

Seismic Performance of Building Structures with Spatial Variability

Jinkoo Kim, Joonho Lee, and Seungho Han

Abstract—In this study the seismic performances of reinforced concrete apartment buildings with Y-shaped plans having central core are investigated. Three types of model structures are designed for each shape depending on the amount of shear partition walls: structures with all shear walls, structures with all columns except the core walls, and structures with shear walls and columns combined. The required amount of concrete is the largest in the all shear wall structures, and decreases as more and more shear walls are replaced with columns. According to nonlinear static and dynamic analysis results, the structures with all shear walls and all columns turn out to have the largest and the smallest strengths, respectively.

Index Terms—Seismic performance evaluation, fragility analysis.

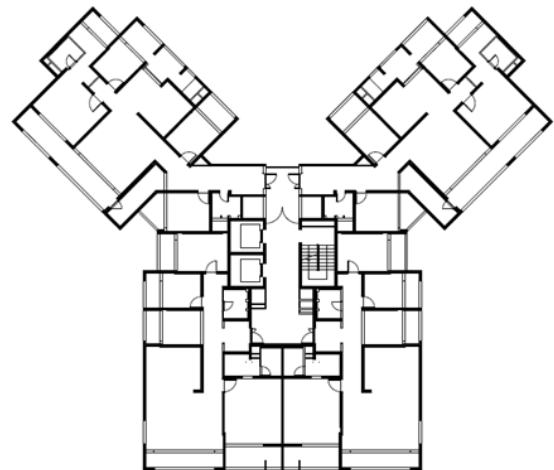
I. INTRODUCTION

One of the new paradigms of the twenty first century construction industry is to design structures more sustainable and resource efficient. In Korea many apartment buildings composed mainly of vertical shear walls have been demolished not because the structures were old and weakened beyond repair but because the plan layouts divided into many small spaces did not fit the changed life style of residences who prefer large open spaces. To enhance the possibility of remodeling of a plan layout of residential buildings, Korean government provides various incentives for apartment buildings designed with spatial flexibility. This can be achieved by replacing the interior shear partition walls of apartment buildings with columns and removable partitions so that new residence can reshape the interior spaces as they like. However the removal of shear walls may result in insufficient lateral load-resisting system against seismic load.

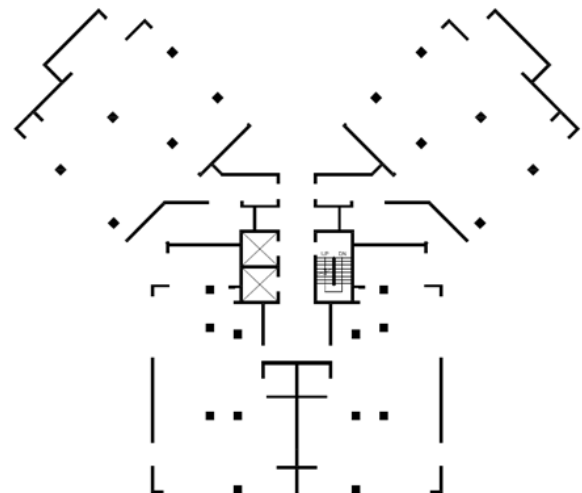
This study investigates the seismic performance of Y-shaped apartment buildings with central RC core and transverse shear partition walls. Three different variations were made depending on the amount of shear walls. Nonlinear static and dynamic analyses were carried out to obtain ultimate strength and collapse mechanism of the model structures.

II. DESIGN AND ANALYSIS MODELING OF EXAMPLE STRUCTURES

The analysis model structures are the twenty-story reinforced concrete (RC) buildings composed of four apartment units per floor. To study the seismic performance of the structures with different spatial variability, the following three types of analysis model structures were prepared: the structures with transverse shear walls (Type-1); the structures with part of the shear walls replaced by columns; and the structures with all transverse shear walls replaced by columns (Type-3). Fig. 1 shows the structural plans of the analysis model structures. All model structures have the same story height of 3m.



(a) Type 1



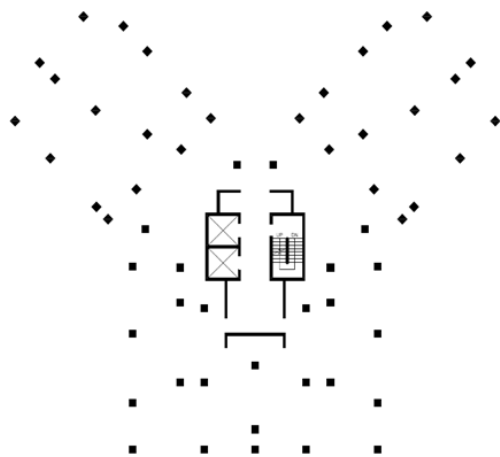
(b) Type 2

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(c) Type 3
Fig. 1. Structural plans of model structures

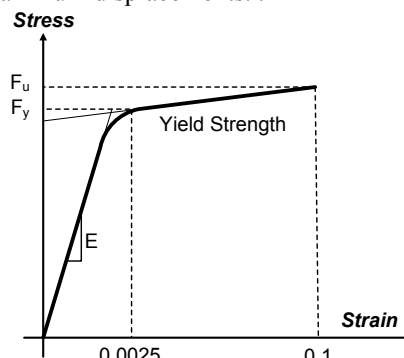
The analysis model structures were designed with both gravity and lateral loads such as wind and seismic loads. The dead load used for design is 7kN/m^2 , and the live load of 2kN/m^2 is used for design. The seismic loads are evaluated using the seismic coefficients S_{DS} and S_{D1} equal to 0.37 and 0.15, respectively, in the IBC (International Building Code) format [1]. The response modification coefficient (R-factor) for Type-1 structures is 4.0 which corresponds to the R-factor for ordinary RC shear wall structures in the category of Bearing Wall Systems. The R-factor of 5.0 is used for Type-2 and Type-3 structures, which are considered as ordinary RC shear wall structures in the Building Frame Systems. The structures were assumed to be built on the Site Class B soil. The thickness of the core wall is 200mm, 250mm, and 300mm in the Type-1, Type-2, and Type-3 structures, respectively. The transverse shear walls have the uniform thickness of 200mm. The model structures were designed in such a way that the strength ratios (the ratios of demand and capacity) of shear walls and columns were maintained between 0.7 and 0.8 in all model structures.

The stress-strain relationships of concrete and reinforcing steel were defined as tri-linear and bi-linear lines, respectively, as shown in Fig. 2 based on the material model of Paulay and Priestley [2] without confinement effect. In the model the ultimate strength and yield strength of concrete are 27 MPa and 18MPa, respectively, and the residual strength was defined as 20% of the ultimate strength. The strain at the ultimate strength is 0.002, and the ultimate strain is defined as 0.004. For reinforcing steel, F_y and F_u are 400 MPa and 480 MPa, respectively. The shear walls were modeled by the Shear Wall fiber elements in the Perform 3D [3]. The axial bending behavior was modeled by vertical fiber elements, and the transverse stiffness of the wall and the out-of-plane bending stiffness were assumed to be elastic.

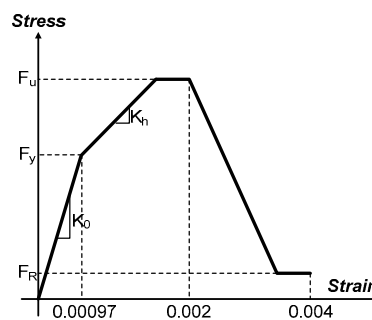
III. PUSHOVER ANALYSIS RESULTS

Nonlinear static pushover analyses are carried out along the principal axis of the structures until the maximum displacements reach 5% of the total height to identify nonlinear force-displacement relationships of the model structures. The

lateral story forces are determined in proportion to the fundamental mode shapes. Fig. 3 shows the pushover curves of the model structures, where the vertical axis represents the applied base shear, V , normalized by the design base shear, V_d , and the horizontal axis represents the roof displacement. The points of four damage states specified in the Korea National Emergency Management Agency are also marked on the curves. The damage states of structures are defined as four levels such as Slight, Moderate, Extensive, and Complete. The states of ‘Slight Damage’ and ‘Moderate Damage’ are defined as the spectral displacements corresponding to 70% and 100% of yield point, respectively. The ‘Extensive Damage’ is defined as the quarter point from ‘Moderate’ to ‘Complete’ damage. The ‘Complete Damage’ is the spectral displacement at which the strength is decreased to 80% of the maximum strength. It can be observed that the maximum strength is the highest in the Type-1 structures with largest amount of shear walls, and decreases as the amount of shear wall decreases. The overstrength ranges from 1.5 (Type-3) to 2.2 (Type-2). The Type-3 structure shows smallest strength and ductility. It is observed that in the Type-1 and Type-2 structures plastic hinges form first in the first story transverse shear walls and spread to shear walls in the higher stories. In Type-3 structures plastic hinges are concentrated in the lower story core walls and the structures experience relatively less energy dissipation and fail at smaller maximum displacements. .



(a) Re-bar



(b) Concrete

Fig. 2. Stress-strain relationships of structural materials

IV. NONLINEAR DYNAMIC ANALYSIS RESULTS

The seismic performances of the model structures are also evaluated through nonlinear dynamic analyses using the seven earthquake records selected from earthquake records provided by the Pacific Earthquake Engineering Research Center (PEER) [4]. The selected records are scaled to fit the

design spectrum for earthquake load with return period of 2,400 years specified in KBC 2009 [5] in such a way that the pseudo accelerations of the records at the natural period of a model structure are equal to the spectral acceleration of the design spectrum at the same natural period. Fig. 4 shows the response spectra of the seven earthquake records, the design spectrum of the KBC 2009, and the median response spectrum of the scaled records. In all cases damping ratio is assumed to be 5% of the critical damping. Fig. 5 depicts the mean inter-story drifts of the model structures. The inter-story drifts of Type-3 with least number of shear walls are almost twice as high as those of the Type-1 structures. It can be observed that the maximum inter-story drifts of the model structures subjected to design level earthquake ground excitation are significantly smaller than the limit state of 1.5% of story height specified in the design code.

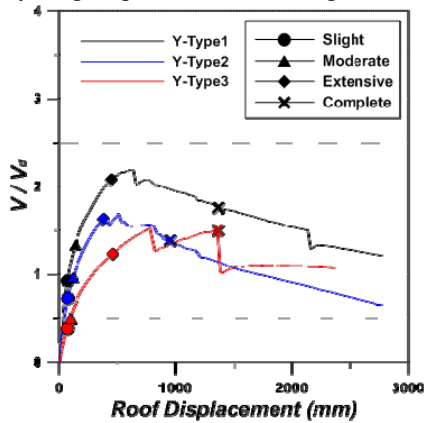


Fig. 3. Pushover curves of the model structures

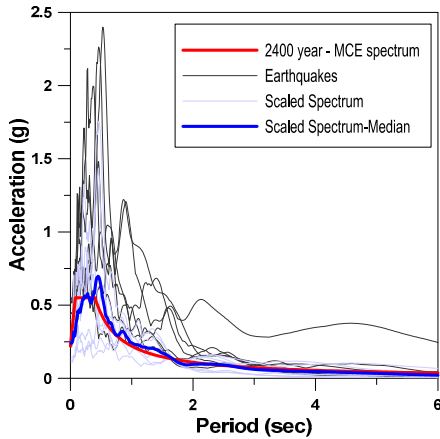


Fig. 4. Response spectra of seven earthquake records and maximum considered earthquake spectrum

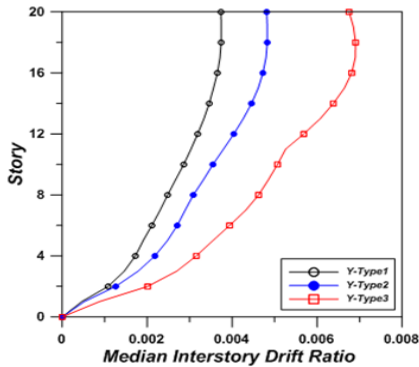
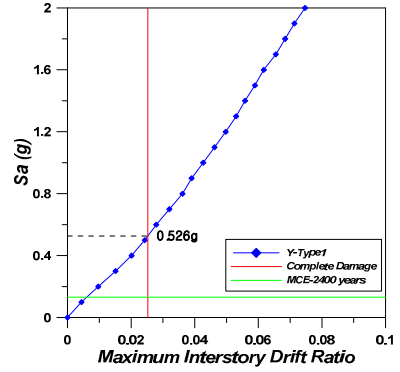
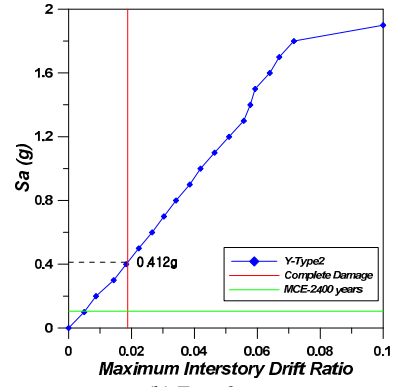


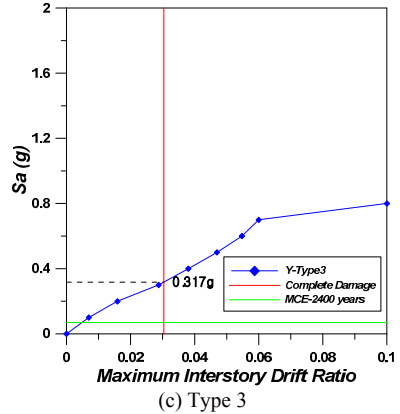
Fig. 5. Mean inter-story drifts of analysis models obtained from non-linear dynamic analysis using seven earthquake records



(a) Type 1



(b) Type 2



(c) Type 3

V. INCREMENTAL DYNAMIC ANALYSIS RESULTS

In this section the incremental dynamic analyses of the model structures are performed using the Superstition Hills earthquake record. A series of nonlinear dynamic analysis are carried out by increasing the response spectral value corresponding to the fundamental natural period of each structure by 0.1g. The response spectra (S_a) and the corresponding inter-story drifts obtained from the incremental dynamic analyses are shown in Fig. 6. The MCE-level seismic intensity in Seoul area with return period of 2,400 years and the inter-story drift at the complete damage state obtained from the pushover analyses are also shown in the figures. The analysis results show that in the Type 1 structure, which is the all-shear wall structure, the complete damage state is reached at $S_a = 0.526g$. The earthquake intensity at the same damage state is reduced to 0.412g in Type 2 structure and to 0.317g in the Type 3 structure. As expected the strength at the damage state keeps decreasing as more and more shear walls are replaced by columns. However in all cases the strengths at the complete

damage states are significantly higher than those corresponding to the MCE-level earthquake.

VI. CONCLUSIONS

This study investigated the seismic performances of apartment buildings with Y-shaped plans having central core. Three types of model structures were designed for each shape depending on the amount of shear partition walls: structures with all shear walls, structures with all columns except the core walls, and structures with shear walls and columns combined. Nonlinear static and dynamic analyses were carried out to compare the structural performances of the model structures with different amount of shear partition walls.

The required amount of concrete to satisfy the specified design loads was the largest in the all shear wall structures, and decreased as more and more shear walls were replaced with columns. The amount of re-bars increased significantly in the structures with columns. According to nonlinear static and dynamic analysis results, the structures with all shear walls and all columns turned out to have the largest and the smallest strengths, respectively. However it is observed that even the all-column structures with central core had proper load resisting capacity for design level seismic load. Based on the seismic performance and the structural materials used to satisfy the design loads, it was concluded that the structure with a central core and the columns replacing partition shear walls could be an efficient structure system for residential buildings with enhanced freedom of spatial variability.

ACKNOWLEDGMENT

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