Development of a seismic design methodology for precast concrete floor diaphragms

R.B. Fleischman  
Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, Arizona, USA

C.J. Naito  
Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, Pennsylvania, USA

J. Restrepo  
University of California San Diego, La Jolla, California, USA

ABSTRACT: A multi-university research project is being performed to develop a comprehensive seismic design methodology for precast concrete floor diaphragms in the United States. The effort, funded jointly by the Prestressed/Precast Concrete Institute, the National Science Foundation, and the Charles Pankow Foundation, involves an integrated analytical/experimental research approach and strong industry oversight. Full-scale experiments of isolated diaphragm details were used to build analytical models of diaphragms for use in nonlinear static (“pushover”) analyses and nonlinear transient dynamic analyses. New details have been developed and are being tested through hybrid (adaptive) experiments of precast panels integrated with computer dynamic analyses. Diaphragm force amplification factors, capacity design rules, and diaphragm detail classifications are being developed for the emerging seismic design methodology. A half-scale shake table test of a three-story diaphragm sensitive structure (one floor of untopped double tee, topped double tee and topped hollow core) will be performed to demonstrate the design methodology.

1 INTRODUCTION

This paper provides an overview of a large ongoing research project in the US on precast concrete floor diaphragms. The project is integrating analytical simulation and large-scale experimentation, together with strong industry oversight, to develop a new seismic design methodology for precast diaphragms. The research is performed among three universities, led by the University of Arizona (UA), and with experimental components at Lehigh University (LU) and University of California-San Diego (UCSD). This effort, coined the “DSDM” project, is jointly funded by the Prestressed/Precast Concrete Institute (PCI), the National Science Foundation (NSF), and the Charles Pankow Foundation (CPF).

1.1 Research approach

The DSDM project integrates analytical and experimental research to provide a comprehensive examination of precast concrete diaphragms (Fleischman et al. 2005b). Each university research (UR) component focuses on a different “level” of behavior that produces the diaphragm seismic response: local behavior of the diaphragm reinforcing details is examined at LU; component behavior of the diaphragm is examined at UA; and system behavior of the structure is examined at UCSD. The LU research activities involve large-scale experiments of reinforcing details and local modeling of the connection region; the UA activities include nonlinear static two-dimensional (2D) and dynamic three-dimensional (3D) finite element (FE) analyses; the UCSD activities include system studies (EQ simulations) and a half-scale shake table test.

Each UR component relies on information obtained by the other and has its own specific set of design deliverables. The effectiveness of the DSDM project depends on strong technical collaboration between the UR groups particularly between UA and LU across the joint/detail interface; and UCSD and UA across the structure/diaphragm interface. These interactions and the specific analytical and experimental activities taking place in the DSDM research program are described in this paper.

1.2 Design philosophy

The design approach for the proposed seismic design methodology is based on performance targets for the
diaphragm seismic response (Fleischman et al. 2005a). The selected performance targets are enforced through a combination of design factors and detailing requirements. It is noted that an early discussion of this approach appeared in *fib* (2003). The design methodology provides the designer with the flexibility of selecting from a number of options.

The basic design objective (BDO) targets elastic diaphragm behavior for the design basis earthquake (DBE). As such, a certain amount of inelastic diaphragm deformation is anticipated in a maximum considered earthquake (MCE). This target is selected based on research findings by Fleischman & Farrow (2001) that show that attempting to enforce elastic behavior in precast diaphragms for all seismic response situations can be impractical. Instead, the BDO involves the use of more realistic diaphragm design forces, higher for most cases than those currently used in U.S. practice, e.g. IBC (2003), in combination with detailing provisions that build a measure of inelastic deformation capacity into the diaphragm.

There are cases where the basic design objective is either impractical or unnecessary. In such cases, two alternatives are offered: (1) An elastic design option (EDO), which may provide the best design option for less demanding cases, such as squat diaphragm geometry or a low Seismic Design Category (SDC) (IBC 2003); and (2) A “relaxed” design option (RDO) in which a limited amount of inelastic diaphragm deformation is accepted in the DBE in order to lower diaphragm design forces. The latter option may be necessary for practical designs in demanding cases, such as long span untopped diaphragms for use in high SDCs.

Figure 1a shows a schematic of diaphragm response in terms of monotonic pushover curves (diaphragm force vs. diaphragm midspan deformation). The lower curve is the performance that might be expected of current diaphragm designs in high SDCs: the diaphragm force in a significant seismic event is expected to exceed current design forces (Rodriguez et al. 2002) and, in the absence of any detailing requirements, the diaphragm will likely undergo a non-ductile failure (shown by the lowest most X). The upper curve is the performance intended by the proposed BDO design approach. Shown on this upper curve are key points related to the design approach.

The design approach employs the following features to achieve its objectives: (1) An amplified diaphragm design force; (2) A higher relative strength for the diaphragm shear reinforcement and the connections to primary (vertical plane) lateral force resisting system (LFRS) elements than the diaphragm chord reinforcement; (3) A classification system for diaphragm reinforcement, and (4) Limits on the diaphragm contribution to interstory drift.

Figure 1. Design Approach: (a) Diaphragm Response Curve (BDO); (b) Diaphragm Force and Deformation Schematic.

As indicated in Figure 1a, the following terminology is used: (1) A diaphragm design force amplification factor $\Psi_D$; (2) A diaphragm shear overstrength factor $\Omega_v$ and an anchorage overstrength factor $\Omega_a$; (3) A diaphragm reinforcement/connector classification categories of LDE (low deformability elements), MDE (moderate deformability elements) and HDE (high deformability elements); and (4) A diaphragm drift limit, $\delta_x$.

The $\Psi_D$ factor is applied to the current code specified diaphragm design force (IBC 2003) to increase the diaphragm strength to the DBE force target. This approach requires some deformation capacity in the diaphragm reinforcement for the MCE event, which may be MDE or HDE depending on the parameters of the design. The $\Omega_v$ factor is applied to the diaphragm shear reinforcement to prevent a non-ductile shear failure from occurring while the diaphragm deforms in the MCE demand. This diaphragm deformation (Fig. 1b) needs to be kept within allowable drift limits (shown in Fig. 1a).

2 FULL SCALE TESTING OF PRECAST DIAPHRAGM DETAILS

The first phase of the LU UR component focused on full-scale experiments on isolated diaphragm reinforcing details under a set of loading protocols. These loading protocols included: (1) monotonic and cyclic
shear deformation, (2) axial deformation, (3) and combinations of shear and axial deformations. To achieve the force combination protocols, an innovative test fixture was developed at LU (See Fig. 2a). The fixture uses three displacement-controlled actuators to permit proportional or non-proportional combinations of shear and axial tension/compression.

The tests provide the stiffness, strength and ductility characteristics of the diaphragm reinforcing details under the load protocols. A “Phase I A” evaluated existing details while a “Phase IB” demonstrated the performance of improved details.

The Phase I A test data was used to extend the database on existing connections and examine the behavior of precast diaphragm connections under combined forces (Naito et al. 2006). Based on these results of Phase I A, certain modifications were proposed (Cao & Naito 2007). These modifications were optimized through analytical research examining the local connection region (See Fig. 2b). On the basis of these modifications, improved details were developed and tested (Naito et al. 2007). These details are to be “prequalified” based on classification ranges being established for qualification protocols as described in Hawkins (2008).

A key use of the Phase I test data was to build accurate diaphragm connection elements for insertion into analytical models of the diaphragm for the UA UR component. Figure 2c shows a comparison of a LU test and the analytical model developed at UA.

3 NONLINEAR PUSHOVER ANALYSES OF PRECAST DIAPHRAGMS

Detailed FE models of the diaphragm were built for the UA analytical component. These models incorporated connector element data such as shown in Figure 2c. The diaphragm models were used to perform a comprehensive parameter study of precast floor diaphragms using nonlinear static “pushover” analyses of simplified representations of individual diaphragms (Fleischman & Wan 2007). The objective of the study was to determine appropriate shear overstrength factors to protect the diaphragm shear reinforcement, consistent with capacity design principles, e.g. Standards New Zealand (1997).

Figure 3a shows a schematic of the 2D diaphragm model used for nonlinear pushover analyses. The parameters that were varied for the study included: (1) diaphragm span and aspect ratio (AR); (2) seismic design category (SDC); and (3) diaphragm detail classification (LDE, MDE, HDE).

Figure 3b shows diaphragm pushover curves for a single set of diaphragm design parameters (AR = 3, L = 54.86 m, SDC D) with increasing diaphragm shear reinforcement relative strength $\Omega_s$. As seen, the greater the $\Omega_s$ value, the more is the deformation capacity achieved by the diaphragm. A $\Omega_s$ of 2.15 is needed to develop the full diaphragm flexural strength. However, using less shear reinforcement ($\Omega_s$ of 1.76 and 1.37), while not preventing shear failure, delays the failure sufficiently to allow some increased inelastic deformation in the diaphragm. Note that, as indicated in the inserts in Figure 3b, a chord failure occurs at midspan, while a shear failure occurs at the first panel-to-panel joint (assuming that $\Omega_s > \Omega_v$). This performance
can be characterized as an overall ductility of the diaphragm, \( \mu \).

The required relative strength of the shear reinforcement (and diaphragm to LFRS anchorage reinforcement) to the chord reinforcement was found to depend on several factors including diaphragm dimensions and configurations, and diaphragm detailing. Accordingly, design charts have been constructed using the results of the studies (Fleischman & Wan 2007). These charts establish, for a given diaphragm geometry, the \( \Omega_v \) values required to achieve specific design targets (diaphragm yield strength, \( M_y \); diaphragm ultimate strength, \( M_u \); diaphragm ductility ratio, \( \mu \); and inter-story drift, \( \phi \)). Likewise, by examining the internal state of the diaphragm model at key states, the required deformation capacity of the diaphragm reinforcement, \( \delta_{\text{t,max}} \), needed to achieve a given design target was established.

A smaller number of 3D-FE nonlinear dynamic transient analyses (NLDTA) of prototype structures are being used to calibrate or verify the findings from this stage, as discussed next.

4 THREE DIMENSIONAL ANALYSES OF PRECAST STRUCTURES

The analytical results obtained from examination of capacity (nonlinear pushover of individual diaphragms) are referenced to expected demands through nonlinear dynamic FE analyses of precast structures. Figure 4 shows such an 3D-FE model of a prototype parking structure used in NLDTA. This structure is also used to perform an adaptive (hybrid) test of a precast diaphragm joint (See section 5).

A key use of the NLDTA has been to predict the response of the shake table test (See section 6). A half-symmetry model incorporating a 2D floor model was used to develop a viable design for the shake table test specimen (See Fig. 5a). Once obtained, the verification was performed with a 3D model that includes

![Figure 3. Diaphragm shear overstrength study: (a) Schematic of 2D FE model; (b) Pushover results showing effect of \( \Omega_v \).](image3)

![Figure 4. 3D FE Model: prototype parking structure.](image4)

![Figure 5. Shake table test specimen: a) 2D floor half-symmetry model; b) 3D floor half-symmetry model.](image5)
Figure 6. Diaphragm reinforcement MCE response (3rd floor) for shake table prediction: a) Chord; b) Shear Connector.

Figure 7. Double tee unseating: a) LB-DT deformed shape (close-up); b) DT-SP unseating deformation (3rd floor).

representation of the columns, spandrels, PT walls, the three-dimensional profile of the floor system, gravity load, and uplift (See Fig. 5b).

Figure 6 shows key analytical results: Figure 6a shows the expected tension force versus joint opening for the half-scale dry chord detail (in this case, six #3 bars) at the critical flexural joint on the pretopped floor (midspan, 3rd floor). Figure 6b shows the expected shear force versus joint sliding for the half scale (JVI Vector) connector at the critical shear joint on the pretopped floor (endspan, 3rd floor). These results are shown for the response under the largest planned shake table motion, equivalent to a Berkeley CA (SDC E) maximum considered earthquake (MCE). The inherent damping is conservatively taken at 1% of critical. It can be seen that the 2D floor model (used to design the shake table specimen) is conservative in its prediction with respect to the 3D floor representation. The reduced 3D model demand is due to supplemental strengthening of the structure from columns and spandrels not captured in the 2D model. However, on the basis of the results of the LU adaptive tests (See section 5) on joints identical to those in the shake table specimen, even the largest demands shown in Figure 6 for the more conservative 2D model, 7 mm opening and 3 mm sliding (at half scale), are attainable by the improved diaphragm details in the specimen.

The 3D floor model has been used to examine the compatible displacements requirements of “secondary” elements in the structure, including, for instance, the required seating for the ledges on which the DT sits (See Fig 7a), measured at 13 mm (See Fig 7b), which is within the allowable seating provided by the spandrel ledges.

5 HYBRID TESTING OF PRECAST DIAPHRAGM JOINTS

In the Lehigh UR Phase II, groups of reinforcing details designed according to the emerging design methodology are tested under likely seismic demands. These tests involved adaptive (hybrid) testing techniques in which the actuator control systems interact with nonlinear dynamic analyses.
The adaptive tests were performed in late 2007. An overhead view of the test setup during the welding of the panels is shown in Figure 8. Visible in the picture is the fixed steel fixture beam (bottom) and the movable steel fixture beam (top). Two of the three actuators are visible (the shear actuator clevis is visible in the top left and one of the two tension/compression actuators is fully visible). Also shown is the LU laboratory technician welding one of the flange-to-flange connectors.

Three tests were performed: Two predetermined displacement histories (PDH) of a critical flexure joint (identical to the shake table specimen critical flexural joint but driven by an analysis of a 3 story parking structure with the same detail) were performed and the adaptive (hybrid) test of the critical shear joint from the shake table specimen (using the analysis of the shake table specimen under a MCE table motion). The tests were successful: Figure 9a shows a comparison of the predicted vs. test response for the critical flexure joint (Charleston MCE) showing excellent agreement. Figure 9b shows the similar excellent agreement of the predicted vs. test response for the adaptive test of the critical shear joint.

6 HALF SCALE SHAKE TABLE TEST OF PRECAST STRUCTURES

Figure 10 shows a schematic of the half-scale shake table planned for 2008. The structure has been designed according to the emerging design methodology and detailed at half scale. Industry partners have been involved in the project management aspects including sourcing producing and erecting the half-scale specimen. Over 400 instruments are planned to measure the data produced in the experiment. Analyses have been used to estimate global floor force demands under the planned ground motions as discussed in Section 4.

ACKNOWLEDGEMENTS

The authors thank PCI, CPF, NSF and several PCI industry members for their support. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.
REFERENCES


