North American Steel Construction Conference

Lessons Learned in the Field

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My introduction to welding *and the field of welded design really began in my childhood. My grandfather owned twenty-three wooden ships, steamboats and barges, on the Great Lakes. They carried salt and limestone up the lakes, and pulp wood down the lakes to the paper mills. In 1917, the year I was born, my grandfather purchased a 200 amp Lincoln welder. Ten years later, I learned to weld using that machine.*

Our last ship burned in 1931, putting us out of business. It was the Great Depression, so in our home town of Duluth, Minnesota, we started a welding shop using that Lincoln welder. My brother, my father and I all welded in the shop, and my mother kept the books. Our work in the shop provided a variety of experience, and soon I was welding on steel structures. I became an iron worker, joining local No. 563 of the International Association of Bridge Structure and Ornamental Iron Workers in Duluth.

By the beginning of World War II, I had become welding superintendent at the Globe Shipbuilding Company in Superior, Wisconsin. From 1941 to 1945, we built and delivered twenty-nine all-welded oceangoing vessels for the U.S. Maritime Commission. From 1931 to 1945, the use of welding electrode in the United States increased almost one hundred-fold.

In 1945, I wrote an article for the Globe Shipbuilding Company newsletter in which I predicted "a far greater use of welding than anything which we can now imagine." However, the writers and codes and structural specifications were unfortunately not aware of my predictions! For example, prior to 1953, the AASHTO Specifications for Highway Bridges listed only 13 places where welding could be used on a steel bridge; a welded plate girder was not among them. Such oversights—and there were many more of this kind—undermined the true potential of welding technology.

In this paper, I will discuss some of the key principles of design that I "did not learn in school." Not all of the examples I use will be structural, but the principles still hold true for structural applications.

And there is one cardinal truth that overrides them all: if the engineer makes the mistake of considering welding as just another type of fastener, alongside such fasteners as rivets and bolts, the structure as designed will fall far short of its potential capabilities. Welding is not a fastener; it is a method of design which, properly used to full advantage, allows structural steel to put its best foot forward.

Lesson #1: Don't Assume Ductility is Inherent

Engineers have been taught that as soon as the applied load reaches the yield strength the material will yield and exhibit ductile behavior. This, however, offers a limited view. Figure 1 shows a stress-strain curve applied to a steel specimen, which is loaded in tension parallel to its length (a). In this type of test, the specimen is free to neck-down once the yield strength is reached (b). As it plastically yields, it strain-hardens to a higher strength (b to c). This stress continues to increase to (d), but because of a reduction in the cross-section, its apparent strength drops from (c) to (d).

Within the limit of elastic behavior occurring from (a) to (b), movement is

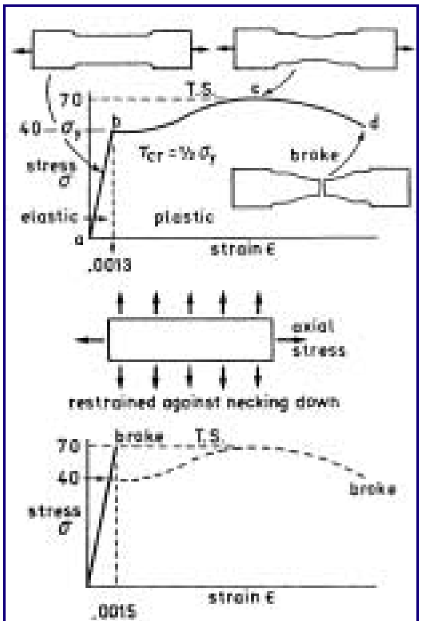

Figure 1. Stress-strain curve for steel.

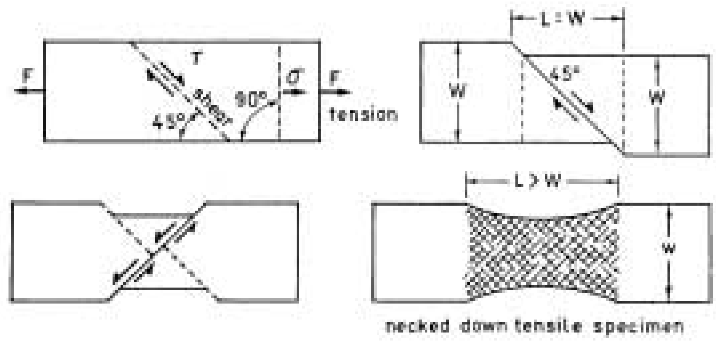

Figure 2. Ductility of Steel

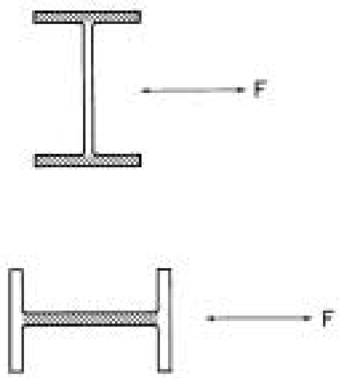

Figure 3.

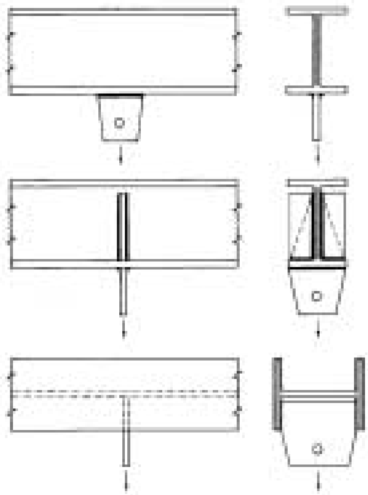

Figure 4.

small and would not be noticed unless measured. If the specimen's load is removed, it will return to its original dimensions with a springlike movement. For example, if a steel flange plate has a yield strength of 40 ksi, the maximum theoretical elastic deflection would be:

$$\varepsilon = \frac{\sigma}{E} = \frac{40{,}000\ \text{psi}}{30 \times 10^6\ \text{psi}} = 0.0013\ \text{in./in.}$$

In the laboratory, it is typical to think of applying a force to a tensile specimen so that its resulting strain or movement may be observed. But this is not what really happens with a tensile testing machine. When the machine is turned on, a motor gradually turns a screw, which slowly stretches or strains the specimen in the longitudinal direction. The resisting force of the specimen against this straining movement is indicated on a gauge. Yield strength is reached when the applied strain exceeds a critical point, and the specimen is free to plastically neck-down.

When an axial force (*F*) is applied to a test specimen, it will cause a normal stress (*s*) on a plane 90 degrees to the direction of the force. It also causes a shear stress (*t*), which reaches its maximum on a plane 45 degrees to this force, and is equal to one-half the value of the tensile stress. When this shear stress exceeds a critical value, a sliding action takes place, allowing the specimen to become longer in the direction of the force and more narrow across its width. If the resulting shear value is low and the critical shear stress point cannot be exceeded, then an increased load will result in failure when the ultimate tensile strength is exceeded.

This is like two horses racing to the finish line. One horse represents the shear stress and the other the tensile stress. If the shear stress reaches the critical shear stress value, then the material will elongated and exhibit ductility. However, if the tensile stress reaches the ultimate tensile strength, then the material will experience a net section fracture will little or no ductility.

Sliding action can also take place on the 45 degree plane in the other direction. If the action continues, a necked-down elongation results in a tensile-tested specimen as Figure 2 indicates. The slip plane lies at 45 degrees, forming a reduced section, initially having a square outline. If the unrestrained length (L) of this section is at least equal to or greater than the width (W), the specimen will be free to neck-down and show full ductility. If the unrestrained length (L) is less than the width (W), the shear component (t) will decrease. A greater applied force will be necessary for the critical shear value to be exceeded, reducing its ductility. This is one reason AISC Supplement 2 requires the weld access hole to extend a distance on each side of the weld, equal to three times the web thickness. Doing so provides an unrestrained length of web, giving the specimen sufficient ductility.

In the field, materials often behave in a triaxial state of stress as opposed to the uniaxial laboratory condition. For example, steel plates are often restrained and not free to neck-down. Additionally, residual tensile stresses are established during the weld solidification process. Under these constrained conditions, materials may fracture in a brittle manner with little or no ductility.

The structural details and their state of stress greatly influences whether the shear stress exceeds the critical shear value to produce sufficient plastic movement before the ultimate tensile strength is exceeded. This will result in a more ductile detail and minimize the chances of cracking.

Lesson #2: Consider the Transfer of Stress Through Members

A common design oversight is the failure to provide a path so that a transverse force can enter that part of the member that lies parallel to the force. Given what is needed for the proper transfer of force (as shown in Figure 3), let's consider some examples.

The top of Figure 4 shows a lug that has been welded to a beam flange in the simplest and most efficient manner—so the force goes directly into the web, the part parallel to it. This way the weld that connects the lug to the flange is uniformly loaded. In the center sketch of Figure 4, the lug is placed across the bottom

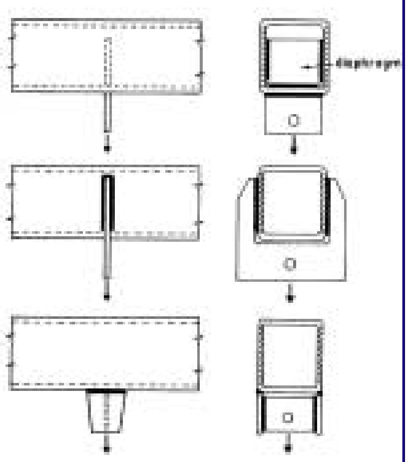

Figure 5.

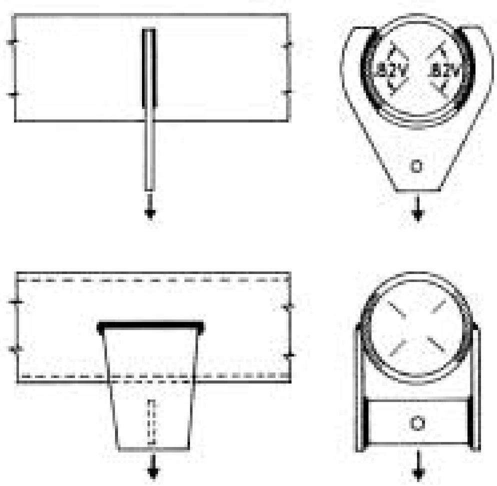

Figure 6.

flange. In this case, the load on the weld in no longer uniform, necessitating the use of stiffeners to transfer the load to the web. If, for some reason, the circumstances require the lug to be placed in this orientation, the stiffeners (with the attendant increase in welding and material usage they entail) are mandatory to even out the stress in the weld. Note that the stiffeners are not welded to the top flange. There would be no reason to weld them there, since the flange will not take the force. At the bottom of Figure 4, the member is in a different position, and the lug is correctly welded to the flanges that will take the load. It is not welded to the web, since that would serve little purpose in transferring the force.

Figure 5 illustrates how a lug might be welded to a box section so as to transfer force to the parts parallel to it. The sketch at the top, of course, is not applicable to the formed section shown, since there would be no way of getting the diaphragm inside the box. But if it were a fabricated box section, the diaphragm could be welded in before welding the top plate on. The center and bottom drawings in Figure 5 show additional ways to attach a lug to a box section. In the center, the lug is shaped as a sling and directly welded to the flange. At the bottom, the lug is designed so it will transfer the force into the two webs. This is a very efficient way to transfer the force on the lug into the webs.

Figure 6 illustrates two methods of applying a transverse force to a circular member. The rationale for these methods of attachment is shown in Figure 7. At the top of Figure 7, the beam is welded to a support. In standard practice, it is assumed that the flanges transfer the bending moments and the web transfers vertical shear. In the case of the circular member at the bottom of Figure 7, however, it is difficult to decide which part of the member is flange, and which part is web. Mathematical analysis has shown that if a tube is divided into four quadrants, the top and bottom quadrants will transfer 82% of the bending moment, and the side quadrants, 82% of the vertical shear. The methods of attaching the lug shown in Figure 6, therefore, are methods that transfer force tending to cause vertical shear into the areas of the circular section most closely parallel to the force.

Figure 8 provides a more complicated example of force transfer. A tank to haul water on a truck is made up of ¼ in. (6.4 mm) thick plate, with the sides overlapping the ends so as to provide fillet welds. Considering the forces from the water pressure on the tank ends, the only place for them to go is through the welds and into the sides—the parts parallel to their direction. The forces get there by bending the end plate. In service, the welds cracked. Three remedies were tried successively, as shown in Figure 8, using longitudinal and corner stiffeners, and finally both longitudinal and end stiffeners with corner stiffeners.

Figure 9 shows the center sill of a piggy back railroad car to which a bracket is welded to carry a 500 lb. (227 kg) air compressor unit. There are no interior diaphragms. The vertical force from the weight of the unit is transferred as moment into the bracket, creating bending at the web. The two horizontal bending forces must eventually transfer to the parallel flanges, but with an open box section there are no ready pathways. As a result, the web flexes and fatigue cracks appear in the web. The sketches at the bottom of Figure 9 illustrate two possible means for correcting the faulty design. In one, a stiffener is added before the web opposite the bracket side is welded into the assembly. The stiffener is welded to both flanges and to one web. There are now paths for the bending forces to get to the flanges. The second way to correct the design is to shape the bracket so it can be welded directly to the sill flanges in new fabrications, or to add pieces to the bracket on existing cars to accomplish the same purpose.

Lesson #3: Don't Design with Your Heart

What do I mean by a statement like "Don't design with your heart?" Well, all too often, before taking the time to rationally think through a problem, engineers make assumptions based on past experiences. These assumptions may or may not be applicable to a given circumstance. Although my illustrations of this lesson are not structural examples, the basic design principles I will discuss can (and should!) be applied to structural design.

A salmon canning plant was having trouble with a cast steel lever that put the tops on the cans. When the lever operated rapidly, inertia forces ($F = ma$) were created, causing deflection and putting the lever out of alignment. An engineer (thinking with his heart) immediately had the idea of making the lever out of aluminum, which has one-third of the density of steel, in order to reduce the mass by one-third, thus reducing the inertial forces. This was a good idea, but would not have alleviated the deflection problem.

To solve the problem the variables that influence deflection must be studied. The following equation defines the lever deflection as a function of the material properties and cross-section.

$$\Delta = \left(\frac{a}{3}\right)\left(\frac{\delta}{E}\right)\left(\frac{A}{I}\right)\left(L^4\right)$$

Where, E/δ is the property of the material, and $I/A = r^2$ is the property of the section.

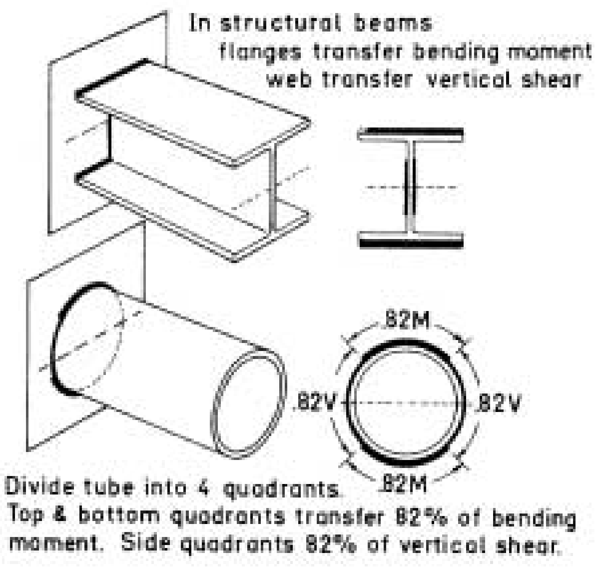

Figure 7.

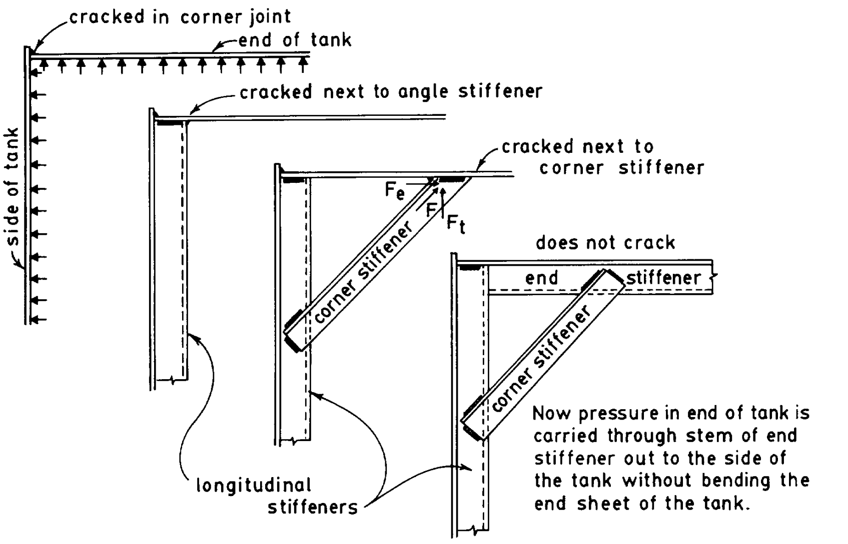

Figure 8.

When the engineer switches to aluminum, he changes the density to one-third that of steel, but he fails to realize that the modulus also changes to one-third that of steel. Remember that for structural metals such as steel, stainless steel, aluminum, magnesium and titanium, the modulus of elasticity is proportional to the density. So although this solution has reduced the density by one-third, it has also reduced the stiffness property by one-third—in other words, nothing has been accomplished. The engineer is right back where he started. The solution will never be found by changing the material, but only by focusing on the geometry of the cross-section.

The design solution to this problem will be found by maximizing I over A, where $I = r^2A$. So the designer must maximize "r," which is the radius of gyration. Increasing the radius of gyration can be accomplished one of two ways: by putting more material out away from the neutral axis, or by subtracting material near the neutral axis. The latter can be achieved by drilling holes in the lever, as shown in Figure 10. This simultaneously decreases the area (and subsequently the mass) and the moment of inertia, while increasing the radius of gyration. Even though the moment of inertia is reduced, the part will be stiffer because the rate of decrease for the moment of inertia is less that that of the area.

In another example, let's look at how one may "design with his or her heart" when dealing with gravity loads. A typical beam for an automatic welder is made as a box section, usually two channels welded together. In this example, a fabricator has the contract to weld the inside of a heat exchanger, 24 in. in diameter and 40 ft. long. This is a simple problem, a cantilever beam, fixed at the support. Assume the welding unit, control box, flux, and wire and weigh about 300 lbs. To get our example going, we will first neglect the dead weight of the beam. The formula for deflection is:

$$\Delta = \frac{FL^3}{3EI}$$

The engineer turned this around to give:

$$I = \frac{FL^3}{3E\Delta}$$

Next, the engineer enters 300 lbs. for the load (F), 40 ft. or 480 in. for the length (L). Since this is steel, E = 30,000,000 psi. Now, what should the deflection (D) be? He determines that the deflection should not exceed 0.01 in. Entering this value into the formula gives us:

$$I = \frac{FL^3}{3E\Delta} = \frac{(300\text{ lb.})(480\text{ in.})^3}{3(30\times10^6\text{ psi})(0.01\text{ in.})} = 36{,}864\text{ in.}$$

As an example, a W36x300 beam has a moment of inertia of 20,300 in.^{4}, half of that which is required. Furthermore, it would not be possible to get this beam into the 24 in. diameter of the heat exchanger.

So, the engineer starts all over. He will select a section that will fit into the heat exchanger and see if we can live with the deflection. Going back to the original formula, the engineer constructs the beam, adds the 300 lb. load, and measures the deflection to about ½ in. The unit is put into operation and runs for the next ten years, when it is moved to a new location. As the 300 lb. welding unit is removed, the beam moves upward ½ in., unnoticed. Now, what in the world does this ½ in. deflection have to do with the proper operation of the welding unit? The answer is nothing.

He must begin again. The beam must hold the welding head fixed, with as little

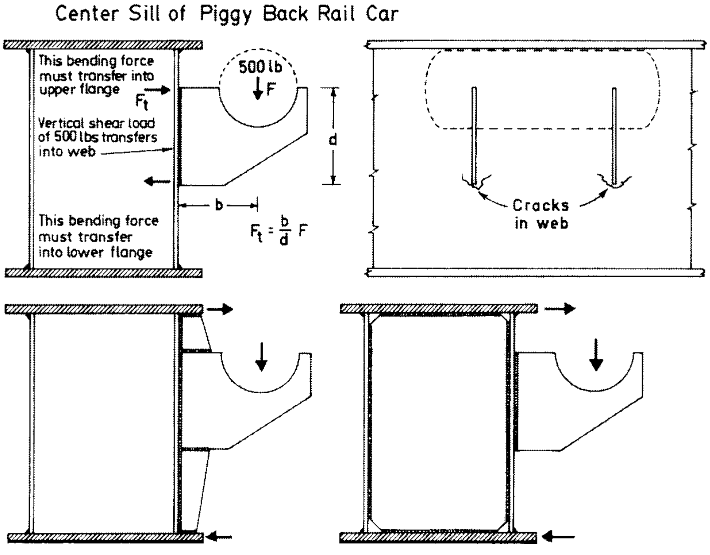

Figure 9.

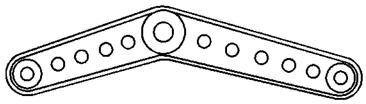

Figure 10.

movement as is possible. If the welding electrode were to move up and down, the arc length would vary, changing the width of the weld and depth of penetration along the length of the weld. If the welding electrode were to move sideways, the weld would weave from side to side, perhaps missing the joint. In which direction will there be the least movement? This is a difficult question.

Most welding beams are deeper than they are wide. This means they may move sideways more than they do vertically. But sideways motion may actually be more harmful. In fact, the welding equipment can compensate for a certain amount of vertical motion, but nothing can compensate for a back-and-forth movement. For the present, I suggest we make all welding beams with a square cross section. If I see a welding beam wider than it is deep, I would assume that the engineer recognized side motion to be very critical. Remember, don't design with your heart! Some situations have very little to do with vertical loading, and this is one of them.

Conclusion

As I stated at the outset of this paper, these are just three of the lessons I learned not in any classroom, but through actual experience in the field. Sometimes we engineers act a little like horses with blinders on: we concentrate so single-mindedly on the problem at hand, that we can't see what is going on around us. Each of the lessons discussed here illustrates how critical it is for us as engineers to take our blinders off, expand our limited world view, and test our assumptions. As a creative exercise, I encourage each reader to compile his or her own list of "lessons learned in the field" and share them with your colleagues. You may be surprised at how often the "obvious" solution turned out to be a dead-end, and pursuing a path that at first seemed counter-intuitive actually solved the problem.