Briefing Paper 1

Building Safety and Earthquakes

Part D: The Seismic Load Path

Introduction

This Briefing Paper 1, *Building Safety and Earthquakes*, consists of four parts describing earthquakes and their effects on buildings. Parts A and B describe the causes of earthquakes and resulting ground motions and explain how earthquake motions create various forces acting on a building. Part C describes typical structural systems and lateral-force-resisting elements used in buildings. This Part D defines the seismic load path elements, describes their functions and the necessary interconnections between them to resist earthquake forces. Also included in this part of Briefing Paper 1 are resources for additional reading on building safety and earthquakes.

Primary Load-Path Elements

Within every building, there are multiple elements that are used to transmit and resist lateral forces. These transmitting and resisting elements define the building's lateral-load path. This path extends from the uppermost roof or parapet, through each element and connection, to the foundation. Load-path elements vary in scale from massive multi-story moment-resisting frames to individual nails connecting wood members. An appreciation of the critical importance of a complete load path is essential for everyone involved in the design, construction, and inspection of buildings that must resist earthquakes.

There are two orientations of primary elements in the load path: those that are vertical, such as shear walls, braced frames, and moment frames, and those that are essentially horizontal, such as the roof, floors, and foundation. The roof and floor elements are known as diaphragms. Diaphragms serve primarily as force-transmitting or force-distributing elements that take horizontal forces from the stories at and above their level and deliver them to walls or frames in the story immediately below. Diaphragms are classified as either flexible or rigid, and the method of distributing earthquake forces from the diaphragm to the resisting elements depends on that classification. Wood-framed diaphragms can be considered either flexible or rigid and concrete diaphragms are considered rigid.

Shear walls and frames are primarily lateral-force-resisting elements but can also perform force-transmitting functions. For example and while not necessarily desirable, an upper-story interior shear wall may not continue to the base of the building and therefore must transmit its forces to a floor diaphragm. Also, at the base of a frame or a shear wall, forces are transmitted into a foundation element. The primary structural elements that participate in the earthquake load path are shown in Figure 1.

Foundations form the final link in the load path by collecting the base shear and transmitting it to the ground. Foundations resist lateral forces through a combination of frictional resistance along their lower surface and lateral bearing against the depth of soil in which they are embedded. Foundations must also support additional vertical loads caused by the overturning forces from shear walls and frame columns.

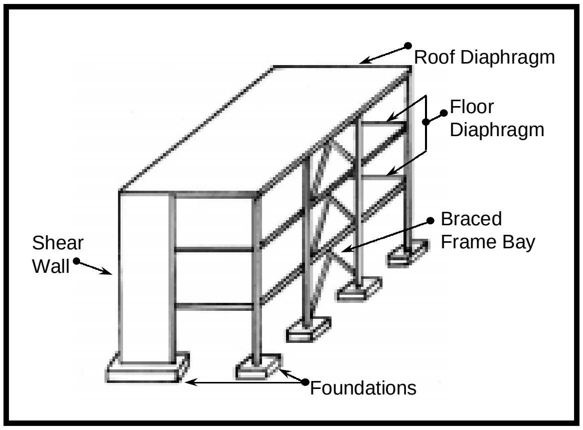

Figure 1. Primary structural load path elements.

Secondary Load-Path Elements

Within the primary load-path elements, there are individual secondary elements needed to resist specific forces or to provide specific pathways along which lateral forces are transmitted. Particular attention must be given to transmitting forces between horizontal seismic elements (diaphragms) and vertical seismic elements. Two important secondary elements are chords and collectors. A chord is a structural member along the boundary of a diaphragm that resists tension and compression forces. A collector is a structural member that transmits diaphragm forces into shear walls or frames. Figure 2 depicts the overall function of chords and collectors.

In the case of floors and roofs, the perimeter edges or boundaries are critical locations because they form the interface between the diaphragms and the perimeter walls. The perimeter is typically the location for vertical seismic elements, although many buildings also have shear walls or frames at interior locations. An interior line of resistance also creates a diaphragm boundary. Boundary elements in diaphragms usually serve as both chords and collectors, depending on the axis along which lateral loads are considered to be applied.

As shown in Figure 2, the forces acting perpendicular to the boundary elements tend to bend the diaphragm, and the chord member must resist the associated tension and compression. Similar to a uniformly loaded beam, a diaphragm experiences the greatest bending stress and largest deflection at or near the center of its span between vertical resisting seismic elements. The chord on the side of the diaphragm along which the forces are being applied is in compression, and the chord on the opposite side is in tension. These tension and compression forces reverse when the earthquake forces reverse. Therefore, each chord must be designed for both tension and compression.

Walls that structurally support diaphragm edges must also resist out-of-plane forces caused by diaphragm bending. In wood-frame walls, the double top plates usually act as chords for the diaphragm at that level. In concrete and masonry walls, reinforcing steel is placed at the diaphragm level to resist the out-of-plane bending in the wall.

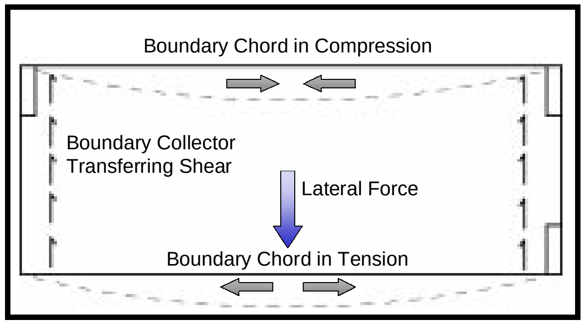

Figure 2. Function of diaphragm chords and collectors.

Collectors are needed when an individual shear wall or frame in the story immediately below the diaphragm is not continuous along the diaphragm boundary (See Figure 3). This is a very common situation because shear walls are often interrupted by openings for windows and doors, and because resisting frames are normally located in only a few of the frame bays along a diaphragm boundary. A path must be provided to collect the lateral forces from portions of a diaphragm located between vertical resisting seismic elements and to deliver those forces to each individual shear wall or frame. The collector member provides that path. Collectors are commonly called drag struts or ties. Collectors are also needed when an interior shear wall or frame is provided (see Figure 3). In this case, the collector is placed in the diaphragm, aligned with the wall or frame, and extends to the diaphragm edges beyond each end of the wall or frame. Collectors can occur in wood-framed walls using headers and top plates to transfer the forces and can occur in spandrel beams, of concrete or masonry construction, that link sections of shear walls together.

Connections

The following statements contained in the 1997 UBC clearly require that a complete load path be provided throughout a building to resist lateral forces.

> "All parts of a structure shall be interconnected and connections shall be capable of transmitting the seismic force induced by the parts being connected."

> "Any system or method of construction shall be based on a rational analysis... Such

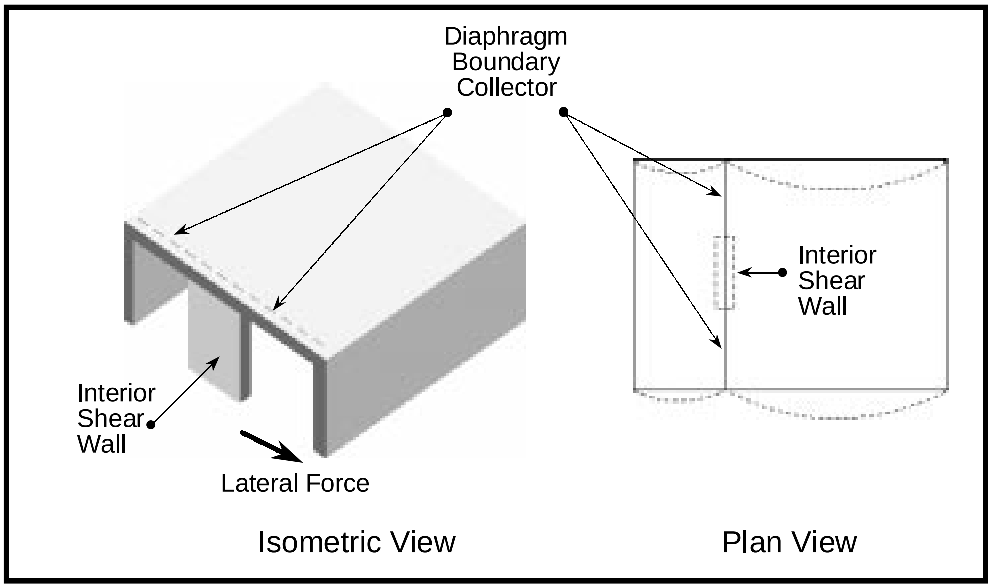

Figure 3. Use of collector element at interior shear wall.

analysis shall result in a system that provides a complete load path capable of transferring all loads and forces from their point of origin to the load-resisting elements."

To fulfill these requirements, connections must be provided between every element in the load path. When a building is shaken by an earthquake, every connection in the lateral-force load path is tested. If one or more connections fail because they were not properly designed or constructed, those remaining in parallel paths receive additional force, which may cause them to become overstressed and to fail. If this progression of individual connection failures continues, it can result in the failure of a complete resisting seismic element and, potentially, the entire lateral-force-resisting system. Consequently, connections are essential for providing adequate resistance to earthquakes and must be given special attention by both designers and inspectors.

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Connections are details of construction that perform the work of force transfer between the individual primary and secondary structural elements discussed above. They include a vast array of materials, products, and methods of construction. For example, forces are resisted in wood-framed diaphragms by the action of nails or other fasteners used to attach structural sheathing to the joists, trusses, beams, ledgers, and blocking that make up the diaphragm framing. Nails, bolts, and prefabricated metal connectors are used for diaphragm chord and collector splices of wood members. In steel construction, metal deck diaphragms use welds to resist diaphragm forces and chord and collector beams are connected by bolts, welds, or a combination of both. In concrete construction, diaphragm reinforcing steel resists forces in the diaphragm and chord tension stresses, and reinforcing dowels are generally used to transfer forces from the diaphragm boundaries to concrete walls or frames.

Connection capacity is determined by performing a detailed analysis of the individual forces the connection must transfer. The capacity actually provided, however, is highly dependent on the implementation of the specific details of its construction. Therefore, two specimens of the same connection can have significantly different capacities, even when the differences in construction are imperceptible. Some common examples can illustrate this point. The capacity of a 3/16" fillet weld is 25 percent less than that of an equal length of 1/4” fillet weld; the capacity of an 18-gauge strap to resist tensile forces is 36 percent less than for a 14-gauge strap of equal width; the shear capacity of a 1/2”-diameter foundation bolt in a 2×4 wood sill is 33 percent less than that of a 5/8”-diameter bolt; and the shear capacity in wood of an 8d box nail is 22 percent less than that of an 8d common nail.

Construction tolerances play an equal role in determining the actual capacities of connections. Parameters such as minimum edge and end distances, required embedment or penetration depths, round versus slotted holes for bolts, spacing of reinforcing ties in concrete, and misalignment of parts causing eccentric loads, can all significantly reduce connection capacity. Careful design and detailing on the drawings and thorough inspection of every connection in the load path is necessary to avoid creating weak links that lead to excessive earthquake damage.

References

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Resources for Additional Reading

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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.

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