Simplifying the COMPLEX

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The third installment of the "But It Worked in the Model!" series focuses on structures with complex geometry.

AS DESIGNERS CONTINUE to break the mold and push the limits with complex architecture and innovative designs, their ability to imagine and develop structures is continually enhanced by the power of the computer.

Collaborative 3D modeling, AKA BIM (building information modeling), has enhanced the design process for increasingly complex projects and can make the most complicated geometry seem simple, even allowing all stakeholders to view and tour a structure before it's built.

But while the 3D modeling process can seem capable of anything, it must be complemented by a deeper understanding of materials, construction concepts, site constraints and the relative costs of fabrication and erection of the various structural options—especially with structurally complex projects such as arenas, stadiums and performance venues. Here, we'll discuss the erection of such structures, the need for the structural engineer of record (SER) to fully communicate the structural design concept and its unique features and how to address those questions that the model does *not* answer.

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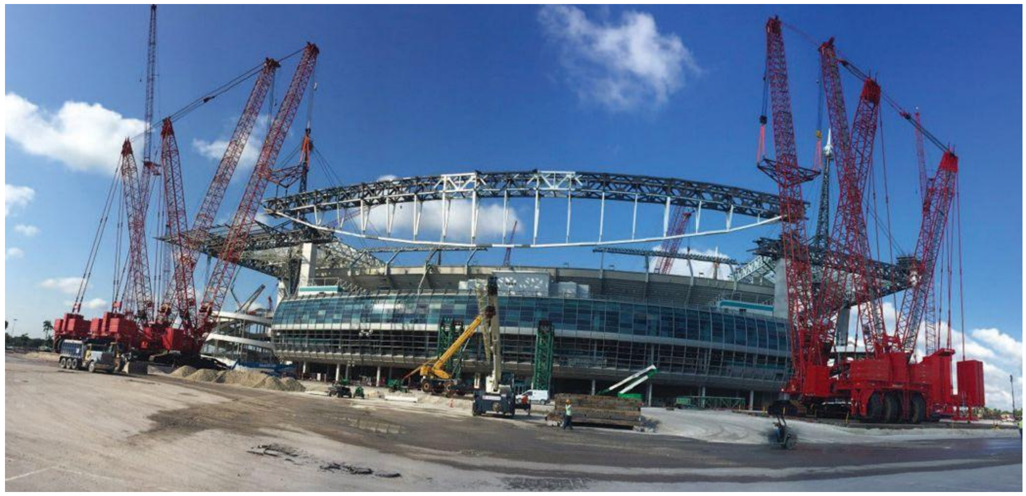
Analyzing and Bracing

During design development, a structure's dead load and subsequent structural steel framing live load analysis establishes the structure's final geometry and the related truss cambers or super-elevations necessary for proper fabrication and installation. However, in the 3D modeling process, the model is focused more on coordination or "clash detection" between the framing system and subsequent building systems based on the undeflected geometry. For a true understanding of the design concept, fabrication and erection tolerances and desired final erected geometry, none of which are included in the 3D model, the erection engineer must develop a procedure to adjust and/or maintain elevation based on the structural concept, its deflection characteristics and the SER's expectations.

When the structure is analyzed as a unit and the dead and live loads are applied simultaneously, the deflection of the steel framing is relatively simple to compute. But the erection engineer must also consider the structure's deflection *as it is built* while maintaining stability one piece at a time. The conscientious erection engineer recognizes that the member's dead load deflection may occur prior to the member's final connections or prior to completion of the structure's lateral load resisting system. The erection engineer must also account for: the sequence of installation; temporary support conditions and their removal; ASTM A6 material tolerances; AISC fabrication and erection tolerances; the impact of temperature variations; installation and connections during plumbing and survey operations; and the movement induced by daily uneven solar heating of the partially completed structure. All of these represent important considerations in developing the erection procedure, maintaining stability and establishing related temporary shoring or bracing requirements.

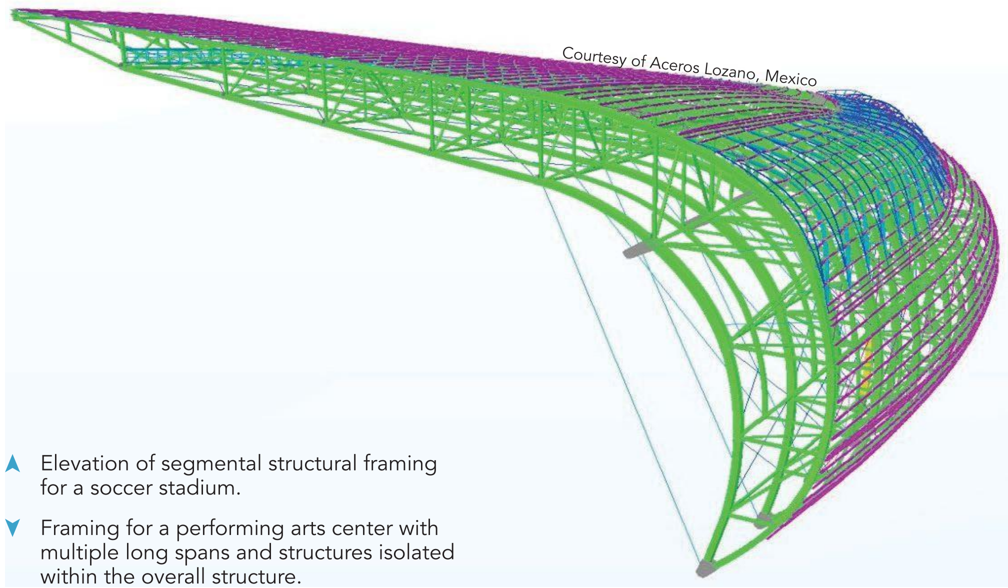


➤ Setting canopy trusses for Hard Rock Stadium in Miami Gardens, Fla.

For long-span and cantilever structures, it is imperative that the SER communicates the nature of the structure, the lateral load resisting system and connecting diaphragm, as well as any special conditions (fabrication or erection) that may be unique to the design concept. At the same time, the construction manager must also be made aware of the nature of the structure, the interdependence of trades or materials and the need to communicate, during the bidding process, the schedule of any nonstructural steel elements necessary for final stability and/or those nonstructural steel elements that may induce additional lateral and/or dead loads during construction.

The erector must be made aware of the many outside elements that may impact the installation of the structural steel. These include the timing of follow-up trades, installation of the metal deck, placement of concrete slabs and installation of cladding or precast panels. All of these elements can have a potential impact on the lateral and vertical deflection of the partially completed structural steel frame and may require subsequent elevation adjustment to the steel. The erection engineer and erector must work with the structural elements as designed, reinforce or modify them as necessary and provide temporary support. It is the SER that must communicate expectations for the final elevation of the bare structural steel frame after installation and prior to subjecting the frame to outside loading. But why is this the case?

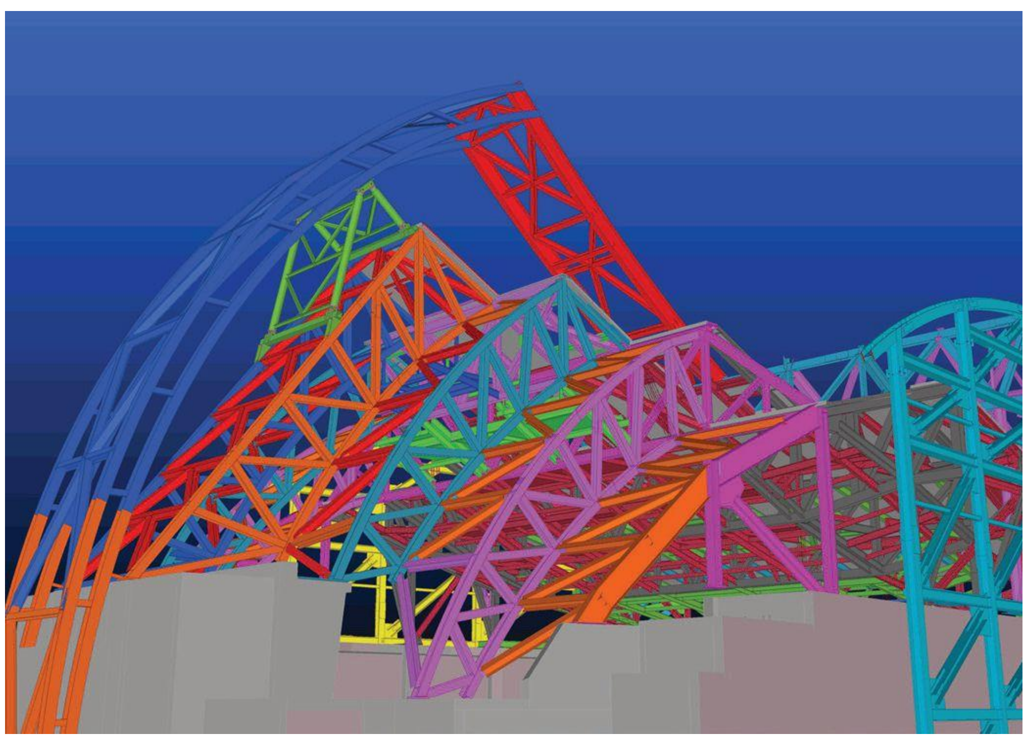
The erector can only control the elevation of the structural steel at the work points, the base plate elevation, beam-column intersections and cantilever or truss support points. The SER must convey information unique to the structural frame and related to any anticipated frame or individual member deflections that are to be accounted for by cambering, super-elevating cantilever elements or any other constraints related to the design concept. This communication is necessary to ensure that the capacity of any temporary support and/or elevation control/jacking procedures are consistent with the design concept. This information allows the erector and erection engineer to understand the SER's design concept and to develop the procedures necessary to meet the SER's target elevations and final expectations.



Courtesy of Aceros Lozano, Mexico

▲ Elevation of segmental structural framing for a soccer stadium.

▼ Framing for a performing arts center with multiple long spans and structures isolated within the overall structure.



Chicago's Frank Gehry-designed Pritzker Pavilion and its complex roof geometry.

Uniquely Complex

In this and previous articles in this series, we've established that the model does not provide all of the answers. But which questions remain unanswered? Let's investigate a hypothetical approach for unique structures with distinctive geometry, cantilevered elements and complex configurations. Challenging traditional architecture and certainly basic structural design principles, these types of structures demand special attention by all shareholders. The structural drawings or model must be complete and fully describe the nature of the structure. Detailing and fabrication cannot proceed without input from the erector/erection engineer. And the erection engineer cannot begin to develop the erection analysis model without a full understanding of the design concept as well as the SER's expectations.

Significant engineering is required to develop fabrication procedures and construction sequencing to provide for erection stability and temporary works, as well as to maintain or establish the erected elevation of the structural steel. The structure's complex geometry also provides additional challenges in that published AISC tolerances do not apply directly. Therefore, the SER's and owner's expectations are necessary to establish acceptable fabrication and installation tolerances consistent with the design concept and proposed erection procedure.

During design and construction of such unique buildings, the SER's primary concern may very likely be elevation control, whether for an amphitheater with cantilevers and a façade or an isolated orchestra hall structure within a larger structure. In any case, it is necessary for the erected (deflected) steel geometry to be coordinated for effective synchronization of the two systems.

Recognizing the elevation control concern, the SER develops and provides a 3D model for bidding purposes. In addition, the SER notes that the actual truss deflections will be influenced by many factors including fabrication tolerances, installation sequences and procedures and installation of nonstructural elements. This would open the door for discussion related to the impact of solar exposure on the structural steel frame, the ability of the erector to

Pritzker Pavilion: the structure behind the complex roof geometry.

maintain elevation, adjusting for deflections and providing a predictable shape.

To account for the unknowns, the SER may consider providing a structural narrative describing the structure, its major components (structural and nonstructural steel) and their interdependence. Supplying a structural narrative with the 3D model is a means for the SER to clearly define the nature of the design concept and to emphasize its unique features prior to the erector and construction manager developing their project plans and installation procedure during the bidding stage.

The SER may also include a schematic erection procedure consistent with the design concept, such as requiring a post-installation survey of the steel structure to be performed to assure that the actual in-situ deflection of the steel is available for subsequent façade fabrication to be performed accordingly. Such a survey may impact the project schedule by delaying façade fabrication and installation. However, it may be the only way to assure that a uniquely configured façade matches the deflected structural steel as envisioned by the SER.

A Change in Thinking

If we, as design and construction professionals, were to ignore the silos that separate us and use 21st century technology, we could go beyond this approach and concentrate on "selling" our knowledge and experience through innovative concepts rather than pitching engineering as a commodity or billable hours. We could educate owners on the virtues of constructability, establish integrated design teams and use 3D modeling technology as a tool for collaborative development of innovative solutions. These solutions, infused with construction knowledge and experience, would align owner's goals with expectations, shorten construction schedules, lower final costs, improve construction safety and reduce or eliminate the disruptions due to changes. As reported in the the Construction Industry Institute's (CII) *Constructability Implementation Guide (Second Edition)*, "When methodically implemented, front-end constructability efforts are an investment that results in a substantial return." In fact, it notes, constructability effort documentation has shown that owners can accrue an average reduction in total project cost and schedule of 4.3% and 7%, respectively.

Integrated design teams would include all stakeholders: owners, designers, contractors, subcontractors and construction managers. This team would collaboratively review the owner's program and openly discuss the owner's expectations. The team would collaboratively develop the design concept including site constraints, labor and skills availability and material considerations. The computer analysis and modeling results would be reviewed by the team, and subsequently the final concept would be jointly developed based on design, material and trade considerations.

While modeling provides the vehicle necessary to successfully communicate throughout the collaborative design process, other changes must also occur. First, the owner must be willing to assemble an integrated design team focused on the concept of constructability. Second, the design community must be willing to champion the concept and be fully engaged as a member of the team. And third, the construction professionals must be engaged in the design process by sharing their knowledge and construction expertise. The project's integrated solution will enhance quality, schedule and inter-trade coordination and will enable signature buildings and other structures to be constructed on schedule and within budget.

The concept of constructability is not a new idea, but it is unique in that it requires an educated owner and quality contractors to realize the full benefit. ■

For more on constructability practices and tools, see CII's Constructability Implementation Guide (**www.construction-institute.org**) *and AISC Design Guide 23:* Constructability for Structural Steel Buildings (**www.aisc.org/dg**). *And for past articles in this series, see the April and July issues, available at* **www.modernsteel.com**.