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Diaphragm seismic design

Jared Brewe

Aligned with the theme of this issue of *PCI Journal* on "Design," one PCI cosponsored research project that has influenced design beyond the precast concrete industry is the DSDM (Diaphragm Seismic Design Methodology) project. This Research Corner summarizes the work of the DSDM project and looks toward how design will continue to evolve from this work.

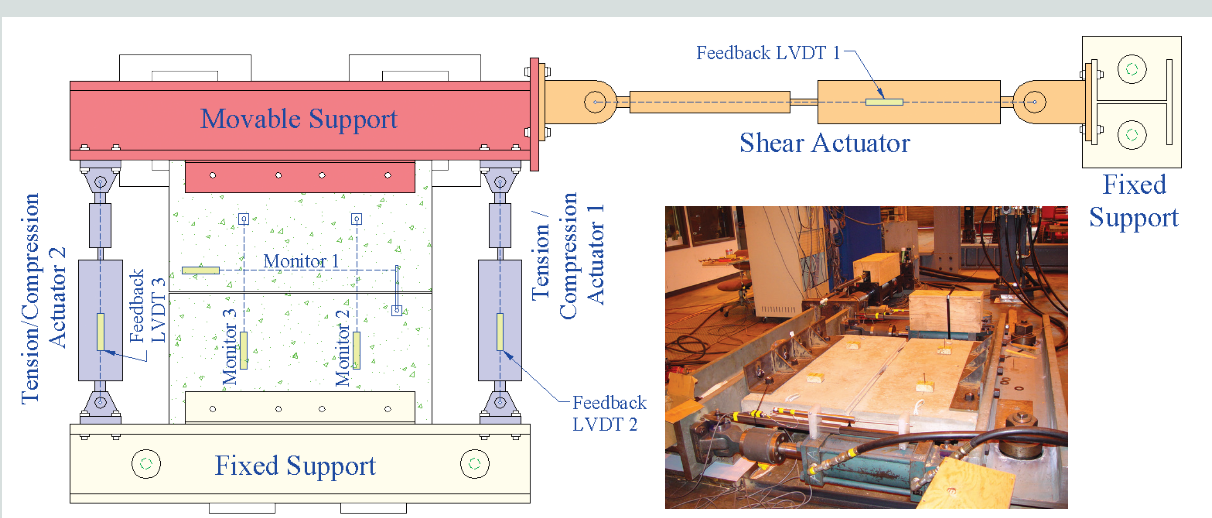
The DSDM project, completed by a consortium of researchers from the University of Arizona, Lehigh University, and the University of California San Diego, was conducted to better understand the behavior of precast concrete diaphragms subjected to earthquake forces. The project was established in 2002 based on the unexpected performance of precast concrete diaphragms in recent earthquakes and research that underscored the need to develop and demonstrate a reliable seismic design methodology for precast concrete diaphragms.[1,2] The project commenced in 2004 and was jointly sponsored by PCI, The Charles Pankow Foundation, the National Science Foundation, and the George E. Brown Network for Earthquake Engineering Simulation. The primary objectives of the DSDM project[3] included developing the following:

- The forces to which precast concrete diaphragms are to be designed.
- The deformations to which precast concrete diaphragms are to be designed.
- The precast concrete diaphragm reinforcing details that can provide this behavior.

Aspects of the research included subassembly tests of diaphragm connectors to establish connector performance;[4,5] a three-story, half-scale precast concrete structure subjected to 16 significant-input ground motions;[6] and detailed finite-element modeling using Ansys.[3]

The overall key outcomes of the research[3] included the following:

- the diaphragm design force levels required to keep diaphragms elastic in the design earthquake
- the relationship between precast concrete diaphragm strength and anticipated diaphragm reinforcement deformation demands at the joints between precast con-



Double-tee diaphragm connectors subassembly test setup.
Source: Naito et al. (2009).

crete components for different diaphragm geometries and seismic hazard levels
- the required increase in diaphragm shear strength with respect to diaphragm flexure strength to prevent undesirable high inelastic shear deformations in precast concrete diaphragms
- the key characteristics of several typical precast concrete diaphragm reinforcements under cyclic tension and shear, including stiffness, strength and reliable deformation capacity
- new precast concrete diaphragm reinforcement concepts that provide improved cyclic performance

Following research completion in 2014, the industry made a concerted effort to incorporate the research findings into codes and standards for design. The first effort involved significant changes to the overall design of diaphragms, achieved through a new section 12.10.3 of ASCE 7-16.[7] The diaphragm design methodology of sections 12.10.1 and 12.10.2 of ASCE 7-16, originating in 1979, has generally resulted in adequate diaphragm performance in past earthquakes. However, past earthquake observations and research, including the DSDM project, have indicated that the diaphragm design forces from sections 12.10.1 and 12.10.2 underestimate the actual diaphragm forces prior to developing the inelastic response of vertical elements of the seismic-force-resisting system, particularly over the height of the structure where higher mode effects results in increased diaphragm inertial forces. The new section 12.10.3 recognizes these effects and considers diaphragm overstrength and deformation ductility to establish new diaphragm design forces. Section 12.10.3 is required for precast concrete diaphragms in structures assigned to seismic design categories C, D, E, or F and is permitted for precast concrete diaphragms in category B, cast-in-place concrete diaphragms, including noncomposite topping slab diaphragms, and in wood diaphragms supported on wood light-framed construction.

Along with the new design forces in ASCE 7-16, two new standards were developed to provide material-specific requirements for precast concrete diaphragms: ACI 550.5-18[8] provides the design requirements regarding seismic demand level, the selection of the diaphragm design option, and the diaphragm connections and reinforcement at joints; ACI 550.4-18[9] supplements ACI 550.5-18 to provide requirements to qualify diaphragm connections and reinforcement at joints through subassembly testing. The content of each of these standards, taken collectively, represents the body of work that resulted from the DSDM research project.

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Note: Affiliations are current for time of project completion.	

Three-story, half-scale precast concrete structure on the shake table.
Source: Schoettler et al. (2009).

Looking forward, ASCE 7-22[10] has retained sections 12.10.1 and 12.10.2 but has broadened the permitted use of 12.10.3 to include bare steel deck diaphragms and concrete-filled steel deck diaphragms. As each new material or system is introduced into 12.10.3, new diaphragm design force reduction factors R_s are established based on the intended yielding mechanism of the diaphragm and the diaphragm overstrength and deformation ductility. These parameters are developed through the NEHRP recommendations update,[11] which informs the subsequent ASCE 7 process. As work begins on the next NEHRP recommendations, anticipated in 2025, interest continues to coalesce around section 12.10.3 becoming the primary diaphragm design method. Accordingly, research continues to refine and improve the design requirements for precast concrete diaphragms, including the diaphragm design force reduction factors in ASCE 7 and the shear overstrength factor in ACI 550.5.

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We urge readers to send in their research ideas to Jared Brewe, PCI's vice president of Technical Services, at jbrewe@pci.org.