



# CHARLES PANKOW FOUNDATION

Building Innovation through Research

**Final Report**  
to the  
**Charles Pankow Foundation**  
from  
**The University of Arizona**

**Development and Design of Untopped Precast Concrete Diaphragm Systems for  
High Seismic Zones**

Revised CPF 08-07 Grant<sup>1</sup>  
Final Report: June 6, 2009

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<sup>1</sup> CPF supplement 08-07 combined with CPF 02-06 grant as per contract revision June 2008.

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**REPORT SUMMARY**

This document is the FINAL report for Charles Pankow Foundation Grant CPF 08-07: “Development of a Precast Floor Diaphragm Seismic Design Methodology (DSDM)”. The time period covered in the CPF support is March 2006 to January 2009. The research was performed by a university research consortium composed of the University of Arizona (UA), Lehigh University (LU) and University of California San Diego (UCSD) with co-funders the Precast/Prestressed Concrete Institute (PCI) and National Science Foundation (NSF). The research was performed with strong industry oversight through PCI producer member industry partners, and a highly active twelve member industry task group, the DSDM Task Group (TG).

The report was submitted in draft form for review and comment to the Charles Pankow Foundation on February 9 2009 (1<sup>st</sup> draft) and March 23 2009 (2<sup>nd</sup> draft). This document represents the FINAL report:

- summarizing the activities of the research project.
- documenting the findings of the research project.
- describing the products representing CPF design deliverables including:
  - viable seismic resistant topped and untopped precast diaphragm systems
  - the precast diaphragm details for use in these systems
  - precast diaphragm seismic design procedures for these systems
- detailing the readiness of these products for commercial application on building construction jobsites and code adoption, including:
  - the specific actions remaining to attain use in building construction practice;
  - the mechanism for implementing the draft design procedures into code;
  - the required activities for obtaining certification regarding suitability of the products for commercial use; and,
  - a final dissemination plan detailing tasks and schedule

Attached to this Final Report is a document *Draft Seismic Design Methodology for Precast Concrete Diaphragms* that provides the components of the seismic design methodology for precast concrete diaphragms. The *Draft Seismic Design Methodology Document* includes four parts:

- A. Precast Diaphragm Seismic Design Procedure
- B. Precast Concrete Diaphragm Reinforcement Classification
- C. Analysis Techniques for Diaphragm Design
- D. Diaphragm Design Charts and Examples

The proposed design and qualification procedures in the draft document are in sufficient detail to allow a knowledgeable engineer to replicate the design using this deliverable as the sole source of technical information. The ongoing PCI supported codification-related research and development activities of the upcoming year (as described in **PART 3**) will permit designers to use a final version of the draft document, i.e., *Seismic Design Methodology for Precast Concrete Diaphragms*, to perform seismic design of reliable precast concrete diaphragm systems.

## PART 1: DSDM PROJECT SUMMARY

### BACKGROUND: DSDM PROJECT OBJECTIVES

The CPF support is associated with its own specific objectives and deliverables, as is the NSF and PCI support. However, as the activities of the overall project were highly integrated, it will be useful to interpret the CPF research within the context of the overall project. Accordingly, the overall objectives of the DSDM project (with funding agency most closely associated with the objective in parentheses) are:

- (1) to significantly advance knowledge of the seismic behavior of precast floor diaphragms through closely integrated experimental and analytical simulations (NSF).
- (2) to develop information on the stiffness, strength, and ductility capacity of critical precast diaphragm elements through experimental work (NSF).
- (3) to use the information from objectives 1 and 2 to develop an industry endorsed design methodology for precast diaphragms including (PCI):
  - a. the forces and displacements for which the diaphragm should be designed;
  - b. the connections and details that can provide this performance; and,
  - c. the required relative stiffness of the diaphragm to the lateral force resisting system.
- (4) to develop and demonstrate untopped and topped precast diaphragm systems that will provide good performance in regions of high seismic hazard (CPF).
- (5) to produce a design and detailing procedure for these system for high seismic zones (CPF).
- (6) to codify this design procedure and create design aids (PCI/CPF/NSF).

While a distinction is seen in the objectives of each funding agency, all major co-funders contributions extend at least partially to each activity of the project (See *Appendix 1* for DSDM funding history), and project results have been obtained from the synthesis of individual research tasks. Thus, each cofounder shares in the overall project outcomes. This is particularly true for the CPF support, which had a significant impact on improving the quality, quantity and reach of the basic scientific information developed by the project, and thus was instrumental to the project achieving its broader objectives. For this reason, appendices of this final report will include activities and findings of the overall project (separated or clearly distinguished from direct CPF deliverables), and all future products of this project not directly related to CPF objectives (technical papers on scientific advances, presentations on advances in the state-of-art in research, etc.) will acknowledge CPF's contribution.

### REVIEW OF PROJECT ACTIVITIES

The DSDM Project involved a multi-university research effort over several years. Thus significant coordination was involved in the research program. A review of the DSDM Project Activities is not a specific requirement of the final reporting. However, a comprehensive summary of the project activities may be useful for interpretation of this project's outcomes or planning/evaluating future projects. Thus, the project activities appear as appendices to this report as follows:

- *APPENDIX I: Project Management* details the manner in which the project accomplished coordination among the different universities and the DSDM Task Group.
- *APPENDIX II: DSDM Project Major Research Activities* describes the major research activities of the overall project.

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- *APPENDIX III: DSDM Project Industry Interaction* describes the significant industry interaction involved in the project activities, arranged within each phase of the research.
- *APPENDIX IV: Shake Table Test Specimen Construction* describes activities related to the design, production and construction of the half-scale shake table, a particularly significant effort within the project and closely associated with the CPF funding.

### REVIEW OF PROJECT FINDINGS

The CPF grant was instrumental in facilitating or enhancing the quality of the overall findings of the DSDM project, including those not directly related to the CPF funding objectives. Accordingly, a comprehensive summary of the overall project findings will be useful for documenting the broader impacts of the CPF support. For this reason, the overall project findings appear as appendices to this report and are arranged as follows:

- *APPENDIX V: DSDM Research Advances*, including (a) Advances in Knowledge; (b) Advances in the State of Art in Research.
- *APPENDIX VI: DSDM Experimental Results*, including: (a) Isolated Connector Testing; (b) Adaptive Testing; and (c) Shake Table Testing.
- *APPENDIX VII: DSDM Research Findings*, including (a) Findings related to Precast Diaphragm Behavior; (b) Findings related to Precast Diaphragm Design.

### DSDM PROJECT MAJOR ACCOMPLISHMENTS

The following is a list broadly describing the major research accomplishments of the project. The activities and findings associated with these major accomplishments are described in more detail in the appendices listed above. Accomplishments prior to the CPF support are shown in *italics*.

1. *Consensus on a design philosophy and the creation of a framework for a new seismic design methodology for precast concrete floor diaphragms.*
2. *A successful testing program of existing precast concrete diaphragm connections.*
3. *The successful building of analytical models of precast diaphragms based on the tests from (2).*
4. *Analysis of existing precast concrete diaphragm capacity using the models developed in (3).*
5. The development of improved precast diaphragm connections based on the needs identified in (4) relative to the results observed in (2)
6. Extension of the analytical models developed for diaphragms in (3) to three-dimensional models of precast concrete structures for nonlinear dynamic analysis.
7. The successful testing of precast diaphragm joints containing the improved details from (5) using next-generation hybrid testing algorithms incorporating the models in (6).
8. Earthquake simulations of diaphragm-sensitive precast concrete structures using the models developed in (6) to estimate design factors needed for the design methodology from (1).
9. A white paper describing the emerging seismic design methodology (1,8) for precast diaphragms accepted by BSSC for inclusion in the 2009 NEHRP Provisions.
10. The successful shake table testing program of a half-scale precast structure designed according to the emerging design methodology from (9) and containing improved connection details from (5) for three different precast diaphragm construction techniques.

Two accomplishments items currently are in partial form with PCI supported research ongoing for completion, as is described subsequently in “ONGOING CODIFICATION ACTIVITIES”.

11. The calibration/verification of the models developed in (3) and (6) using the shake table test data.
12. Calibration of design factors for the design methodology using the verified models from (11) leading to codification.

## PART 2: DSDM PROJECT PRODUCTS

### DSDM PROJECT DESIGN DELIVERABLES

The DSDM project has produced the following **design deliverables**, with final calibration of design factors an ongoing process:

1. A **seismic design methodology** for precast concrete diaphragms based on:
  - a. A set of design targets based on acceptable damage in service, design-basis and maximum considered earthquakes (SVE, DBE and MCE) including:
    - i. A Basic Design Option (BDO) targeting elastic diaphragm behavior in the DBE and requiring inelastic deformation capacity in the MCE;
    - ii. An Elastic Design Option (EDO) targeting elastic diaphragm behavior in the MCE, intended for squat diaphragms in regions of lower seismic hazard; and,
    - iii. A Relaxed Design Option (RDO) allowing limited inelastic diaphragm behavior in the DBE and requiring significant inelastic deformation capacity in the MCE; intended to produce practical designs (in terms of reasonable connector size and spacing) for regions of high seismic hazard.
  - b. A diaphragm force amplification factor  $\Psi_d$  to be applied to current code diaphragm design forces.
  - c. Overstrength factors applied to certain diaphragm reinforcement including the shear reinforcement ( $\Omega_v$ ) and diaphragm anchorage to shear walls/moment frames ( $\Omega_a$ ) to eliminate the potential of nonductile diaphragm behavior.
  - d. A classification system for precast diaphragm reinforcement based on connector inelastic deformation capacity: low, medium and high deformability elements (LDE, MDE, HDE).
2. A **design procedure** based on the seismic design methodology that:
  - a. Permits a designer to select a design option (BDO, EDO and RDO) and then match an appropriate diaphragm design force amplification  $\Psi_d$  and required overstrength factors ( $\Omega_v$ ,  $\Omega_a$ ) to the classification category of the desired connector.
  - b. Contains procedures to determine the internal forces at critical regions of the diaphragm based on the amplified diaphragm forces.
  - c. Possesses design aids (spreadsheet methods, etc.) to provide designers calculation procedures for diaphragm service range stiffness and diaphragm probable strength.
3. A set of **prequalified precast diaphragm connectors** for the emerging seismic design methodology classified as low, moderate and high deformability elements (LDE, MDE or HDE) that can be used to create precast diaphragm systems for different levels of seismic hazard.
4. A **diaphragm connector qualification procedure** including testing protocols, detailing requirements, and inspection procedures to allow future engineers or entrepreneurs to develop new diaphragm connector concepts.

These **design deliverables** are contained within the document DRAFT SEISMIC DESIGN METHODOLOGY FOR PRECAST CONCRETE DIAPHRAGMS which is *provided as an attachment* to this report. This draft document includes four parts:

- A. Precast Diaphragm Seismic Design Procedure
- B. Precast Concrete Diaphragm Reinforcement Classification
- C. Analysis Techniques for Diaphragm Design
- D. Diaphragm Design Charts and Examples

Part B of the design methodology references a second document, *also attached*: Draft Acceptance Criteria for Precast Concrete Diaphragm Connectors Based on Structural Testing. The documents are written in sufficient detail to allow a knowledgeable engineer to replicate precast diaphragm designs using these two documents as the sole source of technical information.

#### DSDM PROJECT RELEVANT PUBLICATIONS

To create the draft design documents, the project has produced the following **information** needed for the new precast diaphragm **design** (*with the reference list provided in the table below*):

1. The expected diaphragm seismic forces that develop in precast diaphragms under a SVE, DBE and MCE event. (*reference [6]*)
2. The proper relative strength of diaphragm shear reinforcement relative to diaphragm flexural reinforcement (*reference [2]*)
3. The strength, stiffness and ductility characteristics of several diaphragm reinforcing details under individual and combined monotonic and cyclic load components. (*references [1],[3],[4],[5]*)
4. A set of shear design overstrength factors and required deformation capacity to meet different performance targets established for different aspect ratios. (*reference [2]*)
5. Design recommendations for spandrel connections based on spandrel connection characteristic, the seismic design hazard level, and diaphragm geometry including: (1) Modification terms for the effect of spandrel beams on the global diaphragm characteristics; and, (2) The required spandrel connecting characteristics to meet the diaphragm design objectives. (*reference [7]*)
6. The appropriate target for a given set of design conditions determined based on the expected demands from seismic simulations. (*references [8,9]*)
7. Calibration of the overstrength values based on analyses of representative floor systems from a prototype structure portfolio under different loading. (*reference [10]*)

The transformation of the documents from draft to final form requires the critical step of **design factor calibration** using models *verified by the results* of the shaking table test. This activity is ongoing and is occurring in parallel with PCI-supported codification efforts. In combination these efforts will permit designers to perform seismic design of reliable precast concrete diaphragm systems, as described next.

#### Journal Publications

[1] Cao, L. and Naito, C., "Design of Precast Diaphragm Chord Connections for In-Plane Tension Demands", ASCE Journal of Structural Engineering, Vol. **133**, No. 11, November 2007.

[2] Fleischman R.B. and Wan G., "Appropriate Overstrength of Shear Reinforcement in Precast Concrete Diaphragms", ASCE Journal of Structural Engineering, Special Issue, Precast-Prestressed Concrete Structures under Natural and Man-Made Hazards Vol. **133**, No. 11, November 2007, pp. 1616-1626.

[3] Naito, C., Ren, R., "Evaluation Methodology for Precast Concrete Diaphragm Connectors Based on Structural Testing", Submitted to the Journal of the Precast/Prestressed Concrete Institute, vol. 54, (2009).

[4] Naito, C., Cao, L., Peter, W., "Precast Double-Tee Floor Connectors Part I: Tension Performance", Accepted to Journal of the Precast/Prestressed Concrete Institute, vol. 54, (2009).

- [5] Cao, L., Naito, C., "Precast Double-Tee Floor Connectors Part II: Shear Performance", Accepted to Journal of the Precast/Prestressed Concrete Institute, p. , vol. , (2009).
- [6] Schoettler, M. J.; Belleri, A.; Zhang, D.; Restrepo, J. I. ;and Fleischman, R.B., "Preliminary results of the shake-table testing for the development of a diaphragm seismic design methodology", The Precast/Prestressed Concrete Institute (PCI) Journal, Vol. **54**, n1, Jan./Feb. (2009)
- [7] Wan, G. and Fleischman, R.B., "Effect of Spandrel Beam to Double Tee Connection Characteristic on Flexure-Controlled Precast Diaphragms", Submitted to ASCE Structures Journal, p. , vol. , (2008).
- [8] Zhang, D; Fleischman, R.B.; Naito, C, Ren, R, "Pretopped Precast Diaphragm Critical Flexure Joint under Seismic Demands, Part I: Analytical Modeling", in preparation for submission to ASCE Structures Journal, (2009).
- [9] Zhang, D.; Fleischman, R.B.; Naito, C.; Ren, R., "Pretopped Precast Diaphragm Critical Flexure Joint under Seismic Demands, Part II: Experimental Evaluation", in preparation/submission ASCE Structures Journal, (2009).
- [10] Zhang, D.; Fleischman, R.B.; and Wan, G. "Appropriate Precast Diaphragm Seismic Force Design Factors", in preparation for submission ASCE Structures Journal, (2009).

### **PART 3: IMPLEMENTATION OF DSDM PRODUCTS**

This section on implementation: (1) details the readiness of the products developed from the DSDM project for commercial application on building construction jobsites; (2) lists the specific actions remaining to bring these products to completion; and, (3) provides the implementation plan to attain commercial adoption.

It is noted that continuing PCI funding for the DSDM project is supporting the implementation of the seismic design methodology. The ongoing activities focus on two areas: (1) finalizing the design documents as described in the first two sections (*readiness/ tasks remaining*); and, (2) codification and implementation activities as described in the last section (*implementation plan*).

#### **READINESS OF DESIGN PRODUCTS**

The current readiness of the design documents *Draft Seismic Design Methodology for Precast Concrete Diaphragms* and *Draft Acceptance Criteria for Precast Diaphragm Connectors* is as follows:

##### **A. Precast Diaphragm Seismic Design Procedure:**

The diaphragm seismic design procedure is completed in draft form and requires the following further steps for finalization:

- Review to ensure the procedures are user friendly, including being clear, succinct and all choices leading to reasonable designs.
- Final calibration of design force factors with respect to diaphragm detail classification.

##### **B. Precast Concrete Diaphragm Reinforcement Classification:**

The diaphragm reinforcement classification chapter is completed in draft form and requires the following steps for finalization:

- Review of the manner in which prequalified connector design properties have been selected from individual connector test data, including consensus on appropriate levels of safe usable strength.
- Identification of any needed supplemental testing for prequalification of a given detail.
- Consensus on qualification protocols in final document *Acceptance Criteria for Precast Diaphragm Connectors* in terms of testing requirements and qualification metrics.

##### **C. Analysis Techniques for Diaphragm Design:**

The “Analysis Techniques” chapter is in rough draft form. The final version of this chapter will benefit from evaluation of the completed products in PARTS A and B. The following steps are required for finalization of PART C:

- consensus on the appropriate analysis techniques to include for design
- early adopter “beta-testing” of the analytical procedures in design office settings
- final writing of the chapter.

D. Diaphragm Design Charts and Examples:

The “Design Chart/Examples” chapter has yet to be created. The writing of this chapter depends on the final form of PARTS A and B, and thus must await finalization of these products. The following steps are required to complete PART D:

- completion of cost study
- completion of design examples for the prototype structure portfolio
- review, consensus and writing of the final version.

**TASKS REMAINING TO COMPLETE PRODUCTS**

The ongoing work to finalize the draft design documents, *Draft Diaphragm Seismic Design Methodology for Precast Concrete Diaphragms* and *Draft Acceptance Criteria for Precast Diaphragm Connectors*, is divided into two parallel tracks: (A) calibration of the design procedures; (B) usability of the design procedures. The former is primarily a technical activity, the latter administrative.

A. Design Procedure Calibration track

The transformation of the documents from draft to final form requires the critical step of **design factor calibration** using models *verified by the results* of the shaking table test.

- Draft Diaphragm Seismic Design Methodology:
  - TASK 1:** UCSD post-processes shake table test data (*completed*)
  - TASK 2:** UCSD creates test data graphical plotting interface (*completed*)
  - TASK 3:** UCSD trains UA on analyzing shake table data (*ongoing*)
  - TASK 4:** UCSD analyzes shake table data for MDOF model calibration (*ongoing*)
  - TASK 5:** UA uses shake table data for FE model verification/modification (*ongoing*)
  - TASK 6:** UCSD performs analytical parameter study using *verified* MDOF model to calibrate  $\Psi_d$  for BDO (2009)
  - TASK 7:** UA performs analytical parameter study using *verified* FE model to calibrate  $\Psi_e$  for EDO and  $\Psi_d$  for RDO (2009)
  - TASK 8:** UA calibration of shear and anchorage overstrength factors,  $\Omega_v$  and  $\Omega_a$ , using the results of the *verified* FE model parameter study (2009)
  - TASK 9:** UA performs analytical parameter study using *verified* FE model to align appropriate diaphragm connector classification (LDE, MDE, HDE) with the diaphragm force amplification factors developed in **Tasks 6 & 7** (2009-10)

These tasks will occur via collaboration between UCSD (through independent contractor M. Schoettler) and UA (R. Fleischman and D. Zhang).

- Draft Acceptance Criteria:
  - TASK 1:** LU provides connector properties based on test data in report form (*completed*)
  - TASK 2:** LU provides qualification acceptance criteria in draft report form (*completed*)
  - TASK 3:** Collaborative discussions between the DSDM TG and the LU/UA teams leading to DSDM TG consensus on the following issues pertaining to the reported test data (2009):



- consistent method for determining design properties:
    - nominal strength
    - service stiffness
    - reliable deformation capacity
  - appropriate selection of safe usable strength for design
  - consensus on classification (LDE, MDE, HDE) for prequalification of each diaphragm connector tested
  - supplemental testing required for prequalification of any connectors
- TASK 4:** Review of the *Draft Acceptance Criteria Document* by the DSDM TG leading to consensus on the following aspects of the qualification protocols (2009):
- qualification metrics
  - qualification testing requirements
  - reporting requirements

These tasks require the deliberation of the DSDM TG with input from LU (*C. Naito*) and UA (*R. Fleischman*).

#### B. Design Procedure Usability track

In the opinion of the DSDM TG code committee experts, of equal importance to calibration is the need for the design values stated in the code provisions to be performance friendly. This is viewed as a needed *first* step, and prior to any prescriptive rules, a range of values for use by the designer may be a sound intermediate step. Accordingly, with the design procedure outlined in detail in the draft *Diaphragm Seismic Design Methodology*, the following steps toward **design procedure usability** are being taken in parallel with the design factor calibration activities:

- *PART A: Diaphragm Design Procedure:*
  - TASK 1:** DSDM TG member performs trial untopped and topped-composite diaphragm designs on prototype structure in regions of high seismic hazard using the *Draft Seismic Design Methodology Documents*. (*ongoing*)
  - TASK 2:** DSDM TG member performs cost comparison study of the designs developed in TASK 1 with respect to current (non-composite) diaphragm designs, documenting the savings that can be realized. (*ongoing*)
  - TASK 3:** In performing TASK 1, the DSDM TG member identifies:
    - Any aspects of the design procedure that can be considered cumbersome, vague, non-unique, redundant, etc.
    - Any design parameter combinations or sequences that lead to impractical or uneconomical designs.
    - Viable revisions or ways in which the procedure can be tweaked to improve usability.
  - TASK 4:** DSDM TG member reports to larger DSDM TG on findings from TASKS 1-3. Deliberation and consensus by DSDM TG designer and code committee members to ensure the design procedure is clear, succinct, user friendly, and leads to reasonable designs. (2009)
  - TASK 5:** Final version of the calibrated Design Procedure completed. (2010)

These tasks are occurring via collaboration between DSDM TG Member (*S. Nakaki*) and UA (*R. Fleischman and D. Zhang*).
- *PART B: Draft Acceptance Criteria:*
  - TASK 1:** Review of qualification procedures by DSDM TG member for practicality and conformance to past codes provisions and recommendations. (2009)

**TASK 2:** Report on results of review by DSDM TG member to larger DSDM TG for deliberation and full consensus. (2009)

**TASK 3:** Final version of the *Acceptance Criteria Document* completed. (2010)

These tasks will occur via collaboration between DSDM TG Member (*N. Hawkins*) and with input from LU (*C. Naito*) and UA (*R. Fleischman*).

- *PART C: Analysis Techniques for Diaphragm Design:*

**TASK 1:** Input from PCI Seismic Committee Meeting on acceptable analysis techniques for diaphragms based on state-of-the-practice. (*PCI Comm. Days, April 2009*)

**TASK 2:** Drafting of chapter or joint document with the PCI Seismic Committee (2009)

**TASK 3:** Review of document by DSDM TG designer members for consensus. (2009)

**TASK 4:** Final version of the *Analysis* chapter completed. (2010)

These tasks will occur with input from the PCI Seismic Committee (*R. Sause, chairman*).

- *PART D: Diaphragm Design Charts and Examples:*

**TASK 1:** Trial high seismic prototype structure design (*PART A, TASK 1*) is revised using final design procedure developed in PART A, TASK 5. (2009)

**TASK 2:** Revised high seismic design for prototype structure is extended to other SDCs (low and medium seismic hazard) and other structures within the prototype structure portfolio. (2010)

**TASK 3:** Review of the design examples by DSDM TG for consensus. (2010)

**TASK 4:** Final version of the *Design Examples* chapter completed. (2010)

These tasks will occur with input from the PCI Seismic Committee (*R. Sause, chairman*) and with designer members of the DSDM TG.

In combination, the design procedure calibration and usability activities will permit designers to perform seismic design of reliable precast concrete diaphragm systems. These activities will occur in parallel with PCI-supported codification efforts, as described next.

## IMPLEMENTATION PLAN

This section provides the implementation plan including: (a) key team members; (b) the mechanism for implementing the draft design procedures into code; (c) the required activities for obtaining certification regarding suitability of the products for commercial use and (d) the dissemination plan; and (e) the schedule associated with these activities.

### (a) Key Team Members

The DSDM TG will be involved in the implementation plan. Key members include:

- Susie Nakaki, President, The Nakaki Bashaw Group, Inc., Irvine, CA is serving as a Seismic Design Consultant to perform an economic comparison for the new systems, and evaluating the design procedures for usability.
- Neil Hawkins, Professor Emeritus, Univ. of Illinois, and Chair, BSSC Technical Subcommittee on Concrete, has worked with the team to prepare a white paper on the Seismic Design of Precast Concrete Diaphragms for inclusion in Part 3 of the 2008 NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures
- The research team is being advised on the proper format of the design procedure by Joe Maffei Seismic Design Consultant, Rutherford & Chekene Engineers, Oakland, CA. The PI will spend time at the R&C design offices this fall (2009).

- Coordination with code cycles and code language is being provided by S.K. Ghosh, President, S. K. Ghosh Associates, Inc. Skokie IL
- Ned Cleland and Richard Sause, former and current Chairs of the PCI Seismic Committee will coordinate the dissemination of project design deliverables in PCI handbooks and guidelines.
- Harry Gleich, Ned Cleland, Tom D'Arcy and Roger Becker will advise on the proper detailing and appropriate classification of the precast concrete diaphragm reinforcing details for the prequalified connections and the acceptance criteria.
- Doug Sutton, Tom D'Arcy and Paul Johal will lead and coordinate PCI's involvement with these activities.

### **(b) Ongoing Codification Activities**

The codification process will be led by S. K. Ghosh and Neil Hawkins. These members have this process underway. Code acceptance procedures are multi-year processes. Thus, the deliverable from the project is a codifiable procedure with the intent of the research team and the DSDM TG to follow this process through to codification. PCI and the DSDM project are committed to meet these industry deliverables regarding codification. In the meantime, accepted design procedures can be used in practice through other mechanisms (e.g. ITCs as have been used for precast walls). The DSDM TG membership and planned mechanisms are critical in this regard.

The following are the steps that will be carried out in order to advance the design (For code adoption) being developed in this project through the codification process and into the form needed for adoption and actual utilization by design and construction practitioners.

#### **Procedure for Transfer of Research Results into Practice:**

A four step process will be used for implementation of the research results:

- 1) The development of a white paper the DSDM TG (Fleischman and Hawkins) describing the proposed codification methodology;
- 2) Cooperation with a design/build contractor in the implementation of the methodology;
- 3) Submission of codification proposals to the ASCE/SEI –7 Code Committee; and
- 4) Submission of codification proposals to the ACI 318 Committee.

**Step 1.** A white paper was submitted in 2007 by the DSDM TG (Fleischman and Hawkins co-authors) to the Building Seismic Safety Council's Provisions Update Committee (BSSC-PUC). The BSSC-PUC assembles the 2008 version of the NEHRP Recommended Seismic Provisions (FEMA 450). The BSSC Committee endorsed the paper, and thus it will be published as part of its 2008 work and sets the stage for the removal in 2011 of the current Appendix A to Chapter 9 of FEMA 450 covering design procedures for Untopped Precast Diaphragms. Dr. Ghosh and Dr. Hawkins are both members of the 30-person BSSC-PUC and guided this step of the implementation procedure. The ASCE/SEI-7 and ACI 318 Code Committees look to the BSSC for leadership in developing seismic design philosophies. Acceptance of the white paper by the BSSC-PUC is key for successful Steps 3 and 4.

**Step 2.** In a manner similar to that used by Pankow Builders for implementation of the special hybrid moment frame methodology, a design/build contractor, or equivalent, will be identified by the DSDM TG in 2009 who is willing to construct a structure (in 2009/2010) in a SDC C region using the technology for a SDC D region. This implementation is essential for identifying practical refinements needed for the methodology's codification. In his parking garage work Dr. Cleland has often found use of an SDC D design for a SDC C region cost effective.

**Step 3.** The ASCE/SEI –7 Committee is responsible for the Standard “Minimum Design Loads for Buildings and Other Structures” which has now become the structural load design provisions of IBC. Provisions covering those portions of the methodology that deal with the design loads for precast diaphragms will be proposed to that 40-person Committee. Dr. Ghosh and Dr. Hawkins are both members of the main ASCE-7 committee and of its Seismic Task Group for the next update of that standard that will be in 2011. They will guide this implementation step.

**Step 4.** The ACI 318 Committee is responsible for the Standard “Building Code Requirements for Structural Concrete” that provides the concrete detailing requirements for the IBC. Provisions covering those portions of the methodology dealing with detailing will be proposed to that 40-person committee for inclusion in the Code. Dr. Ghosh and Dr. Hawkins will both be members of the main ACI 318 committee and of its subcommittee dealing with seismic design for the next update of that standard which will probably be in 2011. They will guide this implementation step.

**(c) Certification Mechanisms**

The suitability of the design procedures for code adoption and use in building design and construction practice must be assured. To do so, the close participation of the DSDM TG is required. The precast construction, seismic design, and code writing expertise on the DSDM TG are ideal for this purpose.

The tasks identified in Design Procedure Calibration track and the Design Procedure Calibration usability track involve the DSDM TG participating in, reviewing and finding consensus on each part of the design methodology. The DSDM TG has regularly met through the primary research phase of the DSDM project and it is the intent that these regular meetings continue during the Codification/Implementation Phase.

**(d) Dissemination Plan:**

The ongoing involvement of PCI in the implementation plan is key to dissemination. The PCI website and PCI publications will be used for this practice. Further, two co-PIs and one DSDM TG member serve as current chair, current co-chair, and past chair of the PCI Seismic Committee. The DSDM project will explore utilizing the expertise and manpower of the Seismic committee to assist in disseminating useful information to the profession. Finally, UA is working with PCI to develop a website containing the products and publications developed by the DSDM project.

The close participation of the DSDM TG will facilitate the adoption of new construction techniques and design procedures in several ways: (1) the strong representation by PCI research staff in the DSDM TG will allow direct and timely inclusion of findings in nationally distributed technical literature; (2) the strong representation by not only precasters and design consultants specializing in precast construction, but also seismic design consultants in the DSDM TG, will facilitate specifying of these systems; (3) the strong representation by members of code writing bodies (ACI 318, ASCE7, IBC) in the DSDM TG will create a direct conduit for proposed design procedures to be balloted and eventually adopted; (4) the regular interaction of the DSDM TG with the university researchers has structured the DSDM research to facilitate transfer to industry, including developing a framework for the emerging design methodology and a prototype structure portfolio prior to initiation of the research. These factors create an environment in which the system developed can be implemented directly after the project completion, with eventual codification.

**(e) Schedule:**

The attached file “DSDM\_Codif-Schedule-CPF-Fin-Rep.xls” provides an itemized schedule of the implementation plan as described in this report.

**APPENDIX to Final Report**  
to the  
**Charles Pankow Foundation**  
from  
**The University of Arizona**

Development and Design of Untopped Precast Concrete Diaphragm Systems for  
High Seismic Zones

Revised CPF 08-07 Grant<sup>2</sup>

February 9, 2009

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(a) Advances in Knowledge;	
(b) Advances in the State of Art in Research.	

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<sup>2</sup> CPF supplement 08-07 combined with CPF 02-06 grant as per contract revision June 2008.

*Appendix VI: DSDM Experimental Results*.....28

- (a) Isolated Connector Testing;
- (b) Adaptive Testing;
- (c) Shake Table Testing.

*Appendix VII: DSDM Research Findings*.....30

- (a) Findings related to Precast Diaphragm Behavior;
- (b) Findings related to Precast Diaphragm Design.

## APPENDIX I. Project Management

### Project Funding

Table A1-1 provides the timeline of the DSDM funding. The stages include the original project (2003), the NSF Supplement for NEES upgrade (2006), and the Charles Pankow original grant (2006), and supplement (2007), which made the testing possible and expanded the scope to include demonstration of a viable precast diaphragm system for regions of high seismic hazard. It is noted that though this project was originally proposed as a NSF Grant Opportunities for Academia Liaison with Industry (GOALI) project in Feb 2003, the experimental components were subsequently upgraded to use the newly-commissioned George E. Brown Network for Earthquake Engineering Simulation (NEES). Not included in Table 1 is the significant “in-kind” contributions from PCI for travel and meeting support. Table A1-2 summarizes the Industry Partner Contributions, which includes funds and product donations from PCI producer members and contributions from designers for engineering support, drawing production/checking, and coordination.

**CPF FINAL Report: June 6, 2009**

**Table A1-1. DSDM Project Funding Timeline**

Research Stage and Date	PCI R&D pledge	type	PCI Industry Members pledge	type	External Agency	External Agency Provides	type	Acad. Inst.	University Provides	type	TOTAL
<b>Original</b> Feb-03	\$200,000	funds	\$25,000	funds	NSF	\$470,430	funds	UA	\$ 35,532	student/trav	
			\$84,000	product				LU			
								UCSD	\$ 20,000	salary	
<b>TOTAL</b>	<b>\$200,000</b>		<b>\$109,000</b>			<b>\$470,430</b>			<b>\$55,532</b>		<b>\$834,962</b>
<b>NEES</b> Feb-06	\$45,000	funds	\$ 5,000	funds	NSF	\$100,000		UA	\$ 14,600	student	
			\$ 79,000	product	NEES	\$ 76,500	@UCSD	LU	\$ 16,563	student	
			\$ 30,000	labor	NEES	\$ 33,130	@LU	UCSD	\$ 25,828	stu/sal	
<b>TOTAL</b>	<b>\$45,000</b>		<b>\$114,000</b>			<b>\$209,630</b>			<b>\$56,991</b>		<b>\$425,621</b>
<b>CPF</b> Mar-06	\$31,987	funds	\$ 39,473	funds	CPF	\$ 105,146		UA	\$ 31,701	student/trav	
			\$ 22,413	product				LU	\$ -		
								UCSD	\$ 45,000	stu/sal	
<b>TOTAL</b>	<b>\$31,987</b>		<b>\$61,886</b>			<b>\$105,146</b>			<b>\$76,701</b>		<b>\$275,720</b>
<b>CPF supp</b> Jun-07	\$ 85,000	funds	\$ 20,000	funds	CPF	304,980		UA	\$ 24,670	student/trav	
			\$ 21,000	product	NEES	\$ 83,500	@UCSD	LU	\$ -		
					NEES	\$ 38,029	@LU	UCSD	\$ 45,000	stu/sal	
	<b>\$85,000</b>		<b>\$41,000</b>			<b>\$426,509</b>			<b>\$69,670</b>		<b>\$622,179</b>
<b>Testing</b> Mar-08	\$ 60,005	retrofit	\$ 10,000	funds	ANNIPAC			UA	\$ 37,800	student/trav	
			\$ 9,000	product		\$ 30,000	support	LU	\$ -		
								UCSD			
								UCLA	\$ 50,000	instruments	
	<b>\$60,005</b>		<b>\$19,000</b>			<b>\$30,000</b>			<b>\$ 87,800</b>		<b>\$196,805</b>
<b>TOTAL</b>	<b>\$421,992</b>		<b>\$344,886</b>			<b>\$1,241,715</b>			<b>\$346,694</b>		<b>\$2,355,287</b>

CPF FINAL Report: June 6, 2009

Table A1-2. Contributions from PCI Industry Members (Not including PCI direct Support)

Company	Lehigh Testing Program				UCSD Testing Program				UA	Composite				TOTAL
	Funds	Product	Discounts	Engineering	Funds	Product	Discounts	Engineering	Funds	Funds	Product	Discounts	Engineering	Contribution
High Concrete		\$ 48,700		\$ 7,500						\$ -	\$ 48,700	\$ -	\$ 7,500	\$ 56,200
Metromont		\$ 45,000		\$ 5,000	\$ 10,000					\$ 10,000	\$ 45,000	\$ -	\$ 5,000	\$ 60,000
JVI	\$ 24,000	\$ 10,000		\$ 12,000		\$ 25,000		\$ 12,000	\$ 15,473	\$ 39,473	\$ 35,000	\$ -	\$ 24,000	\$ 98,473
Ivy Steel		\$ 5,000				\$ 5,000				\$ -	\$ 10,000	\$ -	\$ -	\$ 10,000
Spancrete				\$ 2,500	\$ 10,000			\$ 2,500		\$ 10,000	\$ -	\$ -	\$ 5,000	\$ 15,000
Blakeslee					\$ 20,000					\$ 20,000	\$ -	\$ -	\$ -	\$ 20,000
Tindall					\$ 10,000					\$ 10,000	\$ -	\$ -	\$ -	\$ 10,000
PCMAC					\$ 25,000					\$ 25,000	\$ -	\$ -	\$ -	\$ 25,000
Concrete Tech					\$ 10,000					\$ 10,000	\$ -	\$ -	\$ -	\$ 10,000
Knife River					\$ 10,000					\$ 10,000	\$ -	\$ -	\$ -	\$ 10,000
Central Premix					\$ 5,000					\$ 5,000	\$ -	\$ -	\$ -	\$ 5,000
ANNIPAC					\$ 40,000					\$ 40,000	\$ -	\$ -	\$ -	\$ 40,000
DSI, Intl							\$ 6,408			\$ -	\$ -	\$ 6,408	\$ -	\$ 6,408
Sirko Assoc.								\$ 15,000		\$ -	\$ -	\$ -	\$ 15,000	\$ 15,000
CEG								\$ 23,000		\$ -	\$ -	\$ -	\$ 23,000	\$ 23,000
Shockey		\$ 3,000		\$ 2,000						\$ -	\$ 3,000	\$ -	\$ 2,000	\$ 5,000
Midstate							\$ 89,319	\$ 53,000		\$ -	\$ -	\$ 89,319	\$ 53,000	\$ 142,319
Lehigh Cement					\$ 3,239					\$ -	\$ 3,239	\$ -	\$ -	\$ 3,239
Hanson							\$ 17,600			\$ -	\$ -	\$ 17,600	\$ -	\$ 17,600
Proctor							\$ 6,000			\$ -	\$ -	\$ 6,000	\$ -	\$ 6,000
Unistress							\$ 2,000			\$ -	\$ -	\$ 2,000	\$ -	\$ 2,000
TOTAL	\$ 24,000	\$ 111,700	\$ -	\$ 29,000	\$ 140,000	\$ 33,239	\$ 121,327	\$ 105,500	\$ 15,473	\$ 179,473	\$ 144,939	\$ 121,327	\$ 134,500	\$ 580,239



**Project Coordination**

Throughout the project, the DSDM researchers held Research Meetings (RMs) jointly with the Industry Task Group and University Research Meetings (URMs) independently. These meetings are listed in Table A1-3. Meetings held prior to the CPF support are shown in *italics*.

**Table A1-3.** DSDM Research Meetings

RM	URM	Loc	Date	Description
#1	#1	PCI HQ	Aug 7, 2003	<i>Develop Consensus on Design Approach and Physical Scope</i>
#2		Orlando FL	Oct 13, 2003	<i>Review/Approve Prototype Structures, Details, SDCs</i>
#3	#2	UCSD	Feb 23, 2004	<i>Review/Approve UCSD MDOF Dynamic Analysis Study</i>
#4		Chicago IL	Apr 25, 2004	<i>Review/Approve Lehigh Phase 1 Testing Program</i>
#5	#3	Napa CA	June 7, 2004	<i>Review/Approve UA Nonlinear Diaphragm Analysis Study</i>
#6		PCI HQ	Nov 12, 2004	<i>Present Preliminary Results/Revise Design Philosophy</i>
	#4	Arizona	Dec 16, 2004	<i>Discuss/Integrate UA/LU/UCSD Year 1 Research Findings</i>
#7	#5	Lehigh	May 5, 2005	<i>Observe Lehigh Phase I Testing</i>
#8	#6	UCSD	Sept 9, 2005	<i>Develop Modified Research Plan for NEES Upgrade</i>
#9		PCI HQ	Apr 30, 2006	Kickoff meeting to guide UCSD Shake Table Test Planning
#10		PCI HQ	Aug 10, 2006	Special Meeting Devoted to Shake Table Test Structure
#11		PCI HQ	Nov 14, 2006	Report on UA 3D Seismic Simulations of Shake Table Test
#12	#7	UCSD	Mar 16, 2007	Finalize Design procedure for System
#13		PCI HQ	Aug 20, 2007	Finalize Specimen/Appoint project manager
#14		PCI HQ	Nov 16, 2007	Review Shake Table Drawings
#15		UCSD	Feb 11, 2008	Observe Shake Table Foundation Construction
#16	#8	UCSD	May 8, 2008	Observe Shake Table Test
#17		PCI HQ	Oct 20, 2008	Review Findings from UCSD, UA, LU. Plan Tech Transfer.

In addition to these full-day or two-day meetings, several half-day WEBEX Conference calls were held during the project. The university researchers held weekly WEBEX Conference calls throughout the project. In the first two years these were group calls with the entire research team. In Years 3 and 4, the calls typically were held between UA and LU to coordinate the hybrid testing; and UA and UCSD to coordinate the shake table test.

Beginning in August 2007 and extending until the beginning of the shake table test program in May 2008, bi-weekly WEBEX Conference calls were held; one focusing exclusively on the run up to the shake table testing. The shake table conference call participants were a special subgroup of the research team (Restrepo, Schoettler, Fleischman, Zhang and Belleri) and the industry task group (Dieter, D'Arcy and Sutton) focusing on the day to day operations of planning the shake table test.

Beginning in Jan 2008, and extending until the beginning of the shake table test program in May 2008, monthly onsite (Englekirk Center) review meetings were held by the shake table subgroup: Jan – production; Feb – erection; Mar – instrumentation; April – testing program, May – observe testing.

Immediate reporting and interaction occurred through a set of collaborative internet workspaces associated with NEES and the Universities and included: (1) the ATLSS ftp site at Lehigh University; (2) the UCSD NEESPOP site; (3) NEESCentral depository; and (4) a detailed hierarchical storage disk dedicated to the DSDM project at the University of Arizona.

## APPENDIX II. DSDM Project Major Research Activities

This section lists the major research activities of the project. The group or groups responsible are indicated in bold. A timeline of project milestones appears in the appendix to this activities report. Accomplishments prior to the CPF support are in *italics*.

The DSDM project completed the following major research activities during the NSF grant:

1. *A summary document of: (1) all design code procedures and changes related to precast floor diaphragms since 1988; (2) all research related to precast floor diaphragms since 1972; and (3) the proposed design philosophy and framework to guide the development of a new seismic design methodology for precast concrete floor diaphragms. (UA/TG)*
2. *The selection of a set of prototype precast structures, representative precast diaphragm reinforcing details and seismic hazard sites from across the U.S. The prototype structures containing the representative diaphragm reinforcing details were designed for each seismic site using the then current code (IBC 2003), producing a set of benchmark structure designs. (UA/TG)*
3. *The selection and scaling of a suite of earthquake ground motions for each seismic hazard site to allow direct evaluation of the benchmark designs (UCSD/TG).*
4. *A database of all existing precast diaphragm connection test results and a survey of the use of current precast diaphragm connection details. (LU/TG)*
5. *A Phase 1 testing program of existing precast diaphragm reinforcing details (connectors) in an innovative test fixture that subjected isolated connectors to cyclic loading protocols involving combined shear and tension. A total of 30 full-scale Phase 1 tests were performed. (LU)*
6. *Incorporation of the LU Phase 1 test results into discrete coupled (shear/tension) connector elements within FE models (using the software ANSYS) of isolated (2D) precast diaphragms for use in nonlinear static “pushover” analyses. (UA/LU)*
7. *Use of the pushover models to: (1) develop a spreadsheet design method to predict the stiffness and strength of precast concrete floor diaphragms; and (2) perform an extensive parameter study on the appropriate level of overstrength required in diaphragm shear reinforcement. (UA)*
8. *Incorporation of the pushover study results in simpler reduced multi-degree of freedom (MDOF) models of structures (using the software Ruomoko) to perform an extensive parameter study on appropriate diaphragm design forces in precast concrete structures. (UCSD/UA)*
9. Local modeling of the Phase 1 connectors using the software DIANA to perform parameter studies to optimize detail geometry. These studies were used to develop improved (Phase 1B) diaphragm connectors. (LU)
10. A Phase 1B testing program of the improved precast diaphragm reinforcing details in isolated fashion in the multi-load test fixture. A total of 34 full-scale Phase 1B tests were performed. (LU)
11. The enhancement of the 2D FE precast diaphragm models to include the effects of “secondary” gravity system elements in the floor system (precast spandrel beams and inverted tees) that are not part of the diaphragm design but nonetheless have an effect on diaphragm response. These models were used to perform an extensive parameter study on the effect of secondary diaphragm elements using nonlinear static “pushover” analyses. (UA)

12. The extension of the discrete coupled connector elements for cyclic response (stiffness and strength degradation, hysteretic characteristics, cyclic ductility) and the extension of the 2D FE (isolated precast diaphragm) models to three-dimensional (3D) FE models of precast structures for use in nonlinear transient dynamic analysis (NLDTA). (UA)
13. Use of the 3D FE NLDTA models to examine the fundamental behavior of discretely connected floor diaphragms within the context of a three-dimensional multi-story structure subjected to bi-directional components of strong ground motions. (UA)
14. The development and fabrication of scaled versions of the improved diaphragm connectors for use in the half scale shake table tests and hybrid experimental program. (LU/UCSD/TG)
15. A set of tests of the half scale connectors isolated in the multi-load test fixture for direct comparison to the full-scale tests in order to provide verification of similitude for the shake table tests and hybrid experiments. A total of 5 half-scale connector tests were performed. (LU)
16. Design and fabrication of half scale precast units for the hybrid test program. The units possessed the half-scale connectors, and were designed according to the emerging design methodology for critical shear and critical flexure joints in precast floor diaphragms. Modification of the multi-load test frame to accommodate the dual panel configuration. (LU)
17. Development of communication protocols between UA 3D FE NLDTA models and ATLSS actuator control system and testing algorithms for hybrid test program. Troubleshooting of hybrid testing algorithms including computer simulations of physical portion of experiment (LU/UA)
18. A hybrid testing program of critical joints in untopped precast diaphragms. A total of 3 tests were performed including a critical flexure joint subjected to predetermined displacement histories (PDHs) from a 3D FE NLDTA of a prototype parking structure; and an adaptive test of the critical shear joint from the shake table test structure. (UA/LU)
19. The planning and selection of an appropriate test structure configuration for the upgrade to the large demonstration shake table test. Identification of industry partners for project management, engineering support, product donations, and supplemental funding. (UCSD/UA/TG)
20. Use of 3D FE NLDTA analyses of a model of the shake table structure to calibrate the design of the diaphragms in the shake table test specimen according to the performance targets of the emerging design methodology. (UA/UCSD)
21. Creation of professional production and erection drawings, drawing checking, sourcing of product, production and erection of the half scale shake table test. (UCSD/TG)
22. Identification of needed instrumentation, in number, type and location; sourcing of supplemental channels and instruments to meet this instrumentation plan; verification of use of limited data to characterize system behavior via NLDTA simulation. (UCSD/UCLA/UA)
23. The design of a foundation system and a slider mechanism to allow the footprint of the shake table to exceed the shake table plan. The design of unbounded post-tensioned rocking walls to allow repetition of testing with similar primary LFRS (vertical plane) characteristics. (UCSD)
24. Enhancement of 3D structure model of shake table specimen to include full depth profile of floor systems in order to study: (a) compatible displacements between the floor units and the gravity system columns; (b) floor plate out-of-plane rotational demands imposed by the rocking walls; and, (c) unseating of the floor units from the supporting beams. (UA)
25. Coordination of a payload project studying isolation systems for sensitive equipment. (UCSD)
26. A shake table testing program of a 3-story diaphragm-sensitive precast concrete structure possessing different diaphragm construction on each level. The half-scale structure was subjected

to earthquake ground motions ranging from a Seismic Design Category (SDC) C design basis earthquake (DBE) to a SDC E maximum considered earthquake (MCE). White noise excitation was applied in-between. A total of **15** strong shaking tests were performed. **(UCSD/UA)**

27. A white paper describing the design methodology being produced by the project. The paper was submitted to the Building Seismic Safety Commission (BSSC) Provisions Update Committee for approval of publication in Part 3 of the 2009 National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Design for New Buildings. **(UA)**
28. An Acceptance Criteria draft document that contains the protocols for use in qualification testing and prequalification procedures for diaphragm reinforcement in precast concrete structures. **(LU)**
29. Post-processing of the shake table data, involving 600 channels for 15 ground motions and 45 white noise tests: Alignment, normalizing, filtering, integrating; writing a powerful yet efficient post-processing program in Matlab. **(UCSD)**

The following activities are ongoing:

30. Analysis of shake table data to identify and characterize system behavior including: (a) internal force paths; compatible displacement demands; different floor response and inter-floor actions; torsional effects; pounding of floor units; progressive damping. **(UA/UCSD)**
31. Construct and perform an extensive set of 3D NLTDA FE analytical studies to characterize the above identified system behaviors **(UA)**.
32. Analysis of shake table data to calibrate 3D NLTDA FE and MDOF models for use in the design factor calibration for the emerging design methodology. **(UCSD/UA)**
33. Complete MDOF Study on Diaphragm Force using calibrated models. **(UCSD)**
34. Calibration of 3D NLTDA FE models using shake table results. **(UA)**
35. Design Factor Calibration for Design Methodology through 3D FE Analytical Parameter Studies of Prototype Structures **(UA)**.
36. Produce Cost Comparisons and Design Examples for Design Methodology using Prototype Structures. **(UA/TG)**
37. Launch website for the precast construction community that contains all design products and background documents produced by the project. **(UA/TG)**
38. Codify Final Design Methodology Procedure. **(UA/TG)**

### APPENDIX III. DSDM Project Industry Interaction

The research project depended heavily on industry interaction throughout the project. These industry contributions took several forms: (1) planning, advice and consensus building; (2) review and oversight; (3) funds and material donations; (4) engineering and consulting and, (5) technology transfer/codification. In particular, the industry contributions to the experimental programs at Lehigh and UCSD were substantial (See Table 3). Among the items listed above in the Major Research Activities section, the following activities involved significant industry interaction:

#### Project Planning Stage:

- The development of the summary design document on precast diaphragms (current and past code provisions, major research findings, and proposed design framework) involved considerable input from members of the **DSDM TG** that serve on code writing committees (*Ghosh, Hawkins, Cleland, Maffei, Nakaki*).
- The selection of a set of prototype precast structures and representative precast diaphragm reinforcing details for the project involved significant input from members of the **DSDM TG** active in precast design and construction (*D'Arcy, Gleich, Cleland, Becker*).
- The selection of the seismic hazard sites from across the U.S for the project was determined by a member of the **DSDM TG** familiar with the latest code provisions. (*Ghosh*).
- The design of the benchmark structures (prototype structures containing the representative diaphragm reinforcing details designed to each seismic site using IBC 2003) involved significant guidance on current design practice from members of the **DSDM TG** active in precast and seismic design (*Gleich, D'Arcy and Nakaki*) via face-to-face meetings and WEBEX calls.

#### Lehigh Connector Testing Program:

- The database of existing precast diaphragm connections was based on a survey of the **precast concrete industry**.
- The selection and detailing of existing connectors for the Lehigh Phase 1A Testing Program involved review, modification and approval by members of the **DSDM TG** (*Gleich, D'Arcy, Cleland, Becker*).
- Fabrication, casting and delivery of the specimens for Lehigh Phase 1A Testing Program was donated by **Industry Partners**. (*High Concrete Structures, Denver PA; Metromont, XXX*).
- The review of the Lehigh Phase 1A Test results by members of the **DSDM TG** (*Gleich, D'Arcy, Cleland, Becker*).
- The subsequent development of the improved Phase 1B details was performed in conjunction with members of the **DSDM TG**. (*D'Arcy, Magnasio, Gleich, Cleland*)
- Fabrication, casting and delivery of the specimens for Lehigh Phase 1B Testing Program was donated by **Industry Partners**. (Phase IB: *High Concrete, Metromont, JVI, Inc, XXX*).
- The development, design and manufacture of scaled versions of the improved diaphragm connectors was performed by an **industry partner** (*JVI*) after considerable discussions and working meetings with the UCSD and Lehigh research teams.
- Fabrication, casting and delivery of the half scale precast diaphragm panels for the Phase II Lehigh Testing Program was donated by **Industry Partners**. (Phase II: *High Concrete, JVI*)

UCSD Shake Table Testing Program:

- The identification of industry partners for product donations and supplemental funding for the shake table specimen upgrade from ¼ scale to ½ scale was led by the **DSDM TG** (*Sutton, D'Arcy, Johal*).
- The planning of the shake table testing program, the selection of a shake table test structure configuration, and the detailing of the diaphragms occurred jointly with the **DSDM TG** over the course of 5 research meetings and one web-based teleconference (*Mar 2006 – Aug 2007*).
- The construction management for the shake table specimen construction was handled by a single **industry champion** (*Dave Dieter, Mid-State Precast (MSP), Concordia CA*). This industry collaboration activity was highly integrated into the project, required an unusual level of commitment from the industry partner, and was crucial to the success of the project. For these reasons, it is described in greater detail later in this section.
- The creation of professional construction drawings for the shake table specimen was closely supervised by **Industry Partners** (*MSP; Consulting Engineers Group (CEG), Dallas TX*), and drawing checking was performed by **Industry Partners** (*CEG; Sirko Associates, Denver CO*). This activity was critical to the shake table test program and required an unusual level of collaboration and coordination between the project graduate students and various industry partners. For these reasons, it is also described in greater detail later in this section.
- The erection of the shake table specimen was coordinated by **industry partners** (*MSP*) and performed at significant discount by **industry partners** (*Pankow Builders Ltd., Pasadena, CA*), including the assigning of an experienced construction superintendant (*Frank Woodman, Pankow*) as a dedicated foreman during the shake table structure erection phase.
- Ongoing engineering support and participation in decision-making during the testing program including on interpretation of damage, retrofit and repair strategies, and modifications to the testing program by **industry partners** (*D'Arcy; H. Valencia, Filtro Sismico, MX*).

Transfer of Research to Practice/Codification Efforts:

- A white paper describing the design methodology being produced by the project. The paper was submitted to the Building Seismic Safety Commission (BSSC) Provisions Update Committee for approval of publication in Part 3 of the 2009 National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for Seismic Design for New Buildings. (UA)
- An Acceptance Criteria draft document that contains the protocols for use in qualification testing and prequalification procedures for diaphragm reinforcement in precast concrete structures. (LU)
- Produce Cost Comparisons and Design Examples for Design Methodology using Prototype Structures. (UA/TG)
- Launch website for the precast construction community that contains all design products and background documents produced by the project. (UA/TG)
- Codify Final Design Methodology Procedure. (UA/TG)

## APPENDIX IV. Shake Table Test Specimen Construction

### Construction Management

The coordination of activities surrounding the shake table testing was a particularly challenging aspect of this project and involved significant researcher/industry collaboration. This section describes the nature of these interactions.

The challenges involved in the construction of the shake table specimen are as follows:

- The half-scale shake table test specimen was in actuality a building three stories high, occupying approximately 4000 sq. ft. of floor space, and, together with its elaborate foundation system, weighing over 1-million pounds.
- The prefabricated parts, though at a large scale from a testing standpoint, were sufficiently small at half-scale that custom made or hard to find components were required for most of the precast units and reinforcing elements.
- The precast units for the structure had to be designed and detailed correctly months before construction to enable the structure to fit together when the UCSD shake table became available.
- A specially-designed outrigger foundation/sliding system had to be conceived, designed, and constructed to permit the testing of a diaphragm sensitive structure wider than the shake table.
- All these activities had to occur while an ongoing research project was assessing its latest experimental and analytical results from other components of the project to fine-tune the emerging design methodology being used to design the specimen.
- The resources for building the specimen (raw materials, forms, equipment discounts, plant availability, supplemental funds) were being raised from industry members across the country and was still ongoing in the lead up to construction.

As the project moved from the design to construction phase of the shake table test, a key organizational restructuring took place within the project. Dave Dieter, President/ General Manager Mid-State Precast, Inc., assumed overall project management responsibilities for the shake table test construction aspects. Mr. Dieter had been added to the DSDM Industry TG as a stipulation of the CPF grant. Mr. Dieter's responsibilities included cost estimation and control, sourcing of product, coordination, and project scheduling related to the production and erection of the half scale shake table test specimen.

Mr. Dieter's first task was to develop a critical path schedule for the shake table specimen construction (drawings, production, transportation, erection). His second task was to source products and equipment and industry contributors, emphasizing the need to maximize discounts and donations. His third action was to assemble all parties (university researchers, industry task group, and the various parties earmarked for the construction) in a face to face meeting and then regular conference calls. He assembled an erection crew and held preconstruction coordination meeting; identified and hired a demolition contractor has been hired with an obtained demolition quote.

As a result of these activities, the shake table construction sequence, an aggressive 6 month accelerated schedule from design finalization, through drawing creation, production, transportation and erection was held to within a 3 to 4 week lag (See Appendix I); and his ability to control project costs brought the production and erection in slightly under budget.

This was a monumental effort. In many cases, Mr. Dieter floated his company's costs for weeks or months as the industry support for making his bills were obtained. He donated several hundred hours

of his time to the project. The importance of Mr. Dieter's contribution to this project in making the shake table test possible can not be overstated.

### **Construction Drawings**

The creation of 100% accurate drawings are a necessity for precast construction in which all the pieces are prefabricated at a plant several weeks before construction and arrive to a job site with construction crews in place. The individual pieces must fit and plate embeds must line up; otherwise the construction project could be brought to a halt for weeks, even months. For this reason, terminology, notation, sequencing, and drafting practice are all industry standards and drawing checking is a necessity, possibly the most important step of the process.

These exacting conditions were equally present for the shake table test structure since the project timeline, the project funding, and the window of availability for the NEES@UCSD shake table required that the structure be built once and built properly. Therefore, the project schedule critical path revolved around the timely issuing of drawings (creating shop drawings, reviewing/checking drawings, releasing production drawings, bill of materials and erection drawings). The industry, recognizing the significant effort required to complete the construction drawings, and the essential nature of this task given the prefabricated nature of the construction, agreed to provide the significant assistance in accomplishing this task.

However, for an industry accustomed to standardization, two atypical conditions existed under which the strict controls had to be exercised: (1) the prefabricated parts and connections had to be custom-made at half-scale; (2) the structure was being constructed for the purpose of experimental research and thus certain aspects of the structural design were developing in parallel as the specimen drawings were being created.

These unique features of this construction effort, different from a typical construction project, required the researchers to be involved in the drawing development. Based on the potential coordination issues involved with the use of a professional detailer (due to the custom nature of the half-scale elements, the use of new rather than established construction details and design procedures, issues pertaining to construction at the UCSD site, and the ongoing nature of the research project), and the desire to control project costs, the DSDM project decided to handle the drawings internally.

UCSD graduate student Matt Schoettler (MS) embraced this major responsibility. MS was uniquely positioned within the project to meet the various requirements as he possessed: (1) the necessary knowledge of the parameters of the UCSD shake table equipment and site; (2) the requisite expertise in experimental dynamics and scaling verisimilitude, and (3) a working relationship with the researchers and familiarity with the research activities at the other two sites, and, (4) a close awareness of the experimental objectives.

The UCSD team engaged several industry partners for their expertise and experience in the design of the shake table test specimen. Industry members from The Nakaki-Bashaw Group, Metromont Inc., Mid-State Precast, Hanson Precast and the Consulting Engineers Group provided the bulk of this assistance through meetings at their offices, teleconference calls and email communications. These engineers provided drafting procedures, reviewed and marked up plans, and suggested alternatives. The industry members shared additional resources such as structural drawings, drawing templates, drafting materials, and made office space available to the research team.

Recognizing that for success of the construction project, MS had to be able to produce timely and accurate drawings of professional quality jointly with close industry oversight, the DSDM team adopted the following controls/mechanisms:



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- Early industry input to the process in which MS and fellow graduate student Andrea Belleri visited the design office of the **Nakaki-Bashaw Group** (Irvine, CA) to discuss current design practices and review the test structure seismic design (*Sept 2006*).
- A “researcher in practice” training approach in which MS and others spent extended time in industry to quickly learn the needed skills” at **CEG** in Dallas (one week) and **MSP** in Corcoran :
  - The Consulting Engineers Group (**CEG**) in San Antonio, TX provided three days of drafting training and assistance to MS. CEG engineer Raul Cabello provided direct drafting assistance and President Tom D’Arcy granted MS access to the entire CEG drafting library. This training improved the drawing quality and reduced drafting time (*Dec 2006*).
  - Mid-State Precast (**MSP**) in Corcoran, CA provided on the job-training and engineering assistance for MS throughout the process. In the first visit, MS reviewed typical seismic connection detailing and fabrication practices. Engineers and V. Oliveri provided feedback on the constructability of the test structure and recommended improvements that were adopted in the next versions of the drawings (*Jan 2007*).
- A collaborative drawing creation environment in which MS was able to work side by side with **MSP** engineers and draftsmen during three multi-day visits as he developed the drawings (*Jan 2007-Sept 2007*).
- A sequencing of drawing review/checking as follows (*Oct 2007-Dec 2007*):
  - an internal check of the original drawings by **DSDM TG** members
  - a review of the revised set by **CEG** personnel (including *T. D’Arcy* who has personally reviewed each drawing)
  - a “plant” review by the actual producers (**MSP/Hanson Precast**), and finally
  - an external review by a PCI-member firm, **Sirko Associates, Inc.** (Denver CO).
- Weekly conference calls between a smaller subset of the research team, DSDM TG members and industry members focusing on the shake table test drawing. During critical stretches, these calls were held bi-weekly (*Aug 2007-Jan 2008*).
- The identifying of two other graduate students at UCSD (by J. Restrepo), supported by other mechanisms external to the project direct funding, to move over from other work to assist in the creation of the shake table drawings (*Aug 2007-Jan 2008*).

The hundreds of man hours in design review, plan review, instruction, and other assistance reflect the generous support of the industry. As a result of these mechanisms, the hard work of the UCSD student, and the commitment of the industry, the assembling of the prefabricated units within the structure occurred without incident.

## APPENDIX V. DSDM Research Advances

The project has **advanced knowledge** on the following topics:

1. The distribution and magnitude of seismic-induced diaphragm inertial forces along the height of structures for different structural configurations and seismic demand levels.
2. The internal load paths that develop in precast diaphragms during seismic excitation, including within irregular floor plans and under bi-directional components of ground motion.
3. The expected distribution of inelastic deformation demands within precast diaphragms during seismic response in terms of opening and sliding profiles of the joints between precast units.
4. The characteristics of the local demands on individual diaphragm reinforcing elements (shear and chord connectors in different regions of the diaphragm) during seismic response, including the evolution under cyclic load of tension-shear force ratios and opening-sliding deformation ratios.
5. The general behavior of typical precast concrete diaphragm connecting elements under combined forces including the nature of cyclic shear in the presence of tension and the development of friction under compression, and insight into the connector mechanics in the presence of confinement perpendicular to the joint.
6. The combined behavior of reinforcing elements along a precast diaphragm joint during cyclic response including the nature of neutral axis migration and shear transfer mechanisms.
7. The participation in diaphragm action of (secondary) gravity system elements in the floor system not currently considered in diaphragm design and their effect on the primary diaphragm elements.
8. The interaction of vertical elements of the gravity load resisting system with precast floor diaphragms at different levels, including modifications to the structure dynamic properties.
9. The confining effects of vertical elements of the lateral load resisting system (shear walls, frames) acting in their out-of-plane direction, and the resulting effect on precast diaphragms response.
10. The three-dimensional nonlinear dynamic response of diaphragm sensitive precast concrete structures, including irregular floor plans under bi-directional components of ground motion.
11. The differences in behavior between untopped and topped precast concrete diaphragms.
12. The vibration modes of precast floor systems, including higher-frequency “ringing” effects due to panel impact.
13. The torsional response of diaphragms induced by eccentricity caused by unsymmetrical softening in primary lateral force resisting system elements.
14. The interaction of rocking walls with precast floor systems, including induced out-of-plane forces acting together with in-place forces.

The project has **advanced the state of the art in research** in the following area:

1. The development of coupled nonlinear spring elements with properties based on experimental data for use as discrete connection elements in nonlinear finite element (FE) models.
2. The enhancement of these elements to capture cyclic characteristics including stiffness and strength degradation, hysteretic signatures such as pinching and slip, and cyclic ductility for use in nonlinear transient dynamic FE analysis (FE NLDTA).
3. New hysteresis rules for concrete structural elements developed for the diaphragm research and introduced into the Ruaumoko3D element library.

4. The development of loading frames with mixed-mode control kinematics for evaluating precast diaphragm connections under non-proportional combinations of cyclic shear with tension/compression (pseudo-static displacement and/or force control).

*It is noted that this approach represents a significant advancement in the experimental evaluation of precast diaphragm connectors as previous tests involved the application of a single component of load to the connector with no (or a slight and unmeasured) restraint in the other direction.*

5. A development of a set of loading protocols to determine the needed parameters to fully define the coupled nonlinear hysteretic spring elements for use in FE NLDTA.
6. Experimentally calibrated and verified analytical models for the examination of precast concrete floor diaphragms including:
  - a. 2D nonlinear static steel/concrete/interface constitutive models for the diaphragm connector and the surrounding concrete region (using the software DIANA).
  - b. 2D FE models of individual precast diaphragms incorporating the discrete connection elements for nonlinear static “pushover” analyses (using the software ANSYS).
  - c. Reduced DOF representations of precast structures for the rapid evaluation of diaphragm seismic force demands over a host of parameters (using the software Ruaumoko3D).
  - d. 3D FE models of precast structures incorporating the discrete diaphragm connection elements for earthquake simulations using NLDTA (using the software ANSYS).

*It is noted that the last model represents the most inclusive model yet built for the examination of precast concrete structures and floor diaphragms, capturing many aspects ignored in previous examinations of precast diaphragm action: in-plane and out of plane degrees of freedom in the floor diaphragm; coupled nonlinear shear and axial response in diaphragm connectors including cyclic phenomena such as pinching, slip, stiffness and strength degradation, and cyclic ductility; accurate representation of the in-plane and out-of-plane restraint of vertical elements (shear walls, moment frames) of the lateral load resisting system (LFRS); capturing of the forces developed due to compatible displacements between the LFRS elements and the gravity system columns; realistic representation of secondary elements in the floor system that are not part of diaphragm design but nevertheless have an effect on diaphragm action; shear friction mechanisms and self-generating compression along joints that are restrained in their perpendicular direction; contact and impact; dynamic modes including higher mode longitudinal oscillations; shear deformations in panels, and the profiles of the floor itself, allowing direct measurement of vertical eccentricity in the load path, compatible rotations and torsion in the precast elements; and slip; unseating of precast elements on ledges and corbels. These models were constructed using experimental data and verified/calibrated using experimental data.*

7. Stable and efficient analysis techniques for the models described in item 6 above, particularly for the 3D FE NLDTA of precast structures which in the past could take days or weeks to perform with a great chance of divergence, filling of the computer hard drive, and cumbersome to handle, both in model modification and data post-processing for interpretation of results. The project upgraded dedicated computational power annually to maximize run-time efficiency; used ANSYS Adaptive Design Parametric Language (ADPL) to facilitate parameter variation during analytical studies; and wrote high-end post-processing utility programs with graphical interfaces to interpret the data from the 3D FE analysis (UA) and the RDOF analyses and shake table testing (UCSD).

8. Hybrid testing (physical experiments integrated with computer simulation) to evaluate the performance of critical joints within precast concrete floor diaphragms, including the communication software and control algorithms, test fixtures and kinematic relationships to subject precast panels to three coupled degrees of freedom (obtained from interface degrees of freedom from the analytical superstructure) that permit the application of cyclic shear, tension and moment to the critical joints. These tests were performed both as predetermined displacement histories (PDH) and as full-fledged (pseudo-dynamic) adaptive tests with force feedback to the analytical model using a Matlab-based explicit integration scheme based on the Alpha-method hybrid algorithm with a fixed number of iterations [Mercan & Ricles, 2005].

*The hybrid test involved controlling 3 coupled DOFs on the experimental substructure and an analytical superstructure involving 134 DOF, making it one of the more complex and larger hybrid tests performed thus far. The PDH test involved an analytical superstructure with approximately 20,000 DOF.*

9. Shake-table testing of a complete, large-scale structural system, exploited to the fullest extent by subjecting the building to 16 significant-input ground motions while 640 sensors dynamically recorded the development of a number of damage-limit states in various elements and connections in the structure, thereby providing a landmark opportunity to analyze precast diaphragms under realistic boundary conditions.

*The shake table test involved a three story half-scale structure 54' x 16' in plan and weighing approximately 1 million pounds; the largest footprint and mass of any structure tested on a shake table in the United States. The world's largest outdoor shake table, at UCSD's Englekirk Structural Engineering Center, together with specially-designed sliding outrigger foundations, permitted the testing of the structure.*

10. A multi-university research approach employing tightly integrated multi-level analysis and experimentation (connector region, diaphragm joint; individual diaphragm and full structural system) and extensive and sustained industry input and oversight to both advance knowledge in the topic and provide quantifiable design deliverables to the profession.

## APPENDIX VI. DSDM Experimental Results

### Full Scale Testing of Isolated Diaphragm Connectors

1. Connection-specific findings, conclusions and design recommendations for:
  - the existing diaphragm connectors studied in the Phase I testing program:
    - Dry Chord Connector
    - Pour Strip Chord Connection
    - JVI Vector Connector
    - Untopped Hairpin Connector
    - Topped Hairpin Connector
    - Cover plate Connector
    - Topping Bond
  - improved diaphragm connectors studied in the Phase IB testing program
    - Debonded Dry Chord Connector
    - Ductile Ladder Mesh
    - Ductile Mesh w/Hairpin
    - JVI Vector Connector

The results presented for each connection included:

- The dependable strength in tension and shear of these connectors and how these values compare to existing design strength calculations or existing models, and improved or new rational expressions for connector shear and tension strength.
  - Identification of the failure modes that control the connection under each load protocol.
  - The tension and shear service stiffness, and expressions to provide these calculations.
  - The available deformation capacity and the ductility classification of each connection.
2. General findings, conclusions and design recommendations including:
    - The manner in which combined forces modifies connector response relative to single load component response, including lower stiffness and yield strength.
    - The manner in which cyclic loading modifies connector response relative to monotonic response, including stiffness and strength degradation and cyclic ductility values
    - The general connector configurations or features that produce flexible or stiff tension and shear behavior.
    - The general conditions (geometry, tolerances weld procedure) that lead to premature weld failures and the connection configurations most susceptible.

- Nature of the response for topped and untopped connectors in shear under the following cases: no tension force; no tension opening; constant tension opening (0.1”).
- Required anchorage details for mesh ladder.

### **Hybrid Testing (Pseudo-dynamic Adaptive and Predetermined Time Histories)**

The results of the hybrid testing included:

1. The moment strength, flexural stiffness and rotational deformation capacity of a critical flexural joint in a pretopped precast concrete diaphragm
2. The shear strength, shear stiffness and sliding deformation capacity of a critical shear joint in a pretopped precast concrete diaphragm.
3. Quantification of the degradation of stiffness and strength of the joints under the expected cyclic response of the joint in earthquakes.
4. The progression of damage at the joint from a sequence of increasing intensity earthquakes
5. Matching of damage levels in the concrete (hairline cracking, significant cracking, crushing) and the steel connecting elements (yielding, fracture) to specific seismic hazard levels.
6. Verification of analytical models which showed good agreement with the test results.
7. Demonstration of the efficacy of the design methodology through the performance observed.

### **Shake Table Testing**

For the half-scale diaphragm sensitive precast, prestressed concrete structure designed with the emerging design methodology (with terminology defined later in the design deliverable section) and tested under significant earthquake demands:

1. Verification of analytical models for precast diaphragms and precast structure under moderate seismic hazard which showed good agreement with the test results.
2. The data to calibrate analytical models for precast diaphragms and precast structure under high seismic hazard.
3. Demonstration of good performing precast concrete diaphragm systems at prototype sites in Knoxville, Seattle, and Berkeley.
4. Demonstration of certain features of the seismic design methodology including:
  - The efficacy of the completely dry system (pretopped double tees with dry chord and JVI Vector connector) for regions of low seismic hazard (LDE).
  - The efficacy of the untopped system (pretopped double tees (DT) with pour strip and JVI Vector connector) up to regions of high seismic hazard (HDE).
  - The efficacy of the topped noncomposite system for hollowcore (topping with ductile ladder mesh) up to regions of high seismic hazard (HDE).
  - The efficacy of the topped system composite system (topped double tees with hairpins and ductile ladder mesh) up to regions of moderate to high seismic hazard (MDE).
  - The ability to target a reliable yield level of the diaphragm at DBE levels through the use of the diaphragm amplification factor, and verification of appropriate values for the RDO regions of high seismic hazard.
  - The ability to mitigate non-ductile shear limit states through the use of shear overstrength factors, and verification of a sufficient value for regions of high seismic hazard.
5. Observation and the collection of valuable data of the following behaviors identified in the advanced analytical modeling during the project, and previously unverified or unaddressed:
  - Elastic and inelastic deformation profiles within the precast diaphragm, between the panels and the joints, and among the joints, for both topped and untopped diaphragms.

- The effect of secondary elements (gravity system elements supporting precast floor units: spandrels (SP) and L-beams) on the response of the diaphragm including protecting of certain joints (supplementing shear strength or suppressing joint opening); concentrating inelastic deformation demands at certain joints; and contributing to dynamic properties.
  - The critical nature of the secondary connections in the floor system (DT-SP, and SP-COL) in both characteristic and deformation capacity.
  - Interaction of walls (in-plane and out-of-plane) including confining effects on floor.
  - Pounding between elements from out-of-phase movement and impact.
  - Concentrated damage at jointed connections, with little damage spreading into or occurring elsewhere in the precast concrete units.
  - Interaction of gravity system columns with the individual floors, including providing secondary lateral load paths.
6. The observation of unanticipated and important effects that can be modeled in future analyses such as the effect of asymmetric damage on the diaphragm response (torsion); redundancy and secondary paths after loss of load carrying capacity in one region of the floor system; compatible displacement mechanisms that lead to unseating of units, combined forces at walls, etc.
  7. Diaphragm amplification as a result of the large floor aspect ratio was captured, allowing for assessment of how flexible diaphragm response differs from an assumed rigid diaphragm.
  8. The effect of connection tolerances and misalignment on diaphragm response.
  9. The performance of a rocking wall and building were demonstrated under seismic loading, including the wall's self-centering capabilities.

#### APPENDIX VII. DSDM Research Findings

The project has produced the following findings related to precast diaphragm behavior:

1. Individual diaphragm reinforcing elements are subjected to different combinations of shear and tension force/deformation demand that differ based on location within the floor and along the joint; change due to the state of that particular diaphragm reinforcing element as well as surrounding diaphragm reinforcing elements; and progressively change as the diaphragm cycles.
2. The pure shear force sliding action of certain precast diaphragm connectors involves a sliding trajectory that is accompanied by joint *opening*. Accordingly, the shear response of precast diaphragm connectors is quite sensitive to the amount of confinement perpendicular to the joint.
  - Connectors in joints that are restrained from opening can develop diagonal strut action ("self-generated compression"), thus achieving significantly higher shear strength and stiffness. This action degrades with cyclic action (reversing diagonal cracking of the surrounding concrete), but can be important for near field motions possessing a large initial forward pulse.
  - Response regimes of the diaphragm connectors were identified based on the trajectory of imposed displacement demands including coupled (tension and shear) and confined (compression and shear). Methods for predicting these boundaries and techniques for modeling this behavior were developed.
  - The effective friction force transferred by these connections reduces with repeated reversals of the shear force (equivalent cyclic coefficient of friction).
3. Gravity system elements supporting the floor system (precast spandrel beams and inverted tee beams), termed secondary diaphragm elements since they are not currently considered part of the diaphragm design, can have the following effects on the diaphragm behavior:

- Spandrel beams in precast floor systems participate in carrying diaphragm shear and flexure forces.
  - Spandrels will tend to increase the overall diaphragm elastic stiffness through contributions to shear and flexural rigidity.
  - The presence of the spandrels leads to a redistribution of joint deformation patterns.
4. The floor diaphragms on different levels in precast concrete structures can interact via vertical structural elements that connect the individual floor systems, including:
    - The development of axial forces in the longitudinal direction of long span precast diaphragms due to the confining effects of transverse shear walls on diaphragm joint opening (tension and compression pairs).
    - Interaction of the vertical elements of the gravity system (columns and light walls) due to the compatible displacements of individual floor diaphragms they connect including:
      - inducing currently unaccounted forces on the reinforcement anchoring the vertical elements to the floor system,
      - the possibility of unseating of the floor units at a level
      - large “captured-column” tributary story shears on individual columns
  5. The out-of-plane stiffness of vertical elements of the lateral force resisting system (shear walls and moment frames) intended for resistance in one direction can reduce diaphragm deformation demands in the other direction for flexible diaphragms.
  6. Higher mode actions in the diaphragm including pounding and longitudinal “ringing” effects.
  7. The amount of inherent damping can have a significant effect on the deformation demands in diaphragm joints for total precast structures under strong ground motions.
  8. In untopped diaphragms, deformation in the chord connectors is shared fairly evenly between the precast unit and the precast joint during elastic response; this deformation tends to concentrate at the precast joint during inelastic diaphragm response.

The project has produced the following **findings** related to precast diaphragm **design**:

#### Diaphragm Design Force

1. Current diaphragm design force levels are not sufficient to maintain elastic diaphragm response in anticipated seismic demands.
2. Diaphragm internal force procedures do not accurately capture force combinations and compatibility-induced deformation demands on individual diaphragm reinforcing techniques.

#### Diaphragm Limit States

1. Diaphragms can be flexure-controlled (FC), i.e. incur failure after sufficient inelastic flexural deformation) or shear controlled (SC) depending on the relative strength of the shear reinforcement to the chord reinforcement, as defined by the shear overstrength factor  $\Omega_v$ .
2. The magnitude of  $\Omega_v$  required to produce a FC design depends primarily on diaphragm geometry.

#### Diaphragm Design Options

1. Long diaphragms may be drift controlled and as such may only require moderate deformation capacity of the reinforcing elements.
2. Short diaphragms achieve high forces without significant ductility demand and as such may benefit from an elastic design with minimal deformation capacity requirements.
3. Elastic DBE design for long span diaphragms in regions of high seismic hazard may not lead to practical designs. The use of lower  $\Psi_d$  values that permit yielding in the DBE together with HDE



details that can accommodate the large inelastic deformation demand in the MCE has been shown to be a viable technique.

#### Diaphragm Design Properties

1. Rational methods have been developed to predict the stiffness and strength of precast diaphragms.
2. Precast diaphragm flexural stiffness and strength is significantly affected by the tension characteristics of the shear reinforcement.

#### Diaphragm Deformation Capacity

1. Loss of shear connectors due to tension demands (or descending branch chord response) in regions of high in-plane flexure tends to create a concentration of inelastic deformation that can significantly reduce the global ductility of a flexure-controlled diaphragm.
2. For flexure-controlled (FC) diaphragms, the presence of spandrels will tend to reduce the diaphragm deformation capacity due to concentration of the inelastic deformation demand. These effects are greater for strong and stiff DT-SP connections.
3. For shear-controlled (SC) diaphragms, the presence of spandrels will tend to slightly increase diaphragm deformation capacity due to participation in the shear transfer of the critical joint.

#### Diaphragm Reinforcement Details

1. Most existing diaphragm details do not possess sufficient deformability to be considered for high seismic hazard applications.
2. Construction tolerances (vertical and horizontal) in typical precast practice can lead to brittle performance in dry chord connectors for untopped precast diaphragms that exhibited otherwise excellent ductile performance in controlled laboratory tests.
3. The pretopped chord connection on the third floor showed no sign of damage at this level of testing despite considerable connection-plate misalignment. With tighter construction tolerances, this connection may have also performed as intended under larger seismic demands. This could be demonstrated with individual connector tests at full scale with realistic offsets.

#### Secondary Connections

1. DT-SP connections in high flexure regions are subjected to large sliding deformation. DT-SP connections in high shear regions are subjected to opening deformation.
2. Current DT-SP connection details may not have adequate sliding deformation capacity to survive inelastic diaphragm action.
3. DT-SP demands are more closely related to the imposed deformations of the diaphragm than the force levels of the diaphragm. Accordingly, DT-SP connections can reach their yield strength prior to the diaphragm reaching its design force.

#### Bond

1. The bond between the topping slab and precast units without any special surface treatment was maintained during both the individual connector tests and the shake table test.

#### Design Factors:

1. Values for the required diaphragm amplification factor  $\Psi_d$  were identified for different sets of design parameters and design targets (BDO, EDO, RDO).
2. Values for the required shear overstrength factor  $\Omega_v$  were identified for different sets of design parameters and design targets.
3. Ranges for the required deformation capacity for different diaphragm reinforcing element classifications (LDE, MDE, HDE).

