The Right Way to Camber a Beam

BY REIDAR BJORHOVDE

Knowing when to drill holes in cambered members is key to reducing the likelihood of cracking.

HORIZONTALLY AND VERTICALLY CURVED MEMBERS HAVE become a popular choice for building and bridge construction. There are two main reasons: architectural expression and, perhaps more commonly, because of how they carry and distribute loads in the structure. The action of an arch makes it possible to cover significant spans, since the load is carried largely in compression instead of through bending action. For certain arch geometries, support conditions, and load distributions, the effects of the imposed loads translate into uniform compression within the entire arch.

In addition to complete structures such as arches, individual curved structural members are also used. Common to most building applications is the fact that the curving of such members is very often done at ambient (room) temperature.

Possibly the most common curved member is a beam that has been cambered to satisfy certain deflection limitations, to ensure that the beam is near level when the structure is placed in service. Cambering criteria vary but are most often expressed as a certain fraction of the anticipated dead load deflection. The principles are self-explanatory; the actual implementation of cambering varies a great deal from structure to structure, from designer to designer, and from fabricator to fabricator.

How to Bend for Cambering

Straightening, cambering, and curving of structural shapes are all representative of bending that involves local yielding of the steel to varying degrees. Although the principles and basic mechanics of these processes are the same, they are used for significantly different purposes and with very different magnitudes of the bending deformations and the strains that develop in the cross-section.

A certain amount of plastic deformation must take place in the cross-section during the process in order for the curving operation to work. Elastic bending and stress analysis cannot be used, since any deformations taking place under such conditions will revert to zero once the applied force or moment is removed.

Straightening

ASTM Standard Specification A6/A6M gives detailed requirements for bars, plates, shapes, and sheet piling used in construction (ASTM, 2008). Among these, it provides the permitted variations for straightness for rolled shapes. For example, the maximum out-of-straightness, *e*, for wide-flange shapes with a flange width larger than or equal to 6 in. is determined as

$$e = \tfrac{1}{8}\, x\ [(\text{number of feet of total length})/10]$$

with the value of *e* in inches. This translates into approximately $\tfrac{1}{1{,}000}$ of the length of the shape. The requirement is the same for camber and sweep, which are the ASTM terms for out-of-straightness measured relative to the strong and weak axes, respectively.

Out-of-straightness is measured by the steel mill during the production of the shapes, and straightening is applied to make any non-conforming element meet the ASTM A6 requirements. Depending on the size of the shape, the straightening is either done in continuous fashion, or if the shape is heavy, it is done through point application of loads. The former procedure is referred to as roller or rotary straightening; the latter is known as gag straightening.

In rotary straightening the local yielding takes place continuously along the length of the shape. Gag straightening causes local yielding in the shape only in short segments along the length of the member, surrounding each of the load application points. Common to both of these methods is the fact that the amount of curving and the accompanying strain demands within the cross section are very small, and the radius of curvature of the bent member is very large.

Straightening of shapes to meet delivery standards is used by all of the world's steel mills. The methods and results are the same, and the equipment that is used operates on the same principles and applications.

In view of the discussion of cambering that follows, however, it is essential to bear in mind that the shapes that are mill-straightened have no holes or attachments of any kind. The shapes are straightened as they come off the cooling bed in the steel mill.

Cambering

For a structural engineer, cambering a beam means to pre-bend the member in the direction opposite to the deflection that will be developed by the anticipated gravity loads. The aim is to have a structural component that is horizontal or nearly so following the application of the most closely known load component. Since the dead load is generally known more accurately than the live load, for example, cambering is almost always done to an extent that equals a fraction or even all of the dead load deflection.

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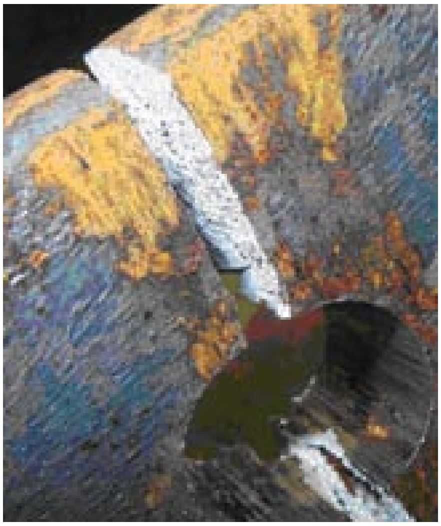

A close-up of a camber crack through a W-shape flange with a punched bolt hole.

Structural cambering can be accomplished through selective heating of areas of the shape, or, as is most common, through gag pressing at ambient temperature of the member while it is installed in a cambering frame. Cold cambering does involve yielding of small areas of the cross section, similar to gag straightening. The accompanying deformation demands for the steel in the shape are very small, and the force necessary to develop the camber curve tends to be fairly small.

While the deformation and force demands associated with cambering are small, it is important to bear in mind the modifications of the cross-sectional area that will occur as a result of punching or drilling of bolt holes and similar fabrication operations. Some fabricating shops are set up for holes to be made at the beginning of the various operations, running the shape through the beam line with preprogrammed hole sizes and locations. The cambering is then done at a later stage.

The cross-sectional area changes associated with punching or drilling can create a preferred plane for yielding, with the potential for localized failure during the cold cambering process. Further, procedures such as punching have a tendency to leave the inside and the lower edge of the hole fairly rough. Micro-cracks may develop inside or at the edge of the holes, with significant potential for crack propagation and overall failure of the shape during the cambering operation. While sub-punching and reaming the holes and/or grinding the hole edges may help, it will not prevent cracking in many cases. This is particularly important for the holes that are located at or near center span of the beam. Small cracks may even appear near drilled holes that were made before cambering.

Cracking during cambering has been observed on a number of occasions in beams that met all ASTM and structural design requirements. As a result of the potential for cracking, it is strongly recommended that holes and similar features near the location of the maximum cambering deformation should be made after the cambering is completed.

A full-flange transverse crack of a W21×93 taking place during cambering.

Material Properties

When the steel has been deformed to produce local yielding, it has undergone permanent deformations that are not removed upon unloading of the material. Upon reloading, the steel response appears to indicate a material with a yield stress and elongation properties as defined by the "new" stress-strain curve. If there is only a small or even no yield plateau, which is typical of higher strength materials, the reloading response appears to be for steel with a yield stress that is larger and an elongation at rupture that is smaller than the corresponding properties of the virgin material. If the steel has been strained into the strain hardening range, the change in the apparent mechanical properties can be substantial.

This behavior must be considered when planning the curving operations for structural shapes. Specifically, a part of the cross section must be deformed plastically in order for the curving to work. The extreme fibers in the cross section will be strained well beyond the level of the initial yield of the steel. If there are stress concentrations such as holes in the flange(s) of the beam, the magnitude of the strain that is imposed by the cambering operation may reach the fracture level at the edges of the holes, with subsequent propagation in the cross section.

Delaying Drilling

It is the fabricator's responsibility to prevent cracking during cambering, and they should make every possible effort to do so, including delaying drilling. In many cases, in order for a beam to be properly cambered, it is essential to delay some of the hole punching, drilling, and similar operations until after the bending is done. This will ensure that cracks will not be initiated at the locations of the holes. Specifically, it is recommended that holes at the center of the span should be drilled after the cambering has been completed. (Note that the scheduling of punching/drilling is a fabricator issue and not something that engineers need to add to their specifications or inspection requirements.)

When the beam has been cambered successfully, with no buckling or localized cracking in the steel, the member will experience strains under actual service conditions that are much smaller than those that are associated with the bending operation. MSC

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