Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

A ROCKING SPINE FOR ENHANCED SEISMIC PERFORMANCE OF REINFORCED CONCRETE FRAME BUILDINGS WITH INFILLS

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ABSTRACT

This research aims to develop a novel approach to improving collapse safety in reinforced concrete frames with infills through the use of strong, stiff structural spines that resist earthquakes through rocking action. The rocking spines can be constructed as slender, stout infill frames or reinforced concrete walls with shallow foundations. The use of rocking action as the primary yielding mechanism significantly reduces the required level of detailing that is needed to achieve ductility in concrete frames, resulting in significant material cost savings. The system relies on gravity and the restraint provided by structural members connected to the spine as the primary sources of overturning resistance. These include the beam elements framing into the spine as well as infill panels constructed in the adjacent bays on either side of the spine. The goal of this study is to characterize the behavior of the rocking spine system and demonstrate its effectiveness in improving collapse performance. The behavior of the rocking spine system is idealized using a system backbone curve that illustrates the effect of the various sources of overturning resistance and yielding mechanisms. Non-linear analysis models are developed and analyzed in OpenSees to evaluate its ability to improve seismic performance.

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Burton H, V., Deierlein G, G. A rocking spine for enhanced seismic performance of reinforced concrete frame buildings with infills. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

DOI: 10.4231/D3VT1GQ6N

A Rocking Spine for Enhanced Seismic Performance of Reinforced Concrete Frame Buildings with Infills

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ABSTRACT

This research aims to develop a novel approach to improving collapse safety in reinforced concrete frames with infills through the use of strong, stiff structural spines that resist earthquakes through rocking action. The rocking spines can be constructed as slender, stout infill frames or reinforced concrete walls with shallow foundations. The use of rocking action as the primary yielding mechanism significantly reduces the required level of detailing that is needed to achieve ductility in concrete frames, resulting in significant material cost savings. The system relies on gravity and the restraint provided by structural members connected to the spine as the primary sources of overturning resistance. These include the beam elements framing into the spine as well as infill panels constructed in the adjacent bays on either side of the spine. The goal of this study is to characterize the behavior of the rocking spine system and demonstrate its effectiveness in improving collapse performance. The behavior of the rocking spine system is idealized using a system backbone curve that illustrates the effect of the various sources of overturning resistance and yielding mechanisms. Non-linear analysis models are developed and analyzed in OpenSees to evaluate its ability to improve seismic performance.

Introduction

Reinforced concrete frames with infill panels (infill frames) is a building system that is commonly used worldwide. In many high seismic regions, they are constructed as non-ductile concrete frames and unreinforced infill. The last decade has seen tens of thousands of earthquake casualties as a result of the poor performance of these buildings, including most recently in Haiti (2010), China (2008) and Indonesia (2004). Despite these challenges, they will continue to be built for the foreseeable future in many urban regions because the building system can be constructed inexpensively with familiar techniques and readily available materials. Strategies to improve their performance must take this reality into account.

Past research and field investigations following earthquakes have demonstrated the benefits of rocking behavior in reducing force and deformation demands in a structure. In recent years, a number of rocking systems have been developed for damage resistant buildings and bridges that facilitate quick and economical post-earthquake repairs. These systems typically involve the use of ductile energy dissipation devices that would be cost-prohibitive in many parts of the world particularly for residential infill frame buildings. This research seeks to leverage the advantages of rocking behavior by making minimal modifications to the current mode of

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construction for infill frame buildings to provide a cost-effective means of achieving an acceptable margin of safety against collapse.

System Description and Behavior

Rocking Spine System Description

A schematic representation of the rocking spine system is shown in Fig. 1. The spine consists of a strong, stiff infill frame with a shallow foundation and is shown centered between two adjacent, traditional infill frames. The terms "spine infill" and "non-spine infill" will be used consistently throughout this paper to distinguish between the infill panels that are part of the spine and those that are located within frames outside the spine. The strength and stiffness of the spine infill is critical to achieving the desired system performance. Ideally the spine infill and framing members are to remain elastic when subjected to low and moderate earthquakes. At larger intensities, a nominal level of damage to the spine can be accommodated based on the desired performance. The rocking spine derives all of its overturning resistance from gravity loads and the adjacent infill panels and beams that frame into it. The non-spine infill and beams in the adjacent frame on the uplift-side of the spine serve as outriggers, transferring additional gravity loads to the spine adding to its overturning resistance. The magnitude of gravity loads transferred to the spine is limited by the strength of these outrigger elements. On the compression-side of the spine, the adjacent elements also provide overturning resistance through compatibility and their constitutive relationships. The non-spine infill and adjacent beams also serve as yielding elements and are relied on to dissipate energy under cyclic loading. Grade beams are used to connect the footings at the base of the spine to the adjacent frames to facilitate the transfer of lateral forces at the foundation after spine uplift has occurred.

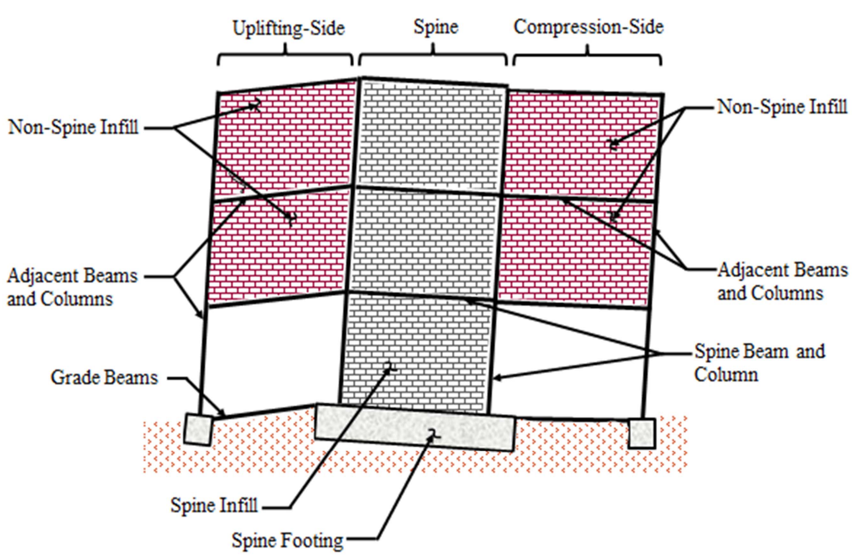

Figure 1. Rocking spine system concept

Idealized Behavior

Fig. 2 shows a loading diagram for the rocking spine system. The infill panels in both the rocking spine and the adjacent frames are idealized as diagonal compression struts. This is one of a number of alternative configurations that can be implemented. The behavior of the spine is significantly influenced by the absence or presence of adjacent non-spine infill (discussed later). At low levels of lateral load, the beams and columns within the spine and adjacent frames undergo elastic deformations with some minor cracking occurring in the infill panels. At higher levels of lateral loading, the overturning moment on the spine exceeds that of the resistance provided by gravity loads resulting in uplift at the footing as shown in Fig. 3. Deflection in the overall system after uplift consists of elastic deformation of the framing members and infill panels and rigid-body rotation of the spine. The deflection of the spine can be described by the angle formed between the rotated footing base and the horizontal plane (θ_{up}). The horizontal (Δ_R) and vertical (Δ_V) displacements due to rigid body rotation of the spine can be calculated by assuming small angles and neglecting the elastic deformations that occur prior to uplift.

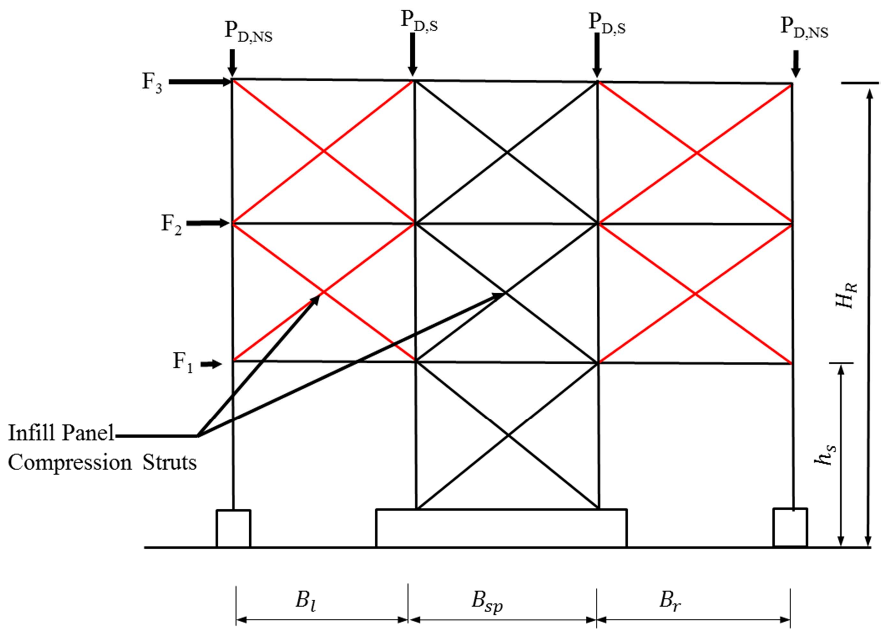

Figure 2. Idealized loading diagram for rocking spine system

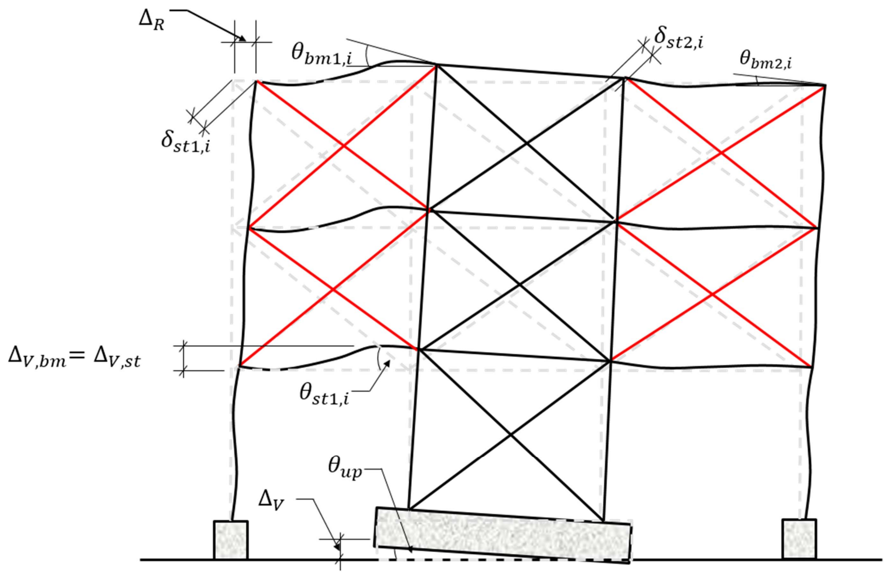

Figure 3. Deflected shape of rocking spine system after uplift

The deformation demands in the adjacent frames can be assessed based on their compatibility with the spine uplift. The lateral deflection in the adjacent frames will be the same as that of the rocking spine. The rotation demands in the adjacent beams framing into either side of the spine after uplift include the rotation due to elastic deformation of the spine plus the rotation due to spine rigid body motion. The beam on the uplift-side of the spine also undergoes a vertical translation ($\Delta_{V,bm}$) at the joint where it frames into the spine. Due to the flexibility and distribution of yielding of the framing elements, there will be some variation in the vertical translation of the adjacent beams at different story levels along the height of the building, but this is considered negligible. The magnitude of this vertical translation is assumed to be the same as the vertical displacement at the spine footing.

The deformation demands in the infill struts can also be assessed using compatibility. The infill struts on either side of the spine will undergo axial shortening as a result of spine deflection. The infill strut on the uplift-side of the spine will undergo an additional axial shortening due to the vertical translation ($\Delta_{V,st}$) at the joint where the strut frames into the spine. As was the case with the adjacent beam, the magnitude of this vertical translation at all story levels is assumed to be the same as the vertical displacement at the spine footing.

Fig. 4 shows a free body diagram of the spine after it has experienced uplift highlighting the sources of overturning resistance. The gravity loads acting directly on the spine ($P_{grav,sp}$) provide a restoring moment. Gravity loads on the column one bay over from the uplift-side of the spine ($P_{grav,ns}$) are transmitted to the spine through outrigger action of the adjacent beams and non-spine infill. The uplift-side adjacent beams provide overturning resistance from its end moment (M_{bm1}) and the restoring moment from its end shear force (V_{bm1}). The compression-side adjacent beams provide overturning resistance from its end moment (M_{bm2}). The uplift-side non-spine infill generates and restoring moment from the vertical component of its strut force

(P_{inf1}).

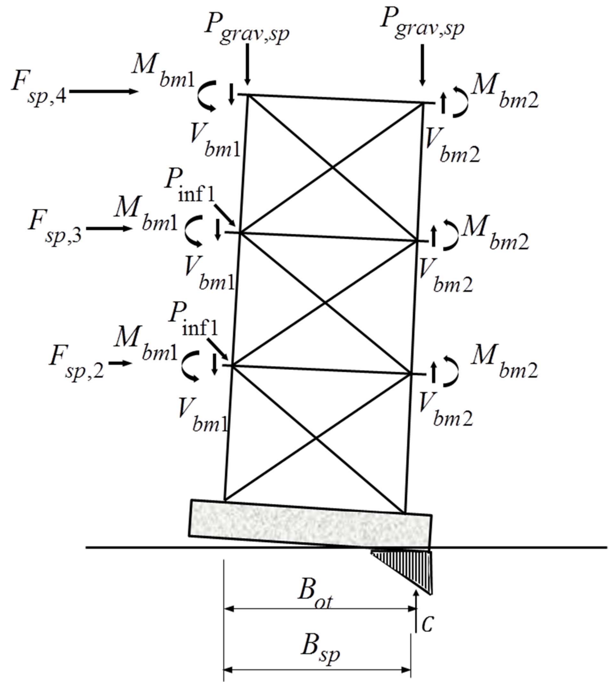

Figure 4. Free-body diagram of spine after uplift

System and Component Limit States

Fig. 5 shows the system and component load-deflection curve for the rocking spine system with and without infill frames on either side. The load deflection relationship is expressed in terms of overturning moment and uplift. After uplift has occurred, the overturning moment can be calculated from the gravity loads on the rocking spine, its vertical displacement and the constitutive relationships for the adjacent beams and infill struts. The behavior of the system can be described in terms of the superposition of strength and restoring actions provided by the gravity loads, adjacent beams and infill panels where present. Fig. 5a shows the idealized pushover curve for the rocking spine system with adjacent infill panels. Fig. 5b shows the idealized pushover curve for the rocking spine system without adjacent infill panels. The presence of infill panels adjacent to the spine significantly changes the pushover response and has considerable implications in the design procedures.

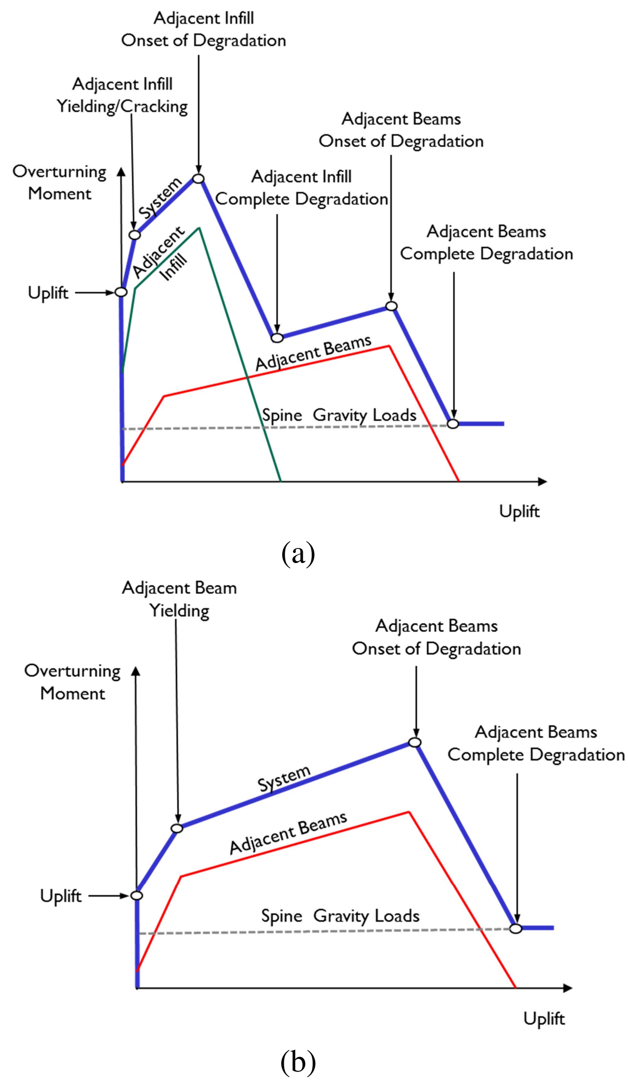

Figure 5. Idealized pushover curve and limit states for rocking spine (a) with adjacent infill panels and (b) without adjacent infill panels

The limit states of the rocking spine system with adjacent infill panels are shown in Fig. 5a. Prior to uplift, the rocking spine experiences very small levels of story drift due to the elastic deformation in the infill panels (minor cracking in the infill is also expected during this stage) and framing members. When the overturning moment exceeds the restoring moment, uplift occurs at the base of the spine footing. As the vertical and lateral deflection of the rocking spine increases the adjacent beams and infill panels undergo increased deformations leading to the onset of significant cracking in the adjacent infill panels. Recall that the infill panels on the uplift-side of the spine experience deformations both due to lateral drift and uplift of the spine while the non-spine infills on the compression-side only experience deformations due to lateral drift. As a result, the non-spine panels on the uplift-side are expected to experience greater levels of damage than those on the compression-side at any given point on the pushover curve. The onset of strength loss in the adjacent infill panels also coincides with the onset of strength loss in the rocking spine system. Repair of the rocking spine system up to this point will likely involve restoration of the adjacent infill panels. As deformations increase beyond this limit state, the non-spine infill panels continue to degrade until they are no longer able to contribute to the restoring moment in the spine. The onset of yielding in the adjacent beams, particularly on the uplift-side, is likely to take place during the degradation of the adjacent infill panels depending on its flexural strength and stiffness. Following the complete degradation of the adjacent infill panels, the adjacent beams continue to undergo inelastic deformations. The onset of strength degradation in the adjacent beams represents a critical limit state which will lead to significant loss of strength and stiffness of the rocking spine system. Therefore this limit is considered a life safety threat. With increased drift demands, the adjacent beams will continue to degrade to the point of complete strength loss. At this point, the gravity loads on the spine becomes the last layer of protection against excessive rocking and overturning. The system backbone curve without adjacent infill panels is governed by the inelastic deformations in the adjacent beams.

Numerical Modeling and Proof of Concept Pilot Study

This pilot study served as a preliminary investigation of the impact of the rocking spine system on the seismic performance of a prototype infill frame building. Numerical models are developed in OpenSees (Mazzoni et al. 2012) and nonlinear static and dynamic analyses are performed.

Prototype Building and Model Description

The prototype building is based on an existing building in Karachi, Pakistan representing typical infill frame construction in low and middle-income communities. It is a six story mixed use building with shops located in the 1st story and residential apartments in the upper stories. Infill panels were constructed using unreinforced concrete masonry units and used as both interior partitions and exterior cladding. Fig. 6 shows a plan view of the prototype building with plan dimensions of 54’-0” wide by 90-0” long with 18’-0” bays in each direction. 12’-0” story heights are used yielding an overall height of 72’-0”.

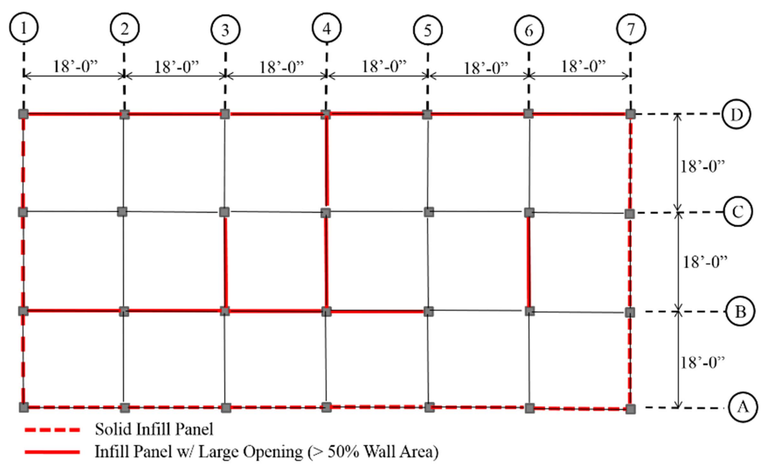

Figure 6. Plan view of prototype building showing infill panel layout

Two-dimensional structural models were constructed for three variations of the perimeter frame at grid Line A. The first model (Model P1) is developed using the same framing member sizes, reinforcement and material properties as the original building. The infill thickness, layout and material properties are also maintained. This model is intended to represent the as-built conditions of the prototype building. The second model (Model P2) is the same as Model P1, except that the infill in the central bay is extended to the 1st story with the same thickness and material properties of the original building. The third variant is used to simulate the strengthening of the infill panels in the central bay to create a rocking spine. A schematic overview of the OpenSees models is shown in Fig. 7. Beams and columns were idealized using elastic elements with concentrated flexural plastic hinges that comprised the Ibarra-Krawinkler material to capture nonlinear behavior (Ibarra et al, 2005). Both the spine (Model P3) and non-spine infill are modeled using a pair of inelastic compression-only struts. The axial force-deformation relationship for the strut element is also based on a tri-linear backbone curve (Burton and Deierlein, 2013). The potential for foundation uplift was incorporated using springs with an elastic compression-only material at the base of all columns. The compression-only elastic material was assigned a large compressive stiffness to simulate a vertical restraint in the downward direction.

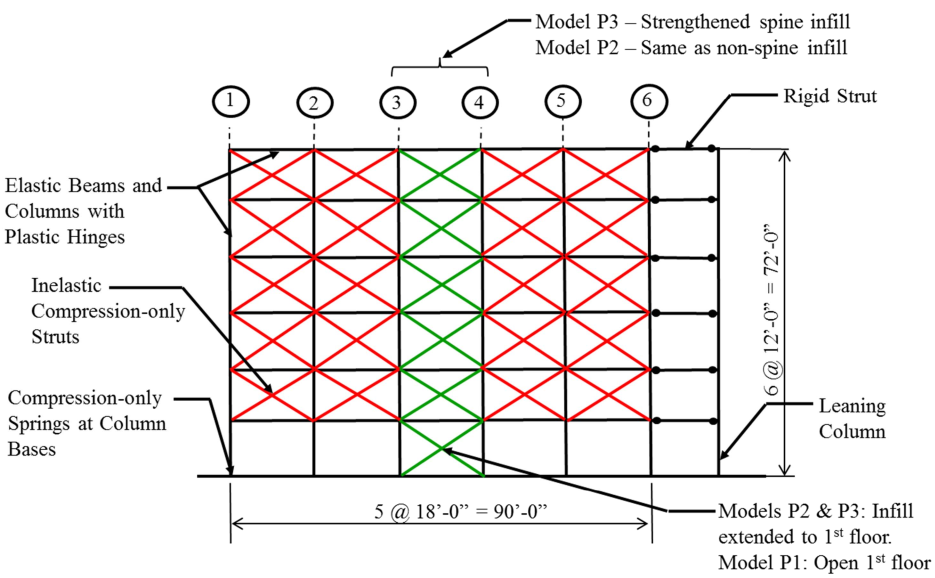

Figure 7. Schematic of OpenSees model for prototype variants

Nonlinear Static Analyses

Static pushover analyses are performed to investigate how the presence, strength and stiffness of the centrally located spine affect the load-deflection relationship of the prototype building. Fig. 8 shows the pushover response for the three models in terms of base shear vs. roof drift and Fig. 9 shows the distribution of story drift corresponding to a roof drift of .75%. It can be observed that Models P1 and P2 exhibit poor post-peak performance experiencing an almost complete loss of lateral strength at .75% roof drift. The behavior of these two models under static lateral loading is dominated by the formation of a 1st story mechanism. The evidence of this can be observed in Fig. 9, which shows that the overwhelming majority of the drift demand is concentrated in the 1st story with drifts exceeding 4% at a roof drift of .75%. From these results we see that extending the central-bay infill panel to the 1st story without changing its strength and stiffness has little to no effect on the overall load-deflection relationship. Fig. 8 also shows a dramatic improvement in the post-peak response with the incorporation of the rocking spine in Model P3. Fig. 9 shows that the rocking response that is induced by the spine produces a uniform distribution of drift demands along the height of the building.

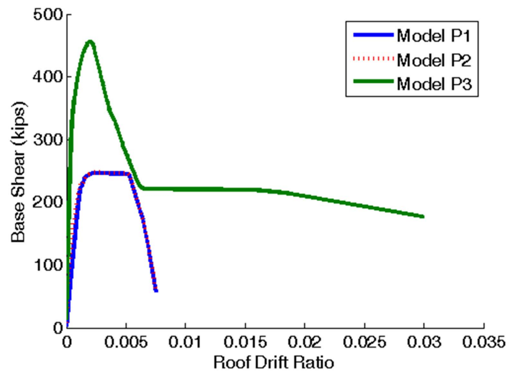

Figure 8. Pushover response of prototype model variants

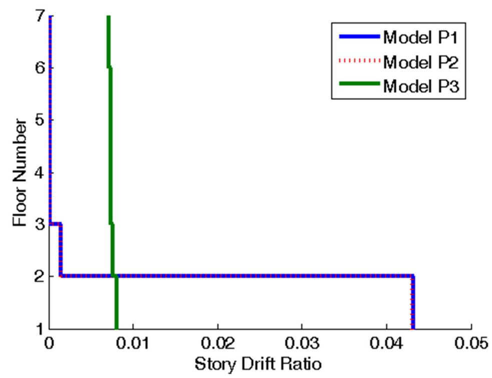

Figure 9. Story drift distribution from pushover response at .75% roof drift

Nonlinear Response History Analyses Pre-Collapse Assessment

A series of nonlinear response history analyses is conducted on the three prototype models to study the behavior of the rocking spine system under dynamic loading. The normalized far-field record set of 22 component pairs of horizontal ground motions used in the FEMA P695 Project (FEMA P695, 2009) is adopted for the analyses. This record set includes a total of 44 records, with two records from each component pair. The existing building from which the prototype models were established is located in a region of moderate seismicity. As such, the seismicity is based on a site located in Sacramento County, with a maximum credible earthquake (MCE) spectral intensity (Sa_{T1}) of .44g. The three prototype models are analyzed using the forty-four ground motions scaled to the design basis earthquake (DBE) and maximum credible earthquake intensities.

Fig. 10 shows the median story drift profile for the three prototype models at the DBE earthquake level. The results of the dynamic analyses are consistent with the pushover response. Models P1 and P2 experience a relatively uniform drift profile from the 2nd through the 6th stories with a significant increase in drift demands at the first story. The maximum story drifts in the 2nd through 6th stories are higher in Model 3 than Models 1 and 2. However, this increase in drift demands at the upper stories is offset by a significant reduction in the 1st story drifts. Comparing the median drift profile for Model 3 to the drift profile from the pushover response (Fig. 9) highlights a limitation of the pushover analyses. From the pushover response, we observe an almost perfectly uniform distribution of drift along the height. However, while not as significant as in Models P1 and P2, we see there is still some level of drift concentration at the 1st story of Model P3 from the dynamic analysis. This suggests some level of damage to the spine, which is not captured in the pushover response. Recall that the spine infill panels are significantly stronger and stiffer than that of the non-spine infill but the ductility of two types of panels is the same. The enhanced performance of the rocking spine system relies on the elastic or near elastic behavior of the spine infill since it will be constructed with non-ductile materials. The spine will be designed as a force controlled element using capacity design techniques. Therefore the strength of the spine is one of the more critical design parameters that will affect seismic performance, particularly at the collapse limit state.

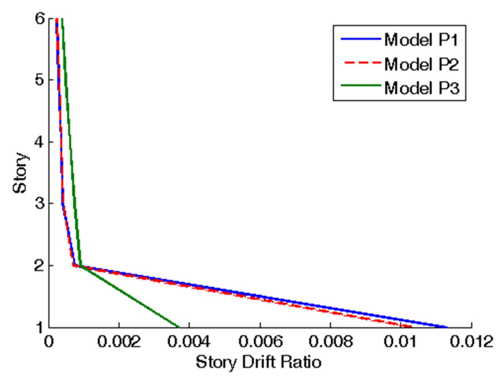

Figure 10. Median story drift profile from response history analyses at the DBE intensity level

Nonlinear Response History Analyses Collapse Assessment

The sidesway collapse capacity of the three prototype models are assessed using the FEMA P695 methodology. The collapse performance assessment only incorporates dynamic instability due to simulated deterioration modes including (1) flexural strength and stiffness degradation of beam-column elements and (2) axial strength and stiffness degradation of infill struts. The effect of other collapse mechanisms is being examined as part of a larger research effort; however, these results are not presented in this paper. The collapse fragility curves for all three models are shown in Fig. 11. Using the probability of collapse at the MCE intensity as the measure of collapse safety, we see that models P1 and P2 perform poorly, both having close to a 50% probability of collapse at that intensity. To put those numbers in perspective, FEMA P-695 requires a maximum 10% probability of collapse at the MCE for new building designs. Model P3 with the rocking spine had a 17% probability of collapse at the MCE. Although this number is still higher than the limit prescribed by FEMA P-695, it represents a marked improvement over the other two prototypes.

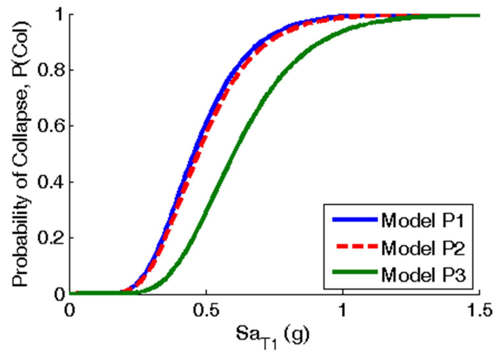

Figure 11. Collapse fragility curves

Conclusions

This paper introduces a new approach to improving the collapse performance of non-ductile infill frame buildings. A spine system is implemented, whose deformation is dominated by rocking action. This has the effect of imposing uniform drift demands along the height of the building reducing the tendency for concentrated deformations, which is typical in traditional infill frame buildings. Idealized backbone curves are used to describe the component and system limits states. A numerical pilot study is conducted on a prototype model based on an existing infill frame residential building located in Karachi, Pakistan. Several prototype models are developed in OpenSees and investigated using nonlinear static and dynamic analyses including an assessment of collapse performance. The models are also used to demonstrate the ability of the spine to reduce drift concentrations and improve collapse safety and overall seismic behavior. The following is a summary of the findings from the pilot study:

- The numerical model representing the as-built condition is characterized by very low ductility with the formation of a sidesway mechanism at the first story where there are no infill panels.

- Extending the infill panels in the central bay down to the first story without changing its properties has very little impact on the strength and ductility of the system. Failure of the infill at the first story where the highest shear forces are generated leads to the formation of a story mechanism.

- A minimum spine infill strength is needed to maintain its elastic response to static loading and induce rocking behavior in the system. For spine strengths below that threshold, the pushover response is characterized by low ductility and the formation of a story mechanism. At higher strengths, the behavior is dominated by rocking action and rigid-body behavior resulting is significant enhancements in post-peak performance.

- Unlike the pushover analysis, the spine infills were damaged when analyzed using nonlinear response history analyses. The median story drift profile for the rocking spine reduces the level of drift concentration observed in the response history analysis, but not to the extent observed in the pushover analysis. These results point to the fact that the structural components that make up the spine should be designed as force-based elements appropriately accounting for dynamic effects.

- The results of the collapse assessment show that the prototype models without the rocking spine have unacceptably high probabilities of collapse (approximately 50% at the MCE level) even with moderate seismicity. The rocking spine system provides significant reductions in the probability of collapse at the MCE level, reducing it by a factor of 2.5.

This study is part of a larger research effort to develop low-cost seismic risk mitigation technique for infill frames. Current and future work includes (1) studying the effect of potential undesirable failure mechanisms such as infill-induced column shear failure, (2) developing a general design procedure and simplified analysis methods to predict earthquake induced drifts and force demands and (3) establishing a framework to assess the impact of the rocking spine system on measures of community resilience.

Acknowledgments

This research is motivated in part by the EERI Framed Infill Network (www.framedinfill.org) initiative and a collaborative project with GeoHazards International. The authors also acknowledge valuable discussions on the research with K. Mosalam, D. Mar, J. Rogers, and S, Gunay.

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