EVALUATION OF SEISMIC PERFORMANCE ENHANCEMENT TECHNIQUES FOR SHEAR WALL BUILDINGS USING ADVANCED MATERIALS AND SYSTEMS

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There has been constant deliberation regarding promising seismic performance enhancement techniques for the reinforced concrete (RC) high-rise structures built before adopting existing seismic design codes. The research reported in this paper focuses on advanced approaches for improving the seismic performance of the shear wall structural system using high-performance reinforced concrete jackets and an outrigger-bracing system consisting of braces with improved hysteresis response. Following the case study region’s seismicity and design criteria, inelastic analyses are conducted to evaluate the demand-to-capacity ratios of primary vertical structural members of a pre-code twenty-six-story building. With the application of the proposed retrofit approaches and their various configurations, the design inadequacy of several structural members is eradicated. After validating the adopted fiber-based discretizations of the retrofit techniques with recent experimental studies, detailed three-dimensional numerical models are developed for the high-rise structures. Inelastic pushover analyses and dynamic response simulations under a diverse set of earthquake ground motions with increasing intensity levels are conducted to capture the buildings’ seismic performance until failure. The probabilistic seismic performance assessment enabled selecting the most effective technique for enhancing the seismic performance of shear wall buildings while minimizing disruption to the building.

Keywords: Pre-code wall structures, Seismic mitigation techniques, Three-dimensional fiber-based modeling, Probabilistic assessment.

1 INTRODUCTION

Earthquakes of different scenarios have exposed the seismic vulnerability of the existing built environment consisting of various structural topologies and led to ponder upon effective seismic retrofit techniques. In compliance with the region’s recently implemented seismic codes and provisions, several pre-code buildings may exhibit lateral capacity degradation and inadequate ductility during earthquakes. Upon reviewing the literature, extensive studies have focused on developing and implementing seismic performance enhancement techniques for low- and mid-rise steel and reinforced concrete (RC) buildings with moment-resisting frame systems (e.g., Mwafy and Elkholy 2017, Issa and Alam 2019). However, limited research investigation exists on multi-story RC shear wall buildings. Various conventional seismic enhancement techniques such as RC jackets, steel braces, and externally bonded FRP have been administered on low-to-medium rise RC buildings. Such traditionally used seismic risk mitigation techniques may not be
deemed effective on RC high-rise wall buildings. Hence, more attention is paid in this study to alternative seismic performance enhancement methods such as thin high-performance RC jackets to increase structural resistance and ductility (e.g. Reggia et al. 2020). The scope of the study also covers outriggers using enhanced bracing systems, which is an attractive technique to increase the structure’s lateral capacity and reduce seismic demands (Taranath 2017).

2 ADOPTED SEISMIC PERFORMANCE ENHANCEMENT TECHNIQUES

The seismic performance assessment of buildings retrofitted with the high-performance RC jacketing technique using fiber-based analyses is limited. Hence, a detailed fiber-based modeling approach that incorporates the high-performance RC jacketing technique was first verified using the results of a previous experimental study (Shao et al. 2021). The cyclic loading test results of strengthened full-scale RC columns were compared with a developed fiber-based numerical model. Figure 1 illustrates the modeling approach in which an inelastic force-based element for both the control and jacketed specimen was considered.

![Figure 1. Numerical modeling approach of high-performance jacketed RC column tested by Shao et al. (2021).](image)

Rigid connection of the RC column with the bottom RC base was modeled through a rigid arm constituted by elastic frame element. The cyclic lateral displacement history applied to the modeled specimens was the same loading protocol used in the experimental program. The hysteretic force-displacement response of the strengthened RC column obtained from the cyclic inelastic analysis is compared with the experimental results. Figure 2 depicts the backbone curve of the RC columns before and after the retrofit with the high-performance RC jacketing method. ‘NC_EXP’ and ‘NC_SIM’ refer to the experimental and numerical backbone curve of the control
RC column specimen, respectively. ‘NC/UHPC_EXP’ and ‘NC/UHPC_SIM’ denote the load-drift response of the jacketed columns obtained from testing and simulation, respectively. The presented results in Figure 2 verify the adopted fiber-based modeling approach before and after retrofitting the column with the high-performance RC jacketing technique. The results also reflect the need to investigate the effectiveness of this retrofit solution on the structure level. Furthermore, Figure 3 shows the uniaxial response curve adopted to model the flag-shaped hysteretic response of the selected self-centering energy dissipating bracing system. Seven different parameters were used in its modeling, including a non-recoverable slip of the external friction fuse present within the brace (Christopoulos et al. 2008). It is noteworthy that verifying the modeling approach using scaled specimens was also adopted in several previous studies, and the presented verification was carried out through an experimentally verified analysis platform (Seismostruct 2022).

Figure 2. Comparison of experimental and numerical results of RC column before and after retrofit with high-performance RC jacket: (a) loading protocol, and (b) backbone curves.

Figure 3. Uniaxial response model adopted to describe the flag-shaped hysteretic response of the self-centering bracing system.

3 DESIGN INADEQUACY AND ENHANCEMENT TECHNIQUES

The floor plan of the benchmark building measures 27m × 27m. The entire height of the building is 84.5 meters, with typical story and ground story heights as 3.2 and 4.5 meters, respectively. The reinforcement used in the design has a yield strength of 240 MPa. The design summary of the main lateral load resisting system is summarized in Table 1. In accordance with the region’s enforced design code, several shear walls were excessively stressed under code-described seismic forces. Table 1 gives further information on the mentioned issue. Using a series of fifteen
enhancement system configurations, initial elastic analysis in line with design requirements and design code (ASCE/SEI 2016) was carried out to evaluate the DCR of the structural members. The evaluation of the high-performance RC jacket technique focused on the jacket thickness, area of reinforcing steel mesh, and locations of RC jacket application at different stories. Out of the investigated configurations, 60 mm thickness (wall width-to-jacket thickness ratio, w/t = 5) concrete jacket and steel mesh retrofit of core walls throughout the first five stories of the 26-story building was selected as the first alternative. This retrofit option also includes 40 mm thick jackets for external piers (w/t = 15), 50 mm thick jackets for coupling beam (w/t = 6), and jacket strength of 130 MPa. Moreover, the presence of a single outrigger system at the middle story is theoretically regarded to be the optimum location for a tall building in terms of structural performance (Taranath 2017). After conducting several inelastic analyses using fiber sections, this retrofit alternative was only effective based on inelastic pushover analyses. The effectiveness of this system was not confirmed from dynamic response simulation due to the occurrence of soft story mechanism above the outrigger level. Based on the initial outcomes from inelastic analyses, the hybrid configuration shown in Figure 4 was put forth using a cap outrigger and belt system along with the application of high-performance RC jacket in the lower two stories. The selection of this second retrofit alternative, which was motivated by the need to reduce the disruption in the building use, gave a comparable performance to the first alternative.

<table>
<thead>
<tr>
<th>Structural Member</th>
<th>Location</th>
<th>Cross-section (mm)</th>
<th>Conc. Grade (MPa)</th>
<th>Vertical steel reinf.</th>
<th>Horizontal steel reinf.</th>
<th>Demand-capacity ratio (DCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pier</td>
<td>Base</td>
<td>600 × 3500</td>
<td>28</td>
<td>66#40</td>
<td>#12@200 mm</td>
<td>0.90</td>
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<tr>
<td></td>
<td>Floor no. 3</td>
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<td>24</td>
<td>52#40</td>
<td>#12@200 mm</td>
<td>0.94</td>
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<tr>
<td></td>
<td>Floor no. 17</td>
<td>400 × 3500</td>
<td>20</td>
<td>36#20</td>
<td>#8@200 mm</td>
<td>0.83</td>
</tr>
<tr>
<td>Core</td>
<td>Base</td>
<td>Web 300 × 8700</td>
<td>28</td>
<td>160#20</td>
<td>#10@200 mm</td>
<td>1.00</td>
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<tr>
<td></td>
<td>Flange 300 × 3300</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floor no. 17</td>
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<td>97#20</td>
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<td>Flange 200 × 3350</td>
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<td></td>
<td></td>
<td></td>
<td>0.55</td>
</tr>
</tbody>
</table>

4 SEISMIC PERFORMANCE EVALUATION

Apart from improving the section capacity of critical wall members to fulfill the recommended design codes, inelastic pushover analyses were undertaken for the benchmark building with and without the selected retrofit techniques. The incremental static analyses provided insight into the collapse mechanism of the structures. For the substandard building, significant stiffness change occurred at the onset of plastic hinge formation on exterior walls and coupling beams, after which immediate concrete cracking of core walls was observed. The attainment of ultimate strength can be estimated at concrete crushing of piers. Through the selected retrofit techniques, improvement in global lateral stiffness and strength with significant enhancement in ductility capacity was observed. Critical local failure modes such as concrete crushing of coupling beam, concrete cracking and buckling of rebars of shear walls at the periphery of the core walls were delayed. Figure 5 shows the capacity curves of ‘O-BUILD’, referring to the existing building, ‘HIGH-PERF JACKETING’ and ‘HYBRID CONFIG’, denoting the retrofit techniques adopted. The global drift criterion in terms of inter-story drift ratios was the response parameter of interest in the non-linear dynamic analyses.
The adopted earthquake record set considering seven severe far-field ground motions has a similar mean to a larger set of records used in previous vulnerability assessment studies (Alwaeli et al. 2020). Figure 6 depicts the time-histories of the earthquake records considered and the mean of the maximum inter-story drift ratios obtained from the dynamic response simulation. It is shown that the drift demands of the benchmark building obtained from the time-history analyses were substantially reduced at different intensity levels through the application of the enhancement techniques. The incremental dynamic analysis results enable describing the structural system response probabilistically and selecting the most effective retrofit technique for enhancing the seismic performance of shear wall buildings.
5 CONCLUSIONS

This study proposed viable seismic retrofit solutions for high-rise RC wall buildings built in the absence of seismic regulations. Implementation of the mitigation techniques on critical stories of the structure was deliberated without exceedingly comprising architectural features and building occupancy. Prior to the numerical application of seismic retrofit techniques, the adopted fiber-based modeling approach at the member level was verified against previous experimental results. The effectiveness of the selected retrofit techniques was bifurcated into local section improvement and global enhancements in terms of initial stiffness, ultimate strength, and ductility capacity, along with reductions in drift demands. The sample results presented in this paper indicated that the hybrid retrofit technique is a promising alternative as it exhibits comparable seismic performance enhancement to the high-performance jacketing while minimizing disruption to the building.

Acknowledgments

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References


