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DEVELOPMENT OF A SEISMIC DESIGN METHODOLOGY FOR PRECAST DIAPHRAGMS

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SUMMARY

A consortium comprised of the University of Arizona (UA), the University of California San Diego (UCSD), and Lehigh University (LU), together with the United States Precast/Prestressed Concrete Institute (PCI) is conducting a collaborative NSF-supported research project to develop a comprehensive design methodology for precast concrete floor diaphragms in buildings under seismic loading. The consortium's research will integrate large-scale experiments at LU, finite element (FE) and nonlinear dynamic analyses at UA, and quasi-static and shaking table tests at UCSD. An Industry Task Group oversees the planning and execution phases of the research.

The integrated research approach involves: (1) Full-scale tests of isolated details under simple load combinations to determine properties for input to FE models. (2) FE models of representative floor plans analyzed under different earthquake loading conditions and verified by direct comparison to quasi-static push tests. (3) Earthquake simulations performed on models of representative structures at different levels of seismic hazard and verified by shaking table tests. (4) Realistic loading patterns applied to portions of full-scale precast units and entire joints at half-scale in a multi-component load frame. These patterns will correspond to histories at different critical diaphragm locations, based on seismic demands obtained in the structural analyses, and force combinations and deformation patterns obtained in the diaphragm analyses.

The research program is structured to produce distinct design deliverables including: (1) an appropriate diaphragm design force pattern; (2) a procedure to determine likely internal force combinations; (3) a unified design for reinforcement in untopped and topped diaphragms; (4) structural integrity provisions including the required ductility characteristics of reinforcement; (5) the strength and ductility characteristics of typical diaphragm details, including prequalification of existing details and a prototcol for qualification testing of new details; (6) design and detailing recommendations for diaphragm anchorage to the lateral system; and (7) diaphragm elastic stiffness calculations and flexibility limits.

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INTRODUCTION

A consortium comprised of the University of Arizona (UA), the University of California San Diego (UCSD), and Lehigh University (LU), together with the Precast/Prestressed Concrete Institute (PCI) is conducting a collaborative research project to develop a comprehensive seismic design methodology for precast concrete floor diaphragms. PCI selected the UA-UCSD-LU consortium through an open competition. The research program is funded by the National Science Foundation (NSF) through the Grant Opportunities for Academic Liaison with Industry (GOALI) Program. PCI is also providing supplemental research funding and in-kind support, and precast producer members are providing test specimens. Industry experts are overseeing the planning and execution phases of the research through an active 10 member Diaphragm Seismic Design Methodology (DSDM) Task Group.

The consortium's research will integrate large-scale experiments at LU, finite element (FE) and nonlinear dynamic analyses at UA, and quasi-static and shaking table tests at UCSD. Each of these research components focus on different but equally important levels of behavior (See Fig. 1) whose complex interaction produce the diaphragm seismic response. Using the closely integrated experimental and analytical simulations, the project intends to develop the needed information on both the capacity of precast diaphragm, and its seismic demands. Guided by the industry expertise at hand, the project will then produce an appropriate seismic design methodology.

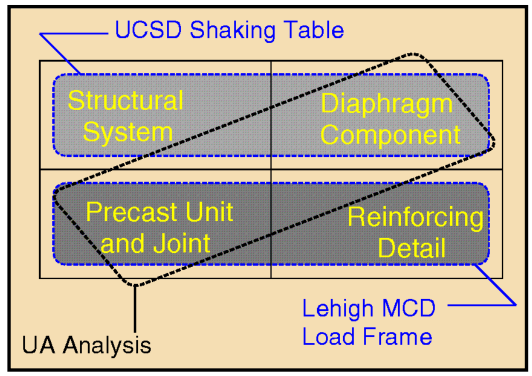

Figure 1. Diagram of research integration

BACKGROUND

The precast concrete industry has mounted a sustained effort to develop seismic-resistant precast concrete construction for buildings, largely supported by Precast Seismic Structural Systems (PRESSS) program funded by the National Science Foundation. However, the PRESSS program focused almost exclusively on the primary (vertical-plane) lateral force-resisting elements. With the poor performance of precast concrete diaphragms, including the collapse of several parking structures during the 1994 Northridge earthquake (Iverson and Hawkins [1]), and the subsequent research (Fleischman et al [2]; Wood et al [3]), it is now recognized that a further step in the process is the development of reliable seismic design methodology for precast floor diaphragms. While recent modifications to diaphragm design practice have been codified, e.g. 1997 UBC (ICBO [4]), it is generally agreed among researchers and practitioners that current design practices require significant further improvement (Nakaki [5]).

Precast Diaphragm Behavior

The behavior of floor diaphragms is one of the most complex and least understood aspects in the seismic response of buildings. In most types of construction, this lack of understanding is forgiven as the floor can be assumed to be nearly rigid and have sufficient strength to transferring inertial forces while remaining elastic. However, the jointed nature and long spans of precast concrete floors expose the significant seismic demands that can occur in floor diaphragms, including: (1) in-plane diaphragm force levels that significantly exceed those prescribed by current building codes; (2) significant diaphragm deformations that amplify gravity-force resisting system drift demands; (3) unexpected diaphragm internal force paths that create force combinations; and, as a result of the first three, (4) inelastic diaphragm behavior that places ductility demands on joint reinforcing details between floor units. These ideas are expanded upon in the following:

(1) Diaphragm design forces are currently obtained through equivalent lateral force (ELF) procedures. Figure 2a, for instance, shows the UBC pattern of diaphragm design forces F_{px}. Subsequent diaphragm design steps depend on F_{px}, thus these design forces should resemble the forces that develop during seismic events. However, evidence shows that ELF design procedures may significantly underestimate diaphragm inertial forces (Rodriguez et al [6]) for wall and frame structures alike (Fleischman and Farrow [7]). Furthermore, the maximum inertial forces may occur in the lower floors of the structure (Fleischman et al [8]), in direct contradiction to current ELF patterns (See Fig. 2c). Large diaphragm forces have also been deduced from accelerations measured during earthquakes (Hall et al [9]).

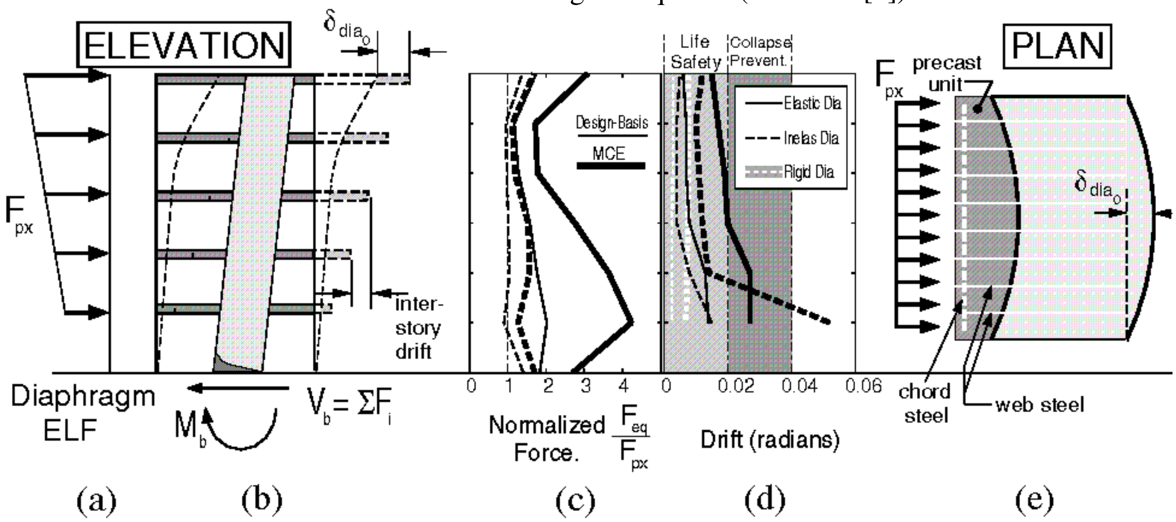

Figure 2. Profiles (Fleischman et al [2002]): (a) Code ELF; (b) Building schematic (c) Force demand; (d) Drift demand; (e) In-plane deformation.

(2) Precast construction is commonly and effectively used for building systems with long floor spans. In these structures, the typical long distances between the primary (vertical plane) lateral force-resisting elements creates a demanding condition for the diaphragms, by generating significant in-plane bending moments and shear forces during seismic events, and also by producing a diaphragm that is quite flexible (See Fig. 2e). In precast construction, diaphragm flexibility is exacerbated by the inherent flexibility of jointed systems compared to a monolithic reinforced concrete diaphragm. Diaphragm flexibility can control a structure's dynamic properties (structural periods, mode shapes, modal participation and number of important modes) (Fleischman and Farrow [7]). Seismic force demands therefore become a function of diaphragm flexibility. Inelastic softening can further amplify the effects of diaphragm flexibility such that the gravity force-resisting system in regions away from the primary lateral force-resisting system elements undergoes amplified drift demands, as shown in Figure 2d for a representative precast structure. For these cases, increases in diaphragm design strength will tend to reduce diaphragm deformation and hence the story drift (Fleischman et al [8]). As such, diaphragm behavior for floors spans of any appreciable distance depends on a complex interrelation of diaphragm strength and flexibility, and is also affected by the *relative* strength of the diaphragm to the lateral force-resisting system elements, the system overstrength, and the ground motion intensity.

(3) Provisions for precast floor diaphragms in high seismic zones require a cast-in-place topping slab for continuity (ICBO [4]). Nevertheless, the joints represent planes of weakness and the slab will tend to crack along the edge of precast units during (or prior to) seismic response. As such, the design of topped and untopped precast diaphragms alike requires adequate joint reinforcement to transfer internal forces across joints between the precast units. Current U.S. practice uses a horizontal beam model (Bockemohle [10]) to determine diaphragm reinforcement. In this procedure, the diaphragm is treated as a simple beam lying on its side to determine the internal forces (moment and shear) due to F_{px} (See Fig. 3). Chord steel is

provided to carry the entire in-plane bending moment; web reinforcement across panel joints parallel to the seismic force is designed to carry the entire in-plane shear. There are a number of difficulties with using the horizontal beam model for precast floor diaphragms, most notably that the method counts somewhat on plastic redistribution to allow the forces to end up as shown in Fig. 4. For instance, Region 1 represents a portion of the diaphragm in which the web reinforcement, designed simply for shear transfer, is under high tension due to the in-plane bending of the diaphragm. Further, many diaphragm regions (e.g., Region 2) are subject to complex force combinations (shear, moment, and thrust coinciding at a section) that are more demanding than the internal forces determined from the simple horizontal beam model. Alternately, a stiffer load path in the floor system (IT beam at Region 3) can redirect the force path in unexpected ways. These force combinations can occur due to restraint or differential movement of vertical elements of the lateral system, the direction of attack of seismic loads (e.g. diagonal), openings or other irregularity. Currently, precast diaphragms have little inherent plastic redistribution qualities, and thus if a section along the force path cannot accommodate the forces, a nonductile failure is likely.

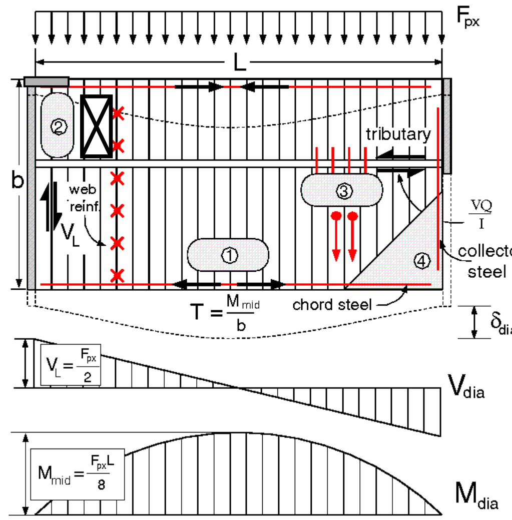

Figure 3. Horizontal Beam Model for Diaphragm Internal Force.

(4) If the aforementioned conditions create a force overload, the inelastic deformation demands will tend to concentrate in the reinforcing details across the joints. These reinforcing details were not originally developed with full consideration of ductility requirements. Indeed, a nonductile failure mode (shear failure of the web reinforcement) is the likely controlling limit state in the event of inelastic diaphragm action (Farrow and Fleischman [11]). Further, tensile deformation demands placed on the web reinforcement in high in-plane bending regions (e.g. Region 1 in Fig. 3) become significant if the chord steel yields and must also be considered. Standard web reinforcement (welded wire fabric and mechanical connectors) possesses limited tensile deformation capacity and thus may fail. The effectiveness of shear friction provided by welded-wire fabric at joints under tension or flexure is also an issue. Diaphragm detailing issues are more complex for irregular floor plans. As an example consider the parking structure diaphragm, an irregular floor plan often constructed using precast elements. A typical parking structure diaphragm exhibits at least four failure-critical locations, one of which will control depending on the loading direction and lateral system layout. Figure 4a shows examples of the deformation patterns that may occur causing complex internal force combinations. The discretely-connected precast units themselves will not necessarily follow plane-sections assumptions of the simple horizontal beam model (see Fig. 4b). Therefore, forces acting on individual joint reinforcing details may not always be accurately predicted by calculations based on beam theory, even if the

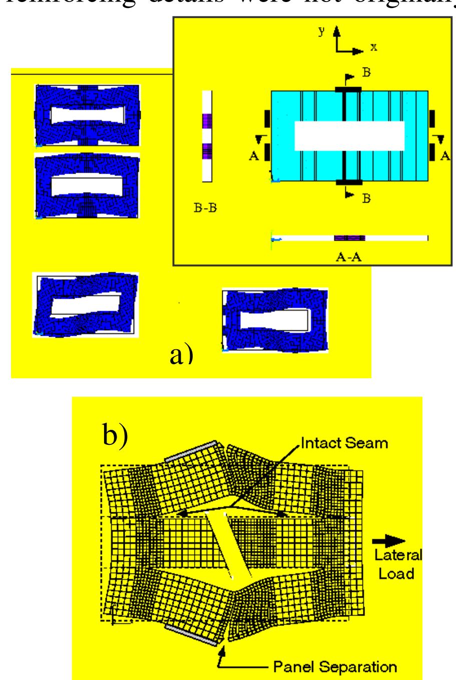

Figure 4. Irregular diaphragm response: (a) diaphragm in-plane deformation modes; (b) precast unit deformation patterns.

internal force combinations are properly estimated.

Impact of Behaviors on Precast Diaphragm Design

Elastic response is the *preferred* behavior for diaphragms (ACI [12]), owing to the desire for in-plane stiffness (Chopra [13]). In many cases, elastic behavior is *needed* to avoid nonductile failure in the floor system, since this component of the structure is not typically provided with detailing for ductility. Clearly, building designs in which the diaphragm is the structure's weak link are to be avoided (Wood et al [3]) since the seismic force reduction coefficients (the so-called "R factors" that reduce elastic earthquake forces to design forces) are based on the expected inelastic behavior of the primary (vertical plane) lateral force-resisting elements (e.g., shear walls or moment frames) and are not valid for buildings that concentrate inelastic behavior in the diaphragms. Such inelastic diaphragm behavior seems to have played a key role in the poor performance of the Northridge parking structures (Fleischman et al [14]). As such, strict building code requirements for elastic diaphragm design might be anticipated. However, even with recent modifications, current code provisions imply elastic diaphragm behavior but do not necessarily accomplish this goal (Nakaki [5]). Indeed, research shows that diaphragms designed according to current practice will not remain elastic under the design basis earthquake (Fleischman et al [8]). Thus, in considering a seismic design methodology for precast diaphragms, a prescriptive elastic design seems warranted (Cleland and Ghosh [15]).

An appropriate way to achieve elastic diaphragm behavior is a capacity design approach (Standards New Zealand [16]). Capacity design aims to prevent nonductile behavior (Paulay and Priestley [17]) by designing ordinary portions of the structure for forces relative to the strength of the special, preselected, properly detailed portions of the structure that serve as structural "fuses". One could imagine using the ELF pattern in Figure 2a to design diaphragms to be stronger than the primary (vertical plane) lateral force-resisting elements of the building, thereby relying on the yielding of these systems (for instance a plastic hinge at the base of the shear wall in Fig. 2b) as the structural fuse to limit the diaphragm force levels. However, as described previously, the inertial forces that actually develop during a seismic event can be significantly larger than those anticipated in ELF design procedures. The uncertainty in quantifying maximum diaphragm forces severely impacts the development of a reliable and economical capacity design approach. For wall structures, in particular, the extreme force events in the diaphragms are driven by modifications to the structure's dynamic properties *after* hinges form at the base of the walls (Eberhard and Sozen [18]). As a result, even a capacity design approach that successfully produces shear wall base hinges while the diaphragms are elastic does not guarantee elastic diaphragm behavior will be sustained throughout the seismic event. A prescriptive elastic diaphragm design, therefore, may be difficult to achieve reliably and economically.

This conclusion, though not based on behavior unique to precast systems, bears significant impact on the development of an appropriate precast diaphragm seismic design methodology. Large force events can be particularly problematic for these paneled floor systems in which forces must be carried across the joints between precast units. Inelastic deformation, if it occurs, will concentrate in these regions, amplifying ductility demand. Complex force paths, due to floor in-plane vibration modes, lateral system restraint, irregularity, etc., can create force combinations that can produce localized inelastic behavior even if the overall diaphragm load remains near design force levels. A major consequence of these conditions is that diaphragm details may become inelastic even when elastic behavior is intended. The jointed nature of the precast floor diaphragms does not provide inherent protection against internal force overloads, and thus the diaphragms may become the critical components of the lateral force-resisting system. Structural integrity requirements, needed to address adequate anchorage of diaphragms to the primary lateral force-resisting system elements, including carrying superimposed gravity loads and accommodating imposed rotations from walls (Menegotto [19]), and maintaining seating of the precast units (Mejia-McMaster [20]), must also include detailing joint reinforcing details for ductility, even if diaphragms are designed to be elastic (Fib [21]; Fleischman and Farrow [11]). Further, for longer floor spans, diaphragm flexibility must be controlled to limit gravity system drifts. The multi-faceted conditions of strength, stiffness and ductility lends itself to a design approach based on comprehensive performance requirements (Fleischman and Farrow [22]) with appropriate design overstrength factors (Rodriguez et al [23]). As described next, the research activities are being structured around this design approach.

Research Approach to Develop Precast Diaphragm Design based on Performance Requirements

The specific advances suggested by the performance issues raised in the previous section are given in Table 1.

Table 1. Advances for design practice suggested by diaphragm performance issues

Estimating Diaphragm Design Forces: (a) Develop a methodology for determining diaphragm design forces based on a more appropriate pattern and the use of overstrength factors; (b) Promote elastic response, but be prudent in anticipating unintended ductility demand.
Limiting Diaphragm Flexibility: (a) Incorporate a rational deflection calculation in diaphragm design. (b) Restrict diaphragm flexibility within limits that ensure safe drift performance in a seismic event. (c) Account for diaphragm flexibility effects on other performance quantities, e.g. force or ductility.
Diaphragm Internal Force Paths: (a) Develop a simple yet effective method of calculating forces at a section based on the relative stiffness of diaphragm reinforcement elements. (b) Provide guidance on how to determine and combine shear and tension components in the analysis of floor systems to permit the design of reinforcement for resultant forces.
Maintaining Structural Integrity – Develop a rational and unified method for treating reinforcing details including: (a) Eliminating the potential for nonductile failure in a internal force overload situations by providing a capacity design for web reinforcement with respect to the chord steel; (b) Providing recommendations for the tensile characteristics of web reinforcement (strength, ductility or compliance) to provide the desired seismic behavior**.**

Thus, prior to developing a coherent design methodology based on performance requirements, the research must provide knowledge to properly: (1) estimate diaphragm force levels and force distributions; (2) estimate drift demands on the attached gravity load-resisting systems and identify appropriate limits on diaphragm flexibility; (3) approximate internal force paths within the diaphragm and determine requirements for reinforcing details to transfer these forces across joints between precast units and at anchorages to the primary lateral force-resisting elements; (4) estimate ductility demands on critical reinforcing details during extreme seismic events and identify the details possessing these characteristics.

As discussed in the background section, diaphragm force levels and distributions are due to nonlinear dynamic system response; diaphragm dynamic response to these forces depends on both the diaphragm strength and flexibility; complex force paths occur due to lateral force-resisting system element layout; and critical diaphragm sections develop force combinations based on the characteristics of individual details. Therefore, the challenge in advancing the knowledge base on precast diaphragms arises from the fact that diaphragm seismic response is a result of a complex interaction of system behavior (the overall structure), component behavior (the floor diaphragms), section behavior (diaphragm panels and joints), and joint detail behavior (individual hardware and reinforcement). Accordingly, the focus of the research must extend through the entire range of these behaviors.

Previous research efforts have attempted this but suffered from the limitation that diaphragm forces and force paths had to be estimated entirely through analytical simulation. These simulations depended heavily on test results for individual joint reinforcing details under highly idealized loading conditions. Direct extrapolation of these test results to estimate the capacity of the system is questionable, because the actual joint behavior depends on a complex interaction of the force combinations (e.g., tension/shear, compression/shear), the load history, and the state of other reinforcing details in the joint (intact, softening, failed). A more direct but challenging approach is to apply in the joint forces in the sequence, magnitude, and proportion as they might occur in an actual seismic event. This approach will be attempted in the research.

The objectives will be achieved by closely integrating experimental research with analytical simulations that extend across the range of behavior. FE models of representative floor plans analyzed under different earthquake loading conditions will be verified by direct comparison to quasi-static push tests. Earthquake simulations performed on models of representative structures at different levels of seismic hazard will be verified by shaking table tests. Realistic loading patterns, corresponding to histories at different critical diaphragm locations, based on seismic demands obtained in the structural analyses, and force combinations and deformation patterns obtained in the diaphragm analyses, will be applied to precast units in a multi-component load frame. Thus, while the project relies, as in the past, on analytical models of precast diaphragms, these analyses will be verified by system-level experiments; and their output used to apply realistic demands to full-scale joint reinforcing detail experiments.

RESEARCH PROGRAM

The integrated analytical/experimental approach used in the research program will include: (1) Full-scale tests of isolated details under simple load combinations to determine properties for input to FE models. (2) Detailed finite element (FE) models of complete diaphragms from representative floor plans to determine critical force combinations and deformation patterns. (3) Nonlinear time-history dynamic analyses (NTDA) of prototype structures to determine diaphragm force demands under earthquake simulations. (4) Quasi-static tests of the diaphragms and shaking table tests of entire structures to verify the FE and NTDA results and guide their combination in creating critical load histories. (5) Full-scale testing of critical portions of the diaphragm in which the reinforcing details are subjected to load histories that more closely represent the actual demands in an earthquake. The manner in which these activities address the needed advances in the knowledge base are summarized in Table 2.

Table 2. Research Activities to Obtain Needed Knowledge

Determine likely diaphragm force demands, and diaphragm-induced drift demands by:

- Perform nonlinear time-history dynamic analyses on a representative set of precast structures under ground motions scaled to hazard levels for different regions of the country (*UA, UCSD*).
- Verify the analyses through shaking table test comparisons (*UCSD*).

Determine the likely (i) force distribution between chord and web reinforcement for different details at a general section; and (ii) force combinations at critical sections of different representative floor plans; and (iii) chord-collector interaction for different seismic loading directions:

- Perform finite element analyses on a set of representative precast floor plans and details under lateral loads from different angles of attack (*UA*).
- Verify the analyses by a limited number of quasi-static diaphragm tests and shaking table tests that reproduce the diaphragm's distributed horizontal geometry (*UCSD*).
- Use the resulting force combinations as loading histories for the full-scale experiments in versatile load frame, allowing several details and locations to be evaluated under an accurate representation of actual force conditions (*LU*).

Investigate deformation patterns and ductility demand, determine characteristics of local deformations:

- Conduct shaking table tests (*UCSD*).
- Examine regular to irregular floor plans analytically to determine demand on details (*UA*).

Perform load tests for key regions of each set of representative floor plans using the load patterns obtained in analysis to produce likely overload (ductility) conditions (*LU*).

Integration of Analytical and Experimental Components

The research activities described in Table 2 occur individually at each university, yet these activities are interdependent and must be integrated to achieve the project outcome. Figure 5 shows a flow chart describing the sequencing and interactions of the research tasks for the integrated approach including:

(1) Individual joint reinforcing detail (element) tests will be performed on at full scale under simple (proportional) cyclic load combinations. The properties determined (in conjunction with prior work) will be used as input to create accurate diaphragm FE models.

(2) The FE models (of representative floor plans) will be analyzed under different earthquake loading conditions. The analytical models will be verified or appropriately modified by direct comparison to quasi-static push tests (2a).

(3) Earthquake simulations will be performed on models of representative structures at different levels of seismic hazard. These analyses will be verified or appropriately calibrated by shaking table tests (3a). The analyses establish seismic demands.

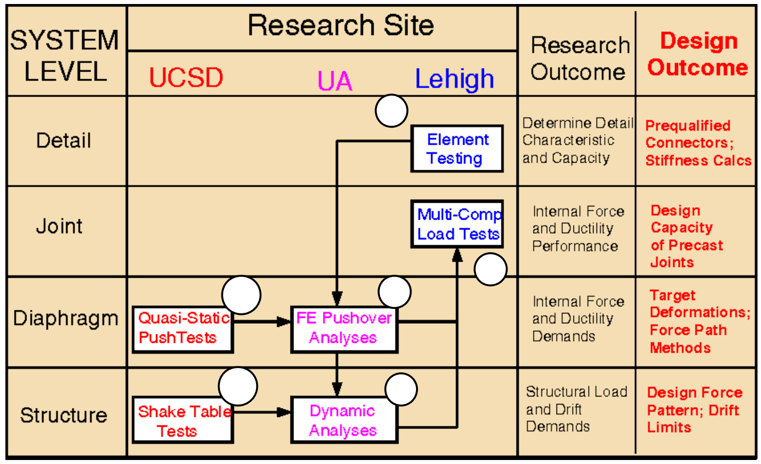

Figure 5: Flow chart of integrated experimental and analytical activities at the three consortium sites

(4) Based on seismic demands obtained in the structure analyses in (3), and force combinations and deformation patterns obtained in the diaphragm analyses in (2), realistic loading patterns are applied to portions of full-scale precast units and entire joints at half-scale in the multi-component load frame. These patterns will correspond to histories at different critical diaphragm locations (maximum flexure, shear, adjacent to wall anchorage, etc.).

As shown in the final column in Figure 5, the research program is structured to produce distinct design deliverables including: (1) an appropriate diaphragm design force pattern in terms of magnitude and distribution; (2) a procedure to determine the likely combination of internal forces at key diaphragm sections; (3) a unified design for reinforcement in untopped and topped diaphragms; (4) structural integrity provisions including the required ductility characteristics of the reinforcement; (5) the strength and ductility characteristics of typical diaphragm reinforcement and connection details relative to these provisions, including prequalification of existing details and a prototcol for qualification testing for new details; (6) design and detailing recommendations for anchorage of the diaphragm to the vertical elements of the lateral (load-resisting) system; and (7) diaphragm elastic stiffness calculations and limits on diaphragm flexibility.

The transfer of the research into design will be facilitated by a 10-member Diaphragm Seismic Design Methodology (DSDM) Task Group. The membership of the DSDM Task Group includes industry people as well as academics. The group possesses expertise and extensive experience with the precast construction practices, seismic design procedures and code writing bodies. The DSDM Task Group was instrumental in guiding the physical scope at the outset of the project, including: (1) providing prototype structures possessing representative floor plans in terms of lateral system types, story height, floor plan, and (2) the selection of representative reinforcement details and construction practice.

The interactions among the researchers and between the researchers and the DSDM Task Group are occurring through: (1) weekly conference calls of the researchers; (2) immediate reporting and interaction with the DSDM Task Group members through a common Intranet site; (3) quarterly face-to-face meetings of the entire project team; (4) special-purpose visits of researchers to experimental sites for detailed discussions on the integration of the analytical and experimental research. In the future, visits to observe experiments are planned as well as extended exchanges of the graduate student researchers among the universities during the summers.

Individual Research Components

Description of Analytical Program

Modeling the behavior of precast floor diaphragms is challenging, requiring detailed models to capture complex deformation patterns, compatibility-induced forces and non-traditional dynamic mode shapes. Thus, the endeavor requires realistic models that capture pertinent behavior through the use of the latest analytical tools and computational power, and must not only involve competent modeling (both nonlinear static and dynamic), but also advanced understanding of the modeling issues. At the same time, it must be kept in mind that simple tools and models need to be developed for practical use in design.

A two stage approach is adopted in the analytical research: Detailed finite element (FE) models of individual floor diaphragms are subject to nonlinear static (pushover) analyses to determine service level stiffness and ultimate strength of the diaphragms (capacity step). Then, multi-degree-of-freedom (MDOF) models (at less detail to facilitate reasonable analysis times) are subject to suite of earthquakes through nonlinear transient dynamic analysis to established seismic demands for structures (demand step).

The FE discretization of the joints between the precast units employs nonlinear springs and contact elements available in ANSYS (See Fig. 6a). The characteristics of the reinforcing elements are based on empirical data, both from previous tests and "baseline" tests performed as part of this research. The MDOF models are developed using a generalized coordinate treatment (Chopra [13]). The properties for these models are derived from the FE pushover analyses. Global diaphragm demands obtained in the dynamic analyses are used as reference points to look up local ductility demands by examining the internal state of the FE model. This symbiotic relationship between the two research stages illustrates the dependence of demand on capacity. As the research progresses, the approach will be refined to include three-dimensional nonlinear dynamic analysis (See Fig. 6b).

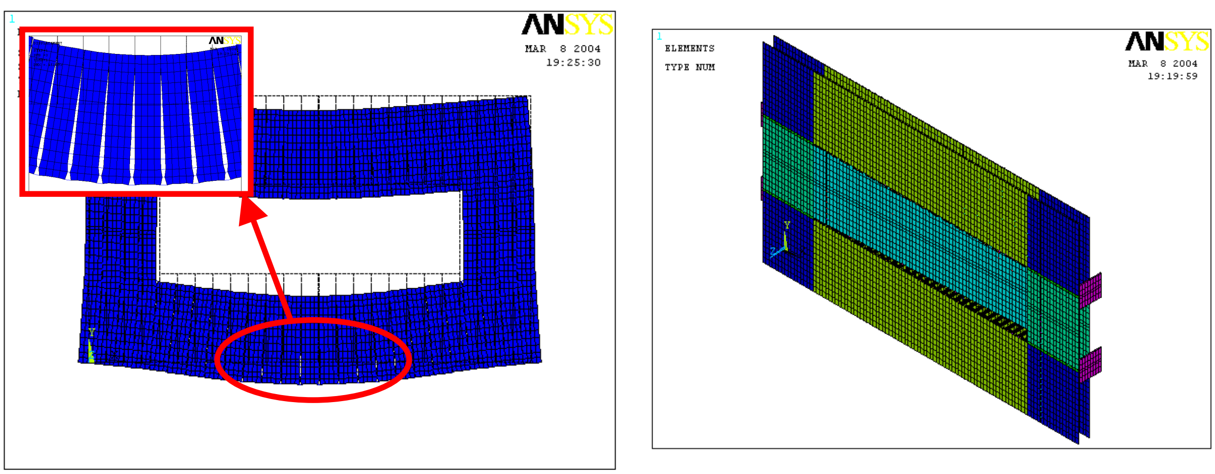

Figure 6: a. 2D-FE Diaphragm Pushover Analysis; b. Three-Dimensional FE Model.

Description of Structural System/Diaphragm Experimental Program

A three-story one-quarter scale building will be built at UCSD. This building will be constructed to observe system behavior under static and dynamic loading conditions. The plan dimensions of the building will be 6 ft 6 in. wide by 19 ft 6 in. long, as shown in Figure 7a. The diaphragm in this building will be constructed using scaled precast concrete floor units and will incorporate connection details identical to those used in practice. The diaphragm reinforcement will be designed in accordance to the requirements of the emerging design methodology. Two floors will incorporate DT floor systems, one untopped and one with a cast-in-place topping; one floor will have HC. Floor units of different widths will be used to build each of the topped floors to represent 3 ft double-T units or 4 ft hollowcore units.

The building will be constructed on the 10 ft by 16 ft uni-directional earthquake simulator facility at the Charles Lee Powell Laboratory. Structural walls will provide the lateral force resistance in the direction of loading. The walls will be supported on a stiff steel base with cantilever outriggers. A similar base was successfully used recently to test a full-scale woodframe house (Filiatrault et al [24]).

Characterization of the building and diaphragm's response will be obtained through quasi-static and dynamic shake table tests. The quasi-static tests will consist on the application of a point load at the center of a diaphragm to about 75 percent of the in-plane load capacity. For this purpose, the floor diaphragm under consideration will be attached to the reaction wall that is adjacent to the shake table, as shown in Figure 7b. The base of the building will be moved slowly by the shake table in order to induce the desired loading to the diaphragm. Each diaphragm will be subjected to three complete cycles to 25, 50 and 75 percent of the theoretical in-plane capacity. Displacement transducers will be set in place to monitor the diaphragm in-plane deformations and to enable the decomposition of the shear and flexural deformations. Strains in different parts of the diaphragms and in the main reinforcement will also be monitored during these tests. The main advantage of this quasi-static testing technique using the complete structural system is the direct inclusion of realistic boundary conditions along the edges of the diaphragms. The ensemble of records for the tests will include pulse-loading, band-limited white noise and historic ground motions, including a near-fault record.

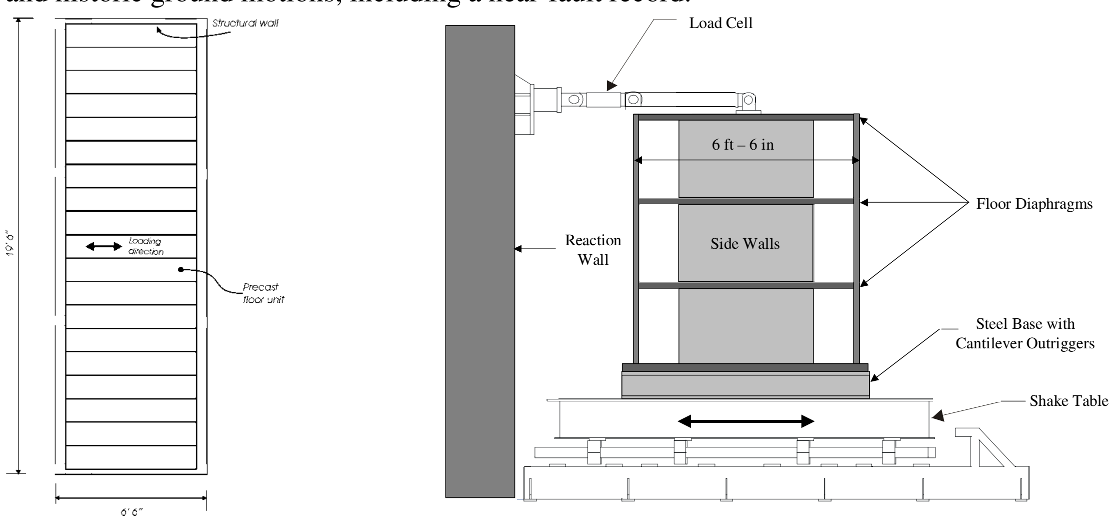

Figure 7: a. Diaphragm Plan View for UCSD System Test; b. Quasi-static Testing of 3rd Floor Diaphragm

Description of Precast Units/Joint Reinforcement Detail Experimental Program

A versatile load frame, the multi-component diaphragm (MCD) test fixture, is being constructed at LU. The MCD is capable not only of standard cyclic load patterns but also force combinations for portions of a joint at full-scale to reproduce load histories that more closely represent the actual demands on the reinforcing details in an earthquake. The MCD testing will be capable of investigating a variety of precast diaphragm joint reinforcement details at full-scale including connections between individual precast units, connections between precast units and intermediate supports, and connections between precast units and collectors such as shear walls (See Fig. 8). Thus, the versatile test system will allow examination of the large number of important design parameters under consideration by the precast industry (topped/untopped; hollow core/double tee; chord, collector, web reinforcement; anchorage, etc). These tests will enable direct evaluation of a detail's ability to transfer joint forces, provide adequate anchorage to the vertical elements of the lateral system, and sustain the diaphragm's structural integrity in extreme seismic events.

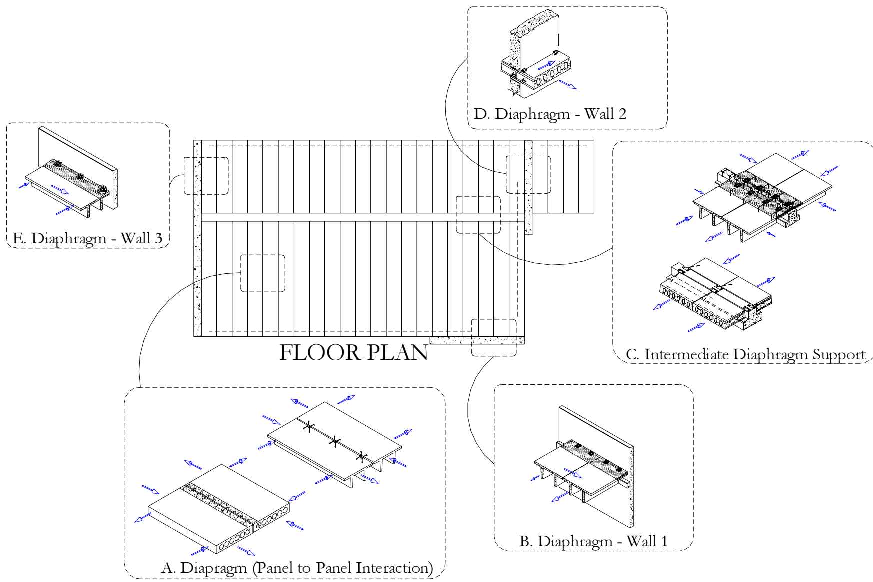

Figure 8: Examples of locations in precast diaphragms to be reproduced in the MCD testing

The majority of testing will focus on the performance of the connected precast units subjected to a combination of shear, axial load, and flexure across key portions of joints between precast units (Fig. 9a). While tests of full-scale panels with joints under simple boundary conditions do not capture all the conditions to which the diaphragm joints are subjected, a limited number of such "baseline" tests will be used to assist in interpreting the more complex load cases. The system will allow for future testing of conditions at walls or supporting beams (See Fig. 9b). Finally, entire panel joints will be tested for reduced-scale double tees units and full-scale hollow core units (See Fig. 9c). Test sub-components will measure approximately 20ft. x 20ft. in plan. The setup will be configured to accommodate both these types of units with and without topping slabs and apply cyclic loading at quasi-static displacement rates. Topped tests will be staged to capture the in-service state and gravity load.

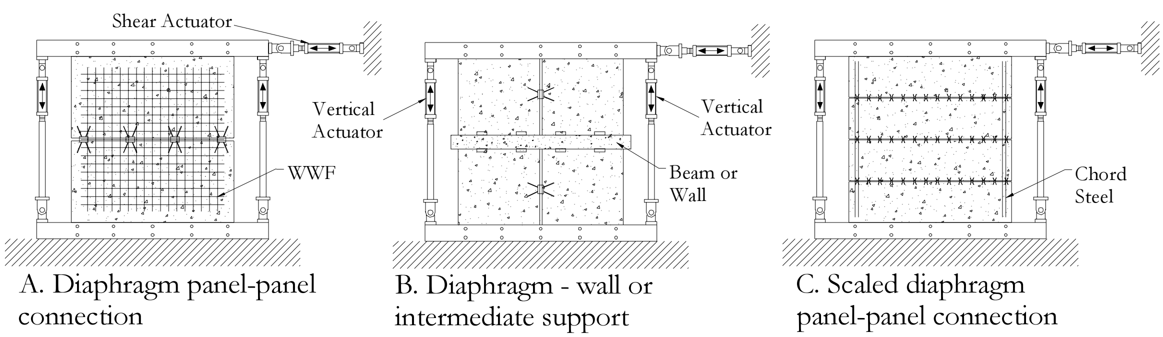

Figure 9: Plan views of MCD fixture showing test configurations A, B, C

The MCD fixture will first be used to evaluate elements or panels under simple demands such as pure shear or axial force (baseline tests). The purpose of these tests is to provide a performance baseline for the subsequent precast joint tests under more complex loading conditions. For example, one baseline study will be the examination of welded wire fabric shear friction capabilities under cyclic shear force as superimposed tension (or flexure) is increased.

Following the baseline experimental program, tests will be conducted using histories of varied levels of axial, shear, and moment determined in the analytical program to define the forces and displacements imposed by the three actuators of the MCD fixture. These tests will evaluate performance under more realistic load histories. Experimental evaluations of the design capacity for key regions of topped and untopped precast diaphragms will occur through testing the selected reinforcement details in portions of precast units and entire precast units at full-scale. Table 4 shows the testing program involving approximately 16 full-scale reduced length precast unit test specimens.

Table 3: Potential joint/unit test matrix

Test Description	Load History	Test Configuration	Double Tee** Untopped	Double Tee** Topped	Hollow Core** Untopped
Simple Panel-Panel Connection Tests					
High Shear Region	Monotonic	A	A1DU	-	A1HU
High Shear and Tension	Monotonic	A	A2DU	-	A2HU
High Shear Region	Cyclic	A	A3DU1 & A3DU2	A3DT	A3HU1 & A3HU2
High Shear and Tension	Cyclic	A	A4DU1 & A4DU2	A4DT	A4HU1 & A4HU2
Diaphragm Panel-Panel Connection Tests					
High Flexure Region	Cyclic	C	C1DU	C1DT	-
High shear and Flexure	Cyclic	C	C2DU	C2DT	C2HU
Multiple Connection Panel-Panel Tests					
High Shear, Tension, & Flexure Region 1	From Analysis	A	A5DU1 & A5DU2	A5DT	-
High Shear, Tension, & Flexure Region 2	From Analysis	A	A6DU1 & A6DU3	A6DT	-
High Shear, Tension, & Flexure Region 3	From Analysis	A	A7DU1 & A7DU4	A7DT	-

** D - Double tee, H - Hollow core, U - Untopped, T - Topped

RESEARCH PROGRESS

As of the writing of this paper (March 2004), the following research tasks have been completed:

- Code review: The initial research step was a formal review and evaluation of existing code pertaining to precast diaphragm seismic design, including a background document on recent modifications. During the first research meeting (RM1) attended by the university researchers and the DSDM Task Group (TG), consensus was achieved on a target design philosophy for developing the precast diaphragm design methodology.
- Database/Literature survey: A literature survey of previous research was completed including the creation of a database of industry/proprietary testing results. An industry survey was also completed via the internet to determine statistics of frequency and condition of use for certain details. During RM1, this industry survey was used to guide the selection of a feasible subset of reinforcement details for the analytical study, including existing and promising new details. Using the experimental database, a subset of details from the larger group was identified for the baseline experimental program.
- Testing Protocol: The research team set a testing protocol for property characterization that includes a uniform sequence of loading trajectories (tension/compression vs. shear), and amplitudes. As the team further develops performance targets and appropriate metrics, a second testing protocol will be developed for qualification.
- Baseline Test Design: Loading fixtures and test specimens are currently under design for the baseline tests on the selected individual reinforcing elements. These elements will be subjected to the recently developed loading protocol. These tests will occur at LU.
- Prototype Structure Portfolio: During RM1, the DSDM TG outlined a generic set of representative precast structural systems that should be included in the study. These descriptions pertained to the floor plan, number of stories, layout of vertical members of the lateral force resisting system, floor system type, etc., and depended on the use of the structure and other considerations. Subsequent to RM1, members of the DSDM TG and other PCI members were tasked to produce actual designs for these structures. Five such structural designs have been

produced including a three bay (central bay) parking garage, a two-bay (helical) parking garage, a distributed core L-wing office building, a central core perimeter wall office building, and a two-direction moment frame parking deck. Members of the DSDM TG are currently converting appropriate structures to alternate designs so as to cover the needed parameters of high vs. moderate seismic zones, topped vs. untopped floor systems, and double tee vs. hollow core floor units.

- Representative Designs/Construction Details: To facilitate the parametric studies, the DSDM TG is further providing seismic design information for the prototype structures. This document includes design forces and diaphragm detailing. The DSDM TG is also creating a summary document on typical construction techniques and detailing procedures for portions of the precast floor system that are not part of the diaphragm design per se, but nevertheless may impact the seismic response. Knowledge of these details will ensure all important behavior is being captured in the analytical models.
- Diaphragm Analyses: Diaphragm pushover analyses are being performed on detailed finite element models representing the prototype structure floor plans. The initial analyses are sensitivity studies: effects of detail characteristics, wall layout, etc. For now, the individual reinforcement detail characteristics are being estimated or based on previous tests. Models will be appropriately revised as the baseline test program progresses.
- Determination of seismic demands: Currently, ground motion selection (geographical regions/seismic zones, multiple hazard levels) is underway. Ultimately, earthquake simulations will be performed on models of the prototype structures.
- Shake Table Test Design: Quarter-scale models of the topped and untopped prototype diaphragms are currently under design for the shaking table tests baseline tests at UCSD.

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