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Seismic Performance Evaluation by Demand Capacity Ratio in Vertical Irregular Buildings

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Abstract

Vertically irregular buildings are vulnerable to earthquake resistance because the lateral load such as earthquake load is concentrated on a specific floor and a specific member. The main purpose of this study is to estimate seismic performance level of vertically irregular buildings by nonlinear based Demand Capacity Ratio(DCR). In this paper, a simple nonlinear based DCR is derived by comparing linear based DCR with nonlinear based DCR and propose a modification factor of DCR. The analytical model was used for low-rise piloti-type buildings damaged by the Pohang earthquake, and the column and shear wall element model was used to consider the flexure shear interaction of the first floor. Comparison of load-displacement results through simulation of the element model and the cylcic load test with shear /flexure / shear-flexure failure of column and shear wall to verify the reliability of element model. The nonlinear based demand and capacity of the building were derived from , nonlinear pushover analysis and nonlinear time history analysis. In the case of the four-story vertically irregular building, simple seismic performance evaluation was possible with linear DCR and DCR modification factor 1.6.

Keywords: vertically irregular; simple seismic performance evaluation; demand capacity ratio; piloti type building

1.Introduction

Due to the 5.4 earthquake that occurred in Pohang on November 15th , 2017, 47 out of 131 low-rise piloti-type buildings in the JangSung area were reported for having been damaged. (AIK, 2018). The damaged piloti-type buildings architecturally consisted of moment frames on the first floor, and shear wall systems on the rest of the floors. As a result of these architectural features, stiffness (vertical) irregularity occurs between the upper and lower levels. Buildings with vertical irregularity are susceptible to earthquakes because seismic demand is concentrated on certain floors with less stiffness.

Seismic performance evaluation is usually conducted on the absence of performance. However, applying this method to every vertical irregular building has practical restraints such as time. In order to resolve these problems, Korea conducts a preliminary seismic performance evaluation that simply deduces the buildings' demand and capacity. However this evaluation method is based on linear static analysis, so it is difficult to make simple seismic performance evaluations on vertical irregular buildings, (thus being problematic.)

Chintanapakee and Chopra(2004), Valmundsson and Nau(1997) compared the interstory drift ratio of each floor through the behavior analysis of models with vertical irregularity. According to whether dynamic behavior is considered, the interstory drift ratio of vertical irregular buildings divide into two groups; models with mass irregularity show similar ratios while models with strength and stiffness irregularity show significantly different ratios. Soni and Mistry (2006) confirmed that when the dynamic behavior of vertical irregular buildings is not considered, adequate performance of strength and ductility for designing is not obtained properly. Wonawane et al (2013) deduced the demand and capacity concerning the weight of 4 story RC moment framework buildings. Through the comparison of the DCR value to 1, the stability of the building can be evaluated. Gunay and Sucuoglu (2004) evaluated the seismic performance of RC buildings through this method and proved(showed) that the result tends to coincide with the nonlinear dynamic procedure and the nonlinear static procedure. These previous research shows both the rationality of the seismic performance evaluation method using DCR and the necessity of dynamic behavior considerance involving vertical irregular buildings. Therefore, in order to evaluate the seismic performance of vertical irregular buildings, the existing DCR method must be improved (reinforced, complemented).

This paper will deduce the demand capacity ration considering the nonlinearity of 4 story vertically irregular buildings. By comparing the DCR values and seismic performance levels of the vertically irregular buildings the correlation tendency will be checked. Also, through comparison of the linear based DCR value and nonlinear based DCR value, a DCR modification factor applicable to vertically irregular buildings will be suggested.

2. Linear based seismic performance evaluation in South Korea

Although undergoing seismic performance evaluation is important, accurately analyzing the seismic performance of every building is practically difficult. In Korea, a simple evaluation is preceded by a seismic performance pre-evaluation based on linear analysis, and if this result doesn't meet the target performance level, an accurate analysis is proceeded. In this chapter, a vertically irregular building prototype model will be made to evaluate the linear based DCR value and analyze the seismic performance level.

2.1 Linear based seismic performance pre-evaluation

The seismic performance evaluation method proposed by the Korea Infrastructure Safety and Technology Corporation (KISTEC) consists of a pre-evaluation and detail evaluation. The pre-evaluation obtains the demand and capacity of the building through linear analysis, and evaluates the corresponding Demand Capacity Ratio (DCR). The DCR value is defined in Eq. (1) and Eq (2).

$$DCR_i = \frac{Demand_i}{Capacity_i} = \frac{S_{DS} \cdot W \cdot \gamma_i}{0.8\sum V_i} \tag{1}$$

$$\gamma_i = \frac{\sum_{l=i}^{n} w_l h_l^{\,k}}{\sum_{l=1}^{n} w_l h_l^{\,k}} \tag{2}$$

Here, S_{DS} represents the spectral response acceleration parameter at short periods,

W represents the efficient weight of the building,

γ_i represents the lateral load distribution factor,

V_i represents the sheer force of the floor I,

w_i represents the weight of the floor i,

h_i represents the height of the floor I

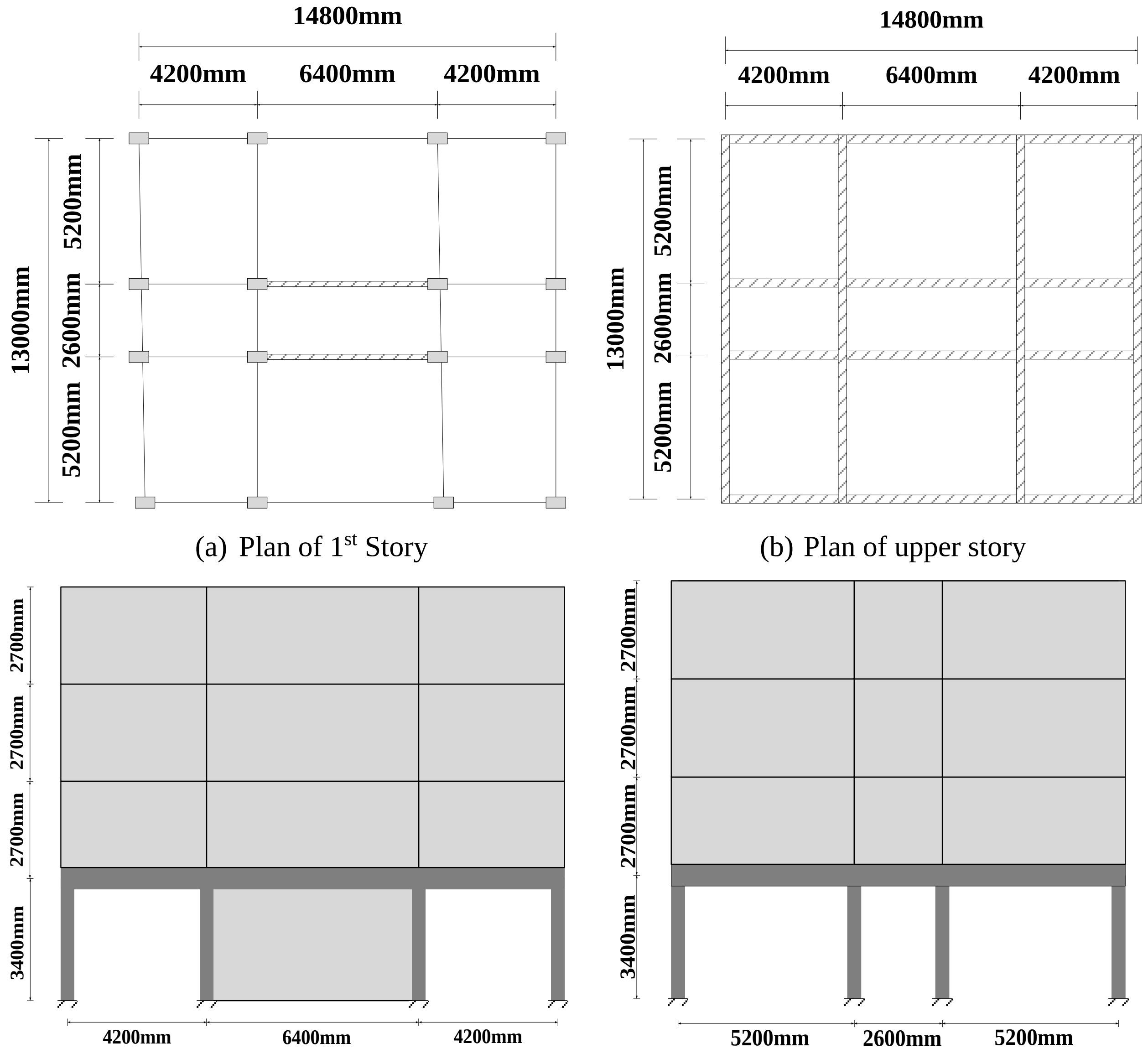
Since it is based on linear analysis, this DCR value has the advantage of relatively simple deduction, but it has the disadvantage of being that much inaccurate. To compensate this drawback, in Korea a boundary of a relatively conservative DCR value is proposed according to the structure of the building. The DCR boundaries for RC buildings are shown in Table 1.

Table 1 – Seismic performance level boundary of RC structure according to DCR

Boundary of DCR	**Seismic Performance Level**
$DCR \le 0.5$	I.O. (Immediate Occupancy)
$0.5 < DCR \le 0.75$	L.S. (Life Safety)
$0.75 < DCR \le 1$	C.P (Collapse Prevention)
$1 < DCR$	C (Collapse)

2.2 3D prototype models

In this chapter, a 3D prototype model made referring floor plans of a vertically irregular 4 story building is analyzed. This model is based on a low-level piloti building that was damaged during the Pohang earthquake. Unlike the other floors that have sheer wall systems, the first floor of the building has a moment frame which makes the stiffness relatively low and results in vertical irregularity. Also, 32 vertically irregular building models were made with the aspect ratio(0.4, 0.5, 0.66, 1, 1.5, 2, 2.33, 2.5) and cross-section area(210000, 245000, 280000, 315000) of the first-floor columns as parameter. The weight and material strength that wasn't included in the floor plan was decided according to the "Existing Structure Seismic Performance Evaluation Method)" of KISTEC.



(a) Plan of 1st Story (b) Plan of upper story

(c) Elavation of X direction (d) Elavation of Y direction

Fig. 1 Dimensions of the vertical irregular buildings

2.3 Linear based seismic performance pre-evaluation of vertically irregular buildings

When pre-evaluated, the prior 32 models showed DCR values and corresponding seismic performance levels presented in Fig.2. When the aspect ratio decreases, the column is governed by flexural behavior, and shear capacity decreases as the area decreases. Therefore it is shown that as the aspect ratio and area decreases, the capacity decreases and DCR value increases. Furthermore, the DCR values of vertically irregular buildings are all below 0.5 and thus have a seismic performance level of I.O. However this result is incompatible with the fact that these buildings were significantly damaged by the Pohang earthquake. Through this result it is evident that when applied to vertically irregular buildings, pre-evaluation is inadequate in evaluating seismic performance level because it lacks consideration of dynamic characteristics.

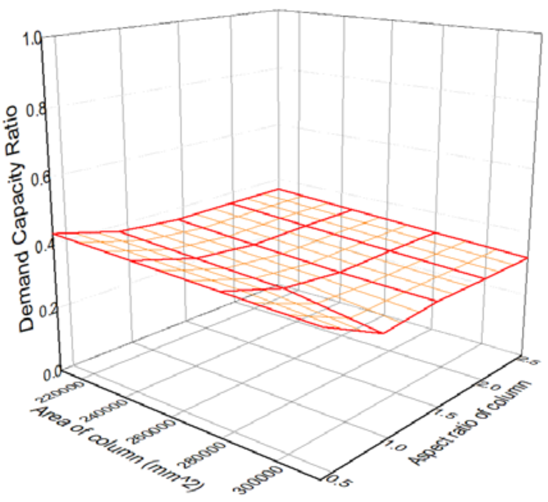


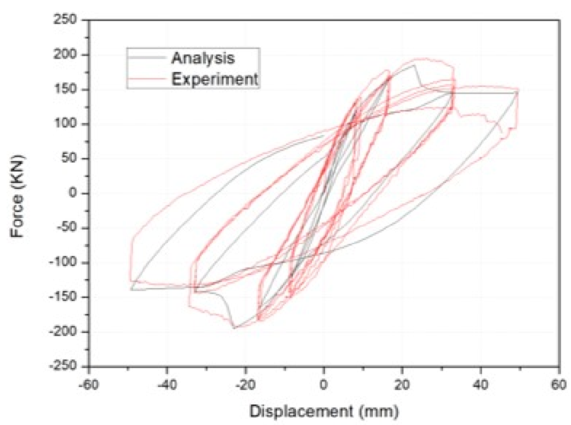
Fig. 2 Demand Capacity Ratio(DCR) according to area and aspect ratio

3. Non-linear based seismic performance evaluation of vertical irregular buildings

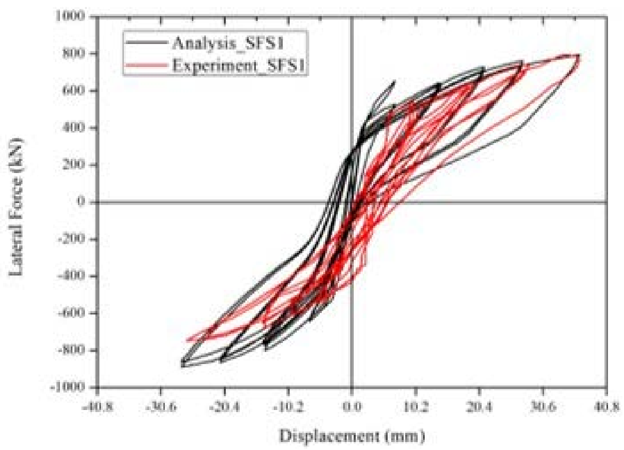
It was confirmed above that when vertically irregular buildings are pre-evaluated based on linear analysis, the results are inaccurate because it lacks consideration of dynamic characteristics. To complement this result, the evaluation will be proceeded on the DCR values deducted from the demand and capacity of the building based on nonlinear analysis.

3.1 Validation of element model

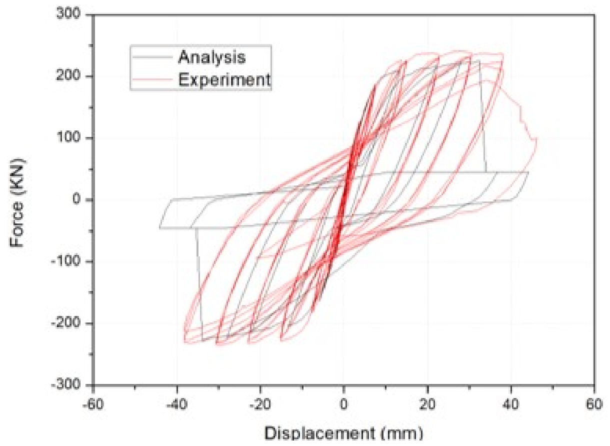
In vertically irregular buildings, the displacement and weight is concentrated on the soft story due to the stiffness difference. In order to simulate the nonlinear behavior concentrated on the soft story, a model that can implement the flexture-shear behavior of the columns and shear walls, members of the soft story. Fiber element and shear spring were used for columns, and SFI-MVLEM model was used for shear walls. Also, to verify the accuracy of this model the actual experimental data was compared with the simulation results. Experimental data from the PEER center of the U.S. was used for the column experiment results, and Datacenterhub experimental data was used for the shear wall experiment results. The following verification results are shown in Fig. 3



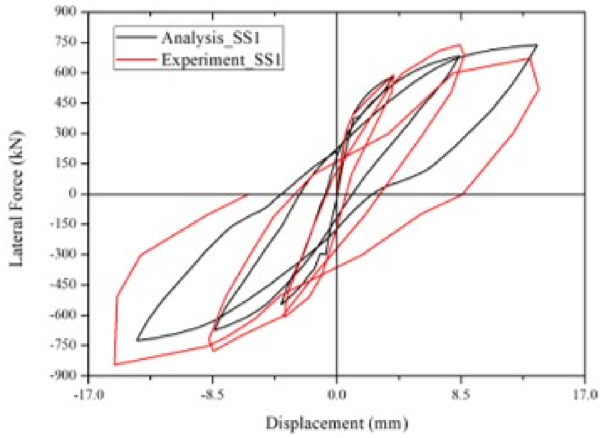
(a) Flexure failure of column



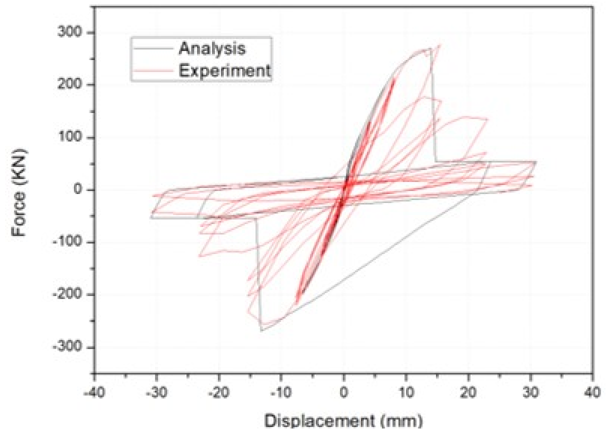
(b) Flexure failure of shear wall



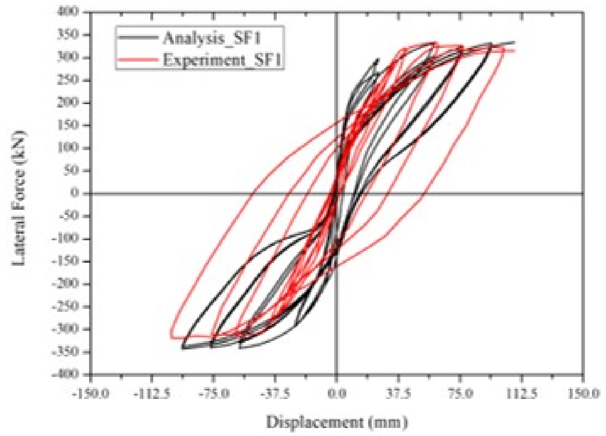
(c) Shear-flexure failure of column



(d) Shear-flexure failure of shear wall



(e) Shear failure of column



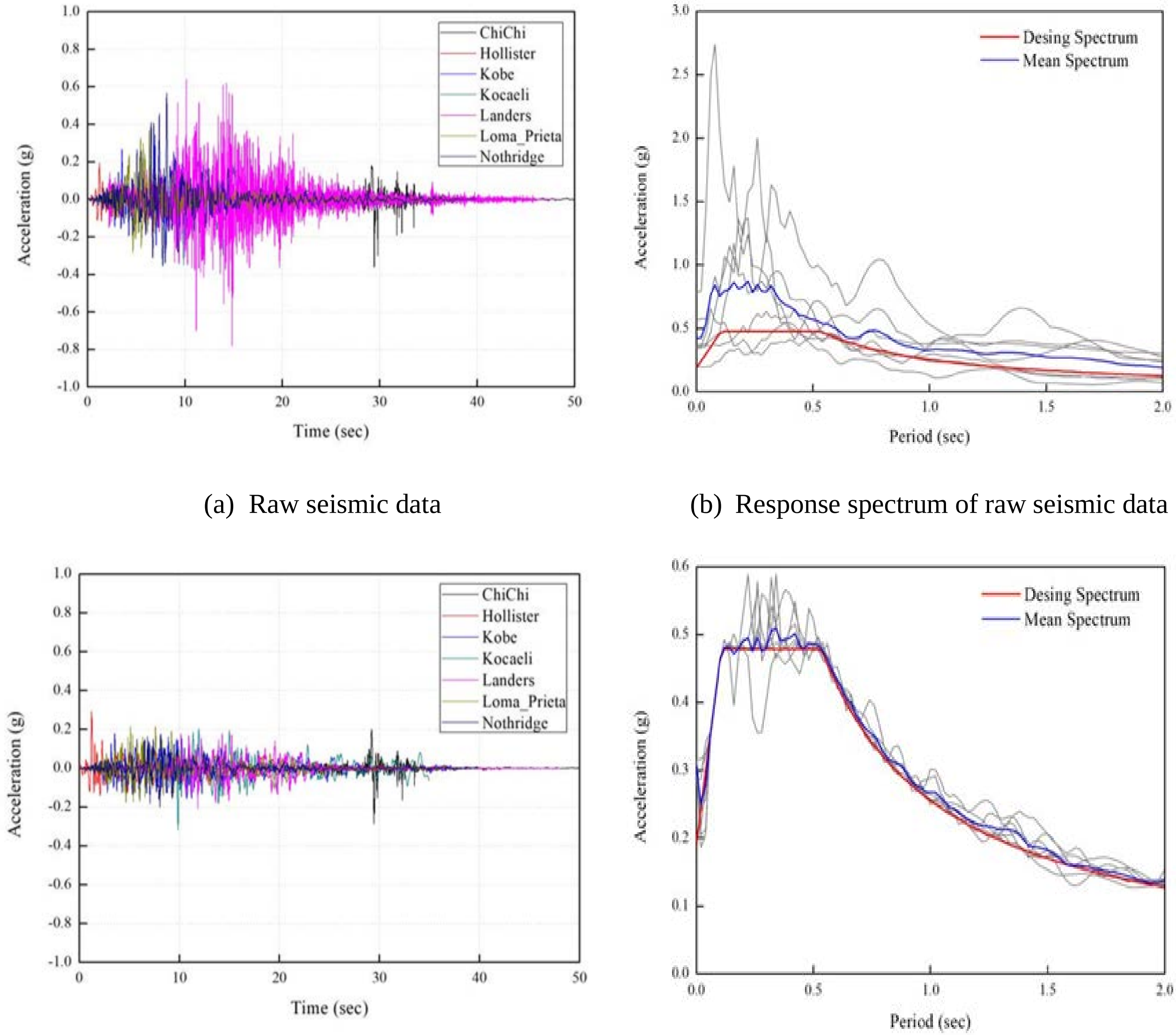
(f) Shear failure of shear wall

Fig. 3 Compare column and shear wall cyclic pushover simulation result with experiment result

The comparison of the experimental data of each specimen and the simulation results proves that the accurate analysis model of the columns and shear walls proposed in this paper represents the experimental data effectively. Comparison of the initial stiffness of the actual data showed that columns had an 3.2%, 2.6%, 5.5% (average 2.6%) initial stiffness error and 5.4%, 3.2%, 5.7% (average 4.8%) maximum strength error. Shear walls had an 4.3%, 0.3%, 3.3% (average 2.6%) initial stiffness error and 3.0%, 4.3%, 0.6% (average 2.6%) maximum strength error, concluding that it effectively represents the flexure/shear behavior of each member.

3.2 Demand of vertical irregular buildings by time history analysis

Time history analysis was proceeded to deduce the seismic demand of vertically irregular buildings. A total of 7 seismic waves were used in the analysis, each through scailing the design spectrum abiding the KBC 2016. The seismic wave spectrum was selected considering the earthquake area I and ground condition Sd based on the KBC 2016.



(a) Raw seismic data

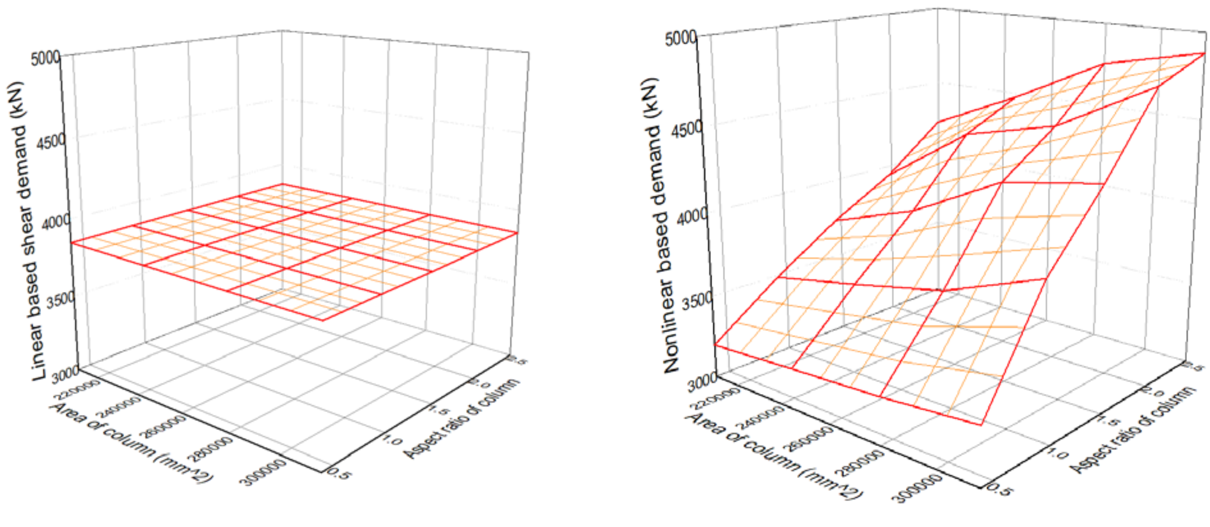
(b) Response spectrum of raw seismic data

(c) Seismic data scaled to KBC 2016 design spectrum

(d) Response Spectrum scaled to KBC 2016 design spectrum

Fig. 1 Scaled seismic data for time history analysis

The shear demand deduced through time history analysis reflecting the dynamic behavior of vertically irregular buildings is shown in Fig.3. When dynamic behavior is reflected, the demand is measured higher than linear analysis because the concentration of displacement on the soft story incurs nonlinear behavior. Also, linear based shear demand is determined by the weight of the building regardless of the shape of the members, while nonlinear based shear demand increases as the column area and aspect ratio increases. This shows that as the column area and aspect ratio increases, the natural period of seismic wave load direction increases, resultingly increasing the demand.

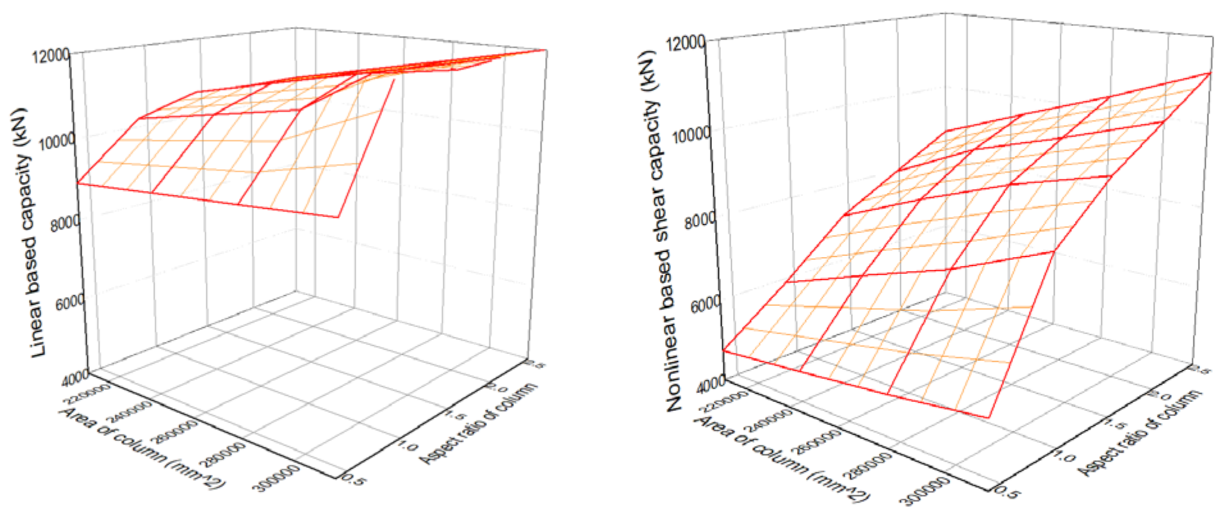


(a) Linear based shear demand (b) Nonlinear based shear demand

Fig. 4 Demand of vertical irregular buildings according to area and aspect ratio of column

3.3 Capacity of vertical irregular buildings by pushover analysis

In order to deduct the capacity of vertically irregular buildings, pushover analysis was conducted. The pushover force was loaded by the mode shape of the building. The capacity of a building is defined as the maximum base shear force on the pushover curve. The capacity of vertically irregular buildings deduced through pushover analysis is shown in Fig,4. Capacity increases as the cross-section area of the column increases, and is dominated by the shear behavior as the aspect ratio increases, thus increasing. However when comparing the overall size, the capacity of linear analysis if about 3 times that of nonlinear analysis. This is due to the face that in linear analysis the capacity includes all of the members while in nonlinear analysis the maximum base shear force is determined by the sequential failure of members.

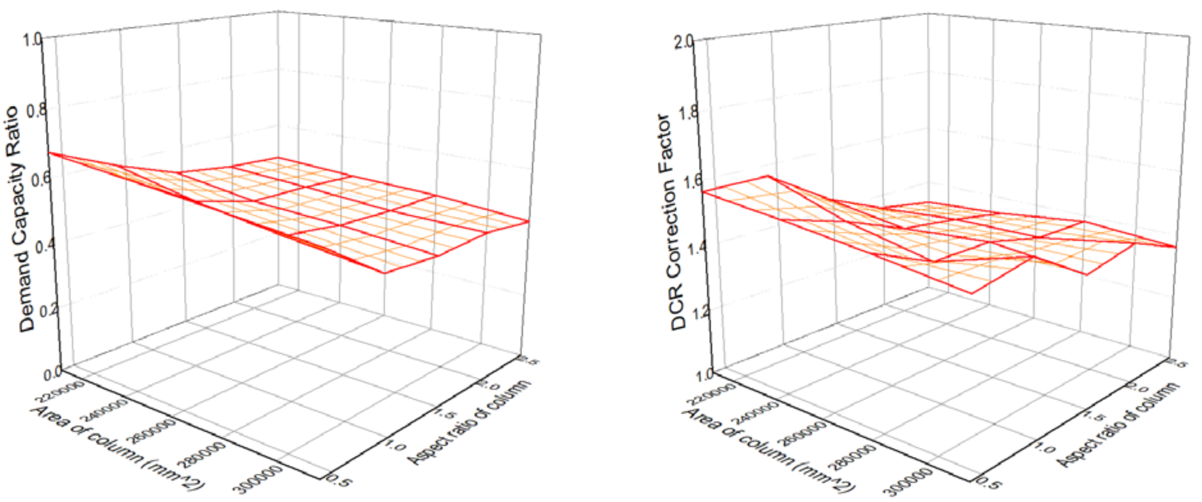


(a) Linear based capacity (b) Nonlinear based capacity

Fig. 5 Capacity of vertical irregular buildings according to area and aspect ratio of column

3.4 Nonlinear based seismic performance pre-evaluation of vertically irregular building

The DCR values deduced using the nonlinear based demand and nonlinear based capacity of vertically irregular buildings obtained above are shown in (a) of Fig 5. When the aspect ratio decreases, the column is governed by flexural behavior, and shear capacity decreases as the area decreases. Therefore it is shown that as the aspect ratio and area decreases, the capacity decreases and DCR value increases. This overall tendency is identical to that of linear based DCR. However, comparison of DCR values show that nonlinear based DCR values are measured approximately 1.4~1.6 times greater. This is because linear and nonlinear demand have little difference, where as linear and nonlinear capacity show significant difference. As the aspect ratio and area of the columns increase, the ration of load that the shear wall bears increases leading to failure in smaller displacements. Accordingly, the ratio of nonlinear based DCR of linear based DCR was defined as the DCR Correction Factor shown in (b) of Fig 5. The DCR Correction Factor tends to increase as the column aspect ration and column area increases. This tendency is owes to the decrease of the building capacity according to the consideration of nonlinearity. Through the suggestion of such a DCR Correction factor, by deducting the linear based DCR through pre-evaluation of vertically irregular buildings and multiplying the correction factor, the nonlinear based DCR can be deduced, and thus a simple seismic performance evalutation may be conducted.



(a) Nonlinear based DCR (b) DCR Correction Factor

Fig. 6 Nonlinear based demand capacity ratio and correction factor of vertical irregular buildings

4. Conclusion

In this paper, seismic performance pre-evaluation of vertically irregular buildings was conducted, and a DCR Correction Factor was suggested to compensated the existing linear based pre-evaluation DCR value. The result was as the following.

1. When seismic performance pre-evaluation was conducted on vertically irregular buildings, the DCR values were all under 0.5, showing I.O levels. However, such performance level was incompatible to the damage phenomenon of the piloti buildings due to the Pohang earthquake. Evaluation of vertically irregular buildings must be conducted with consideration of the displacement concentration due to the dynamic behavior of the buildings.
2. The duction of the demand and capacity of vertically irregular buildings based on linear and nonlinear analysis showed that the capacity difference considering nonlinearity was relatively larger than that of the demand. This indicates that linear analysis fails to consider load distribution of members leading to a greater difference in irregular buildings where load is concentrated on certain members.

3. All 32 vertically irregular models used in this paper showed linear based DCR values deducing I.O level seismic performance. Meanwhile, when nonlinearity was put into consideration 15 out of 32 models deduced L.S levels. Because pre-evaluation is a simple method used for screening structures that do not need accurate analysis, it is crucial to conservatively compensate the existing linear analysis results. Accordingly, the DCR Correction Factor can be proposed, and 1.6 may be used in the case of 4 story vertically irregular buildings with a soft story on the first floor.

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