CONSIDERATIONS FOR STEEL FRAMED FLOORS

SEAC/ RMSCA Steel Liaison Committee

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STATEMENT OF INTENT

Over the last 20 years many changes have occurred in the steel construction industry. Years ago, the steel mills provided most of the cambering while today the Fabricator typically does the cambering in his shop. In the past, the Fabricator had to straighten the steel before fabrication to remove mill sweep. Today mills have eliminated the need for the straightening process.

Material costs are increasing in relation to labor costs, and that relationship usually is a moving target. Structural steel weight savings are common these days due to the widespread availability 50 ksi material (in lieu of 36 ksi) as well as weight savings realized from the newer LRFD design methodology (as opposed to ASD design). However, weight savings in the steel frame does not always reflect a cost savings to the steel frame or the project.

In light of the changing industry, it is the intent of this paper to discuss design and construction issues that are typically expressed today by Owners, Architects, Structural Engineers (EOR), General Contractors, Fabricators, Detailers and Erectors. If these issues are sufficiently addressed by the design / construction team, then a successful steel framed floor system can be realized by the project.

Each participant on the design / construction team has responsibilities that affect cost, schedule, quality and constructability. Often, the participants carry unique perspectives that may not be obvious to other members of the team. If the issues are addressed and coordinated early with the team, an economical and successful steel framed floor can be constructed.

This paper was prepared by the SEAC/ RMSCA Steel Liaison Committee, a coalition of Front Range Fabricators, Detailers, Erectors, General Contractors and Structural Engineers dedicated to improving the steel construction industry.

The following are considerations that can influence the success of a steel framed floor.

A. DESIGN CONSIDERATIONS

Steel framing is an economical system commonly used for supporting floors. The floor framing is part of the complete building system. As such, the design of the floor framing needs to be integrated into the overall architectural design of the building. In order to have a successful design, the EOR needs to achieve the following goals:

1. Conformance with the governing code for minimum live load, maximum live load deflection limits and fire rating requirements. These are requirements based on the building use and are not negotiable.
2. Serviceability including deflection, vibration limitations, acoustic separation, floor flatness/ levelness and load capacity in addition to the code required minimum.
3. Constructability with considerations such as steel erection, deck erection, conduit routing, curtain wall erection, placing a flat floor, and achieving a concrete surface that can accept floor finishes.
4. Economy. The desire is to achieve the three previous goals at the least reasonable cost.

These goals are not mutually exclusive. However, designing a steel framed floor that meets the requirements for serviceability and constructability may increase the cost of the framing beyond that required for the minimum building code requirements. Another consideration during the design process is the selection of the amount of camber in a floor beam and floor system. Therefore, the EOR, Architect, and Owner need to make a series of timely informed choices as part of the design process.

B. FRAMING LAYOUT AND GEOMETRY

Typically, the column locations and bay spacings are determined by the Architect with input from the EOR. Numerous parametric studies have shown that bay sizes in the range of approximately 30 feet square provide an economical framing system. Studies have shown that floor systems with rectangular bays are more economically framed with longer beams and shorter girders, with a plan ratio in the range of 1.25 to 1.50.

Another important decision is the selection of the column size and orientation. Normally, a column is oriented so that the girders connect into the column flanges.

C. COMPONENT SELECTION

After the column spacings, loads and fire rating requirements have been determined, the next step is to select the slab and deck system. Usually the minimum slab thickness is selected based on the fire rating requirements for the project.

If fire rating is not a requirement, then a minimum slab thickness on top of the deck flutes of 2 ½” is suggested, although vibration considerations may dictate a thicker slab. Many design offices use a minimum slab thickness of 3” to 3 ½”, which helps provide the floor system stiffness needed for serviceability and allows for some routing of electrical conduits.

The selection of the deck type, depth and gage determines the spacing and layout of the beams. Comparative material costs for different deck types can be seen in Table 1, where the cost comparison sets the 0.6C form deck or 1.5VL wide rib deck at unity. All percentages are relative to this deck type. Typically selecting the lightest deck is not recommended. Selecting the deck that has the greatest spanning capacity consistent with the given bay sizes and framing depth limitations will result in a design with the minimum number of beams. Typically, this configuration will reduce beam fabrication and erection costs and improve vibration performance. It is recommended that the greatest beam spacing be limited to the maximum available deck length available for a three span condition while the deck selection should be based upon a two span condition. Due to safety concerns during erection, the beam spacing should not exceed the maximum deck sheet length covering three spans. There may be some single deck span conditions due to floor openings for stairs, elevators, mechanical shafts, atriums, etc…

Some shoring may be required in these areas if the deck selection exceeds the single span section of the ‘SDI Maximum Un-shored Clear Span’ portion of the steel deck tables.

The beams in the floor system can consist of either; non-composite or composite steel joists, non-composite beams (cambered or un-cambered), or composite beams (cambered or un-cambered). The composite beams may either be shored or un-shored. Shored construction is generally considered to be uneconomical and is not recommended. However, framing around large floor openings such as elevators may warrant shoring due to the accumulated deflections that can occur in column-free framing. Also, surveys during construction may determine that shoring may be necessary if beams have less camber than specified. Shored systems are not considered in the following discussion.

Headed Anchor Studs (HAS) for composite members should be limited to ¾” diameter with one length throughout the project. Normally the most economical use of HAS is in partially composite construction. Overuse of the HAS, such as arbitrarily specifying a layout of 12” on center, will increase construction costs for the Erector and the Fabricator. Normally, short secondary beams do not need to be designed as composite, nor should HAS be added for the sake of having studs on all beams.

D. CAMBERING

Since all beams deflect under the weight of wet concrete, cambering provides an effective means of limiting the unwanted increase in thickness of the concrete slab. The question of whether or not to camber and how much to camber often involves a number of considerations. There are typically three choices that the EOR can make:

1. Select the lightest beam that meets the code requirements and camber to counteract the dead load deflection. This approach may result in an excessively cambered beam that is relatively shallow, and the selected beam may not meet the serviceability (deflection & vibration) requirements for the project. These beams also tend to have a lot of HAS required. In addition, fabrication, detailing, and erection considerations would need to be addressed.
2. A second approach would be to design the structure stiff enough that camber is not required. The down side to this choice is that the selected beams tend to be deeper and heavier.
3. The third choice would be to choose a partially composite design approach resulting in a reasonable amount of camber and HAS with beam weights that are in between choices 1 & 2.

Cambering in the fabrication shop is more of an art than a science. The process is accomplished by either laying the beam on its side and cold-bending the beam in the hard direction until it yields or by positioning the beam in a vertical position and heating and shrinking the beam to the required camber. The heating process is not used frequently because it is much more expensive than the cold-bending process. The cold-bending process is usually accomplished with hydraulic rams pushing the beam into position.

AISC allows the tolerance of the cambered beam to be minus 0 inches and plus 1/2 inch. Cold-bending camber results in significant residual stresses in the cambered beam. It is therefore possible to lose some of the camber after the initial shop cambering process although this rarely happens. The loss of camber can be caused by the residual stress state, combined with forces imposed due to handling, stacking and transporting prior to erection. AISC addresses quality control of camber verification indicating it should only be checked in the shop with the beam laid on its side. Actual in-place camber could vary from the shop measurements. See the AISC COSP, Section 6.4.4 for further information. It is the opinion of the committee that less than 5% of the beams on a project can have significant camber loss.

The intent of this section of the paper is not to provide limits and requirements for cambering, but rather to give general guidelines that have produced successful projects. There are excellent resources available with more in-depth discussions of these topics, including the following articles from Modern Steel Construction: "Specifying Camber," July 2006; "Tolerating Tolerances," June 2005; and "Elevated Slab Tolerances," August 2007; as well as "Cambering of Steel Beams", Lawrence A. Kloiber, Steel Structures Proceedings Steel Congress '89, ASCE/San Francisco, CA May 1-5, 1989.

Both absolute limits and relative guidelines should be considered for determining the camber. In absolute terms, camber should generally be in the range of 3/4" to 1 1/2". In relative terms, the camber in any beam should not exceed approximately L/360.

AISC camber tolerances require the camber to be equal to or greater than that specified. However, end restraint of the beam end connections may result in less deflection than calculated. Therefore, engineers should consider specifying camber that is less than the calculated non-composite dead load deflection. Standard engineering practice varies on the percent of non-composite dead load deflection to use for camber, ranging from 60% to 100%. Once the target camber has been selected, it is recommended that the EOR increase the size of the beam to satisfy the selected camber limit. In a partially composite system, the cost of the increased beam size can generally be offset by reducing the number of HAS required.

Members that should not be cambered include beams with bracing or moment connections, edge beams, jumper beams (short beams framing openings), and beams with cantilevers. Beams in moment frames and braced bays may have fit up problems if cambered. Cambered spandrel beams supporting curtain wall systems can present problems in the curtain wall connections. It is recommended that stiffer, un-cambered spandrel beams be designed so that minimal deflection will occur as the curtain wall is constructed. Consideration could also be given to not cambering girders since they usually do not deflect as much as the filler beams.

Local Fabricators have found the following practices will produce the most predictable and cost-effective results:

- Specify camber in ¼ inch intervals.
- Specify camber in the range of ¾ inch to 1½ inches.
- Only camber beams 14 inches and greater in depth.
- Column sections can be cambered when used as beams.
- Camber beams with web and flange thicknesses ¼ inch and greater.
- Camber beams with a length of at least 24 feet.
- Do not camber cantilevered beams.
- Special considerations are required when cambering beams over 40 feet in length. Multiple pushes are required and it is difficult to achieve consistent results.

A suggestion offered by the committee would to be to consider cambering only compact sections as defined by AISC.

When cambering beams greater than 1 ½", consideration must be given to end rotation and web and flange crippling during the cambering process. Since most beam lines punch the holes for bolted connections before the cambering operation, large cambers will cause excessive rotations at the beam ends and consequent fit-up problems for bolted connections in the field. We recommend contacting a local Fabricator to verify what is practical in your area.

Non-composite steel joists, as opposed to steel beams, are manufactured with a standard camber based upon the length. Composite steel joists are cambered specifically to compensate for the non-composite construction loading. Contact a local joist supplier for more information.

E. CONNECTIONS

The overall success of a steel frame building project will require the Detailer to understand the intent of the Design Team, the Fabricator, the Erector, and the General Contractor by presenting the requirements in the shop and erection drawings. The connections may be designed by either the EOR or an engineer engaged by the Detailer or Fabricator. Considerations are:

1. The strength of the connections
2. The Fabricator's shop standards with regard to bolting, welding, coping, etc, and
3. The Erector's concern for maintaining safety during the erection sequence and his preferences for erectability issues.

In order for these considerations to be handled in a timely manner, it is essential that the Detailer be brought onboard as early as possible starting with a "Pre-Detailing Meeting." A guideline for this meeting titled "*Pre-detailing Meeting Agenda"* has been prepared by this committee and provides an excellent resource for preparation of the detailing process.

In addition, listed below are a few specific considerations for steel framed floor systems that will allow for a better finished product:

1. Take advantage of the connection tables for LRFD and ASD designs under *Part 10* in the *AISC 13th Edition Steel Construction Manual*. The calculations for standard connections have been updated and often allow for greater capacities.
2. Limit the bolts used on a project to one size, or if multiple sizes are necessary use bolt sizes separated by at least ¼" (the ¼" difference will help eliminate errors in fabrication and erection). Also avoid using both A325 and A490 bolts of the same diameter on the same project.
3. Permit the use of horizontal short slots for steel-to-steel shear connections. Normally the slots would be placed in the connecting material, not the connecting member, since beam lines normally only punch round holes. The short slots will allow for some construction tolerance and the bolt-up of cambered beams.
4. Avoid using slots at beam to column connections as a general rule, to avoid the field labor cost of spacing columns in every bay of the structure.

F. ELEVATION CONTROL

The structural design is based on camber in place while the COSP requires camber to be checked in the shop. Thus we have a conflict between work in the shop and what is required in the field. It is important to recognize that the cambering method as defined by the AISC COSP has worked successfully for many years and should be used as a standard for measuring camber. Should the project require large cambers and /or light beams, cambering measurements may be necessary to be done in the field as discussed later. The measurement of camber in the field goes beyond the AISC COSP (which are the rules by which the Fabricator plays) and will add cost to the project. The AISC COSP is a legal document and going out side of it puts all parties at risk. There is also the practical matter of who is responsible if the measurements do not meet the required camber specified in the documents.

One of the floor design goals is to meet the flatness requirements for the project. The method most commonly used is ASTM E1155, measuring Floor Flatness F_f. Floor Levelness, F_l, is normally only measured for slab-on-grade and is not recommended for elevated floors since deflection occurs as the floors are loaded with the non-composite weight of the concrete. F_l can be measured if a laser is used as the concrete is being placed (and the structure deflects) or if the structure is shored during concrete placement. It should be noted that the camber of the floor beams and the in-place erection tolerances of the steel frame do not directly determine the top of concrete location for a floor. The erected position of the steel framing, including the in-place camber provides a starting point for the concrete contractor to use in meeting the project flatness requirements. Floor flatness is a measurement of finishing tolerances, not a measure of slab performance, and is typically measured 24 to 48 hours after the concrete placement. The slab performance will depend on other factors, such as stiffness and deflection of the floor system under superimposed dead and live loads.

Typically the only elevations that the Erector has direct control of are the elevations of the first tier steel columns and the elevation of steel beams that connect directly to concrete in some manner. Column elevations are usually established by the setting of shims or leveling nuts under the column base plates. This is a critical beginning point to achieve a reasonably level floor slab. Beyond this, the Erector is largely dependent on the accuracy of the fabricated structural steel, including cambered beams, to establish proper elevations for concrete slab support.

The AISC COSP, Section 6.4.4 and Commentary states “For the purpose of inspection, camber shall be measured in the Fabricator’s shop in the unstressed condition.” And, due to variables out of the Fabricator’s control, “Therefore, inspection of the Fabricator’s work on beam camber must be done in the fabrication shop in the unstressed condition.” Therefore, the following discussion is outside of the Fabricator’s responsibility. Fabricators believe that if accuracy of cambering is a concern, then the Owner should have beam camber checked in the fabrication shop as prescribed by AISC.

However, the desire by the EOR, Architect, General Contractor and Owner is to know the camber of the erected steel. This knowledge will help predict the success of attaining the floor flatness. Some engineering firms specify that all of the steel framing elevations be surveyed and documented prior to and after placement of the concrete. Although these extensive elevation/camber surveys help in determining causes of problems, the Owner may not realize an adequate benefit to justify the cost of the survey, reporting and review by the EOR. The primary purposes of the survey are to obtain flatness without remedial work, to ensure that the minimum slab thickness has been met for the required U.L. rating, and to avoid an excessive slab thickness that could overload the structure. This can be accomplished by checking beam camber and elevations before and after concrete placement. In lieu of an extensive and costly survey, the following could be a more cost-effective solution: Require a specified percentage of random field checking of camber as the beams are unloaded off the trucks, placing emphasis on immediate verification of the first several cambered beams delivered to the project. Once the frame is erected, check a specified percentage of beams prior to erection of the steel deck. If problems are found, the construction team could decide on an appropriate course of action. Then after the slab is placed, the same beams should be checked again, for the amount of deflection that occurred during the concrete placement, to confirm the estimated deflection. This information will provide feedback to the design and construction team so that adjustments can be considered, if needed. The goal would be to confirm if the camber control system is working, rather than documenting the camber of every erected beam.

Since the remedial action necessary to correct an out-of tolerance slab on steel deck to accept floor finishes can often exceed the cost of the survey, this limited survey makes economic sense. The assignment of responsibility and scope for the survey must be clearly specified in the Design Documents, preferably in Section 3, Execution/ Field Testing in the specifications to prevent this task from being assigned to the Erector without fair compensation. It is suggested that the Owner be responsible for the cost of the survey which would be performed under the direction of the Testing Agency and that the General Contractor provide the equipment and labor.

G. CONCRETE PLACEMENT METHODS AND SEQUENCING

The required slab thickness, levelness requirements and tolerances should be clearly defined in the Contract Documents. The requirements or expectations for slab performance should be discussed by the team, including the Owner, prior to or during design. The resulting design assumptions should be clearly stated on the drawings.

There are two placement methods for establishing the top of concrete elevation:

1. "Level" top of concrete - The "level" top of concrete placement method will result in a varying slab thickness, thus requiring more concrete and a heavier structure because of beam deflection and ponding that occurs to the deck.
2. Uniform concrete thickness – The bottom of slab will roughly follow the contours of the steel beams. A uniform slab thickness results in a predictable slab loading, but potentially increases construction cost because the placement method is slower and yields a floor with less levelness. The successful interaction between the beam camber and the actual deflection that occurs during the concrete placement will dictate the floor levelness.

With both systems, the minimum and maximum slab thicknesses should be stated. The minimum thickness will often be determined by the required fire-rating, and the assumptions for additional concrete weight used in design should be incorporated with a maximum thickness (and/ or average thickness).

Contractors typically prefer a "level" top of slab. Laser level technology has simplified the task of concrete placement. Owner requirements for floor levelness and flatness may also dictate a "level" floor. If a "level" floor is required, the deck, steel beam/ joist, and girder deflections need to be carefully considered in the design to accommodate ponding effects caused by the concrete placement. If the additional concrete weight is overlooked in the design, the result could be beam overstress and excessive deflection under the weight of the non-composite concrete and full service loads. The Contractor should be aware of the potential for the additional concrete required to achieve a "level" slab surface. It is also possible for the resulting slab thickness to be less than that specified, particularly if the non-composite concrete load deflection does not fully counter the camber in some beams, resulting in the HAS not having the required minimum cover, or a slab with less than the minimum thickness for the required fire rating. This condition is less likely with a uniform slab thickness placement method described below.

The "uniform" option gages the floor to a uniform thickness, thus controlling the weight of the concrete placed on the structure. The concrete subcontractor must gage the slab thickness at multiple locations along beams to maintain this uniform thickness. This method is more labor intensive than laser level monitoring of the top of the slab. Variations in beam camber combined with actual vs. calculated beam deflections can result in unevenness in the slab surface.

Placement techniques of concrete for floor slabs such as pumping or dumping from crane buckets can affect the final product. Dumping of concrete in large quantities at one location may cause excessive localized loading and deflection. Pour sequencing can affect dissipation of camber in beams and girders. Hardened concrete on one side of a beam or girder could stiffen the floor enough to resist dead load deflection for fresh concrete placed on the other side of the beam or girder, leaving too much residual camber.

The specified content of fly ash and other concrete admixtures should be carefully considered by the design and construction team. For example, high concentrations of fly ash can significantly affect the concrete set time making finishing more difficult. This can also impact the construction schedule, increasing the overall project cost. Additional considerations beyond the scope of this paper are topics such as the unit weight of light weight concrete and vapor transmission for seamless flooring applications.

For fire rated floors, U.L. does not allow for a minus (-) slab thickness. ACI 117 allows for a minus (-) tolerance of ¼" for slab thickness. Some design offices will consider an average slab thickness after concrete placement before requiring the placement of spray applied fireproofing to the underside of the deck to satisfy U.L. Another consideration for accomplishing a flat floor would be to allow for a topping slab or leveling compound to be installed after placement of the structural slab. Once the structural concrete slab has hardened, the floor system will be very stiff and the subsequent deflections due to the placement of the topping slab or leveling compound would be small.

H. PROJECT BUDGET

The weight of a framing system is easy to quantify. However, there are many other factors which need to be considered in order to arrive at the cost of a given framing system. It is difficult to compare the costs of different floor systems without the assistance of a Fabricator, Erector and General Contractor.

The cost of a steel framed floor is affected by design issues, erectability, concrete finishing methods, material costs, schedule and other factors.

The process of cambering may not be necessary if the material weight is increased a small amount. This could result in savings to the project and should be considered in the design process. AISC has developed comprehensive articles on this subject, some of which are listed in the references.

CONCLUSION

If successful steel framed floors are going to be achieved, then a cooperative collaboration is necessary between all team members including the Owner, Architect, EOR, General Contractor, Fabricator, Detailer and Erector. The EOR is the team member that can have the greatest impact on the potential economic success of the project, since a buildable design is fundamental. Open communications via design meetings, pre-detailing meetings and pre-construction meetings will provide an opportunity for success.

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