Cambering Steel Beams

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DEFINITIONS

A dictionary definition of the verb *camber* is: "to arch slightly, to bend or curve upward in the middle." The noun *camber* is defined as "the curve resulting from the camber process."

The noun *sweep* is defined as "a widely or gently curving line, form, or part." As applied to steel beams, it usually pertains to the gentle curve of a beam about its weaker axis. The term camber generally applies to the curve about the strong axis of the member. This paper deals primarily with camber.

The camber process as applied to steel beams can be expressed as: "the pre-deforming of a member so that, in a loaded state, it more nearly approximates its theoretical presumed shape."

TYPES OF CAMBER

Natural mill camber is the out-of-straightness remaining after the initial rolling, cooling, and straightening of the member at the mill. Tolerances for natural mill camber are listed in the AISC *Manual of Steel Construction.*[1]

Induced camber is that which is applied subsequent to the initial rolling and straightening process. Induced cambering can be done at either the rolling mill or the fabricating shop. Tolerances for induced camber are also listed in the AISC *Manual of Steel Construction.*

THE CAMBER CURVE

The deflection curve for a horizontal uniformly loaded member of constant cross section theoretically approximates a parabola. However, since the sag ratio for beams, that is, the ratio of mid-ordinate to chord, is so small, it is generally accepted that adequate accuracy results if the camber curve is considered to be a segment of a circular curve. Some camber calculations are based on circular curves.

Camber is usually expressed in terms of the maximum ordinate at midspan. If it is desired to find the camber at other locations along the span, a handy method is shown in Fig. 1. Divide the span into an even number of equal segments as desired. This example shows eight equal segments. Number the points as shown starting with zero at the support. Multiply the points as shown to form a "factor fraction." If the centerline camber is, say, 1.5 in., the camber at the other points is found as follows:

Point #1 ordinate = $\frac{7}{16}$ (1.5) = 0.65 in. = $\frac{5}{8}$ in.
Point #2 ordinate = $\frac{12}{16}$ (1.5) = 1.125 in. = $1\frac{1}{8}$ in.
Point #3 ordinate = $\frac{15}{16}$ (1.5) = 1.4 in. = $1\frac{3}{8}$ in.

The resulting camber curve is shown in Fig. 2. This method is especially useful for calculating the camber at truss panel points. If six segments were laid out, the factors would be as shown in Fig. 3.

The AISC *Manual of Steel Construction,* 8th ed., pages 2–130, gives various co-efficents for determining the centerline deflection for various load combinations. Once the deflections are determined, the desired amount of camber can be selected.

The selection of camber is often arbitrary. The methods of cambering are relatively crude, and the results are less than precise. There is little need nor justification in meticulous mathematical manipulation or methodical multifarious meditation when it comes to determining camber requirements.

METHODS OF CAMBERING

At one time, cambering was done at the rolling mills during the rolling process by means of adjusting (gagging) the rollers. Most mills are now reluctant to use this method. Instead they use presses and/or offset rollers and cambering (or straightening) is done subsequent to the shaping process.

The method most popular at this time is *cold* cambering utilizing brute force. Steel members can be purchased with the cambering performed at the mill, or the fabricator can order the straight beams and do the cambering in his own shop.

Beams can also be cambered by the application of heat at various points along their length. This will be discussed later on.

A combination of *heat and force* can be used to induce camber.

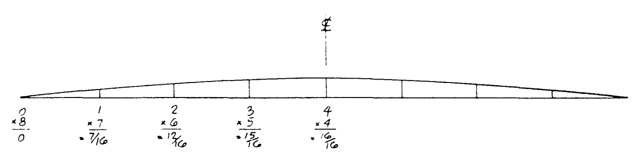

Figure 1

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A recent development in curving methods is the use of *induction benders*. In this process the steel is heated by electricity while being forced into precise bending guides. This is the most accurate method of bending. It is used extensively to curve pipes and tubes.

When camber is required in plate girders, the web plate is usually cut to the desired camber profile before assembly.

METALLURGY[3]

Whether we cold camber using force or apply heat, we must be aware of important metallurgical changes in the steel.

Cold Cambering Using Force: The types of steel used for structural purposes are ductile, that is, they have the property of deforming extensively under substantially constant stress. This deformation is about 10 to 20 times the amount of deformation exhibited in the elastic range and is represented by the horizontal portion of the classic stress-strain curve for mild ductile steel (see Fig. 4). When we cold camber a beam, the extreme fibers reach stresses and deformations which are on the horizontal portion of the stress-strain curve. With most cold-cambering devices, it is impossible or difficult to maintain a constant stress. The rams which deliver the force advance when the button is pushed and halt when the button is released. When the ram is halted, the deformation and stresses come to balance in a brief moment and equilibrium is reached. When the ram is retracted, the beam relaxes and some residual deformation is evident by the fact that the beam is no longer straight. This essentially is the cold-cambering process.

We all know that bending a wire back and forth enough times will weaken it to the point that it will fail with very little effort. What about the cold-cambered beam which we bent in one direction to make the camber curve and are now loading in the opposite direction with its service loads? Another of the seemingly endless wonderful properties of structural steel is that, if allowed to rest for a few hours at room temperature, steel has the tendency to recover its elastic properties. The application of mild heat, about 225°F for a few minutes, will accelerate the period of recovery.

Mention should be made here of the term "strain hardened." This consists of an alteration of the elastic properties of cold-worked steel, and a raising of the proportional-limit stress, as a result of the aforementioned aging or application of mild heat.

Two facts emerge from this brief discussion of cold-bending.

1. The same allowable stresses (or load factors) can be applied to cold-cambered beams as to uncambered beams provided they are allowed to "age" for a few hours.
2. *Never* attempt to reduce the camber in an over-cambered beam by immediately applying force in the opposite direction. If this caution is ignored, *strain-weakening* will result and the elastic-limit will be lowered. If normal, allowable stresses are subsequently assigned to the member, the factor of safety will be reduced.

Cambering Using Heat: The heat application must not exceed 1100°F for ASTM A514 steel nor 1200°F for other structural-type steels. The temperatures should be monitored by heat-sensitive crayons or other suitable means. There is no reason to exceed these temperatures. In fact, most cambering can be done at temperatures lower than these maximums. (Heat-cambering methods will be discussed later on.)

MEMBERS TO CAMBER

Members Which Lend Themselves to Cambering

a. Filler beams
b. Girder beams
c. Composite floor beams
d. Members with uniform cross section

Members Which Do Not Lend Themselves to Cambering

a. Crane beams or crane girders
b. Spandrel beams, especially those supporting facia materials

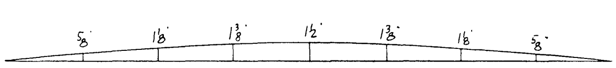

Figure 2

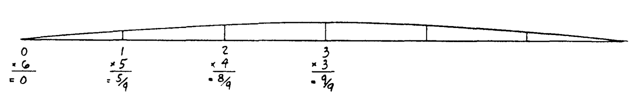

Figure 3

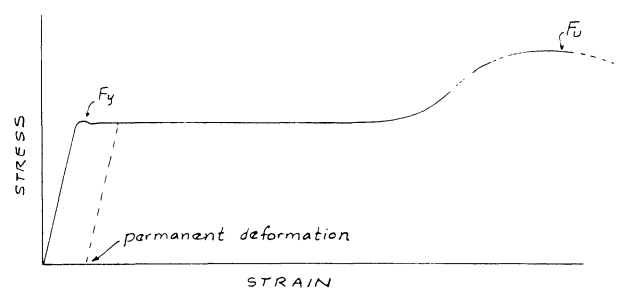

Figure 4

c. Beams with single or double cantilevers
d. Beams braced with knee braces
e. Beams with full moment connections or significant semi-rigid moment connections
f. Beams with welded cover plates, especially if the cover plate does not extend full length
g. Members of non-uniform cross section
h. Beams with significant non-symmetrical loading
i. Short beams—less than 20 ft in length
j. Shallow beams—wide flange shapes less than nominal 14 in. depth and standard beams less than 12 in. depth
k. Beams subject to significant torsion loads
l. Beams which would require less than 1 in. of camber. (Small camber requirements can often be satisfied by natural mill camber.)

ESTABLISHING THE AMOUNT OF CAMBER

Beams may be cambered to accommodate part of the dead load deflection, the full dead load deflection, or dead load deflection plus part of the live load deflection, at the discretion of the engineer. He may be influenced by the relative percentages of dead and live load, the probable frequency and intensity of live load, the performance history of similar members, aesthetics, or other pertinent factors.

As stated before, the AISC *Manual of Steel Construction* lists maximum amounts of natural mill camber permitted in various sizes and lengths of rolled sections. Also listed are maximum and minimum amounts of induced camber which the mills will agree to supply and the tolerances for this camber. (It should be noted that all mills do not follow AISC camber recommendations. The mills should be consulted regarding their individual practices.) The manual also lists camber ordinate tolerances. Camber tolerances are always on the plus side. When beams are cambered at the mill, some of the camber is lost by the time the members reach the fabricator. This is due to the aging process or relaxation of stresses. The vibration associated with rail or truck travel, whether the members are shipped standing up or lying down, and the positioning of the dunnage are also contributing factors. If a beam is ordered with 1½ in. camber, the mill will probably provide about 2 in. camber. By the time the member reaches the fabricator, the camber may be approximately 1½ to 1¾ in. Most mills will not provide camber less than 1 in. Camber amounts greater or less than those available from the mills can be supplied by most fabricators using heat- and/or cold-cambering processes.

As previously mentioned, the determining of the amount of camber is a very inexact process. After the cambering process, the performance of the member is often not according to the script. In general, the anticipated amount of beam deflection does not occur. This probably is due to some degree of end fixity of the beam connections. Strain-hardening should not be a factor because the service stresses are or should be well within the elastic range.

WHEN TO CAMBER

Usually the cambering, if performed by the fabricator, is done after the member has been cut to length and punched or drilled. Beams which require square and parallel ends, such as for end plate or welded moment connections, must be cut after cambering (see Fig. 5). Any interior hole groups will be perpendicular to the flanges at their locations. The fact that the beams which frame to these hole groups will not be exactly vertical is of small consequence.

CAMBERING BY HEAT APPLICATION[3,4,7]

As previously stated, A514 steel should not be heated above 1100°F, and other structural type steels should not be heated above 1200°F during the cambering process. The consequences of overheating are not readily apparent to the naked eye but nonetheless they are present in the form of microstructure changes in the steel. Most heat cambering is accomplished by heating wedge-shaped segments at intervals along the length of the member. If the member is overheated beyond the transformation temperature of approximately 1350°F, there will occur "islands" of altered microstructure; in other words, the steel will be non-homogenous. This is to be avoided.

The number of wedge-shaped heated segments varies depending on length and size of the member and the amount

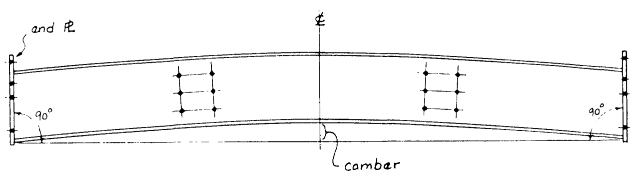

Figure 5

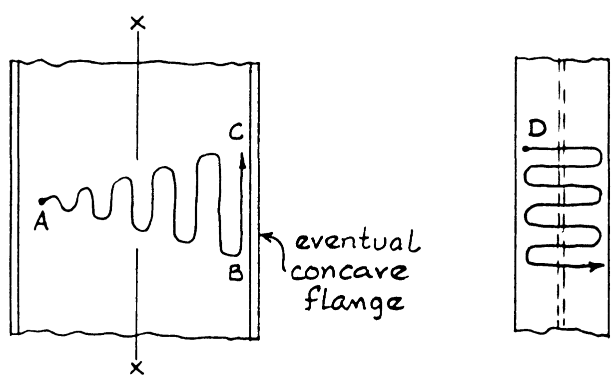

Figure 6

of camber required. For starters, try two heated areas at the $\frac{3}{8}$ and $\frac{5}{8}$ locations. Experience will be the best teacher. Before heating, install a plumb line or other device so that the movement can be monitored.

Once the heating starts, it should not be interrupted until the serpentine path described below is completed. As the heating proceeds, the member will start to bend in the direction opposite to that intended. However, after the heating is finished and the beam starts to cool, the beam will commence to straighten and then continue to bend in the desired direction.

The following procedure will produce camber about the *strong* axis. (ASTM A36 steel is assumed.) Refer to Fig. 6. Start the flame spreader at point A. Heat spot A to a light red color (1110°F). Proceed slowly in a serpentine path in the direction of the arrow. Direct the torch toward that direction, moving slowly, bringing each area to a light red color. The area B A C should be roughly the shape of an isoceles triangle with the angle at A varying from 20° to 40°, the larger number producing more movement. It is not necessary to return to point A to reheat. When the web heating is finished, start the flange heating at point D and proceed toward the center. (The flange heating may be started, using an additional torch, as the web heating is nearing completion.) Thick material, say over 1½ in., may be heated simultaneously at both the near and far surfaces. Always advance the torch along the path bringing the steel to a light red color as it proceeds. The flange to be heated is on the concave side of the camber curve; consequently, point A should be about 2 in. in from the convex side of the camber curve. For best results, let the heated member cool by itself. The heat cambering process can be enhanced by positioning the member so that gravity will aid in producing the curve. Note that the heat wedges do not necessarily have to be equally spaced, but they should be symmetrical about the centerline of the span (see Fig. 7).

The following procedure will produce camber about the weak axis. Refer to Fig. 8. Start the flame at point E and move in a serpentine path bringing each area to a light red (1110°F). The heated area is about 3 in. wide. Heat each flange simultaneously starting at point F and weaving an expanding path toward points G and H very near the eventual concave edge of the flange. The area G F H should approximate an isoceles triangle with the angle at F varying from about 20° to 40° depending on the amount of movement desired, a larger angle producing more movement. In this case, the flange heating can be done simultaneously with the web heating. Points G and H are located on the concave side of the camber curve. Point F should be about 2 in. in from the convex flange edge for beams less than 8 in. wide, and for wider beams point F should be about one quarter of the flange width in from the convex flange edge. As in cambering about the strong axis, gravity can be used to advantage when cambering about the weak axis. Care should be taken in spacing the dunnage supports so that the member will not sag too much as the heating progresses (see Fig. 7). For best results, allow the beam to cool naturally.

If the initial heating does not provide enough camber, additional wedges may be heated until the desired results are obtained. In order to cut down the time expended on heat cambering, several wedges can be heated simultaneously, as required.

Channels, angles, tees, and tubes may also be curved using the principles described above for wide flange members (see Fig. 9). Heat can also be used to straighten members.

The heat source can be anything that works—natural gas, propane, and oxyacetylene mixtures all work well. A commonly used torch nozzle is a medium to large (approximately 1½ in. diameter) "rosebud" type.

Heat cambering should be limited to low carbon steels.

COLD CAMBERING BY FORCE

When a beam is to be cold cambered by force, it is usually mounted in some type of rigid frame which holds the beam

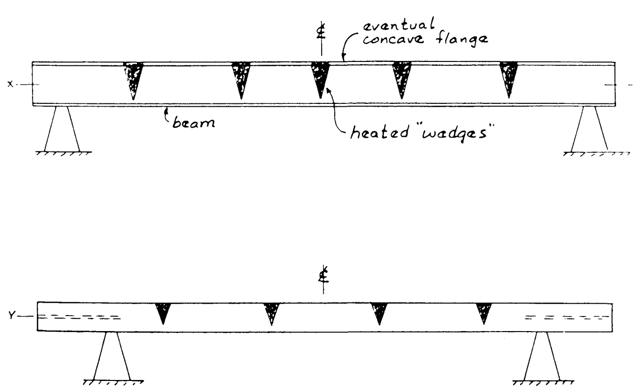

Figure 7

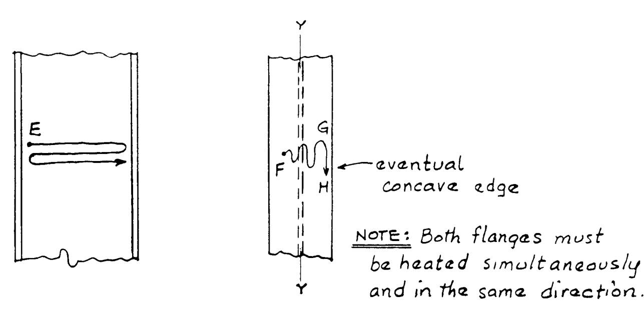

Figure 8

secure while the force is delivered. The ends of the beam must be laterally supported in addition to the compression flange. The fulcrums must be so devised that the ends are free to rotate because of the severe arc to which the beam is forced in order to produce the residual strain. There are usually two points at which the load is delivered to the beam. These points may be about six or eight ft apart while the resisting supports can be 22 ft or so apart. This will produce a curve that is very close to duplicating a parabola.

When the operator activates the cambering device, the rams advance and the beam deflects, often as much as two or three times the amount of desired camber. The rams are halted and kept in place for a few seconds during which the steel microstructure undergoes rearrangement and the stresses relax somewhat. When the rams are retracted, the beam springs back, stresses drop to zero, and a permanent set is left in the beam. If the deformation is insufficient, the rams may be immediately reactivated to add more camber.

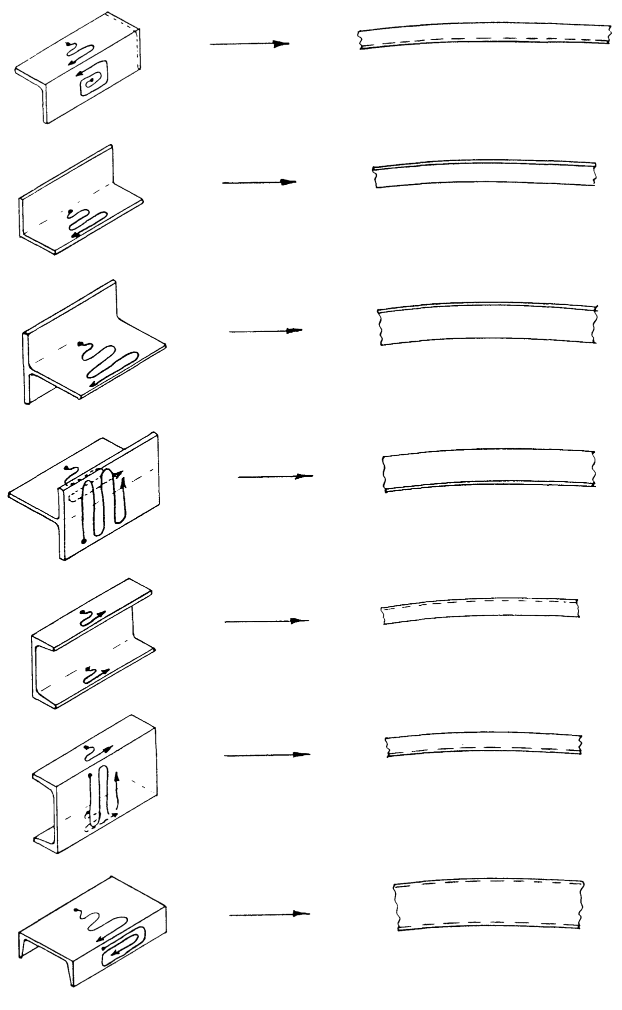

Figure 9

Contrary to popular belief, cold cambering does not result in significant residual stresses, at least in the flange areas. A bar shape, if bent cold to a tight radius, will contain residual stresses but, when a beam is bent, the radius of the bend is so large that the tension flange undergoes nearly pure tension while the compression flange is subject to nearly pure compression. Pure tension "stretching" and compression "squeezing" do not produce residual stresses; therefore, there should be no concern over this phenomenon when cold cambering beams.

Some commercial cambering devices can handle certain 36 in. wideflange shapes without the aid of heat. If the rams do not have enough power to produce permanent set, the application of mild heat will usually persuade the beam to deform. At 900°F, the yield stress for A36 steel has dropped from the normal 36 ksi to about 31 ksi. At 1100°F, it is down around 15 ksi. At 1200°F, the yield stress is negligible.

Some fabricating shops have devised clever methods of cambering two equal-sized beams at the same time by securing the ends and placing a jack(s) between them to force one beam away from the other. This often works well except that all beams do not have identical yield points, and some means must be devised to prevent the weaker beam from receiving more camber than the stronger beam.

CORRECTION FOR OVER-CAMBERING

If the initial cambering attempt results in too much camber, the following corrective measures can be utilized.

Heat-cambered members: Repeat the original process on the opposite side of the member but to a lesser extent depending on the amount of correction necessary. If heat had originally been applied at four locations, the corrective heat would be applied at one or two locations or until the camber curve is reduced to the desired profile.

Cold-cambered members: Apply mild heat in the 200°F to 550°F range for a few minutes. This will accelerate molecular relaxation. The heat should be applied as uniformly as possible along both flanges in the most stretched and compressed portions of the beam. This usually is in the middle third of the member. Never attempt to reverse a member in the cambering device with intent to remove some of the camber with cold force. This may cause strain-weakening. If the application of mild heat does not remove enough camber, a heated wedge or two at the *convex* flange as previously described for heat cambering should provide the necessary adjustment.

THE EFFECTS OF CAMBERING ON CONNECTION DETAILS

Figures 10 and 11 illustrate connection types which are commonly found in steel framed buildings. The following paragraphs will discuss the effects of cambering on the various connections.

Detail A is a traditional two-angle filler beam connection. The cambering can be done after the filler beam is cut and punched. Even though the beam end will be out-of-square, there is enough flexibility in the connection angles so that they will warp into contact when the bolts are tightened. If using A307 bolts or untorqued A325 bolts, care must be taken that the faying surfaces are in solid contact. (The magnitude of camber is greatly exaggerated in the sketches for illustrative purposes.)

Details B, C, and D show common filler beam connections popular in modern steel construction. Usually the beam end rotation resulting from the cambering operation can be accommodated by the use of short slots at the field bolted connection.

Detail E illustrates a moment connection consisting of three plates shop welded to the column. If the beam is cambered after cutting and punching, the top flange holes will be a little closer to the column than they should be and the bottom flange holes a little farther away. Whether this results in serious hole misalignment should be investigated by the fabricator's drafting department. Some fabricators circumvent this problem by punching oversized holes in the flange connection plates and taking the necessary bolt value reduction penalty. The web connection is usually not a problem because the web connection plate is punched with short horizontal slots.

Detail F shows a moment connection (semi-rigid) to a column web utilizing a seated connection. The seat plate is extended in length as required to accommodate the bolts. The fact that the cambered beam has an arched profile is of small consequence since the extended plate has enough flexibility to conform to the camber profile. The top plate, being field applied, will fit regardless of camber or other geometric aberrations.

Detail G represents an end plate connection to a column flange. (The same comments will apply if it is connected to a column web.) As can be imagined, if the end plate is not parallel to the flange, the erector will be required to install tapered shims. The very thought will send a shiver down the spine of a fabricator and erector. Tapered shims are expensive! An alternate approach is to cut the beam ends so that they are parallel to each other. This must be done after the cambering operation. This, too, is expensive because it requires special treatment in the shop. In other words, it can be done, but at a cost. For this reason and considering the high degree of end fixity, it is advisable not to camber beams which have end plate moment connections.

Details H and I illustrate AISC Type I rigid moment connections. As mentioned under Detail E, the web connection is usually not a problem because the web connection plate (or angle) is punched with short horizontal slots which accommodate the beam end rotation in addition to the weld shrinkage. However, attention must be paid to the flanges. If the beam end is cut prior to cambering, the end rotation resulting from cambering will cause the top flange root gap to be too small and the bottom flange root gap to be too large. In view of this, the fabricator may elect to cut the beam ends and do the necessary weld preparations *after* the beam is cambered. This constitutes another shop operation and adds to fabrication costs. In order to avoid this and in view of the near 100% end fixity, the designer may opt *not* to camber beams involved in full moment connections of this type.

CAMBER CAUTIONS

a. Don't over-camber beams which receive shear studs for composite action. The over-cambering may result in the heads of the studs protruding from the top of the concrete slab. There are two ways to pour a floor slab: with a uniform thickness of slab which conforms to the

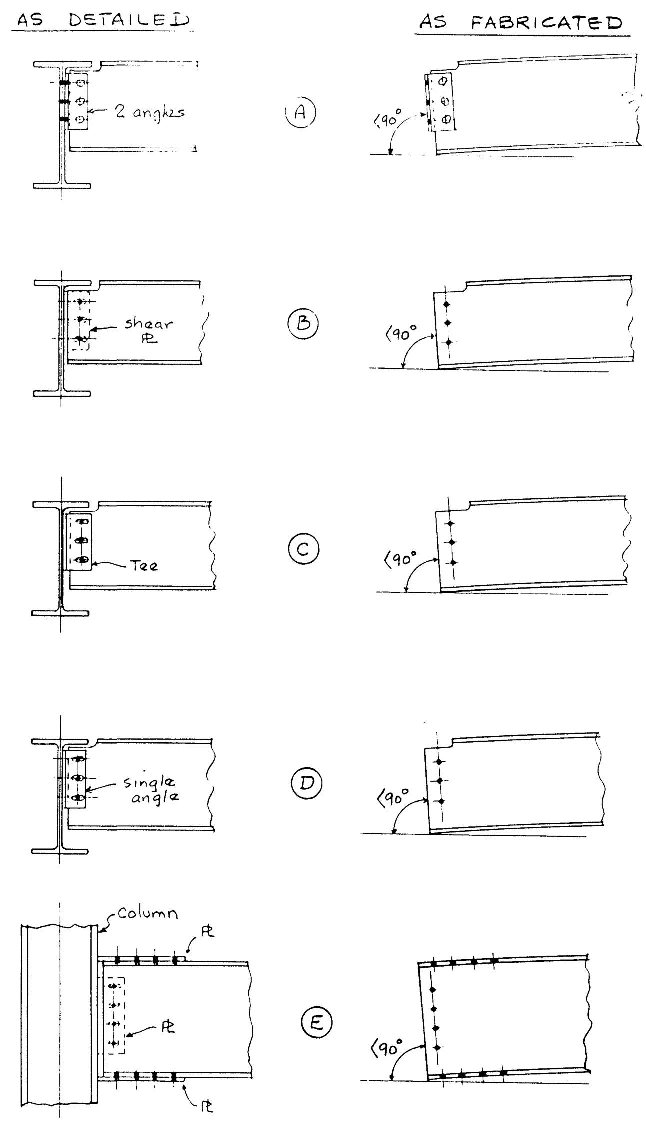

Figure 10

deflected supporting beam, or with the top of the slab horizontal resulting in a non-uniform slab thickness. Specifications now permit the top of the studs to be within ½ in. of the slab surface. If a horizontal slab surface is constructed, an over-cambered beam may arch so much as to result in a thinner-than-desired floor slab with a row of stud heads protruding like a dinosaur's spine.

b. Don't cold camber beams to which a cover plate will subsequently be welded. The heat thus generated at one flange will generally be enough to significantly alter the camber curve.

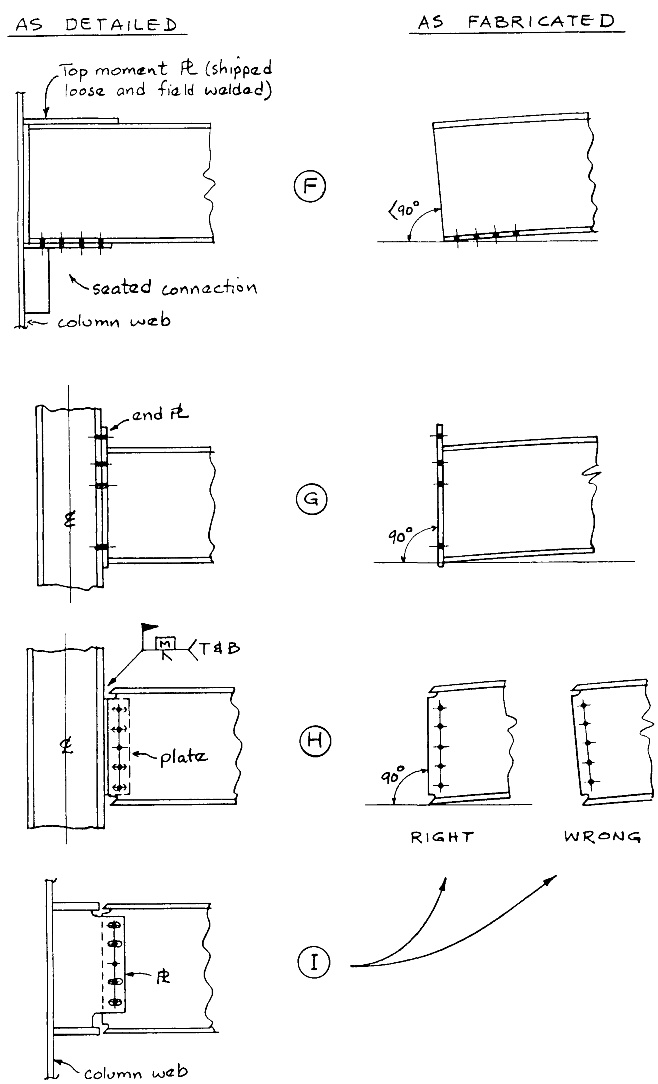

Figure 11

c. When cold cambering by force, make sure that there is sufficient length of bearing at the load points in order to prevent local flange and web buckling. The fulcrums must be free to rotate so as to conform to the camber curve.

d. When heat cambering, do not overheat the steel.

e. Do not force-cool heated members with water or air spray if their temperature is over 700°F.[6]

f. Columns comprised of section sizes normally associated with beams should, when ordered from the mill, be noted "no camber permitted." Otherwise, the mill may provide the members with a small amount of "natural" mill camber.

g. Heat cambering should be performed only on low carbon steels. Application of heat to medium and high carbon steels increases the danger of embrittlement. A36, A572 Gr. 50, A588, A441, and A242 are popular low carbon steels.

h. When using the heat-cambering method, it is not necessary to reheat previously heated areas when following the serpentine path. Allow the steel to cool naturally behind the torch.

i. Cold cambering of certain beam section sizes by certain mills is restricted. The user is advised to consult the mills for their recommendations.

REFERENCES

1. American Institute of Steel Construction, *Manual of Steel Construction,* 8th ed., Chicago: AISC, 1980.
2. Blodgett, Omer, "Distortion. . . ," *Welding Innovation Quarterly,* Spring 1985, p. 4. Cleveland, Ohio: The James F. Lincoln Arc Welding Foundation.
3. Van Den Brock, J. A., *Theory of Limit Design.* New York: John Wiley & Sons, 1948.
4. Brockenbrough, Roger L., *Fabrication Aids for Girders Curved with V-Heats.* U.S. Steel Corp. ADUSS 88-5539-02, 1973.
5. Brockenbrough, Roger L., *Fabrication Aids for Continuously Heat-Curved Girders.* U.S. Steel Corp. ADUSS 88-5538-01, 1972.
6. Welding Research Council, *Control of Steel Construction to Avoid Brittle Failure.* Edited by M. E. Shank, 1957.
7. Cary, Howard B., *Modern Welding Technology,* Englewood Cliffs, N.J.: Prentice-Hall, 1979.
8. Linnert, George E., *Welding Metallurgy,* Vol. II, American Welding Society, 1967.
9. Cambco, P.O. Box 35902, Houston, Texas 77235.
10. Roeder, Charles W. and Stephen P. Schneider, "Heat Curving of Structural Steel," *Proceedings of National Steel Construction Conference* (sponsored by AISC), 1988.