Paper No. 1150. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ANALYTICAL CONSIDERATIONS IN THE DESIGN OF CONCRETE PARKING STRUCTURES

DAVID R. BONNEVILLE, RICHARD J. LOVE, and KATHLEEN DAIGLE

Degenkolb Engineers
350 Sansome Street, San Francisco
California, U.S.A. 94104

ABSTRACT

Compared to most other modern building systems, concrete parking structures performed poorly in the 1994 Northridge, California earthquake. In the heavily shaken area, eight parking structures had partial to total collapse and many others had substantial damage. Due to the poor performance, the Seismology committee of the Structural Engineers Association of California (SEAOC) formed an ad hoc subcommittee to develop guidelines for improved parking structure design in high seismic areas. The object of this paper is to summarize the analytical evaluations that form the basis for the Guidelines and to present key aspects of the Guidelines.

KEYWORDS

earthquake, parking structures, diaphragms

INTRODUCTION

Compared to most other modern building systems, concrete parking structures performed poorly in the 1994 Northridge, California earthquake. In the heavily shaken area, eight parking structures had partial to total collapse and many others had substantial damage. (Iverson and Hawkins provides a comprehensive survey description of damage to 30 parking structures in the PCI Journal.) Due to the poor performance, the Seismology Committee of the Structural Engineers Association of California (SEAOC) formed an ad hoc subcommittee to develop guidelines for improved parking structure design. The object of this paper is to summarize the on-site and analytical evaluations that form the basis for the Design Guidelines and to present key aspects of the Guidelines.

A committee of ten members consisting of practicing structural engineers, contractors, and professional affiliates from the concrete industry was formed to study the issues and develop guidelines for future analysis and design of parking structures in high seismic zones. The committee began in January of 1995 and will complete its work in 1996. The following efforts are being undertaken by the committee:

Review the performance of parking structures damaged in the Northridge earthquake. This work is accomplished primarily through a review of work previously completed by a task force of the City of Los Angeles. Members of the L.A. task force also serve on the SEAOC ad hoc committee.

Establish the distinctive characteristics of parking structure design, analysis, and resulting seismic performance in terms of system and configuration. Systems include fully cast-in-place, fully precast, and combinations of cast-in-place and precast construction. There are numerous parking structure configurations including variations on the single and double helix layouts. Most configurations are characterized by sloping, or ramped, parking surfaces with resulting discontinuities in the floor diaphragms.

Conduct two and three-dimensional static and dynamic parametric analyses with various diaphragm configurations and primary lateral force resisting systems to study the dynamic interactional effects of sloping ramps, diaphragm aspect ratios, and primary system rigidities.

Develop seismic detailing recommendations for improved ductility in lateral and non-lateral load resisting elements.

Discuss relevant current building code revisions affecting parking structure systems and elements.

Discuss project delivery considerations. (The design/build approach is frequently used in parking structures.)

The results of the SEAOC ad hoc subcommittee will be presented in a set of Guidelines for design and construction of parking structures. The Guidelines document will be reviewed by the full SEAOC Seismology Committee and then released to the SEAOC membership as a resource document for improved seismic design and performance of parking structures.

PARKING STRUCTURE CHARACTERISTICS

Concrete parking structures have a number of distinctive characteristics when compared to conventional concrete buildings. The characteristics affect the seismic performance in ways not fully appreciated prior to the Northridge earthquake. The key characteristics which make these structures more susceptible than other structures to seismic damage include:

1. Lack of Redundancy: Parking structures are often very large in plan dimensions and contain relatively few primary seismic resisting elements such as shear walls or moment resisting frames. The seismic resisting elements are widely spread throughout the structure and result in large diaphragm spans between the resisting elements. This layout addresses concerns such as concrete volumetric change requirements caused by thermal, shrinkage and creep effects, the need for clear lines-of-sight for security reasons, and minimized construction costs.

2. Lack of Continuity: Parking structures are often constructed of precast, prestressed elements which are inherently more difficult to interconnect than monolithic concrete construction. Methods used in the past to tie these structures together have shown limited ductility capacity in large seismic events.

3. Diaphragm-controlled Response: The large diaphragms with split openings which allow sloped ramp surfaces have typically been analyzed as rigid diaphragms as a matter of analytic simplicity. However, because of the large diaphragm aspect ratios and large spans between resisting elements, these diaphragms can behave as flexible diaphragms when compared to the rigidity of the primary resisting elements. The interaction of the diaphragm flexibility and the flexibility of the primary system has not

been recognized in most designs. This results in inaccurate design lateral force distribution and significantly greater diaphragm deflections than anticipated by past design methods. As a result, non-lateral load resisting elements were not adequately detailed to provide ductile behavior at the real earthquake displacements.

4. Limited Damping: The relative lack of interior non-structural elements such as partitions, ceilings, and mechanical systems leads to lower structural damping than is typically available in other buildings. The use of 5 percent damped response spectrum overestimates the damping available and results in underestimated lateral displacements. In this sense, parking structures behave more like bridges than buildings.

5. Project Delivery: Parking structures are often constructed through the design/build process. In the process, the owner selects the contractor to build a parking structure for a specified price. The contractor selects the design team including the engineer to provide a design for construction. In the design/build process, the price of construction is established prior to the design. This process contrasts with that normally used for conventional building construction where the owner contracts with a design team including the engineer, contract documents are developed, and the contract documents are competitively bid to determine the price of construction. Although excellent structures can be produced in the design/bid process, there may be a tendency to provide the minimum acceptable structural system allowed by building codes even where engineering judgement may suggest a higher degree of conservatism.

Parametric Studies

In order to investigate the interaction between large diaphragm response and the primary lateral load resisting system, a series of simplified elastic analyses were performed. Others have studied and reported on generic studies of flexible diaphragm analysis including inelastic behavior (Kunnath, et.al.). This study investigated:

1. the relative stiffness between the large diaphragms and two prototype primary lateral force resisting elements, shear walls and ductile moment resisting frames,
2. the maximum lateral displacements, or drifts, of the diaphragms over the height of the building,
3. the vertical seismic force distribution to the various levels of a garage;
4. the horizontal force distribution of diaphragm inertial loads to primary seismic elements;
5. the applicability of simple "stick" computer models for analysis of lateral force distributions.

Methodology. A single helix concrete parking structure was chosen as a prototype garage to study the various parameters of interest. This garage was selected due to its relative simplicity compared with other parking structure configurations. The dimensions, including overall building length, width and bay spacing were obtained from drawings of an actual garage. The overall length, width, floor heights, and slab thicknesses were kept constant for all analyses for meaningful comparison of results.

Because the diaphragm is most flexible when loaded in the direction perpendicular to the ramps, or transverse to the structure, the parametric study concentrated on seismic loading in this direction only. Longitudinal seismic loading was not included in the study.

The parameters of interest included the height of garage, or number of levels, and the basic lateral force resisting system, either shear walls or ductile concrete moment resisting frames. The number of levels was varied to include three building heights corresponding to two levels, four levels, and six levels of parking. The element geometric properties including areas and moments of inertia were held constant for all three building heights. This constant property assumption was based on the assumption that the element strength could be varied within the same size elements to meet increased demand forces as the building heights were increased. For example, as a shear wall building is increased in height, the amount of reinforcement in the walls can be increased without need to increase the length or thickness of the wall. This assumption, while not strictly true for all structures, allows the comparison of relative diaphragm stiffness to wall stiffness for all three structural heights.

After analysis of the various models, data were gathered for comparison of diaphragm displacements, primary lateral system displacements, and modal response characteristics such as fundamental period, mode shapes and mass participation factors.

Prototypical Structure Description. The prototype parking structure is 82.3m long by 38.4m wide. In the longitudinal direction, the building has 16 equal column bays of about 5.1m each. The prototype structure assumes non-lateral load resisting precast columns with precast beams and a cast-in-place slab. In the transverse direction, there are two bays of 19.2m each. Each floor level is 3.0m high.

The sloping ramps are the full width of each of the two transverse bays. Each ramp rises 1.5m over a distance of about 61m. The ramps are centered along the length of the building, leaving 10.4m wide portions of flat diaphragm at each end of the building. All diaphragms are 125mm thick.

The primary lateral load resisting elements are located at the ends of the building. There are no interior lateral force resisting elements. For the shear wall system, the concrete walls are 11m long and 425mm thick. For the concrete moment resisting frame system, a frame with six equal bays of 6.1m each was created. The columns were assumed to be 700mm square and the girders were assumed to be 560mm wide by 800mm deep. (These dimensions were obtained from an actual parking structure as representative of suitable sizes.)

Analytic Model. The garage elements were modeled in two dimensions, x and z (vertical), to create a planar frame that is 82.3m long with 3.0m floor heights. The seismic loading is applied orthogonal to the planar frame, or transverse (y-direction) to the ramps. The model was reasonably quick to generate using a general purpose three-dimensional analysis program. In modelling the diaphragms, the in-plane stiffness was incorporated to study the diaphragm stiffness relative to the vertical primary load resisting elements.

For consistency, all elements were assumed to possess their full uncracked geometric properties. There was no reduction for cracking that can occur during an earthquake. This assumption is clearly not realistic when attempting to predict absolute lateral deflections. However, when studying relative displacements, this simplification was considered acceptable for this study. (The issue of cracked vs uncracked sections requires additional study.) The nonlateral load resisting precast columns were not included. They were assumed to provide no lateral stiffness to the structure. Their lateral displacements are completely controlled by the response of the diaphragm. The model diaphragm elements are 2-dimensional beam elements to simulate the width and slab thickness.

The shear wall elements were modelled as single beam-column stick elements with areas and moments of inertia based on the length and thickness of the shear walls. For the moment resisting frame models, an equivalent stick model was developed to represent the bending and shear behavior of a moment resisting frame. The model included a column stick element with "outrigger" beam elements at each level. The outrigger beams, oriented in the transverse, or "y" direction, provide rotational restraint to the stick column element to achieve the deflected shape of a moment resisting frame. The stiffness properties of the moment frame columns and outrigger beams had been determined using a simple 2-dimensional frame analysis program. Using a set of applied loads and resulting deflections from the 2-dimensional frame analysis, an equivalent stick model was created with equivalent stiffness for the 3-dimensional model.

For both moment frame and shear wall cases, restraints were imposed on the models to remain consistent with the 2-dimensional approach. Nodal joints were allowed only y-deflection and z-rotation. At the base of the primary "stick" elements, a fixed condition was assumed for simplification. (Possible foundation rocking was not included in this study. This is an area where additional analysis is warranted.)

Both the moment resisting frame and shear wall models were analyzed using a generic response spectrum with a PGA of .4g and a plateau of 1.0g between 0.15 seconds and 0.4 seconds. For comparison of resulting displacements and forces, the prototype models were also analyzed using an equivalent static lateral force procedure. The base shear force was distributed vertically using a triangular distribution as traditionally required by codes. However, the forces at each diaphragm were determined based on the elevation of sloped diaphragm elements of the ramp at their midpoints. These points are located between the floor level elevations commonly used for determination of the vertical distribution. Therefore, because two ramps are required for each level, the base shear is distributed to twice as many levels as there are floors.

A total of six models were created with moment resisting frames or shear walls, two-, four-, and six-story building heights. Both response spectrum and equivalent static load cases were applied to each model for comparison of results.

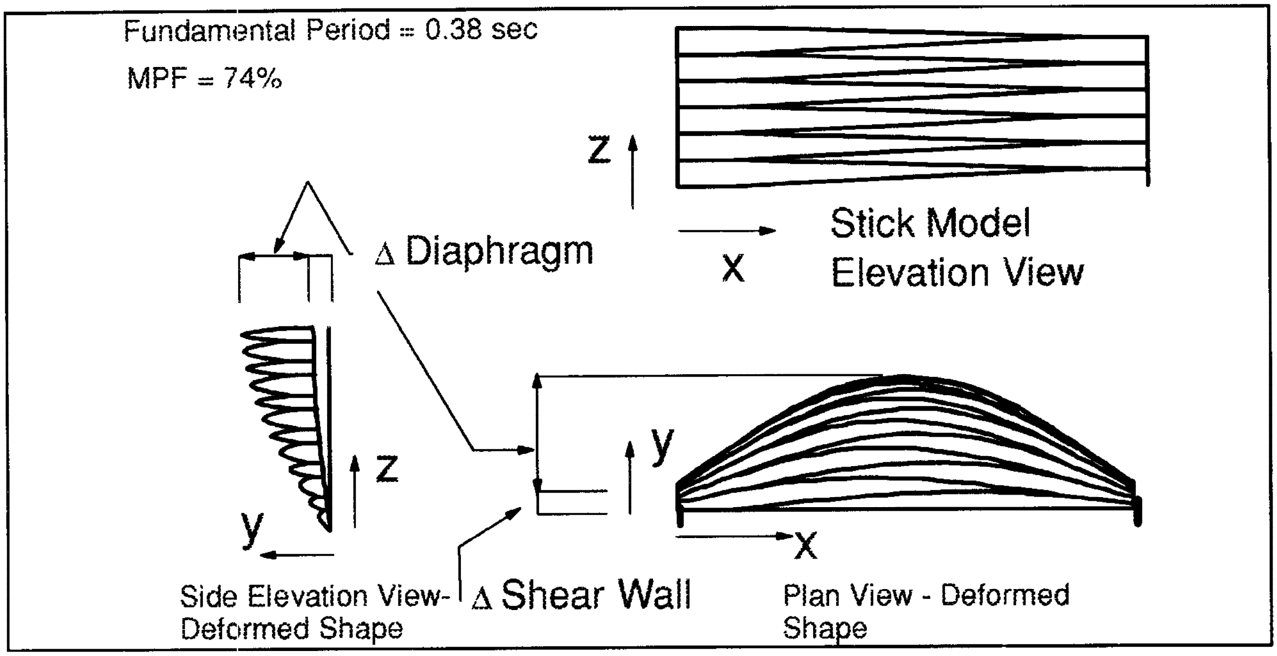
Results

Shear Wall Prototype Analyses. The rigidity ratio of the diaphragm to the wall, defined as the maximum diaphragm displacement divided by the wall displacement at that level, was calculated for each case as shown in Table 1 below. The 1994 Uniform Building Code defines flexible diaphragms as those whose rigidity ratio exceeds 2 at the associated story. Results from both equivalent static analyses and response spectrum analyses were compared to this standard. As can be seen in the table, the diaphragm rigidity ratio decreases with increased height of structure due to the increased flexibility of the primary resisting system. As should be expected, the taller the wall, the less rigid it was with respect to the diaphragm. However, even at the 6-story level, the diaphragm rigidity ratio was around 4, indicating flexible diaphragm behavior with respect to the shear walls.

Table 1. Rigidity Ratios for Shear Wall Prototypes

Number of Stories	Analysis Type	Deflection (mm) at top of Shear Wall	Deflection (mm) at Centerline of Diaphragm	Relative Deflection (mm)	Diaphragm Rigidity Ratio - Diaphragm/Wall
2	Equivalent Static	0.2	5.4	5.2	29
2	Response Spectrum	0.2	5.6	5.4	35
4	Equivalent Static	0.7	6.9	6.2	8.7
4	Response Spectrum	0.6	6.7	6.1	9.5
6	Equivalent Static	1.3	6.6	5.3	4.0
6	Response Spectrum	1.2	6.4	5.2	4.3

Using a response spectrum analysis, the mode shapes and resulting force distributions were investigated. The first mode periods of the three shear wall cases varied from 0.33 to 0.38 seconds, a very small increase if the period were related to the height of the structure as normally assumed in seismic design. In reality, the first mode reflects primarily the dynamic response of the diaphragms. In all three cases,



about 75 percent of the mass participated in the first mode. As shown in Figure 1 below, the diaphragm mode shapes can be seen in the deflected shapes both in plan and in elevation.

Based on the analyses of two to six story shear wall prototype structures, the diaphragms should be analyzed as flexible diaphragms with actual geometric properties instead of the common rigid diaphragm assumption used in analyses. Diaphragm deflections are significantly greater in the midspan area when compared to the regions near the shear walls. This increased deflection directly affects the expected ductility demands on nonlateral load resisting columns.

Moment Resisting Frame Prototype Analyses. Based on the analysis of the moment frame structures, the diaphragm rigidity ratios, defined as above, had some similarities to the shear wall analyses. The diaphragm rigidity ratio decreases with increased structure height due to the increased flexibility of the primary resisting system. As would be expected, the moment resisting frames were considerably more flexible than the shear walls. For the 2-story case, the diaphragm is still flexible relative to the moment frame. For the 4-story case, the rigidity ratio was about 1, and for the 6-story level the ratio was 0.5. Therefore, the diaphragms for both the 4 and 6 story prototype are considered as rigid when determining the horizontal distribution of seismic forces to the primary resisting elements.

Table 2. Rigidity Ratios for Moment Resisting Frame Prototypes

Number of Stories	Analysis Type	Deflection (mm) at top of Moment Resisting Frame	Deflection (mm) at Centerline of Diaphragm	Relative Deflection (mm)	Rigidity Ratio - Diaphragm/ Wall
2	Equivalent Static	1.3	5.8	4.5	3.5
2	Response Spectrum	1.1	6.1	5.0	4.5
4	Equivalent Static	5.3	10.7	5.3	1.0
4	Response Spectrum	5.1	10.6	5.5	1.1
6	Equivalent Static	9.7	14.5	4.8	0.5
6	Response Spectrum	9.1	13.4	4.3	0.5

The first modal period of the moment frame cases had greater variability than the shear wall cases. The fundamental periods ranged from 0.34 seconds for the two story structure to 0.62 seconds for the six story structure. It is obvious that for the two story structure, the first mode is still primarily dominated by the flexible diaphragm response. For the six story structure, the fundamental response is dominated by the flexibility of the moment resisting frame as normally assumed in seismic analysis procedures. Figure 2 below shows the relative displacement of the diaphragms and moment resisting frames.

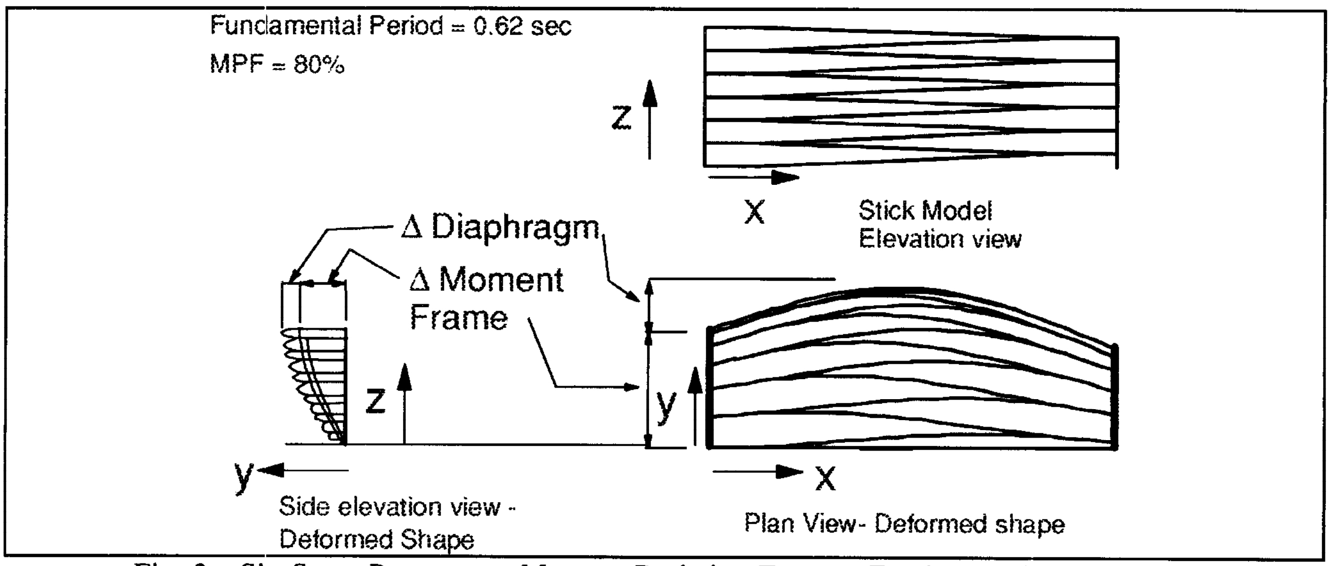


Fig. 2 Six Story Prototype - Moment Resisting Frame - Fundamental Mode Shape

Prototype Analysis Conclusions. Based on the analyses of six prototype parking structures including shear wall and moment resisting frame systems of three building heights, it is possible to conclude that:

1. Diaphragm response is significant in shear wall structures up to six stories tall. The fundamental period is based on the response of the diaphragms rather than the height of the structure. Diaphragm forces can be distributed to the shear walls based on a flexible simple beam analogy instead of rigid beam analogy. The midspan diaphragm drift is significantly greater than at the shear wall support and

should be considered when determining the ductility requirements of the interior gravity columns of the structure.

2. The response of moment resisting frames dominates the response for parking structures greater than two stories tall. The diaphragms in the taller structures were determined to be rigid when compared to the primary frames. Therefore, rigid diaphragm analysis techniques would be appropriate for these relatively flexible structures.

CONCLUSIONS

A comprehensive effort involving research and guidelines development was undertaken by the Ad Hoc Parking Structures Subcommittee of the SEAOC Seismology Committee. This subcommittee will develop Guidelines for the analysis and detailing of parking structures to improve the expected seismic performance of parking structures in high seismic zones.

The Guidelines will be oriented towards practicing engineers involved with the design of new parking structures in California or other high seismic zones with similar construction practices. The Guidelines will provide suggested practice based on the numerous observations of actual seismic performance and limited analytical studies.

Since the Northridge Earthquake, several seismic code changes addressing parking structure problems have either been accepted for the 1996 UBC Supplement or are proposed for the 1997 UBC. These include the following: design and detailing of columns not part of the lateral force resisting system, stricter requirements for deformation compatibility, increased minimum thickness for concrete topping slabs, consideration of near-source effects and consideration of redundancy in the seismic system. These changes and proposals will have a substantial effect on the seismic performance of parking structures.

ACKNOWLEDGEMENTS

The authors greatly appreciate the efforts of all the members of the SEAOC Ad Hoc Subcommittee; Ray Bligh, Andy Curd, Terry Dooley, S.K, Ghosh, Mark Kluver, Doug Mooradian, Richard Phillips, Barry Schindler, and David Seagren.

REFERENCES

Iverson, J. K., N. M. Hawkins (1994). Performance of Precast/Prestressed Building Structures During Northridge Earthquake, PCI Journal, Vol. 39, no.2, pp 38-55.

Kunnath, S. K., N. Panahshahi, and A. M. Reinhorn (1991). Seismic Response of RC Buildings with Inelastic Floor Diaphragms, ASCE Journal of Structural Engineering, Vol. 117, No.4, p. 1218.

Los Angeles City Department of Building and Safety/Structural Engineers Association of Southern California Joint Task Force on Parking Structures. Conclusions and Recommendations

International Conference of Building Officials, Uniform Building Code (1994), Whittier, California.