# TOLERATING TOLERANCES

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Communication between structural engineers and contractors about what's achievable, what can be expected, and how to get results consistent with a structure's design can prevent problems with required construction tolerances.

An architect designs a building with the expectation that all the floors will be level and that all the walls will be plumb. Tolerances of construction play an important role in producing a quality product that can help meet those expectations.

The establishment of required tolerances can become complex, and may be especially critical in the exterior walls of multi-story structures where the cladding must be attached to a structural frame. Significant deviations of the verticality of that frame, if not accounted for in proper positioning of the frame and adjustments of the connections, may be reflected in the building's finished appearance. If a floor is significantly out of level, this reflects badly on the quality of the constructed product. However, floor levelness is too often attributed to lack of construction tolerance control, while instead it is mainly influenced by the design methodology employed (see box).

The structural engineer, when designing the framing system, must be cognizant of what is achievable, what can be expected, and how to get results consistent with the design intent. The ultimate questions that need to be answered by quantification are how straight is straight, how level is level, and how plumb is plumb? This is where tolerances come into play, but tolerance is not the whole story. Usually, it is only a part of the puzzle.

Tolerances in structural steel construction are stipulated in the AISC *Code of Standard Practice for Steel Buildings and Bridges* (COSP). The current March 7, 2000 issue of this document is available as a free download from the AISC web site at **www.aisc.org**.

The tolerances for steel construction can be divided into three general areas:

- Mill Tolerances
- Fabrication Tolerances
- Field Tolerances

## Mill Tolerances

Mill tolerances for structural steel sections are given in ASTM A6, *Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling*. ASTM A6 is incorporated as part of the COSP by reference. ASTM A6 stipulates the limiting tolerances for items such as material properties, dimensions, and weight of the member as produced by the mill. Permissible sweep and camber of steel members are also included in ASTM A6. Camber of a W-shape is the deviation of the member from straight as measured in the plane of the web. Sweep of the W-shape is considered in the opposite direction, the deviation being measured perpendicular to the plane of the web. ASTM A6 generally limits the permitted variation in straightness for a W-shape used as beam to 1/8" × (number of feet of total length/10) for both camber and sweep. Thus for a 30'-long beam, the general permissible variation from straightness would be 3/8". There are exceptions for shapes used as columns and for sweep in beams with a narrow flange. See ASTM A6 for more comprehensive information on mill tolerances of steel shapes.

On some occasions mill material is shipped to a service center where preliminary finishing processes may be performed prior to shipping to a fabricating facility. In other cases the mill product is shipped directly to the fabricating plant.

## Fabrication Tolerances

Fabrication tolerances are covered in Section 6.4 of the COSP. When the plain material sections arrive at the fabricating plant, members are cut to length, finished, and fabricated. Various tolerances are stipulated on the fabricated dimensions of the pieces to facilitate the erection fit-up and positioning of the members.

For beams and trusses that are detailed without specified camber, the member is fabricated so that after erection, any incidental camber due to rolling or shop fabrication is upward. When beams are specified in the contract documents to require a camber and the beam is received by the fabricator with 75% of the specified camber, then no further cambering is required.

Otherwise, there is an allowable variation in the specified camber that always includes a minus 0″ tolerance with a plus variation depending on the length of the member. The plus tolerance is ½″ for beams fewer than 50′ in length. See the COSP for additional information on fabrication tolerances.

An important thing to remember is that specified camber is the instruction that is given to the fabricator and, according to COSP requirements, is always to be measured in the shop in the unstressed (lay-down) position. It is commonly a misunderstood principle on the part of the designer to expect the specified camber to be in the field erected position, sometimes even in the fully loaded state. There are numerous factors that will affect the final curvature of the member in place that are a function of the design process and beyond the control of the fabricator.

Camber should not be confused with curvature or elevation positioning of the erected member in the field. Specified camber is actually a tool used in the design process in attempt to position a member at a certain location and at a certain point in time. The extent of the role that camber plays in achieving that desired position is fundamentally a function of the design process and needs to be determined by the project design professionals.

### Field Tolerances

Field tolerances can be divided into two basic areas:

**Site preparation** is generally the responsibility of the owner's designated representative for construction (GC). This involves the accurate positioning of foundations, piers, and abutments; the accurate location of building lines and benchmarks; and the installation of anchor rods, foundation bolts, and other embedded items. The steel erector must have the correct starting point, or everything is "out of tolerance" at the beginning. The junction of anchor rods and base plates is where the trades meet.

AISC has historically recommended extra-oversize holes in base plates for many decades in an attempt to accommodate dislocation possibilities of anchor rods. The oversize recommendations were recently increased to avoid a higher percentage of these common dislocation problems. However, there are realistic limits as to what plate hole sizes can be provided in bases and what dislocation settings can be accommodated. Section 7.5 of the COSP stipulates dimensional tolerances to which anchor rods and other embedded items are required to be placed. These tolerances provide consistency with the base plate hole sizes recommended by AISC.

"Structural Steel Frame Tolerances" in Section 7.12 contains a single statement that "The accumulation of mill tolerances and fabrication tolerances shall not cause the erection tolerances to be exceeded." The commentary for this section states "that accumulations of mill tolerances and fabrication tolerances generally occur between the locations at which erection tolerances are applied, and not at the same locations."

Consider the surface elevation of a floor beam in the middle of a bay between columns. The camber of the horizontal beam should have been measured in the shop to be within permissible tolerance, either by ASTM A6 or of a project-specified camber. When this beam reaches the field it may or may not have the same camber as when it left the shop. When the beam is erected into place it will deflect under self-weight, reducing any upward camber that may have been present. The members to which the beam is connected may be other carrying beams that in turn deflect as the member weight is added. When decking and concrete are applied, the members will deflect even more. Therefore, the camber of the horizontal framing members in the erected position may have little relation

## Floor Flatness? Level With Me!

Floor Flatness (FF) and Floor Levelness (FL) are terms used in many project specifications and given quantifying values as a level of performance that the contractor is expected to meet. This system of measurement is described in ASTM Standard E1155.

There are often misconceptions about the meaning of the FF and FL terms and about what the system is intended to do. Many design and construction professionals relate this system to a measurement of the expected final floor elevation. In actuality, the FF/FL system is a measure of the resulting floor finish in terms of the required flatness and levelness produced by the concrete setting and finishing processes. **It is not intended to be a measure of the structural performance of the floor system.** The measurements are to be taken at the completion of the concrete finishing operations, with shoring still in place.

The FF/FL system of evaluation is not appropriate for framed floors that can deflect as the weight of the concrete is applied. The measurement system is applied to evaluate the slab finishing techniques in some cases of metal deck and concrete fill systems. However, when this is done, a non-uniform slab thickness must be assumed in the design to account for the deflected shape of the structural system, and the placement of the concrete must be coordinated to achieve a level floor. The measurement system can be, and often is, used in framed floors that are rigidly shored during construction as a measure of the floor finishing techniques. However after the shores are removed and the framing system deflects, the previous FF/FL measurements become irrelevant in terms of the floor elevation. Therefore, don't expect that specifying stringent FF/FL requirements will assure a level framed floor in the final structure.

Once the myth of the FF and FL expectation is dispelled, the design team can get down to the job of assessing the tolerance requirements for the structural steel portion of the building system. As previously stated, the AISC COSP is a standard widely used in the steel construction industry as a method of judging the acceptability of structural steel framework. This document is often incorporated in project specifications as part of the contract documents issued by the project design professional.

If the design professional requires tolerances other than those stated in the COSP, this information is to be stipulated in the contract documents. However, it is unrealistic to expect the contractor to achieve unrealistic goals by stipulating requirements that are out of the realm of their control. Specifying that floors be level or in a certain position in the completed structure are generally unrealistic goals to place on the contractor. Much of the prerequisite to achieving the ultimate goal is a function of the design process, a function that is beyond the control of the builder. ★

to the camber that was originally present in the members. Also, the beam midspan location where the camber had been measured is not at the location where elevation erection tolerances are applied for the frame, which is primarily at the column work points.

**Erection tolerances** are covered in Section 7.13 of the COSP. As stated in the section commentary, "The erection tolerances defined in this Section have been developed through long-standing usage as practical criteria for erection of structural steel." Additional information is given in this commentary on the historical development of the criteria and discussion of aspects concerning some of the various common erection conditions that may require consideration.

Permissible angular variation of column work lines are given with respect to a plumb line which is generally 1/500 of the distance between working points. Additional limitations are stipulated for columns adjacent to elevator shafts and for exterior building columns. Members other than column shipping pieces, that are straight shipping pieces without field splices, will generally be considered acceptable if the variation of alignment is caused solely by variations in column alignment and/or primary supporting member alignment.

There are additional limitations of members connected to columns, cantilever members, members containing field splices, members that consist of irregular shape, and for members that are identified as adjustable items. See COSP Section 7.13 for further information on erection tolerances.

## Avoiding Tolerance Troubles

The best way to avoid problems is to anticipate where they will occur and adjust accordingly. An invaluable resource is to look at what problems have occurred in the past (hopefully not on your project) and find ways to avoid the same problem in the future. This may not always be possible if you are working with an unusual structure that is "breaking new ground" in terms of technology. However, for the steel-framed project that utilizes usual and common procedures of design, detailing, and erection, the COSP is a document developed to solve past common points of problem, dispute, or controversy.

As with any type of construction, there are likely some areas of tolerance control that are more troublesome than others. For insight into what steel fabricators and erectors see as the more common areas of contention regarding the COSP tolerance requirements in the industry today, AISC's Steel Solutions Center chatted with a Midwestern steel contractor, who asked to remain anonymous, for his thoughts on the subject.

### *Is there any specific problem of erection involving construction or fabrication tolerances that seems to occur most frequently?*

Misplacement of anchor rods is probably the most frequently encountered problem. However, the interviewed steel contractor feels that the COSP is quite clear in the definitions of responsibility and that the document is usually quite helpful in establishing dialog to get the discrepancies resolved in a timely manner.

Another frequently encountered problem that was mentioned has to do with the sweep of edge beams and resulting control of edge slab locations. Much of the problem may stem from the connection details of the wall attachments and lack of adjustment control.

### *Is there any specific problem of erection involving construction or fabrication tolerances that seems to be the most difficult to remedy?*

Again, "anchor rods" is the first response. Dislocations, bent rods, and short rods are all sources of frustration. While the steel contractor feels the responsibility for remedial action is clear, possible delay is also a consideration. A clear understanding of the responsibilities and action required of each party is a positive advantage when it comes to getting a timely resolution.

### *Over the past decade, have you noticed an increase, decrease, or little change in terms of ability to control tolerances and to avoid problems associated with tolerance?*

There does not seem to be a feeling that setting of anchor rods has gotten any better, despite the modern instrumentation tools. Even when set accurately, bending of anchors due to construction activities is often a problem.

### *Are there areas of the tolerance issue in the AISC* Code of Standard Practice *that, in your experience, cause confusion?*

There does not seem to be a lot of confusion on the part of the steel contractor concerning the contents of the COSP, probably because they are dealing with these issues on an almost daily basis. However, it is felt that many design professionals are obviously not as aware of the intricacies of the document, and thus often will not follow identified procedures that could help to make a smoother-running project for all involved. While some of these procedures and stipulations involve tolerance issues, such as properly specifying beam camber and recognizing the limits involved, other issues may involve more general communications on the project. A few of the examples mentioned are the requirements to show complete information on the bid documents clearly showing the work to be performed, methods to "bubble" and identify changes, and recognizing that changes made on the shop drawings during the approval process are an "authorization to proceed."

### *Are there commonly occurring tolerance issues that are not covered in the AISC* Code of Standard Practice*?*

One common problem area not covered by the COSP has to do with galvanized steel and the effect on the tolerance of fabricated members. The COSP primarily defines the responsibilities and relationships between the owner, owner's representative for design (A/E), owner's representative for construction (GC), and the prime steel contractor. The COSP does not define the relationships or responsibilities between the steel contractor and any sub-contractor. Steel members that are within acceptable tolerance limitations when sent to a galvanizer often do not meet the acceptance criteria after the galvanization process. The problem then arises as to whether the members have to be reworked to be brought back within normal tolerances and, if so, who is responsible. Some steel contractors recognize the problem and are adding language in bid proposals to address the issue.

The contractor's advice is that effective communication is the key to achieving harmony on the project, so that everyone can come out a winner. ★

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