Diaphragms for seismic loading — Part 2

A philosophy for analysis and design

By Rafael Sabelli, P.E., S.E, Warren Pottebaum, S.E., and Brian Dean, LEED AP

As all structural engineers familiar with building design know, diaphragms constitute an integral part of the lateral-load resisting system. When the load under consideration is seismic, the diaphragms themselves often constitute a majority of the inertial mass, as well as the means of delivering inertial forces to the vertical elements of the seismic-load resisting system (SLRS).

This article is the second in a two-part series; the first article — which discussed diaphragm forces, classification, and analysis in detail — was printed in the January 2009 issue of Structural Engineer. This article will focus on diaphragm design.

Load combinations

The mechanics of diaphragms involves both ductile and nonductile limit states. In general, shear yielding of the diaphragm is considered to be more ductile, while failure of a collector or one of its connections is considered less so. In higher seismic design categories (SDC C and above) ASCE 7-05 requires that different approaches be taken for these two classes of element performance: ductile modes are designed to resist forces from the basic load combinations of Section 12.4.2.3, while nonductile modes are designed using forces from the special seismic load combinations of Section 12.4.3.2. (This is a force corresponding to LRFD design; if a designer chooses to use ASD, a 20-percent increase in allowable strength is permitted by Section 12.4.3.3.)

By way of clarification, it should be noted that Section 12.4.3.1 (which applies to the special seismic load combinations that include the overstrength factor, Ω_o) defines Q_E, the seismic load effect, as the result of either the ELF design base shear from Section 12.8.1 or the component force from section 13.3.1. The omission of both the MRS base shear and the diaphragm force is an oversight that should be corrected in the next edition of ASCE 7 (a code-change proposal is in process with the seismic subcommittee).

Table 1: Recommended load combinations for diaphragm components

Component	Basic seismic load combinations (Section 12.4.2.3)	Special seismic load combinations (Section 12.4.3.2)
All components of wood diaphragms braced by light-frame shear walls	•	
All components of diaphragms in SDC A and B	•	
Components of diaphragms not conforming to either of the above:		
Collector (and its connections)		•
Collector connection to diaphragm		
Nailing of wood diaphragm	•	
Reinforcement in cast-in-place concrete diaphragm	•	
Attachments of precast diaphragms		•
Shear studs in composite diaphragm[1]		•
Screws in metal deck diaphragm	•	
Welds in metal deck diaphragm		•
Diaphragm shear	•	
Chord (and its connections)		•

[1] Does not require the 25-percent reduction in capacity per AISC 341 Part II (composite).

For structures in SDC C and above, Section 12.10.2.1 requires that collectors and their connections be designed for the special seismic load combinations of 12.4.3.2, which amplify the design force by the system-specific overstrength factor Ω_o, thus ensuring the performance of the structure is not limited by the nonductile failure of these elements. The requirement to use the special seismic load combinations is intended to approximate the maximum forces that are likely to be generated as the vertical elements of the SLRS surpass their design strength, yield, strain harden, and redistribute forces. The diaphragm delivering this force in shear is designed for the basic load combination, however. In theory, the maximum force that can be delivered to the collector is limited by the capacity of the diaphragm. However, determination of the diaphragm capacity, including multiple sources of overstrength and possible strain hardening, is daunting and often does not result in significantly reduced forces.

Where does the collector (the nonductile element) end, and where does the more ductile shear-yielding diaphragm start? This depends on the system. Wood diaphragms in light-frame shearwall buildings are exempted from the overstrength requirement because such systems are intended to provide more widespread yielding, and collectors in these structures typically yield in a more ductile manner. In cast-in-place concrete buildings the shear connection of the diaphragm to the vertical elements is often of identical composition to that of the diaphragm itself. In steel buildings, the connection to the diaphragm can be significantly less ductile than the diaphragm; shear studs in a composite deck, for example, should be designed for the special seismic load combinations because of their reduced ductility under cyclic loads. Tremblay (2004) has found some ductility in metal deck diaphragms, especially those with mechanical fasteners.

The action of chords is similar to that of collectors. In some cases, redundant chords exist away from the diaphragm boundary. However, chords typically do not exhibit high levels of ductility. While ASCE 7 does not require chords to be designed for the special seismic load combinations, it is recommended to do so here unless the necessary chord ductility is provided.

Table 1 summarizes the components or mechanisms and the recommended load combination to be used for their design. In some cases, the recommendation exceeds the code minimum.

Collectors within braced frames

A common question is whether beams within braced frames are considered collector beams and are thus required to be designed for the special seismic load combinations of Section 12.4.3.2. The answer is yes (generally). Braced frames designed for ductility ($R > 3$; OCBF, SCBF, and BRBF) anticipate the brace being the fuse of the system. Connections are designed to remain essentially elastic ($\varphi R_n \geq R_u$) for amplified forces. Design of the beam for those systems is typically consistent with the connection design, and both the collector forces and the forces from levels above should be amplified. For braced frames designed with $R = 3$ in SDC C, amplified forces are required only for the collector forces. In lower SDCs, amplified forces are not required at all.

Conclusion

Building codes have paid careful attention to diaphragm design, however, this area remains rife with ambiguity and differing opinions. While this two-part article will not put an end to such debate, it will serve as one example of a coherent philosophy of diaphragm design for seismic loading.

Acknowledgements

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Rafael Sabelli, P.E., S.E., is director of seismic design at Walter P Moore. He can be reached at 415-963-6300 or via e-mail at rsabelli@walterpmoore.com. Warren Potterbaum, S.E., is an associate at DASSE Design. He can be reached at 510-433-9370 or via e-mail at pottebaum@dasse.com. Brian Dean, LEED AP, is a graduate engineer at Walter P Moore and can be reached at 415-963-6300 or via e-mail at bdean@walterpmoore.com.