

Seismic Design Methodology for Precast Concrete Diaphragms

Part 1: Design Framework



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The Precast/Prestressed Concrete Institute (PCI) is conducting a large “area of emphasis” research project on precast concrete diaphragms. The effort, jointly funded by the National Science Foundation, has an overall objective of developing an industry-endorsed comprehensive seismic design methodology for precast/prestressed concrete floor diaphragms. A multi-university research team from the University of Arizona (UA), Lehigh University (LU), and the University of California San Diego (UCSD) has been selected to perform this collaborative research. An active industry task group is overseeing the planning and execution phases of the research. These groups comprise the DSDM (Diaphragm Seismic Design Methodology) Consortium. The DSDM Consortium research closely integrates finite element analyses of the diaphragm at UA with full-scale re-

inforcing detail experiments at LU and shaking table system tests at UCSD. The purpose of this article and a companion paper is to outline the foundation for this research, and provide context for the technical papers to follow as well as the eventual design methodology. During the DSDM project’s first year, consensus has been established on: (1) the underlying design philosophy that will guide the research; (2) the physical scope of the project; and (3) the integrated analytical/experimental research program. This paper describes the underlying design philosophy and the resulting framework that will serve as a basis for the emerging design methodology. The companion paper focuses on the research program itself, including the integrated research approach, the project’s physical scope, and the specific analytical and experimental research activities.

The Precast/Prestressed Concrete Institute (PCI) is conducting a large “area of emphasis” research project on precast concrete diaphragms. The effort, which is jointly funded by the National Science Foundation (NSF) through the Grant Opportunities for Academic Liaison with Industry (GOALI) Program, has an ultimate goal of developing a comprehensive seismic design methodology for precast/prestressed concrete floor diaphragms. The project has been coined “DSDM” (Diaphragm Seismic Design Methodology).

The research team is comprised of members from the University of Arizona (UA), the University of California San Diego (UCSD), and Lehigh University (LU). An active panel of industry experts, the DSDM Task Group (DSDM TG), oversees the planning and execution phases of the research. Together, the university researchers (URs), the DSDM TG, and PCI representatives comprise the DSDM Consortium.

A research program has been conceived that will provide a comprehensive examination of precast concrete diaphragms. Each university research group focuses on different but equally important levels of behavior (see Fig. 1) whose complex interaction produces the diaphragm seismic response: local behavior of the reinforcing details at LU; component behavior of the diaphragm at UA; and system behavior of the structure at UCSD.

The LU research component involves full-scale experiments of reinforcing details, supported by analytical modeling of the connection region. The UA research component is entirely analytical, entailing nonlinear static and dynamic finite element (FE) modeling. The UCSD research component includes a shaking table test of a precast/prestressed structure and analytical studies of systems under earthquake simulations.

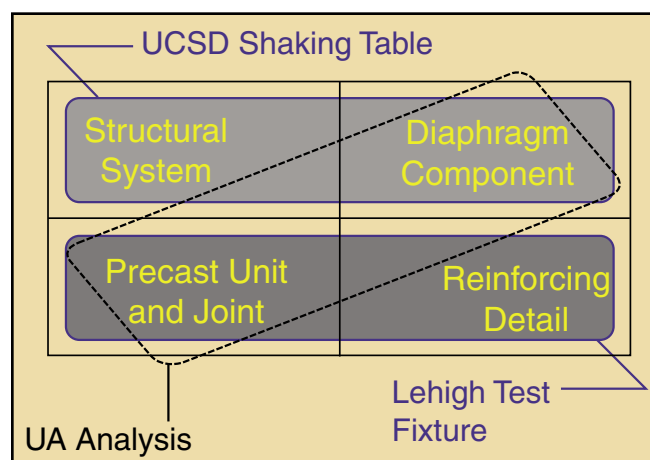


Fig. 1. Diagram of research integration.

These components are closely integrated to produce the needed information on diaphragm behavior. Thus, the effectiveness of the research effort depends on strong technical collaboration between the UR groups at the interfaces between these levels: UA and LU at the joint/detail-level interface; UCSD and UA at the structure/diaphragm-level interface.

The integrated analytical/experimental research plan is structured to develop the needed information on both the capacity of precast diaphragms and the seismic demands to which they are subjected. Research findings are heavily dependent on the diaphragm designs that are studied; thus, it is essential that from the outset of the project the research be aligned with a cohesive design philosophy as it applies to representative precast/prestressed concrete diaphragm designs. Using this design philosophy as a framework, and guided by the industry expertise at hand within the DSDM TG, the information gained on precast concrete diaphragms will be used to produce an appropriate seismic design methodology.

The DSDM project is in its first year. In this and the preceding ramp-up year, the DSDM Consortium held seven Task Group Meetings (TGMs) and three University Research Meetings (URMs). During the TGMs and the URMs, consensus was established on:

1. The underlying design philosophy that will guide the research;
2. The physical scope of the project; and
3. The details of the integrated analytical/experimental research program.

The purpose of this paper is to outline the foundation for the research by presenting the underlying design philosophy and resulting design framework that will serve as the basis for the emerging design methodology. In this way, context will be provided for the technical papers to follow and the eventual design methodology at the project's conclusion. A companion paper, "Seismic Design Methodology for Precast Concrete Diaphragms—Part 2: Research Program," describes the specific analytical and experimental activities taking place in the research.

BACKGROUND

The precast/prestressed concrete industry has mounted a sustained effort to develop seismic-resistant precast concrete

structural systems for buildings, largely supported by the NSF-funded Precast Seismic Structural Systems (PRESSSS) research program. However, the PRESSSS program focused almost exclusively on the primary (vertical plane) lateral force-resisting elements. The unexpected performance of precast concrete diaphragms in recent earthquakes,¹ and the subsequent research^{2,3} has underscored the need to develop and demonstrate a reliable seismic design methodology for precast/prestressed floor diaphragms.

While recent modifications to diaphragm design practice have been codified, e.g., 1997 Uniform Building Code (UBC),⁴ it is generally agreed among researchers and practitioners that current design practices require significant further clarification.⁵ For this reason, PCI issued an RFP in October 2002 for the development of a seismic design methodology for precast concrete diaphragms, and subsequently awarded the project to the DSDM Consortium.

DSDM CONSORTIUM

The DSDM Consortium is comprised of URs, PCI personnel, the DSDM TG, and participating producer members (see Fig. 2).

UR Team

The DSDM project is being led by the University of Arizona under Principal Investigator (PI) Dr. Robert B. Fleischman. The Co-PIs are Dr. Clay J. Naito and Dr. Richard Sause of Lehigh University and Dr. José Restrepo of the University of California San Diego. Dr. André Filiatrault, formerly of UCSD, participated in the proposal phase. The industry Co-PI, as per the NSF GOALI program, is Dr. S.K. Ghosh. The graduate student researchers are Ge Wan and Anuja Kamat of the University of Arizona; Liling Cao and Wesley Peter of Lehigh University; and Matt Schoettler of UCSD.

DSDM TG

The selection of the physical scope of the DSDM project and the transfer of the research into practical design methodology at the project's conclusion is being facilitated by a ten-member DSDM TG. The membership of the DSDM TG includes:

- S.K. Ghosh, DSDM Project Co-PI, president, S.K.

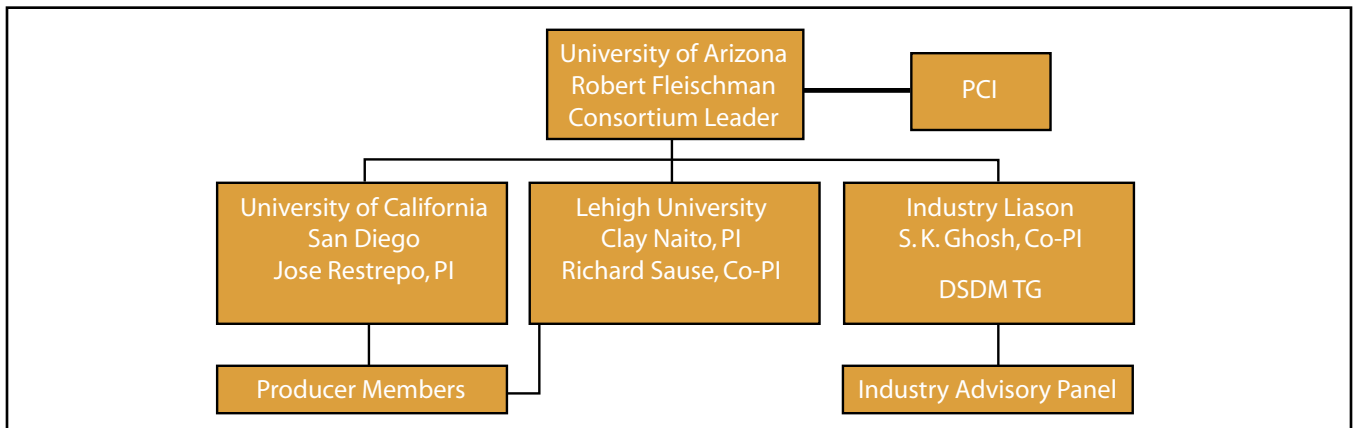


Fig. 2. DSDM Consortium.

Ghosh Associates, Inc., Skokie, IL;

- Tom D'Arcy, DSDM Task Group Chair, PCI R&D Committee; founder, The Consulting Engineers Group, San Antonio, TX;
- Roger Becker, vice president, Spancrete Industries, Inc., Waukesha, WI;
- Ned Cleland, president, Blue Ridge Design, Inc., Winchester, VA;
- Harry Gleich, vice president-engineering, Metromont Prestress, Greenville, NC;
- Neil Hawkins, professor emeritus, University of Illinois, Urbana-Champaign, IL;
- Paul Johal, PCI research director, Precast/Prestressed Concrete Institute, Chicago, IL;
- Joe Maffei, structural engineer, Rutherford & Chekene Engineers, Oakland, CA;
- Susie Nakaki, president, The Nakaki Bashaw Group, Inc., Irvine, CA;
- Doug Sutton, chair, PCI Research & Development Committee, and professor, Purdue University, West Lafayette, IN.

The DSDM TG possesses expertise and extensive experience with precast construction practices, seismic design procedures, and particularly code writing bodies. The DSDM TG has representation across the United States, including the West Coast, the East Coast, and the Midwest.

During the ramp-up year and the first year, the DSDM TG has participated in seven TGMs largely focused on develop-

ing consensus and providing guidance on defining the project scope. Research meeting coordination and support is provided by PCI personnel Paul Johal, research director and Jason Krohn, technical director.

In addition to the formal meetings, interactions among the researchers and the DSDM TG occur through: (1) bi-weekly conference calls of the researchers and (2) immediate reporting and interaction through a collaborative internet workspace established by the NSF George E. Brown Network for Earthquake Engineering Simulation (NEES).

These communication tools have facilitated development of the details of the integrated analytical/experimental research program, including the needed interactions between each UR group and critical path dependencies.

Participating Producer Members

The experimental components depend heavily on contributions from PCI producer members for specimen details. The following producer members have donated or have pledged future donations of products for the testing program:

- Blakeslee Prestress, Inc.
- High Concrete Structures
- Precast/Prestressed Concrete Manufacturers Association of California, Inc.
- Spancrete, Inc.
- Tindall-Virginia
- Ivy Steel & Wire
- Metromont Prestress

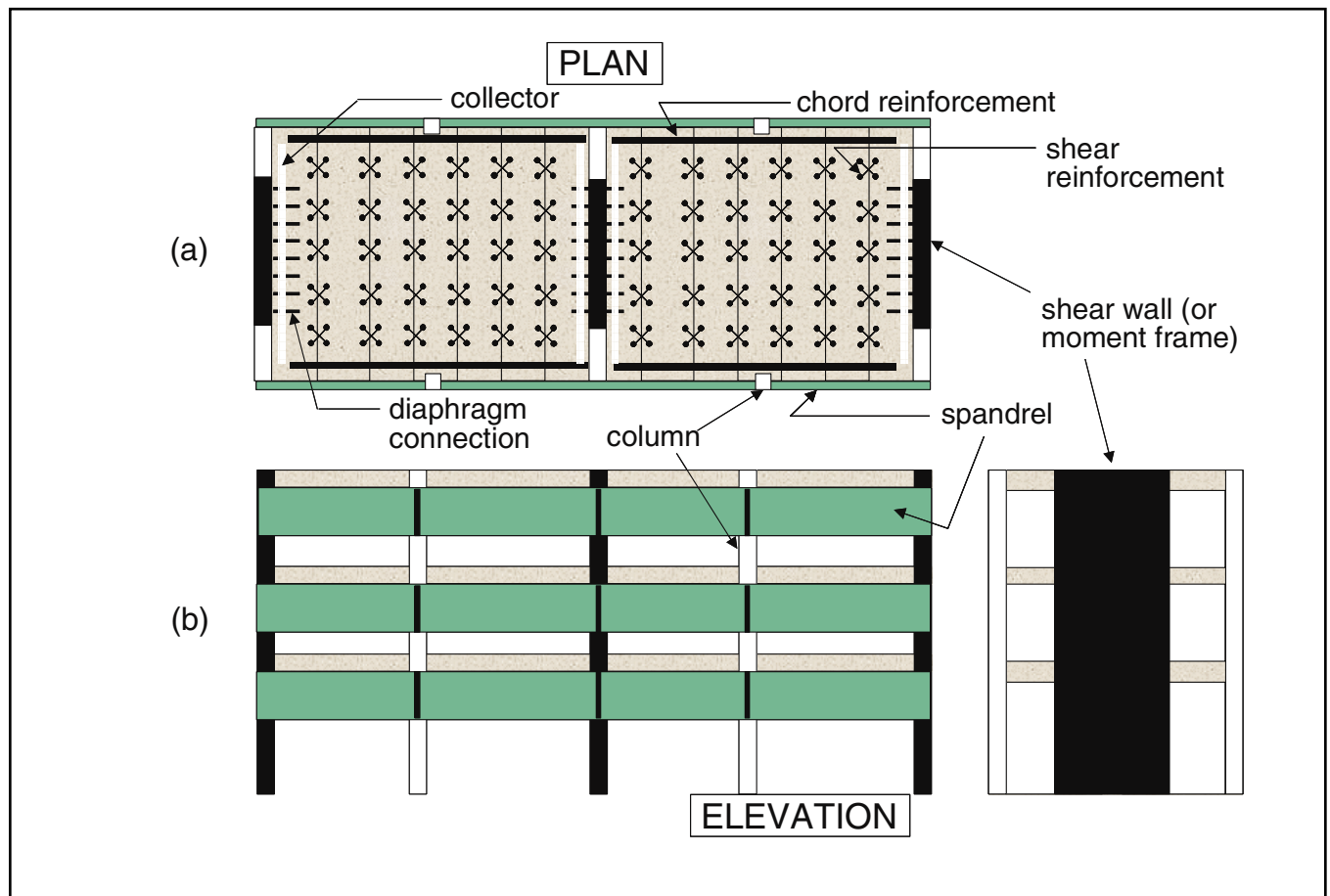


Fig. 3. Lateral Force Resisting System (LFRS) Schematic: (a) Diaphragm elements; (b) Vertical elements.

TERMINOLOGY AND DEFINITIONS

It may be useful at the outset to provide a consistent set of terminology and definitions for the interpretation of information provided in this and subsequent papers produced by the DSDM project. The reader is referred to Chapter 3 of the PCI Handbook⁶ for a more extensive treatment.

Floor Diaphragm

Floor diaphragms (see Fig. 3a) serve as the horizontal elements of the lateral force resisting system (LFRS), in which the primary (vertical plane) elements are typically shear walls or moment frames (see Fig. 3b). Floor diaphragms serve both to connect the individual vertical elements to create the LFRS, and in the context of seismic design, transfer the inertial forces that develop in a seismic event (see Fig. 4a).

Thus, while the role of the precast/prestressed floor system (double tee or hollow core units, inverted tees, and spandrels) is often considered as providing support for gravity loads acting out of the plane of the floor, it also plays a key role by providing strength and stiffness in the plane of the floor, so-called diaphragm action.

Precast floor diaphragms are classified as one of three construction types:

1. Untopped Diaphragm—An untopped diaphragm refers to a floor system comprised only of precast units (often pretopped). In this case, diaphragm action must be provided by the precast units and the connections between the precast

units. This type of diaphragm is not currently permitted in high seismic zones. The extent of this system's applicability into high seismic zones will be studied in the DSDM project.

2. Topped Noncomposite Diaphragm—A topped diaphragm refers to a floor system in which a cast-in-place topping is placed over the precast units. Topped noncomposite construction employs a structural topping designed to carry the diaphragm forces entirely. Connections between the precast units can exist for the purpose of erection stability, serviceability, or structural integrity but are not part of the formal diaphragm design. The topped noncomposite diaphragm is the typical construction used currently in high seismic zones. Since this system ignores the contribution of the precast elements, it will not be a focus of the DSDM research.

3. Topped Composite Diaphragm—A topped composite diaphragm relies on both the topping and the precast units for diaphragm action. Implied in such a design is the ability for the topping and the precast units to act compositely, i.e., transfer shear at the interface of the topping and the underlying precast unit. This system will be the type of topped diaphragm studied in the DSDM project.

Diaphragm Reinforcement Groups

Floor diaphragms can be considered to act as horizontal deep beams. Accordingly, diaphragm reinforcement is composed of three primary reinforcement groups (see Fig. 3a):

1. Chord Reinforcement—Chord (or flexural) reinforce-

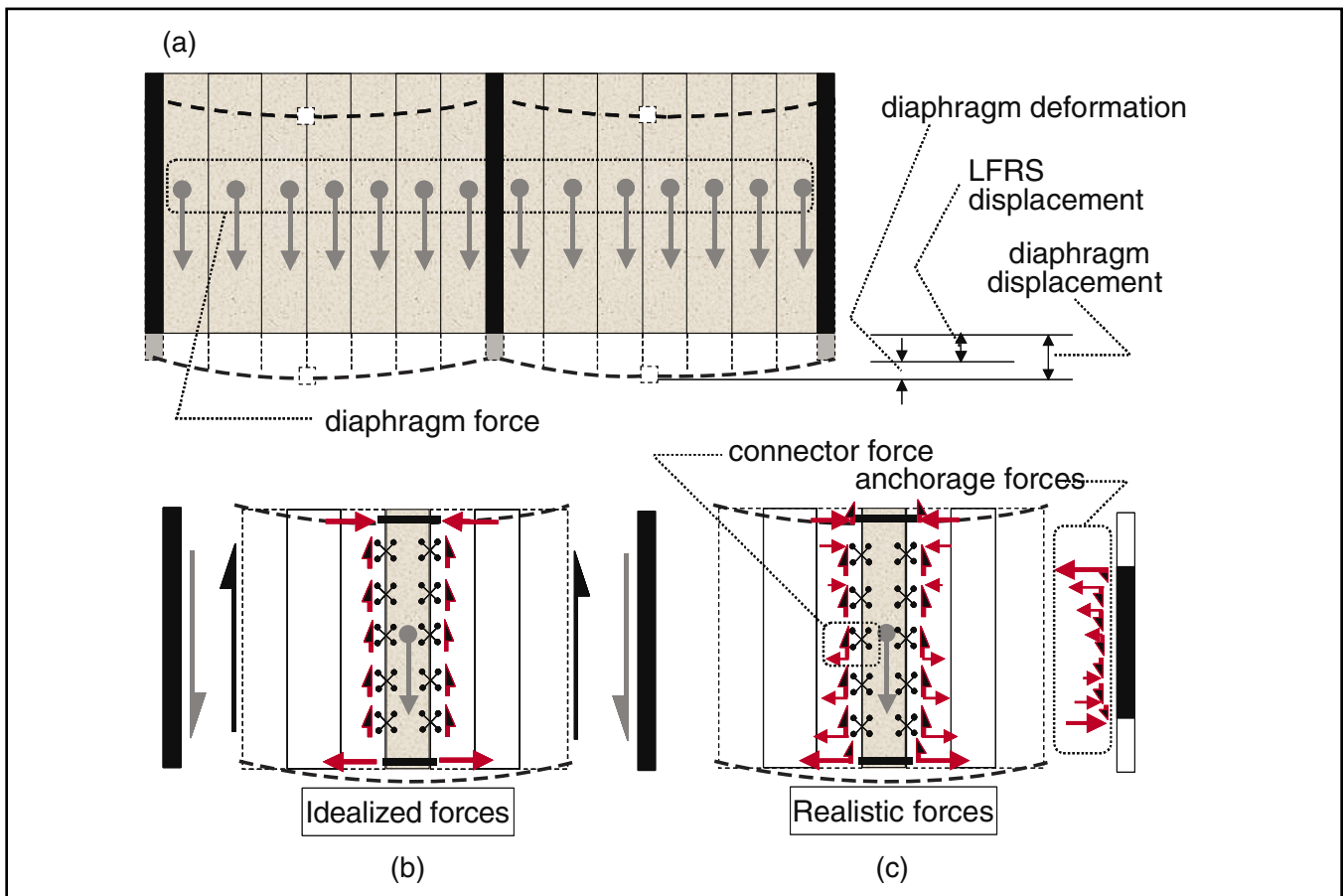


Fig. 4. Schematic of diaphragm forces and deformations.

ment is designed to resist in-plane bending of the diaphragm. The term “chord” refers to the placement of the reinforcement at opposing ends of the floor or floor segment.

2. Shear Reinforcement—Shear reinforcement is designed to resist the in-plane diaphragm shear, analogous to “beam” shear. Additionally, tributary shear reinforcement is required along transverse internal beams (shown in Fig. 8).

3. Collector Reinforcement—Collector reinforcement is designed to “collect” the diaphragm forces back to the primary elements of the LFRS (walls or frames), analogous to beam reactions of a horizontal beam. A wall/frame (to diaphragm) anchorage⁴ transfers force from the diaphragm to the primary LFRS elements.

Diaphragm Reinforcing Details

In precast concrete diaphragms, the critical condition for the diaphragm reinforcement occurs at joints between the precast units. This remains the case even for topped diaphragms, as the locations where the slabs cross the joint represent planes of weakness. Therefore, the primary focus is on the reinforcing details that cross these joints, whether that be discrete reinforcing elements such as flange-to-flange connectors or simply the portion of continuous rein-

forcement crossing the joint.

1. Chord Reinforcing Details—In a topped system, chord reinforcement is typically continuous bars placed in the topping slab. In untopped systems, a “dry” chord connection detail refers to connectors that are continuous across a precast unit (see Fig. 5a). Alternatively, continuous bars can be placed in pour strips (see Fig. 5b).

2. Shear Reinforcing Details—In the topping, shear reinforcement can be provided in the form of welded wire reinforcement or reinforcing bars. Shear reinforcement between precast units is provided by flange-to-flange connectors, whether alone as in the case of an untopped system (see Fig. 6a) or in conjunction with the topping in a topped composite system (see Fig. 6b). In untopped hollow-core slabs, shear reinforcement can also be provided by grouted keyways in conjunction with shear friction of the chord reinforcement.

3. Collector Details—Where required, the collector detail is continuous bars in the slab or precast unit parallel to the diaphragm force that extend to the primary LFRS elements. The diaphragm anchorage detail may consist of bars or threaded inserts extending into the topping/pour strip, or a stud group in the wall connecting to a flange connector in the precast unit (e.g., Fig. 11a).

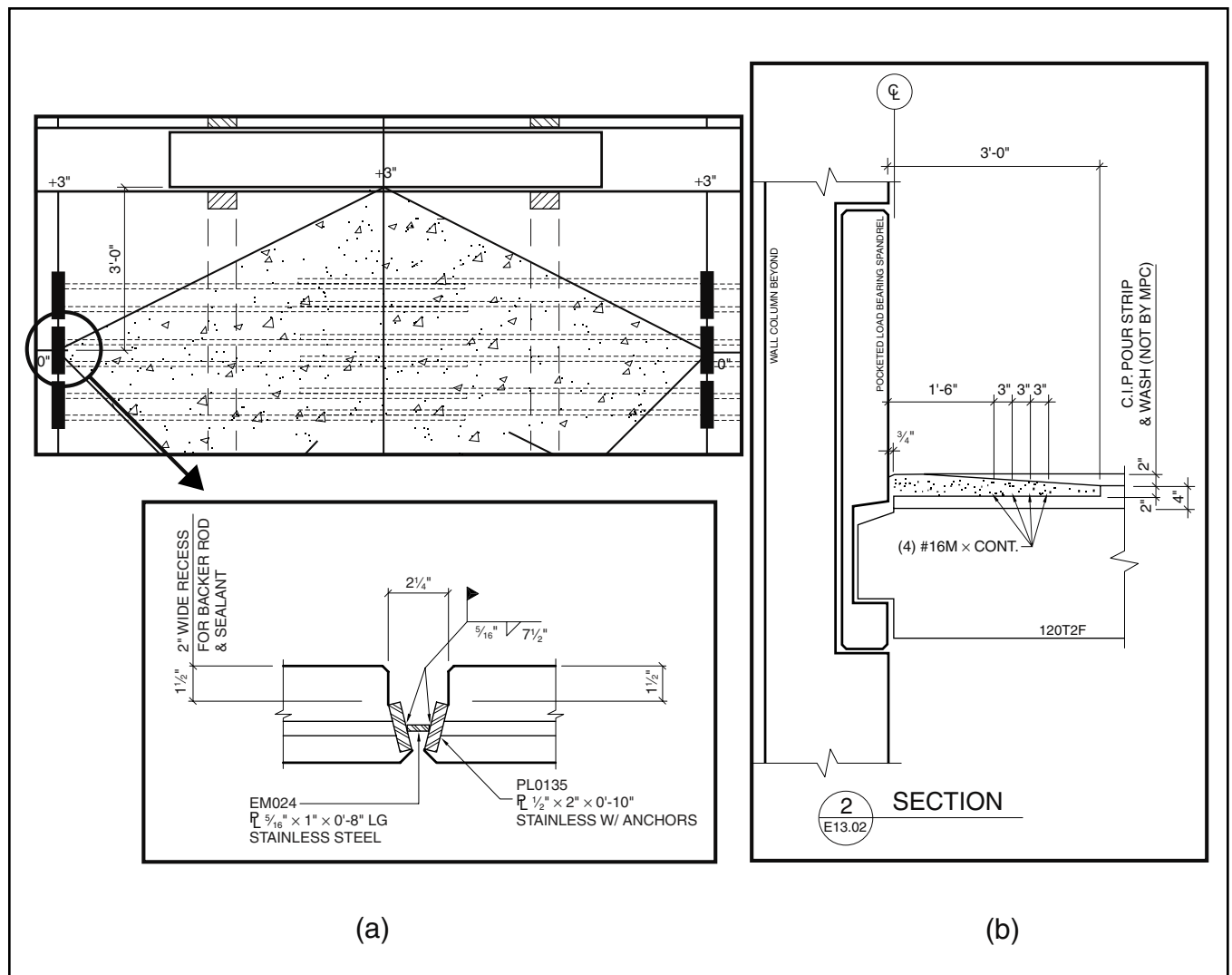


Fig. 5. Typical chord reinforcing details: (a) Untopped diaphragm; (b) Topped/pour strip.

Diaphragm Seismic Demands

In the DSDM research, diaphragm seismic demands will be expressed globally (e.g., diaphragm force, diaphragm drift, diaphragm deformation), at a joint (internal force component), and locally (e.g., connector force, connector deformation).

1. Diaphragm Force—Diaphragm force refers to the total lateral (inertial) force that acts on a diaphragm at a given level (see Fig. 4a). In DSDM research papers, diaphragm force will refer to actual inertial force values expected in a seismic event (a demand); diaphragm “design” force will refer to the value used in design. The term “large diaphragm force event” describes a diaphragm force exceeding the design force.

2. Diaphragm Drift—Diaphragm drift will refer to the lateral displacement of the floor diaphragm at a given level. The gravity system columns at the region of maximum diaphragm drift must be able to support the floors while undergoing this lateral displacement (see Fig. 4a). For convenience, the lateral displacement of the primary LFRS elements will be termed “LFRS drift.”

3. Diaphragm Deformation—Diaphragm deformation refers to the diaphragm drift relative to the LFRS drift at that particular floor level (see Fig. 4a). Precast concrete diaphragms are often classified as flexible diaphragms in which maximum deformation can be significant.

4. Diaphragm Internal Forces—Diaphragm forces are carried through load paths that cross joints between the precast units. Thus, reinforcing details at the joints are subjected to local forces, e.g., connector forces, chord forces, anchorage forces (see Fig. 4c). These local forces typically contain both a component parallel to the joint (shear component) and perpendicular (axial component). The set of local forces acting along a joint can be resolved into diaphragm internal force components (shear, moment, thrust) acting on the entire joint. The term “internal force combination” will be used when two or more of these force components coincide at a joint. The term “internal force overload” will be used to refer

to the occurrence of a set of internal force components that cause the elastic limit of a diaphragm reinforcing detail to be exceeded.

5. Local Deformation—A significant portion of precast diaphragm deformation may be due to joint opening between the precast units. As such, reinforcing details will be subjected to local deformation demands at the joints. For low intensity seismic events, this deformation will tend to be elastic; however, in stronger seismic events the possibility exists that these deformations reach inelastic levels (termed “local ductility demands”).

Diaphragm Design Properties

In the DSDM research, diaphragm design properties will be expressed globally (e.g., diaphragm strength, diaphragm stiffness, diaphragm deformation capacity, drift capacity) and locally (e.g., connector strength, connector stiffness, connector deformation capacity).

Note that a distinction will be made between nominal and actual properties as they may not coincide. Diaphragm designs will be evaluated by comparing expected seismic demands to expected capacities (i.e., force demand versus strength, deformation demand versus deformation capacity, drift demand versus drift capacity).

A key role of the diaphragm is to provide “structural integrity,” i.e., maintain the floor system’s gravity load-carrying capacity while undergoing diaphragm action. While a designer could attempt to achieve this objective through diaphragm strength alone, it is the consensus of the DSDM Consortium that the key characteristic of the diaphragm with respect to structural integrity is “deformation capacity” of the diaphragm reinforcing elements.

The following terms are used:

1. Ductility—A measure of an element’s capacity to undergo significant inelastic deformation.

2. Non-Ductile Failure Mode—A limit state character-

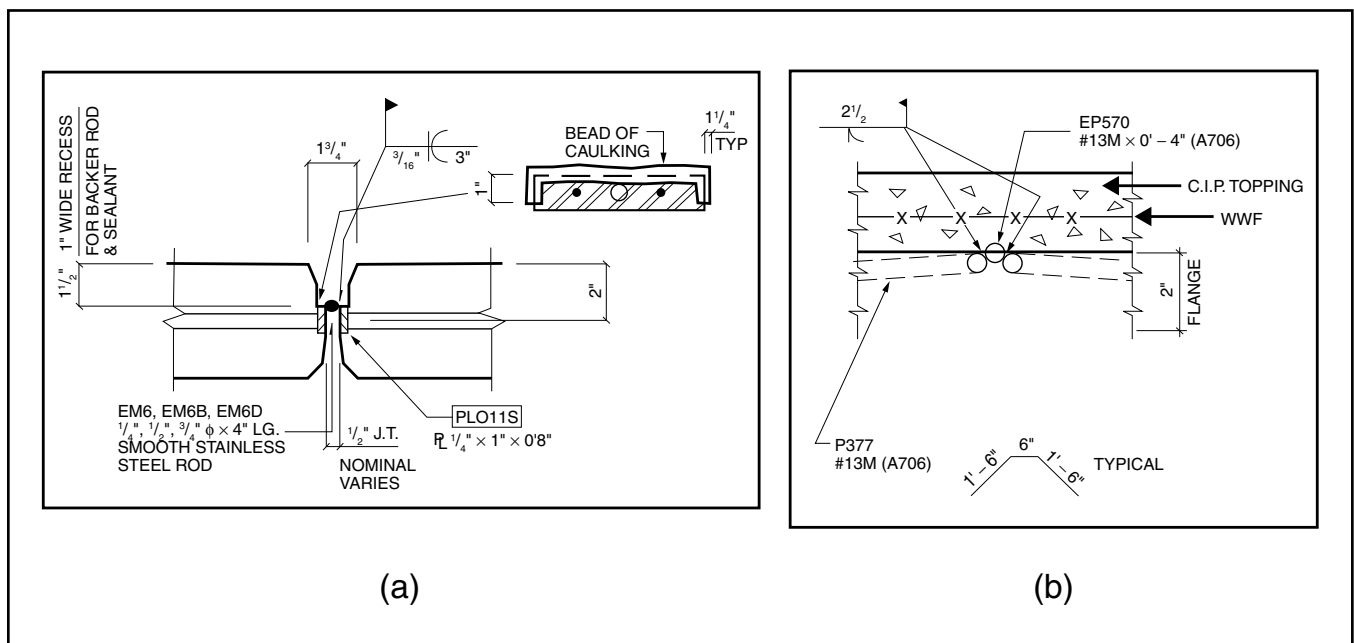


Fig. 6. Typical shear reinforcing details: (a) Untopped diaphragm; (b) Topped diaphragm.

ized by a sudden loss of load-carrying capacity with little or no inelastic deformation, i.e., brittle fracture.

3. Inelastic Mechanism—A limit state characterized by yielding of reinforcing steel and little or no loss of load-carrying capacity.

Seismic Hazard Levels

The DSDM project will evaluate diaphragm performance using seismic input based on two seismic “hazard levels” for each geographic region being considered:

1. Design Basis Earthquake (DBE)—The level of seismic hazard used in design, corresponding to a 10 percent chance of occurrence in 50 years (475-year return period).

2. Maximum Considered Earthquake (MCE)—The maximum level of seismic hazard considered credible for a geographical area, roughly equivalent to a 2 percent chance of occurrence in 50 years (2475-year return period).

DSDM PROJECT OBJECTIVES

The objective of the DSDM project is to develop an industry-endorsed design methodology for precast/prestressed concrete diaphragms including:

1. The forces, displacements, and deformations for which the diaphragm should be designed;
2. The diaphragm reinforcing details that can provide this performance; and
3. The required stiffness of the diaphragm relative to the primary LFRS elements.

Meeting these objectives is challenging in that diaphragm seismic “demands” are sensitive to the structure’s dynamic properties, the diaphragm stiffness and strength, and the ground motion characteristics. Diaphragm “capacities,” in turn, are based on complex force paths involving individual precast floor units and joints between units whose response is heavily influenced by the nonlinear and potentially non-ductile behavior of discrete reinforcing elements (flange-to-flange connectors, chord reinforcement, anchorages, etc.).

Determining proper diaphragm performance, i.e., maintaining demands within accepted limits with respect to capacities, must, therefore, account for a complex interaction of behaviors from the detail level to the system level. The DSDM project is using an integrated analytical/experimental research approach to develop the needed information on these behaviors. However, these behaviors are also highly dependent on choices made in design. Thus, a further feature of the research is that it will be applied to representative designs aligned with a cohesive design philosophy established at the outset of the project.

The integrated analytical/experimental research approach is described in detail in the companion paper. The remainder of this paper focuses on the underlying design philosophy and the crafting of a design framework that will serve as the basis for the emerging design methodology. First, the seismic design concepts that are employed in the framework are briefly reviewed. Then, the key aspects of diaphragm behavior that shape the design philosophy are discussed. Finally, the design framework itself is presented.

SEISMIC DESIGN CONCEPTS

The design framework is based on concepts associated with two seismic resistant design methods: (1) Capacity Design and (2) Performance Based Earthquake Engineering (PBEE). In a capacity design,⁸ element capacities are designed relative to the capacity of other elements in the structure, rather than (or in addition to) designing element capacities for an expected seismic design force. The primary use of capacity design is to prevent non-ductile behavior by designing ordinary portions of the structure to have greater relative strength than the pre-selected elements of the structure that serve as structural “fuses” by virtue of their special detailing for ductility.⁹

The concept of capacity design enters the DSDM project design framework at the diaphragm reinforcement group (joint) level and reinforcing detail level. Factors that reduce the effectiveness of a capacity design at the structure/diaphragm level, and thus prevent its “across the board” use as the exclusive philosophy of the design framework, are given in the next section. Instead, a performance-based approach is adopted herein to guide the development of the overall diaphragm design methodology.

PBEE is an emerging design philosophy for seismic resistant design.¹⁰ While the design philosophy is being extended into a comprehensive probabilistic framework that considers factors such as societal and economic impact, cost benefit considerations, and performance of non-structural elements,¹¹ its use in the DSDM project takes the form of “First Generation PBEE” as incorporated into seismic rehabilitation documents such as the FEMA-273 guidelines.¹²

The primary concept of First Generation PBEE being adopted here is the idea of identifying performance targets (force, drifts, deformations) associated with the damage that is acceptable for different levels of seismic input. Of the several seismic input levels identified,⁷ the DSDM project will focus on performance at the DBE and the MCE.

KEY ASPECTS OF PRECAST DIAPHRAGM BEHAVIOR

The behavior of floor diaphragms is one of the most complex and least understood aspects in the seismic response of buildings. Floor diaphragm behavior can be simplified in some cases as the floor can often be assumed to be nearly rigid and have sufficient strength to transfer inertial forces while remaining elastic. However, the jointed nature and long spans of precast concrete floors can create a demanding condition for the floor diaphragm. Therefore, a full awareness of the key aspects of precast concrete diaphragm behavior is important to appreciate the need for the design philosophy and the research approach taken in the DSDM project.

Diaphragm behavior that must be addressed includes:

1. Diaphragm force levels that may significantly exceed those prescribed by current building codes;
2. Significant diaphragm deformations that may amplify gravity-force resisting system drift demands;
3. Unexpected diaphragm internal force paths that can create force combinations; and, as a result of the first three items,

- Inelastic diaphragm behavior that places ductility demands on reinforcing details at the joints between floor units.

Each of the diaphragm behaviors listed previously are expanded upon in the following paragraphs. It is important to keep in mind that the behaviors discussed may be associated with high seismic hazard intensity and demanding construction conditions, and some of the issues raised stem from designs without full consideration of these conditions. Clearly then, an important objective of the DSDM research program is not only to provide design and detailing procedures that ensure safe performance in these extreme events, but also to understand under what conditions these design measures are unnecessary.

1. Diaphragm Seismic Force

A schematic of diaphragm force was shown in Fig. 4a. In practice, diaphragm design forces are usually obtained through Equivalent Lateral Force (ELF) procedures. Fig. 7a, for instance, shows the pattern of diaphragm design forces, F_{px} , used in several codes.^{4,7} Subsequent diaphragm design steps depend on F_{px} ; thus, these design forces should resemble the forces that develop during seismic events. However, evidence shows that ELF design procedures may significantly underestimate diaphragm inertial forces¹³ for wall and frame structures alike.¹⁴

The analytical results shown in Fig. 7c indicate that these large diaphragm force events can occur in the DBE, but may be more significant in the MCE. Furthermore, Fig. 7c also indicates that the maximum inertial forces may occur in the lower floors of the structure,¹⁵ in direct contradiction to current ELF patterns. These occurrences have also been deduced from accelerations measured during earthquakes.¹⁶

In some cases, the large diaphragm force events are driven by modifications to the structure's dynamic properties *after*

yielding of the primary elements of the LFRS.¹⁷ As a result, even a capacity design approach in which the diaphragm is designed stronger than the primary (wall or frame) LFRS elements and that successfully produces first yielding in these primary LFRS elements while the diaphragms are still elastic is no guarantee of sustained elastic diaphragm behavior throughout the seismic event. A prescriptive elastic diaphragm design, therefore, may be difficult to achieve reliably and economically.

Needed Design Improvement: An appropriate diaphragm design force pattern and appropriate diaphragm design force levels.

2. Diaphragm Flexibility

Precast concrete construction is commonly and effectively used for building systems with long floor spans. In these structures, the typical long distances between the primary (vertical plane) LFRS elements creates a demanding condition for the diaphragms, by generating significant in-plane bending moments and shear forces during seismic events, and also by producing a diaphragm that is quite flexible. In precast concrete construction, diaphragm flexibility is further increased by the inherent flexibility of jointed systems compared to a monolithic system.

For these flexible diaphragms, the floor system, and connected gravity force-resisting system in regions away from the primary LFRS elements, can undergo amplified drift demands (as was shown schematically in Fig. 4a). Thus, interstory drift, typically measured as the difference in LFRS drift on adjacent floor levels, must now also include the diaphragm deformation (δ_{dia} in Fig. 7b). These interstory drifts can be significant for long span precast/prestressed concrete structures in a MCE (see Fig. 7d).

Diaphragm flexibility can also modify a structure's dynamic properties (structural periods, mode shapes, modal

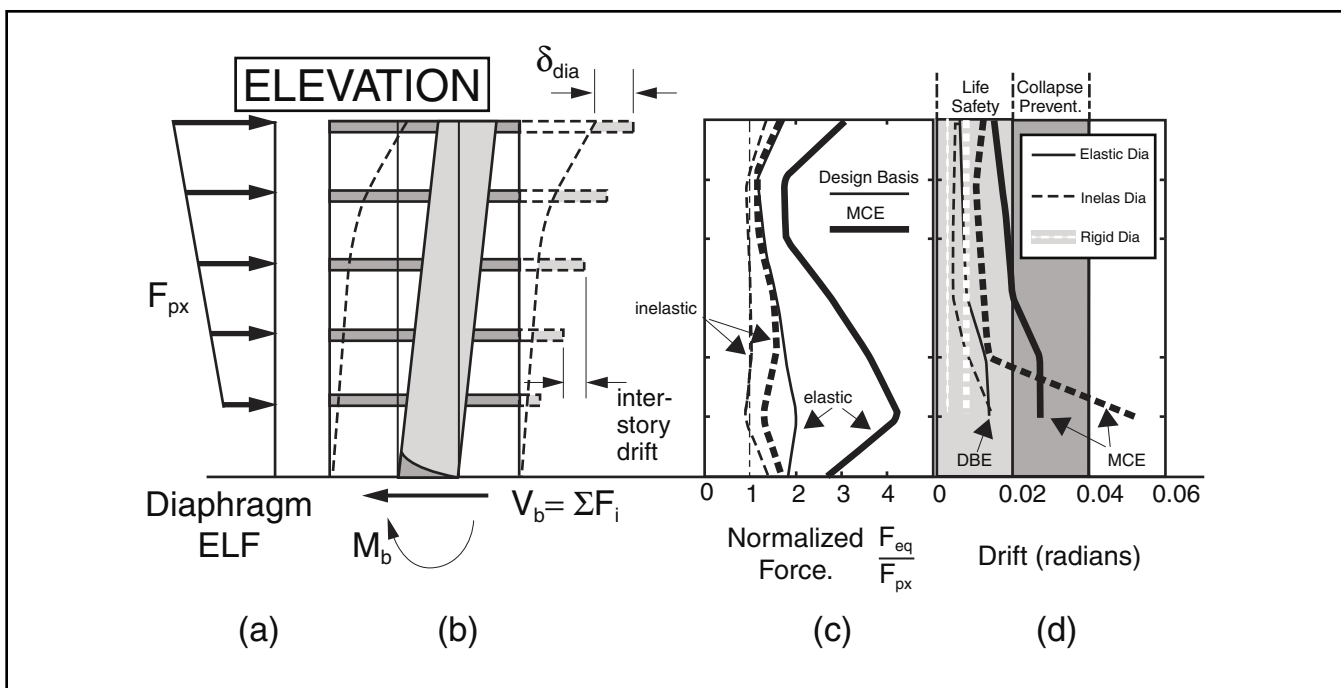


Fig. 7. Profiles:¹³ (a) Code ELF; (b) Building schematic; (c) Force demand; (d) Drift demand.

participation, and number of important modes).¹⁵ Therefore, the seismic forces experienced by the structure are affected by diaphragm flexibility.

Yielding of the diaphragm reinforcement will also increase the diaphragm flexibility. For these cases, increases in diaphragm design strength will tend to reduce diaphragm deformation and hence the overall interstory drift demand.¹⁴ As such, diaphragm behavior depends on a complex interrelation of diaphragm strength and flexibility.

Needed Design Improvement: A diaphragm elastic stiffness calculation used to properly estimate seismic design forces and check drift limits.

3. Diaphragm Internal Force Paths

Current U.S. practice uses a horizontal beam model¹⁸ to determine diaphragm reinforcement. In this procedure, the diaphragm is treated as a simple beam lying on its side to determine the internal forces (moment and shear) due to F_{px} (see Fig. 8). Chord reinforcement is provided to carry the entire in-plane bending moment; shear reinforcement across panel joints parallel to the seismic force is designed to carry the entire in-plane shear (as shown in Fig. 4b).

There are a number of issues with using the horizontal beam model for precast concrete floor diaphragms, most notably that the method relies somewhat on plastic redistribution to allow the forces to end up as shown in Fig. 4b. For instance, Region 1 of Fig. 8 represents a portion of the diaphragm in which the shear reinforcement, designed simply for shear transfer, is under high tension due to the in-plane bending of the diaphragm (refer to Fig. 4c). Furthermore, many diaphragm regions (e.g., Region 2) are subject to complex force combinations (shear, moment, and thrust coinciding at a section) that are more demanding than the internal forces determined from the simple horizontal beam model.

Alternately, a stiffer load path in the floor system (the inverted tee beam at Region 3, or spandrels, litewalls, etc.) can redirect the force path in unexpected ways. These force combinations can occur due to restraint or differential movement of vertical elements of the LFRS, the direction of attack of seismic loads (e.g., diagonal), openings or other irregularities.

Currently, there is no requirement that precast concrete diaphragm details have the ductility needed for plastic redistribution, and thus if a section along the force path cannot accommodate the forces, a non-ductile failure may occur. Secondly, there is no rationally-based distinction between the *relative* design strengths of different types of reinforcement (shear and chord reinforcement, for instance) to attempt to control the limit state under a large diaphragm force event, for example by providing ductile flexural yielding before a non-ductile shear failure.

Furthermore, there is no guarantee that the primary diaphragm reinforcement (chord, shear, collector reinforcement) will be the only reinforcement attracting seismic force. Reinforcement exists that connects spandrels to precast units, internal beams to topping for composite action to gravity loads, columns to spandrels, litewalls to precast units in their out-of-plane direction, and so forth. These so-called “secondary” reinforcement details may enhance the stiffness and strength of the diaphragm, but may also lead to unexpected non-duc-

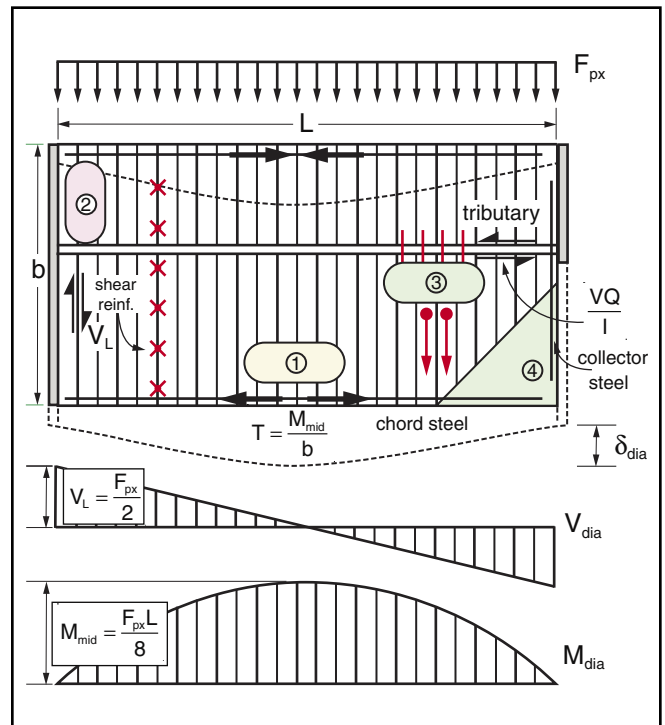


Fig. 8. Horizontal beam model for diaphragm internal force.

tile failure modes and must, therefore, be assessed.

Needed Design Improvement: An accurate but straightforward method for determining diaphragm internal forces that includes the likely force combinations on individual reinforcement or reinforcement groups.

4. Diaphragm Local Deformation Demands

If the aforementioned conditions (large diaphragm force events, internal force combinations) create an internal force overload, the inelastic deformation demands will tend to concentrate in the reinforcing details across the joints. These reinforcing details were not originally developed with full consideration of ductility requirements. In the absence of provisions to consider ductility, a non-ductile failure mode may be the controlling limit state in the event of inelastic diaphragm action.¹⁹

Consider, for example, a high in-plane bending region such as Region 1 in Fig. 8. Tensile deformation demands on the shear reinforcement will become significant if the chord reinforcement yields. Standard shear reinforcement (welded wire reinforcement or flange-to-flange connectors) may possess limited tensile deformation capacity and thus could fail. Furthermore, the effectiveness of shear friction provided by welded-wire reinforcement as a joint opens is also an issue.

Diaphragm detailing issues are more complex for irregular floor plans. As an example, consider the parking structure diaphragm (see Fig. 9a), an irregular floor plan commonly constructed using precast/prestressed concrete components. A typical parking structure diaphragm exhibits at least four failure-critical locations, one of which could control in a large diaphragm force event, depending on the seismic loading direction and LFRS layout.

Fig. 9b shows examples of the deformation patterns that may occur in a three-bay parking structure diaphragm caus-

ing complex internal force combinations.

The discretely-connected precast units themselves will not necessarily follow plane-sections assumptions of the simple horizontal beam model as shown in the exaggerated deformed shape of a three-bay parking structure undergoing a twisting mode under a strong earthquake (see Fig. 9c). Therefore, forces acting along the joint may not always be accurately predicted on individual reinforcing details by calculations based on beam theory, even if the internal force combinations are properly estimated.

Needed Design Improvement: The deformation capacity required of individual diaphragm reinforcing details as well as information on the strength and ductility characteristics of typical diaphragm reinforcing details.

Impact on Underlying Design Philosophy

In considering the approach for a precast diaphragm seismic design methodology, a prescriptive elastic design seems warranted.²⁰ Elastic response is preferred for its high in-plane stiffness²¹ and would seemingly avoid a non-ductile failure of the floor system. However, it is important to consider the issues related to precast concrete diaphragm behavior outlined in this section in crafting the underlying design philosophy for the methodology. An economical design that guarantees elastic diaphragm behavior in all seismic events may be difficult to achieve due to the possibility of large diaphragm force events that may develop, particularly for the MCE.

The potential for these large diaphragm force events, though not based on behavior unique to precast concrete systems, bears significant impact on the selection of an appropriate precast concrete DSDM. Large force events can be problematic for precast concrete floor systems in which internal force paths extend across the joints between precast units. Inelastic deformation, if it occurs, will concentrate in these regions, amplifying local ductility demand in the reinforcing elements.

Complex force paths, due to floor in-plane vibration modes, LFRS element restraint, irregularity, and other factors, can create force combinations that can produce internal force overloads, and hence localized inelastic behavior even if the overall diaphragm load remains near design force levels. Furthermore, for longer floor spans, diaphragm flexibility may create large gravity system drifts during these events.

A major consequence of these conditions is that diaphragm

details may become inelastic even when elastic behavior is intended. The jointed nature of the precast concrete floor diaphragms does not provide inherent protection against internal force overloads, and thus the diaphragms may become the critical components of the LFRS. Therefore, an underlying philosophy of the design methodology is to promote elastic response, but to be prudent in anticipating unintended ductility demand.

Structural integrity requirements have typically focused on adequate anchorage of diaphragms to the primary LFRS elements, including carrying superimposed gravity loads and accommodating imposed rotations from walls,²² and maintaining seating of the precast units.²³ It seems prudent that these structural integrity requirements should be extended to provide diaphragm reinforcing details a measure of ductility, even if diaphragms are designed to be elastic.²⁴

The need to address multi-faceted conditions of strength, stiffness, and ductility lends itself to a design approach based on comprehensive performance requirements;²⁵ the need to protect certain diaphragm reinforcing elements lends itself to a capacity design approach. These concepts form the basis of the framework adopted by the DSDM Consortium to develop the seismic design methodology.

DESIGN FRAMEWORK GUIDING THE RESEARCH

The DSDM Consortium has endorsed the development of a seismic design methodology for precast concrete diaphragms based on performance requirements and incorporating capacity design concepts. This consensus was reached following a formal review and evaluation of existing code provisions pertaining to precast/prestressed concrete diaphragm seismic design, including the creation of a background document on recent code modifications, and consideration of the important precast concrete diaphragm behaviors as summarized in the previous section. The underlying design philosophy has been formalized into a framework that will be used to guide the DSDM research and the development of the emerging methodology.

Overview

The methodology will aim to satisfy design requirements at three “levels of resolution” within the structure: the dia-

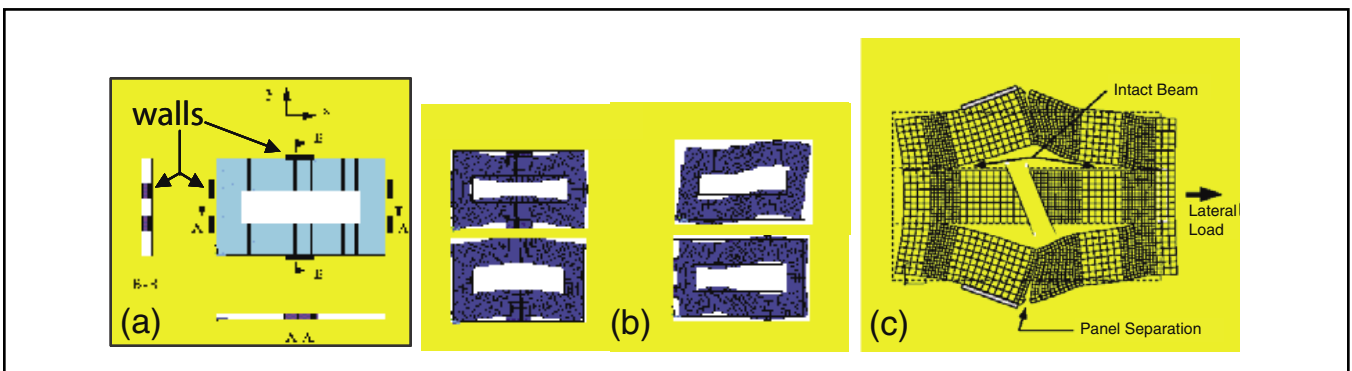


Fig. 9. Irregular diaphragm response:² (a) Parking structure diaphragm; (b) Diaphragm in-plane deformation modes; (c) Precast unit deformation patterns.

phragm level, the joint level, and the detail level (see Fig. 10). Performance targets are set at the diaphragm level and the desired behavior is ensured by controlling the relative strength of reinforcement at the joint and detail level through capacity design concepts.

At the diaphragm level, elastic behavior is the performance target for the DBE while some inelastic deformations are anticipated in a MCE (see Fig. 10a). For this approach, it is important to form a desirable inelastic mechanism when the seismic input level exceeds the DBE level.

This objective is accomplished at the joint level by using capacity design concepts to produce a hierarchy of design strengths among the diaphragm reinforcement groups intended to protect the shear reinforcement and diaphragm anchorages in favor of more ductile yielding of the chord reinforcement (see Fig. 10b). Finally, within each reinforcing detail, a hierarchy of strengths is to be provided for the sequence of elements in series (bars, plates, welds, stud group, etc.) to promote ductile behavior in the event of an internal force overload (see Fig. 10c).

It should be noted that the inelastic deformation capacity or “ductility” required in the floor diaphragm should be viewed as a toughness measure for structural integrity, not as a primary energy dissipating mechanism as is the case for primary elements of the LFRS.

Recognizing that practical issues or expected seismic demands may not always require the strictest detailing, the methodology intends to provide safe designs based on classification of diaphragm reinforcement for different levels of deformation capacity. The design framework is further discussed for each level of resolution in the framework.

Diaphragm Level

The performance target of elastic diaphragm response in the DBE event will be accomplished in the design through the introduction of appropriate diaphragm design force multipliers in the form of design overstrength (Ω) factors.¹³ It should be noted that other choices exist for targeting the diaphragm design force level. As is implied in the schematic of Fig. 10a, designing for elastic behavior in all events may lead to exces-

sively high design forces and there is still no guarantee of elastic diaphragm behavior. Designing for lower diaphragm force levels and expecting greater inelastic deformation demand under the DBE could lead to excessive ductility (or drift) demand in the diaphragm during the MCE.

It is recognized, however, that there will likely be conditions where it will be cost effective to target elastic behavior in the MCE and provide only the minimum level of ductility in the diaphragm. These options are intended to be available in the design methodology through the use of different diaphragm design overstrength factors Ω , depending on the condition and the classification of the reinforcing details used in the diaphragm.

The DSDM Consortium has experience in this area as research team members have in the past proposed diaphragm overstrength factors $\Omega^{13,14}$ and DSDM TG members have begun to adopt these concepts into design guidelines.⁶ The major advancement afforded by the DSDM project is the significant analytical and experimental research planned to calibrate these overstrength factors (see companion paper).

Joint Level

Given the recognition that large diaphragm force events can occur, and complex diaphragm load paths can exist in the diaphragm leading to internal force combinations, internal force overloads and hence inelastic deformations are expected in the MCE. In this case, it is important to form the desired inelastic mechanism.

Control of the inelastic mechanism can be attained by using capacity design concepts to create a hierarchy of strengths among the different types of reinforcement in the diaphragm as shown in Fig. 10b. It is noted that this approach will enhance the structural integrity of the floor system for overloads in general.

The consensus of the DSDM Consortium is to promote flexural limit states in the chord reinforcement through the use of appropriate strength factors for shear reinforcement (ϕ_s) and reinforcement anchorages (ϕ_a) relative to the chord reinforcement (ϕ_b) to protect against non-ductile failure modes. Similar approaches have been included in certain codes of

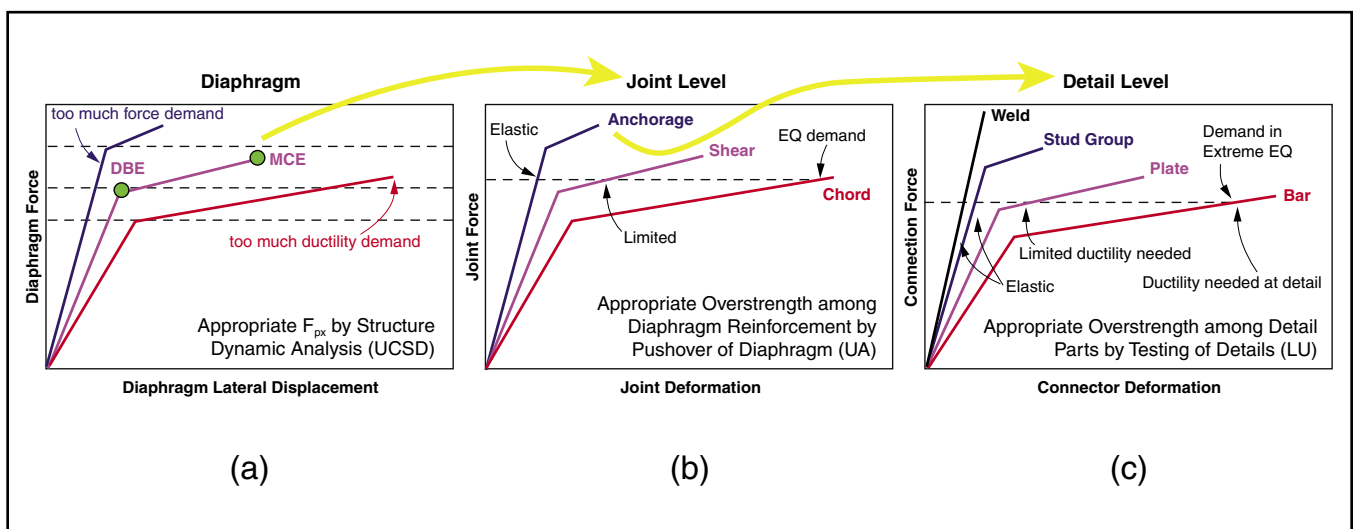


Fig. 10. Precast diaphragm design based on performance requirements and capacity design concepts.

practice dealing with anchorages and collectors.⁷

It is important to recognize that force paths in the diaphragm are often complex and the development of appropriate strength reduction factors requires detailed finite element analyses of representative precast concrete structures under an assortment of loading conditions as is being attempted in the DSDM project (see companion paper).

Detail Level

The diaphragm overstrength factors and the strength reduction factors for diaphragm reinforcement groups are only useful if the individual reinforcing details provide the behavior anticipated when these factors are developed. There are two aspects of this: (1) the reinforcement details studied by the DSDM project should have similar characteristics to the details precasters use (or will use) and (2) the details precasters use (or will use) should possess the characteristics to produce the desired level of performance.

For this reason, the DSDM TG and the URs have invested significant effort in identifying representative details for use in the research program. It is hoped that the representative details studied in the DSDM project can be prequalified for certain conditions. Furthermore, as there are many different types of reinforcing details, including proprietary reinforcement systems, the approach being taken by the DSDM project is to create a classification system for reinforcing details for precast concrete diaphragms.

These classifications will be based on deformation capacity and will be tied to the diaphragm overstrength factors. Accepted terminology will be used for the categories: low deformability (LD), limited deformability (MD), and high deformability (HD) elements.²⁶ The DSDM Consortium intends to develop a qualification procedure (based on detailing requirements and a testing protocol) to allow new or untested diaphragm reinforcing details to be qualified by interested parties. The detailing procedures are intended to follow a strength hierarchy as shown in Fig. 10c.

An examination of current detailing practice for representative details (see Fig. 11a) indicates that such hierarchies may

not be present in current details (see Fig. 11b). Such strict detailing hierarchies can only be effective if practical considerations are also addressed (e.g., construction, welding, etc). The needed expertise in these areas is provided by the DSDM TG.

Finally, the design procedures created in the methodology are anticipated to require an elastic stiffness calculation. It is envisioned that this calculation will be used in determining the diaphragm overstrength factor; it will be used to make a diaphragm flexibility calculation; and it may impact the connector classification type allowed. Several researchers have proposed elastic stiffness calculations.^{5,19} The DSDM Consortium plans on developing effective moduli (G_{eff} , E_{eff}) for this stiffness calculation. This method and the previously proposed methods will be compared and the best approach calibrated to provide this design calculation.

Design Deliverables

Table 1 summarizes a set of “design deliverables” to be produced by the DSDM project in support of the emerging seismic design methodology. These deliverables are aligned with the “needed design improvements” listed previously and are consistent with the design framework proposed in this section.

DSDM PROJECT RESEARCH APPROACH

Rationale

From the contents of Table 1, it is clear that prior to developing a coherent and effective design methodology based on performance requirements, the research conducted in the DSDM project must provide knowledge to properly:

1. Estimate diaphragm force levels and force distributions;
2. Estimate drift demands on the attached gravity load-resisting systems and identify appropriate limits on diaphragm flexibility;
3. Approximate internal force paths within the diaphragm and determine requirements for reinforcing details to

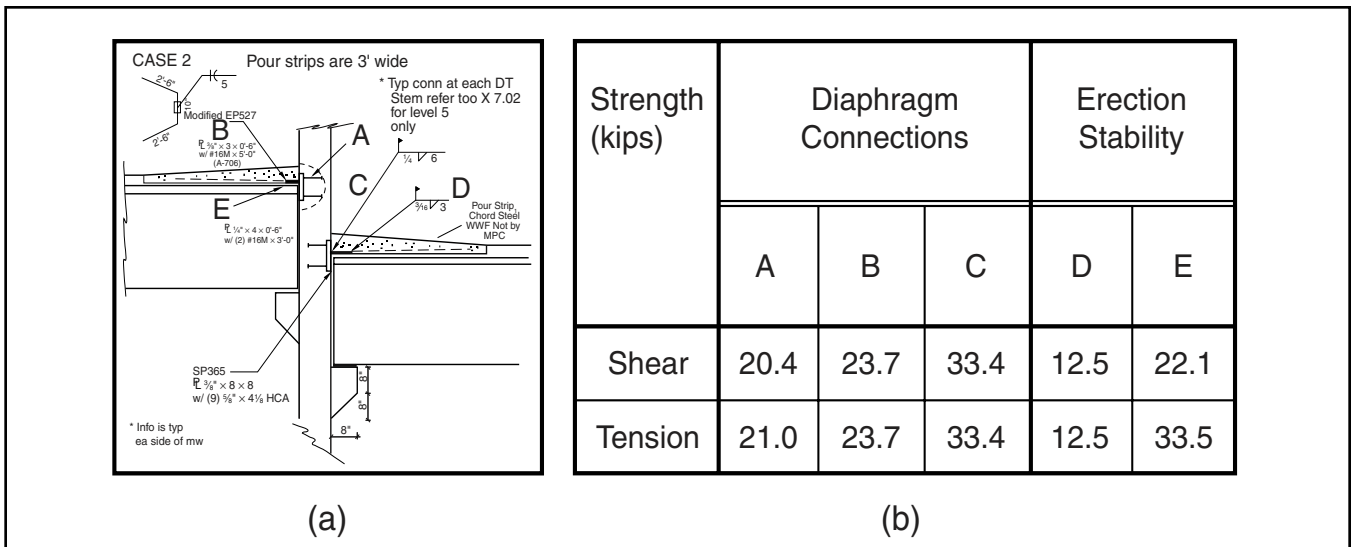


Fig. 11. Representative detail: (a) Typical detailing; (b) Relative design strengths.

Table 1. Design deliverables of the DSDM research project.

Diaphragm Design Focus	Design Deliverables	Design Factors
Seismic Force	An appropriate diaphragm design force pattern and diaphragm design force levels calibrated to produce elastic diaphragm response for the design earthquake through the use of diaphragm force multipliers.	Ω
Flexibility	A diaphragm elastic stiffness calculation in terms of effective properties that are based on plan geometry, construction type and reinforcing details and used to properly estimate seismic design forces and check drift limits.	G_{eff}, E_{eff}
Internal Force Paths	An accurate but straightforward method for determining internal forces that includes the likely force combinations on individual reinforcement or reinforcement groups; appropriate strength reduction factors for shear reinforcement and anchorages relative to the chord reinforcement to protect against non-ductile failure modes in overloads.	ϕ_v, ϕ_a, ϕ_b
Local Deformation Demands	A classification system for precast diaphragm reinforcement in terms of available deformation capacity relative to that required based on structural integrity provisions; the strength and ductility characteristics of typical diaphragm details, including prequalification of existing details and a protocol for qualification testing of new details.	LD, MD, HD

transfer these forces across joints between precast units and at anchorages to the primary lateral force-resisting elements; and

4. Estimate ductility demands on critical reinforcing details during extreme seismic events and identify the details possessing these characteristics.

Acquiring this knowledge is challenging because, as discussed in the section on diaphragm behavior:

1. Diaphragm force levels and distributions are due to nonlinear dynamic system response;
2. Diaphragm dynamic response to these forces depends on both the diaphragm strength and flexibility;
3. Complex force paths occur due to lateral force-resisting system element layout; and
4. Critical diaphragm sections develop force combinations based on the characteristics of individual details.

In other words, diaphragm seismic response is the result of a complex interaction of system behavior (the overall structure), component behavior (the floor diaphragms), section behavior (diaphragm panels and joints), and joint detail behavior (individual reinforcing details). Accordingly, the research activities performed in the DSDM project must extend through the entire range of these behaviors.

Previous research efforts have attempted to accomplish this in a number of different ways, but these efforts suffered from the limitation that diaphragm forces and force paths had to be estimated entirely through analytical simulation. These simulations depended heavily on test results for individual joint reinforcing details under highly idealized loading conditions.

Direct extrapolation of these test results to estimate the capacity of the system is questionable, because the actual joint behavior depends on a complex interaction of the force combinations (e.g., tension/shear, compression/shear), the load history, and the state of other reinforcing details in the joint (intact, softening, failed). Further, other “system level” assumptions associated with models of the diaphragm and the structure have yet to be experimentally verified.

A major feature of the DSDM project research, then, is to integrate experimental work with the analytical research to both build appropriate models and verify simulated results. Thus, while the project relies, as in the past, on analytical models of precast concrete diaphragms, these analyses will be conducted using models built with data from a closely-aligned reinforcing detail experimental program and verified by system-level experiments.

Table 2. Research matrix of design deliverables.

Design Deliverables	LU		UA		UCSD	
	Detail Tests	Local Models	2D FE	3D FE	EQ Simul.	Shake Table
Diaphragm seismic force				○	•	✓
Diaphragm flexibility				○	•	✓
Diaphragm internal force paths	↔	↔	•	•		✓
Diaphragm local deformation demands	•	•	↔			✓

Note: Primary Deliverable • Secondary Deliverable ○ Data Input ↔ Verification ✓

Integrated Analytical/Experimental Research Approach

The DSDM project research is integrating analytical and experimental research to provide a comprehensive examination of precast concrete diaphragms. Each UR component focuses on different levels of behavior that produce the diaphragm seismic response: local behavior of the reinforcing details at LU; component behavior of the diaphragm at UA; and system behavior of the structure at UCSD. These research activities involve large-scale experiments of reinforcing details (detail tests) and modeling of the connection region (local models) at LU; nonlinear static (2D) and dynamic (3D) finite element (FE) analyses at UA; and system studies (EQ simulations) and a shake table test at UCSD.

Table 2 indicates the design deliverables provided by each UR component and how the UR components interact. The effectiveness of the DSDM project depends on strong technical collaboration between the UR groups at the interfaces between these levels: UA and LU at the joint/detail interface; UCSD and UA at the structure/diaphragm interface. These interactions and the specific analytical and experimental activities taking place in the DSDM research program are described in detail in the companion paper.

CONCLUDING REMARKS

The DSDM Consortium is conducting a large “area of emphasis” research project on precast concrete diaphragms. The DSDM project has an overall objective of developing an industry-endorsed comprehensive seismic design methodology for precast/prestressed concrete floor diaphragms. During the DSDM project’s first year, consensus has been established on the underlying design philosophy that will guide the research and the resulting framework that will serve as a basis for the emerging design methodology.

The methodology will aim to satisfy design requirements at three “levels of resolution” within the structure: the diaphragm level, the joint level, and the detail level. At the diaphragm level, elastic behavior is the performance target for the DBE while some inelastic deformations are anticipated in a MCE. A desirable inelastic mechanism is achieved when the seismic input level exceeds the DBE level by using capacity design concepts to produce a hierarchy of design strengths at the joint and detail level.

Design deliverables were identified and a research approach has been conceived to provide these deliverables. The particular experimental and analytical research activities being performed in the research program are described in a companion paper, “Seismic Design Methodology for Precast Concrete Diaphragms—Part 2: Research Program.”

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APPENDIX – NOTATION

E_{eff}	= effective elastic modulus
F_{eq}	= diaphragm earthquake (inertial) force
F_{px}	= diaphragm design force
G_{eff}	= effective shear modulus
h_i	= floor-to-floor height of <i>i</i> th story
M_{dia}	= diaphragm in-plane moment
V_{dia}	= diaphragm in-plane shear
δ_{dia}	= diaphragm deformation
ϕ_v	= strength (phi) factor for shear reinforcement
ϕ_a	= strength (phi) factor for anchorage reinforcement
ϕ_b	= strength (phi) factor for chord reinforcement
Ω	= diaphragm design overstrength factor
Δ_i	= interstory drift of <i>i</i> th story