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

Technology Meets Constructability: Part II

BY DAVID RUBY, SE, PE

IN THE PREVIOUS ARTICLES in our "But It Worked in the Model!" series, we focused on issues related to incomplete or inaccurate assumptions in the model that did not translate well into the fabrication and erection of structural steel. The last article—"Technology Meets Constructability," in the May issue—raised the concern related to the computer modeling of the concrete slab/metal deck diaphragm and how the diaphragm as modeled will deliver the lateral forces to the lateral force-resisting system (LFRS) without a direct path—i.e., without collectors or drag struts in the final structures—and we'll continue that discussion here.

A rigid diaphragm compensates for an incomplete lateral load path in the model by acting as the lateral force distribution mechanism. This process, completely transparent to the designer, allows the analysis program to use the diaphragm for local and global stability and for distribution of the lateral forces to the LFRS while providing primary member results, drift within allowable limits and a finalized stable structure. A rigid diaphragm distributes the lateral forces, not as envisioned by the structural engineer, but based on the stiffness of the lateral load resisting elements even without a complete load path—i.e., missing collector elements/drag struts. The structural engineer, trusting the computer analysis completely, sees no need to refine the design model as the graphic representation of the analysis indicates the structure's primary members to be blue or green. In this case, "out of sight, out of mind" unfortunately applies and as a result, the computer has become the decision maker and has given the designer a false sense of security.

As outlined in the previous article, the attributes of the concrete diaphragm—whether rigid, semi-rigid or flexible—and its supporting elements must be addressed during modeling. The modeler must develop a model with a well-defined load path that delivers the lateral forces from the diaphragm to the LFRS. In addition to lateral force distribution, the responsibilities of the diaphragm include:

1. Delivering gravity loads to the vertical gravity-resisting subsystems—i.e., the columns
2. Providing fixity and stability while maintaining geometry for the vertical load carrying elements—i.e., lateral bracing of beams and columns
3. Equalizing the lateral displacement of the vertical subsystems—i.e., distributing lateral loads based on relative stiffness of the braced and/or moment frames
4. Acting to resist localized compressive buckling of the vertical load-carrying subsystem by tying them together

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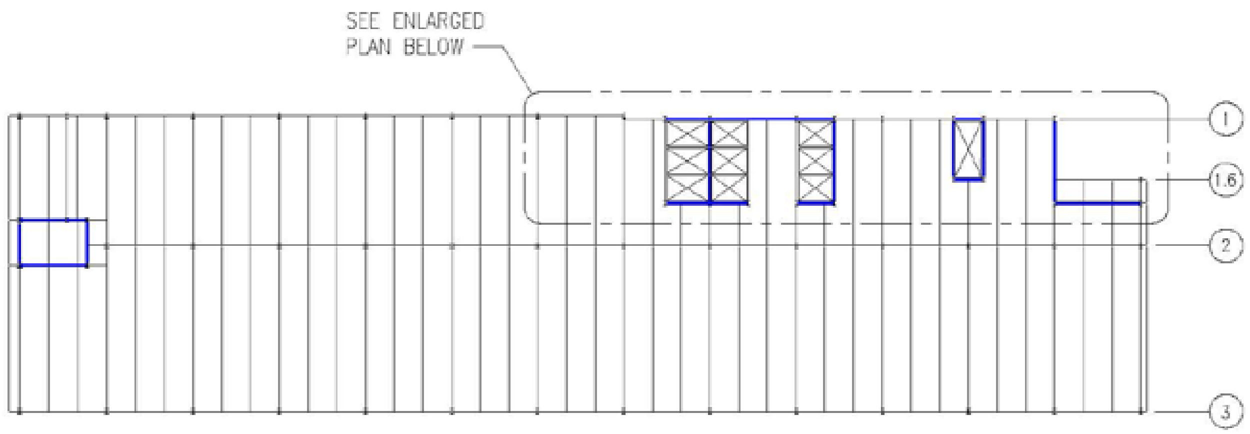
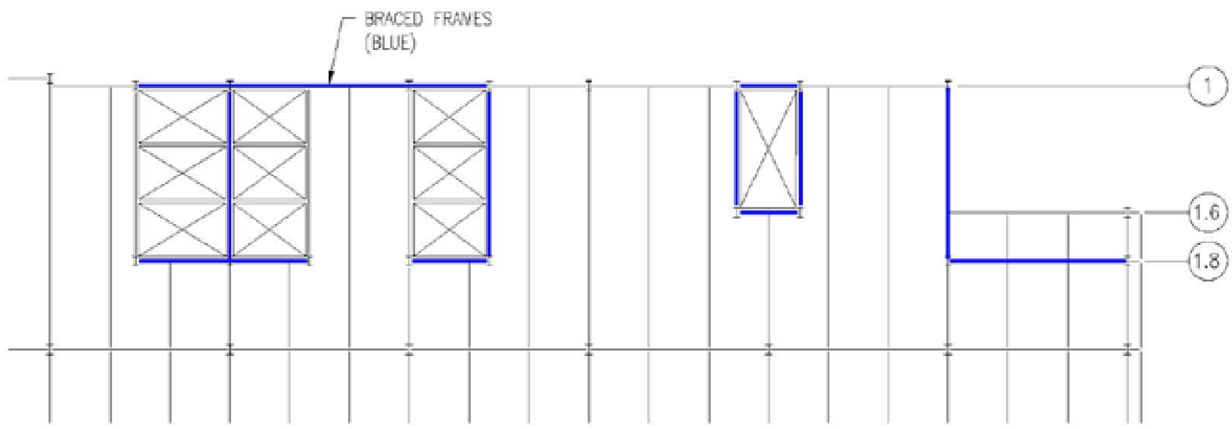
"But it Worked in the Model " Series

Articles available at **www.modernsteel.com/archives**

1. "But it Worked in the Model," April 2017
2. "Technology, Meet Constructability," July 2017
3. "Simplifying the Complex," October 2017
4. "Beyond Limits," December 2017
5. "Technology Meets Constructability," May 2018



Example 1. Enlarged floor plan showing the braced frames.



Force Distribution Via Load Path

In a structural steel building, lateral forces are not directly distributed by the concrete-filled metal deck slab (diaphragm) to the LFRS but rather are distributed via the collector beams and drag struts that support the diaphragm. However, due to the nature of analysis software, these forces remain in the diaphragm and are not shown or reported as floor beam axial forces in the typical computer output.

The distribution of the lateral forces requires the existence of a load path from the diaphragm to the LFRS. To determine the magnitude of these forces, the structural engineer may choose to revise the model's diaphragm constraints or take a hands-on approach. This approach includes reviewing the results, verifying the continuity of the load path, establishing the magnitude of the collector forces, preparing joint balance calculations, defining the metal deck diaphragm attachment requirements and including the beam axial forces and connection capacity requirements in the design documents.

Up-Front Planning

A designer's rush to develop the analysis model may be shortchanging the development of the structural concept by minimizing or skipping the schematic and preliminary stages in initial project planning. At the schematic stage, the designer conceptualizes the fundamental design options, including the interaction (load path) of the subsystems. In the preliminary stage, the designer proves the feasibility of the interacting subsystems and establishes basic dimensions. Details of this interaction become part of the final design/analysis stage where the focus is to refine the preliminary stage decisions by specifying all elements and related connection details. This is when the designer confirms that a load path does exist within the structural concept.

A concrete-filled metal deck diaphragm uses continuous collectors or struts as collection elements for the distribution of the lateral forces originating in other portions of the structure to the LFRS.

ASCE 7-10: *Minimum Design Loads for Buildings and Other Structures* clearly defines diaphragm design provisions for moderate- to high-seismic areas (SDC B-F) and the importance of identifying structural irregularities that may trigger an increase in the design forces. Diaphragm requirements for a structure whose LFRS is governed by wind are noted in ASCE 7-10 Chapter 26. A simple diaphragm is defined as "a building in which both windward and leeward wind loads are transmitted by roof and vertically spanning wall assemblies, through continuous floor and roof diaphragms, to the main wind force-resisting system (MWFRS)."

ASCE 7-10 defines a diaphragm as "a roof, floor or other membrane or bracing system acting to transfer lateral forces to the vertical MWFRS. For analysis under wind loads, diaphragms constructed of un-topped steel decks, concrete-filled steel deck and concrete slab, each having a span-to-depth ratio of two or less, shall be permitted to be idealized as rigid."

SDI DDM003 states: "Some authorities define diaphragms as in the list that shows direct comparisons."

Diaphragm Stiffness	SDI G′ (kip/in.)
Flexible	14.3 to 6.67
Semi-flexible	100 to 14.3
Semi-rigid	1,000 to 100
Rigid	over 1,000

The stiffness of a concrete-filled metal deck diaphragm is a function of the metal deck gage, span and number of side-lap fasteners. For a typical concrete-filled floor slab with a 2-in. 20-gage metal deck spanning 6 ft, 3 in. with side-lap fasteners at 15 in., the diaphragm stiffness G' = 2,558 kips/in. (according to the *Vulcraft 2008 Steel Roof and Floor Deck Catalog*) > 1,000 kips/in.; therefore, a typical concrete-filled metal deck floor slab may be considered rigid.

A Diaphragm Working Overtime

A revisit of Example 1 from the previous article in this series finds that the collectors necessary to transfer the lateral forces to the LFRS on Column Line 1.8 do not exist (see Example 1, previous page). The LFRS consists of vertically braced bays of varying levels of stiffness (shown in **blue**). The braced bays are located at the elevator and stair shafts, with the majority off the building grid. With the exception of the columns on Column Line 1 and two north-south braced bays, the braced bay columns do not have any collectors or other members attached.

It is common to assume that the floor slab will provide a reasonably stiff diaphragm in the analysis of multistory buildings, providing stability, picking up the gravity loads and distributing the lateral loads to the braced bays. However, in this structure the diaphragm will be working overtime. The floor plan is void of any east-west collectors and has limited collectors in the north-south direction. The only mechanism delivering the lateral forces to the braced bays is the beams on Column Line 1. There is no framing on Column Line 1.8 to distribute the lateral forces from the diaphragm to braced frames. "No load path" is the concern.

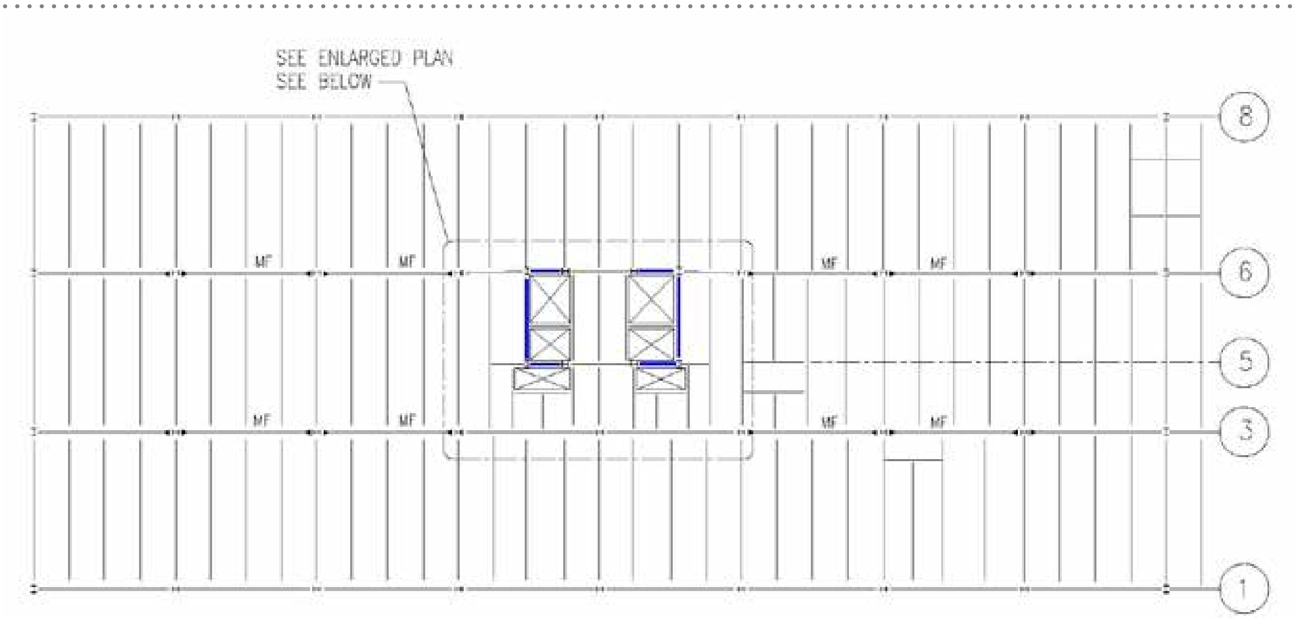
The lack of framing on Column Line 1.8 leads one to question the adequacy of the original design concept as there are no specific details, notes or specifications that address the strength, stiffness and connection of the diaphragm to the LFRS. Typical metal deck attachments are shown without any details relating to the distribution of the diaphragm's lateral forces directly to the braced frames on Column Line 1.8.

It is no doubt that this concept "worked in the model" and the rigid diaphragm may distribute some portion of the lateral loading to the stand alone braced bays. But will that distribution echo the original analysis and subsequent final design?

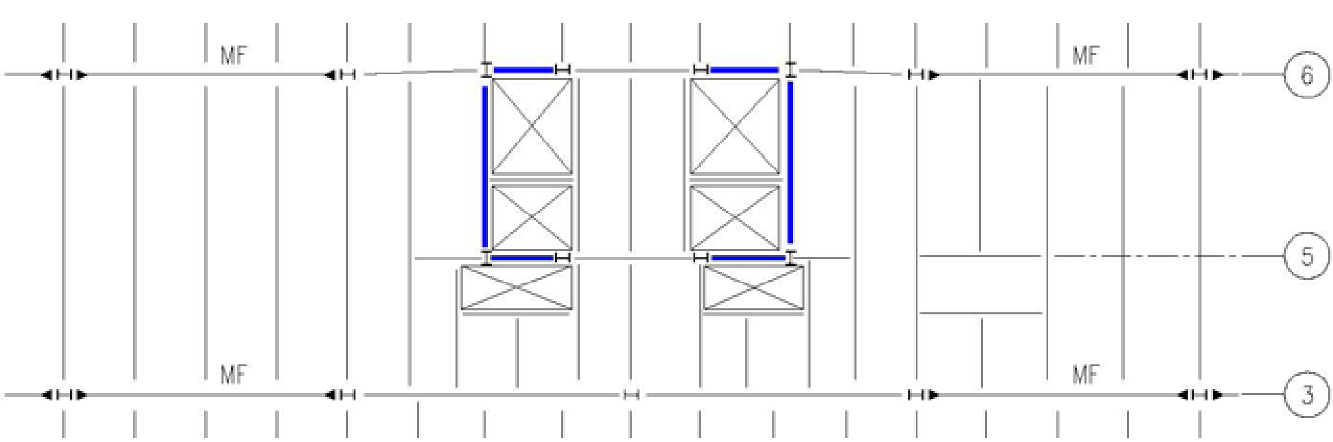
No Load Path!

A revisit of Example 2 from the most recent article, although similar, has a very different issue.

As previously stated, the concrete-filled metal deck slab provides a rigid diaphragm in the analysis of multistory buildings. Traditionally, the concrete diaphragm provides stability, picks up the gravity loads and distributes the lateral forces to the LFRS. However, in this structure the diaphragm will again be working overtime.

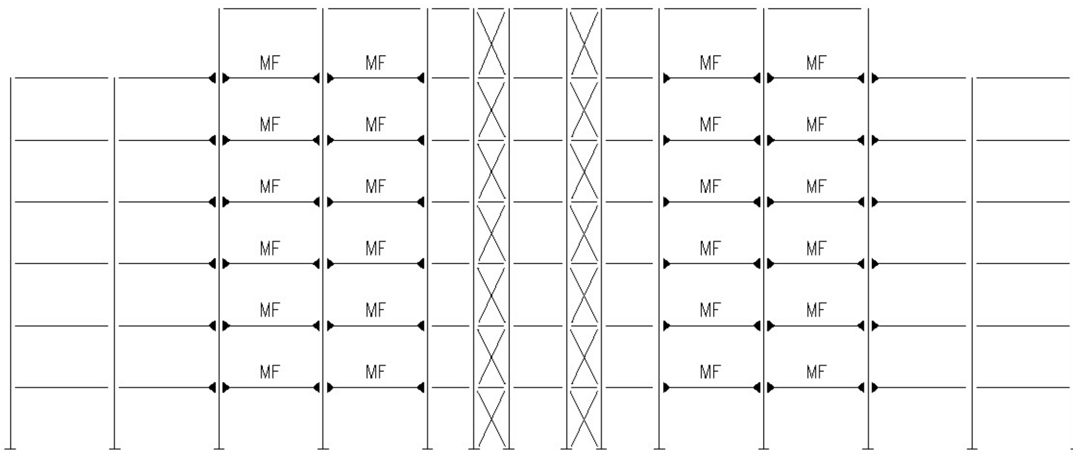


Example 2. Floor plan.



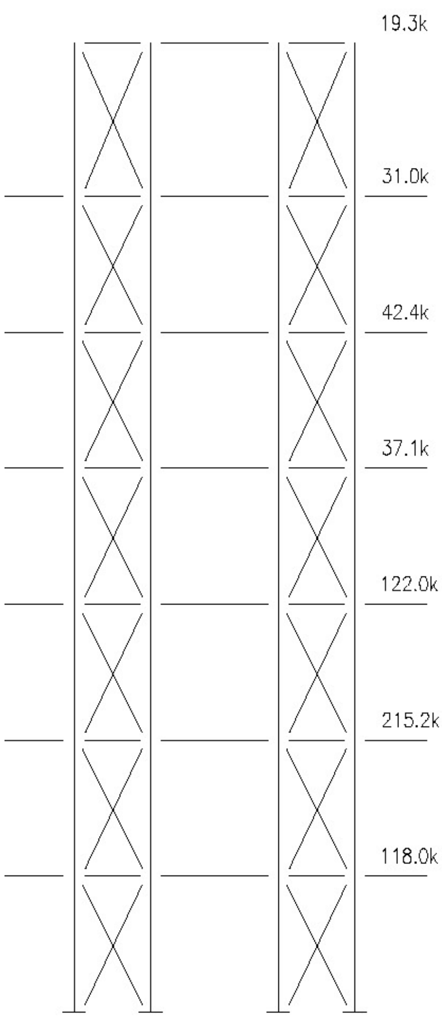
UNIT LD DEFLECTION / FLOOR

MF	BF
.05"	.08"
.07"	.07"
.08"	.07"
.09"	.05"
.14"	.04"
.41"	.04"



Example 3: Moment and braced frames on Column Line 6.

Example 4. Column Line 5 bracing.



Note that the Column Line 6 moment and braced frames are sharing lateral load resistance responsibility, while the moment frames on Column Line 3 and the braced frames on Column Line 5 are independent of each other as shown in the floor plan. However, upon review of the design documents, it appears that the engineer accepted the computer's lateral load distribution since the bracing forces on Column Line 3 are very similar in magnitude to the bracing forces on Column Line 5.

The east-west LFRS consists of moment and braced frames on Column Line 6, braced frames on Column Line 5 and moment frames on Column Line 3. There are collectors delivering lateral forces to Column Lines 3 and 6, but no collectors delivering the lateral forces to the braced frame on Column Line 5. Again, "No load path" exists.

Of Greater Concern

A review of the relative stiffness of braced frames vs. moment frames on Column Line 6 indicates that the braced frames are significantly stiffer than the moment frames in the lower levels. A review of the lateral forces imposed on the bracing elements reveals a dramatic increase in loads at the second and third floors. Further evaluation confirms that the stiffer braced frames are *unloading* the moment frames at levels two and three.

Within Column Line 6, these forces must be transferred from the moment frames to the braced frames by the existing floor beams. Is there capacity in the beam connections?

There is a similar imbalance for the Column Line 3 moment frames when compared to Column Line 5 braced frames, based on a review of the axial forces in the Column Line 5 braced frame. Although a mechanism existed within the model, there is no mechanism in the final structure with the capacity to deliver or to redistribute forces in the magnitude shown in Example 4 between the moment frame on Column Line 3 and the braced bay on Column Line 5. How will these forces be distributed?

In developing the LFRS for any structure, the structural engineer must satisfy the structural requirements of the architectural concept. The efficiency of the LFRS may have to be compromised to suit architectural constraints. However, the cost of that compromise and the potential impact on the structure's performance must be communicated to the architect and the owner.

The mating of a braced frame with a moment frame is a very inefficient lateral load resisting concept. First, braced frame structures are less expensive than moment frame structures. Secondly, shared lateral loads based on equalized frames prevent loads moving from one frame to another. The stiffness of the moment frame and the braced frames must be balanced. This becomes an economic issue, since the braced frames become stiffer by adding area, while the moment frames require an increase in the moment of inertia to increase stiffness.

In this case, the analysis was performed by the computer model and the model does not understand economics. The proper equalization of stiffness never took place.

The model provided a blue and green result, which subsequently appeared on the design documents. But what was lacking?

- Stiffness equalization of moment frames and braced frames
- Review of the braced frame lateral force for imbalance
- Review of the load path for lateral force distribution
- Verification of the collector beams' existence and capacity to distribute the lateral load between the braced frames and moment frames
- Verification of the collector beam connection capacity
- Awareness that no load path existed between Column Line 6 moment frames and Column Line 5 braced frames

A potential load path issue exists.

In both examples, let us remember: "It worked in the model!"

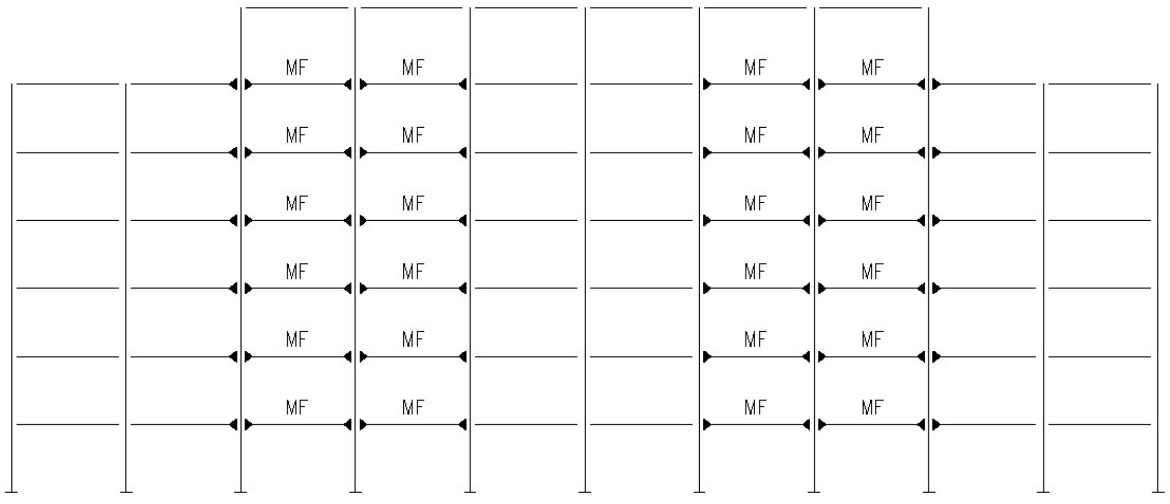
The examples used in this and preceding articles were taken from as-built structures and/or structural drawings of structures issued for pricing purposes. Our review of the structure was based on the sizes and loading shown on the design documents. It is possible that many of these concerns were corrected during the building process, but the original design documents did not properly represent the complete scope of work to be priced and executed by the fabricator and/or the erector.

What Lessons Have We Learned?

1. Structural software has become the primary source for structural design and analysis for structural engineers. However, without an understanding of the fundamental concepts of structure, the results may be your worst nightmare. Structural engineers require an understanding of structures and their behavior to prevent devastating errors that are often overlooked during the analysis and design process.
   a. A well-defined load path is essential.
   b. Structural steel and concrete are different materials and their structural analysis should reflect this.
   c. The concrete slab and the concrete-filled metal deck serve different functions in their respective models.
      i. According to ACI 318, Section 12.3, concrete diaphragms must have sufficient thickness so that all applicable strength and serviceability requirements are satisfied.
      ii. The concrete-filled metal deck in a structural steel building must satisfy all applicable strength and serviceability requirements while providing stability and lateral stability bracing of the structural steel elements.
   d. In concrete structures, the slab, acting as a diaphragm, transfers the lateral shear forces directly to shear walls (LFRS). In systems that contain beams or ribs, the elements below the concrete slab stiffen the diaphragm even further.
   e. In steel structures, the concrete-filled metal deck transfers the lateral forces to the LFRS by way of collector beams or drag struts (load path).
   f. Approval of shop drawings, often performed by junior staff, should include the review of essential elements of the structure's LFRS. This is best performed with direct oversight by senior staff.
   g. Final design details must reflect the model's boundary conditions.
   h. Designs require review by an experienced structural engineer.
   i. Computer programs provide information and are not decision makers.
   j. The computer is only a tool, nothing more.
2. Remember, claiming "But it worked in the model!" means very little and certainly does not guarantee success.

Designing structures is an art that incorporates earned as well as learned knowledge: knowledge gained from experience, knowledge gained from mentors and knowledge gained from successes. But perhaps most of all, it incorporates the knowledge gained from our failures. Henry Petroski, in his book *To Engineer is Human*, states, "Thus the colossal disasters that do occur are ultimately failures of design, but the lessons learned from those disasters can do more to advance engineering knowledge than all the successful machines and structures in the world."

Failures provide perspective for moving forward and they promote the quest for answers and alternate solutions. Collaboration between designers and contractors can satisfy that quest through



Example 5. Moment frames on Column Line 3.

sharing earned, as well as learned, knowledge and jointly developing designs based on collective knowledge and experience. Remember, as noted in *Structural Concepts and Systems for Architects and Engineers*: "It is only with a thorough understanding of the strength and behavior of structures as total systems and the requirements for their subsystems and component interaction that one can design a safe and economical structure to fit the various functional requirements and environmental conditions found in modern architecture."

And it is only through a thorough understanding of the scope of work to be performed that one can expect the contractor to provide a quality project on time and within budget. ■

For past articles in the "But It Worked in the Model!" series, see the April, July, October and December 2017 and May 2018 issues, all at ***www.modernsteel.com***.

Additional Suggested Reading

1. "On the Right Path," *Modern Steel Construction*, November 2014 (all *Modern Steel* articles can be found in the Archives section at **www.modernsteel.com**)
2. "Developing Diaphragm Analysis," *Modern Steel Construction*, May 2018
3. *Structural Concepts and Systems for Architects and Engineers* by T. Y. Lin and S.D. Stotesbury
4. "Design of Reinforced Concrete Diaphragms for Wind," *STRUCTURE*, April 2018
5. *To Engineer is Human: The Role of Failure in Successful Design*, by H. Petroski
6. ACI 318-14 *Building Code Requirements for Structural Concrete and Commentary*
7. AISC Design Guide 23: *Constructability of Structural Steel Buildings* (all AISC Design Guides can be found at **www.aisc.org/dg**)
8. AISC Design Guide 5: *Design of Low- and Medium-Rise Steel Buildings*
9. AISC Design Guide3: *Serviceability Design Considerations for Steel Buildings*
10. ASCE 7-10: *Minimum Design Loads for Buildings and Other Structures*
11. FEMA-310: *Handbook for the Seismic Evaluation of Buildings*
12. SDI DDM03 *Diaphragm Design Manual*, Third Edition