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SEISMIC RETROFIT OF NON-DUCTILE REINFORCED CONCRETE INFILLED FRAME BUILDING USING ROCKING SPINES

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ABSTRACT

This paper presents the preliminary results of a case study examining the feasibility of using rocking spines to retrofit non-ductile reinforced concrete frame buildings with unreinforced infill masonry walls. This novel retrofit technique involves introducing a strong stiff "spine" into the lateral system of an existing infill frame building with foundation elements designed to allow for uplift. Earthquake effects are resisted through rocking action relying on uplift at the spine foundation as the yielding mechanism. The primary goal of the retrofit technique is for the rocking spine to impose uniform drifts over the height of the structure reducing the tendency for concentrated drift demands which would typically occur at lower levels. The building used in the case study is a six story non-ductile concrete frame building with infill at the upper levels and an open ground floor creating a soft story. Preliminary results from pushover and nonlinear response history analyses show that the rocking spine retrofit provides significant improvement in the seismic performance.

Keywords: *Infill Frames; Masonry; Reinforced Concrete: Rocking systems; Seismic Effects; Retrofit*

1. INTRODUCTION

1.1. Background on Infill Frames

Reinforced concrete frames with masonry infill walls (infilled frames) are among the most commonly used building systems around the world particularly in less affluent communities. In many high seismic regions, these buildings have been constructed with little or no regard to seismic resistance usually consisting of non-ductile concrete frames and unreinforced infill. With rapid growth of the urban populations around the world, infill frames are also being used for taller residential buildings that are often constructed with an open ground floor creating a soft story. These structures are likely to exhibit complex behavior under seismic loads and due to their low strength and ductility, they would be unable to withstand high levels of drift making them highly susceptible to collapse. In the past decade, there have been thousands of earthquake casualties as a result of poor performance of infilled frame buildings, including most recently in Haiti in 2010, China 2008 and Indonesia 2004.

1.2. Rocking Spine Retrofit Technique

Over the past four decades, a number of retrofit techniques have been developed for non-ductile concrete frames with infill. The main focus of these previous retrofit techniques have been to improve the strength, stiffness and in some cases ductility of the masonry infill. This is typically achieved by applying some type of material overlay to the infill to improve its seismic performance. Cement plaster with wire mesh reinforcement has been shown to add strength and stiffness but with little impact on ductility. The application of advanced composite materials such as Engineered Cementitous Composites (ECC) has been shown to add strength, stiffness and ductility (Kyriakides *et al.*, 2010) to infilled frames. However the cost of these types of materials often renders them impractical for implementation in a seismic retrofit particularly in less affluent communities where these types of buildings are prevalent. Another retrofit approach that has been used in the past involves the incorporation of a reinforced concrete shear wall into the lateral system of the building. This usually results in good seismic performance provided that the proper detailing is employed to achieve the desired level of ductility.

In this new approach rocking action of a strong stiff spine is used to resist earthquake effects relying on uplift of the foundation as the yielding mechanism. Lateral force demands on the spine are limited by uplift allowing for elastic behavior. As shown in Figure 1, this can be contrasted with previous retrofit techniques that rely on the strengthened infill frame/wall structure as the yielding mechanism. This new approach precludes the added complication of detailing for ductility and also results in additional material cost savings since the spine would typically be more slender than a conventional shear wall.

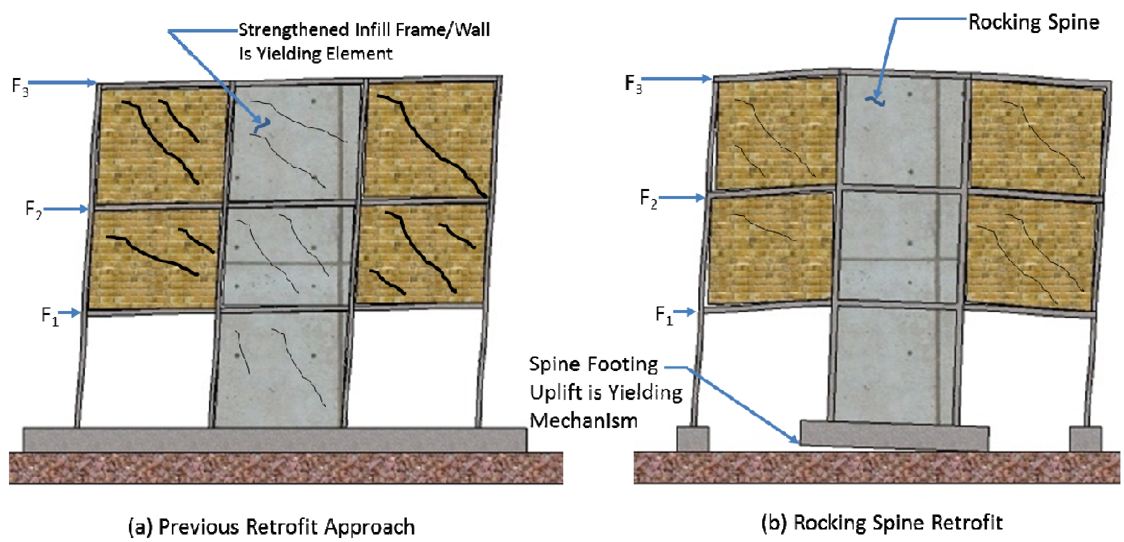


Figure 1 – Schematic Illustration of Rocking Spine Retrofit vs Previous Retrofit Techniques

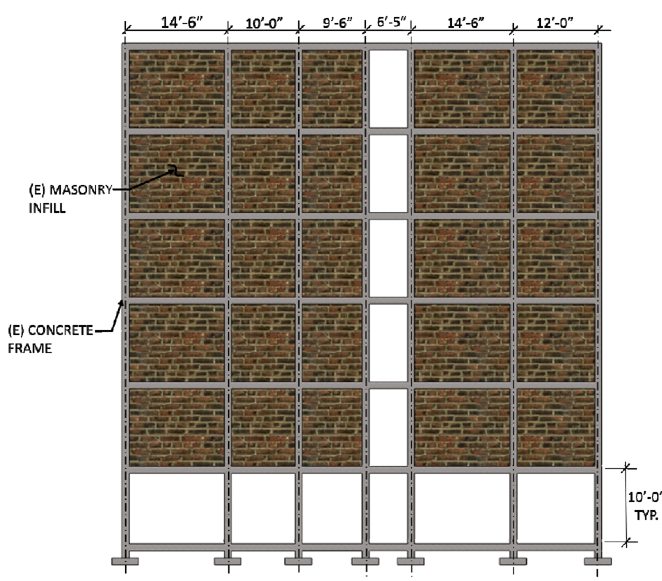
1.3. Overview of Case Study Building

The building used in the case study is a six story mixed use building with shops located in the ground floor and residential apartments in above floors. The building is located in Karachi, Pakistan and was constructed before the 2005 Kashmir Earthquake. It is one of nine buildings that were evaluated as part of a collaborative project between NED University of Engineering and Technology and GeoHazards International (GHI), a California based non-profit organization. The goal of the project was to build capacity in Pakistan's academic, public, and private sectors to assess and reduce the seismic vulnerability of existing buildings and to construct new buildings better. Figure 2 shows a photo taken from the front of the building. The building has a reinforced concrete moment frame system with 6” thick unreinforced concrete block walls. The foundations are reinforced concrete spread footings.

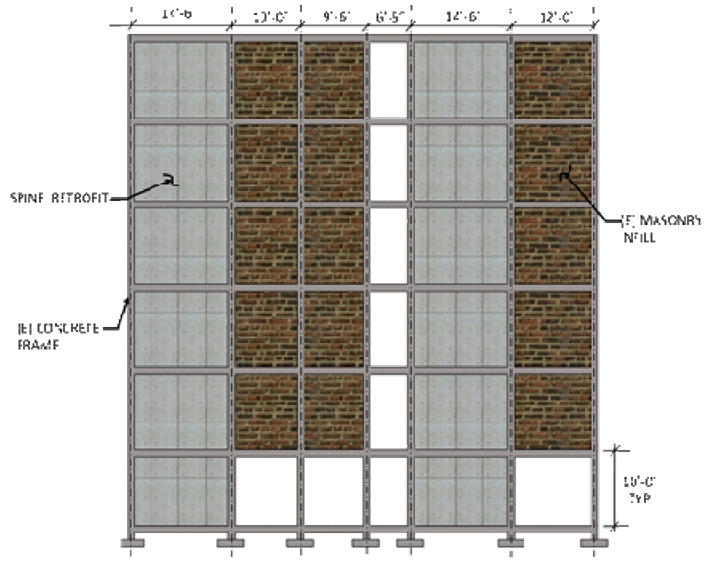
Typical beam sizes are 8" x 24" with 6-#6 bars top and bottom. Story heights were typically 10'-0" with 12" x 24" columns with 8-#8 bars in ground and first floor columns and 8-#6 bars in columns from 2nd floor to roof. Concrete compressive strength was taken as 3000 psi, yield strength of steel was taken as 60,000 psi and compressive strength of infill masonry was taken as 300 psi.

Figure 2 – Front view of the building during construction

A preliminary assessment of the feasibility of the rocking spine retrofit technique was performed through pushover and nonlinear response history analyses of the six-story, six bay frame longitudinal perimeter frame of the case study building. Analyses were performed on both the as-built and retrofitted frames. Figure 3a shows the infill configuration in the as-built frame. Five of the six bays contain infill at all levels except the ground floor creating a soft story configuration and one bay consists of a bare frame at all levels. The retrofitted condition was developed by incorporating strong, stiff uplifting spines in the first and fifth bays of the existing frame as shown in Figure 3b. The spine can be constructed using the existing infill augmented with concrete and mesh reinforcement or any other overlay that provides the appropriate strength and stiffness allowing for elastic behavior.



(a) As-Built Frame



(b) Rocking Spine Retrofit

Figure 3 – Elevation showing layout of as-built and retrofitted frames

2. OVERVIEW OF BUILDING MODELS

The Open System for Earthquake Engineering Simulation (OpenSees 2006) was used to develop nonlinear analaysis models for the case study building. Two-dimensional models were created for both the as-built and retrofitted cases incorporating material nonlinearity in beams and columns, infill walls as well as nonlinearity due to uplift of the retrofitted spine. As shown in Figure 4, a leaning column was used to account additional P-Δ effects from loads on the gravity system that are not included in the analysis model.

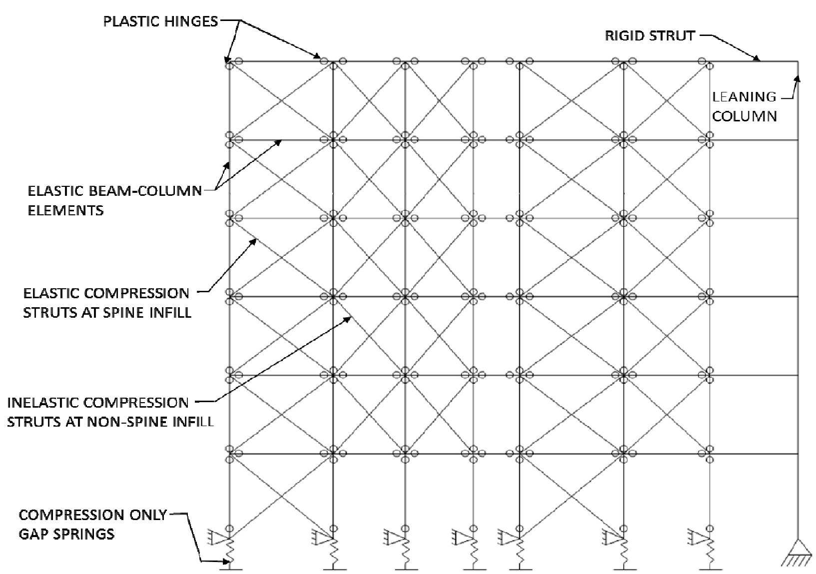


Figure 4 – Schematic of OpenSees Model

Beams and columns were modeled as elastic elements using Ibarra-Krawinkler plastic hinge model to capture non-linear behavior. The model has a tri-linear backbone curve and was calibrated to data from 255 reinforced concrete column tests by Haselton and Deierlein (2007), the outcome of which was a set of equations that could be used to predict its parameters.

Infill walls were modeled as diagonal compression-only struts. Recall that in the case of the retrofitted frame, the infill walls that are incorporated as part of the spine will be strengthened to allow for elastic behavior at uplift. As a result, these struts will be modeled as elastic elements. For the infill panel struts in the as-built structure as well as those in the retrofitted structure that are not part of the spine, material nonlinearity was incorporated by implementing a peak-oriented hysteretic model in OpenSees. The force-displacement backbone curve of the strut model is described by five parameters (F_y, Δ_y, K_s Δ_c and K_c) as shown in Figure 5. The parameters were computed based on modeling guidelines for infilled frames provided in ASCE/SEI 41-06.

In the case of the spine retrofitted frame model, the contact points at the base of all columns were modeled with vertical elastic compression only springs with infinitely high stiffness in compression and zero strength in tension to allow for uplift

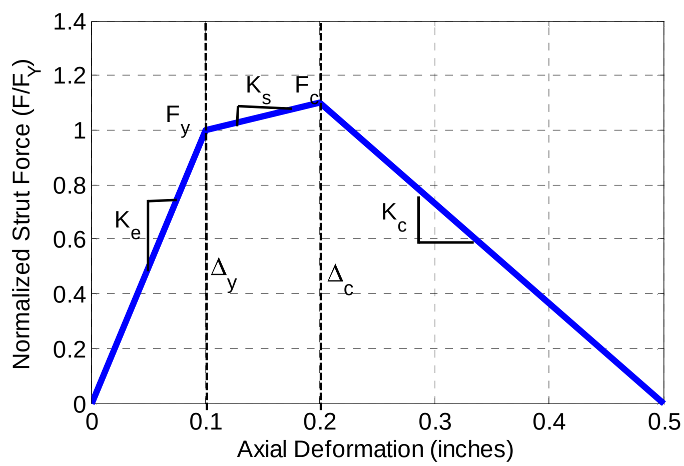


Figure 5 – Backbone Curve for Infill Strut Model

3. PUSHOVER ANALYSIS

Monotonic static pushover analyses were performed on both the as-built and retrofitted structures with lateral loads applied according to the equivalent lateral force distribution specified in ASCE 7-05. The results from the static pushover analysis for both frames are shown in Figures 6a and 6b.

Figure 6a shows a plot of base shear vs roof drift for both frames. It shows that the spine retrofit increases both the strength and drift capacity of the existing frame. The as-built frame has a lateral strength of 470 kips which occurs at a roof drift of .4%. At this point the second story infills begin to degrade with the infills in floors above being undamaged. At a roof drift of .8% a soft story mechanism forms due to hinging in the ground floor columns and the structure becomes unstable. The retrofitted frame has a lateral strength of 631 kips which occurs at a roof drift of .8%. At this point the non-spine infills at all levels begin to degrade uniformly. At 1.8% roof drift the beams in the bay with no infill begin to degrade rapidly due to the deformation demands from the uplifting spine.

Figure 6b shows a plot of the "drift concentration factor" vs roof drift for both frames. The drift concentration factor is defined as the ratio of the maximum story drift to the roof drift and is used to indicate the extent of drift concentration at a particular level. In both models the maximum drift occurs at the ground floor level. Both frames start with a drift concentration factor of about 2, after which the as-built frame experiences an increase in drift concentration up to 6. For the spine retrofit, the drift concentration factor reduces to one.

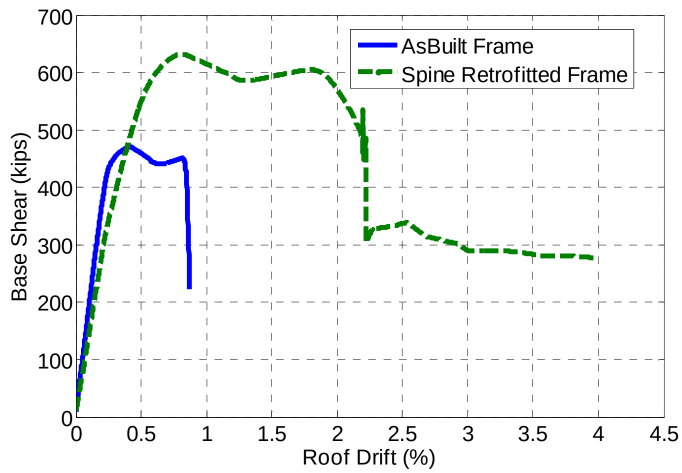


Figure 6a – Base Shear vs Roof Drift from Pushover Analysis

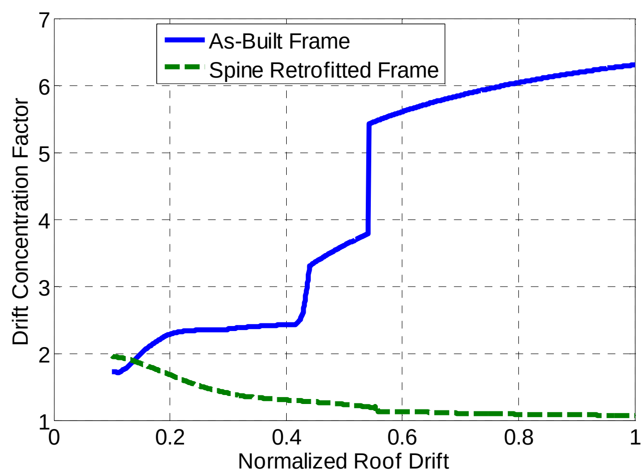


Figure 6b – Drift Concentration Factor vs Normalized Roof Drift

3. NONLINEAR TIME HISTORY ANALYSIS

The seismic performance of the as-built and retrofitted frames was also assessed using nonlinear response history analysis. Incremental Dynamic Analysis (IDA) was performed using twenty far-field ground motions taken from the FEMA 695 Guidelines on Quantification of Building Seismic Performance. In IDA, the structural model is subjected to each of the ground motions and analyzed to predict structural response. This analysis is repeated, each time increasing the intensity on the input ground motion. The first mode spectral acceleration (S_{aT1}) was used as the ground motion intensity measure and this was incrementally increased to a maximum value corresponding to the Maximum Considered Earthquake (MCE) ground motion for the building site.

Figure 7 shows an IDA plot for the as-built model of first mode spectral acceleration vs maximum interstory drift. It shows that at the MCE ground motion level (.48g) 11 of the 20 ground motions have caused collapse of the frame which corresponds to a 55% probability of collapse at that intensity level. Collapse is characterized by dynamic instability of the structure or a large increase in interstory drift resulting from a minute increase in ground motion intensity. For the spine retrofitted frame, none of the 20 ground motions caused collapse up to the MCE level. This suggests a significant reduction in the probability of collapse with the spine retrofit.

Figure 8 shows a plot of the median interstory drift profile for the as-built and retrofitted models for a ground motion intensity corresponding to the Design Basis Earthquake (DBE) for the site. The plot validates the effectiveness of the spine retrofit in imposing uniform drifts over the height of the structure compared to the concentrated drifts at the ground floor in the as-built model.

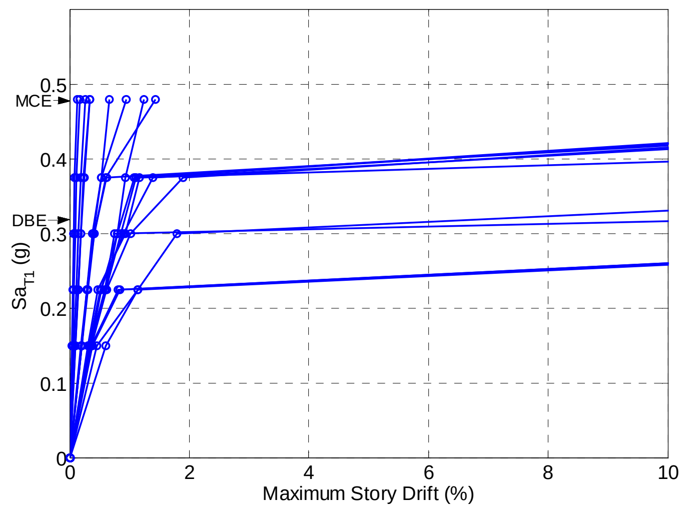


Figure 7– Incremental Dynamic Analysis Plot for As-Built Model

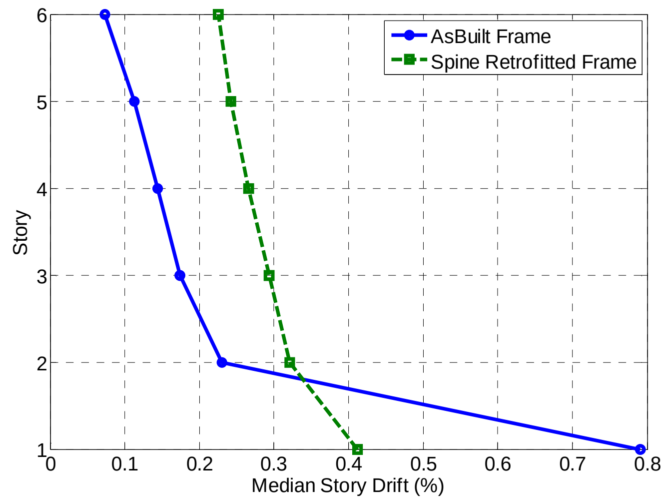


Figure 8 – Median Story Drift Profile for Design Basis Earthquake

4. CONCLUSION AND FUTURE WORK

This paper presents the preliminary results of a case study examining the feasibility of using rocking spines to retrofit non-ductile reinforced concrete frame buildings with unreinforced infill masonry walls. Nonlinear static and response history analyses was used to demonstrate the effectiveness of the spine retrofit in reducing interstory drift demands by imposing uniform deformations over the height of the structure thereby reducing the tendency for drift concentrations at lower stories. Incremental Dynamic Analysis was used to show that the spine retrofit has the potential to significantly reduce the probability of collapse.

The collapse statistics reported for both structures are likely to be unconservative since collapse due to loss of vertical load carrying capacity resulting from column shear failure was not considered. Future work will incorporate column shear failure in the assessment of collapse safety as well as the influence of soil effects on the behavior of the rocking spine. Work is also ongoing to develop the tools and criteria that are necessary to design and assess retrofitted structures.

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