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THE EFFECT OF BEHAVIOUR FACTOR ON THE SEISMIC PERFORMANCE OF LOW-RISE AND HIGH-RISE RC BUILDINGS

MOHD ZULHAM AFFANDI MOHD ZAHID[1,]*,
TAKSIAH A. MAJID[2], ADE FAISAL[3]

[1]Department of Civil Engineering Technology, Faculty of Engineering Technology,
Universiti Malaysia Perlis, 02600 Pauh Putra, Perlis, Malaysia
[2]Disaster Research Nexus, School of Civil Engineering, Universiti Sains Malaysia, 14300,
NibongTebal, Pulau Pinang, Malaysia
[3]FakultasTeknik, Universitas Muhammadiyah Sumatera Utara, Medan, Indonesia
*Corresponding Author: mohdzulham@unimap.edu.my

Abstract

This study investigates the performance of RC buildings designed according to Eurocode 8. Two families of RC buildings (i.e., 3 storey and 18 storey) are investigated using nonlinear static or push over analysis (POA). Each family of the buildings consists of five generic RC models with different behaviour factor namely 1, 1.5, 2, 4 and 6. The effect of behaviour factor to the buildings response characteristic parameters, i.e., elastic and inelastic stiffness, base shear strength at yield and maximum strength level and top displacement ductility are discussed thoroughly in this study. It is found that, the behaviour factor has a significant effect on the performance of RC buildings. Furthermore, this study also propose the relationship between displacement ductility and behaviour factor for high-rise and low-rise RC buildings and this equation which has high correlation factor can be used by designer or engineer to estimate the ductility capacity of low rise and high rise RC buildings based on their designed behaviour factor.

Keywords: Behaviour factor, RC building, Push over analysis.

1. Introduction

Design requirements for lateral loads, such as winds and earthquakes, are fundamentally different from those for vertical (dead and live) loads. While design for wind loads is a primary requirement, due to the frequency of loading scenario, seismic design deals with events with lower probability of occurrence.

Nomenclatures

C_t	Fundamental period coefficient
H	Height of the buildings, m
Q	Behaviour factor
$S(z/H)$	Stiffness reduction factor
T_1	Fundamental period
V_d	Design seismic base shear, kN
V_e	Elastic shear force, kN
V_{max}	Maximum base shear, kN
V_y	Base shear at yield, kN

Greek Symbols

α_u/α_1	Overstrength factor
Δ_y	Yield roof drift, m
Δ_y/H	Roof drift ratio at yield, m/m
δ	Ratio of lateral stiffness at top to the bottom of the structure
δ_u	Ultimate displacement, m
δ_y	Yield displacement, m
μ_d	Displacement ductility, m/m

Abbreviations

DCH	High Ductility Class
DCL	Low Ductility Class
DCM	Medium Ductility Class
POA	Push Over Analysis
RC	Reinforced Concrete

It may be highly uneconomical to design structures to withstand earthquakes for the performance levels used for wind design. For example, buildings structures would typically be designed for lateral wind loads in the region of 1% to 3% of their weight. Earthquake loads may reach 30%-40% of the weight of the structures, applied horizontally. If concepts of plastic design used primary loads are employed for earthquake loads, extremely heavy and expensive structures will ensue. Therefore, seismic design, by necessity, uses concepts of control damage and collapse prevention. Indeed, buildings are designed for 15-20% only of the elastic earthquake forces, V_e and the concept of equal energy is used to reduce the design force from V_e to V_d (denoting elastic and design force levels, respectively). Therefore, damage is inevitable in seismic response and design. It is the type, location and extent of damage that is target of the design and detailing process in earthquake engineering. The ratio between elastic base shear, V_e and seismic design base shear V_d is defined as behaviour factor, q [1]:

$$q = \frac{V_e}{V_d} \tag{1}$$

Very recently, Faisal et al. [2] investigated the relationship between maximum storey ductility demand on various type of fundamental period of vibration, plastic rotation capacity and behaviour factor. However, to the best authors' knowledge, there was no study assess the correlation between top displacement ductility demand with behaviour factor and fundamental period of vibration of reinforced concrete buildings. Therefore, this study attempts to examine the elastic and inelastic response (i.e., stiffness, roof drift ratio, lateral strength and top displacement ductility) of the low rise and high rise reinforced concrete building designed for various behaviour factors.

2. Materials and Methods

The 3-storey and 18-storey single bay models proposed by Faisal et al. [2, 3] considered in this study to represent the low rise and high rise reinforced concrete models, respectively as shown pictorially in Fig. 1. These models also were employed by Zahidet al. [4] to investigate the effect of repeated earthquake on the ductility demand of RC buildings and Adiyantoet al. [5] to study nonlinear behaviour of reinforced concrete building under repeated earthquake excitation. These generic frame models have a constant storey height of 3.6 m and 7.2 m of bay width. Moreover, these 3D models are extended from 2D models used by Medina and Krawinkler [6] and Ruiz-Garcia and Miranda [7]. The extension from 2D to 3D was intended to consider the bi-directional seismic forces. Note that the validation of 2D model was carried out by Medina and Krawinkler [6] and the detail design of the models can be found in Ade Faisal's [3] study.

The seismic assessment of this building model was carried out with reference to five values of behaviour factor, q value: the behaviour factor, q values vary between behaviour factor, q = 1 (strong building) and behaviour factor, q = 6 (weak building). Note that the behaviour factor, q values were estimated with reference to the ductility level, i.e., Low Ductility Class (DCL), Medium Ductility Class (DCM) with 1.5≤ q ≤4 and High Ductility Class (DCH) with 1.5≤ q ≤ 4 for the seismic design of RC buildings as proposed by Eurocode 8 [8].

It should be noted that, the fundamental period of the 3-storey and 18-storey buildings are 0.45 s and 1.71 s, respectively. It was computed based on following equation as proposed by Eurocode 8 [8].

$$T_1 = C_t\, H^{3/4} \tag{2}$$

where, C_t is 0.085 for moment resistant space steel frame, 0.075 for moment resistant space concrete frame and for eccentrically braced steel frames and 0.05 for all other structures. H is height of the building in meter from foundation or top of a rigid basement.

In order to achieve targeted building fundamental period, the weight at each floor and the moment inertia of the structural member need to be tuned. The result from the tune process, the weights at every floor for all models, are assumed to be 1240 kN and irregularity in mass along the height is not taken into account as there is no significant effect on the response of the structure [9-11]. This study adopts the beam to column ratio equal to 1.3 as proposed by Eurocode 8 [8].

Besides that, this study also adopts overstrength factor of α_u/α_1 = 1.3 as suggested by Eurocode 8 [8] for multi-storey. Since the Eurocode 8 [6] provisions do not explain on how to distribute the factor, in this study the factor was distributed uniformly along the height of the buildings.

The reduction of the stiffness along the height of the buildings *S* (*z*/*H*) is followed the method by Miranda and Reyes [12] and the ratio of lateral stiffness at the top to the bottom storey, δ is equal to 0.25 as proposed by Ruiz-Garcia and Miranda [7].

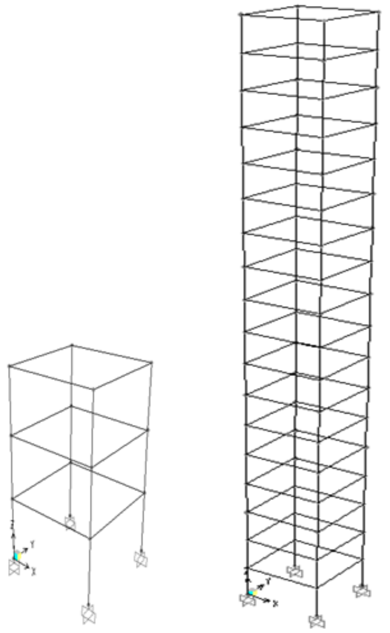


Fig. 1. 3-storey and 18-storey model.

For the purpose of having more realistic distribution of lateral stiffness, a decreasing stepwise distribution of lateral stiffness, which followed parabolic stiffness distribution as shown in Fig. 2, was used in this study. The lateral stiffness of the global structure changes for every three stories. The lateral stiffness was calculated using the equivalent cantilever method as explained by Taranath [13].

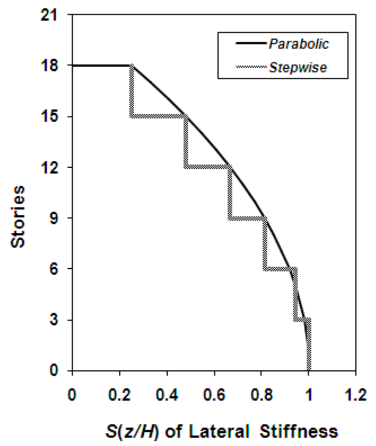


Fig. 2. Decreasing stepwise distribution of the lateral stiffness for 18-storey model.

This study utilized SAP 2000 [14] software to carry out nonlinear static analysis or pushover analysis. All ten models were pushed at the top floor until no top displacement occurred which is considered as fail.

3. Results and Discussion

The relationships between the base shear force and top displacement of the buildings with various strength levels or behaviour factor are presented in Fig. 3. It shows that the elastic stiffness of 3-storey buildings are same for all level of strength from q = 1 until q = 6 which is equal to 70.5×10^3 kN/m^3, meaning that the behaviour factor do not influence the elastic stiffness of the buildings. The behaviour factor also do not affect the elastic stiffness of 18-storey buildings, however, the elastic stiffness of 18-storey buildings is 3.5 times lower than 3-storey buildings which is equal to 20.4×10^3 kN/m^3. As mentioned previously, the fundamental period of 3-storey buildings and 18-storey buildings is 0.45 s and 1.71 s, respectively. Therefore, we know that the elastic stiffness of the buildings decreases as the fundamental period increases.

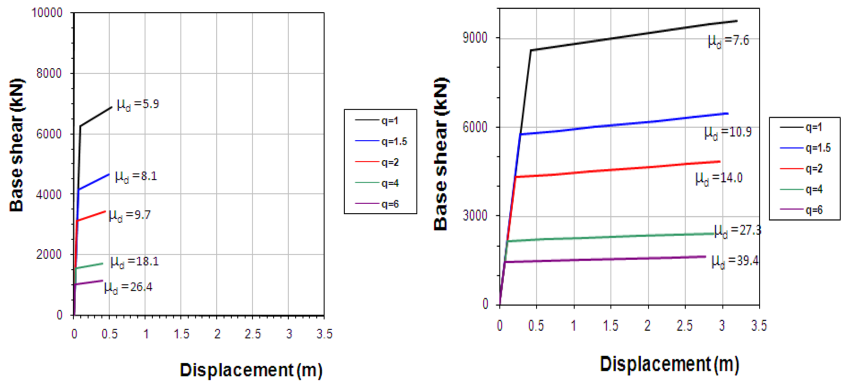


Fig. 3. Capacity curve for 3-storey (top) and 18-storey models (bottom).

However, when the roof drifts ratio at yield, *Δy*/*H* of the buildings were investigated, it shows that the roof drift ratio of the buildings decreases as the behaviour factor increases as shown in Fig. 4. Roof drift ratio is drift of the roof at yield *Δy* normalized by the total height of the buildings, *H* and also can be used to quantify the lateral stiffness of the structural systems [1]. In other words, Fig. 4 shows that the elastic lateral stiffness of the buildings decreases as the behaviour factor increases and lateral stiffness of low rise RC buildings approaching lateral stiffness of high rise buildings as the behaviour factor increases. Therefore, the gradient of the base shear-displacement curve in elastic region is not adequate to indicate the lateral stiffness of the RC buildings.

In terms of inelastic stiffness, the behaviour factor influences the inelastic stiffness of the buildings significantly. As shown in Fig. 5, the inelastic stiffness of 3-storey and 18-storey buildings decreases as the behaviour factor increases and the gradient for 3-storey buildings curve is higher than 18-storey buildings showing that the rate of stiffness decrease is higher for 3-storey buildings compared to 18-storey buildings. At high value of behaviour factor, the inelastic stiffness of low rise building approaching inelastic stiffness of high rise building.

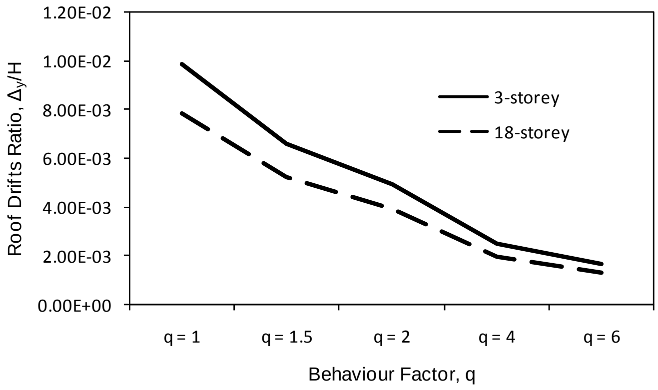


Fig. 4. Roof drifts ratio.

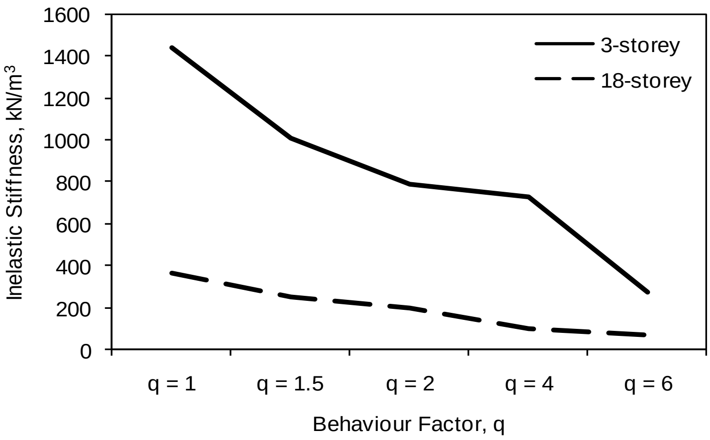
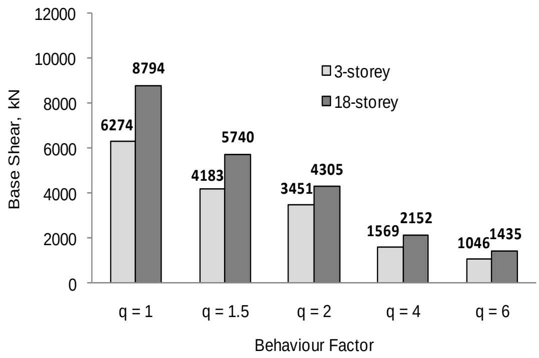


Fig. 5. Inelastic stiffness.

In this study, lateral strength capacity of the buildings is measured based on the shear at yield, V_y and at maximum strength, V_{max} as shown in Fig. 6. The lateral strength at yield and at maximum of 18-storey buildings is higher than 3-storey buildings and the lateral strength reduces proportionally as the behaviour factor increases. For example, lateral strength at yield of 3-storey buildings with q = 1 is equal to 6274 kN, which is 6 times lower than lateral strength of 3-storey buildings with q = 6. This trend also can be seen for 18-storey buildings.



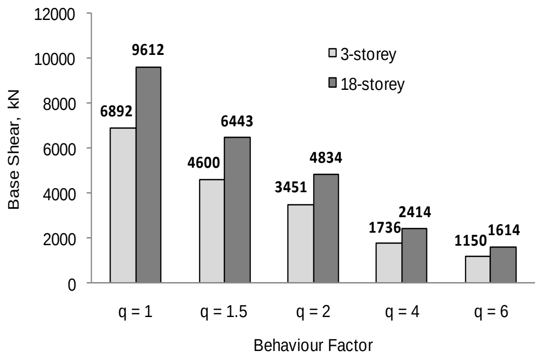


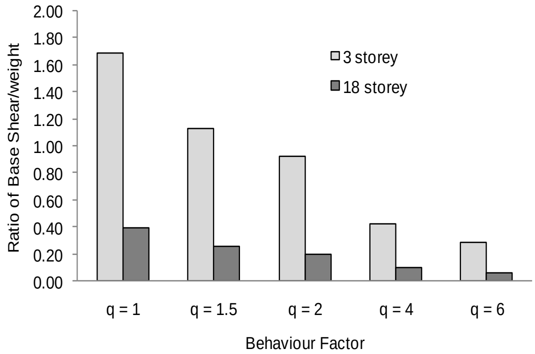
Fig. 6. Lateral strength: Base shear at yield (top) and maximum base shear (bottom).

Even though the lateral strength of the 18-storey buildings is higher than 3-storey buildings as shown in Fig. 7, in fact, 3-storey buildings are stronger than 18-storey buildings. This is because 3-storey building can resist lateral force up to 1.8 times of its weight. For 18-storey buildings, even the strongest 18-storey building, i.e. the one with q = 1, it can resist only lateral force of 40% of its weight. Unlike most other types of dynamic forces, earthquake effects are not imposed on the structure but generated by it. The vibrated structure due to earthquake wave posse inertia force that makes it continue to vibrate until the vibration energy dissipates entirely. This fictitious force extremely depends on the mass of the structures. In other words, earthquake produces lateral forces proportional to the weight of the structure and its fixed contents or the heavier the building then the higher earthquake force to be borne. Therefore, in this study, it shows that the low-rise structure possess high lateral strength compared to the high-rise one.

In high seismicity region, most structures are designed to behave inelastically for economic reasons and inelastic behaviour of the structure is highly depends on its ability to absorb and dissipate energy by ductile deformation. Therefore, in order to evaluate the inelastic performance of the investigated buildings, ductility is an appropriate response characteristic parameter and it is computed as following equation:

$$\mu_d = \frac{\delta_u}{\delta_y} \tag{3}$$

where, μ_d is a top displacement ductility, δ_u is an ultimate top displacement and δ_y is a yield top displacement.



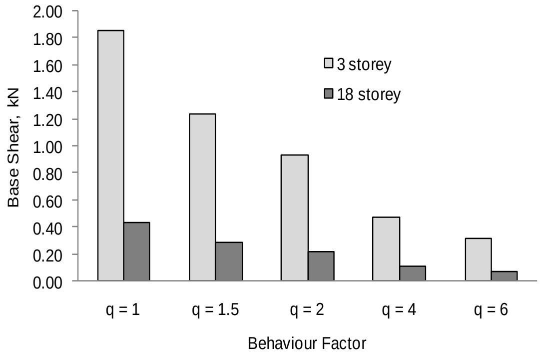


Fig. 7. Ratio of lateral strength to weight at yield (top) and maximum (bottom).

Figure 8 plots the graph of displacement ductility, μ_d, versus behaviour factor, q. It depicts that the relationship between displacement ductility and behaviour factor is linear. Based on the available data from push over analysis, the simple regression analysis is carried out using MS-Excel and it proposes the following relationship between displacement ductility, μd, and behaviour factor, q:

$$\mu_d = mq + c \tag{4}$$

where, m = 4.103 and 6.344 for 3-storey and 18-storey, respectively, and c = 1.752 and 1.535 for 3-storey and 18-storey buildings, respectively. The correlation factor, R^2, which describes the degree of above mentioned relationship, is very high which is equal to 0.999. However, the proposed regression models are valid only for single and multi-bay regular frames as according to previous researchers [6, 7, 15], the simplified single bay frame is adequate to represent global seismic response exhibited by regular multi-bay frames at different level of inelasticity. Therefore, further effort need to be carried out to obtain the relationship between displacement ductility and behaviour factor for irregular type of reinforced concrete buildings.

Figure 8 illustrates also the displacement ductility of 18-storey buildings is higher than 3-storey buildings for all behaviour factors. The slope of the μ_d-q line for 18-storey buildings is greater than 3-storey buildings indicates that the different of the ductility between 3-storey buildings and 18-storey buildings become larger as the behaviour factor increases.

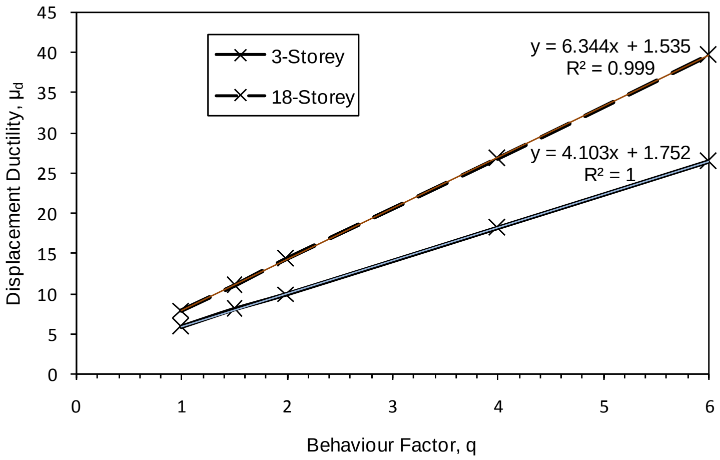


Fig. 8. Correlation between displacement ductility capacity and behaviour factor.

As discussed earlier, 3-storey buildings or low rise buildings posse better elastic performance characteristic parameters namely elastic stiffness and lateral strength capacity at yield relative to its weight compared to high-rise one. For inelastic behaviour, eventhough low rise buildings have better shear capacity at maximum strength relative to its own weight, the high-rise buildings posse better ductility capacity compared to low-rise buildings. Therefore, under strong earthquake events, high-rise buildings have better performance to dissipate vibration energy and low-rise buildings may experience brittle failure.

4. Conclusion

In this paper, the nonlinear static analysis was employed to investigate the effect of behaviour factor on the seismic performance of RC buildings. A detailed study of the problem leads to the following conclusion:

- Based on the gradient of base shear-displacement curve, the elastic stiffness of 18-storey buildings is 3.5 times lower than 3-storey buildings and the behaviour factors do not affect the elastic stiffness of 18-storey buildings. However, in terms of the roof drift ratio, elastic lateral stiffness of the buildings decreases as the behaviour factor increases and lateral stiffness of low rise RC buildings approaching lateral stiffness of high rise buildings as the behaviour factor increases. Therefore, the gradient of the base shear-displacement curve in elastic region is not adequate to indicate the lateral stiffness of the RC buildings.

- Low-rise buildings have low shear strength capacity at yield and maximum strength compared to high-rise buildings; however, low-rise RC buildings have better lateral strength relative to its own weight compared to high-rise buildings. Furthermore, lateral strength of RC buildings decrease as the behaviour factor increases.
- The correlation between displacement ductility and behaviour factor is linear in which the displacement ductility increases as the behaviour factor increases. This study proposes the following equation to estimate the displacement ductility from the designed behaviour factor, q value: $\mu_d = 4.103q + 1.752$ and $\mu_d = 6.344q + 1.535$ for low-rise and high-rise buildings, respectively. These equations have high correlation factor, R^2. However, the proposed regression models are valid only for single and multi-bay regular frames, therefore, further effort is required to obtain the relationship between displacement ductility and behaviour factor for irregular type of reinforced concrete buildings.

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