steelwise

DEVELOPING DIAPHRAGM ANALYSIS

Diaphragm analysis, design and connection considerations in steel seismic force-resisting systems.

BY JOHN A. KENNEDY, SE, PE

John Kennedy (jkennedy@saii.com) is vice president of Structural Affiliates International, Inc.

THE PROCESS OF DIAPHRAGM design in steel-framed structures can be quite complex.

It ranges from code analysis, force derivation, stiffness and classification of rigidity, shear strength checks, design considerations for components such as chords and collectors and connections of the diaphragm and its components to the lateral load-resisting system.

Although diaphragms are an important part of structural design for buildings in wind-controlled environments, a particular emphasis on diaphragm design provisions and attention to detailing is merited for buildings in moderate- to high-seismic areas. Here, we'll explore considerations and best practices when it comes to diaphragm design.

Diaphragms in most steel-framed structures commonly consist of a composite concrete slab over metal deck or metal deck alone for roof construction—but the diaphragm system of the horizontal deck works in concert with the supporting steel framing. Diaphragm components such as collectors, drag struts, chords and distributors commonly consist of steel beams whose member selection and connections to the primary seismic force-resisting system (SFRS) are to be properly designed for the required axial load.

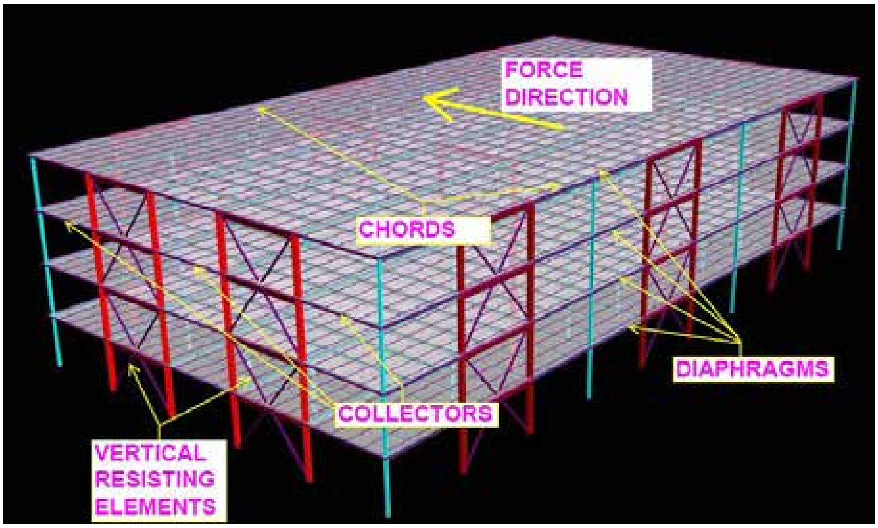
Start with Codes

An understanding of relevant building and design codes is necessary to establish diaphragm forces and analyze the entire system. In addition, some state-specific building codes such as the 2016 *California Building Code* (Chapter 16A) even have additional provisions mandating maximum diaphragm aspect ratios based on the calculated flexibility factor of the diaphragm. These code analyses and provisions are important to understand and check early in the design process, as the SFRS system is identified within the building layout.

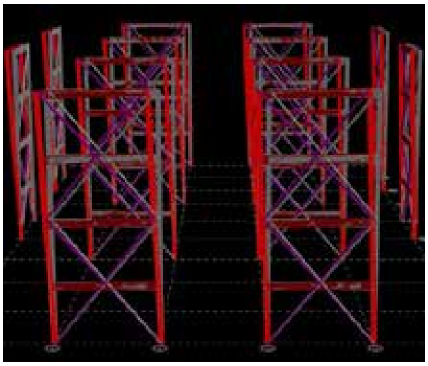
Most model building codes in the U.S. refer to American Society of Civil Engineers/ASCE 7-10: *Minimum Design Loads for Buildings and Other Structures* for diaphragm design provisions and force derivation. A first important check for projects in moderate- to high-seismic areas (SDC B-F) is an identification of structural irregularities in Tables 12.3-1 and 12.3-2 of ASCE 7-10. Irregularities applicable to diaphragm provisions include Horizontal type 1a, 1b, 2, 3 and 4 and Vertical Type 4. Depending on design category, these irregularities trigger provisions that require increasing the design forces by 25% for connections of diaphragms to vertical resisting elements and to collectors, as well as for collectors and connections themselves, unless forces are calculated including the overstrength factor. The categorization of these irregularities also directly affects the seismic analysis procedure required (Equivalent Lateral Force vs. Modal Response Spectrum or Response History).

A second important check is to understand the stiffness of the building diaphragms (both at floor and roof) relative to the stiffness of the vertical SFRS. This establishes a rigidity classification for the diaphragm. ASCE permits a rigid diaphragm assumption only for concrete-filled metal decks with aspect ratios of 3:1 or less in structures that have no horizontal irregularities—and it permits diaphragms to be idealized as flexible for systems of un-topped steel deck with braced frame or shear wall resisting

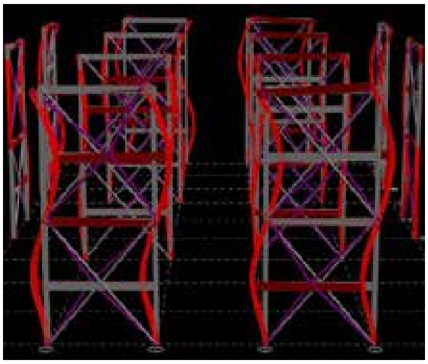
A conventional steel-framed building with a composite slab-on-metal-deck diaphragm.



Elements of an SFRS and diaphragm components.



Primary mode displaced shape.



Higher mode displaced shape.

elements, or where the computed in-plane diaphragm deflection is greater than two times the average story drift of adjoining vertical elements in the level under consideration. In reality, most diaphragms are semi-rigid—only the degree to which they more closely approximate flexible or rigid varies with the type of construction. A semi-rigid diaphragm that considers the stiffness of the diaphragm for horizontal force distribution most closely resembles the expected behavior. Most current commercially available analysis software has simplified the modeling process for semi-rigid diaphragms, which is helpful for irregular buildings where an idealization of rigid is not permitted and semi-rigid diaphragm modeling is required by code.

Once the vertical SFRS system is established and preliminary designs are made, a diaphragm shear strength evaluation is an important next step. Seismic diaphragm forces are provided by ASCE 7-10, Equation 12.10-1, as:

$$F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px}$$

This equation has lower and upper bound limits:

$$0.2S_{DS} I_e w_{px} \le Fpx \le 0.4S_{DS} I_e w_{px}$$

The redundancy factor, ρ, may be taken as 1.0 for the Fpx forces, but diaphragm transfer forces from the stories above shall have ρ equal to the value required for the structure. In multi-story buildings, for all levels except the roof, the Fpx force typically governs over the story force at the level under consideration. This is due to the observation that higher-mode responses of lower levels of multistory buildings may exceed the story force from the analysis procedure for the vertical system. Because these higher-mode responses do not happen simultaneously in the response history of the structure, nor necessarily in the same magnitude or sense as the other levels, it is not necessary to design the vertical system for the diaphragm Fpx forces. Rather, the Fpx forces should be applied separately at each individual level for analysis.

Notably, it is also not the intention of the code to have the diaphragm system, nor its components, be a primary source of inelastic response in a seismic event. This idea is reflected in the force provisions of ASCE 7-10 for diaphragm and component forces.

Balance and Force

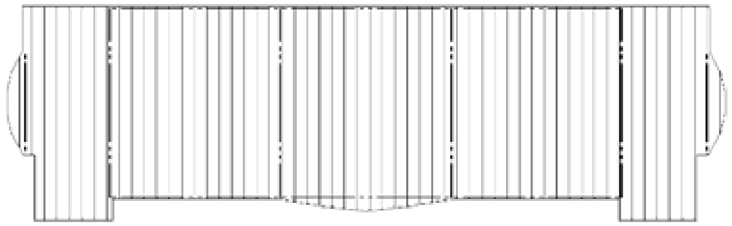
A spreadsheet tabulating story forces, weights, *Fpx* forces and lower/upper bounds is commonly helpful to establish the governing diaphragm forces at each level. To implement them in your analysis model, they should be placed incrementally at each story to assess the associated frame reactions one level at a time. Placing the diaphragm forces at each floor in one simultaneous analysis may unnecessarily affect the frame reactions at the level under consideration due to the transfer force from loads redistributing through the diaphragm as a result of varying relative stiffness of the resisting elements on that level.

From this point, frame reactions balancing the mass load of the diaphragm can be used to generate shear and moment diagrams in each direction for further design. This may be accomplished through the use of a spreadsheet for the overall diaphragm. Alternatively, shear and moment values can be reviewed directly from an analysis model at areas of interest through section cuts in a semi-rigid diaphragm model. Shear diagrams are used to check diaphragm shear capacity and total collector forces while moment diagrams are used to derive axial chord forces when divided by the diaphragm depth. It may be observed that the moment diagram often does not fully close. This is attributed to the torsional moment in the diaphragm resulting from eccentricities (inherent and/or accidental). Procedures have been published to correct the moment diagram for this effect (see "Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms" in NIST's *NEHRP Seismic Design Technical Brief No. 5*).

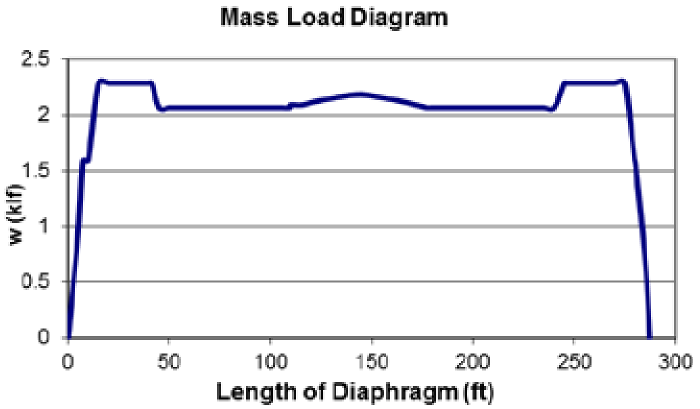
From the generated shear diagrams, a shear capacity check can be made for the diaphragm. For concrete-filled metal deck slabs, the shear strength may be calculated considering the concrete above the flutes—or alternatively, the Steel Deck Institute's (SDI) *Diaphragm Design Manual* publishes equations and tables of shear resistance based on a combination of concrete cover and the contribution of deck-to-steel framing fasteners in the diaphragm field. Bare metal deck diaphragms also require an analysis per SDI procedures for shear capacity, but many deck manufactures have published tabulated values that have been evaluated by the ICC-ES based on deck parameters, connections to framing and sidelap fastener arrangement. Metal deck shear checks should be performed early in design, as the need for a composite slab roof is not uncommon in high-seismic areas, depending on the building type and SFRS. The quandary with composite slab roofs is that a composite slab provides higher shear strength, but it also adds mass to the system thereby increasing seismic forces. The need for a composite slab roof may also affect architectural and MEP details, hence the need for a decision early in the design process.

Collectors, Chords and Connections

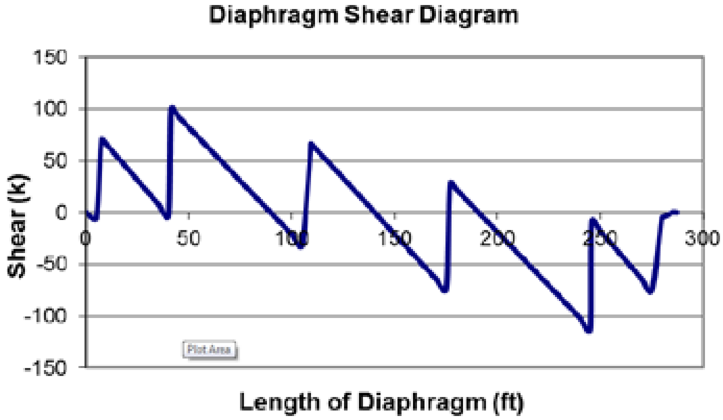
Diaphragms in steel buildings also typically consist of collector and chord member components, which are necessary to transfer the forces to the primary SFRS. These members are loaded axially and are commonly composed of steel floor beams. ASCE 7 provides three equations to establish the governing design force for collectors and



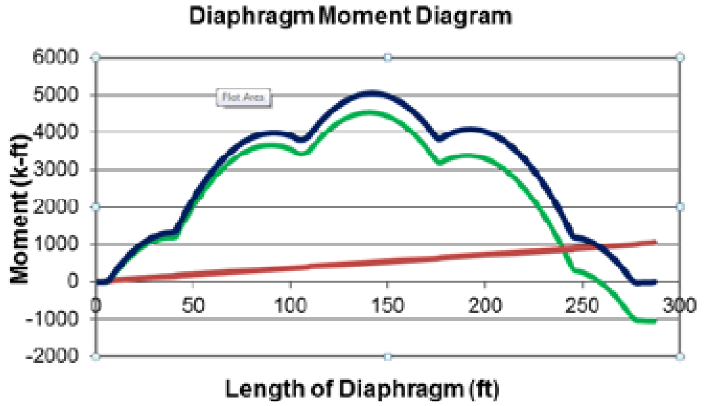
An example floor plan and SFRS elements for diaphragm analysis.



Mass load diagram of diaphragm.



Shear diagram of diaphragm.



Moment diagram of diaphragm (constructed with superposition of integrated shear diagram with linear moment correction due to M_T).

their connections: the greater of the forces resulting from $\Omega_0 F_i$, $\Omega_0 Fpx$ or the lower-bound value of Fpx from ASCE 7-10, Equation 12.10-2. In many cases, the amplified (omega level) seismic forces govern. Note that these forces apply to collectors and chords for buildings in Seismic Design Category C and above.

Axial compression commonly governs the selection of collector and chord members. In high-seismic areas (SDC D and above or any system with $R>3$) sections for chords and collectors should also meet the width-to-thickness requirements of the *Seismic Provisions for Structural Steel Buildings* (ANSI/AISC 341) and properly braced to limit slenderness. Connection design of chords and collectors may be performed in accordance with the *Specification for Structural Steel Buildings* (ANSI/AISC 360). With amplified seismic forces required for these members and their connections, it is not uncommon for multiple lines of bolts to be needed to transfer the required forces. Other more robust welded connections or flange plate transfer mechanisms are also possible and may be prudent in some situations. (Both the *Specification* and *Seismic Provisions* are available at **www.aisc.org/specifications**).

The connections of the diaphragm itself to frame members and to collector and chord elements are commonly accomplished through welded shear studs for composite slabs or metal deck attachments for non-composite roof construction. Spacing of these connections must be carefully assessed to transfer the appropriate forces. Spacing of shear studs to frames and collector/chord members will typically be closer than that required for composite or partially composite gravity beams. Elements like shear studs and puddle weld deck attachments to SFRS members may even be treated as collectors and designed for the required collector forces per ASCE 7-10. Such a distinction enables an assurance that the forces get to the system as designed, keeping the expected inelastic behavior of the SRFS contained within the vertical resisting elements.

Mechanical fastening of decks is also increasing in popularity. It has been observed through published research that while mechanically fastened decks (screw attachments or powder-actuated fasteners) may not be as strong as puddle-welded connections, they can possess greater ductility (see "Inelastic Seismic Response of Frame Fasteners for Steel Roof Deck Diaphragms" in ASCE's *Journal of Structural Engineering*, 2003). Both concepts of strength and ductility are important in seismic design, and the unique details of any one project may lend themselves to the selection of one or another.

In summary, the requirements and provisions for diaphragm design are voluminous. Although final design may only be completed toward the end of the construction document phase, critical design decisions—such as diaphragm aspect ratios, preliminary shear capacity checks, collector and chord locations and ensuring a workable system is ultimately achievable—are all important parameters to establish early in the design process. It is also recommended that designers familiarize themselves with the relevant building and design codes and advanced literature available on these topics. Even if certain code provisions and/or topics are not necessarily required for one particular project or jurisdiction, the ideas presented in the recognized literature and codes are the best information we have available in the engineering community to achieve appropriate and practical diaphragm designs for steel structures in high-seismic areas. ■

This article is based on Session N18 "Diaphragm Analysis, Design and Connection Considerations in Steel Seismic Force-Resisting Systems" from the 2018 NASCC: The Steel Conference, which took place April 11-13 in Baltimore. Visit ***www.aisc.org/nascc*** *roughly a month following the conference to view the presentation.*