# MAXIMUM FLOOR DISPLACEMENT PROFILES FOR THE DISPLACEMENT-BASED SEISMIC DESIGN OF REINFORCED CONCRETE FRAMES

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**ABSTRACT :**

A new method to estimate the maximum floor displacement profiles of regular RC frames at different damage levels subjected to earthquakes is proposed in this study for the purpose of displacement-based seismic design. At first, a set of 25 RC plane frames with different characteristics was designed. A set of 16 physical accelerograms containing different frequency spectrum was employed as input ground motions. The maximum floor displacement profiles were obtained for each pair of frame and accelerograms by nonlinear dynamic analysis when the frame just arrived at slight, moderate, and severe damage state respectively. For each frame the median and coefficient of variation of maximum floor displacement under each set of ground motions were calculated to take the statistical characteristics of seismic responses into consideration. Secondly, the shape of the maximum displacement profile and the distribution of coefficient of variation over the height were analyzed. The fundamental period, column-to-beam strength ratio, and damage level were identified as the main factors having significant effects on the maximum displacement profiles. On the basis of regression analysis of the results, the expressions to estimate the maximum displacement profiles were generated to associate the maximum floor displacement with the maximum story drift ratio over the height and the main structural parameters of the frame. The developed profiles are independent of sections and reinforcement of the frame so that they can be used as the starting design variables in displacement-based seismic design.

**KEYWORDS:** displacement-based seismic design, maximum floor displacement profile, reinforced concrete frame

## 1. INTRODUCTION

Seismic damage is directly as well as closely related to displacement or deformation. After the first release of performance-based design framework (SEAOC 2000), a lot of effort has been made on displacement-based seismic design (Panagiatakos et al. 1999; Kowalsky 2002; Xue et al. 2003). These research works highlight the importance of employing displacement as a performance quantifier. Displacement-based seismic design approach has been recognized as the most promising as well as effective tool for performance-based design. To some extent, performance-based design and displacement-based design have been used interchangeably.

Estimation of seismic deformation demands is of primary importance and regarded as the fundamental concern in a displacement-based seismic design. Capacity spectrum method is one of the most representative and well accepted procedures to estimate the maximum displacements of multi-degree-of-freedom (MDOF) building structures (Fajfar 1999). This method requires that both the capacity curve and the demand curve be represented in response spectral ordinates. The capacity curve is developed from pushover curve by using the concept of equivalent single-degree-of-freedom (SDOF) system. In recent years, a lot of research efforts have been devoted to develop improved pushover analysis procedures accounting for higher mode effects (Gupta et al. 2000; Chopra et al. 2002; Kalkan et al. 2006). Since a pre-design structure is needed in pushover analysis, these procedures are suitable for seismic evaluation of existing structures or for the performance check after the initial design of new structures.

In the direct displacement-based seismic design, the maximum displacement associated with particular performance or damage level should be used as the starting design variable. For an MDOF system, the maximum floor displacement profile is usually needed (Priestley et al. 2000). However, few researchers have studied the maximum floor displacement profiles. To the authors' knowledge, in the literature only Loeding et al. (1998) proposed the maximum displacement profiles of plane RC frames based on elastic time history analysis and Karavasilis et al. (2006) developed the maximum displacement profiles of plane steel moment resisting frames based on nonlinear time history analysis respectively. The proposed displacement profiles in the above literature are limited in application. In this work the maximum floor displacement profiles are studied for regular RC frames undergoing elastic and inelastic response. The expressions to estimate the maximum floor displacement profiles at three different damage levels are proposed for the purpose of direct displacement-based seismic design.

## 2. GENERIC FRAME MODELS

### *2.1. Design Parameters*

The deformation distribution in a frame is closely related with the mechanism of formation and development of plastic hinges in structural members. It has been well recognized that the strength distribution in structural members has considerable influence on the sequence of occurrence and distribution of plastic hinges. The column-to-beam strength ratio in a joint, $\eta_c$, defined as below, is used here to reflect the relative strength relationship between beams and columns connected to the same joint:

$$\eta_c = \frac{\sum M_{Rc}}{\sum M_{Rb}} \tag{2.1}$$

where $\sum M_{Rc}$ is the sum of the flexural strengths of all columns framing into a joint, and $\sum M_{Rb}$ is the sum of the flexural strengths of all beams framing into that joint. Five values, 0.8, 1.0, 1.2, 1.6, and 2.0, were specified in the design phase. The subject structures range from 3 to 15 stories in three-story increments, covering the ordinary scope of number of stories appropriate to RC frames. A set of 25 frames was designed.

The number of bays, spans of bays, story height, and cross sections of beams are identical for all frames. The cross sections and reinforcement of columns and the reinforcement of beams vary every three stories. For the frames with same number of stories, the reinforcement of beams is identical while the reinforcement of columns, determined by $\eta_c$ and the reinforcement of beams, is different. The dimensions of a 15-story frame are illustrated in Figure 1. The initial input parameters were defined as follows: dead load 6kN/m$^2$, live load 2kN/m$^2$, seismic protection intensity VIII, site soil class IV, design group 1, yield stresses of longitudinal and transverse steel 300 and 210 MPa, and concrete compressive strength 30 MPa according to current Chinese design code. The reinforcement was determined by strength-based seismic design method.

### *2.2. Analytic Model and Ground Motions*

The basic analysis approach consists of performing nonlinear time history analysis for a given structure and ground motion, using three-dimensional nonlinear analysis computer program Canny 2006 (Li 2006). Uniaxial spring model and multi-axial spring model were employed for beams and columns respectively. The interaction between axial force and flexural moment was considered in column models. A set of 16 ground motions containing different frequency spectrum and duration was used as the seismic excitations. The elastic spectrum acceleration with the same peak ground acceleration of 0.2g is presented in Figure 2.

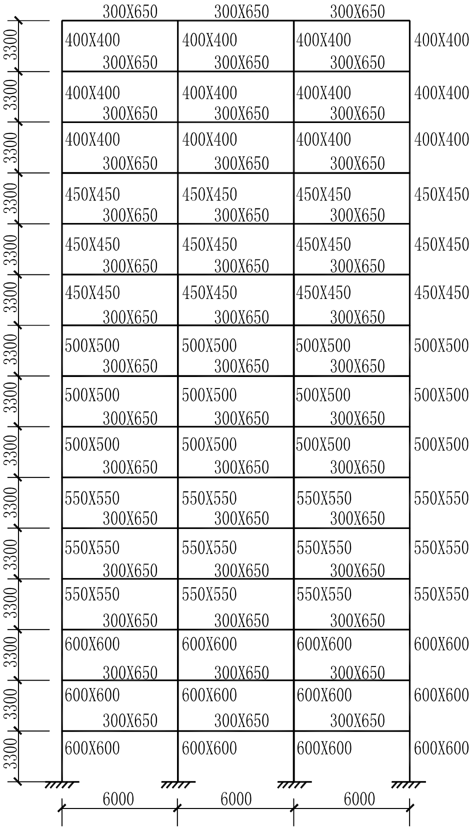



Figure 1 Dimensions of a 15-story plane frame (mm)

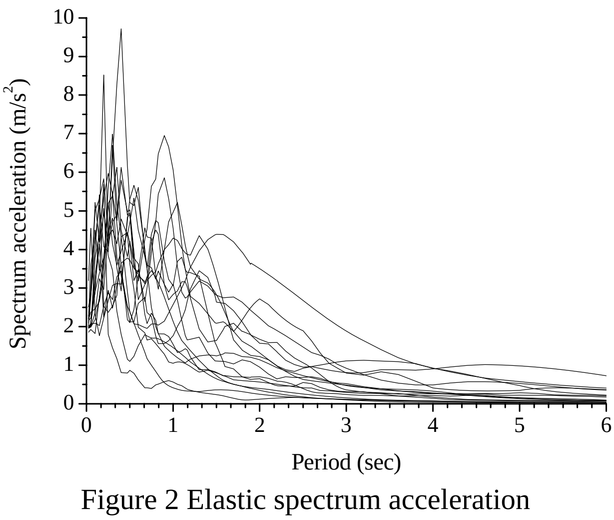



Figure 2 Elastic spectrum acceleration

It has been realized that the damage level of structural and nonstructural components is closely related with story drift ratio which is often used as damage indicator in building structures. In this study the maximum story drift ratio was employed as the performance quantifier to measure the damage degree in a frame after the first occurrence of yielding in structural members. Three damage states were defined: slight damage (indicated by the first occurrence of yielding in structural members), moderate damage (the maximum story drift ratio reaches 0.01), severe damage but collapse prevention (the maximum story drift ratio reaches 0.02). The maximum floor displacement profiles corresponding to the above three damage states were analyzed. To obtain the maximum displacement response of the frames just arriving at individual damage state, iterative computations were required. In total 1200 maximum floor displacement profiles were produced.

## 3. COMPUTATIONAL RESULTS AND REGRESSION ANALYSIS

### *3.1. Computational Results*

For each frame at individual damage state, 16 maximum floor displacement profiles were obtained for each set of ground motions. The median of the profiles and coefficient of variance (COV) were calculated on the basis of the appropriate assumption that the earthquake response is log-normal distribution (Cornell et al. 2002). The median is the central value determined by the following formula:

$$D_{m,j} = \exp\left(\frac{\sum_{j=1}^{n} \ln D_{i,j}}{n}\right) \tag{3.1}$$

where $D_{m,j}$ is the central value of the maximum displacement of the *j*th floor, $D_{i,j}$ is the maximum displacement of the *j*th floor subjected to the *i*th seismic excitation, and *n* is the number of seismic excitations, here *n* is equal to 16.

The standard deviation of the logarithm of the *n* sample values for the *j*th floor and COV are defined as

$$\sigma_{m,j} = \sqrt{\frac{\sum_{i=1}^{n} \left(\ln D_{i,j} - \ln D_{m,j}\right)^2}{n-1}} \tag{3.2}$$

$$COV = \exp\left(\sigma_{m,j}{}^{2}\right) - 1 \tag{3.3}$$

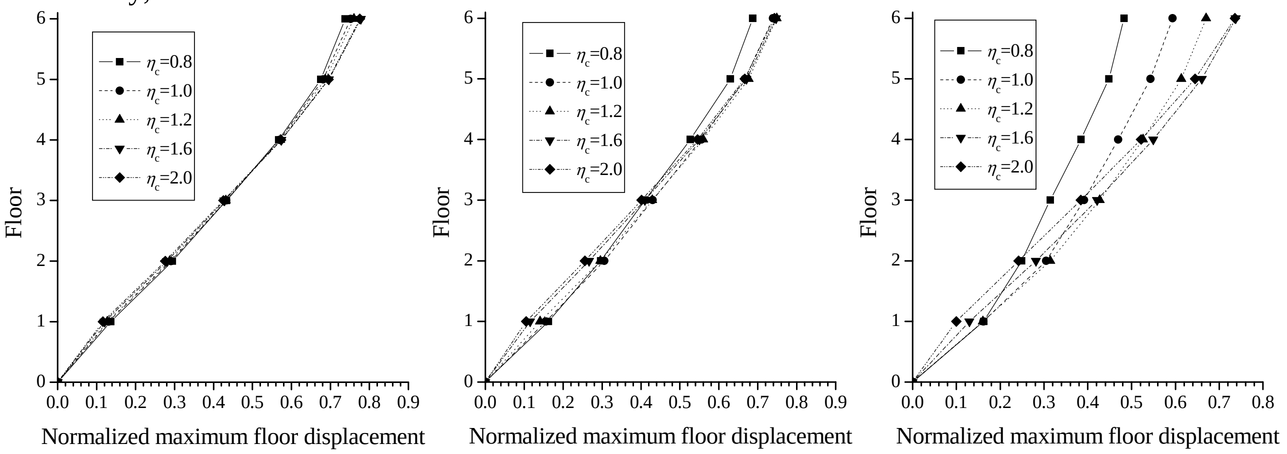
To be convenient for comparison, the maximum floor displacement is normalized as below:

$$D_{nor,j} = \frac{D_{m,j}}{H\theta_{s,\max}} \tag{3.4}$$

where $D_{nor,j}$ is the normalized maximum displacement of the *j*th floor, $H$ is the total height of the frame, and $\theta_{s,\max}$ is the maximum storey drift ratio over the height.

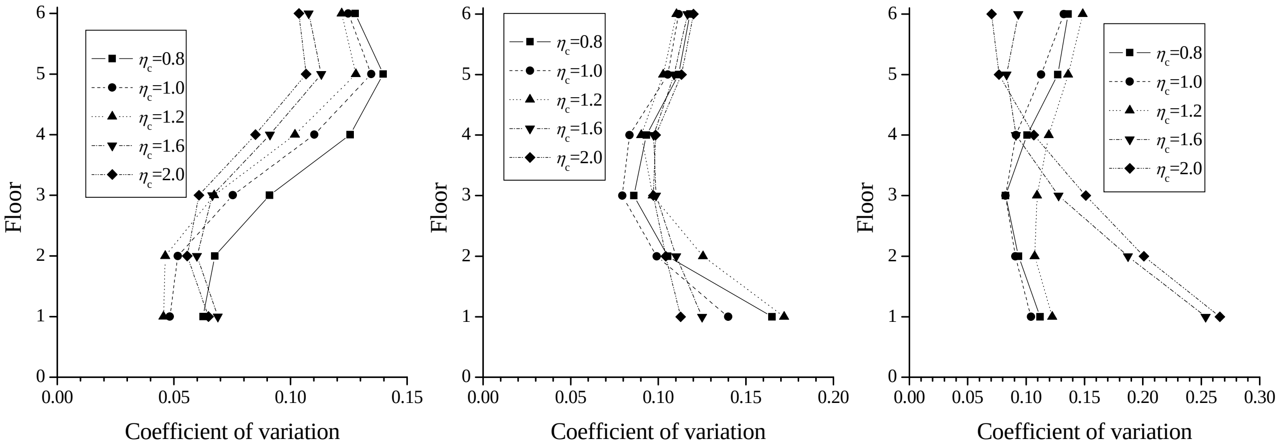
Figures 3 and 4 show the median of normalized maximum floor displacement and the corresponding COV for 6-story frames having different column-to-beam strength ratios at each damage state. From the figures it can be concluded that for the frames having same stories but different column-to-beam strength ratio, the displacement profiles are roughly identical at slight damage state, some different at moderate damage state, and considerably different at severe damage state. With the increase of column-to-beam strength ratio, the inter-story deformation distributes more uniformly along the height. Dispersion is small at slight damage state. With the increase of damage degree the larger value of dispersion appears at the lower stories.

Figure 5 compares the median of normalized maximum floor displacement for 9-story frames at different damage state. It is obviously that the shape of the profile is different at different damage states. With the decrease of column-to-beam strength ratio, the shape of the profile at different damage state becomes more distinctively, and the deformation inclines to concentrate at lower stories.



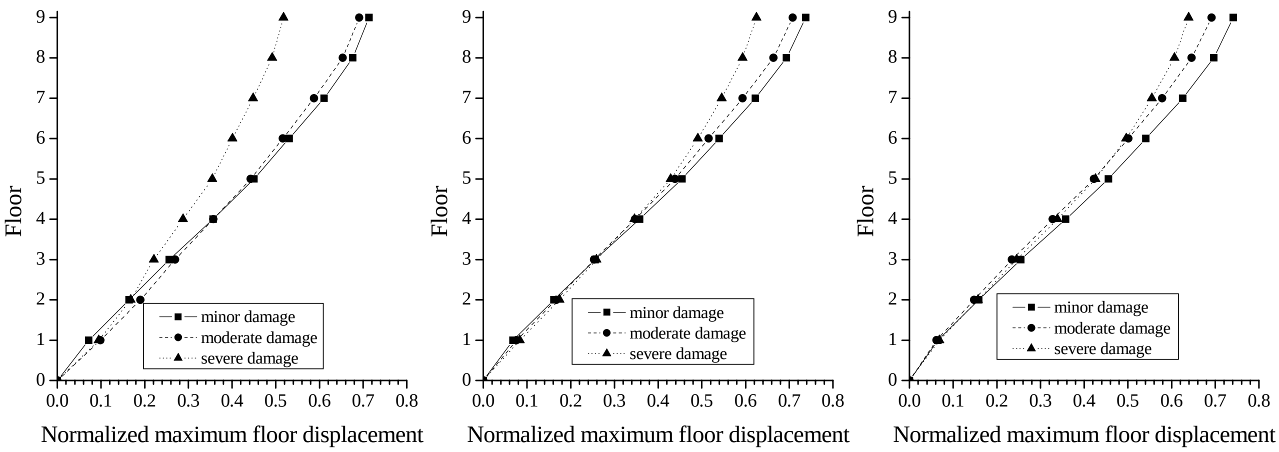

(a) Slight damage (b) Moderate damage (c) Severe damage

Figure 3 Median of normalized maximum floor displacement for 6-story frames




(a) Slight damage (b) Moderate damage (c) Severe damage

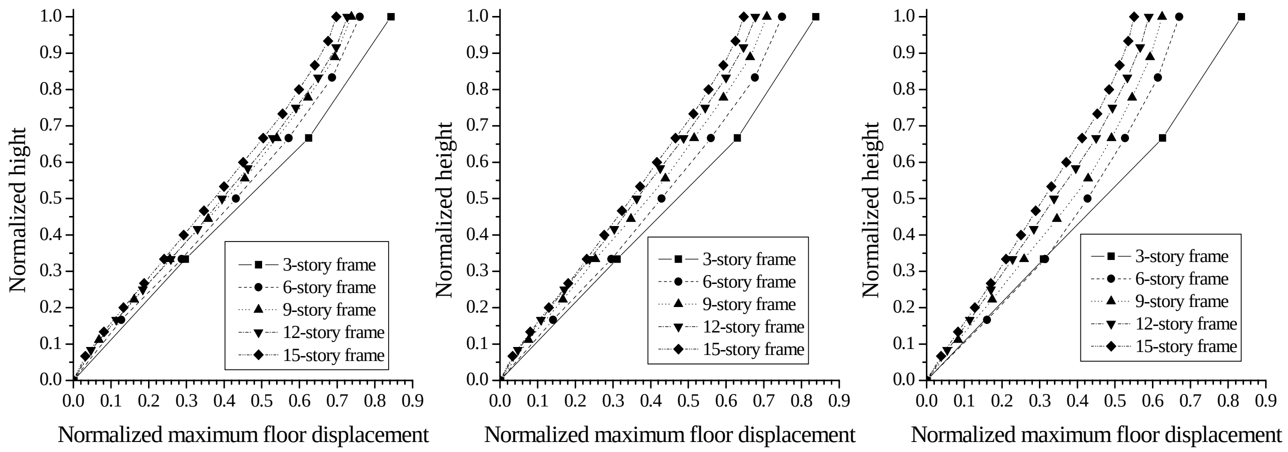
Figure 4 Coefficient of variation of normalized maximum floor displacement for 6-story frames




(a) $\eta_c$=0.8 (b) $\eta_c$=1.2 (c) $\eta_c$=1.6

Figure 5 Median of normalized maximum floor displacement for 9-story frames

Figure 6 compares the median of normalized maximum floor displacement having the same column-to-beam strength ratio of 1.2 but different number of stories. The shape of the profile is substantially affected by the number of stories. With the increase of number of stories, the vibration period is prolonged so that the higher mode effect becomes more evidently, and the value of normalized maximum floor displacement at most floors decreases. This difference becomes more obviously with the increase of damage degree. Based on the above discussion, the number of stories, damage level, and column-to-beam strength ratio were identified as the main factors influencing the normalized maximum floor displacement.




(a) Slight damage (b) Moderate damage (c) Severe damage

Figure 6 Median of normalized maximum floor displacement for frames with different stories ($\eta_c$=1.2)

### *3.2. Regression Analysis*

On the basis of above analysis of the calculation results, the least-squares regression analysis of the maximum displacement profile was conducted for frames at individual damage state. The elastic fundamental period was employed to represent the effect of number of stories. The following equation was generated:

$$D_j = (P_1 x_j + P_2 x_j^2 + P_3 x_j^3) H \theta_{s,\max} \tag{3.5}$$

where $D_j$ is the maximum floor displacement at the $j$th floor, $x_j$ is the relative height of the $j$th floor normalized by the total height, $x_j = H_j / H$, in which $H_j$ is the height of the $j$th floor measured from the ground level, $P_1$, $P_2$, and $P_3$ are the parameters depended on the damage state as below:
For slight damage state,

$$P_1 = 0.851 - 0.175 T_1 \tag{3.6}$$

$$P_2 = 0.528 + 0.077 T_1 \tag{3.7}$$

$$P_3 = -0.513 \tag{3.8}$$

For moderate damage state,

$$P_1 = 1.563 - 0.456\eta_c + \left(0.246 - \frac{1.155}{\eta_c + 1.162}\right) T_1 \tag{3.9}$$

$$P_2 = -0.888 + 0.853\eta_c + (0.414 - 0.217\eta_c)T_1 \tag{3.10}$$

$$P_3 = 0.066 - 0.322\eta_c \tag{3.11}$$

For severe damage state,

$$P_1 = 1.698 - 0.449\eta_c + \left(-0.203 - \frac{0.06}{\eta_c - 0.553}\right)T_1 \tag{3.12}$$

$$P_2 = -1.678 + 1.224\eta_c + (0.493 - 0.249\eta_c)T_1 \tag{3.13}$$

$$P_3 = 0.489 - 0.548\eta_c \tag{3.14}$$

where $T_1$ is the elastic fundamental period of the frame in seconds.

## 4. CONCLUSIONS

New expressions are generated in this study to estimate the maximum floor displacement profiles of regular moment resisting RC frames at slight, moderate, and severe damage state individually on the basis of a statistical analysis on the results obtained by nonlinear time history analysis conducted on 25 frames with different design parameters. The shape of the profile is quite different at different damage states. The developed expressions associate the maximum floor displacement profile with the maximum story drift ratio over the height, the elastic fundamental period, and the column-to-beam strength ratio. The dispersion of the maximum floor displacement was measured by the coefficient of variance. Dispersion is small at slight damage state. With the increase of damage degree the dispersion at the lower stories grows. The profiles developed in this study are sections and reinforcement independent so that they can be conveniently applied at the first step of the direct displacement-based seismic design. The proposed relations are valid for regular plane moment resisting RC frames. The extending of these expressions to irregular RC frames needs further research work.

## ACKNOWLEDGEMENTS

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