Estimating floor acceleration in nonlinear multi-story moment-resisting frames

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SUMMARY:
In this paper, a new shear building model is used to study floor response spectra of multi-story structures. The stories of shear building model are set to have the lateral stiffness and hysteretic force-deformation behaviours equivalent to the corresponding story of given moment-resisting frame. Incremental dynamic analyses are also performed on different shear building models and the variation of peak floor acceleration with the intensity of earthquake is investigated. The effects of fundamental period of structure, strength reduction factor, and level of installation are also studied on the acceleration response of non-structural components. A new formulation is proposed for extracting elastic acceleration spectrum of every floor from peak ground acceleration. This procedure could be taken as an alternative in using the resonance factor proposed by Eurocode 8. The effect of nonlinear behaviour of structure is then considered by calculating the required influence factors.

Keywords: Non-structural components; Peak floor acceleration; Nonlinear behavior; Dynamic analysis; Shear-building model.

1. INTRODUCTION

Nonstructural components (NSCs) are installed in the floors of a building that are not part of intended load-bearing structural system. Nonstructural elements are generally classified into three categories: 1) architectural components; 2) mechanical and electrical components; 3) building contents.

Viti et al. (1980) presented a computational scheme for developing nonlinear floor response spectrum (FRS). The results were shown, assuming missile impact on a reactor building. Then the expected reduction values were discussed for seismic or missile impact excitations with respect to the linear case. Fiouz and Ghafoury Ashtiany (2003) presented a simplified method for analyzing secondary systems using spectral analysis. Taghavi and Miranda (2005) applied a simplified model of a multistory building to develop a method for estimating peak floor acceleration of buildings. Their presented method can be used to estimate floor acceleration demands at any floor for a given ground motion record. The dynamic characteristics of building were approximated by using a simplified model based on the equivalent continuum structure consisting of a combination of flexural and shear beams. Medina et al. (2006) evaluated peak component acceleration demands for acceleration-sensitive NSCs. These systems were attached to the elastic and inelastic regular moment-resisting frames. The responses of a variety of stiff and flexible multi degree of freedom frames subjected to a set of 40 far-field ground motions studied. Villaverde (2006) proposed an approximation method to estimate the seismic response of nonlinear nonstructural components supported by nonlinear structures. The method was based on the procedure previously developed for analyzing linear nonstructural components attached to a linear primary structure. Furtmuller (2008) presented a procedure to analyze nonstructural components mounted on different floors of inelastic primary structures. Oropeza et al. (2009) investigated nonstructural component response in the presence of nonlinear behavior of supporting structure using floor response spectra method (FRS). The effects of several parameters such as natural frequency of primary and secondary systems, strength reduction factor and hysteretic model have been studied.

In this study, NSCs mounted on elastic and inelastic multi degree of freedom moment resisting frames are analyzed using modified shear building models and floor response spectrum method. For this sake, OpenSees software has been used for time history analysis. The amplification factor and resonance factor of stories have been calculated. Accordingly, the quantities of Eurocode 8 for computing the forces exerted to the secondary systems have been reformatted for elastic behaviour of primary structures. The effect of nonlinear behaviour of structure is then considered by calculating the required influence factor.

2. EUROCODE 8 EQUATION

In Eurocode 8 the following equation is recommended for calculating the force exerted on NSCs on a floor of structures:

$$F_s = \frac{S_s . W_s . \gamma_s}{q_s} \tag{2.1}$$

where,

$$S_s = \alpha . S . \left[\frac{3.\left(1 + {Z}/{H}\right)}{1 + \left(1 - \frac{T_s}{T_p}\right)^2} - 0.5 \right] \tag{2.2}$$

W_s: weight of non-structural element
γ_s: Importance factor
q_s: behaviour factor of NSC
S_s: Floor Response Spectrum (FRS)
α : ratio of ground design acceleration type (A) to ground gravitational acceleration (g)
S: soil type coefficient;
T_s: natural period of NSC
T_p: natural period of structure
Z: height of installation location of NSC in structure
H: total height of the structure

In this formulation α.S is considered as peak ground acceleration (PGA) with a given soil type and the effect of inelastic behavior of primary structure is not considered.

3. MODELING AND ANALYSIS METHOD

In order to study the response of nonstructural components in multi degree of freedom structures, three, five and seven-story moment resisting frames with different natural periods and strength are examined, Table 3.1. These frames are designed based on ASCE 2005 requirements.

Table 3.1: Examined frames characteristics

system type	frames		span length (m)	height of stories
	span	storey		
moment resisting frame	1	3	5	3
	3	5		
	5	7		

The modified shear building models were constructed in order to conduct expanded parametric studies on various frames with different stiffness and strength. To prepare these models, story shear-floor displacement curves are attained by performing nonlinear static analyses on the frames. Then they are replaced by triple-line curves and used as the behavioral curves for shear building model tabulated in Table 3.1. This shear building model is enough accurate and offers acceptable results for the purposes of this study.

In this study, eight periods are considered for each frame: 1/4, 1/3, 1/2, 2/3, 1, 4/3, 2 and 4 seconds. In order to achieve the proper period of shear-building models the initial stiffness of first story is adjusted proportionally, keeping the stiffness ratio of stories unchanged. Floor mass and triple stiffness ratio and strength ratio are not changed in the floors, Fig. 3.1.

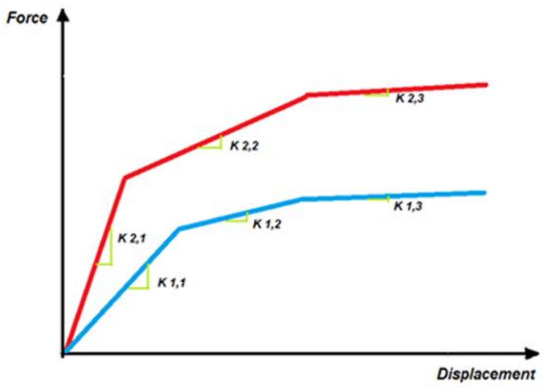

Figure. 3.1: Method of changing period of structure by keeping stiffness ratios constant.

In order to change the strength and exercising various strength reduction factors (R), maximum floor shear force (F_e) is calculated assuming the structural behavior completely elastic. Then the model is analyzed by applying the selected earthquake. Floor shear strength (yielding strength) is considered as F_e/R to exercise different strength reduction factors. The ratio of secondary strength to the yielding strength is remained unchanged in the story. In this study elastic behavior and four strength reduction factors (2, 3, 4 and 5) are considered as well, Fig. 3.2.

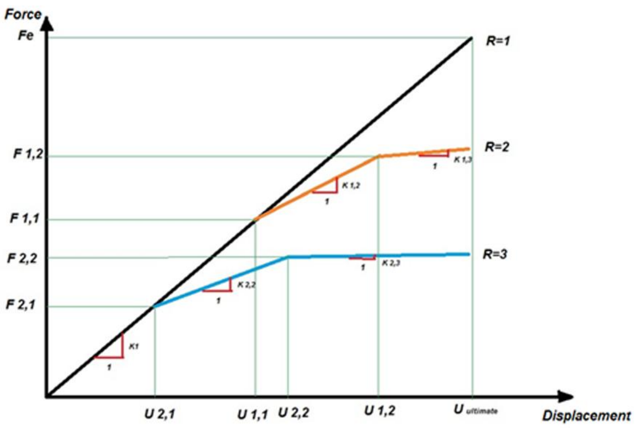

Figure. 3.2: Force-displacement curve for producing a frame with inelastic behaviour.

4. PEAK FLOOR ACCELERATION

In this section the effects of linear and nonlinear behaviors are studied on the peak acceleration applied on non-structural elements. Peak floor acceleration of elastic structures (PFA_e) would be applied on rigid NSCs (with very low period).

4.1. The effect of NSC location on the structure

One of the most important parameters affecting peak floor acceleration is the location of NSC in the structure. According to Fig. 4.1, the NSCs attached to the higher floor of structure will experience more acceleration. This trend is almost the same for all structures with different periods (up to 4.0 sec); however, the height wise distribution of acceleration would be more uniform in the structures with higher periods.

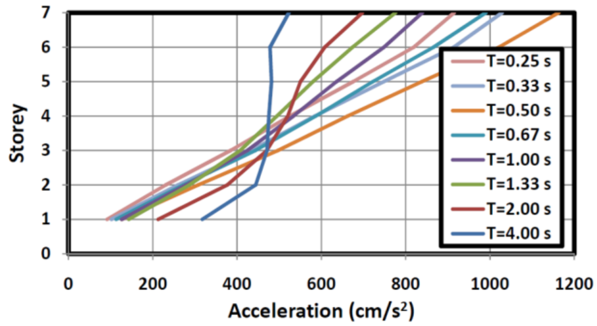

Figure. 4.1: Peak floor acceleration of 7-story elastic frames with eight different periods.

4.2. The effect of primary system period

The maximum PFA_e of top floor and minimum PFA_e of first floor are presented in Fig. 4.2 for seven-story elastic frames with different periods. According to the figure, as the natural period increases, maximum PFA_e decreases and minimum PFA_e increases.

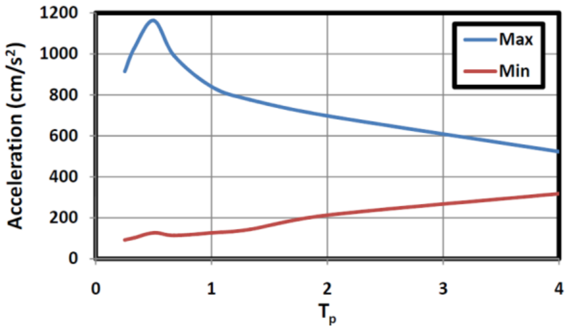

Figure. 4.2: Peak floor acceleration of seven-story elastic frames with different periods.

4.3. The effect of earthquake intensity

Another parameter considered in this study is the effect of applied earthquake intensity on PFA_e. This effect on average PFA_e is shown in Fig. 4.3 for the first and top floors of a 7-story frame subjected to 15 far-field records. As it has been observed, an increase in earthquake intensity causes the decrease of PFA_e in the first floor and increase in the higher floors. This effect was not considered in Eurocode 8 or any other provisions.

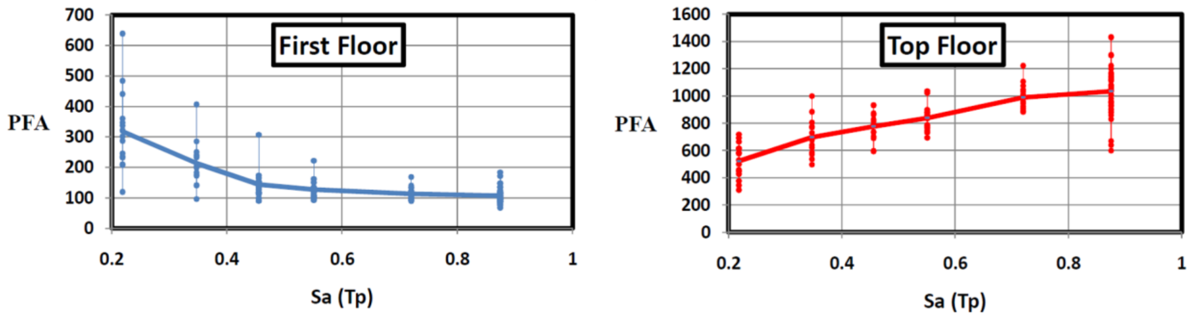

Figure. 4.3: Average PFA_e for the first and top floors of a 7-story frame subjected to 15 far-field records.

5. FLOOR RESPONSE SPECTRUM (FRS)

The period of secondary system (T_s) can affect the response of NSCs. The average elastic response spectrum (FRS_e) is plotted for the floors 1 to 7 of seven-story frame with a period of 0.67 second subjected to 15 far-field records, Fig. 5.1. In this figure the effect of NSC period is clearly observed. As it is seen, FRS_e reaches its maximum when the period of secondary system is equal to the natural period of the primary system. PFA_e and maximum FRS_e of the above mentioned frame is shown in Fig. 5.2. As an example maximum FRS_e value for 7th story is five times PFA_e, seen in the figure.

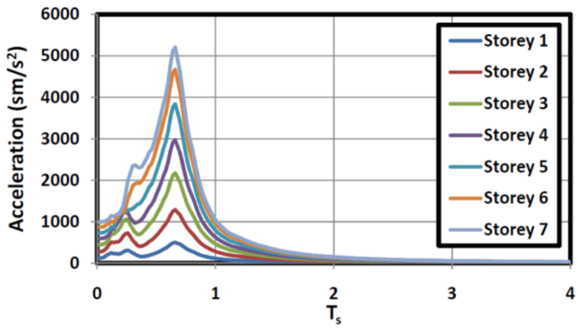

Figure. 5.1: Average FRS_e of the 7-story frame with a period of 0.67 second.

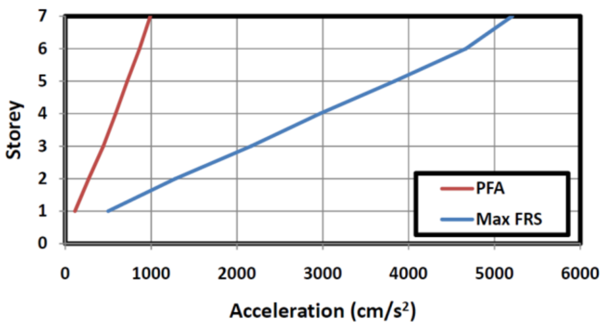

Figure. 5.2: PFA_e and maximum FRS_e of a 7-story frame with a period of 0.67 second.

6. AMPLIFICATION FACTOR (λ)

The ratio of PFA_e to Peak Ground Acceleration (PGA) is called amplification factor (λ) and defined as:

$$\lambda = \frac{PFA_e}{PGA} \tag{6.1}$$

This factor is shown in Fig. 6.1 for 3, 5, and 7-story elastic structures with a period of 0.67 second. The values of amplification factors resulted from other expressions (λ=1+Z/H, Eurocode 8; λ=1+3Z/H, UBC 97; λ=1+2Z/H, ASCE 2010) similar to Eqn. 2.2 are presented in this figure as well. According to the results obtained here the number of stories (up to seven) has no significant effect on the amplification factor. Moreover, the values of amplification factors obtained in Eurocode 8 are higher for lower floors and lower for higher floors comparing to the calculated quantities.

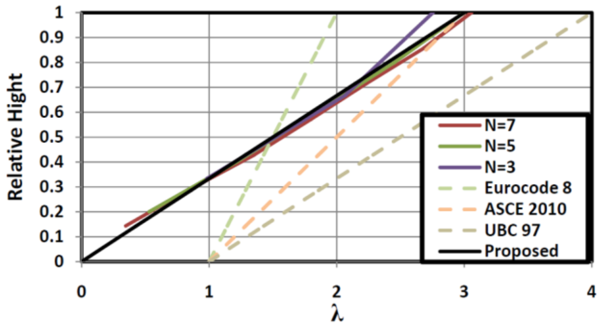

Figure. 6.1: Average amplification factors for 3, 5, 7-story elastic structures with a period of 0.67 second.

Based on the results obtained in this research, the following relation seems more appropriate for calculating amplification factor (λ) in comparison with that of Eurocode 8:

$$\lambda = 3.\left[Z/H \right] \tag{6.1}$$

7. ELASTIC RESONANCE FACTOR, β_E

Floor elastic resonance factor (β_e) is derived from dividing elastic acceleration spectrum (FRS_e) by peak floor acceleration (PFA_e) as:

$$\beta_e = \frac{FRS_e}{PFA_e} \tag{6.2}$$

The Eqn. 2.2 is used to calculate elastic resonance factor (β_e) in Eurocode. In this equation the expression in brackets could be considered as $\beta_e.\lambda$. Fig. 7.1 shows β_e as per Eurocode (Eqn. 2.2) for Z/H=1.0. The resonance factor is negative for T_s/T_p ratio more than 4.32 which is not rational.

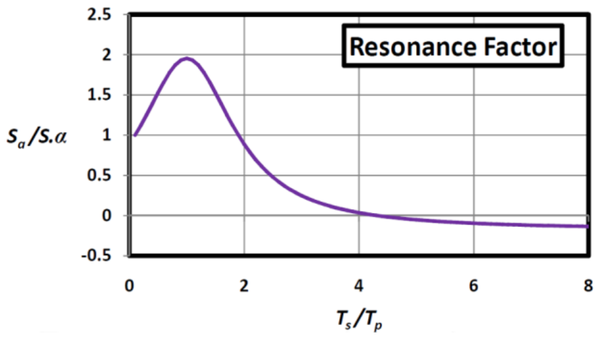

Figure. 7.1: Resonance factor according to Eurocode 8 formulations.

The studied frames (3, 5, and 7-story with 0.67 sec. period), are subjected to 15 earthquake records and their average resonance factors are shown in Fig. 7.2. The elastic resonance factors resulted from Eurocode are shown in this figure as well. According to the figure, Eurocode underestimates the resonance factor where NSC and structural periods are close together. This fact is confirmed by Oropeza et. al.; their proposed values are also indicated in the above mentioned figure.

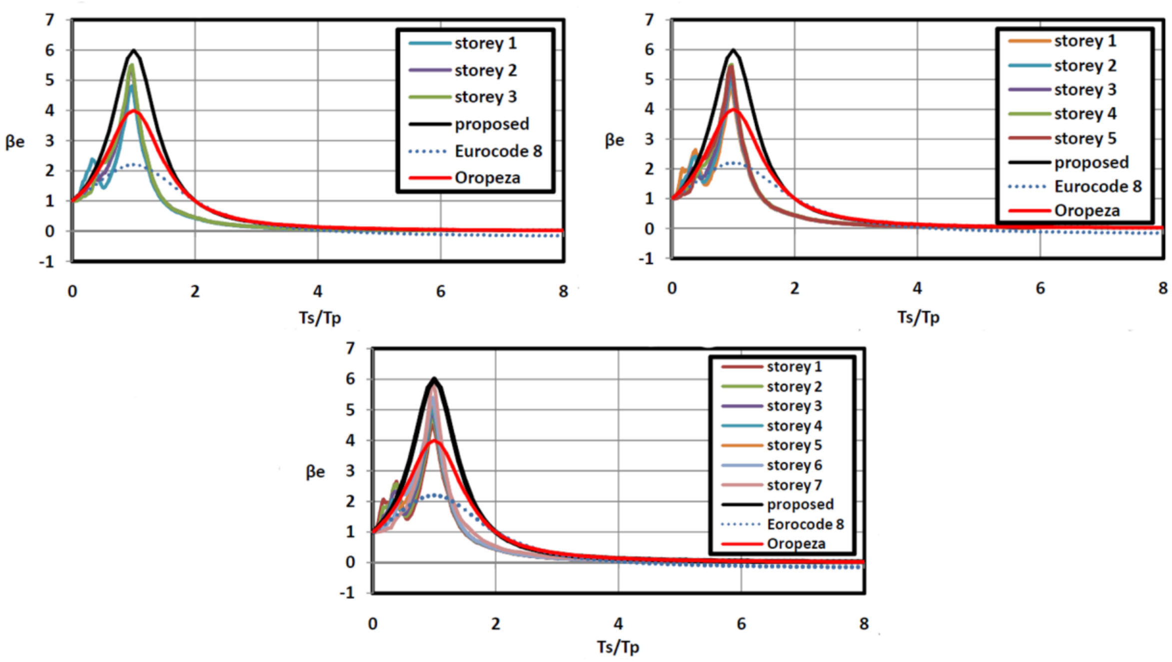

Figure. 7.2: Average β_e for 3, 5, and 7-story frames with the period of 0.67 sec. subjected to 15 records.

Maximum resonance factor (β_{emax}) is almost independent of the number of stories (up to 7), Fig. 7.2, i.e. β_e is almost independent of NSC location. Based on the above mentioned points, the following equation is suggested for calculating elastic resonance factor (β_e):

$$\beta_e = \frac{1.2}{0.2 + \left(1 - \frac{T_s}{T_p}\right)^2} \tag{7.1}$$

This equation is compared with Eurocode and Oropeza et. al (2009) in Fig. 7.2. According to this figure, elastic resonance factor more accurately (and more conservatively) can be calculated by Eqn. 7.1 comparing to Eqn. 2.2.

7.1. The effect of primary structure period (T_p)

The effect of natural period of primary structure is studied on β_{emax} parameter for a seven-story frame and shown in Fig. 7.3. It can be concluded that β_{emax} decreases as natural period of primary structure increases. The expression, $(0.5/T_p)^{0.3}$, is proposed here to encounter the effect of T_p on β_e; β_{emax} remains unchanged for the periods less than 0.5 sec. The results obtained from suggested equation are drawn in Fig. 7.3.

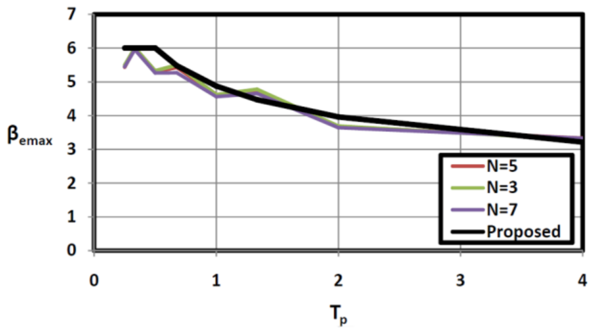

Figure. 7.3: Comparing β_{emax} of 3, 5, and 7-story structures subjected to 15 far-field records.

Based on what explained so far, the Eqn. 7.1 should be modified in order to observe the effect of primary structure period (T_p), as:

$$\beta_e = \frac{1.2}{0.2 + \left(1 - \frac{T_s}{T_p}\right)^2} \left(\frac{0.5}{T_p}\right)^{0.3} \leq 6.0 \qquad (7.2)$$

8. THE EFFECT OF INELASTIC BEHAVIOR OF PRIMARY SYSTEM

As it was mentioned earlier the strength reduction factors (2, 3, 4, and 5) were considered for examining the effect of inelastic behavior of primary system. The peak floor acceleration of nonlinear structure (PFA_p), would be different from PFA_e. The ratio of PFA_p to PFA_e is called inelastic behavior influence factor (η) and defined as:

$$\eta = \frac{PFA_p}{PFA_e} \Rightarrow PFA_p = \eta . PFA_e \qquad (8.1)$$

Having PFA_e and η, PFA_p could be calculated from Eqn. 8.1. In Fig. 8.1 the average values of parameter α are shown for 3, 5 and 7-story inelastic structures with the period of 0.67 sec. and the strength reduction factors (*R)* of 3 and 5. According to this figure, the number of stories or strength reduction factor has no significant effect on η. Moreover, inelastic behavior influence factor decreases as the NSC location level decreases. Considering Fig. 8.1, the following expression is suggested for calculating η values and the obtained results are shown there as well.

$$\eta = 0.5\left(\frac{Z}{H}\right)^{-0.85} \qquad (8.2)$$

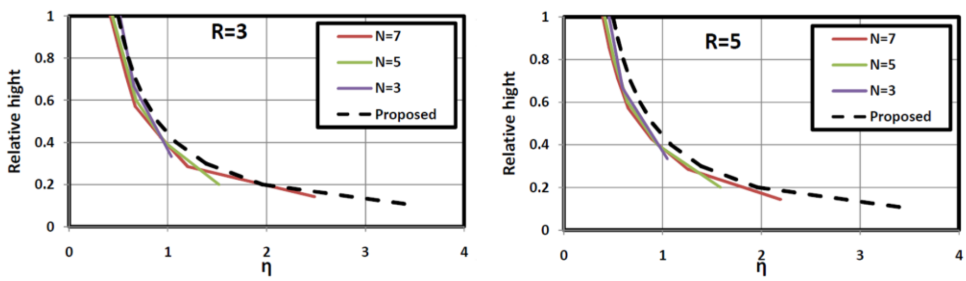

Figure. 8.1: Average parameter η in 3, 5, and 7-story inelastic structures with the period of 0.67 sec. and reduction factors (R) of 3 and 5, subjected to 15 far–field records.

9. SUMMARY AND CONCLUSION

Here, the effects of periods of secondary and primary systems, nonlinear behavior and height of primary system are studied on peak acceleration exerted on non-structural elements located on different floors. A method is suggested for calculating peak floor acceleration of linear and nonlinear structures in moment resisting frames (up to seven stories) by modifying provision Eurocode 8. The equations used in this method are:

$$F_s = S_s.W_s.\gamma_s \tag{9.1}$$

Where, S_s is acceleration spectrum and calculated as follows:

$$\frac{S_s}{\alpha.S} = \beta_e.\lambda = \frac{1.2\times(1+3\frac{Z}{H})}{0.2+\left(1-\frac{T_s}{T_p}\right)^2}\left(\frac{0.5}{T_p}\right)^{0.3} \leq 6.0 \qquad \text{for elastic structures} \tag{9.2}$$

Accordingly, the incremental dynamic analyses are also performed indicating that the higher earthquake intensities cause the decrease of peak floor acceleration in lower floors and its increase in higher floors of structures.

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