in Milwaukee, WI. Pat took the photo on September 10, 2010 during his ride around Lake Michigan on his Harley. The round bars are connected to a round plate with a "hole" in the center to add architectural interest. As simple as this looks, it was a technical challenge to design. The stresses in the plate are fairly complex because of the several induced stress concentrations that occur at each of the bolt holes, as well as at the hole in the center of the plate. It took an experienced connection designer to insure this bolted connection will act as intended while safely transferring the loads of the diagonal members as they resist racking of the building.

The design of bolted connections is beyond the scope of this course. There are many fine books available that cover the design aspects of bolted connections. However, to illustrate the main methods of failure of a bolted bearing connection, the simple lap joint shown in Figure 9 will be used to illustrate the allowable load of a bolted connection.

For the illustration, the following plate and bolt properties will be used:

- Bolt size: $^{5}/_{8}$" diameter
- Bolt Type: ASTM A325
- Allowable single shear load: 9.2 kips per bolt
- Plates size: 2 ½" wide by ¼" thick
- Plate allowable bearing stress: 69,600 psi
- Plate allowable tensile stress: 21,600 psi

The lap joint can fail in one of four ways:

1. End tear-out
2. Bearing failure
3. Tensile failure
4. Bolt shear

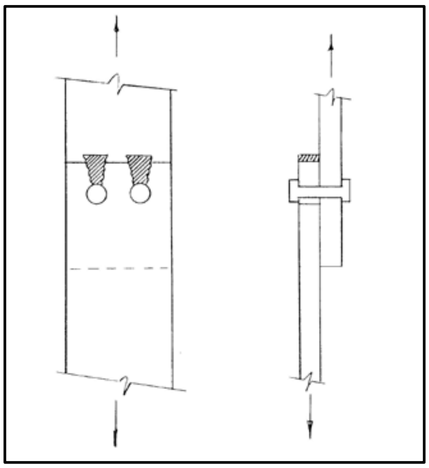

Figure 11 - End tear-out failure

End tear-out occurs when the end of either plate tears out from the pressure of the bolts bearing on the plates as depicted in Figure 11. By allowing an adequate distance from the end of the plate to the center of the bolt, tear-out should not occur. The distance from the center of the bolt to the edge of the plate measured in the direction of the bearing pressure should be at least three times the diameter of the bolt. When designing a bolted connection, the calculations for the distance from the center of the bolt to the end of the plate should be made. Assume that adequate plate distance has been provided in this illustration - no calculation will be done. The bolted connection will not fail in end tear-out.

Bearing failure occurs when the bolts bear on the plate material and the plate material crushes as illustrated in Figure 12. Since the bolts usually have a higher allowable bearing stress than the connected plate materials, the allowable bearing stress is usually based on the connected plate material.

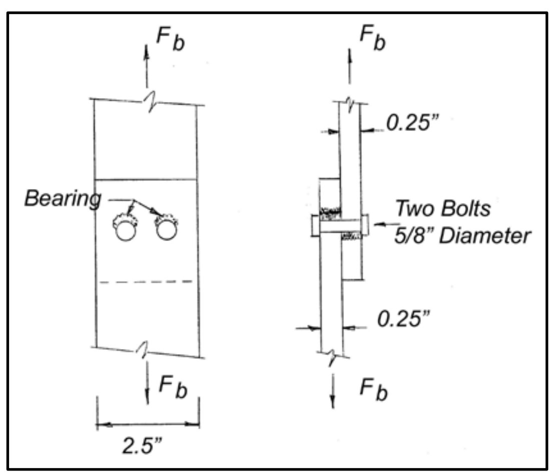

Figure 12 – Bearing failure

When a cylindrical bolt bears against the wall of a hole in a plate, a non-uniform pressure exists between them. As a simplification of the actual stress distribution, it is assumed that the area in bearing is the rectangular area found by multiplying the diameter of the bolt times the thickness of one plate times the number of bolts.

The capacity of the joint in bearing then is the allowable bearing stress of the plate material times the bearing area.

$$F_b = \sigma_b A_b$$

Where F_b = Capacity of the joint in bearing
σ_b = Allowable bearing stress of plates = 69,600 psi
A_b = Bearing area = ($^5/_8$ inch diameter) x (¼ inch thick plate) x (2 bolts) = 0.31 in^2

Then

$$F_b = \sigma_b A_b = (69{,}600 \text{ psi})\ (0.31 \text{ in}^2) = 21{,}576 \text{ lb}$$

The capacity of the joint in bearing is **21.6 kips.**

Tensile failure occurs when the plate material tears across the section with the minimum area to resist the tensile force in the joint. For the case of this lap joint, Figure 13 shows the location of the section. The minimum cross sectional area is the section through the center of the bolt pattern. The cross sectional area of the weakest section of the plate is calculated by multiplying the width of the plate less the bolt hole diameters times the thickness of the plate. There are two bolts and the holes are $^1/_{16}$ inch larger than the bolt diameters.

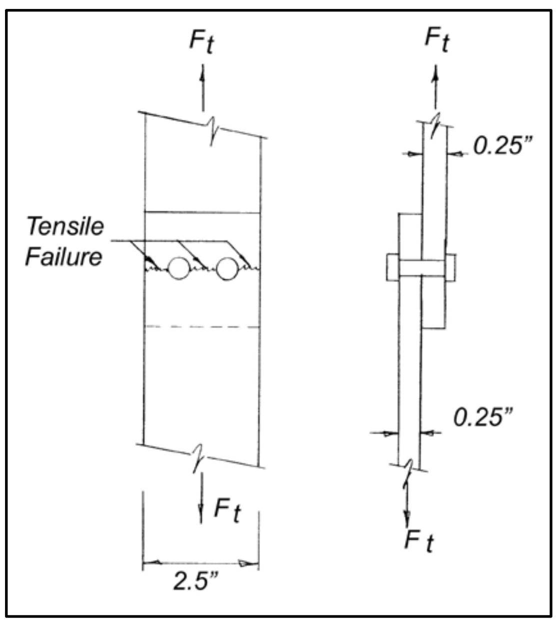

Figure 13 – Tensile failure

Then the allowable load in the joint based on tensile failure is the allowable tensile stress of the plate times the area of the weakest cross section.

$$F_t = \sigma_t A_t$$

Where F_t = Capacity of the joint in tension
σ_t = Allowable stress in tension of plates = 21,600 psi
A_t = Net tension area =
= (width of plate – 2 holes) x (plate thickness)
= [(2.5" wide plate) - (2 holes x $^{11}/_{16}$ inch diameter)] x (¼ inch thick plate)
= 0.28 in^2

Then

$$F_t = \sigma_t A_t = (21{,}600 \text{ psi})(0.28 \text{ in}^2) = 6{,}048 \text{ lb}$$

The capacity of the joint in tension is **6.0 kips.**

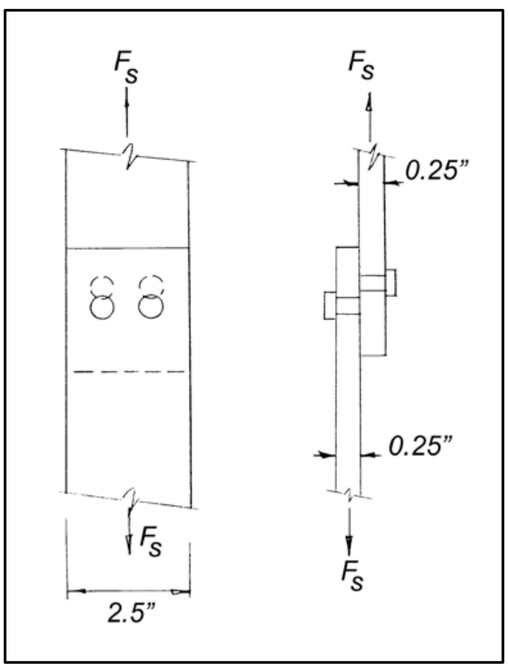

Figure 14 - Shear

Bolt shear occurs when the tensile load on the joint fails the bolts in direct shear as shown in Figure 14. The body of the bolts is assumed to be in direct shear when the line of action of the applied load passes through the centroid of the bolt pattern. It is also assumed that the total applied load to the joint is shared equally among all the bolts.

Then the allowable load in the joint based on shear failure of the bolts is the allowable load in shear of the bolt times the number of bolts.

$$F_s = P_B N$$

Where $F_s =$ Capacity of the joint in bolt shear
$P_B =$ Allowable load in shear in a bolt = 9.2 kips
$N =$ Number of bolts = 2

Then

$$F_s = P_B N = (9.2 \text{ kips}) (2 \text{ bolts}) = 18.4 \text{ kips}$$

The capacity of the joint in bolt shear is **18.4 kips.**

Comparing the loads to fail the joint in different modes:

Plate bearing failure capacity	21.6 Kips
Plate tension failure capacity:	6.0 kips
Bolt shear failure capacity:	18.4 kips

Comparing the three maximum loads in the three modes of failure, it is seen that the bolted joint will fail in plate tension at 6.0 kips. Therefore, the capacity of this bolted connection is 6.0 kips.

Large Bolted Bearing Connections

In large bolted bearing connections, ones with many bolts and in intricate arrangements, frictional forces and bearing forces interact in a complex way. In very large and long bolted connections, the specialized work of the connection designer must include being aware of the causes – and therefore solutions to – what is called unbuttoning. Following is a simplified explanation of the causes of **unbuttoning**.

In a bearing connection, when the joint is first loaded, the resisting force of the connection is by friction between the plates. The tightened bolts of a bolted connection will press the connected plates against each other causing friction between the plates. This initial resisting force is initially transferred by friction forces concentrated near the ends of the joint – near the end bolts of the joint. As the load increases, the friction zone expands toward the center of the joint with the frictional forces at the ends continuing to increase as this spreading occurs. At this point in the process, the frictional forces at the ends of the joint are higher than anywhere else in the joint. There may not yet be any frictional forces at all in the center of the joint.

Eventually, as the load continues to increase, the maximum value of static friction is exceeded at the ends of the joint and **partial slip** occurs – the plates at the end of the joint move a bit. As the load continues to increase, the static friction continues to spread over the joint, and, at some point, the limiting value of static friction is exceeded over the whole contact surface of the connected plates and the **major slip** of the plates occurs whereby the plate comes in contact with the bolts of the joint. As the major slip propagates through the bolt pattern, the plates will come in contact with the end bolts first. Keep in mind that the structural carbon steel plates are an elastic material and "stretching" of the plates occurs. Eventually the major slip will take up the entire $^{1}/_{16}$-inch bolt-hole clearance of all the bolt holes, and all of the bolts will be in contact with the plates. It is now a true bearing connection although there are still frictional forces at work. Mathematically, this is a very complex situation.

As described above, in the initial stages of the major slip, only the end bolts come into bearing against the plates. As the load increases, these end bolts will deform a bit until the second bolts come into bearing. The process continues until all bolts are in bearing on both sides against the two connected plates. The bolts do not carry an equal share of the load. The end bolts carry more – the center bolts carry less.

In short connections, with a few fasteners in line, almost complete redistribution of forces occurs before the end bolts fail. In longer connections, however, the end fasteners can fail in shear before the full strength of the remainder of the fasteners can be developed. The premature, sequential failure of fasteners, progressing from the ends of the joint toward the center, is called **unbuttoning**.

Once unbuttoning begins, failure of the joint is imminent unless the forces on the joint are immediately reduced. The bolts will fail in shear beginning at the ends of the joint. Once the end bolts have failed, the second to end bolts try to pick up the slack, and they too will fail. The progression leads to complete failure of the joint. Joint designers must not let unbuttoning become a factor in bolted joint load carrying capacity.

STEEL BAR JOISTS

Steel bar joists are a special built-up beam. They are a lightweight, prefabricated steel beam made from thin plates or angles, and round bars. The basic steel bar joist is ideally suited to carry uniformly distributed loads. In their basic form they are a truss with the top chord parallel to the bottom chord. The web is a round bent bar welded to the top and bottom chords. They have a superior load to weight ratio and they are economical to purchase and efficient to install.

Steel bar joists are a versatile structural member. They can be built to accommodate many special uses. For example, the top chord can be sloped to provide roof drainage from one end to the other. Or, the top chord can be sloped both ways with the peak, or high point, in the middle of the span, thus shedding water both ways. The steel bar joist can be modified to accept relatively large, concentrated loads. They can also be used as girders – a big beam that carries little beams. In many cases, the joist girder usually carries smaller bar joists. Big box stores such as Wal-Mart, Lowe's, and the like, typically have steel columns that support the large joist girders, which in turn supports the bar joist roof system which includes, in addition to the bar joists, the metal decking and waterproofed and insulated roofing system.

Steel bar joists are commonly used in building construction as floor or roof joists. They are typically supported on either steel beams or trusses, or on masonry walls. Once in place, the bar joists support steel decking which is sheet metal that is shaped to allow it to span the space between the individual bar joists. The sheet metal decking then acts as a form for the concrete for the floor or roof structure.

There are various manufacturers of steel bar joists, each with slightly different details for use. However, the principle behind the structural system is basically the same for everyone. For the small to average sized bar joist, the top and bottom chords are fabricated from thin strips of steel. The steel is bent into a sort of "W" shape to resist local buckling. A round bar is bent into a shape that allows it to be welded to the top and bottom chords. The ends of the bar joist are reinforced with a short piece of chord material to provide a support and with an additional piece of round bar, or two small angles, to resist the shear forces near the end.

Photo No. 6 shows an order of bar joists sitting in the manufacturer's yard ready for delivery. Notice the square ends. Perhaps the ends are reinforced for an increased load at the end of the joist, or, perhaps, the ends are simply squared off to accommodate an architectural feature of a roof overhang. These joists are a "special" order of some kind.

Photo No. 6 - Bar joists ready for delivery

Photo No. 7 is a typical series of bar joists supported in a masonry wall.

Photo No. 7 - Typical steel joists in masonry wall

And, Photo No. 8 is a series of bar joists supported by a steel beam.

Photo No. 8 - Joists supported by a steel beam

All steel bar joist manufacturers must adhere to the specifications in the AISC ***Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings***, and the American Iron and Steel Institute (AISI) ***Specification for the Design of Cold-Formed Steel Structural Members*****.**

The thickness of plate used for the chords as well as the diameter of the bar used to form the web varies according to the capacity and span of the bar joist. Longer spans and heavier loads require larger and thicker materials.

Manufacturer's catalogs list many sizes of bar joists ranging from around 8 inches deep to around 30 inches deep for the standard bar joist. For deep, long span joists and joist girders, the depths of the joists range from about 18 inches to about 6 feet. These are heavy duty, high capacity members. Typically these larger members have top and bottom chords made of double angles, similar to those shown in Photo No. 9.


Photo No. 9 – Supporting metal decking

Within each depth of joist, there are several "grades" of joist. They have different load carrying capacities for the same depth. The load capacities are increased by using thicker steel for the top and bottom chords and by using a larger diameter rod for the web.

Tables prepared by the joist manufacturers state the allowable TOTAL safe uniformly distributed load-carrying capacities in pounds per linear foot of span. The weight of the dead loads, including the weight of the joists, must be deducted from the total load to determine the safe live load carrying capacity of the joist.

WEAKNESSES OF STRUCTURAL STEEL

Structural carbon steel, as strong as it is, is vulnerable to conditions or situations that will totally debilitate it. Steel members, in some situations, will literally lose all of their strength and completely collapse.

In spite of its far superior strength, the main factors that make structural carbon steel elements unsafe are:

- Fire
- Instability
- Physical damage
- Corrosion

Fire

Heat is required to make steel – no heat, no steel. As strong as steel is, its strength can be reduced to zero in the heat of a fire. Structural steel must be protected from fire. In effect, just as it was created, it can be destroyed.

Photo No. 10 is a photo of a steel floor frame after a fire. The steel beams are twisted and sagging under their own weight because of the heat of the fire. Reinforcing steel rods are draped over the steel beams. The steel in this photo has lost all of its strength during the fire.

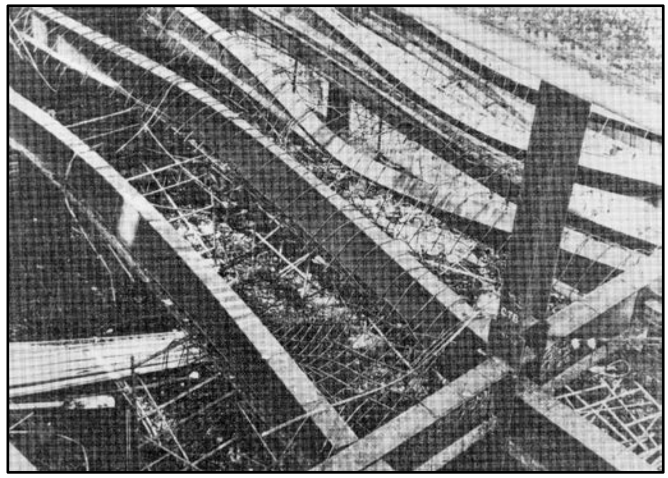

Photo No. 10 - Steel beams after a fire

Photo No. 11 - Steel bar joists after a fire. Notice buckled top chord.

Photo No. 11 shows the roof framing – steel bar joists – after a restaurant fire in Lafayette, Indiana several years ago. The bar joists have buckled top chords and are sagging under their own weight. The steel used to make the bar joists lost all of its strength during the fire.

Main structural steel members used in buildings must be protected from fire. The building codes are specific in which members need fire protection and they also allow different means for protecting steel. For example, fire protection for columns and beams can be accomplished by wrapping the member in fire rated drywall or masonry.

Photo No. 12 - Protecting a steel column from fire using masonry

Photo No. 12 shows a steel column being protected against the effects of fire by using masonry.

Photo No. 13 - Spray-on fire protection

Another method of creating a barrier between the heat of a fire and the structural member is a spray-on material. Photo No. 13 shows steel beams that have been protected against the heat of a fire by using a spray-on material. There are other products on the market to protect steel from fire including fire suppressant systems – fire sprinklers

Photo No. 14 graphically shows the difference between large timber members and steel beams in the aftermath of a fire. As it turns out, wood in the form of a large beam, is stronger in a fire than unprotected steel beams. The photo shows two steel beams draped over a timber beam after a fire. The timber beam still has enough strength to support the dead weight of the completely failed steel beams. Notice the nails still in the timber.

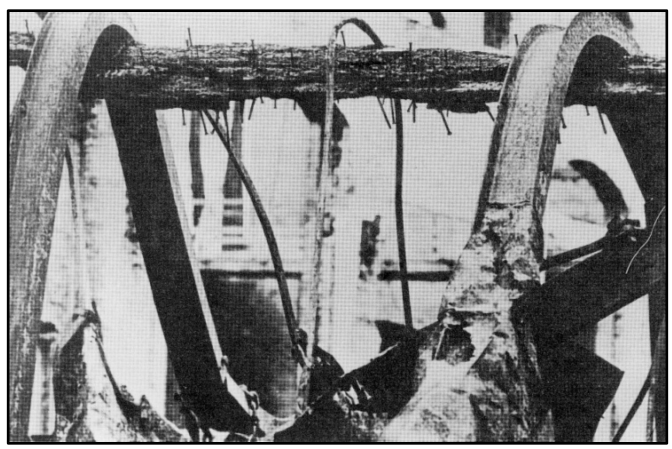

Photo No. 14 - Fire reduced strength of steel to zero

Spray-on fire protection is often used in larger buildings. It is an inexpensive, efficient, and effective way to protect structural steel. However, an important consideration in using the spray-on protection is that the fireproofing product itself must be protected from physical damage not only during construction but also after the building is occupied.

Photo No. 15 shows spray-on fire protection on a column. And that spray-on material is itself being protected from damage by the drywall wrapping around the column. It is only necessary to wrap the column with drywall up to the suspended ceiling that will be hung in the finished space.

Photo No. 15 - Spray on fireproofing. Notice drywall protection for fireproofing which will be below the suspended ceiling

The spray-on fire protection systems are applied early in the construction period of a building. Once the steel is in place and the floor system is complete, the fire protection firm will come through and spray all the appropriate members. This is a good time for the fire protection companies to do their work because the area is free of obstacles. It is the best and easiest time to see and have access to all the structural members. There is open space to set and move their scaffolding, to place their equipment and hoses, and it is very efficient to spray the members with the fire protecting materials.

Once all of the appropriate structural members have been fireproofed with the spray-on material, the trades will come though and install the electrical, HVAC, and the plumbing systems. These trades, and others, will necessarily scrape portions of the fireproofing material away while installing their work. Countless "hangers" for their equipment, ducts, conduit, piping and a number of other items need to be securely attached to the beams and columns. To do this, a bit of the fireproofing material must be scraped away. Also, during the construction process, columns and beams get "bumped". These are usually accidental, but, none-the-less, fireproofing material often gets removed. All of these scrapes and bumps, and other imperfections in the spray-on fireproofing must be repaired prior to completing the project. It takes a diligent individual to identify, highlight, and see that all the imperfections in a sprayed on fire proofing system are repaired prior to completion of the project.

Instability

Steel has incredible strength when compared to the other common building materials. However, with that strength there is a weakness that must be recognized, considered, and be accounted for. The weakness is **instability** in compression.

Instability is the tendency for a steel member in compression to buckle, either locally such as local flange buckling or local web buckling, or buckling of the entire compression flange where the entire beam leans to one side or the other.

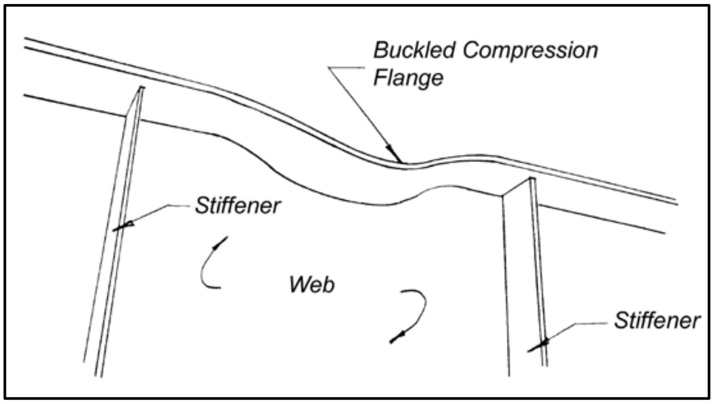

Figure 15 - Instability due to vertical buckling of compression flange

Figure 15 is a drawing of local buckling of the top flange of a beam. The top flange buckled vertically between the stiffener plates. Once a beam has been compromised in this way, it has failed structurally.

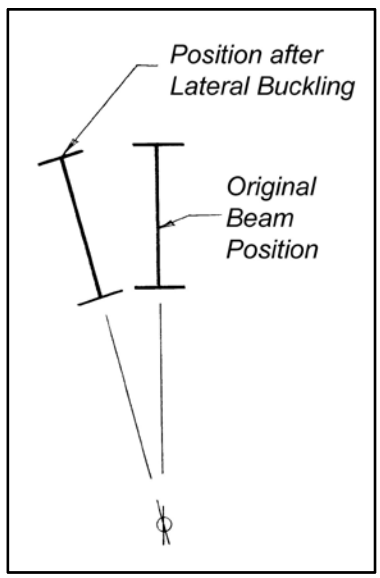

Figure 16 - Lateral buckling of top flange

Figure 16 is an illustration of lateral buckling of the top (compression) flange of a beam. As the top flange buckles laterally, the entire beam in that area displaces laterally also. This phenomenon can be easily demonstrated using a simple yardstick. Have someone hold the yardstick horizontally, one hand on each end. This represents a simple span 36" long. Hold the yardstick so the skinny axis is vertical. Now simple apply a small load to the center of the yardstick with your hand or finger. The yardstick will buckle laterally almost immediately. In fact, the person holding the yardstick at the ends cannot prevent the lateral buckling of the yardstick.

Photo No. 16 - Laterally buckled beams

Steel beams will be displaced in a manner similar to the yardstick, although not as dramatically, when the top flange buckles laterally. Using testing machines and full sized steel box beams, the concept of buckling of the entire top flange was demonstrated. The beams were rectangular in cross section, simply supported, and loaded from the top. This created tension in the bottom flange and compression in the top flange. The top flange buckled laterally causing the entire beam in the area of flange buckling to rotate as shown in the Photo No. 16.

Notice in the previous Photo Nos. 7, 8, and 9, the horizontal and or cross bracing between the bar joists. The bracing is there to prevent lateral buckling of the top chord during the erection process. The bar joists are very unstable until the decking is securely attached to the joists.

The reason for instability can be shown using the simple P/A stress calculation. For example, say a 22 kip compressive load can be supported by one-square inch of material that has an allowable stress of 22,000 psi (22,000 # / 22,000 psi = 1 sq. in.). If higher strength steel is used, say, one with an allowable stress of 44,000 psi, the area required would be ½ square inch of material to support the same load. The thought process for using the higher strength steel is that less steel means less weight which translates to less cost.

The problem with using higher and higher strength steel is that at some point the compression member becomes too small to maintain its shape and it buckles. It becomes unstable.

This instability is most obvious in columns when they buckle. The slenderness ratio is the critical component used in the calculation to determine which formula to use in determining the allowable load of a column. The calculated allowable load is dependent on the radius of gyration which is a function of the cross sectional area and the configuration of the section. The radius of gyration has nothing to do with the strength of the steel. Column buckling is mostly affected by the **size** and **shape** of the cross section.

In beams, the buckling can occur in the compression flange either as local buckling or as buckling as the entire top flange. The after-fire photo (Photo No. 10) shows lateral buckling of the top flange of several beams. The lateral buckling of the top flange is similar to column buckling.

Another type of instability in steel beams is local buckling of the web. This can occur at supports where the reaction of the support is too much for the web to carry. Stiffener plates are required to maintain the structural integrity of the member. Photo No. 17 shows a stiffener plate at the bridge pier in the middle of a two span bridge. This prevents buckling of the web.

Photo No. 17 - Stiffener plate at support

Steel bar joists are another type of structural element that has a very real upper limit on the strength of steel used in its manufacture. The top flange, the compression flange, is a thin plate shaped to resist compressive forces without buckling (and also to receive the bent bar web). As the strength of the steel increases, the cross sectional area of the top chord required to resist the compressive forces decreases. Again, the thought is that less steel translates into less cost. However, when the strength of the steel increases too much, the cross sectional area becomes too small to successfully resist the compressive forces without buckling locally.

The same reasoning can be applied to the web member. The web is made of a round rod bent to form the interior members of a truss. As the bar joist gets deeper, the compression part of the web – the bent bar – becomes a long column and is subject to buckling. The higher strength steel will eventually not provide enough cross sectional area to maintain its stability in compression.

Physical Damage

Physical damage in structural carbon steel members can be explained very simply using an analogy involving an empty can of pop. The can is aluminum and it is round. Trying to compress the can with your hands – one hand on the top and one hand on the bottom – is very difficult. The can is strong and resists the compressive forces of your hands. Of course, if you are fairly strong, once you exceed the maximum compressive stress of the side walls of the can, the can crushes very quickly. For those of us not that strong, we can use the concept of physical damage to allow us to crush the can. As soon as you begin to apply force to the top and bottom of the can with your hands, you simply use your thumb and put a "crinkle" in the side of the can, the can crushes almost immediately. The crinkle caused the side walls of the can to lose all of their strength.

So it is with structural carbon steel. If something physically damages the flange of a member under **compressive** stress, the member will lose its ability to resist the force of the loads. The member will fail. Generally speaking, columns are under compressive stresses over their entire cross section. Physical damage to one of the flanges can cause the column to lose its load resisting ability and fail.

We've probably all seen a damaged bridge beam over an interstate highway. A truck with an excessively high load collided with the bottom flange of the bridge beam and damaged the bottom flange. One might think that the bridge would be weakened to the point of impending failure. This might be true if the bottom flange had been completely torn apart – if it were no longer a continuous piece of steel. However, usually, the bottom flange is just mangled a bit – not torn into two pieces. And, the accident usually occurs over the paved roadway – after all, that is where the truck is traveling – so it's likely that the bottom flange of the beam where the damage is located, is in tension. A tensile member is not susceptible to local buckling failure. Therefore, the bridge beam, and therefore the bridge, is probably not is much danger of catastrophic failure. Of course the beam must be repaired as soon as possible, but road closure on the bridge is usually not necessary.

A beautiful example of protecting compression members from physical damage is Lambeau Field, home of the Green Bay Packers in Green Bay, Wisconsin. Photo No. 18 shows the author at Lambeau Field for a Packers football game on September 1, 2001 during the renovation of the stadium.

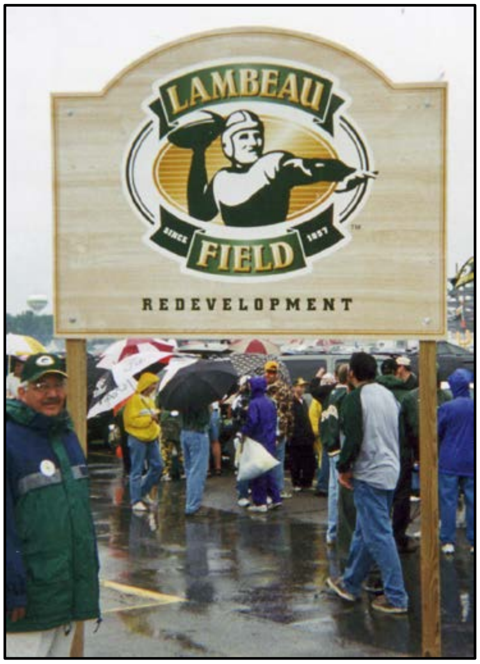

Photo No. 18 - Pat Glon at Lambeau Field during the stadium upgrade

Photo No. 19 - Columns encased in concrete to protect them from physical damage

After the renovation was complete, Pat was riding his Harley around Lake Michigan and took Photo No. 19 at Lambeau on September 9, 2010. The photo shows that columns under the stands were protected from physical damage by surrounding the lower portion with concrete. This is important because physical damage to a column at Lambeau could occur from many sources. The playing field is natural grass, so there will be earth moving equipment passing by the columns, as well as lawn mowers, trucks to carry the heavy and voluminous football equipment of the players, and delivery trucks for the concessionaires. These columns are protected from physical damage.

Masonry can also be used to encase steel columns against physical damage as well as for fire protection as shown previously in Photo No. 12.

Corrosion

If structural carbon steel is protected against corrosion, there is almost no limit as to how long it will last.

Dr. David B. Steinman, the designer of the Mackinac Bridge over the Straits of Mackinaw between the Upper and Lower Peninsula of Michigan, said of his suspension bridge, "It will last a century." He was then "corrected" by Mr. Grover Denny, the construction superintendent for the foundations. Mr. Denny said that he wanted to go on record as saying "...that this bridge will be standing a thousand years from now!" Both, of course, implied in their predictions that the steel used in the construction of the bridge would be protected from the elements of the Straits of Mackinac.

If steel is protected from the elements, it will last virtually forever. Iron tools are constantly being excavated that were made thousands of years ago. These tools have been exposed to the destructive elements of the earth – moisture, and the many trace elements of the soil – and still survived. With protection, they will last another thousand years.

The most common form of protection is simply paint. The steel is coated first with the reddish colored primer. After being placed in service, the steel is then painted – a simple enough procedure for a long term solution to the problem of corrosion.

Painting – it's simple, but not always easy as demonstrated by the maintenance of the Mackinac Bridge. Dr. Steinman "...chose a two-color combination for the bridge - foliage green for the span cables and ivory for the towers." He probably got some teasing for the "ivory towers."

To keep the bridge steel properly protected against the elements with paint, the painting process is continuous. By the time the paint crews complete painting the entire bridge, the part that was painted first needs it again. Painting is truly a continuous process to protect the Mackinac Bridge from corrosion.

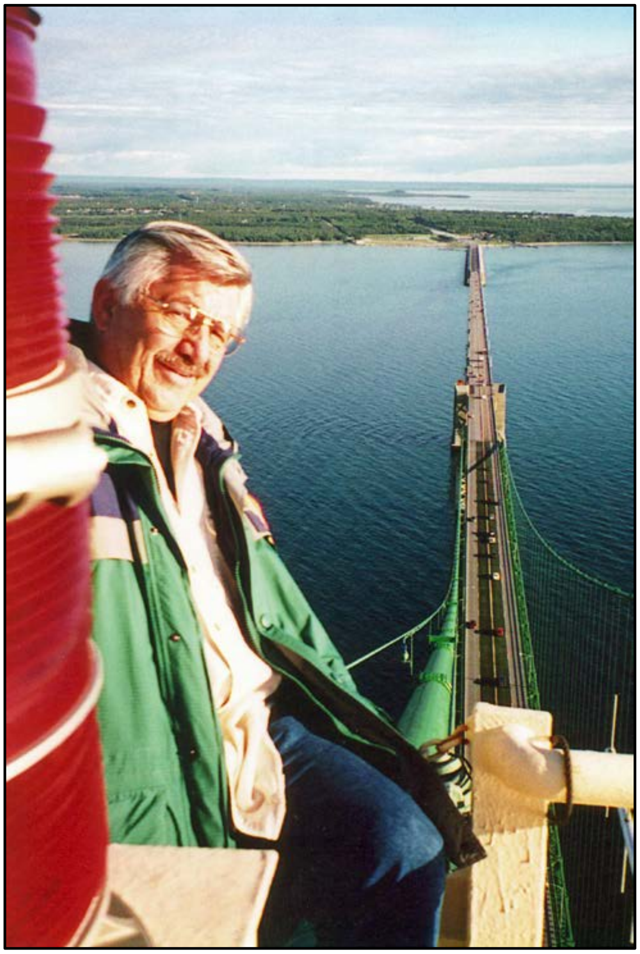

Photo No. 20 - Pat on the north ivory tower of the Mackinac Bridge

Photo No. 20 shows Pat next to the red light on top of the north ivory tower on the Mackinac Bridge in Michigan. Notice the thickness of the paint on the vertical railing post. They want to make sure the steel is protected against the Michigan weather.

As a protection against the weathering of bridge steel, the highway bridges in Michigan have the steel beams painted a pleasant light blue color. The highway bridges in Indiana are a nice looking green.

Back in the 1960's, self protecting steel was developed. The brand name was Cor-Ten steel. This steel very quickly developed a thick coating of rust when exposed to the weather. Once it rusted to a certain thickness, it stopped corroding. The rust protected the steel underneath from further deterioration. If the rust coating got damaged and some was chipped off, the underlying steel simply rusted again to seal up the damaged area. It was very effective at reducing the maintenance costs of protecting the steel from weather.

The steel was mostly used for bridges where the underside was not easily accessible. These included bridges located in remote regions where maintenance was an issue, and bridges above high gorges and rivers.

The Cor-Ten steel did have one drawback though. When it rained on it, some of the rust product washed off and stained what was below. A small town mayor in northern Indiana learned this the hard way. The town purchased street lights made of Cor-Ten steel because of the attractive color and also to reduce city maintenance costs. When it rained, the staining ran onto the sidewalk, over the curb into the gutter, and down the gutter to the street drain. It was unsightly and the street posts were replaced.

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 and malleable and can be rolled and welded to meet almost any need. It is used to frame and structurally support buildings and bridges. It is 100% recyclable.

Connecting structural steel elements is a complex and indeterminate mathematical process. However, assumptions are made to simplify the process. The design of steel connections has become a specialized segment of the steel industry. Steel has some very serious weaknesses which must be recognized and properly addressed including protection from fire, weather, and physical damage.