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Safety analysis of independent columns mounted on isolated bearing system

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Abstract

This paper explores the safety performance of independent column mounted on isolated bearing. Considering large displacement of the isolator bearing under earthquake, the accumulated permanent deformations in the independent column may render gravity forces the dominant forces and make the system collapse by lateral instability. By means of dynamic response simulation of the system under seismic excitations, the safety of system is derived by optimality method and expert systems. The results show that the safety of system mainly depends on the lateral force, irrespective of the axial force. The lateral force is largely influenced by the displacement of the system. The absolute value of the constraint moment has significant effect on the safety of column. The more the absolute value of the constraint moment is, the worse the safety of system is. The independent column is impossible to be instability with an adequate section of column employed.

Keywords*:* safety analysis, isolated bearing, independent column, optimization, expert systems

1 Introduction

Road traffic injuries are a major cause of death and disability globally, with a disproportionate number occurring in developing countries. The problem is increasing at a fast rate in developing countries due to rapid motorisation and other factors. In order to increase the traffic safety, except for developing intelligent transport system[1~3], the traffic planning design pays great attention to cut the traffic flow and to design the pedestrian-and-vehicle dividing system. As for the pedestrian and roadway dimensional-dividing building, the substructure of building is independent columns with big column spacing. To improve the seismic behavior of the special building, the isolators are mounted on independent columns. In this type of building, the independent column and isolator are subjected to the axial compression and the lateral dynamic force simultaneously, the lateral force results to isolator with large displacement, which may cause the structural instability. Buckle and Kelly[4] studied the stability of elastomeric bearings using a model bridge deck tested using a shaking table. Bearing overturning or rollover was evident in these tests. Designers are concerned about the stability of rubber isolation bearings under large compressive loads and their ability to withstand tensile loads[5-6]. In order to assurance the traffic safety, the safety performance of independent column mounted on isolator system is discussed.

The theoretical approach for the stability of rubber bearings has been to make use of Haringx's theory based on linearity and small displacements [7~8]. Koh and Kelly[9] have developed a model that accounts for the influence of axial load on the horizontal stiffness of elastomeric bearings. Experimental results show that the critical load decreases with increasing horizontal displacement. The nonlinear horizontal tangential stiffness is dependent in both horizontal displacement

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and axial load. However, the special system can not satisfy the condition of Haringx's theory. Because the isolated bearing mounted on the independent column is different from the isolated bearing mounted on the foundation. The independent column has limited stiffness, the top section of independent column which is connected with the isolated bearing has rotation angle under lateral and axial load. Thus, mechanical models are needed that can accurately predict the force-deformation behavior of bearing mounted on independent columns under extreme variations in axial loading.

Several studies have investigated the stability performance of the special system. Most of them were focused on the lateral stiffness of the isolator serial with the independent column. For example, Zhou et al[10]. Zhang et al[11] discussed the dynamic stability of the system, they simplified seismic wave as harmonic wave, and analyzed the main instability region by Bolotin method. Liu et al[12] tested the various lateral stiffness of isolated bearing with the rotation angle of the bottom of bearing increasing. The test results showed that rotation angle influenced the lateral stiffness of bearing under the small lateral displacement. However, the lateral stiffness ranged by as much as 10%~30% with the rotation angle increasing when the lateral shear displacement ratio was more than 100%.

The main objectives of this study are to assess the stability of the special system under seismic excitations, and to examine a number of values of the behavior factors effect on the stability of system.

2 Model of the system

The elasto-plastic behavior of such structures is possible to be analyzed by FEM taking into account the nonlinear behaviors[13~14]. However, parametric study is carried out to be investigated the dynamic ultimate strength subjected to the static axial compression and the lateral force. Thus, the structure stability can be simplified as the independent column mounted on the isolator stability.

Isolation bearing is connected to the independent column and superstructure. To simply analysis, owing to the infinite stiffness of the superstructure, the top of isolated bearing is taken as be fixed. The bottom of isolated bearing connected with independent column is happened to rotate. Based on this simplification, the system is represented by the serial system which is illustrated in Fig.1.

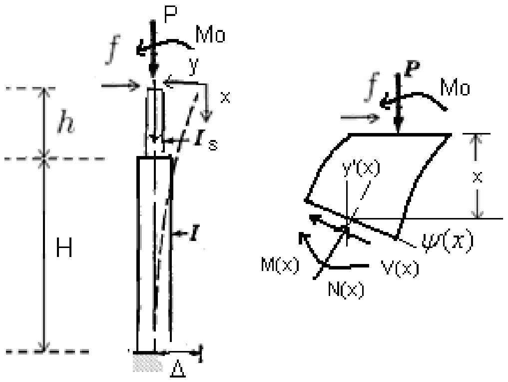

Fig.1 Independent column in series with the isolation bearing system

The system is subjected to a static load P, the dynamic lateral load f and the constraint moment M_0 owing to the superstructure fixed. In the figure, h is the height of isolated bearing, H is the height of column. EI, EI_s are the bending rigidity of the column and the bending rigidity of the isolator respectively. y is the displacement of the system. x is the length of the system.

In such a system, the equilibrium equation of the bearing is given by,

$$\begin{aligned} M(x) &= -Py - fx + M_0 \\ V(x) &= f\cos\psi + P\sin\psi \approx f + P\psi \end{aligned} \tag{1}$$

In which $M(x)$ is the moment of the system, $V(x)$ is the shear force of the system, ψ is the rotational angle of the system. $y'(x)$ is the shear displacement of the system .

Meanwhile,

$$M(x) = \alpha\psi'(x), V(x) = \beta[y'(x) - \psi(x)] \tag{2a}$$

Where[15],

$$\begin{aligned} &\alpha = E_{rb} I_s \frac{h}{t_r}, \beta = GA\frac{h}{t_r} \\ &E_{rb} = \frac{E_r E_b}{E_r + E_b}, E_r = 3G\left(1 + \frac{2}{3}\kappa S_1^2\right) \end{aligned} \tag{2b}$$

f, P are axial load and lateral force under earthquake excitation respectively, M_0 is the constraint moment of the superstructure. H, h are the height of independent column and the height of isolation bearing respectively, $M(x), V(x), N(x)$ denote the moment, shear force and axial force of the system,

$y^{'}(x), \psi(x)$ are the displacement and shear angle of the system. $E_r, E_b, G, \kappa, S_1, t_r, I_s, A$ are the rubber coefficients.

Substituting Eq.(2) into Eq.(1), the equilibrium equations of the system become,

$$\alpha\psi' + Py = M_0 - fx \tag{3a}$$

$$\beta y' - (\beta - P)\psi = f \tag{3b}$$

ψ' is obtained by the differential analysis of Eq.(3b),

$$\psi' = \frac{1}{1 - \frac{P}{\beta}} y'' \tag{4}$$

And substituting Eq.(4) into Eq.(3a), the following relationship is obtained,

$$y'' + q^2 y = \frac{M_0 - fx}{P} q^2 \tag{5a}$$

In which:

$$q^2 = \frac{P}{\alpha}\left(1 - \frac{P}{\beta}\right)$$

By the similar way, another relationship is written as,

$$\psi'' + q^2\psi = -\frac{f}{P} q^2 \tag{5b}$$

The above equations solve are expressed by,

$$y(x) = A\cos qx + B\sin qx - \frac{f}{P}x + \frac{M_0}{P} \tag{6a}$$

$$\psi(x) = \frac{P}{\alpha q} B\cos qx - \frac{P}{\alpha q} A\sin qx - \frac{f}{P} \tag{6b}$$

Considering the constraint conditions, the top of bearing is fixed, thus, $x = 0, y = 0, \psi = 0$, the constants are obtained,

$$A = -\frac{M_0}{P}, B = \frac{f}{P^2}\alpha q \tag{6c}$$

Similarly, the equilibrium equation of the bearing is given by,

$$EIy_2^{''} = -Py_2 - fx + M_0 \tag{7a}$$

Where, $k^2 = P / EI$, Eq.(7a) is also written as,

$$y_2^{''} + k^2 y_2 = -\frac{f}{EI}x + \frac{M_0}{EI} \tag{7b}$$

The Eq.(7) solve is expressed by,

$$y_2(x) = R\cos kx + S\sin kx - \frac{f}{P}x + \frac{M_0}{P} \tag{8}$$

Considering the constraint conditions, the bottom of independent column is fixed, thus, $x = H + h, y_2 = \Delta, y_2^{'} = 0$, the constants are obtained,

$$R = -\frac{f}{Pk}\sin k(h+H) + \left[\Delta + \frac{f}{P}(h+H) - \frac{M_0}{P}\right]\cos k(h+H) \tag{9a}$$

$$S = \frac{f}{Pk}\cos k(h+H) + \left[\Delta + \frac{f}{P}(h+H) - \frac{M_0}{P}\right]\sin k(h+H) \tag{9b}$$

Because the deformation of the top of independent column is same with the deformation of the bottom of bearing, the relationship is also obtained,

$$x = h, y_2 = y, \quad y_2^{'} = \psi,$$

$$-\frac{M_0}{P}\cos qh + \frac{f\alpha q}{P^2}\sin qh = -\frac{f}{Pk}\sin kH + [\Delta + \frac{f}{P}(h+H) - \frac{M_0}{P}]\cos kH \tag{10a}$$

$$\frac{f}{P}\cos qh + \frac{M_0}{\alpha q}\sin qh = \frac{f}{P}\cos kH + [\Delta + \frac{f}{P}(h+H) - \frac{M_0}{P}]k\sin kH \tag{10b}$$

the constraint moment of the superstructure is expressed by,

$$M_0 = \frac{f}{\cos qh - \cos kH}[\frac{\alpha q\sin qh}{P} + \frac{\sin kH}{k} - (H+h)\cos kH] - \frac{\Delta P\cos kH}{\cos qh - \cos kH} \tag{11}$$

The displacement corresponding to the lateral force is obtained,

$$\Delta = \frac{f}{P}\frac{1}{\alpha qk\sin kH\cos qh + P\cos kH\sin qh}\cdot[2\alpha q - 2\alpha q\cos qh\cos kH - (H+h)k\alpha q\sin kH\cos qh - P(H+h)\sin qh\cos kH + \left(\frac{PEI + (\alpha q)^2}{kEI}\right)\sin qh\sin kH] \tag{12}$$

3 Stability criterion of the system

When the column or isolated bearing is collapse, the system will be not safety. Collapse is defined as the condition at which the displacement of the system is infinite during a seismic excitation. It may be caused by the gradual deterioration in the stiffness and strength of the system subjected to large deformation. Thus, when column stirrup ratio exceeds the maximum stirrup ratio, or isolated bearing displacement exceeds the limitation of displacement, the system can be considered not safety. It can be written as[16~17],

$\rho \le 5\%$, $[u] \le \min(0.55D, 3t_r)$

Where, ρ is the stirrup ratio of independent column, D is the diameter of isolation bearing, t_r is the rubber thickness of bearing.

The safety analysis process can be described with the following steps：

(1)Suppose the section of column, bearing and axial force P , when f is gradually increased，Δ and $y(h)$ will be obtained by Eq.(12) and Eq.(8) respectively.

(2)The moment of the bottom of independent column can be written as, $M_u = -P\Delta - f(H+h) + M_0$.

(3)The reinforcement area of the column can be estimated according the above force.

(4)When $y(h)$ >[u] or $\rho > 5\%$, the system is not safety. Therefore, the lateral force exceeds safety criterion first is defined as the ultimate lateral force f_{cr} .

4 Example and parameters

On the basis of the above procedure, a typical independent column mounted on isolators building is idealized by the independent column mounted on isolator system and the dynamic stability behavior of the system is investigated for various sets of parameters.

The 5-storey RC building has been employed for the parameters study in this work. Basement is independent column and one floor, the superstructure are isolated frame structure. The grade of concrete is C30. The seismic intensity is 8 degree, design basic acceleration of ground motion is 0.20g. The parameters of the structure are shown in Table 1. A isolated bearing GZY400 and a column 600*600mm^2，under the static lateral force 148kN, are investigated.

Table.1 Bouc-Wen model parameters of the isolated building

The ith floor	Mass10^{2}kg	Stiffness (kN/m)	f (kN)	γ	β	$[\theta]$	Height(m)
Independent column	1303	584220	12119	-186	558	0.018	3.3
Isolated layer	6200	198067	1272	0.5	0.5	0.8	0.3
1	7651	485000	8134	-284	853	0.02	4.7
2	7536	339000	7056	-185	554	0.02	3.9
3	7678	199000	4177	-410	1230	0.02	3.9
4	7311	190000	3794	-201	602	0.02	3.9
5	5344	14600	500	-68	205	0.02	3.9

4.1. *Ultimate axial force and lateral force*

The fundamental dynamic collapse behavior of the system subjected to the lateral force is examined in this analysis. In this case, the axial force of the system is constant and the lateral force ranging from 0kN to 150kN is used. The dynamic displacement responses are calculated by using above procedure with the different lateral forces. The relation between the displacement and the lateral force of the system is shown in Fig.2.

Fig.2 suggests that the displacement of system linear increases as the lateral force increases. Meanwhile, it is noted that the effectiveness of axial force is not significant on the safety of system, because the displacement of the system is not nearly changed though the axial force magnifies ten times. The result indicates that the system safety is sensitive to the lateral force. The tendency is perceived irrespective of the amount of the axial force.

Fig.3 shows that the relation between the axial force and the lateral force. In this case, both the axial force and the lateral force increases, the displacement of the system increases linearly. The ordinate shows the ultimate axial force P_{cr} and the value of P_{cr} for the corresponding system. From the figure, it is revealed that P_{cr} decreases and approaches 3269kN and 2790kN respectively, as the lateral force increases by 20kN and 50kN one step. This is because the stability of system is concentrated on the lateral force and the lateral force is largely influenced by the displacement of the system, irrespective of the axial force.

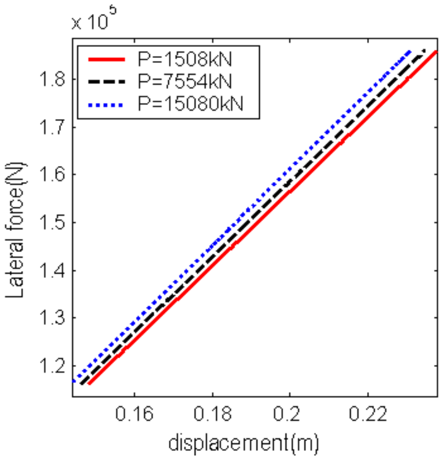

Fig.2 Lateral force versus displacement

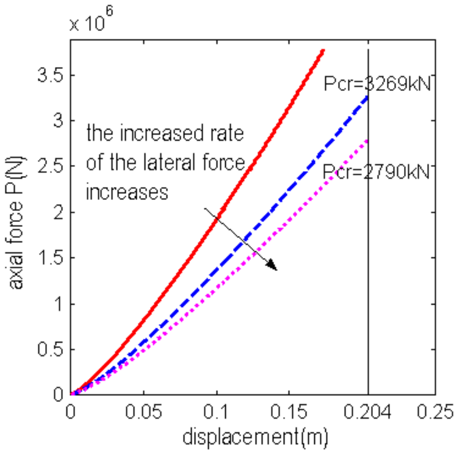

Fig.3 Axial force versus displacement

4.2 *The displacement of independent column*

The dynamic stability behavior of the independent column subjected to the displacement of column and the section of column is examined in this analysis.

The relation between the displacement of independent column and the lateral force is shown in Fig.4.

Fig.4 shows the relation between the lateral force and the displacement of the top of column. It can be seen from the figure that the displacement of the column has the peak point with the lateral force increasing. Note that a steeper slope of the displacement of column increases as the lateral force increases, after the peak point, the displacement of column decreases with the lateral force increasing. Because the lateral force results to the displacement of isolated bearing which leads to change the sign of the constraint moment of superstructure. In general, the absolute value of the constraint moment has significant effect on the safety of column. The more absolute value of the constraint moment is, the worse the safety of independent column is.

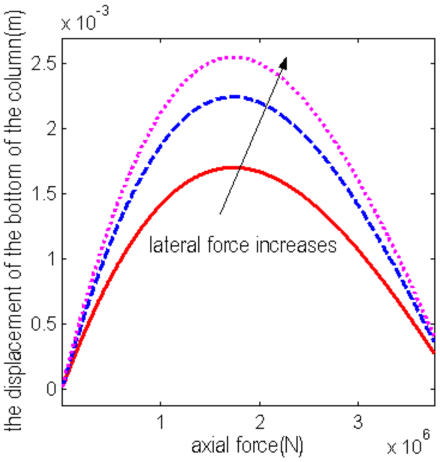

Fig.4 Lateral force versus displacement

The relation between the displacement of independent column and the section of the column is shown in Fig.5.

In this case, the lateral force of the system is constant and the section of column $400*400mm^2$,$500*500mm^2$,$650*650mm^2$ are used. The dynamic stability of independent column is calculated by using above procedure with the different section of column.

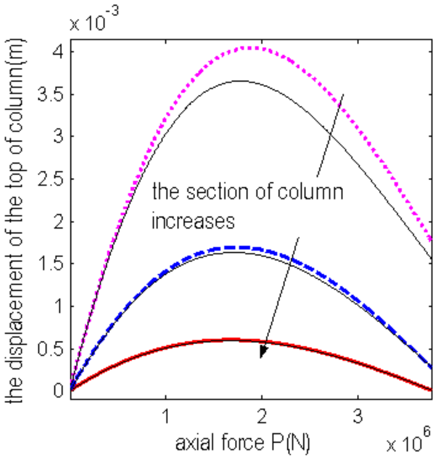

Fig.5 relation between column Section and displacement

From the Fig.5, the displacement of the column decreases as the section of column increases. This implies that the independent column is impossible to be instability with an adequate section of column employed here.

The elastic displacements of columns represent the real lines and elastic-plastic displacements of columns represent the dot lines as shown in Fig.5. It noted from this figure that the column is elastic when the value of the lateral force is small. The column deformation will be plastic as the lateral force increases. However, the plastic deformation of column with a small amount does neglect. In this example, the section of column is 400*400mm^2, the plastic deformation of column is only 1mm. Because the lateral force results to the small value of the plastic displacement of column, in general, the elastic independent column can represent accurately the actual column in this system.

4.3. Effect of the lateral ground motions

El Centro record and Taft record are adopted in this paper. The peak acceleration of all the recorded earthquake waves is 4.0m/s^2. With these restrictions, the dynamic responses of the system are investigated.

Fig.6a and 6b show plots of the story drift time history for El Centro record and Taft record.

Fig.6a and 6b clearly reveal that the story drift of the isolated layer is largest in all of these stories, each story drift is limited. The maximum story drift of the isolated layer is equal to 0.4785 for El Centro record, and the maximum story drift of the isolated layer is equal to 0.3161 for Taft record. Note that the values for El Centro record and Taft record are smaller than 0.8, which is the maximum story drift of isolated layer.

With regard to the maximum story drift experienced by the system for the El Centro record, it is interesting to note in Fig.6a the story drift of the independent column layer is nearly larger than that of the first floor, even though the section of independent column was larger than the section of column in the first floor. Therefore, the result shows that the system performance highly relies on the damage of independent column layer. Similar results are shown for the Taft record in Fig.6b.

While Fig.6a indicates that the story drift of independent column is equal to 0.0199 for El Centro record which is larger than the limited value and leads to the damage in the independent column, Fig.6b reveals that the story drift of independent column is equal to 0.0119 for Taft record which satisfies the limited values. Thus, the response of the model system to the El Centro earthquake is more sensitive to the rate of damage evolution in comparison to Taft earthquake. The result shows that the characteristic of the ground motion plays an important role on the damage-dependent behavior.

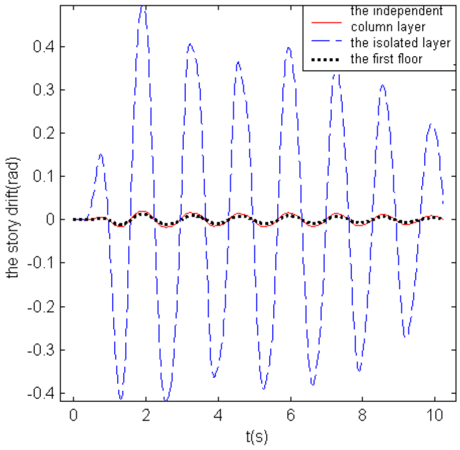

Fig.6a Story drift time history for El Centro record

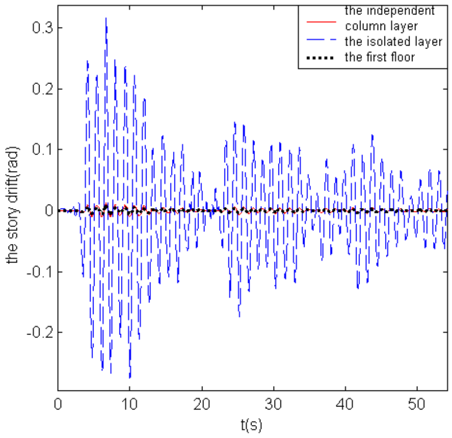

Fig.6b Story drift time history for Taft record

Fig.7a and 7b reveal the influence of the magnitude of the earthquake acceleration from 1.75m/s^2 to 6.2m/s^2 on the computed response.

Looking solely at the Taft record, it is possible to observe the effect of the magnitude of the earthquake on the structural response. The values of the story drift approximately linearly increase as the magnitude of earthquake acceleration increases, however, the response of the system always converges. Note that the amplitude story drift for the independent column layer and the second superstructure floor are higher than other stories in Fig.7a, it clearly reveals that the most higher-amplitude story drift is the second floor of the superstructure. The largest magnitude of story drift occurs 0.02, with satisfied magnitude of other story drifts when the peak acceleration is equal to 4.2m/s^2. The results indicate that the essentially damage acts on the second layer caused by the an earthquake, over certain limited ranges, faster rates of the damage accumulation actually led to collapse and be instability of the system. Fig.7b shows that the story drift of isolated layer when the magnitude of the earthquake acceleration from 1.75m/s^2 to 6.2m/s^2. Unlike the results shown in Fig.7a, Fig.7b indicates a linear dependence upon the magnitude of the earthquake, possibly suggest that the stability of the system is more a function of the weak layer of the system than the properties of isolated layer. Both the independent column layer and the weak layer of the superstructure play an important role on the safety behavior.

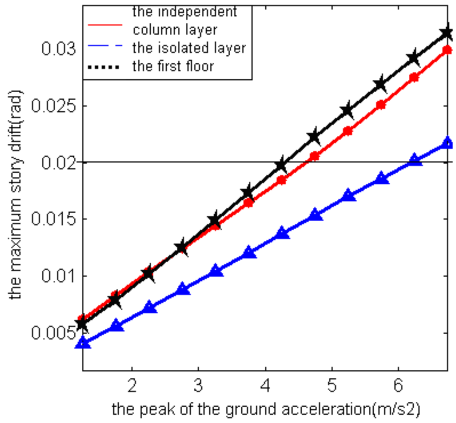

Fig.7a Maximum story drift as function of the magnitude of the ground acceleration

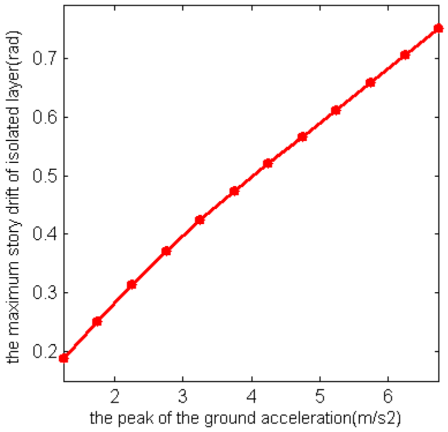

Fig.7b The maximum story drift of isolated layer as function of the magnitude of the ground acceleration

5 Conclusions

This paper discussed the safety of the system which is consisted of the independent columns mounted on the isolated bearing under seismic excitation. A method of evaluating the dynamic collapse of the system is subjected to a static axial compression and a lateral dynamic loading. Therefore, a parametric study is carried out to investigate the ultimate lateral force and the section of the column influenced on safety of system.

In the analysis, the building is simplified an independent column mounted on isolator, the system is assumed to be subjected to the static lateral force and axial force. The system is fixed on the base and superstructure, therefore, the constraint moment of the superstructure employs the top of the system. Considering the equilibrium of moment about the system, the relation between the displacement of system and the lateral force is calculated. The analysis results indicate several key issues on the following:

(1) The displacement of the system is not nearly changed though the axial force magnifies ten times. The stability of system is concentrated on the lateral force, irrespective of the axial force.

(2) The lateral force is largely influenced by the displacement of the system. The more value of lateral force is, the worse the safety of the system is.

(3) The displacement of the column has the peak point with the lateral force increasing. After the peak point, the displacement of column decreases with the lateral force increasing. In general, the absolute value of the constraint moment has significant effect on the safety of column. The more absolute value of the constraint moment is, the worse the safety of system is.

(4) The displacement of the column decreases as the section of column increases. This implies that the independent column is impossible to be instability with an adequate section of column employed. The lateral force results to the small value of the plastic displacement of column, the elastic independent column can represent accurately the actual column in this system.

(5) The safety of system highly relies on the damage of independent column layer and the magnitude and parameters of the ground motion.

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