Seismic Design Methodology for Precast Concrete Diaphragms Part 2: Research Program

Robert B. Fleischman, Ph.D.
Assistant Professor
Department of Civil Engineering and Engineering Mechanics
University of Arizona
Tucson, Arizona

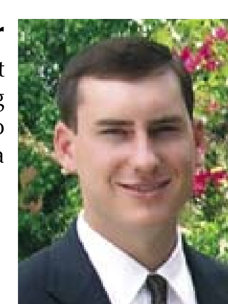
S.K. Ghosh, Ph.D., FPCI
President
S. K. Ghosh Associates, Inc.
Palatine, Illinois

Clay J. Naito, Ph.D.
Assistant Professor
Department of Civil and Environmental Engineering
Lehigh University
Bethlehem, Pennsylvania

Ge Wan
Graduate Student
Department of Civil Engineering and Engineering Mechanics
University of Arizona
Tucson, Arizona

José Restrepo, Ph.D.
Associate Professor
Department of Civil Engineering
University of California San Diego
La Jolla, California

Matt Schoettler
Graduate Student
Department of Civil Engineering
University of California San Diego
La Jolla, California



Richard Sause, Ph.D.
Professor
Department of Civil and Environmental Engineering, and Director, ATLSS Center
Lehigh University
Bethlehem, Pennsylvania

Liling Cao
Graduate Student
Department of Civil and Environmental Engineering
Lehigh University
Bethlehem, Pennsylvania

The Precast/Prestressed Concrete Institute (PCI) is conducting a large "area of emphasis" project to develop an industry-endorsed comprehensive seismic design methodology for precast 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 reinforcing detail experiments at LU and shaking table system tests at UCSD. The purpose of this and a companion paper, published in the September-October 2005 issue of the PCI JOURNAL, is to outline the foundation for this research and provide context for the technical papers to follow as well as the eventual design methodology. The earlier companion paper described the underlying design philosophy and the resulting design framework that will serve as a basis for the emerging design methodology. This 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).

A multi-university research team from the University of Arizona (UA), Lehigh University (LU), and the University of California San Diego (UCSD) is performing the research. 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 companion paper[1] has detailed the rationale for the integrated research approach and underlying design philosophy adopted by the DSDM Consortium, and outlined the resulting design framework that will serve as a basis for the emerging design methodology. The previously published companion paper also supplies a list of terminology and definitions.

This paper focuses on the research program itself, including the project's physical scope and the specific analytical and experimental research activities. First, the DSDM research approach and design framework presented in the companion paper is summarized.

SUMMARY OF DSDM CONSORTIUM APPROACH

As described in the companion paper,[1] and summarized in this section, the research approach and design framework adopted by the DSDM Consortium, as well as the design deliverables to be produced, are structured along four "levels of resolution": system level, component level, section level, and local level.

Integrated Research Approach

Two key factors led to the selection of the DSDM research approach. First, 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 local behavior (individual reinforcement details). Secondly, research to date has had to estimate diaphragm response almost entirely through analytical simulation, and in turn, these simulations were based on sparse test data of reinforcing details under highly idealized loading.

Thus, the unique features of the DSDM research approach are: (1) Each UR focuses on one of the behavior levels producing 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; and (2) the research closely integrates analysis and experimentation: LU large-scale experiments with LU local modeling and UA static finite element (FE) analyses; and a UCSD shaking table test

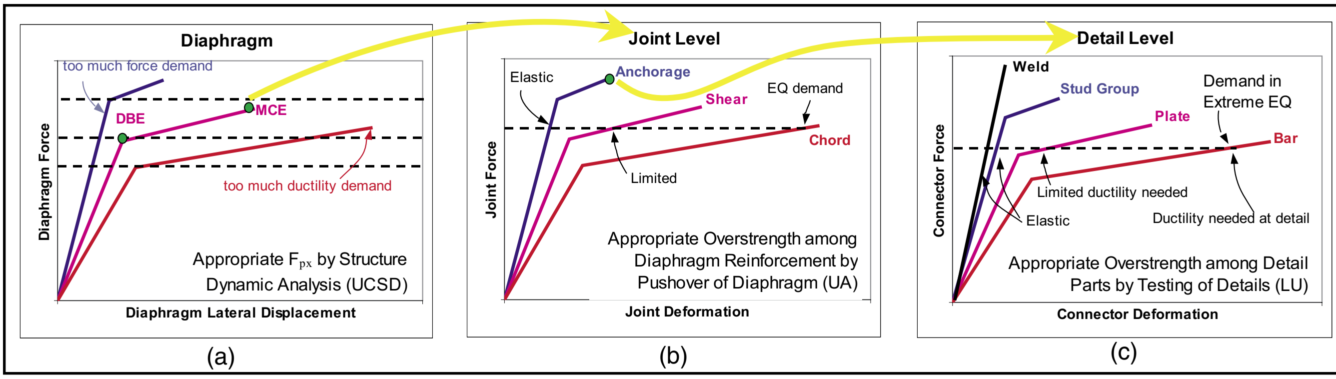


Fig. 1. Precast concrete diaphragm design based on performance requirements and capacity design concepts.

with UCSD system studies and UA dynamic FE analyses.

Using this approach, the DSDM research team intends to perform a comprehensive examination of precast concrete diaphragms to gain the knowledge required to produce an effective design methodology (see Table 1). The effectiveness of the project depends on strong technical collaboration between the UR groups at the interfaces between levels: UA and LU at the joint/detail interface; and UCSD and UA at the structure/diaphragm interface.

Design Framework

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. The methodology will aim to satisfy design requirements at the three "resolution levels" within the structure: the diaphragm level, the joint level, and the detail level (see Fig. 1). 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 (see Fig. 1a), elastic behavior is the performance target for the design basis earthquake (DBE) while some inelastic deformations are anticipated in a maximum considered earthquake (MCE). For this approach, it is important to form a desirable inelastic mechanism when the seismic input level exceeds the DBE level.

The objective of forming a desirable inelastic mechanism 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. 1b). 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. 1c).

A classification of low, limited, and high deformability (LD, MD, HD) elements will be assigned to reinforcing details. Diaphragm design factors will depend on classification, diaphragm span, and seismic hazard site, thus providing choices in design.

Design Deliverables

On the basis of this design framework, the DSDM research program is structured to produce distinct design deliverables including at the:

1. **Diaphragm level**
   a. An appropriate diaphragm design force pattern and design force levels that target elastic DBE response; and
   b. Diaphragm elastic stiffness calculations based on plan geometry, construction type, and reinforcing details, including diaphragm flexibility limits.
2. **Joint level**
   a. A straightforward method for determining internal forces including the likely force combinations on individual reinforcement or reinforcement groups; and
   b. Appropriate strength reduction factors for shear reinforcement and anchorages relative to chord reinforcement to protect against non-ductile failure modes.

Table 1. Research matrix of design deliverables.

Design Deliverables	LU		UA		UCSD	
	Detail Tests	Local Models	2D FE*	3D FE*	Earthquake Simulation	Shake Table
Diaphragm seismic force and flexibility				❍	∞	✓
Diaphragm internal force paths	↔	↔	∞	∞		✓
Diaphragm local deformation demands	∞	∞	↔			✓

Note: Primary Deliverable ∞ Secondary Deliverable ❍ Data Input ↔ Verification ✓
* FE is finite element model.

3. **Detail level**
   a. A classification system for diaphragm reinforcement in terms of available deformation capacity relative to that required for structural integrity; and
   b. The strength and ductility characteristics of typical diaphragm details, including prequalification of existing details and a protocol for qualification testing of new details.

It is noted that in creating these design deliverables, the DSDM Consortium is attempting to provide a unified design methodology for reinforcement in untopped and topped diaphragms across different seismic zones.

DSDM PROJECT PHYSICAL SCOPE

The seismic response of a precast concrete diaphragm is highly dependent on the design decisions and details used in its construction. The consensus of the DSDM Consortium is that the DSDM research be applied to representative designs from the outset of the project to ensure meaningful findings for the industry. During the project's ramp-up year, the DSDM Consortium conducted several Task Group Meetings (TGMs) largely focused on defining the physical scope of the project.

The results of the TGMs include the:
1. Development of a portfolio of prototype structures;
2. Identification of representative precast concrete reinforcing details;
3. Selection of seismic hazard sites;
4. Creation of baseline designs using existing codes; and
5. Selection of an initial research scope including industry-sanctioned points of emphasis.

Prototype Structures

The prototype structure (PS) portfolio provides the project with a set of representative precast/prestressed concrete structures encompassing typical structure geometry and construction practice. The portfolio includes:

- PS#1: a three-bay side-by-side parking structure (Fig. 2a)
- PS#2: a two-bay helical parking structure (Fig. 2b)
- PS#3: a distributed core, L-shaped office building (Fig. 2c)
- PS#4: a central core, perimeter wall office building (Fig. 2d)
- PS#5: a two-way, moment frame parking deck (Fig. 2e)

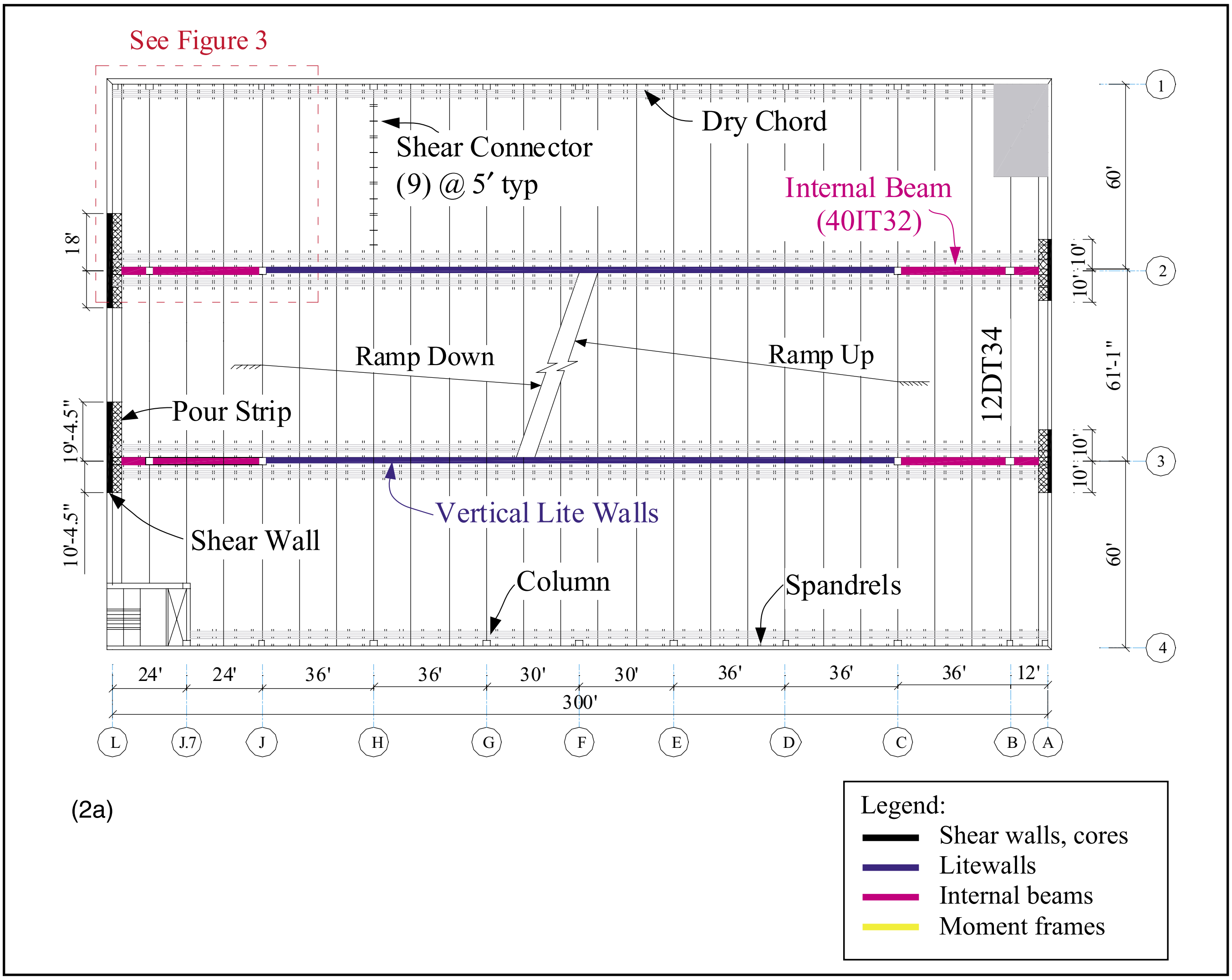


Fig. 2. Prototype structures (2a): Plan of PS#1: Side-by-side parking structure, four stories. Note: 1 ft = 0.308 m; 1 in. = 25.4 mm.

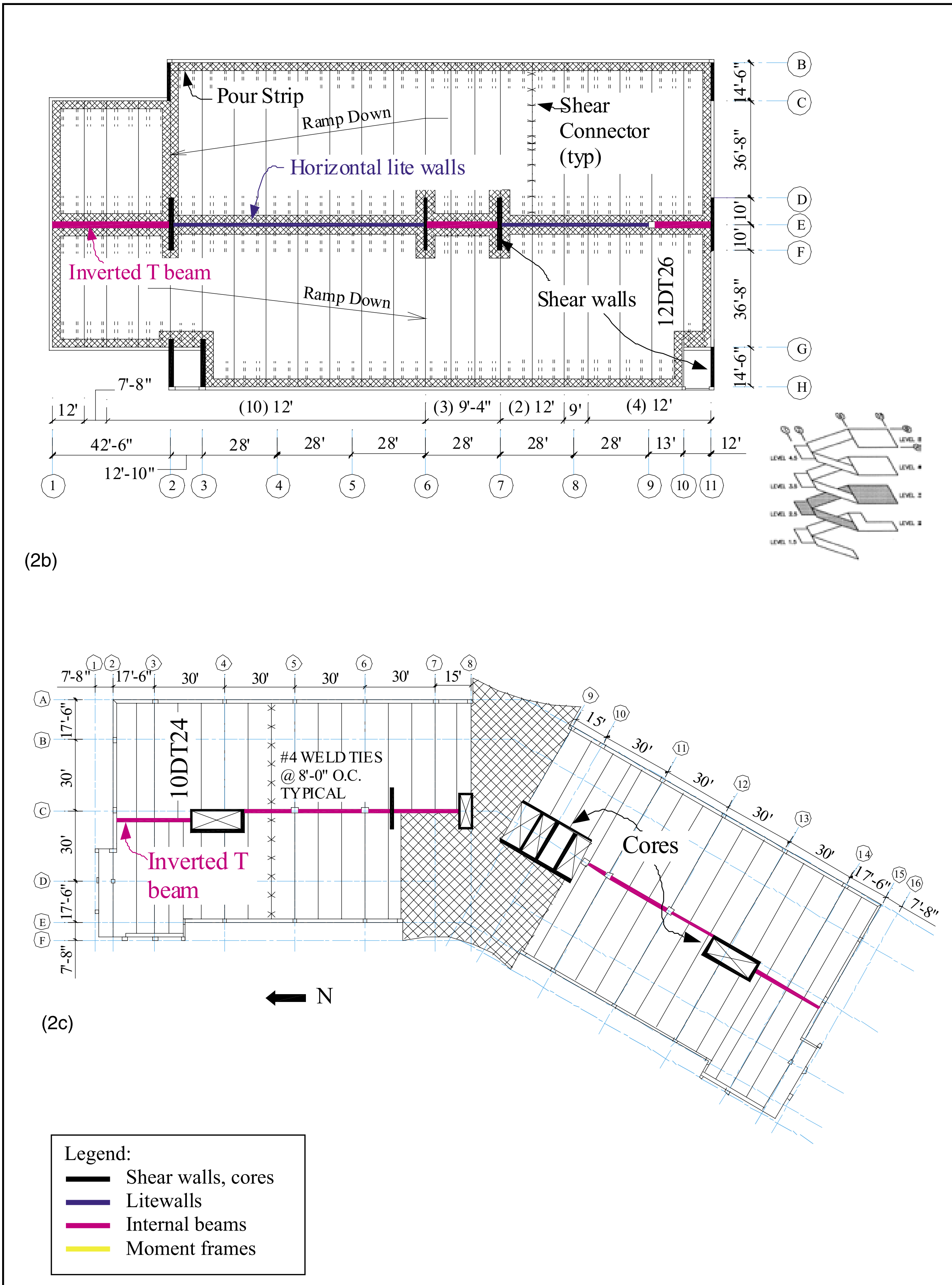
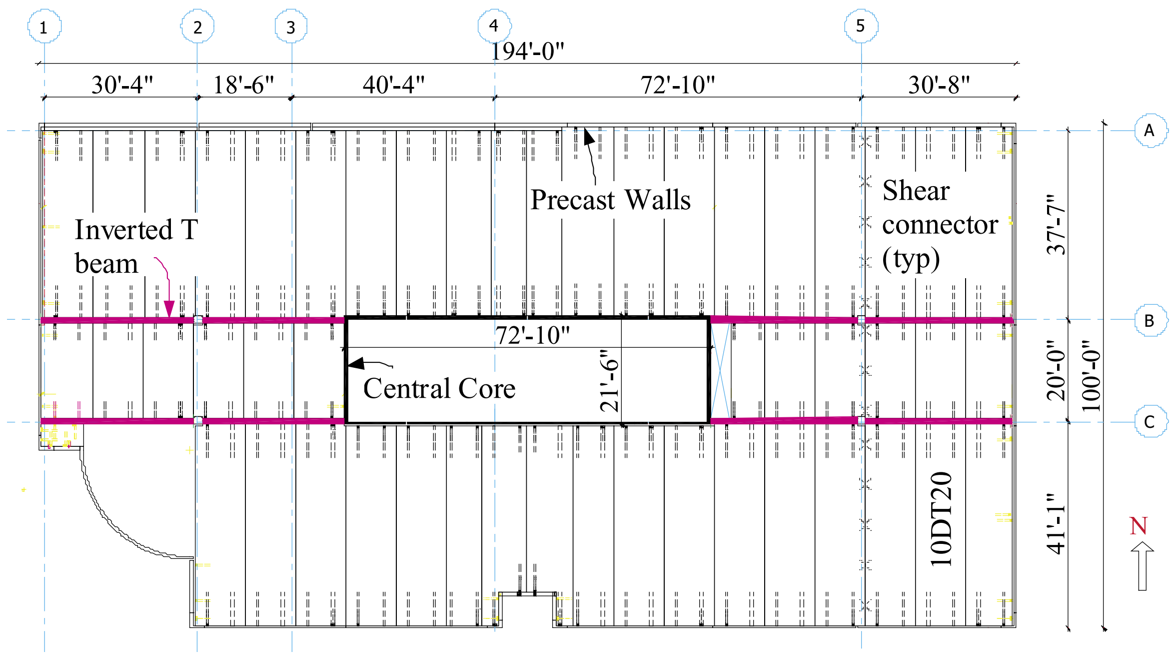
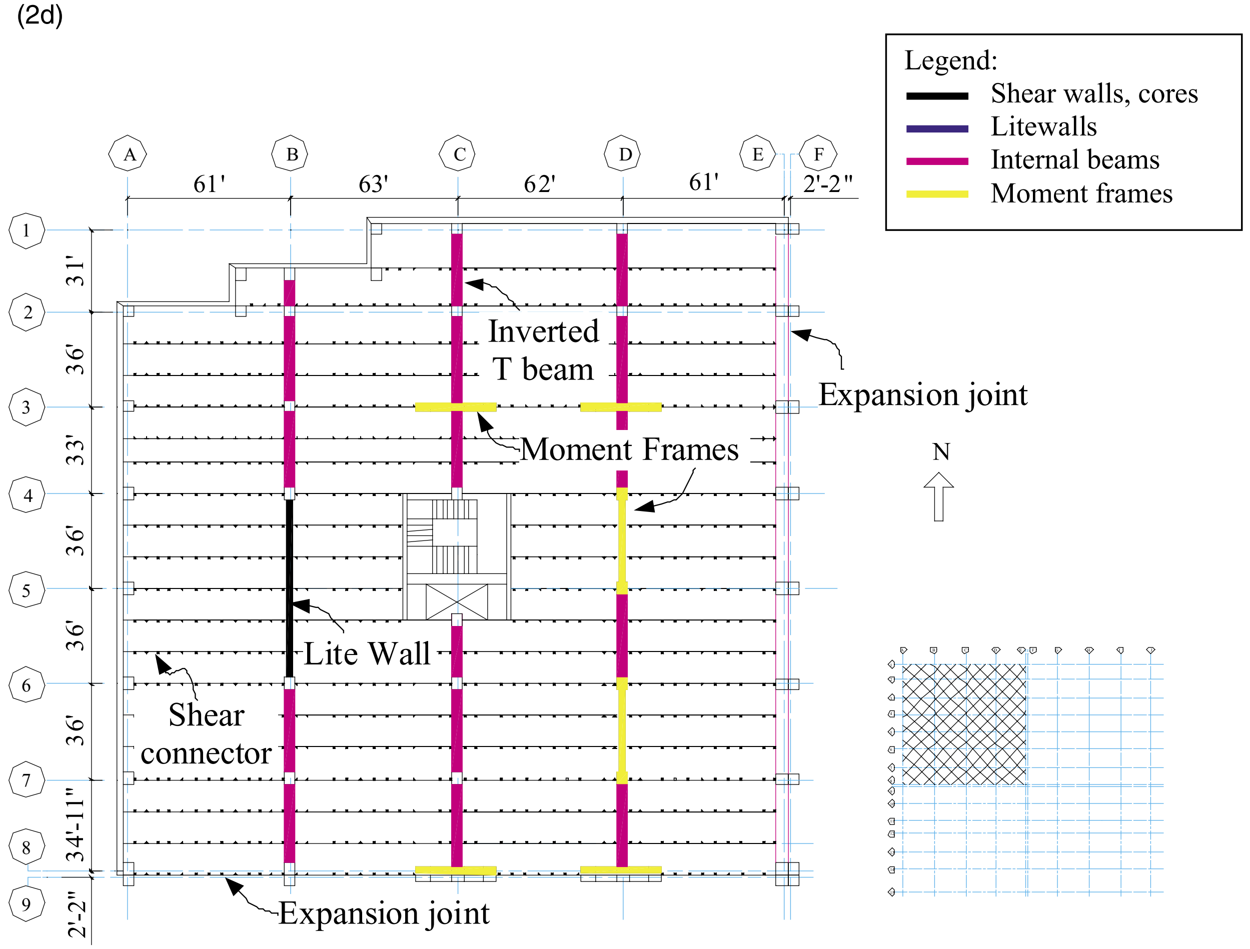


Fig. 2 (cont.). Prototype structures (2b): Plan of PS#2: Helical parking structure, four stories; (2c): Plan of PS#3: Distributed core L-wing office building, five stories. Note: 1 ft = 0.308 m; 1 in. = 25.4 mm.



(2d)



(2e)

Fig. 2 (cont.). Prototype structures (2d): Plan of PS#4: Central core perimeter wall office building, four stories; (2e): Plan of PS#5: Two-way moment frame parking deck, two stories. Note: 1 ft = 0.308 m; 1 in. = 25.4 mm.

Table 2. Prototype structure portfolio.

PS #	Description	Lateral Force Resisting System	Floor System	Location	SDC	Stories
1	Three-bay parking structure	c.i.p. perimeter SW; vertical litewalls	Untopped DT, dry chord	MA	C	4
1B	Three-bay parking structure	c.i.p. internal walls, vertical litewalls	Untopped DT, dry chord	MA	C	2
2	Two-bay parking structure	Precast SWs; horizontal litewalls	Untopped DT, pour strip	SC	E	4
3	Office building	Distributed cores, L-shaped building	Topped DT	CO	C	5
4	Office building	Central core	Topped DT	SC	C	4
5	Parking deck	Two-way moment frame	Untopped DT, pour strip	NJ	C	2

Note: SDC = Seismic design categories (C and E correspond to moderate and high seismic zones, respectively); c.i.p. = cast in place; SW = Shear wall; DT = Double tees.

Table 3. Seismic hazard site summary.

Site Class	S_S	F_a	S_{MS}	S_{DS}	S_1	F_v	S_{M1}	S_{D1}	SDC
Moderate: Knoxville, TN (37915)									
C	0.58	1.17	0.68	0.45	0.147	1.65	0.24	0.16	C
High: Seattle, WA (98101)									
C	1.58	1.00	1.58	1.05	0.55	1.30	0.71	0.47	D
Near Field: Berkeley, CA (94705)									
C	2.08	1.00	2.08	1.39	0.92	1.30	1.21	0.81	E
Soft Soil: Charleston, SC (29401)									
F	1.39	0.94	1.31	0.87	0.4	2.75	1.10	0.73	E

These structures include a number of design parameters that are of interest in the DSDM project (see Table 2). The PS portfolio will be used in three ways:

1. The applicability of research findings based on generic diaphragms will be assessed through analyses of the PS;
2. The design methodology will be verified through analyses of PS designed with the new methodology; and
3. The PS will be used in design examples to explain the new design methodology.

Each PS corresponds to an actual design from different areas of the United States and based on an assortment of codes. Accordingly, a set of baseline designs has been created for these structures for use in the DSDM project (as will be described subsequently).

Representative Reinforcing Details

The representative reinforcing details established by the DSDM Consortium can be grouped into two main categories:

1. Primary diaphragm reinforcing details,[1] i.e., chord reinforcement, shear reinforcement (between precast concrete floor units), and collectors/anchorages (to lateral force resisting system walls or frames); and
2. Secondary diaphragm reinforcing details, i.e., connections between precast units and spandrels, internal beams, columns, etc.

Primary reinforcement is the diaphragm reinforcement selected during the diaphragm seismic design. The section on LU Phase I Testing describes the primary reinforcing details included in the DSDM project. Secondary reinforcing details are not explicitly part of the seismic-resisting system. However, these details may affect alternate or parallel force paths in the precast concrete floor system. Therefore, these details must be accounted for in an accurate assessment of actual behavior.

As an example consider Fig. 3, which includes a portion of PS#1 (moderate seismic zone). The design capacity of the primary reinforcement is indicated by the boxed numbers; the circled numbers are the estimated capacities of the secondary reinforcement. As can be seen from the values listed in Fig. 3, the supplemental strength provided by the secondary reinforcement may not be a negligible quantity.

The relative strength of the secondary reinforcement relative to the primary reinforcement may be quite different for different seismic zones; the former are typically governed by industry standard details while the latter is calculated based on actual (predicted) seismic forces. Furthermore, the amount of force the secondary details attract is based in part on their relative stiffness compared to the primary details. Therefore, if the primary details yield and soften under seismic loading, the secondary details may attract more load.

The intent of the investigation of secondary details within the DSDM project scope is not necessarily to include these details in the seismic design. It is instead to understand the stiffening and strengthening effects these details have on the diaphragm, and to identify and eliminate any unexpected behavior related to these details (including behavior that may compromise the intended function of the primary reinforcement, or can lead to non-ductile failure modes in the alternate load paths that rely on the secondary details).

Seismic Hazard Sites

The consensus of the DSDM Consortium is to evaluate diaphragm designs for the entire United States, not only those regions of high seismicity. Accordingly, a set of candidate sites was identified, of which four emerged as the seismic hazard sites to be used in the DSDM research project (see Table 3).

The set includes (the first three sites place a "normal" demand on a structure during a seismic event for their corresponding seismic zones):

1. A moderate seismic zone site in Knoxville, TN;
2. A Charleston, SC, soft soil site, selected because flexible diaphragms may be more sensitive to longer period motions.

Two other sites incorporate the results of previous research:[2]

3. A Seattle, WA, site, and
4. A Berkeley, CA, near-field site (selected because diaphragm forces can be significant in near field events).

The seismic hazard sites are used by the DSDM project in two ways. First, they are used to create suites of ground motions that represent the expected seismic hazard in the region. Second, they are used to create baseline designs for the PSs. This approach creates a one-to-one relationship between the structure (and diaphragm) designs used in the DSDM project and the seismic demands to which they are subjected in the evaluations.

The ground motions included in each suite are selected based on site tectonics, site class, and spectral shape. Ten ground motions are selected for each site that adequately reflect the hazard level of 10 percent in 50 years (475-year return period) for the respective site. An additional ten ground motions are selected to correspond to the 2 percent in 50 years hazard level (2500-year return period).

These ground motions are scaled to a uniform hazard spectrum (5 percent damped) within the period range of 0.15 to 1.20 seconds (see Fig. 4) by minimizing the squared error. Each ground motion possesses a transverse and longitudinal component, which will be used in the three-dimensional FE analyses in the second phase of the DSDM project.[3]

The Berkeley site is based on the unrotated ground motions from the PEER test bed of the UC Berkeley Life Sciences Building.[4] The motions include near-fault directivity effects [recorded ground motions within 8 miles (13 km) of a fault rupture]. The soft soil ground motions for the Seattle site will include ground motions developed by the SAC Steel Study[5] corresponding to NEHRP Soil Classification F.

Baseline Designs

The consensus of the DSDM Consortium is to perform all research for the DSDM project with respect to a single design code. The 2003 IBC[6] (International Building Code) was chosen as this common code. Using the 2003 IBC, baseline designs have been developed for each prototype structure at each seismic hazard site. The baseline designs serve as a "starting point" from which needed modifications are determined (to ensure that this research is consistent with the design framework established in the companion paper[1]).

For this reason, the baseline designs follow current design

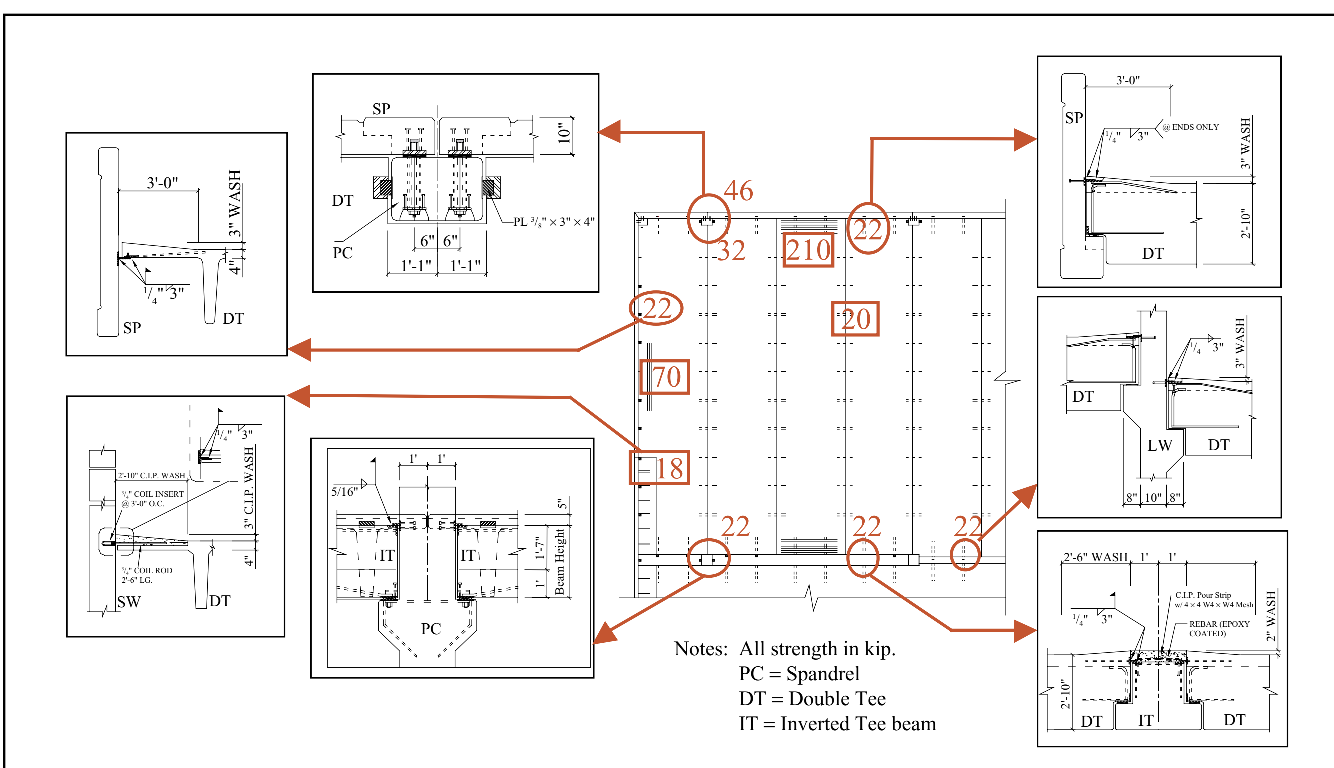


Fig. 3. Diaphragm secondary details. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN; 1 ft = 0.3048 m.

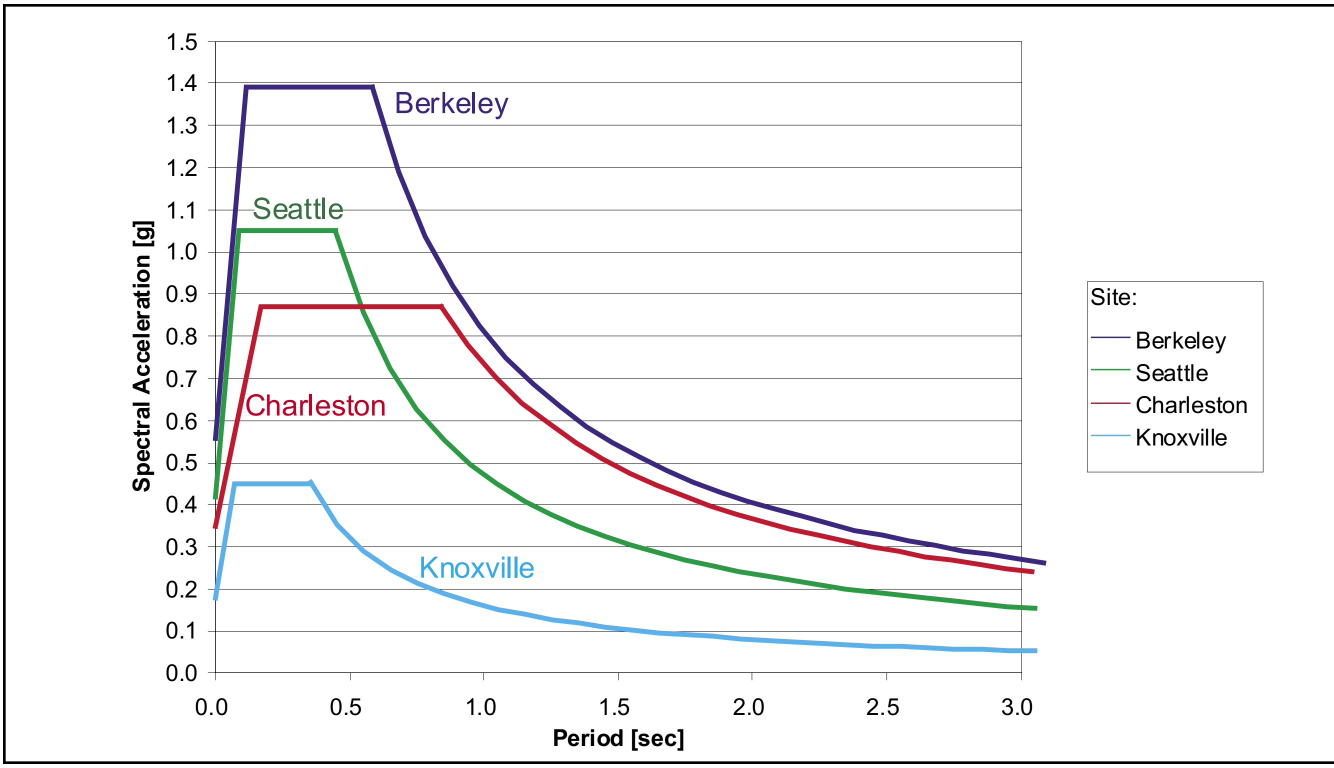
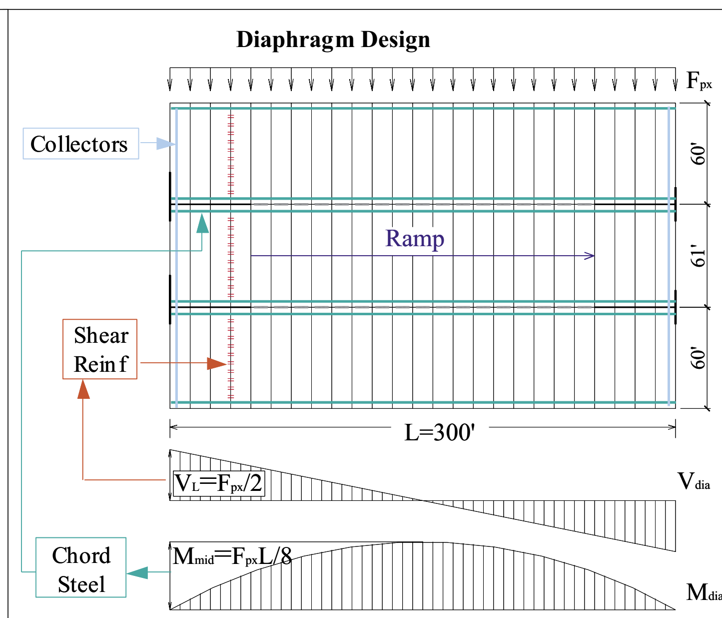


Fig. 4. Target acceleration response spectra—Design earthquake.

Structure Parameters:

Location:	Knoxville
Construction:	Pretopped
No. of Stories:	4
LRFS:	Shear wall
Height of a typical story	10.5 ft
Typical floor weight:	115 psf
Total Structure Weight, W	= 24,964 kip
Structure Design:	
Design Code	IBC 2003
S_s	0.58
S_1	0.147
Soil Site Class	C
Seismic Design Category	C
F_a	1.17
F_v	1.65
$S_{ms}= F_a \times S_s$	0.68
$S_{m1}= F_v \times S_1$	0.24
$S_{DS}= 2/3 \times S_{ms}$	0.45
$S_{D1}= 2/3 \times S_{m1}$	0.16
East/West Dir. Shear Walls	$R=5$, $\Omega_0=2.5$, $C_d=4.5$



	h_x (ft)	w_x (kip)	$w_x h_x^k$	C_{vx}	F_x (kip)	Story Shear (kip)	O.T. Moment (k-ft)	F_{px} (kip)	$F_{p,max}$ (kip)	$F_{p,min}$ (kip)
Roof	47.5	6241	296,448	0.37	550	0	0	550	1123	562
4	37.0	6241	230,917	0.29	429	550	5,780	490	1123	562
3	26.5	6241	165,387	0.21	307	979	16,061	429	1123	562
2	16.0	6241	99,856	0.13	185	1286	29,567	368	1123	562
1	0.0	0	0	0.00	0.0	1472	53,115	0	1123	562
Sum	47.5	24,964	792,607	1.0	1472	1472	53,115			

Fig. 5. DSDM baseline design: Prototype Structure #1 moderate seismic. Note: 1 ft = 0.308 m; 1 kip = 4.45 kN; 1 ft-k = 1.36 kN-m; 1 psf = 0.048 kPa.

practice methods. Each baseline design is detailed with the particular set of the representative reinforcing details under evaluation. An example of a baseline design is shown in Fig. 5 for PS#1-moderate seismic.

Initial Research Scope

The scope of the DSDM project originally requested by PCI[7] called for a seismic design methodology for precast concrete diaphragms including:

1. Topped and pretopped diaphragms;
2. Hollow-core and double-tee precast concrete units;
3. Low to high seismic zones; and
4. Existing and potential reinforcement details.

The DSDM Consortium has selected a manageable subset of the comprehensive RFP (request for proposal) issued by PCI as the initial research scope for the development of a seismic design methodology, including an early focus on:

1. Existing details;
2. Double-tee floor systems;
3. Pretopped systems; and
4. Moderate and high seismic zones.

The project scope will expand to include topped systems in the future; the LU test database provides the needed information. Also in the future, hollow-core slabs will be incorporated into the project scope by testing with the UCSD shaking table. Likewise, as the design methodology matures, other researchers can apply it to innovative reinforcing details, thus, expanding the applicability of the methodology to a larger scope.

Several points of emphasis were raised by the DSDM TG during the initial TGMs.[8] These included a desire to have the DSDM project:

1. Focus the research scope on topped composite and untopped precast concrete diaphragm designs;
2. Provide information on the extent of "upward" applicability of construction techniques used in lesser seismic zones to higher seismic zones; and
3. Determine the "downward" relevance of the extreme behaviors observed in recent analytical research[2] on long-span precast concrete diaphragms subjected to very strong ground motions.

Currently, neither topped composite (where precast concrete units and a cast-in-place concrete topping carry the diaphragm forces together[1]) nor untopped diaphragm designs are currently used in high seismic zones in the United States. Instead, diaphragm designs for precast concrete floor systems have been prescribed as topped noncomposite; the cast-in-place topping is designed for full diaphragm forces and the contribution of the precast concrete units and connections are ignored.

Accordingly, the applicability of the construction techniques associated with untopped and topped composite diaphragms must be evaluated for high seismic zones. Examples include properly detailed welded connections, bar connections, and anchorages common in many other regions of the United States. Current practice in high seismic zones is to use a mesh of reinforcing bars in the topping as a means of ensuring integrity of the diaphragm. Thus, the applicability of welded-wire reinforcement will also be examined, including wire spacing and/or materials that promote better deformation capacity.

To facilitate the adoption of DSDM project findings in high seismic regions, the DSDM Consortium has presented their research plans on several occasions to practicing engineers from the Structural Engineers Association of California (SEAOC). The DSDM Consortium has also discussed holding future presentations in a question-and-answer format as research findings emerge.

DSDM RESEARCH PROGRAM

Fig. 6 shows a flowchart describing the sequencing and interactions of the tasks for the DSDM research program. Experimental components at LU and UCSD depend heavily

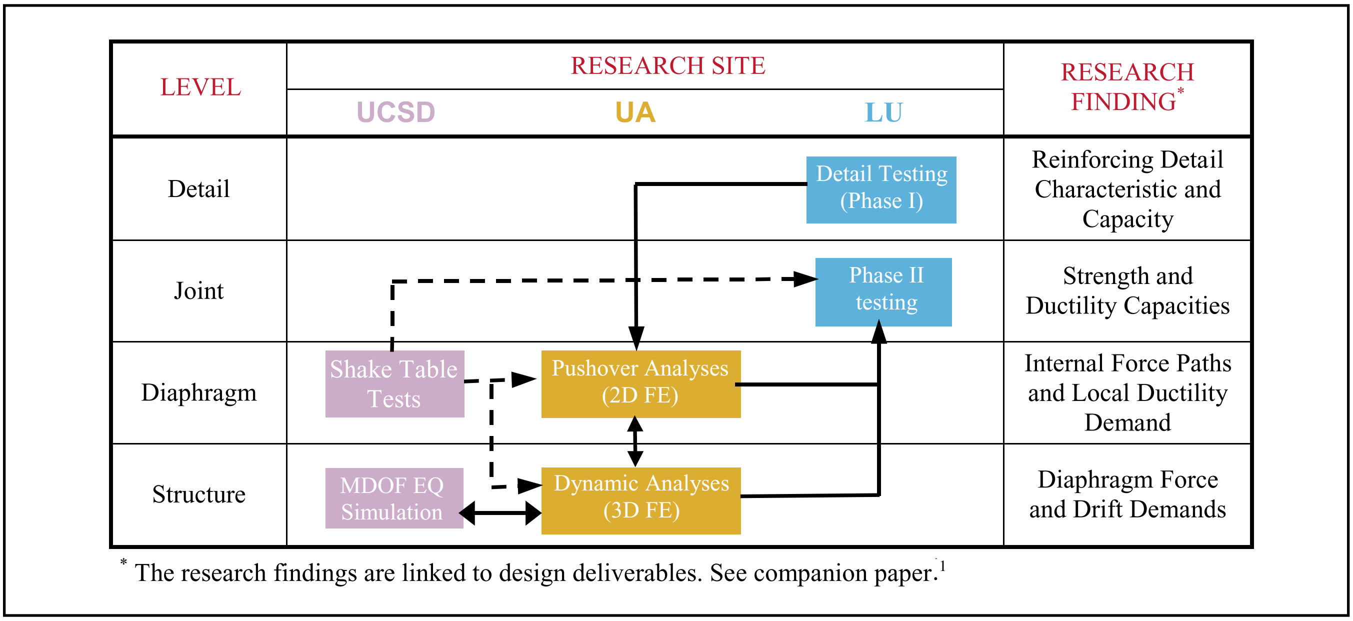


Fig. 6. Sequence and integration of analytical and experimental research tasks.

on contributions from PCI producer members. Individual research tasks in the DSDM research program include:

1. Full-scale tests of isolated details under simple load components and load combinations (LU1), supported by local modeling of the connector region (LU2), to determine properties for input by UA to FE models of complete diaphragms;
2. Pushover analyses of detailed FE models of representative floor plans (UA1) analyzed under different earthquake loading conditions to determine critical force combinations, diaphragm deformation patterns, and local ductility demands;
3. Earthquake simulations performed on simple models of generic structures at different levels of seismic hazard (SD1) to determine diaphragm force demands;
4. Verification of earthquake simulation results in Task 3 by detailed models of the prototype structures (UA2);
5. Realistic loading patterns (obtained in Task 4) applied to portions of full-scale precast concrete units based on entire joints at half-scale in a multi-component load frame (LU2); and
6. Shaking table tests (SD2) to provide experimental data on diaphragms under realistic boundary conditions to verify Tasks 2 through 5, and also to serve as a demonstration of the design methodology.

The research activities described previously occur individually at each university, yet these activities are interdependent and must be integrated to achieve the DSDM project objectives. Thus, while the individual research components (reinforcing details, diaphragms, structural systems) occur at each university, major interactions must also occur between each university research team.

The interactions among researchers, and between the researchers and the DSDM TG, are occurring through:

1. Weekly conference calls of the researchers using advanced, web-based communication tools;
2. Immediate reporting and information sharing with project members through a common internet archiving site;
3. Quarterly face-to-face meetings of the entire project team; and
4. Special-purpose visits of researchers to experimental sites for detailed discussions on the integration of the analytical and experimental research.

Diaphragm Reinforcing Detail Research Component (LU)

The research component at LU focuses on the diaphragm reinforcing details. This research component is primarily experimental with supporting analytical research. In Phase I of this research component, the characteristics of the reinforcing details are established under predetermined loading protocols. In Phase II, groups of reinforcing details designed using the emerging design methodology are tested under likely seismic demands.

Phase I focuses on determining the stiffness, strength, and ductility characteristics of the primary diaphragm reinforcing details. These characteristics will be determined under monotonic and cyclic shear deformation, axial deformation, and combinations of shear and axial deformations.

The primary objective of the Phase I testing is to provide the required input data to build accurate analytical models of the diaphragm for the UA diaphragm research component. Phase I tests will also extend the database on precast concrete diaphragm reinforcing details. As such, the information derived in this testing will be used to prequalify connection details, establish classification ranges, and develop qualification protocols.

Table 4 shows the Phase I testing matrix; the listed tests provide coverage of the representative primary reinforcing details. These details were established through consensus of the DSDM TG. The selection was based on a literature survey of previous research that included the creation of a database of industry/proprietary testing.[9]

The selected details satisfy one or more of the following criteria. They: (1) are prevalent in current precast concrete construction; (2) are viewed as promising to the DSDM TG; (3) are without sufficient test data in the existing test database; or (4) may promote the use of precast concrete in high seismic zones.

It should be noted that while the literature survey identified several dozen previous tests of precast concrete reinforcing details, most of these tests do not provide the needed data for the DSDM project because they involve tests of details under a single monotonic force component. Recent research has pointed to the importance of force combinations (e.g., shear and tension) on the response of the precast concrete diaphragm reinforcing details.[10] Furthermore, the limited data on cyclic tests of precast concrete reinforcing details[11-13] have shown the significant effect of cyclic loading on stiffness and

Table 4. Phase I test matrix.

Type	ID	Description	No. of Tests
Shear	O	JVI Vector connector in 4 in. pretopped panel	4
	A	#4 Hairpin in 2 in. untopped panel	3
	C	#4 Hairpin in 2 in. panel with 2 in. topping	5
	D	Welded plate connector in 2 in. panel with 2 in. topping	4
Chord	B	Welded chord connector 2 – #5 in 4 in. pretopped panel	4
	F	Chord pour strip 2 – #5 on 2 in. panel with 2 in. topping	5
Topping	E	2 in. panel with WWR in 2 in. topping	5

Note: 1 in. = 25.4 mm; WWR = welded wire reinforcement.

strength degradation, and ductility reduction.

The DSDM project is able to gather information on the hysteretic characteristics of precast concrete reinforcing details under force combinations through the use of the innovative test fixture developed at LU (see Fig. 7). The fixture uses three, displacement-controlled actuators to permit proportional or non-proportional combinations of shear and axial tension/compression (T/C).

This feature represents an advancement over previous testing to date, in that most testing setups are based on a single load component.[14] Also, in the rare instances when load combinations have been attempted,[12] the shear and tension have been components of a single force vector, which artificially couples the force components. Furthermore, the ability to measure (through the load cells in the dual T/C actuators) the force that builds up perpendicular to the joint, when the joint is subject to a shear force, has not been present in previous testing.

The Phase I loading protocols include a number of control patterns to fully characterize each connection detail. A number of duplicate specimens will be created for each connection detail and tested under each of the defined loading protocols. The load protocol patterns include:

1. Simple deformation trajectories: monotonic shear and monotonic tension to create backbone envelopes;
2. Cyclic shear and cyclic T/C depending on the reinforcement type (shear reinforcement, chord reinforcement, etc.) to determine stiffness/strength degradation characteristics and cyclic ductility; and
3. Deformation combinations in which the ratio of shear to tension demand has been estimated based on the preliminary analytical FE model diaphragm studies for typical locations of the detail in question.

These load combination tests will provide a monotonic envelope for combined deformation demands.

Fig. 8 shows the Phase I test specimens. Each specimen is fabricated at full-scale and includes a tributary portion of the precast concrete unit. Test specimens have been detailed to avoid issues identified by the DSDM TG, including constructibility issues such as limited weld access and under-designed welds.

The Phase I testing matrix involves approximately 30 full-scale tests. This program allows examination of the representative details under several loading conditions. To enhance

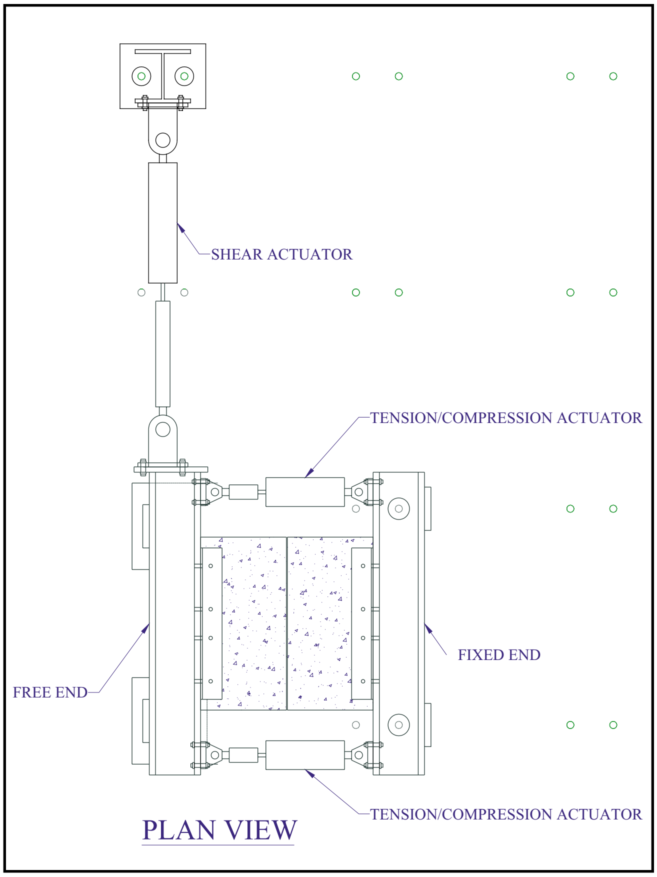


Fig. 7. LU Phase I test fixture.

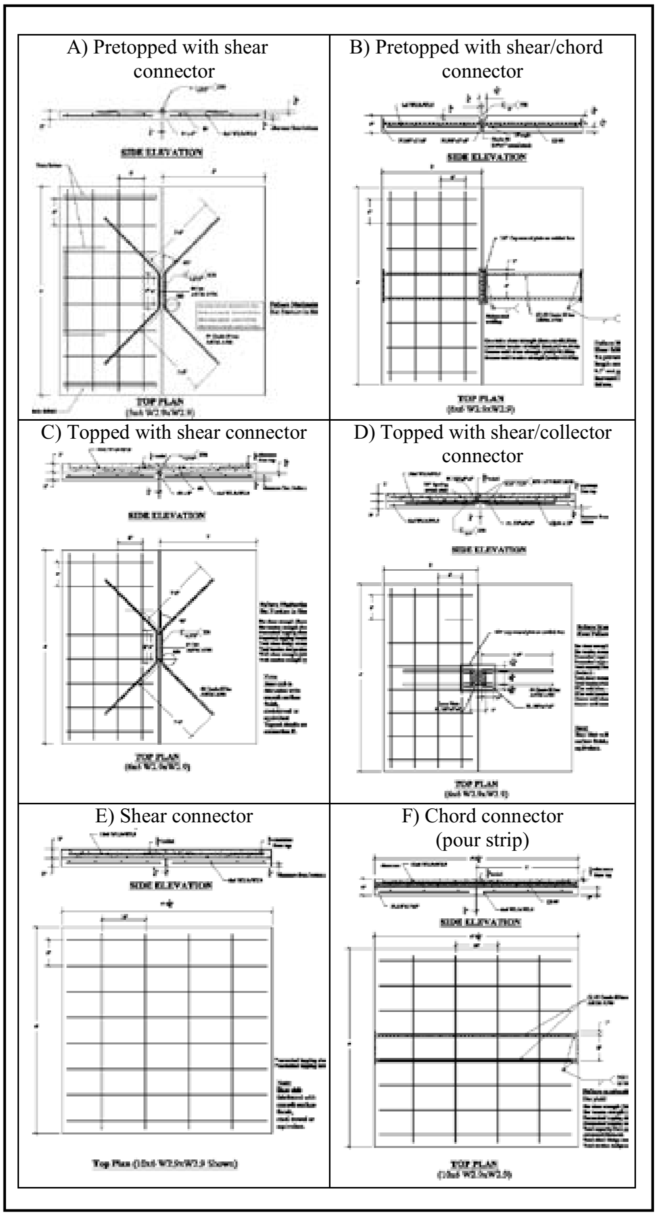


Fig. 8. LU Phase I test matrix. A) Pretopped with shear connector; B) Pretopped with shear/chord connector; C) Topped with shear connector; D) Topped with shear/collector connector; E) Shear connector; and F) Chord connector (pour strip).

the information provided by the Phase I testing, the LU team is performing local modeling and analyses of the diaphragm reinforcing detail and the surrounding concrete (see Fig. 10d).

The local modeling permits:

1. Parametric studies on the welding detail and slug placement to enhance the pretest review;
2. Determining of the sensitivity of the performance to the construction or design parameters, which is not possible in a single test; and
3. Prediction of the response under the different loading protocols prior to testing to determine the most appropriate protocol for a particular reinforcing detail.

The LU Phase II testing will focus on the performance of connected precast concrete units subjected to a combination of shear, axial, and flexural loads across key portions of joints between the units (see Fig. 9a). For these tests, force combinations will be applied that reproduce load histories that approximate the demands on the reinforcing details during a seismic event. These load patterns will correspond to the response histories at different critical diaphragm locations, based on seismic demands on the details obtained from the structural analyses (SD2), and force combinations and deformation patterns obtained from the diaphragm analyses (UA2).

Specific information regarding the types of tests performed in Phase II will be determined in future TGMs as research findings emerge. Phase II may include testing of a variety of precast concrete diaphragm joint reinforcement details found to be critical in the UA analytical research, for instance full-scale tests of connection groups (e.g., chord reinforcement and shear reinforcement); connections between precast units and internal members (e.g., inverted tee beams or litewalls) as shown in Fig. 9b; or connections between precast units and primary elements of the lateral force resisting system (e.g., shear wall anchorages). Conversely, entire panel joints may be tested at a reduced scale to supplement the data from the UCSD shake table test (see Fig. 9c).

Precast Concrete Diaphragm Research Component (UA)

The central component of the research is the analytical investigation of precast concrete floor diaphragms at UA. To achieve the DSDM project's research objectives, the diaphragm models must:

1. Capture the behavior of the jointed system, including the response of the discrete, nonlinear, and potentially non-ductile reinforcing details;
2. Include the additional features of the precast concrete floor system that will affect diaphragm response; and
3. Reasonably reproduce the boundary conditions of the floor system in an actual building.

At the same time, it is necessary that the tools and models developed for practical use in design be simple.

The analytical investigation of precast concrete diaphragms in the DSDM project begins with realistic models that capture the effect of design choices on important seismic behavior. As the research progresses, the models are extended to account for other behaviors. Thus, at the outset of the DSDM research, the analytical modeling of the precast concrete diaphragm is limited to:

1. In-Plane Behavior—The effects of out-of-plane actions, including gravity load and imposed rotations at the vertical elements of the lateral force resisting system, need to be considered eventually; however, these actions add a level of complexity to the study and could confuse the needed understanding of in-plane behavior of these systems. Thus, the analytical modeling will focus on in-plane (two-dimensional) behavior. It may be possible to verify aspects of the design methodology in the presence of out-of-plane effects, through three-dimensional analysis, in the later stages of the project. However, the primary opportunity to examine out-of-plane effects will occur during the UCSD shake table test.

2. Static Monotonic Response—The seismic response of the diaphragm is dynamic and cyclic. However, much information can be obtained on the impact of different design parameters on diaphragm behavior through static and monotonic loading, provided the models capture nonlinear behavior of the diaphragm reinforcing elements. Thus, the two-dimensional models of the diaphragm will be subjected to static monotonic body forces. These body forces will be applied usually through a uniformly distributed load pattern to approximate the inertial forces that develop during an earthquake. Under low load levels, the elastic response provides a measure of the elastic stiffness of the diaphragm. As different reinforcing details yield, information on strength

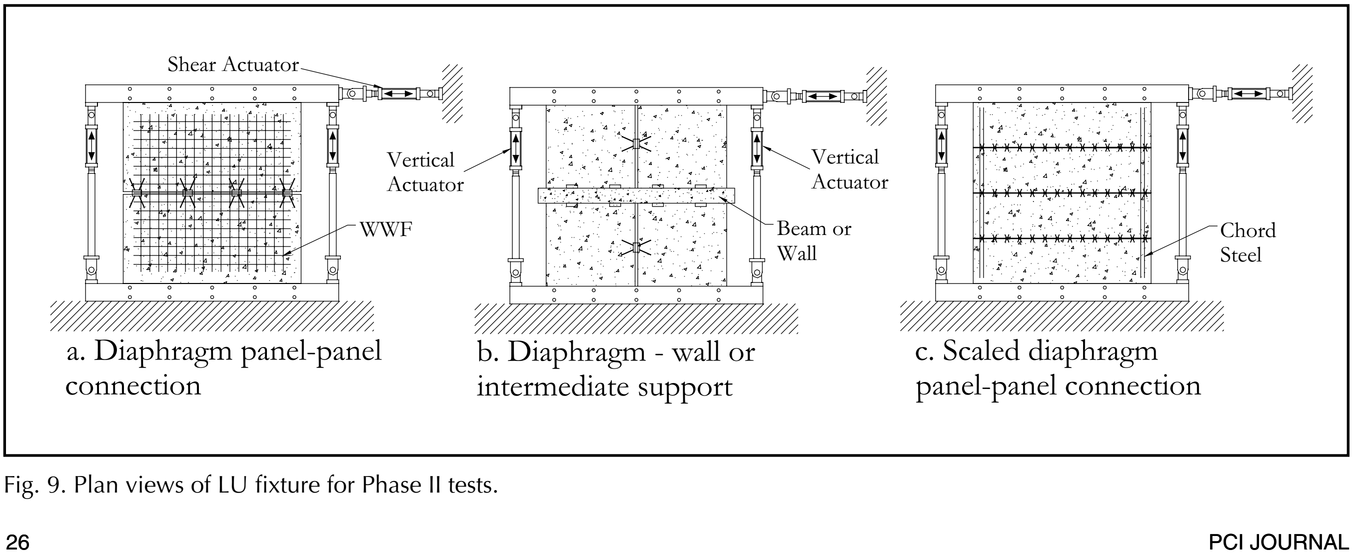


Fig. 9. Plan views of LU fixture for Phase II tests.

and ductility capacity of the diaphragm is obtained. For this reason, these analyses can be considered as nonlinear "push-over" analyses of the diaphragm.

The analytical models are created using FE formulations from the general purpose FE package ANSYS. Fig. 10a shows a typical two-dimensional FE model, a single floor of PS#1 subject to transverse body force. The major response of the floor system occurs in the joints between the precast concrete units as shown in the inset of Fig. 10a.

The FE discretization of the joints between the precast units employs nonlinear springs and contact elements (see Fig. 10b). The precast concrete units are modeled as elastic members; thus, the spring elements are intended to fully capture the nonlinear behavior of the diaphragm-reinforcing element and the surrounding concrete in the connection region. Thus, the spring properties are obtained directly from the LU Phase I test data (and existing test data where appropriate, see Figs. 10c and 10d).

The challenges in modeling the reinforcing detail elements include capturing:

1. The coupled shear/tension response of these details;
2. Nonlinear and/or nonductile response; and
3. The effects of confinement, including possible self-generated compression forces perpendicular to the joint due to transverse loading of the joint.

The precast concrete floor system models being developed will not only include the primary reinforcing details, but also the other members (spandrels, gravity system beams, and columns) and any respective connections that may impact the actual behavior of the floor system. The LU Phase I tests will provide estimates for these secondary details; for instance, the connections of double tee-to-inverted tee beams will be assumed to behave as one side of a flange-to-flange connector.

Floor systems will be evaluated with and without these "secondary" reinforcing details to determine the sensitivity of the diaphragm response to these secondary elements. Given the dependence of precast concrete diaphragm behavior on the specific details, the models must be consistent with respect to design considerations and construction methods used in practice.

The analytical studies to be performed include examining:

1. The effect of different reinforcing detail characteristics and floor plan geometry on diaphragm response;
2. Force and deformation demands at critical regions, including wall anchorages;
3. The appropriate relative strength of diaphragm shear reinforcement with respect to chord reinforcement strength; and
4. Sensitivity studies on the effect of secondary details, the effect of lateral system layout, and the direction of the body force.

Parametric studies will be applied to generic diaphragms. The design findings that emerge from these studies (and the UCSD studies) will be verified using the PSs. In these analyses, it is critical that the boundary conditions associated with

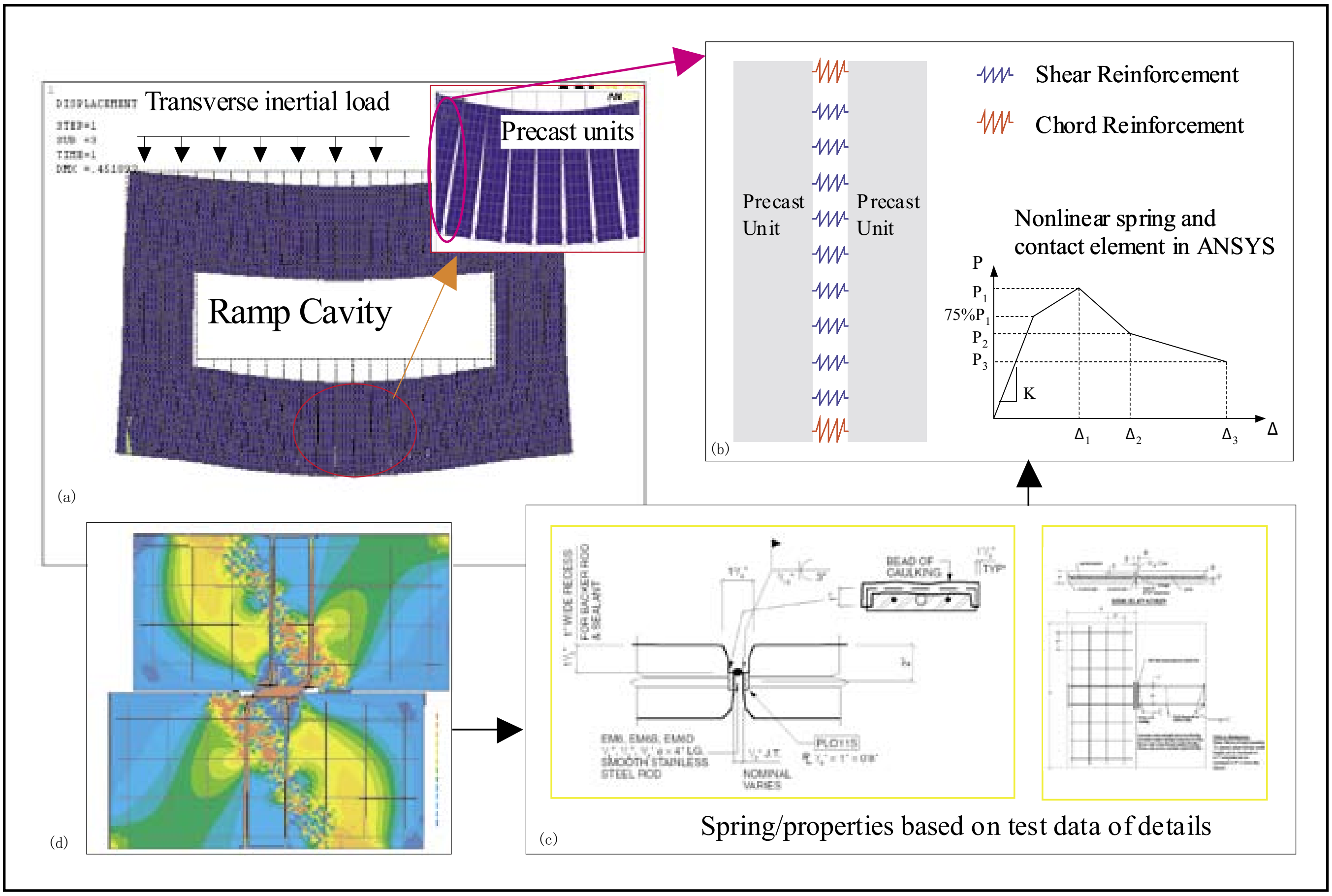


Fig. 10. Creating two-dimensional, finite element model of diaphragms (PS #1).

the model permit the floor system to deform in the same manner that it would in the actual structure.

The two-dimensional models are not effective at capturing all the responses of more complicated structures, such as a parking structure. For these structure types, a full three-dimensional model is needed to capture the response of all the components such as ramps, litewalls, etc. (see Fig. 11a). The extension of the UA models to three dimensions, including cyclic and dynamic response, is closely tied to the UCSD system studies, and is discussed in the following section.

Structural System Research Component (UCSD)

The structural system research component at UCSD involves two main activities: earthquake simulations of multi-degree of freedom (MDOF) models of structures and a shake table test of a three-story precast concrete structure.

The MDOF models developed at UCSD (see Fig. 11b) used simpler representations of the diaphragm than those used in the UA pushover analyses. The diaphragm properties are derived from the FE pushover analyses at UA. The MDOF structures will be subjected to seismic simulations in nonlinear transient dynamic analyses (NTDA) using the suites of ground motions developed for the seismic hazard sites.

The MDOF structures will be generic to facilitate the variation of several important design parameters. Global diaphragm demands obtained in these analyses are used to establish the:

1. Expected diaphragm force levels in DBE and MCE events;
2. Expected diaphragm deformations and associated gravity system column drifts in MCE events; and
3. Expected diaphragm global ductility demands in MCE events.

The latter will be used as reference points to estimate local ductility demands by examining the internal state of the FE models (developed at UA) at these global deformations.

The specimen for the UCSD shake table experiment will be a three-story diaphragm-sensitive precast/prestressed concrete building structure. The original research proposed a one-quarter scale building with plan dimensions 6 ft 6 in. wide × 19 ft 6 in. long (1.98 m wide × 5.95 m long) to be tested on the 10 × 16 ft (3.05 × 4.88 m) uni-directional earthquake simulator facility at the Charles Lee Powell Laboratory. However, the subsequent dedication of the world's second largest shake table at UCSD's Camp Elliott Field Station, commissioned as part of NSF's $100 million NEES initiative, now provides a unique opportunity for testing at a larger scale and allows the possibility of the shaking table test to serve as a highly visible demonstration project.

The Camp Elliott facility possesses a payload capacity of more than 50 times the capacity of the shake table available when the DSDM project began. This increased capacity will easily accommodate the mass of a one half-scale precast concrete building. However, while the table dimension is 50 ft (15.25 m) in the direction of motion (the long dimension for most test specimens), it only provides 24 ft (7.32 m) transverse to the direction of motion (the long dimension needed for diaphragm sensitive structure tests). Thus, the test for the DSDM project relies on a modified outrigger design to accommodate the required building footprint on the shake table.

Fig. 12 shows the specimen planned for testing on the NEES shake table, pending supplemental NSF funds: a half-scale three-story building, 18 ft tall (5.49 m) with a 16 ft wide × 48 ½ ft long (4.88 m wide × 14.79 m long) plan dimension. Structural walls will provide the lateral force resistance in the direction of loading. The walls will be supported on a large reaction mass on rollers to counteract overturning, thus avoiding the need for the construction of an expensive table outrigger.

The UCSD shake table experiment will be used to observe system behavior under static and dynamic loading conditions. The diaphragm in this building will be constructed using scaled precast concrete floor units and will incorporate scaled connection details identical to those used in practice.

The diaphragm reinforcement will be designed in accordance to the requirements of the emerging design methodology. Two floors will incorporate double-tee floor systems, one untopped and one with a cast-in-place concrete topping; and one floor will use hollow-core slab units. Floor units of different widths will be used to build each of the topped floors to represent 3 ft (0.91 m) wide double-tee units or 4 ft

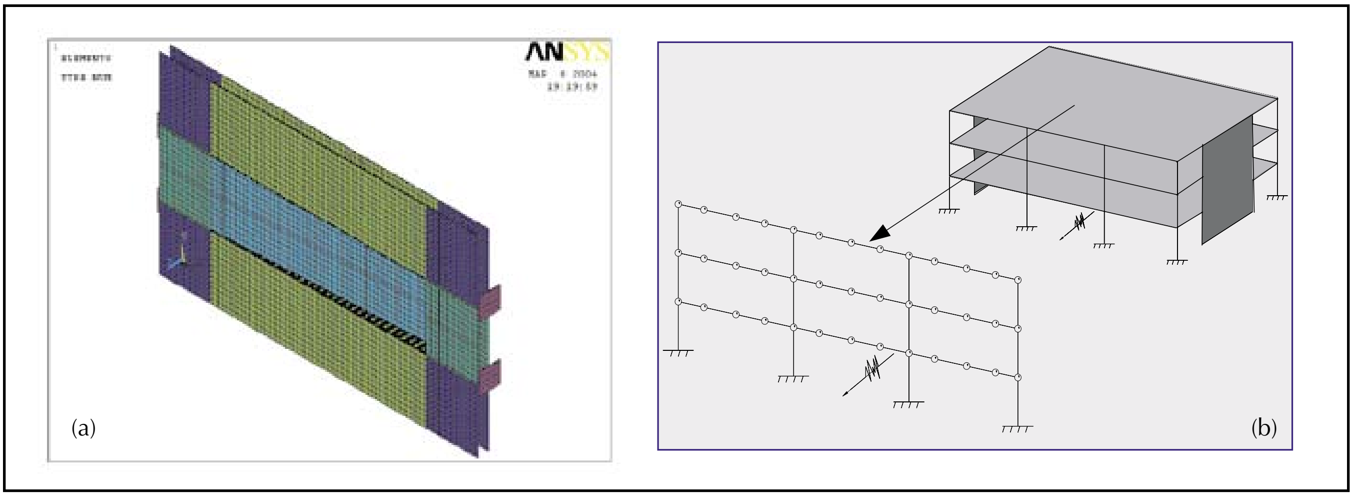


Fig. 11. Structure models: (a) Three-dimensional FE model; (b) UCSD MDOF model.

(1.22 m) wide hollow-core units.

Characterization of the building diaphragm's response will be obtained through dynamic shake table tests. Displacement transducers will be set in place to monitor the diaphragm in-plane deformations and to enable the decomposition of the shear and flexural deformations. Strains in different parts of the diaphragms and in the main reinforcement will also be monitored during these tests. The ensemble of records for the tests will include pulse-loading, band-limited white noise, and historic ground motions, including a near-fault record.

A system test is critical to the success of the project as it provides a considerable amount of information that cannot be obtained elsewhere in the project (see Table 5, top). It is recognized that a larger scale test specimen would provide the best approximation of realistic conditions (see Table 5, bottom), thus enhancing the quality of certain information or making other data attainable.

Furthermore, testing at the now available one-half scale will eliminate certain compromises including distorted diaphragm elements (accurate scaling of key dimensions only) and idealized connections (capturing scaled stiffness and strength, but not matching physical appearance). These aspects may be acceptable for a laboratory validation, but are not desirable for a highly visible demonstration project. Regardless, the knowledge to be acquired in this test at either scale represents a large step forward; shaking table tests of precast concrete floor systems are rare.

Table 5. Information provided by shaking table test.

The shaking table test will provide information on:

- Vertical distribution of lateral load along structure
- Force path within floor diaphragms
- Internal force distribution along individual joints
- Relationship between global and local ductility demand
- Hysteretic characteristic of diaphragm

The information will be acquired under "actual" conditions:

- Realistic development of floor inertial loads
- Realistic vertical profile of the floor
- Realistic confinement effects from vertical elements
- Realistic distributions along series of joints in parallel

SUMMARY OF RESEARCH PROGRESS AND PLANS

As of the writing of this paper, during year one of the DSDM project, the following research tasks have been completed:

- **Code Review—**A formal review and evaluation of existing code provisions pertaining to precast concrete diaphragm seismic design was performed, including a background document on recent modifications.

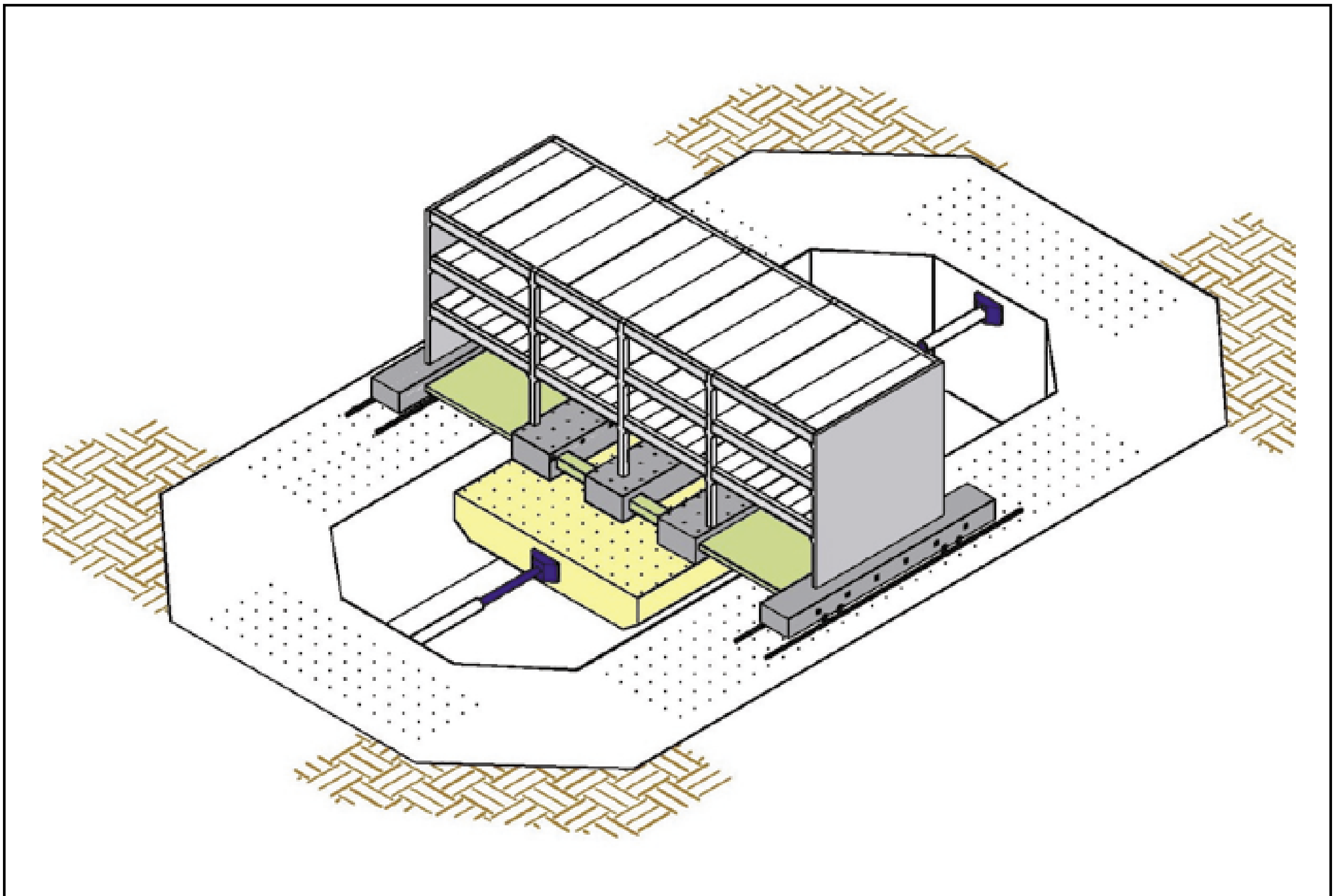


Fig 12. UCSD shaking table test: Half-scale model on NEES shaking table.

- **Framework for Design Methodology—**Based on the review of codes of practice and recent research, consensus was achieved during the initial TGMs on a design framework for developing the precast concrete diaphragm seismic design methodology (as described in the companion paper[1]).
- **Database/Literature Survey—**A literature survey of previous research was completed including the creation of a database of industry/proprietary testing results.
- **Representative Details—**Based on the literature survey, a consensus was reached on a set of representative details to study. These details were included in the LU Phase I testing matrix.
- **Testing Protocol—**A testing protocol was developed for detail characterization that includes a sequence of loading trajectories (tension/compression versus shear) and amplitudes. As performance targets and appropriate metrics are further developed, a different testing protocol will be developed for qualification.
- **Phase I Testing—**The test fixture was completed, test specimens were designed and created, and LU Phase I testing is being performed.
- **Prototype Structure Portfolio—**A portfolio of PS has been assembled. The portfolio contains five structures that provide coverage of the key design parameters.
- **Seismic Hazard Sites—**A set of seismic hazard sites has been selected including a representative moderate and high seismic zone sites, and near-field and soft-soil sites. Suites of ground motions have been assembled corresponding to DBE and MCE input levels.
- **Baseline Designs—**Each prototype structure has been designed for each seismic hazard site according to the current IBC. These designs will be used as a baseline for the research.
- **Model Development—**A reinforcing detail element has been developed for insertion in FE analyses. The element captures the nonlinear coupled response to shear and axial load.
- **Diaphragm Analyses—**Nonlinear pushover analyses of two-dimensional diaphragm models incorporating the reinforcing detail elements are being performed within design parameter studies.
- **MDOF System Studies—**MDOF models of diaphragm-sensitive structures have been created. Ground motion suites have been scaled. Earthquake simulations are being initiated.
- **Shake Table Test Design—**The preliminary design of the shaking table test specimen and fixture system has been completed.

CONCLUDING REMARKS

PCI is conducting a large area of emphasis research project to develop a seismic design methodology for precast/prestressed concrete diaphragms. A team comprised of researchers from UA, UCSD, and LU is performing the work with strong oversight from an industry TG. A companion paper has presented the design philosophy and research approach being taken in the DSDM project.[1]

This paper has described the project physical scope and the individual analytical and experimental research activities that will occur. This paper, and the previously published companion paper, is intended to outline the foundation of the DSDM project and provide context for the technical papers to follow.

ACKNOWLEDGMENTS

This research is being supported by the National Science Foundation (NSF) and the Precast/Prestressed Concrete Institute (PCI). The authors are grateful for this support. The authors would like to acknowledge the tremendous support provided by the members of the DSDM TG: S.K. Ghosh, Roger Becker, Ned Cleland, Tom D'Arcy, Neil Hawkins, Paul Johal, Joe Maffei, Susie Nakaki, Doug Sutton, and Harry Gleich. In addition, the authors would like to express their gratitude to the PCI JOURNAL reviewers for their constructive comments.

Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1. Fleischman, R. B.; Naito, C.; Restrepo, J.; Sause R.; and Ghosh, S. K., "Seismic Design Methodology for Precast Concrete Diaphragms, Part 1: Design Framework," PCI JOURNAL, V. 50, No. 5, September-October 2005, pp. 68-83.
2. Fleischman, R. B.; Farrow, K. T.; and Eastman, K., "Seismic Response of Perimeter Lateral-System Structures with Highly Flexible Diaphragms," *Earthquake Spectra*, V. 18, No. 2, May 2002, pp. 251-286.
3. Restrepo, J., and Schoettler, M., "DSDM Report on Ground Motions," https://central.nees.org/
4. Somerville, P., "Report on UC Science Building ground motions", http://www.peertestbeds.net/UCS/Somerville%20Dec%202001%20UCS%20ground%20motions.pdf
5. Woodward-Clyde Federal Services, "Suites of Earthquake Ground Motions for Analysis of Steel Moment Frame Structures – Draft Report," http://nisee.berkeley.edu/data/strong_motion/sacsteel/draftreport.html
6. IBC, *International Building Code*, 2003 Edition, International Code Council, Inc., Falls Church, VA, 2003.
7. PCI, Request for Proposal (RFP), "Development of a Design Methodology for Precast Diaphragms," Precast/Prestressed Concrete Institute, Chicago, IL, October 2002.
8. DSDM, Meeting Minutes, RM#1, Chicago, IL, August 7, 2003, http://central.nees.org/
9. Naito, C., and Cao, L., "Precast Diaphragm Panel Joint Connector Performance," Paper 2722, Proceedings, 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 2004.
10. Fleischman, R. B.; Sause, R.; Pessiki, S.; and Rhodes, A. B., "Seismic Behavior of Precast Parking Structure Diaphragms," PCI JOURNAL, V. 43, No. 1, January-February 1998, pp. 38-53.
11. Pincheira, J. A.; Oliva, M. G.; and Kusumo-Rahardjo, F.

I., "Tests on Double Tee Flange Connectors Subjected to Monotonic and Cyclic Loading," PCI JOURNAL, V. 43, No. 3, May-June 1998, pp 82-96.

12. Oliva, M. G., "Testing of the JVI Flange Connector for Precast Concrete Double-Tee Systems," Structures and Materials Test Laboratory, College of Engineering, University of Wisconsin, Madison, WI, June 2000.

13. Shaikh, A. F., and Feile, E. P., "Report on the Results of Laboratory Testing of JVI Vector Connector for Precast Double-Tee Members," University of Wisconsin-Milwaukee, Milwaukee, WI, 2002.

14. Cao, L.; Naito, C.; and Sause, R., "Phase 1 Experimental Evaluation of Diaphragm Connections: Program Overview," Report by DSDM LU Group, Lehigh University, Bethlehem, PA, 2005.

15. Alsiwat, J. M. and Saatciogu, M., "Reinforcement anchorage slip under monotonic loading", *Journal of Structural Engineering*, V. 118, No. 9, September 1992, pp. 2421-2438.

APPENDIX– NOTATION

C_{vx} = vertical distribution factor

F_a = acceleration-based site coefficient (at 0.3-second period)

F_v = velocity-based site coefficient (at 1.0-second period)

F_x = lateral seismic force at level x

F_{px} = diaphragm design force at level x

$F_{p,\max}$ = upper bound of diaphragm design force

$F_{p,\min}$ = lower bound of diaphragm design force

h_x = height above base at level x

k = distribution exponent

S_S = mapped maximum considered earthquake, 5 percent damped, spectral response acceleration at short periods

S_1 = mapped maximum considered earthquake, 5 percent damped, spectral response acceleration at a period of 1 second

S_{DS} = design, 5 percent damped, spectral response acceleration at short periods

S_{D1} = design, 5 percent damped, spectral response acceleration at a period of 1 second

S_{MS} = maximum considered earthquake, 5 percent damped, spectral response acceleration at short periods adjusted for site class effects

S_{M1} = maximum considered earthquake, 5 percent damped, spectral response acceleration at a period of 1 second adjusted for site class effects

w_x = portion of total gravity load of structure located or assigned to level x