Briefing Paper 4

Seismic Response of Concrete & Masonry Buildings

Part B: The Role of Diaphragms

Introduction

Briefing Paper 4, *Seismic Response of Concrete and Masonry Buildings*, consists of four parts. Part A provides a brief overview of how earthquakes affect reinforced concrete and masonry buildings. This Part B describes the detailed response of a floor (or roof) diaphragm to the horizontal forces generated within it, and how the forces are transmitted horizontally to the building walls and frames. Part C describes the vertical load path carrying the horizontal loads down the building walls and frames, through the foundations and into the ground. Part D explains that as well as providing the load paths, some specific components must have the ductility necessary to handle the large distortions from major earthquakes.

Diaphragm Response

Floor and roof diaphragms span between shear walls of concrete or masonry, or frames of concrete or steel. When subjected to lateral seismic loads, diaphragms effectively respond like beams responding to vertical floor loads. The schematic provided in Figure 1 illustrates the two fundamental types of forces produced at the diaphragm edges (shear, and tension or compression). Seismic loads pushing against the long side of the diaphragm (Figure 1) produce shear forces (parallel to the seismic forces) at each end of the diaphragm (in the short direction) and are transferred to collector beams and shear walls (or to vertical frames) at those locations. On the side of the diaphragm opposite the seismic forces, tension develops in the chord, and on the side on which the forces are acting, compression develops. Reverse situations apply on reversal of the seismic load. When loading is applied in the direction parallel to the long axis of the diaphragm, the forces act similarly. Just how these forces are resisted within the diaphragm itself depends on its construction.

Engineers classify diaphragms into two groups for design purposes. Floors and roofs con-

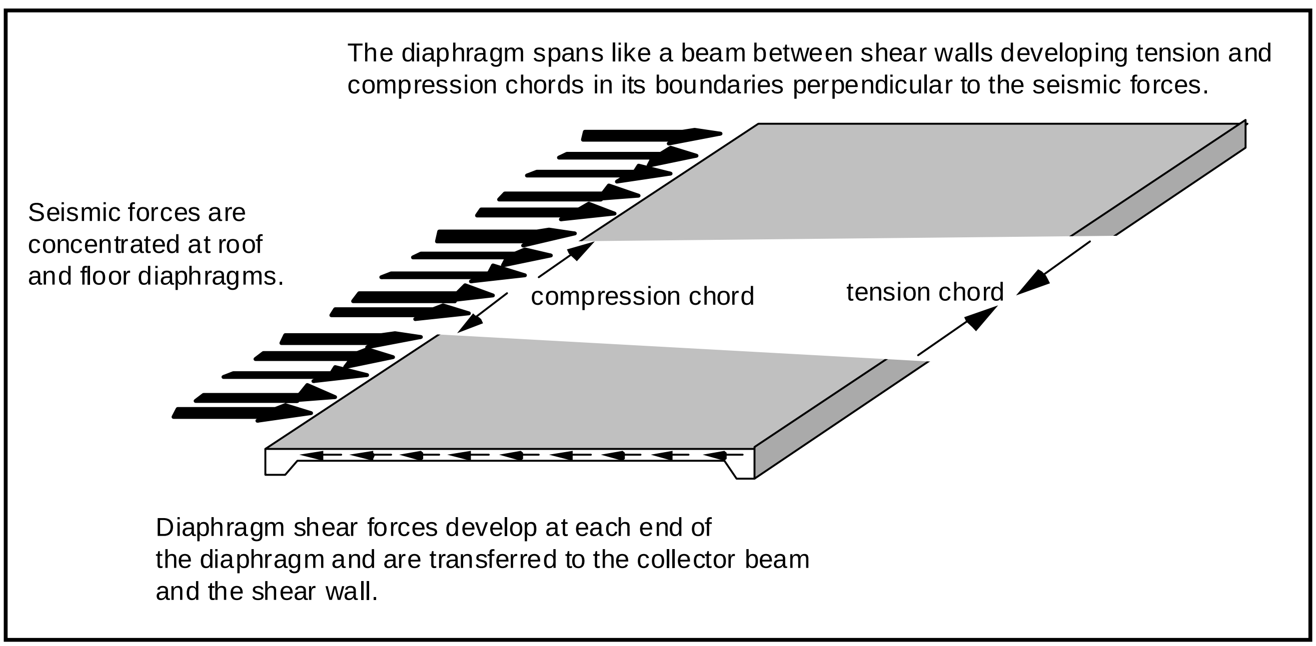

Figure 1. Diaphragm seismic loads and resulting forces

structed of reinforced concrete or concrete fill on metal deck are designated as rigid diaphragms (that is, rigid in their own plane). The concrete of the diaphragm is effective in resisting shear, as long as it is tied together with reinforcement (rebar). This is usually rebar laid out in both directions at a uniform spacing. Welded wire fabric is an alternative. Most rigid diaphragms have beams at their four edges. Concrete beams are already reinforced with longitudinal rebar. Often this reinforcement is sufficient to resist chord forces. In some cases, however, additional steel must be added. In retrofit construction, inadequate chord reinforcing may require the addition of steel plates to concrete beams. When the vertical seismic elements are steel frames, chord forces are typically resisted by the steel beams at the diaphragm edges.

Floors and roofs of wood construction are flexible diaphragms. Shear forces within the diaphragm are resisted by the sheathing, which might consist of decking or flat boards in older buildings, or plywood in newer construction. The shear capacity is controlled by the nailing of the sheathing to the supporting wood framing. In retrofit construction, additional nailing is sometimes required to increase the capacity. In other cases, plywood is installed to replace or reinforce the existing sheathing. Chord forces are usually resisted by wood or steel beams at the edges of the diaphragm. Sheet metal straps between wooden chord members may be required to resist tension forces.

Forces similar to chord forces also can develop around openings (e.g., stairwells or duct work) in both rigid and flexible diaphragms. This is why the edges of these openings often are reinforced with additional longitudinal reinforcing steel in concrete diaphragms, or steel members or straps in wood construction.

Transfer of Diaphragm Forces

Forces in diaphragms must be transferred to the surrounding walls or frame elements. These forces include diaphragm shear forces acting in the plane of the wall or frame.

Several mechanisms are used to accomplish this shear transfer from concrete diaphragms. One is known as shear-friction. This concept is based on the assumption that the diaphragm cannot slide with respect to the wall or beam component without yielding of the reinforcing steel that crosses the separation between the two. The shear capacity of the connection between the diaphragm and the wall or frame component is a function of the amount of steel crossing the construction joint and the roughness of the surface between the two. Another mechanism for transferring shear forces is called dowel action. This assumes that all the shear forces are transferred from the diaphragm into the wall or beam through the reinforcement acting in shear like an anchor bolt. Forces can be large enough to require that the construction joint itself have built-in bumps or deformations to provide dowel action.

In flexible diaphragms, shear forces are usually transferred by nailing from the sheathing to a wood beam called a ledger that is bolted to the wall or frame.

Out-of-Plane Forces

The connections between diaphragms and their supports also transmit earthquake forces that tend to push and pull these supports away from the diaphragms. These out-of-plane forces act perpendicularly to the plane of the wall or frame, causing direct tension and compression across the connection to the diaphragm.

Out-of-plane forces are not usually a problem for rigid diaphragms, but they have caused serious problems in past earthquakes for flexible diaphragms. For example, wood ledgers connecting roof diaphragms to exterior walls have repeatedly failed in past earthquakes. This behavior has resulted in the collapse of tilt-up buildings, as illustrated in Figure 2. One solution is to install blocking with straps to prevent side-grain bending of the ledger. This can be done for both new and existing construction. Whatever the mechanism, it is important in the field to pay close attention to the joint between diaphragms and wall or frame components. No matter how strong or stiff the diaphragm and its supporting components are, the lateral-force-resisting seismic elements will not have a chance to act if the connection between the two fails.

Figure 2. Failure of connection of wood diaphragm to concrete wall in Northridge earthquake

Collectors or Struts

Shear forces in diaphragms are sometimes not transferred directly into a shear wall or lateral-load-resisting frame. For example, a supporting shear wall might not be as long horizontally as the edge of the diaphragm. The edge of the diaphragm that extends beyond the wall will be supported only by a beam. The shear force in the diaphragm is transmitted to the beam which "collects" the forces and transfers them to the wall. A beam that functions in this way is called a collector or a strut. For concrete diaphragms, additional reinforcing might be added to collectors, particularly where they frame into the wall. For flexible wood diaphragms, wood or steel beams are often added to serve as collectors in both new and retrofit construction.

Resources for Additional Reading

ABK Joint Venture, 1984, *Methodology for Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings*, Topical Report 08, Agbabian Associates, El Segundo, California.

ATC, 1997, *Seismic Evaluation and Retrofit of Concrete Buildings*, funded by the California Seismic Safety Commission, Applied Technology Council, Report ATC-40, Redwood City, California, 1997.

Bolt, B.A., 1997, *Earthquakes: A Primer,* W.H. Freeman and Company, San Francisco.

Hart, G.C., Priestley, M.J.N., and Seible, F., 1992, "Masonry Wall Frame Design and Performance," *The Structural Design of Tall Buildings*, John Wiley and Sons, Inc., New York, New York.

Paulay, T., and Priestley, M.J.N., 1992, *Seismic Design of Concrete and Masonry Buildings*, John Wiley and Sons, Inc., New York, New York.

About this Briefing Paper Series

Briefing papers in this series are concise, easy-to-read summary overviews of important issues and topics that facilitate the improvement of earthquake-resistant building design and construction quality.

This briefing paper was prepared by the ATC/SEAOC Joint Venture, a partnership of the Applied Technology Council (ATC) and the Structural Engineers Association of California (SEAOC). Funding for the series was provided by the California Seismic Safety Commission, Proposition 122 Retrofit Practices Improvement Program.

Copies of Briefing Papers can be downloaded from ATC's World Wide Web site (www.atcouncil.org), or are available from:

ATC/SEAOC Joint Venture
c/o Applied Technology Council
555 Twin Dolphin Drive, Suite 550
Redwood City, California 94065