Seismic Design of Concrete Parking Structure Ramps

Seismology Committee, Structural Engineers Association of California

Beginning in 1959 and extending to 1996, the Seismology Committee of the Structural Engineers Association of California (SEAOC) published printed editions of *Recommended Lateral Force Requirements and Commentary*, which was commonly called the Blue Book. The "Requirements" portion of those publications was in large part adopted verbatim by the International Council of Building Officials as the seismic regulations of the Uniform Building Code. With the unification of the three major model building code organizations in the United States to form the International Code Council, and the nationwide use of the NEHRP seismic design provisions that are developed under the auspices of the Federal Emergency Management Agency and the Building Seismic Safety Council, SEAOC directed its focus to developing forward-looking seismic design articles. Those articles provide commentary and guidance for engineering practitioners and building officials, clarifying ambiguities in codes and standards and identifying needed improvements in them. The result is a set of articles, *SEAOC Blue Book, 2009 Edition*, published by the International Code Council. The SEAOC Seismology Committee is continually developing new articles, which are web-accessible at **www.seaoc.org/bluebook**.

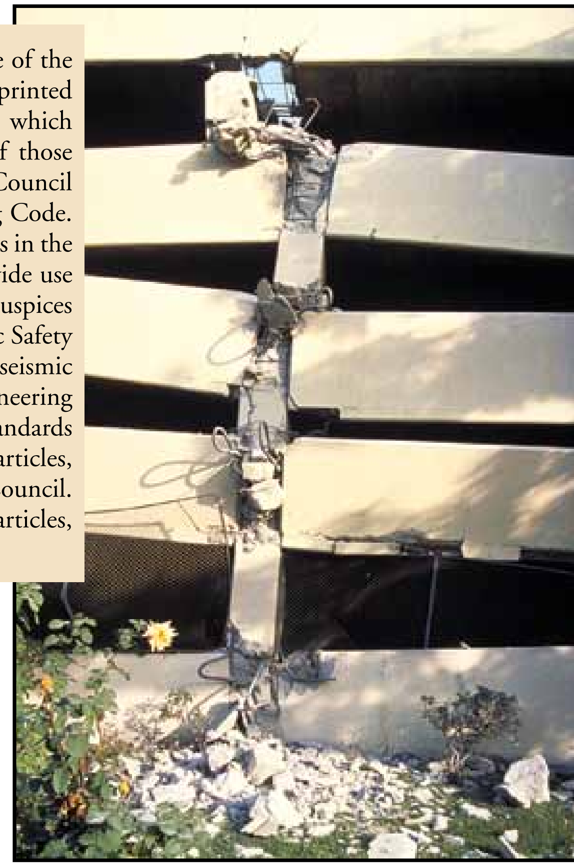

Figure 1: Collapsed parking structure, 1994 Northridge Earthquake. Courtesy of Robert Reitherman.

In the January 17, 1994 Northridge Earthquake, eight major parking structures suffered partial or total collapse (*Figure 1*) and at least twenty others were heavily damaged. Most of these structures were relatively modern, having been constructed in the 25 years prior to the Northridge earthquake.

No other modern concrete building type performed as poorly relative to the primary code objective of safety. A variety of damage occurred and was noted in the Earthquake Engineering Research Institute reconnaissance report on structural damage: collapse of the gravity load-resisting systems sometimes occurred while perimeter walls and frames that were part of the lateral force-resisting system were undamaged; failure of diaphragm collectors and chords; large diaphragm deflections; and distress at precast connections due to lateral movements. On the other hand, many parking structures in the area of strong shaking received little or no damage, suggesting that some design and construction practices used in these structures were inherently better than others.

Unique Seismic Issues of Parking Structures

Parking structures are usually very large in plan area, with relatively thin post-tensioned or precast concrete diaphragms as compared to a typical office building. Architectural, traffic, security, and economical demands push for long spans and large open areas. Prestressed concrete is a system that is suitable because long spans are economical with smaller member sizes. The long-span floor systems tend to vibrate, but the resulting vibrations are acceptable to uninhabited spaces such as parking garages. As a result, the structural long-span framing systems often used in parking structures are not usually found in other types of building occupancies. Additionally, the open nature of parking structures has resulted in less redundant structures with fewer shear walls, frames, or other lateral force-resisting systems. Parking structures have very few interior nonstructural elements, such as partitions, ceilings, and mechanical systems. This inherently leads to lower damping than could be expected from a typical office or other building. Damping ratios ranging from 3% to 4% were observed in an instrumented parking structure during the Northridge earthquake.

Typical parking structures differ from office buildings in that they may not have discrete story levels. Instead the stories may be connected with long, slightly-sloping ramps, which may constitute entire parking levels and are sometimes called parked-on ramps, or shorter ramps of greater slope that provide one or two lanes of inter-level access, which are called speed ramps. Ramps can be detrimental to the intended seismic response of the building by acting as unintended diagonal braces. Additionally, ramps often create interior short columns which are likely to be governed by shear action rather than bending. This article is confined to this important issue of the seismic design and analysis of ramps. A more complete treatment is available in the Structural Engineers Association of California Blue Book paper on *Concrete Parking Structures* available at **www.seaoc.org/bluebook**, which includes references and also covers design issues related to columns and diaphragms.

Ramps

We can speak in general of a parking structure being a particular number of stories in height, but in terms of its structural actions, the concept of stories can be an ambiguous concept. Parking structures often have a spiral or split level configuration that is not clearly represented by discrete story levels. For example, the same segment of the deck could connect level three to level four. Ramps that connect directly to shear walls or moment frames further deviate from the idealized distinct story levels used in the current codes.

The actual performance of an integrated ramp structure may not match the ductile behavior upon which seismic factors, such as the *R* factor, were based. Ramps can change the stiffness and deflection patterns of the building and change the distribution of loads to the designated seismic resisting elements, in some cases attracting a significant percentage of the force. For example, the *R* factor in *ASCE 7-05* or the 2006 *International Building Code* for a special moment resisting-frame (SMRF) is 8. For comparison, the *R* factor for a special shear wall in a building frame system is 6. In other words, the base shear for a SMRF building is permitted to be 75% of that of a shear wall building because of the relative implied ductility (6/8) for the two systems by the code. If a ramp in a SMRF parking structure stiffens up the building, reducing the true flexibility and altering the hinge formation mechanism, then the use of *R* = 8 in this case is non-conservative.

Treatment of Parking Structures by Building Codes

Based on observations from the 1994 Northridge Earthquake, the following code changes (*Table 1*) were subsequently added for concrete structures in regions of high seismicity.

Current building codes do not provide specific guidelines suitable for analyzing the complex story interactions that can occur in parking structures, nor provisions for detailing seismic capacity in the ramps. In some cases, assuming discrete story levels may be too simplified an approach and could cause the designer to overlook unintended structural shortcomings.

Shear walls and moment frames are recognized lateral force-resisting elements in building codes, but ramps are not codified. Yet, some ramps can be stiff and massive enough to interact with the designated seismic resisting systems. A literal interpretation of the 2006 *International Building Code* might place ramps in the "other components" category like gravity columns and non-frame beams, which are often excluded in seismic analysis models. When ramps are categorized as non-seismic elements, their effect on the seismic behavior of the structure could be inadvertently overlooked.

Ramps can be considered as inclined slabs, but codes lack specificity in detailing guidelines suitable for slabs to function as vertical elements of the primary seismic force-resisting system. Interconnected ramps are not held to the ductility detailing provisions prescribed for the shear walls and frames. The diaphragm collector and shear reinforcement is not intended to yield, and thus boundary member confinement would not be required. Similar concerns regarding the greater force demands

Table 1: Building code changes since 1994 affecting concrete parking structures.

Structural Element	Intent of Code Change	ASCE 7-05	ACI 318-05
Diaphragm and Collectors	Specified the minimum thickness of topping slabs. Limited the spacing and bar size at lap splices for force transfer		ACI 21.9.4 ACI 21.9.8.3
Collector Design Forces	Increased the collector design forces	ASCE 12.10.2	
Prestress Tendons	Excluded the use of prestressing tendons in boundary and collector elements, except for the precompression from unbonded tendons		ACI 21.9.5.2
Strength Factor, Φ	Reduced Φ from 0.85 to 0.60 for the design of reinforcement used for diaphragm chords and collectors placed in topping slabs over precast		ACI 9.3.4
Beam-to-Column Connection	Added requirements for precast concrete gravity frames for improved beam to column connections		ACI 21.11.4
Transverse Reinforcement of Frame Members	Prescriptive requirements for transverse reinforcement for frame members not proportioned to resist seismic-induced forces		ACI 21.11.2 ACI 21.11.3

have been raised pertaining to the discussion of highly flexible diaphragms with perimeter-only lateral restraint systems. Stiff ramps also can alter the balance of lateral resisting components, causing secondary torsion effects that redistribute the story forces, potentially increasing loads to specific seismic resisting elements.

Design Approaches

It is common practice to release ramps at grade, but to provide positive connections at the elevated parking decks. This may result in soft and/or weak story performance in areas of high seismicity. The shift from connected to disconnected levels can cause a local redistribution of the shear forces, causing the second story diaphragm to act like a transfer slab with substantial load demands. This is more critical for moment frame structures than for other structures. In some configurations, the top-level floor may have shear-resisting elements on three sides only, and thus relies on cantilever diaphragm rotation to distribute seismic forces at that level. The horizontal irregularity types noted in the building code lack guidelines to limit cantilever diaphragm distance.

It is common in the industry to neglect the interconnectivity of the story levels in the analysis stage of design. A less common approach, due to its impracticality, is to design the ramp with a physical release at each level, using expansion joints to change the structure to match the code. While analytically possible, this construction approach is impractical as the lateral seismic loads imposed by the sloped ramps, which are connected to the horizontal diaphragms on one side only, contribute to undesirable torsional effects. Additionally, the added initial cost, ongoing maintenance, and the added aesthetic drawbacks of the expansion joints further undermine this approach.

Some practitioners believe that interconnecting sloped floors provide for structural "toughness," judging that a well tied-together building is inherently more robust. While it is valid to assert that connected ramps provide reserve stiffness or redundancy to a building, it also is true that concurrent load paths are inherently unpredictable. Secondary systems can inadvertently absorb a disproportionate share of the load, even functioning as primary load paths. For example, stiff non-ductile ramps can dominate a moment-frame system, short-circuiting the ductile members that are designed to dissipate the energy.

Many practitioners prefer to include shear walls in the direction of the ramps, while maintaining more flexible moment-resisting frames in the orthogonal direction. This practice allows less seismic deformation along the sloped ramps and reduces seismic loads imposed on short columns. In any event, it should be noted that ramps have two different characteristics: orthogonal and longitudinal. In the longitudinal direction, ramps act as truss elements transmitting axial forces. The concern in the orthogonal direction is the aspect ratio of the diaphragm and the deformation associated with it. Designers should properly account for these issues.

In the absence of published guidelines, the best approach currently being used to study these effects is project-specific computer analysis, with each unique building being modeled to evaluate the effects of the particular ramping configuration. Today's computational tools permit more complex analysis, including flexibility of diaphragms, and more complex definitions of deck levels, including sloped ones. However, the current computer output is even more difficult to correlate with the prescribed design approach specified in the building code because seismic loads are resisted by other members of the structure such as the ramps, not just the designated lateral force-resisting system recognized by the code.

Summary

Parking structures have a number of unique characteristics, compared to conventional concrete buildings, which affect their seismic performance. While this article has focused specifically on issues regarding ramps, additional topics are addressed in the full SEAOC Blue Book article. Ramps will impact the seismic behavior of parking structures to varying degrees, depending on the interconnectivity of the ramps and the primary seismic force-resisting system. An appropriate level of analytical sophistication is required to identify and properly design for these effects. A three-dimensional computer analysis, which includes consideration of the ramps, is an effective tool to capture the behavior and is highly recommended. The challenge, and responsibility, of the structural designer of a parking structure is to overcome the disparity between the configuration of the structure and the current code procedures, and to demonstrate and detail a rational load path through the structure.▪

Mehran Pourzanjani, Chair of the Seismology Committee of the Structural Engineers Association of California, ***mehran@sbise.com****.*