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Seismic Design for Composite Steel Deck and Concrete Diaphragms

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Course Author: Mathew Holstrom

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1. Introduction

Building structures are typically composed of horizontal spanning elements, such as beams and floor and roof decks; vertical elements, such as columns and walls; and foundation elements. Together these elements comprise an integral system that resists both vertical and lateral loads. Seismic design of building systems entails controlling the building displacements, typically by providing resistance to the inertial forces generated by the acceleration of the building mass. Often the great majority of the load is derived from the mass of the roof and floor systems themselves, and resistance is composed of a continuous lateral load path from these spanning elements to vertical elements that have lateral resistance (e.g., walls, braced frames, moment frames), which in turn deliver the forces to the foundation.

The first segment of this load path is composed of the diaphragm system. This system is typically conceived of as spanning horizontally between the vertical elements of the lateral load-resisting system. Without this element of the load path there would be no resistance to the movement of the distributed building mass, and thus large movements, and perhaps collapse, would result. Thus, diaphragms are a critical component of seismic design and must be properly designed to ensure adequate performance. Additionally, diaphragms serve a number of other functions in providing structural stability and resistance to lateral loads, as discussed in Section 2.

This course addresses the design of diaphragms composed of steel beams and steel deck with concrete fill. In passing, the Course addresses some issues related to the design of diaphragms with non-composite (bare) steel deck, but a future Technical Brief devoted entirely to bare steel-deck diaphragms is anticipated.

The National Earthquake Hazards Reduction Program (NEHRP) Seismic Design Technical Brief No.3, *Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors*, includes a great deal of useful information on diaphragm design in general. In order to maximize the utility of this Technical Brief as a stand-alone design reference work, some material is duplicated here, however, this material is integrated with a treatment of conditions beyond the scope of the reinforced concrete diaphragm Technical Brief, such as semirigid and flexible diaphragms.

This course covers seismic design issues pertaining to Seismic Design Category B up through Seismic Design Category F. As Seismic Design Category A is exempt from seismic design, it is not specifically addressed, although many of the diaphragm analysis and design methods described herein are applicable to the design of diaphragms to resist wind forces and provide structural integrity in Seismic Design Category A buildings.

Sidebars in the Course

Sidebars are used in this course to illustrate key points and to provide additional guidance on good practices and open issues in analysis, design, and construction.

Items not covered in this document

A number of important issues related to diaphragm design are not addressed in this document; these include:

- Formed concrete diaphragms on steel members (these are addressed in *Seismic Design Technical Brief No.3: Seismic Design of Cast-in-Place Concrete Diaphragms, Chords, and Collectors*);
- Out-of-plane wall support and design of sub-diaphragms;
- Design of open-web joists as chords or collectors;
- Ramp issues in parking garages;
- Saw-tooth roofs and similar discontinuities;
- Detailed treatment of steel-deck only systems;
- Strut-and-tie analysis methods; and
- Expansion joints and seismic separation issues.

The design forces and analysis requirements for diaphragms are contained in ASCE/SEI 7-10 *Minimum Design Loads for Buildings and Other Structures* (ASCE 2010, herein referred to as ACSE 7). ASCE 7-10 is the latest published version of that standard, though in a particular case at the time a reader may consult this Course, a jurisdiction may reference the previous (2005) edition in its code regulations. The forward-looking approach here in this Course will facilitate its use over the next several years, because ASCE 7-10 has been adopted into the 2012 edition of the *International Building Code* (IBC 2012, herein referred to as IBC), which establishes general regulations for buildings. The 2012 IBC adoption of ASCE 7-10 has no modifications relevant to composite or concrete-filled steel deck diaphragm design.

Component strengths are determined using ANSI/AISC 360 *Specification for Structural Steel Buildings* (AISC 2010, referred to here as AISC 360) for steel and composite members. ANSI/AISC 341 *Seismic Design Provisions for Structural Steel Buildings* (AISC 2010b, herein referred to as AISC 341) contains additional requirements, including limitations and quality requirements. The IBC adopts both of these standards.

The design in-plane shear strength of concrete-filled or unfilled steel deck can be determined by calculation, or it may be done by testing and subsequent development of an evaluation report. Historically, two approaches have commonly been used to calculate the in-plane shear strength. These approaches are described in the Steel Deck Institute *Diaphragm Design Manual* (SDI 2004, referred to here as SDI DDM, with SDI DDM03 citing the third edition) and the *Seismic Design of Buildings - TI 809-04* (USACE 1998.) Neither is a design code, however IBC recognizes the SDI DDM. Note that TI 809-04 often called the Tri-Services Manual, was superseded by UFC 3-310-04, *Seismic Design for Buildings* in 2007 and updated in 2010 (UFC 2010.) The specific design information that appears in TI 809-04 for diaphragms does not appear in UFC 3-310-04. A consensus standard for steel deck diaphragms that is predominately based on the SDI DDM03 is under development by the American Iron and Steel Institute. In cases where the designer wishes to ignore the presence of steel deck in concrete-filled systems, the in-plane strength of the concrete above the top flange of the deck is evaluated using Building Code Requirements for Structural Concrete and Commentary (ACI 2008, herein referred to as ACI 318). The attachment of the slab to the steel framing would then need to be addressed using one of the other documents, as ACI 318 does not explicitly address this condition. (References to the building code in this Course refer to the editions cited above.)

Together these documents comprise the building code requirements applicable to composite deck and steel deck diaphragms. While each of these documents has been developed or revised over numerous cycles to work with the others, there nevertheless exist ambiguities, and engineering judgment is required in their consistent application. This Course is intended to address these ambiguities and to provide guidance on the appropriate design of composite deck and steel deck diaphragms. While numerous respected practitioners, researchers, and other authorities have been consulted, this Course represents only the opinion of the authors on matters not explicitly defined by building codes, design standards, or design manuals, and other interpretations may be reasonable.

This course was written for practicing structural engineers and is intended to provide guidance in the application of code requirements for the design of diaphragms in steel systems. This course will also be useful to others wishing to apply building code provisions correctly, such as building officials, and to those interested in understanding the basis of such code provisions and of common design methods, such as educators and students.

This cCourse begins by generally discussing the role of diaphragms (Section 2), identifying the components of diaphragms (Section 3), and proceeding to the behavior of diaphragms (Section 4). Next the Course describes the building analysis necessary to obtain appropriate diaphragm design forces (Section 5), and the analysis of the diaphragm itself (Section 6). The Course proceeds to detailed guidance on the design of diaphragm components (Section 7). Additional requirements are given in Section 8, and constructability concerns are discussed in Section 9. References are listed in Section 10. Section 11 contains a list of notations, abbreviations, and a glossary. Section 12 provides credits for figures contained within this document.

2. The Roles of Diaphragms

2.1 Typical Conditions

Diaphragms serve multiple roles to resist gravity and lateral forces in buildings. **Figure 2-1** illustrates several of these roles for a building with a podium level at grade and with below-grade levels. The main roles include:

- *Transfer lateral inertial forces to vertical elements of the seismic force-resisting system* – The floor system commonly comprises most of the mass of the building. Consequently, significant inertial forces can develop in the plane of the diaphragm. One of the primary roles of the diaphragm in an earthquake is to transfer these lateral inertial forces, including those due to tributary portions of walls and columns, to the vertical elements of the seismic force-resisting system.
- *Resist vertical loads* – Most diaphragms are part of the floor and roof framing and therefore support gravity loads. They also assist in distributing inertial loads due to vertical response during earthquakes.
- *Provide lateral support to vertical elements* – Diaphragms connect to vertical elements of the seismic force-resisting system at each floor level, thereby providing lateral support to resist buckling as well as second-order forces associated with axial forces acting through lateral displacements. Furthermore, by tying together the vertical elements of the lateral force-resisting system, the diaphragms complete the three-dimensional framework to resist lateral loads.
- *Resist out-of-plane forces* – Exterior walls and cladding develop out-of-plane lateral inertial forces as a building responds to an earthquake. Out-of-plane forces also develop due to wind pressure acting on exposed wall surfaces. The diaphragm-to-wall connections provide resistance to these out-of-plane forces.
- *Transfer forces through the diaphragm* – As a building responds to earthquake loading, lateral shears often must be transferred from one vertical element of the seismic force-resisting system to another. The largest transfers commonly occur at discontinuities in the vertical elements, including in-plane and out-of-plane offsets in these elements. **Figure 2-1** illustrates a common discontinuity at a podium slab. The tendency is for a majority of the shear in the vertical elements above grade to transfer out of those elements, through the podium slab, and to the basement walls. Large diaphragm transfer forces can occur in this case.
- *Support soil loads below grade* – For buildings with subterranean levels, soil pressure bears against the basement walls out-of-plane. The basement walls span between diaphragms or between a diaphragm and the foundations, producing compressive reaction forces at the edges of the diaphragms.

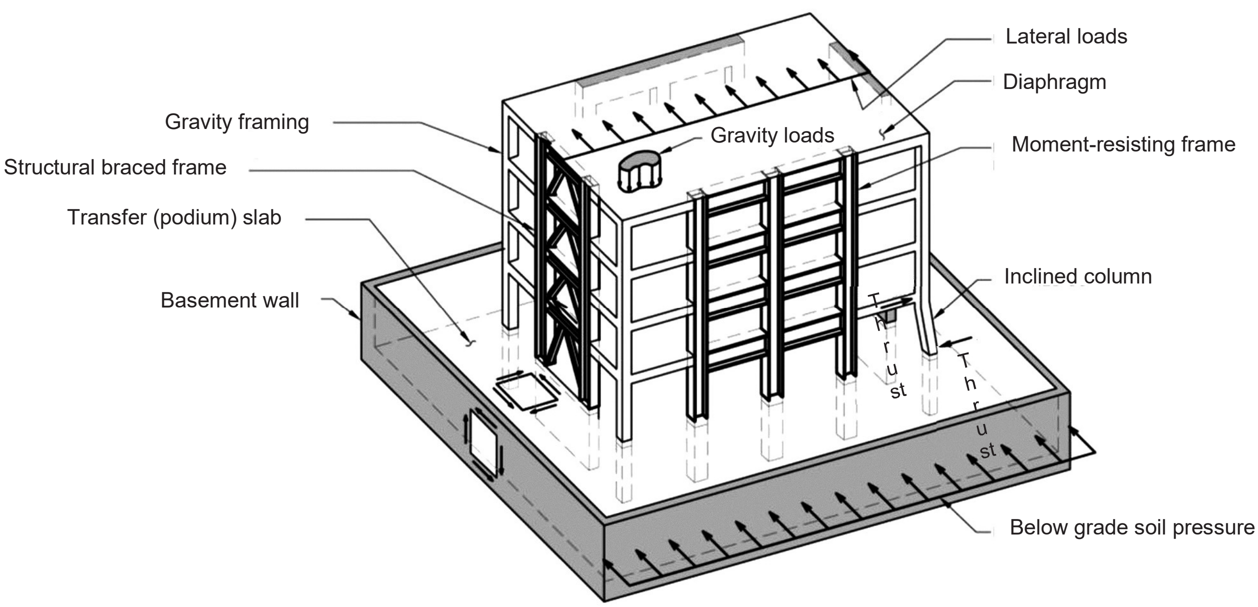

Figure 2-1 – Roles of diaphragms.

2.2 Additional Functions

Diaphragms also serve a number of specialized functions, which include:

- *Redistribution of loads around openings* – For buildings with stairway openings, mechanical shafts, elevator shafts, and other large openings such as atria, the diaphragm assists in redistributing lateral forces around the openings and to the lateral force-resisting elements.

- *Redistribution of forces due to torsion* – Some architectural configurations result in torsional response due to the application of lateral forces. Diaphragms with sufficient strength and stiffness are capable of distributing forces to the lateral force-resisting elements. Relatively flexible diaphragms generally do not facilitate the distribution of lateral forces due to torsion.

- *Resist thrust from inclined and offset columns* – Architectural configurations sometimes require inclined or offset columns, which can result in large horizontal thrusts acting within the plane of the diaphragms, due to gravity and overturning actions. Additionally, vertical columns become somewhat inclined when the building undergoes significant drift. The thrusts can act either in tension or compression, depending on orientation of the column and whether it is in compression or tension. The diaphragm or components within it need to be designed to resist these thrusts.

Chapter 12 of ASCE 7 classifies a number of horizontal structural irregularities, such as reentrant corners, diaphragm discontinuities, and torsional irregularities that may impact the response of a diaphragm and must be considered by the designer. While designers often attempt to evenly distribute vertical elements of the seismic force-resisting system throughout the footprint of the diaphragm, portions of the diaphragm without vertical seismic elements may sometimes exist and extend a considerable distance from the main body of the diaphragm. These diaphragms cantilever horizontally from the bulk of the diaphragm and need to be carefully evaluated by the designer. Generally speaking, aspect ratios associated with flexural behavior, e.g., aspect ratios greater than 1.5 to 2, may require diaphragm chords to develop the tension component of flexural demand. Although not a code requirement, the importance of maintaining an integral load path suggests that the magnitude of the chord force assumed in design should be sufficient to maintain elastic behavior under all but the largest earthquakes. Use of building code seismic demands amplified by Ω_0 , the system overstrength factor, is one approach to accomplish this goal. The development of these chord members may extend a considerable distance into the main body of the diaphragm. In addition, the cantilevered diaphragm's aspect ratio may result in significant horizontal displacements at the extreme edges that are not accurately captured by analytical models that assume essentially rigid body response.

Another common condition that demands the attention of the designer is where a chord or collector is laterally unbraced over a significant distance, such as at openings in the diaphragm around its perimeter, as shown in **Figure 2-2**, or as a part of a bridge connection between adjacent segments of diaphragm. In these conditions, the effect of the unbraced length on the available compression strength must be considered.

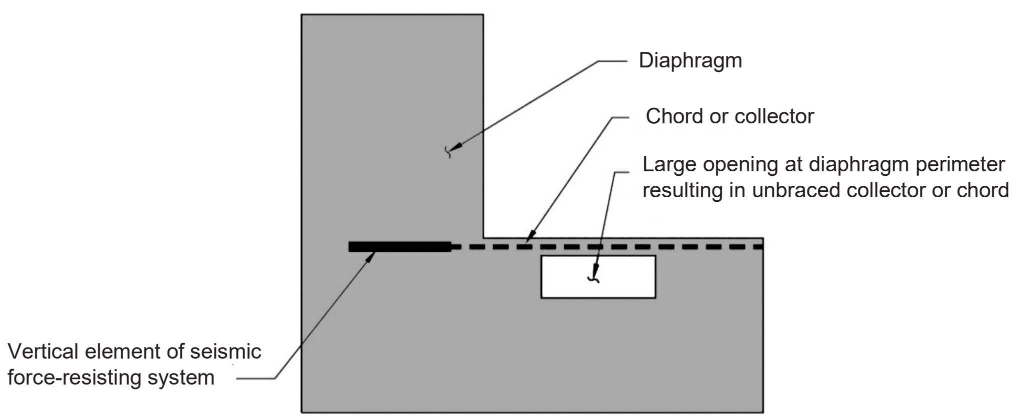

Figure 2-2 – Unbraced collector or chord.

3. Diaphragm Components

Diaphragms consist of several components, each of which must be considered as part of the strength determination and response. These components consist of the deck (bare steel deck or composite slab), chords, collectors (also known as drag struts) and fasteners used to attach the deck to the perimeter framing members. The Glossary in Section 11 defines the specific meanings of these and other terms used in this Course. The diaphragm is commonly idealized as a beam spanning horizontally as shown in **Figure 3.1**. The supports for the beam are the vertical elements of the lateral load-resisting system, such as braced frames, moment frames, or walls. The top and bottom flanges of the beam, referred to as chords, are made up of the steel framing at the perimeter of the floor. The web of the beam is the deck, which provides the shear resistance. The perimeter fasteners are required to tie the deck to the chords and to the vertical elements of the lateral load-resisting system. In cases where the vertical elements of the lateral load-resisting system are not the full depth of the diaphragm, the framing members along the frame line function to "collect" the diaphragm shears and deliver these forces to the frame.

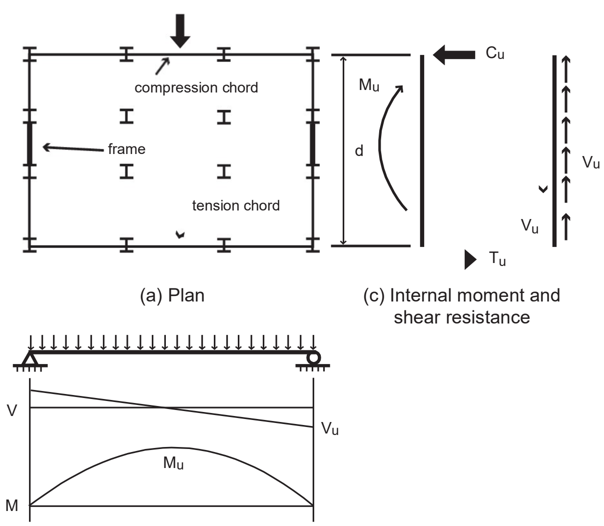

Figure 3-1 – Diaphragm component idealization.

The chord components must be designed to resist the tension or compression generated from beam behavior. These members may be considered non-composite, or, depending on the means by which they are attached to the deck, the designer may wish to consider their composite strength. Given that the diaphragm typically involves multiple bays, the chord members must be tied together through the connections to columns. This results in an axial component of force through the connection that must be considered.

Collectors, or drag struts, occur where the deck forces are transferred to a frame line over a partial length, that is, where the beams that are part of the braced or moment frame do not extend the full depth of the diaphragm. This is illustrated in **Figure 3.1** at the outer frame lines. The remaining spandrel members in **Figure 3.1** are attached to the deck through fasteners collecting inertial forces from the deck and in turn delivering those forces to the frame members. These collector members must transfer the forces to each other across their connections to the columns. Collector forces are illustrated in **Figure 3.2**.

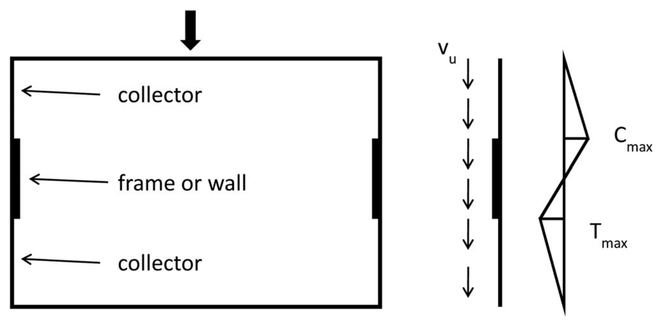

Figure 3-2 – Diaphragm collectors.

The diaphragm deck may consist of either an unfilled steel deck (typical for roofs) or a filled steel deck, or composite steel deck and concrete-filled diaphragm. In all cases, the steel deck consists of individual deck sheets, seam (or stitch) fasteners at the edges of sheets, and structural fasteners at locations of deck support.

The seam fasteners are important to the shear behavior of the unfilled steel deck. Their role in the filled deck diaphragm is less important. They are critical at the construction stage in filled diaphragms, but after the concrete has cured, they are not the mechanism for load transfer, which is achieved through bond of the steel deck to the concrete over essentially the entire diaphragm area. More details and design approaches are given in Chapter 7.