SEISMIC PERFORMANCE EVALUATION OF HIGH-RISE BUILDINGS WITH RC FLAG WALL SYSTEMS

S. A. Reddy\textsuperscript{1} and N. Anwar\textsuperscript{2}

ABSTRACT

The seismic performance of high-rise buildings is primarily controlled by their lateral load-resisting system. An efficient building system is characterized by an optimum combination of structural and non-structural components with certain desirable properties in terms of stiffness and ductility, resulting in an improved overall structural integrity and desirable lateral response. In recent years, several new structural systems and techniques have been developed to improve the lateral stiffness and the performance of reinforced concrete (RC) high-rise buildings subjected to lateral excitations. The use of flag wall system (i.e. the RC walls in selected floors, not reaching the foundation) can be an efficient way to achieve this goal. The underlying idea is that the certain number of selected partition walls (which are generally made of brick masonry) can be effectively replaced with RC walls, and therefore, can be used as structural components of lateral load-resisting system. This study evaluates the seismic performance of such flag wall structural systems used as an alternative to the conventional outrigger system. Using a case study high-rise RC building, the detailed analysis is carried out for various configurations of flag walls. It is shown that the use of flag walls as part of lateral load-resisting system can significantly improve the structural performance of high-rise buildings, and therefore, the idea can be further considered for detailed evaluation under different loading scenarios.

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Proceedings of the 11\textsuperscript{th} National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.
Performance Evaluation of High-rise Buildings with RC Flag Wall Systems

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\textbf{ABSTRACT}

The seismic performance of high-rise buildings is primarily controlled by the stiffness of their lateral load-resisting system. All structural components contribute their individual stiffnesses to the overall system. In recent years, several new structural systems and techniques have been developed to improve the lateral stiffness and the seismic performance of reinforced concrete (RC) high-rise buildings. The use of flag wall system (RC walls in selected floors, not reaching the foundation) is among an efficient way to improve the resistance of high-rise buildings against lateral excitations. Partition walls, general made of brick masonry, are a necessary component of both commercial and residential high-rise buildings. However, they may not be used as outriggers due to discontinuity. These partition walls can be effectively replaced with RC walls and therefore, can be used as structural components. This study evaluates the seismic performance of such flag wall structural systems used as an alternative to the conventional outrigger system. Using a case study high-rise RC building, the detailed nonlinear seismic analysis is carried out for various configurations of flag walls. It is shown that the use of flag walls as part of lateral load-resisting system can significantly improve the structural performance of high-rise buildings.

\textbf{Introduction}

The structural efficacy of tall buildings heavily depends on the lateral stiffness and resistance capability. Among several structural systems for tall buildings, outrigger system is among the common and economic systems, particularly for those with comparatively regular architectural plans. Historically, the use of outriggers in building structures can be linked to the use of deep beams. Conventional outrigger systems were simply accustomed to provide further stiffness to reduce drifts and deflections. However, new applications for outrigger systems currently involve providing additional damping to reduce wind response and acceleration, and conjointly may also be used as structural fuse to safeguard the building under a severe earthquake condition (Taranath, 2009).

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Flag walls are concrete walls in selected floors, not reaching the foundation. They provide additional stiffness, strength and ductility to the overall structure. They can be effective in reducing overall lateral roof drifts, inter-story drifts and building periods similar to outriggers. Partition walls, general made of brick masonry, are a necessary component of both commercial and residential high-rise buildings (ASCE 41-13, 2013). However, they may not be used as outriggers due to discontinuity. These partition walls can be effectively replaced with RC walls and therefore, can be used as structural components. The advantages of flag wall system includes economy and better space planning to suit architectural, mechanical and leasing criteria which outriggers sometime cannot do (Hi Sun, 2012; Goman, 2016). However, it can also lead to abrupt changes in local response of walls and frames if not placed properly.

There is little research on investigating the adequacy of flag wall structural system as a lateral load resisting system. This study evaluates the seismic performance of such flag wall structural systems used as an alternative to the conventional outrigger system. Using a case study building located in a high seismic risk area, the suitable location for flag walls is determined to improve the global response for seismic design. The performance of final configuration is evaluated against a maximum considered earthquake (MCE) using nonlinear analysis (ATC 72, 2010). The presented results are of practical importance as they provide an insight about the effect of flag walls on lateral response of individual components as well as overall story-level response (TBI, 2010).

**Methodology**

The case study building is located in Ortigas Centre, Mandaluyong City, Phillipines. The residential tower is a 50-story high-rise building (170m high). The gravity loads are primarily resisted by flat slab in the tower. The gravity load from each floor is transferred through reinforced concrete core wall and peripheral columns to the foundation. The lateral loads are resisted by the special reinforced concrete core wall, built around the elevator shaft, staircases, and other services. Flag walls are also used in Y direction of the case study building to improve the lateral stiffness and to resist the lateral loads. Figure 1 shows the typical floor plan of the tower.

![Figure 1. The typical floor framing plan of residential tower](image1)

![Figure 2. The response spectra used in this study](image2)
The code-prescribed gravity loads are applied in addition to the self-weight of the structure. The minimum loading requirements were taken from Table 4-1 of ASCE 7-10. The seismic input is obtained from a detailed study aimed to carry out the probabilistic seismic hazard analysis and to determine design ground motions for Sonata Premier, Ortigas, Mandaluyong City Philippines. The performance of the building is checked under the MCE-level ground motions, i.e. with an approximate return period of 2475 years (2% probability of exceedance in 50 years) (ASCE 7-10, 2010). Figure 2 shows the response spectra used in this study.

For both linear and nonlinear analysis, the detailed three-dimensional structural models were created in ETABS 2016 (CSI, 2016). The models include core walls, columns, coupling beams, flag walls, beams, slabs. In linear model, the core walls, flag walls, slabs, walls are modeled using shell elements, whereas the columns, coupling beams, and beams are modeled using frame elements. The nonlinear models include inelastic member properties for elements which were anticipated to be loaded beyond their elastic limits (NEHRP 2010; 2012; 2016). These include flexural response of coupling beams, slab-beams, and shear wall. The columns are modeled using P-M2-M3 fiber elements whereas the rotations are checked according to ASCE 41-13 (2013) table 10-8. The core wall are modeled as fiber P-M3 elements. The shear capacity is calculated using expected strengths and strength reduction factor of 1.0 (LATBSDC, 2014). The elements that are assumed to remain elastic are modeled with elastic member properties. These include shear walls, flag walls and diaphragm slabs, and columns.

Table 1 The acceptance criteria for Maximum Considered Earthquake (MCE)

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transient drift</td>
<td>Maximum of mean values shall not exceed 3%.</td>
</tr>
<tr>
<td>Coupling beam inelastic rotation</td>
<td>≤ 0.05 radian for both conventional and diagonal reinforced beams</td>
</tr>
<tr>
<td>Column (Axial-flexural interaction and shear)</td>
<td>According to table 10-8 in ASCE 41-13</td>
</tr>
<tr>
<td>Shear wall reinforcement axial strain</td>
<td>≤ 0.05 in tension and ≤ 0.003 in compression</td>
</tr>
<tr>
<td>Shear wall concrete axial compressive strain</td>
<td>Fully Confined ≤0.015, Intermediately Confined ≤ 0.004, No Confinement ≤ 0.003</td>
</tr>
<tr>
<td>Shear wall shear</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Columns shear</td>
<td>Remain elastic</td>
</tr>
<tr>
<td>Flag walls shear</td>
<td>Remain elastic</td>
</tr>
</tbody>
</table>

Results and Discussions

First, the linear elastic models with five different configurations of flag walls are analyzed using
the linear dynamic analysis i.e. response spectrum analysis (Figure 4). The model which has the best lateral response is chosen for the detailed performance assessment using the nonlinear multimode pushover analysis. The story displacements and inter-story drift ratios from different models are compared (Figure 5). The local responses of members include the core wall shear and moment and columns shear and moments along the height (Figures 6 and 7).

Figure 4. The configurations of flag walls compared in this study to optimize the local performance of connecting members

Figure 5. The global responses of models with all five configurations of flag walls

Figure 5 shows that for all five configurations, the inter-story drift ratio is within the acceptable limits. Figures 6 and 7 shows the combined shear force and moment in selected shear wall panels and columns in Y direction of the case study building (with different configurations of flag walls). It can be seen that config 1, config 3 and config 4 show relatively better seismic responses. These configurations can be recommended to be used for design against a DBE-level earthquake. For detailed performance assessment, the config 1 (shown in Figure 8) is used in this study as it resulted in the most economical design compared to the other configurations.
Figure 6. The local responses of core wall (shear and moment in Y direction)

Figure 7. The local responses of selected columns (shear and moment in Y direction)

Figure 8. The final configuration selected for the detailed nonlinear analysis
The nonlinear multi-mode pushover analysis is carried out for the selected configuration. The equal-displacement assumption is used for the determination of target displacement for each significant vibration mode of the building in selected (Y) direction. The maximum elastic displacement of each vibration mode is extracted from the response spectrum load case of elastic model subjected to MCE-level spectrum. These peak elastic displacements are assumed to be the target displacements for each significant mode. The peak modal responses from each modal pushover load case are extracted and combined using the SRSS combination rule to obtain the overall nonlinear seismic demands of the case study building.

Figure 9(a) shows the story shear of the nonlinear model containing the selected configuration of flag walls. It can be seen that the shear is well below the maximum limit, implying the satisfactory performance. Figure 9(b) shows the comparison between linear and nonlinear base shear for MCE-level earthquake. It can be seen that an effective response modification factor (R) of 1.95 is exhibited in the selected direction.

The local response of selected columns and shear wall panels in the direction of flag walls are reviewed under the MCE-level seismic hazard. Figures 10 and 11 show the column fiber rotations and axial rotations in shear wall fibers, respectively. It can be seen that the column rotations are well below the maximum limit. However, the selected panel of core wall has yielded at three locations (other than base) above the story where the flag wall story ends (Figure 11). This requires a careful investigation and further assessment, if required.

The response of flag walls is also reviewed by checking the shear demand-to-capacity (D/C) ratio. Figure 12(a) shows the four example walls (FW1, FW2, FW3 and FW4) for which the shear D/C ratio check is presented in Figure 12(b). It can be seen that the D/C ratios are less than
1 along the whole height of case study building.

Figure 10. The rotations in the selected columns compared against the yield limit

Figure 11. The axial strains in the selected panel of core wall compared against the yield limit

(a) The location of flag walls reviewed
Figure 12. The seismic performance of flag walls in terms of shear demand-to-capacity ratios

Conclusions

Flag walls can be effectively used as an alternative to outriggers to control the global seismic response of the buildings. However, they may create local concentration of forces which can be controlled by selecting an optimum and symmetric configuration of flag walls. Generally, the flag walls placed closer to the core wall exhibit better global response. An increase in the number of stories having flag walls results in less shear demand in walls but increases the shear in the core wall elements.

References

CSI. Extended Three Dimensional Analysis of Building Systems 2016. Computers and Structures, 2016, California, USA.
Goman Wai-Ming Ho, A. The evolution of outrigger system in tall buildings. CTBUH, 2016.
LATBSDC. An alternative procedure for seismic analysis and design of tall buildings located in Los Angeles region, 2014.


NEHRP. Seismic design of cast-in-place. NEHRP seismic design technical brief no. 6, 2012.

