Technology Meets Constructability

BY DAVID RUBY, SE, PE

THERE ARE MANY BENEFITS attributed to the integration of analysis and 3D modeling software: achieving efficient designs, maximizing profitability and satisfying a client's expectations, for starters.

These successes are the result of collaborative solutions developed by experienced structural engineers and knowledgeable contractors exiting their comfort zones and jointly engaging in the design development process. The process demands an atmosphere of trust, a willingness to share concepts and ideas and the active engagement of all in discussions beyond their silos of familiarity. This trust and willingness to share allows the integrated design team to develop a design concept that not only echoes the owner's needs and wants, but that also satisfies code, budget and schedule constraints.

So why has 3D modeling not provided similar results in the traditional design-bid-build project delivery process? The analysis and modeling software is the same and the construction knowledge is available throughout the industry (as well as via the AISC Steel Solutions Center). But the silos remain a barrier to open communication. Has the computer become the decision-maker?

Perhaps the solution is to concentrate more on the journey and less on the destination. When I entered the engineering profession, the analysis phase did not begin until the basic project concept and its lateral load-resisting system had been vetted, initial assumptions confirmed and concept feasibility verified. The next step included development of code-mandated loading, dimensions and drift limitations and evaluation of constructability. This was followed by preparation of approximate check calculations to confirm that the concept and all its elements met the project's objective. Upon the successful completion of these preliminary steps, the design development stage would begin.

This time-consuming process provided an opportunity to reflect on each component of the structure, suitability of its foundation concept, applicability of the horizontal diaphragm requirements, stiffness balancing of the various elements of the lateral load-resisting system and overall structural integrity. Granted, my experience predates the personal computer, but the basic elements and their interactions necessary to ensure structural integrity have not changed. So the questions remain: Has the simplicity of automated load development and the subsequent computer analysis and design robbed us of the opportunity to share our knowledge and experience? Has recognition of the importance of the subsystems and their necessary interactions been lost in the process?

Opportunities for Discovery

In our firm's capacity as erection engineer, we have the opportunity to review a wide variety of lateral load-resisting systems: low-rise, high-rise, stadiums and arenas, commercial and industrial. During our staged stability analysis, we often encounter load path questions related to the floor or roof diaphragm and their ability to properly distribute the temporary erection forces. We discover diaphragms without collectors or drag struts. We find columns with minimal framing attached, which creates stability issues during installation and likely in the final structure. Lightly loaded columns may lead to uplift/tension in the temporary connections at the foundations, as well as within the column splice connections. We have concluded that if there is a load path issue during erection, there will likely be a load path issue in the final structure.

A revisit of the structure's subsystems and primary purposes, as described by T.Y. Lin and S.D. Stotesbury in *Structural Concepts and Systems for Architects and Engineers*, may provide a refresher for many. It focuses on the function of a floor diaphragm as a horizontal gravity load-carrying component that also functions as a transfer mechanism of story shears and torsional moments to the vertical subsystem (lateral load-resisting system).

What constitutes a horizontal subsystem, and how does it transfer lateral and gravity loads to the vertical subsystem? Generally, for structural steel buildings, the concrete on metal deck floor slab (diaphragm) and its supporting elements (beams) deliver the lateral and gravity loads to the vertical subsystem.

What constitutes a vertical subsystem? The columns and lateral load-resisting system are the elements that provide structural integrity and transfer the gravity and lateral loads to the building foundations. In short, the designer need only to concentrate on delivering the gravity and lateral loads to the vertical and horizontal structural elements consistent with the building's architectural concept—i.e., a well-defined **load path**.

When developing the structural concept, the designer must focus on the basic vertical and horizontal subsystems, the floor diaphragm, the lateral load-resisting system and their interactions. Initially, subsystems are assumed to interact as necessary by delivering gravity and vertical loads (load path) thus ensuring total system integrity. The designer with a continued focus on the load path can further develop the basic subsystems and the interactions necessary to achieve total overall integrity.

Back to the Basics

At the *conceptual stage*, the designer need only keep in mind the four basic structural subsystem interactions that must be provided in order to achieve overall integrity in the structural action of a form (again, refer to Lin and Stotesbury):

1. Horizontal subsystems (*diaphragm*) must pick up and transfer vertical loads to the vertical subsystems.
2. Horizontal subsystems (*diaphragms, supporting framing*) must also pick up horizontal loads accumulated along the height of a building and distribute them to the vertical shear-resisting subsystems. (Author's note: The primary focus of a diaphragm is to distribute lateral forces.)
3. Vertical subsystems (*columns, lateral load-resisting systems*) must carry the accumulated dead and live loads and some must be capable of transferring shear from the upper portions of a building to the foundation.
4. Key vertical subsystems (*columns, lateral load-resisting systems*) must act to resist bending forces due to overturning moments. Where possible, they should be connected by horizontal subsystems (*beams and the diaphragms supporting the framing*).

It is important to also note for structural economy that the horizontal diaphragm supporting elements (*beams and girders*) should be framed to deliver the maximum gravity load to the vertical subsystems, thus reducing or eliminating the impact of uplift and reducing foundation and connection requirements.

During the *schematic design stage*, the designer lays out the subsystem design options, considers the options and confirms the required interactions. The *preliminary design stage* concentrates on proving the feasibility of the concepts related to the interacting subsystems and establishes the basic dimensions. This process provides an opportunity to reflect on the subsystems, thus allowing exploration of options toward understanding the total-system behavior. Now the final design process may begin.

These three levels of initial design development—conceptual, schematic and preliminary—should be distinguishable and not merged. But note that feedback is necessary to optimize the interaction between total and subsystem thinking. At the schematic and preliminary stages, the emphasis is placed on overall thinking and quick analysis of fundamental properties by approximation. Approximation allows optimization of basic components of interacting subsystems. The optimized scheme provides a context for dealing in depth with the final design of all elements and details (once again, see Lin and Stotesbury).

However, when these initial developmental stages are ignored or merged, the design concept is rushed to analysis prior to its maturity. How often is your first idea the best idea? Is there information related to construction, material or the trades that you do not know in the early stages? Have the structural geometry and the architectural requirements been coordinated? Is there a load path for the distribution of the code-mandated lateral loads? Does the initial analysis/design model rigid diaphragm and support framing accurately depict the desired structure? Do the computer model's components shown in blue and green provide a false sense of security?

Two Examples

Horizontal subsystems as defined above warrant additional discussion. Any roof, floor or ceiling can participate in the distribution of lateral forces to the lateral load-resisting system

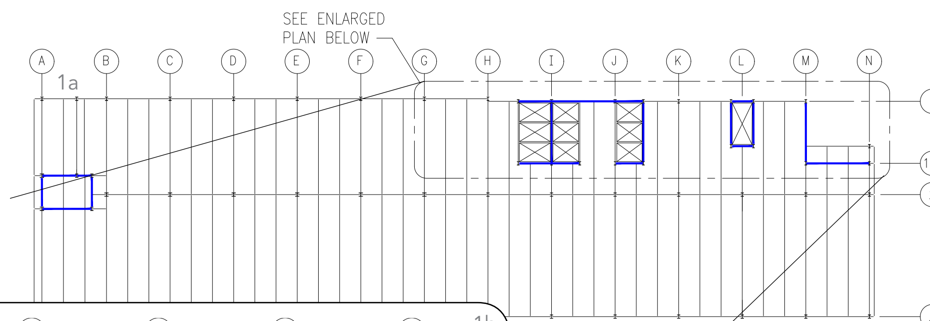
The fifth installment of the "But It Worked in the Model!" series tackles the balance between technology and constructability, with a focus on load paths.

David Ruby (druby@rubyandassociates.com) is the chairman and founding principal of Ruby+Associates Structural Engineers in Bingham Farms, Mich.

up to the limit of its strength. The degree to which it participates depends on relative stiffness and its related connections. However, the typical structural analysis program's output does not include the column through-forces and the lateral load-related axial forces in the support framing, collectors or drag struts since the diaphragm is rigidly attached to the building nodes and thus delivers the lateral forces directly to the lateral load-resisting system.

In reality, the as-built diaphragm does not transfer the lateral forces directly to the lateral load-resisting system. The forces are transferred from the diaphragm through the attachment of the metal deck to the supporting structure or through shear studs welded to the top flanges of the supporting structure. This in turn transfers the lateral forces to the lateral load-resisting system through shear and axial connections to the columns. How are these forces distributed? Through a detailed tracking of the structure's loading and the load path by the structural engineer of record. In the following examples, this was not done.

Example One. Floor framing controlled by geometry without consideration of the distribution of gravity and lateral loading. The analysis model's rigid diaphragm in Figure 1 distributes the code-mandated loads to the lateral load-resisting system (noted in blue below). Where is the load path?



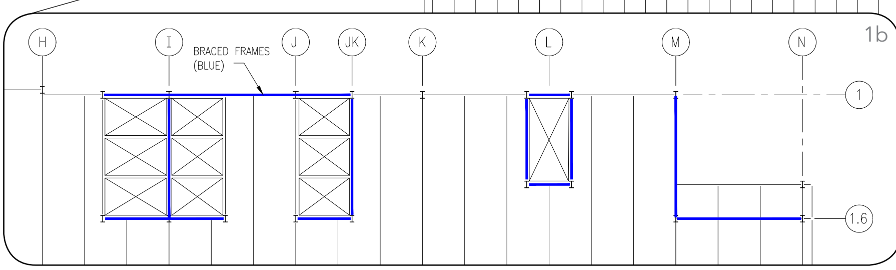
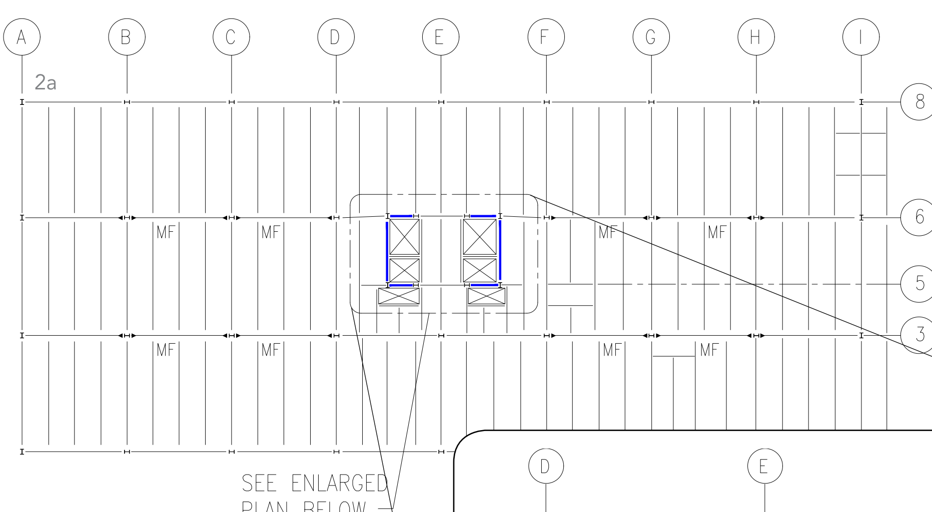
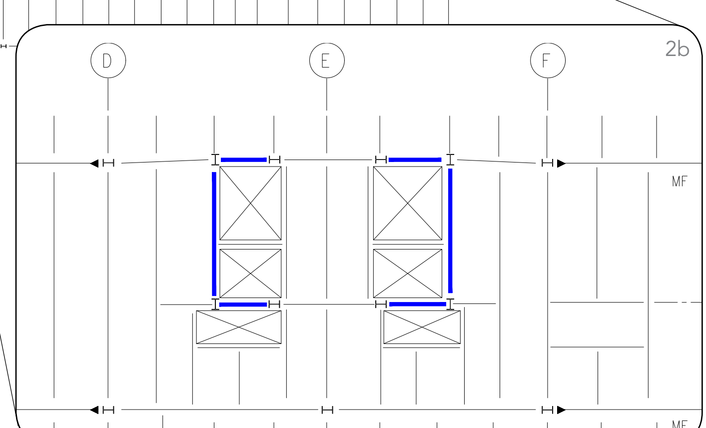


Figure 1a: Framing following a typical grid without consideration of gravity loading to braced bay columns.

Figure 1b. Enlarged plan showing the primary lateral load-resisting system. *Note: No collectors on Col. Lines 1.6, JK or L—i.e., no lateral load transfer mechanism.*





Example Two. Floor framed to suit the architectural design without consideration of delivering gravity or lateral loads to the braced bay's columns. The rigid diaphragm in Figure 2 distributes the lateral loads to the lateral load-resisting system. Is there a means (load path) for the concrete slab on metal deck (diaphragm) to distribute the lateral loads to the lateral load-resisting system?

And remember, in both examples, "It worked in the model!"

Figure 2a. Floor plan for an eight-story hospital building.

Figure 2b. Enlarged plan showing braced frames in blue. *Note: Minimal collectors on Col. Line 5—and no lateral load transfer mechanism between braced frame on Col. Line 5 and moment frames on Col. Line 3.*

Has the design profession charged the rigid diaphragm with the responsibility for the structure's integrity and blindly accepted the computer results without a thorough review of the computer output, the lateral load-resisting system and confirmation that a sufficient lateral load distribution path actually exists?

We'll continue this discussion in Part Two, which will appear in an upcoming issue. ■

Suggested Reading

1. *Structural Concepts and Systems for Architects and Engineers* by T. Y. Lin and S. D. Stotesbury
2. AISC Design Guide 23: *Constructability of Structural Steel Buildings* (**www.aisc.org/dg**)
3. AISC Design Guide 5: *Design of Low- and Medium-Rise Steel Buildings* (**www.aisc.org/dg**)
4. AISC Design Guide 3: *Serviceability Design Considerations for Steel Buildings* (**www.aisc.org/dg**)
5. FEMA *Handbook for the Seismic Evaluation of Buildings*
6. "Economics of Low-Rise Steel Framed Structures," 3rd Quarter AISC *Engineering Journal* (**www.aisc.org/ej**)

*For previous installments of "But It Worked in the Model!" see the April, July, October and December 2017 issues, available at **www.modernsteel.com**.*