EVALUATION OF RANDOM SEISMIC RESPONSE OF MID-RISE BUILDINGS WITH MASS IRREGULARITY CONSIDERING SOIL-STRUCTURE INTERACTION EFFECTS

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ABSTRACT

Seismic response of non-geometric vertically irregular steel buildings with non-uniform distribution of mass along the height is investigated in the framework of random analysis. As foundation flexibility influences structural responses, soil-structure interaction effects are also considered. A 10 story elastic shear steel building with fully restrained moment connections was considered as the superstructure. For the interaction forces at foundation level, frequency-independent springs and dashpots set in parallel were used and equations of motion of the superstructure resting on an elastic homogeneous half-space were established. Since in many engineering cases, the applied loads are random, in this study, structural response is evaluated in the framework of non-stationary random excitation.

According to the curves of mean square value of structural response, it is observed that in spite of the same specifications of structures, non-uniform distribution of mass through the structure height influences displacement demands. It is shown that regardless to the position of irregularity, a large portion of displacement demands have been concentrated on the lower stories. Meanwhile, depending on the position of the heavier floors through the structure height, demand distribution would be affected. As the heavier story moves to the upper floors, demand concentration reduces in the lower stories. Placement of the heavier stories at the upper half floors or through the bottom half ones has the maximum demand variations (up to 28%), compre to the regular structure.

INTRODUCTION

Uncertainty extensively exists as external actions to a system in nature and engineering area that forms random excitation. One of the most disastrous natural events that threats the human life and property is earthquake. It is a random phenomenon that widely affects structures and facilities. Therefore evaluation of structures and buildings response to the earthquake loading has been widely investigated (Romão, Costa et al. 2004; Jangid 2005; Tremblay and Poncet 2005; Adhikary, Singh et al. 2014; Fragiadakis, Vamvatsikos et al. 2015). Vertically irregular buildings have been reported to have different performance compare to the regular ones (Karavasilis, Bazeos et al. 2008; Pirizadeh and Shakib 2013). Constructions of mid to high-rise buildings, with different story usage, impose mass irregularity to the structures. In spite of the random nature of seismic events, the majority of seismic assessments of this type of structures belongs to the time history analysis with recorded earthquakes. Due to the variability of earthquake records, this procedure can't fully consider the whole randomness effects. A solution to this shortcoming is to consider the applied loads as non-deterministic ones.

Random analysis is a powerful tool that can predict structural response under random excitations. The analysis with uncertainty in loads is usually performed to satisfy the critical cases of design of structures. It gives the response of structures in a realistic way, whose performances play an important role in safety criteria.

In this paper, the effects of mass irregularity through the structure height, are evaluated in seismic response of a 10 story steel building. As foundation flexibility influences the structural response (Shakib and Fuladgar 2004; Moghaddasi, Cubrinovski et al. 2011; Rajeev and Tesfamariam 2012), soil-structure interaction effects are also considered. The results are compared in form of the mean square value of structural displacement response at each story level. The maximum values of demands of irregular structures are compared to the regular one, as well.

STRUCTURAL MODELS AND EQUATIONS OF MOTION

The structural system considered in this study is a three dimensional elastic shear building with 10 stories that is resting on an elastic homogeneous half-space (Fig.1). The mass at each story level was assumed to be concentrated at the center of mass (CM) and eccentricity distance of CM to CR (center of stiffness) was assumed zero (no asymmetric in plane). The floor systems were assumed to be rigid in their own planes and inextensible columns with the Young's modulus of $2e5\,N/mm^2$, support the rigid floor decks. Efficiency of structural elements was evaluated according to the earlier Iranian Seismic Codes (2014; 2014). Similar to common residential building of Iran, gravity loads was supposed to be 700 kg/m^2 and 200 kg/m^2 for dead and live loads, respectively(2014). The level of mass irregularity at different story levels was limited to 200%, compare to the regular structure. To make a fair comparison, the main specifications of regular and irregular structures were kept the same(Pirizadeh and Shakib 2013).

For the superstructure, 3 DOFs namely two lateral translations and a rotation about the vertical axis were considered per floor. Adding 5 degrees of freedom due to the interaction forces at the foundation level, the equations of motion for the whole system are given as:

$$[M]\{\ddot{v}(t)\}+[C]\{\dot{v}(t)\}+[K]\{v(t)\}=-\{P\} \tag{1}$$

In the above equation, displacement vector $\{v(t)\}$ is defined as:

$$\{v(t)\}=\left\{\{U_{xj}^{tot}\}_{10\times1} \quad \{U_{yj}^{tot}\}_{10\times1} \quad \{U_{zj}^{tot}\}_{10\times1} \quad U_{x0} \quad U_{y0} \quad U_{zo} \quad \cdot_{0} \quad ¤_{0}\right\}_{35\times1}^{T} \tag{2}$$

where, $U_{xj}^{tot}, U_{yj}^{tot}, U_{zj}^{tot}$ are the total displacements of the superstructure at the corresponding DOFs:

$$U_{xj}^{tot}=U_{x0}\{1\}+¤_{0}h+U_{xj} \quad , \quad U_{yj}^{tot}=U_{y0}\{1\}+\cdot_{0}h+U_{yj} \quad , \quad U_{zj}^{tot}=U_{z0}\{1\}+U_{zj} \tag{3}$$

where, $\{1\}$ is a column identity vector and h is a column vector of stories heights from the above surface of foundation. Fig.1 describes the physical meaning of these equations.

Mass $[M]$, damping $[C]$ and stiffness $[K]$ matrices could be decomposed in to specific sub matrices as:

$$[M]=\begin{bmatrix}[M_{ss}] & [M_{so}]\\ [M_{os}] & [M_{oo}]\end{bmatrix}_{35\times35} , [C]=\begin{bmatrix}[C_{ss}] & [C_{so}]\\ [C_{os}] & [C_{oo}]\end{bmatrix}_{35\times35} , [K]=\begin{bmatrix}[K_{ss}] & [K_{so}]\\ [K_{os}] & [K_{oo}]\end{bmatrix}_{35\times35} \tag{4}$$

The subscripts "s" and "o" are referring to the structure and foundation respectively.

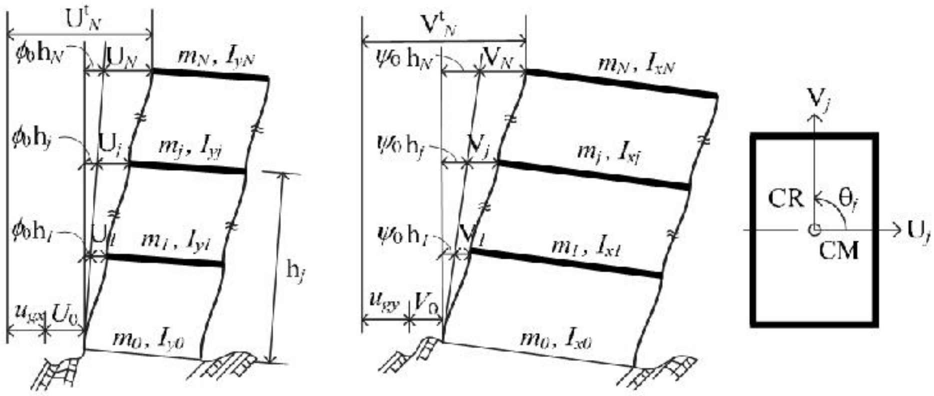

Figure 1. structural model

Frequency independent spring-dashpot set in parallel was considered at foundation level to simulate the interaction forces. For a circular footing with radius of r_0, resting on a linear half-space with shear wave velocity of V_s, Poisson's ration of ³ and mass density of ° , the frequency independent spring coefficients for transitional (T), vertical (V) and rotational (R) DOFs of the system are expressed as (Richart, Hall et al. 1970):

$$k_T = \frac{32\left(1-³\right)}{7-8³} G r_0 \quad , \quad k_Z = \frac{16}{3} G r_0^3 \quad , \quad k_R = \frac{8}{3\left(1-³\right)} G r_0^3 \tag{5}$$

where G is shear modulus of soil:

$$G = V_s^2 \, ° \tag{6}$$

For frequency independent damping coefficients, the following relations are given:

$$c_T = 18.432 \frac{1-³}{7-8³} r_0^2 \sqrt{° G} \quad , \quad c_Z = \frac{5.657}{° r_0^5 + 2 I_Z} \sqrt{\frac{\left(1-³\right) G r_0 I_Z}{7-8³}}$$
$$c_R = \frac{6.4 I_R \, ° \, r_0^9 \sqrt{° G}}{\left(1-³\right)\left(8 \, ° \, r_0^5 - 3 I_R \left(1-³\right)\right)} \tag{7}$$

The fundamental period of the flexible base structures is 1.28 sec.

NON-STATIONARY RANDOM RESPONSE OF STRUCTURES

In this paper, structural response is evaluated in the framework of random vibration analysis. The ground motion acceleration $\ddot{x}_g\left(t\right)$ is assumed to be the uniformly modulated non-stationary random process:

$$\ddot{x}_g\left(t\right) = A\left(t\right) f\left(t\right) \tag{8}$$

where $A\left(t\right)$ is a given deterministic modulation function of the input acceleration, and $f\left(t\right)$ is a zero-mean-valued stationary random Gaussian process. The envelop function is considered as (Takewaki 2004; Gao 2007):

$$A\left(t\right) = \exp(-0.13t) - \exp(-0.45t) \tag{9}$$

Substituting in to Eq.1, the equations of motion of the SSI system under random excitation is expressed as:

$$[M]\{\ddot{v}(t)\}+[C]\{\dot{v}(t)\}+[K]\{v(t)\}=-[M]\{R\}A(t)f(t) \tag{10}$$

where $\{R\}$ is an index vector of the inertial forces. Evaluation of the above coupled differential equations can be obtained in terms of the Duhamel integral:

$$\{v(t)\}=\int[\Phi][h(t-\tau)][\Phi]^T[M]\{R\}A(\tau)f(\tau)d\tau \tag{11}$$

where $[\Phi]$ and $[h(t)]$ are the normal modal matrix and the impulse response function matrix of the structure, respectively. The correlation function matrix of the displacement response of the structural system $[R_v(t,\tau)]$ can be evaluated as:

$$\begin{aligned}\left[R_v(t,\tau)\right]=E\left[\{v(t)\}\{v(t+\tau)\}^T\right]=\int_0^t\int_0^{t+\tau}[\Phi][h(t-\tau)][\Phi]^T[M]\{R\}A(\tau_1)\left[R_f(\tau_1-\tau_2)\right]\times \\ A(\tau_2)\{R\}^T[M]^T[\Phi][h(t-\tau)][\Phi]^T d\tau_1 d\tau_2\end{aligned} \tag{12}$$

By performing a Fourier transformation of the correlation function matrix of the displacement response, the time-dependent power spectral density (PSD) matrix of the displacement response can be obtained as:

$$\begin{aligned}\left[S_v(t,\omega)\right]&=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left[R_v(t,\tau)\right]e^{-i\omega\tau}d\tau \\ &=[\Phi]\left[H(\omega)\right][\Phi]^T[M]\{R\}A(t_1)\left[S_f(\omega)\right]A(t_2)\{R\}^T[M]^T[\Phi]\left[H^*(\omega)\right][\Phi]^T\end{aligned} \tag{13}$$

where, $\left[H(\omega)\right],\left[H^*(\omega)\right]$ are the frequency response and the complex conjugate function matrix of the structure:

$$[H(\omega)]=\begin{bmatrix}\dfrac{1}{\omega_1^2-\omega^2+i2\xi_1\omega_1\omega} & 0 & \cdots & 0 \\ 0 & \dfrac{1}{\omega_2^2-\omega^2+i2\xi_2\omega_2\omega} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \dfrac{1}{\omega_n^2-\omega^2+i2\xi_n\omega_n\omega}\end{bmatrix}_{n\times n} \tag{14}$$

$\left[S_f(\omega)\right]$ is the equivalent one-sided power spectral density matrix of a stationary random Gaussian process. In this paper, the modified version of Kanai-Tajimi model was adopted for describing the ground motion acceleration (Clough and Penzien 1975; Li, Zhang et al. 2004):

$$S_f(\omega)=\frac{\omega^4 S_0\left(\omega_g^4+4\omega^2\omega_g^2\xi_g^2\right)}{\left(\left(\omega^2-\omega_g^2\right)^2+4\omega^2\omega_g^2\xi_g^2\right)\left(\left(\omega^2-\omega_f^2\right)^2+4\omega^2\omega_g^2\xi_f^2\right)} \tag{15}$$

where, ω_g, ξ_g are the natural frequency and critical damping of the soil layer, respectively. For stiff soil layer, $\omega_g=15\,rad/s$, $\xi_g=0.6$. S_0 is the ordinate of the power spectral density of the bedrock acceleration that is considered $1.0\, m^2/s^3$. μ_f , , $_g$ are parameters to assure a finite power for the ground displacement that are assumed $1.5\, rad/s$ and 0.6, respectively.

The mean square value of the structural displacement could be obtained by integrating the PSD matrix of the displacement response within the frequency domain:

$$
\begin{aligned}
E\left[v^2(t)\right] &= \int_0^\infty \left[S_v(t,\mu)\right] d\mu \\
&= [\Phi]\left[\int_0^\infty \left[H(\mu)\right][\Phi]^T [M]\{R\} A(t_1)\left[S_f(\mu)\right] A(t_2)\{R\}^T [M]^T [\Phi]\left[H^*(\mu)\right] d\mu \right][\Phi]^T
\end{aligned}
\tag{16}
$$

The diagonal terms of the mean square value of the displacements matrix are used in the assessment procedure.

RESULTS AND DISCUSSION

The mean square value of structural displacement response at each story level and comparison of the maximum demands of the irregular structures to the regular one were plotted in Figures 2 to 12. It is observed that the effects of mass irregularity on the mean square value of structural non-stationary seismic displacement are different. Depend on the position of the heavier story, demand distribution varied through the structure height.

In case of regular structure, distribution of the displacement demands is maximal at the 3rd and the 10th stories. Meanwhile, existence of the mass irregular floor reduces the demands of the upper floors in many irregularity cases. Mass irregularity of the 1st floor has the height-wise demand distribution similar to the regular structure except at the highest floor that the mean square value of displacement reduced 80% at the 10th story (Fig.3 & 4). Similar to the regular structure, the maximum demand position is at the 3rd story with 7.5% differences in the demand value. This result is also observed in case of mass irregularity at the 3rd floor. However, the maximum demand of the 3rd floor increased up to 15%, compare to the regular structure (Fig.5 & 6). As shown in Fig.8, position of the irregular story at the middle height of structure (story 5) makes the distribution of the displacement demands similar to the regular structure, especially at the lower and upper floors. However, the maximum mean square value of displacements reduced up to 15% in comparison to the regular structure. Although the maximum displacement demands are concentrated at the 3rd and the 10th stories, a portion of displacement is observed through the middle stories (stories 5 &6).

Among all the mass irregularity models, the maximum demand variation is observed at the 3rd floor of the mass irregularity at the 7th story (Fig.9 & 10). Compare to the regular structure, the mean square value of the displacement demand of this floor reduced up to 28%. The maximum displacement demands of the bottom stories decreased as well. In return, distribution of heavier stories through the 1st to the 5th floors shows moderated variations of displacement demands at the bottom half floors (Fig.11 & 12). Nevertheless, displacement demands increased through the top half stories. In spite of the same position of the maximum demand (the 10th story), the maximum mean square value of the displacements increase 22%, compare to the regular structure.

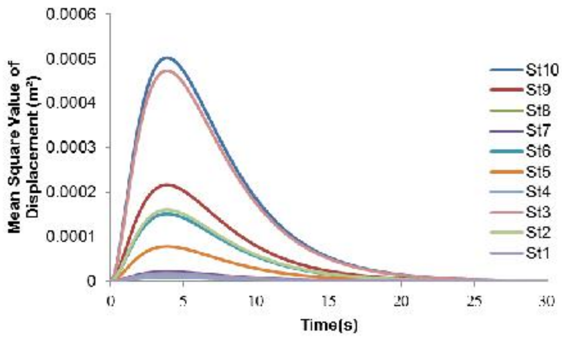

Figure 2. mean square value of story displacement for the regular model

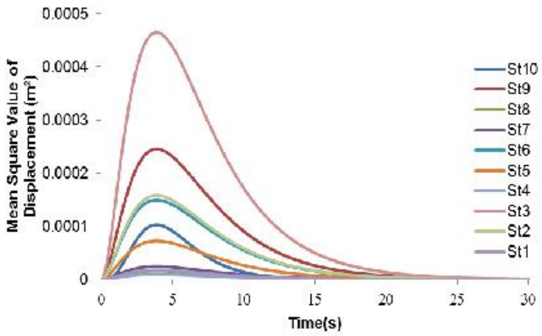

Figure 3.The mean square value of structural response for the 1st floor irregularity model

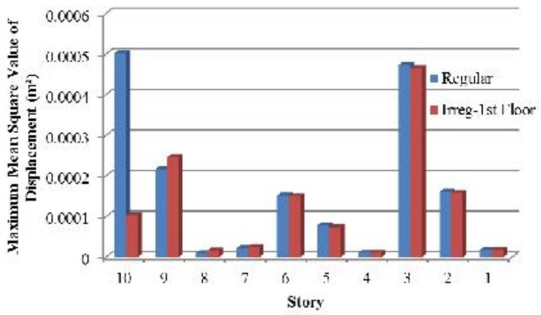

Figure 4. The maximum mean square value of displacement (regular & mass irregularity at the 1st floor)

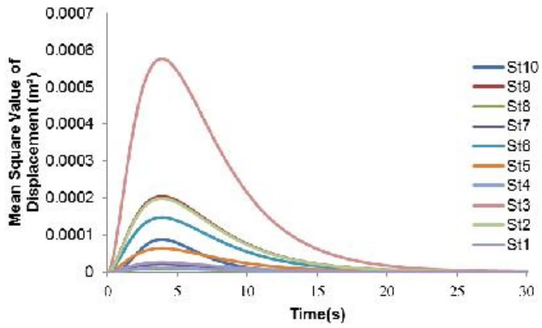

Figure 5. The mean square value of structural response for the 3rd floor irregularity model

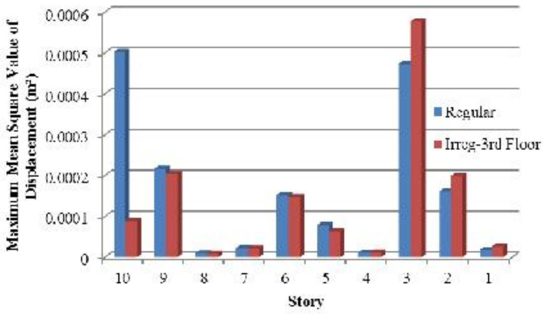

Figure 6. The maximum mean square value of displacement (regular & mass irregularity at the 3rd floor)

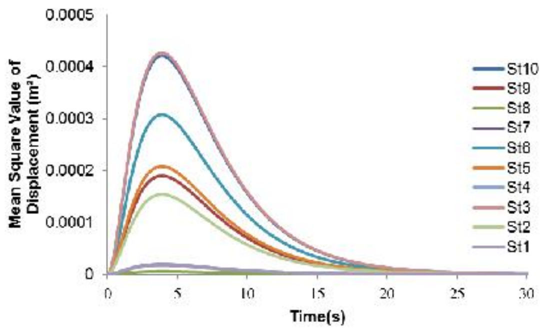

Figure 7. The mean square value of structural response for the 5th floor irregularity model

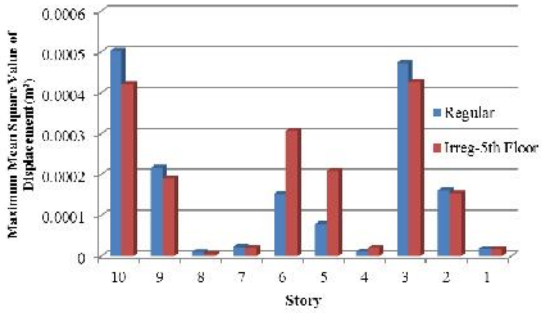

Figure 8. The maximum mean square value of displacement (regular & mass irregularity at the 5th floor)

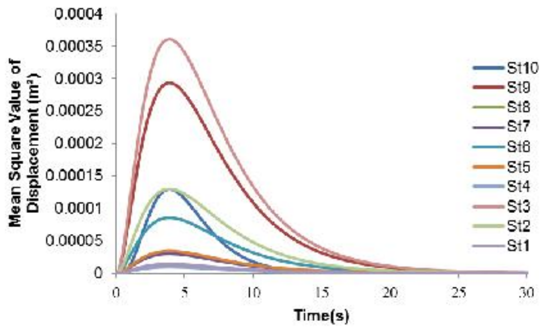

Figure 9. The mean square value of structural response for the 7th floor irregularity model

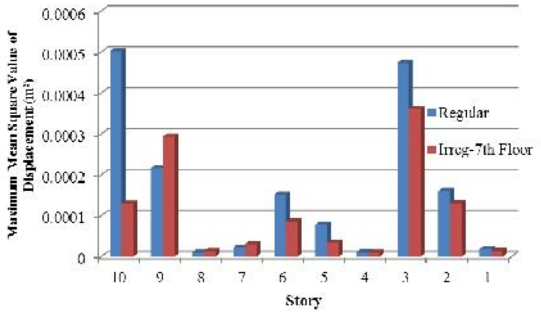

Figure 10. The maximum mean square value of displacement (regular & mass irregularity at the 7th floor)

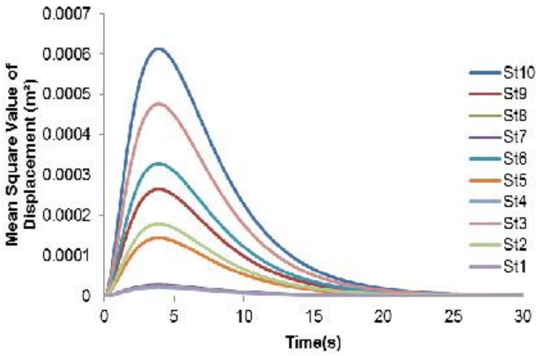

Figure 11. The mean square value of structural response for the 1st to the 5th floor irregularity model

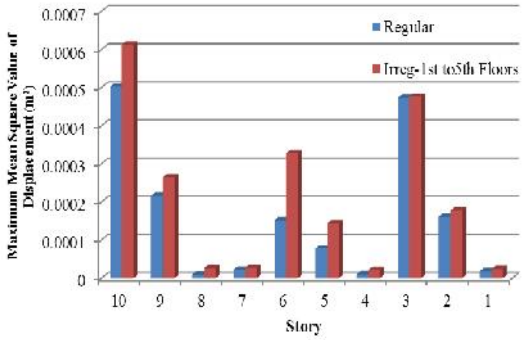

Figure 12. The maximum mean square value of displacement (regular & mass irregularity though the 1st to the 5th floors)

CONCLUSIONS

In this paper, the seismic response of non-geometric vertically irregular steel buildings with non-uniform distribution of mass along the height is investigated in the framework of random analysis. The soil-structure interaction effects were also considered in response evaluation of a 10 story steel building. For the interaction forces at the foundation level, frequency-independent springs and dashpots set in parallel were used.

Structural responses were evaluated in form of the mean square value of displacements at different floors. It was observed that the distribution of the displacement demands through the regular structure height varied so that the maximum demands are concentrated at the highest stories and at the middle of the bottom half floors. Appearance of the mass irregularity through the structure height varied the demand distribution in coparison to the regular model. Since in most irregular structures, the demand concentration was potentially at the 3rd floor, placement of the heavier story at this story increased the maximum demand of the irregular structure up to 15%.

The highest variation of the demands was observed at two iregularity cases. Placement of the heavier story at the 7th floor showed the maximum mean square value of displacements reduction up to 28%. Meanwhile, 22% increase of the displacement demands was observed if the irregularity is distributed through the 1st to the 5th stories. In spite of the demand reduction of the highest floor, mass irregularity at the bottom story has no significant effect in demand distribution through structure height, compare to the regular structure.

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