Civil Engineering Infrastructures Journal, 47(2): 273 – 290, December 2014
ISSN: 2322 – 2093

A Phenomenological Study on Inelastic Torsion Caused By Nonlinear Behavior Changes during Earthquake Excitations

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Received: 14 Jan. 2013; Revised: 01 Oct. 2013; Accepted: 19 Nov. 2013

ABSTRACT: Torsion of many symmetric structures, which were designed based on the seismic codes, is due to their asymmetricity induced during inelastic behavior. Although the structure was designed symmetrically assuming elastic based criteria, different factors such as material inconsistency in structure, construction details discrepancy and construction errors may result in asymmetric behavior in inelastic deformation range. So far, these considerations have been rarely contemplated in previous published investigations and should be studied regarding the importance of irregularity in increase of seismic demand of structures in the inelastic range. In this paper, as the first step, the asymmetry and irregularity in plan due to non-similar inelastic characteristics with respect to axis passing through center of gravity as well as the effect and importance of each irregularity factors are studied by changing the excitation properties applying to one-storey one-bay steel structures. This simplified structure is chosen due to studying and illustrating the absolute effect of this kind of irregularity in which higher mode effect is eliminated. The results show that the behavior of a structure with inelastic asymmetry is completely different from the structure with elastic asymmetry. As for inelastic asymmetry structure, although the translational and rotational oscillations before yielding were uncouple, these DOFs after yielding become coupled until reaching the terminal rotation point (rotation reaches a constant value) and then become uncoupled, i.e., again oscillated symmetrically. This behavior is different from the structures with elastic asymmetricity, in which the translational and rotational movements being coupled during all the excitation time. This effect has not been recognized in previews studies on inelastic behavior of initially elastic symmetry buildings. The study of these behaviors aids the designer to choose the appropriate rehabilitation method for a vulnerable irregular structure.

Keywords: Asymmetric, Inelastic Torsion, Nonlinear Behavior, Pushover Analysis, Seismic Analysis.

INTRODUCTION

Experiences from the past earthquakes showed that deformation caused by torsion is an important factor that may destroy the structures designed according to the

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provisions of seismic building codes (Bugeja et al., 1999).

Many modern codes contained specific rules for considering the torsional deformations and control of these deformations if possible. The direct application of these rules is mainly for structures behave elastically. One of the strategies used in general design to decrease the torsion is to maintain symmetry in plan and height (non-setback) of a structure. However, in some cases, the structure should be asymmetric in plan or height due to architectural requirements. Asymmetric structures are more vulnerable to earthquake than symmetric structures. When the structure plan is asymmetric or when distribution of the lateral load resisting systems is not symmetric with respect to mass distribution, the induced torsion due to the distance between mass and stiffness centers causes significant damages (De Stefano and Pintucchi, 2008). The structure rotates due to the torsion and thus, the deformations and stresses increase in lateral load resisting members with respect to proportional distance from stiffness center (De Stefano and Pintucchi, 2010). The vulnerability of asymmetric structures to strong ground motions was frequently observed in past earthquakes. The investigation and analysis of the structures damaged during the 1985 Mexico City earthquake show that about 50% of all failures were related to the asymmetricity of structure configuration, non-uniform distribution of stiffness, strength and mass (Priestley, 1997). Asymmetricity and irregularity in structure are usually determined based on superficial factors e.g., the symmetry in plan, setback, and the parameters related to elastic behavior of a structure in seismic provisions (Priestley et al., 2007). The assessment of seismic responses for structures may be important for seismic evaluation due to non-uniform the inelastic demand on the structural frames induced by torsional effects. Literature reviews on the seismic torsional responses were given by Rutenberg (2002) and by De Stefano and Pintucchi (2008). An additional literature survey also indicated that although extensive research has been reported on torsional response, general and consistent conclusions are still of interest because a large number of parameters are needed to accurately characterize inelastic torsional responses. Perus and Fajfar (2005) attempted to explore the general trends in the seismic response of plan-asymmetric structures by using bilinear models. They indicated that the influence of using more realistic models on torsional response should be investigated. De Stefano and Pintucchi (2010) investigated the features of inelastic torsional response by carrying out extensive parametric analysis and indicated that the investigation of effects of degradation of resisting elements on torsional response is required. The effects of asymmetricity in nonlinear behavior range of structural members that may results in torsion formation and damage induced to structure are rarely studied. During a strong ground motion, the majority numbers of structures enter the post-yield range and thus, the asymmetricity due to the nonlinear behavior of structural elements is of great importance (Mansuri, 2009). This study concludes that nonlinear analysis needs to be performed necessarily and linear classic analyses alone are not sufficient for analysis of torsionally irregular structures (Emrah, 2008).

It should be noted even in symmetric or regular structures that are designed elastically, asymmetricity could be occurred in inelastic deformation ranges through the construction fault or asymmetric construction. It is caused by using uncertain material properties as well as the changes of inelastic behavior of structures pertain to unsymmetrical rehabilitation schemes.

Source of nonlinear irregularity may be observed in a local retrofitting scheme. For instance application of FRP sheets for retrofit of structures are recently getting popular due to the simplicity, fast implementation and economic advantages. This type of retrofitting is a good example for increasing confining pressure around plastic hinge zone at RC beam-ends and whole length of deteriorated RC columns. It is concluded from Figure 1, while the elastic stiffness is not changed, this may alter the nonlinear behavior of retrofitted elements and if the retrofit plan accomplished in such a way that asymmetricity forms, this may lead to nonlinear irregularity.

A conceptual study on influence of asymmetric nonlinear irregularity on response of a simple structure may provide suitable information in performing and choosing rehabilitation program in a complex structure.

The asymmetricity generated in post-elastic range behavior of the symmetric structures under a larger earthquake is not adequately accounted in the design provisions used for such buildings. However, the conclusions of numerous world-wide research works in this area cannot directly be applied to this type of irregularity.

ANALYTICAL MODEL

To describe the subject and to make a conceptual investigation on major coupled parameters, the torsion due to the inelastic asymmetricity in a one-bay one-storey steel structure is studied. It is tried to present a limited study on the inelastic torsional behavior of an initially elastic symmetry structure using idealized simple model. The symmetric moment resisting steel frame shown in Figure 2 was designed based on AISC and IBC seismic code. The frame is 5m x 5m dimension in plan and the height of the structure is 3 meters. The values of dead and live loads are 500 and 150 kg/m^2, respectively. The column section profiles are of HE180B. For the sake of simplicity and deep inside understanding of the structural responses and the related influencing parameters, a rigid beam corresponding to the rigid floor and bearing springs corresponding to the lateral stiffness of columns were substituted. The translational and rotational mass concentrated at mass center was calculated by the following equations:

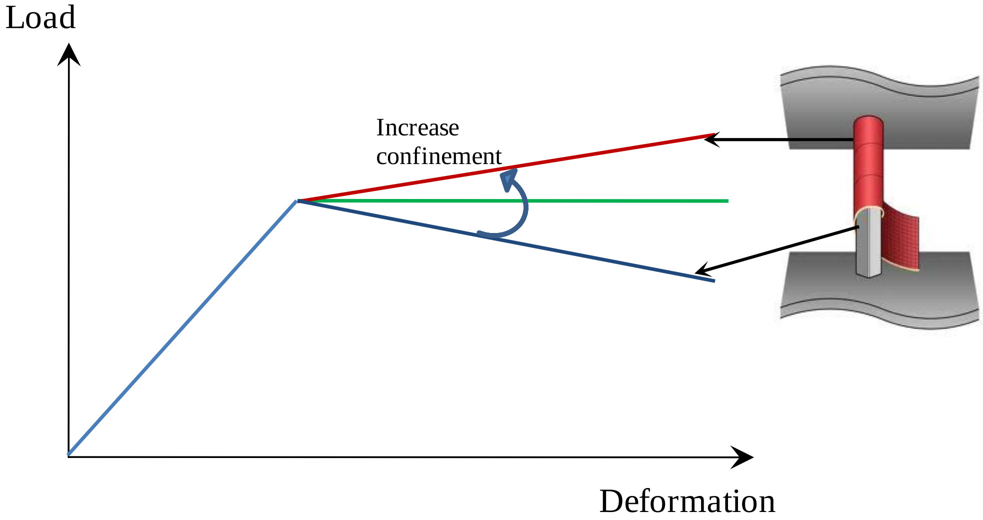


Fig. 1. Change of nonlinear behavior of a column retrofitted with FRP.

$$m = (500 + 0.2 \times 150) \times 5 \times 5 = 13250\,kg \qquad (1)$$

$$I = \frac{mL^2}{12} = 276.04 \times 10^6\,kg.cm^2 \qquad (2)$$

where *m* is the transitional mass, *L* is the bay length and *I* is the mass moment of inertia. It should be noted that k_1 (behavior of column 1) is kept constant and k_2 (behavior of column 2) can be varied.

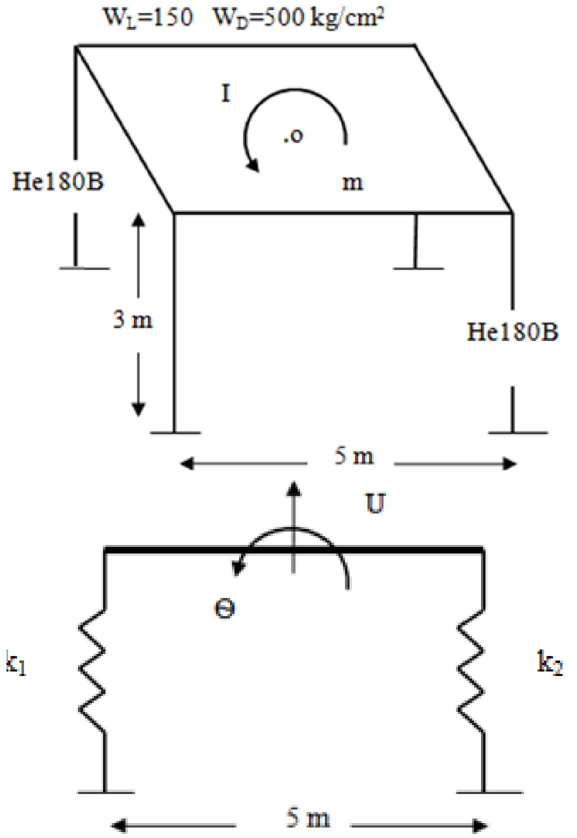


Fig. 2. Structure model and the substituted structure.

This two-degree of freedom system has two transitional and rotational modes. The natural period of transitional and rotational vibration modes are depicted in Table 1.

Table 1. Natural vibration periods of the substituted symmetric model.

Mode No.	1(u)	2(θ)
Period	0.273	0. 5336

These modes are completely uncoupled considering the elastic symmetry of the structure shown in Figure 3. It should be mentioned that the one story building is just designed to find the customize stiffness and mass for simplified substituted beam. We ignore the flexibility in minor direction respect to major one. Our ideal structure is a rigid beam with asymmetric respect to vertical centerline.

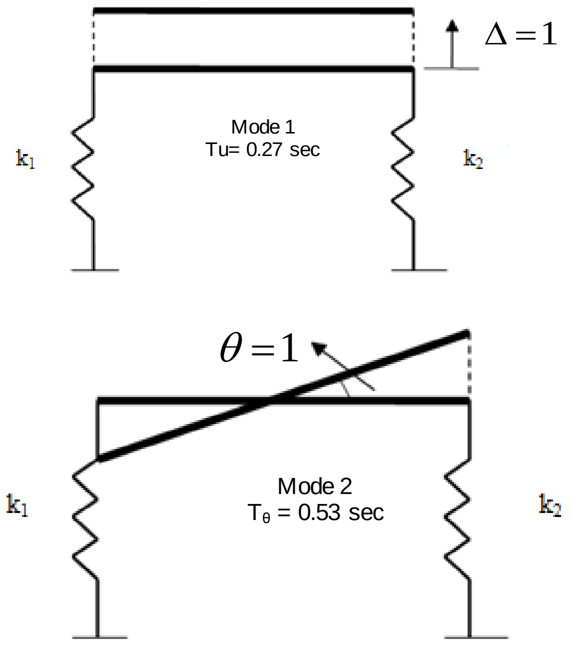


Fig. 3. Vibration mode shapes ($k_1 = k_2$).

SEISMIC EXITATION SPECIFICATIONS

To study the effect of excitation type on behavior of frames, recorded earthquake ground motions on two different soil types were considered. Three acceleration records were used for each soil type to cover the dispersion of the results. In most studies, the nonlinear analyses have been performed for a limited number of seismic records. Therefore, use of three records for each local soil type to characterize the inelastic torsional responses has not been considered yet. The specifications of records are shown for type C and type E for stiff and soft soil types in Tables 2 and 3, respectively.

Table 2. Record selection for soil type C.

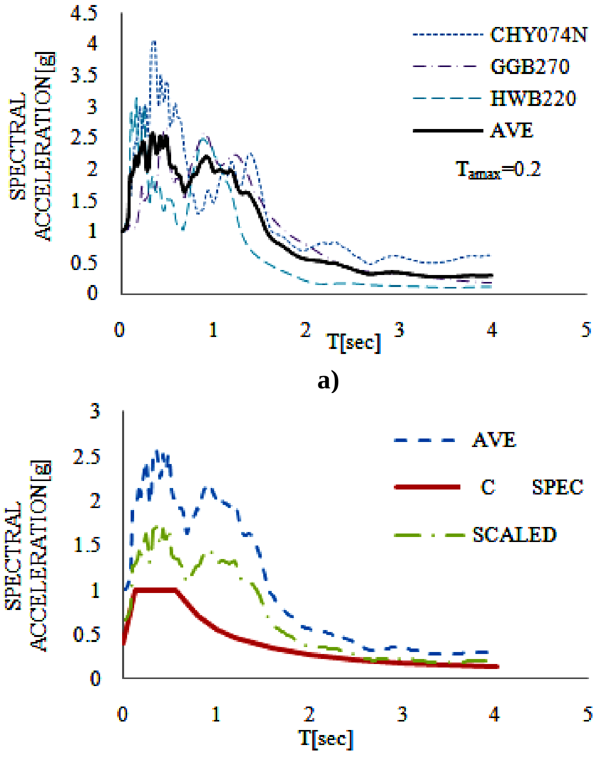
soil(II), (Soft Rock or Very Dense –soil), (360<Vs<750) m/s												
Station	**Data Source**	**Record/ Component**	**Magnitude**	**D (Km)**	**HP (Hz)**	**LP (Hz)**	**PGA (g)**	**PGV (cm/s)**	**PGD (cm)**	**NPTS**	**DT (Sec)**	**Duration (Sec)**
CHY074	CWB	CHICHI/ CHY074-N	7.6	82.5	0.02	40	0.158	23.6	11.74	18000	0.005	90
1678 Golden Gate Bridge	USGS	LOMAP/ GGB270	6.9	58.1	0.2	22	0.233	38.1	11.45	7615	0.005	38.075
58498 Hayward BART Sta	CDMG	LOMAP/ HWB220	6.9	58.9	0.2	31	0.159	15.1	3.72	7990	0.005	39.95

Table 3. Record selection for soil type E.

soil(IV), (Very Soft –soil), (Vs<180) m/s												
Station	**Data Source**	**Record/ Component**	**Magnitude**	**D (Km)**	**HP (Hz)**	**LP (Hz)**	**PGA (g)**	**PGV (cm/s)**	**PGD (cm)**	**NPTS**	**DT (Sec)**	**Duration (Sec)**
Ambarli	KOERI	DUZCHE/ ATS030	7.1	193.3	0.05	12	0.038	7.4	5.07	17238	0.005	86.19
TAP095	CWB	CHICHI/ TAP095-E	7.6	111.56	0.03	50	0.151	26.9	13.37	24600	0.005	123
TAP003	CWB	CHICHI/ TAP003-E	7.6	104.34	0.03	70	0.126	34.8	20.61	35000	0.005	175

The records were selected in a manner that their characteristics including site soil type, intensity and the source distance are similar. They were scaled using the design spectrum of the ASCE/SEI 41-06 provision for class-C and class-E soil types. The magnitudes of these earthquakes are between 6 and 7.6 and they are all belonging to far-field earthquake specification. The scaled earthquake spectra are shown in Figures 4 and 5.

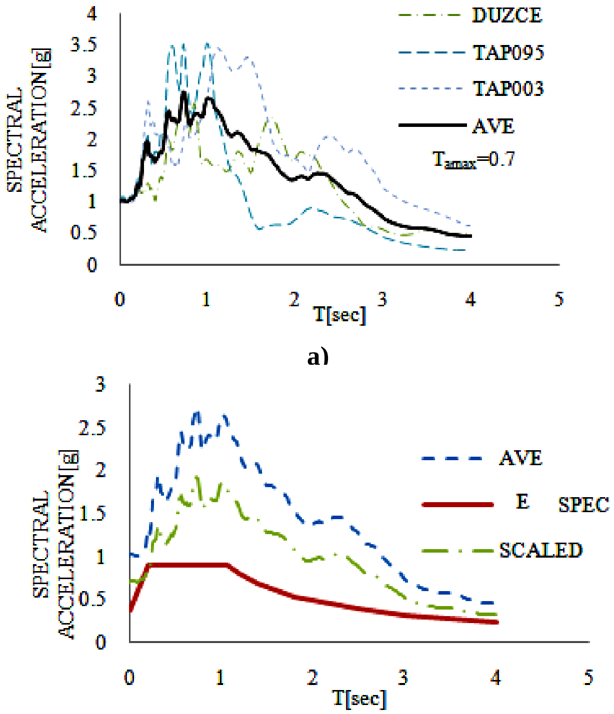
The records are selected in such a way that the frequency content of the excitations are higher (C-type) and lower (E-type) than the natural frequency of the structure for which the investigation about the structure behavior under two groups of earthquake excitation would be possible. The scaled records caused the columns in all groups motivated in the post-yield range.



a)

b)

Fig. 4. a) Average of the acceleration response spectra of the three selected accelograms and **b)** the final response spectra for class-C type soil.



a)

b)

Fig. 5. a) Average of the acceleration response spectra of the three selected accelograms and **b)** the final response spectra for class-E type soil.

PROPERTIES OF THE SYSTEMS

To investigate the asymmetricity due to the change in nonlinear behavior of structure, four series of structures were developed through changing the affecting parameters including post-yield stiffness, yield strength and elastic stiffness. There groups denoted as:

A- Changing the post-yield stiffness as increasing value [$k_{s\ (\mathrm{hardening})}$: variable]
B- Changing the post-yield stiffness as decreasing value[$k_{s\ (\mathrm{softening})}$: variable]
C- Changing the yield strength [P_y: variable]
D- Changing the elastic stiffness [k_{el}: variable]

These structures were then studied subjected to selected strong seismic ground motions.

The asymmetric changes of nonlinear properties of structural systems A, B and C induced inelastic torsion; otherwise the changes of elastic stiffness in the group D resulted to apply elastic torsion. The fourth structure group was developed to compare the elastic and inelastic asymmetric systems.

To induce torsion, the property of the spring 2 was changed. The spring 1 has invariable property in all groups. It should be noted that the units used in this paper are centimeter for displacement, kN for force and second for time

Group A

In this group, following four structures with different post-yield stiffness (for spring 2) were compared.

I. The structure is symmetric elastic.
II. The structure is symmetric inelastic and is selected for post-yield stiffness of zero.
A_1. The structure is asymmetric inelastic and the post-yield stiffness of the spring 2 is considered to be equal to 10% of the elastic stiffness.
A_2.The structure is asymmetric inelastic and the post-yield stiffness of the spring 2 is considered to be equal to 30% of the elastic stiffness. The constitutive properties of structures are depicted in Table 4 and force-displacement relationships are shown in Figure 6.

Group B

In this group, following four structures with decreasing post-yield stiffness were compared, besides elastic symmetry structure as an indicator.

I. The structure is symmetric elastic.
II. The structure is symmetric inelastic and post-yield stiffness is selected to be zero.
B_1. The structure is asymmetric inelastic and the post-yield stiffness of the spring 2 is considered to be equal to -10% of the elastic stiffness.
B_2. The structure is asymmetric inelastic and the post-yield stiffness of the spring 2 is considered to be equal to -30% of the elastic stiffness. The constitutive properties of structures are depicted in Table 5 and force-displacement relationships are shown in Figure 7.

Group C

In this group, following four structures with different yield strengths were compared.

I. The structure is symmetric elastic.
II. The structure is symmetric inelastic and yield strength of both springs is selected as $P_{y1} = 13.6$ kN
C_1. The structure is asymmetric inelastic and the yield strength of the spring 2 is considered to be equal to 1.4 times of the yield strength of spring 1.
C_2. The structure is asymmetric inelastic and the yield strength of the spring 2 is considered to be equal to 1.8 times of the yield strength of spring 1.

The constitutive properties of structures are depicted in Table 6 and force-displacement relationships are shown in Figure 8.

Group D

In this group, following four structures with different elastic stiffness were compared.

I. The structure is symmetric elastic.

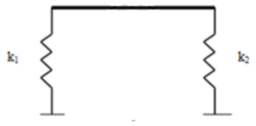
II. The structure is inelastic symmetric and elastic stiffness of both springs is selected as $k_{el} = 452$ kg/cm.

D_1. The structure is inelastic asymmetric and the elastic stiffness of the spring 2 is considered to be equal to 20% of the elastic stiffness of spring 1.

D_2. The structure is inelastic asymmetric and the elastic stiffness of the spring 2 is considered to be equal to 40% of the elastic stiffness of spring 1.

The constitutive properties of structures are depicted in Table 7 and force-displacement relationships are shown in Figure 9.

Table 4. Springs properties in group A.



	Spring 1 Properties			**Spring 2 Properties**			
Group	k_{el}	P_y	k_s	k_{el}	P_y	k_s	k_{s2}/k_{el}
I	0.045	-	-	0.045	-	-	-
II	0.045	13.6	0	0.045	13.6	0	0
A_1	0.045	13.6	0	0.045	13.6	0.0045	0.1
A_2	0.045	13.6	0	0.045	13.6	0.0136	0.3

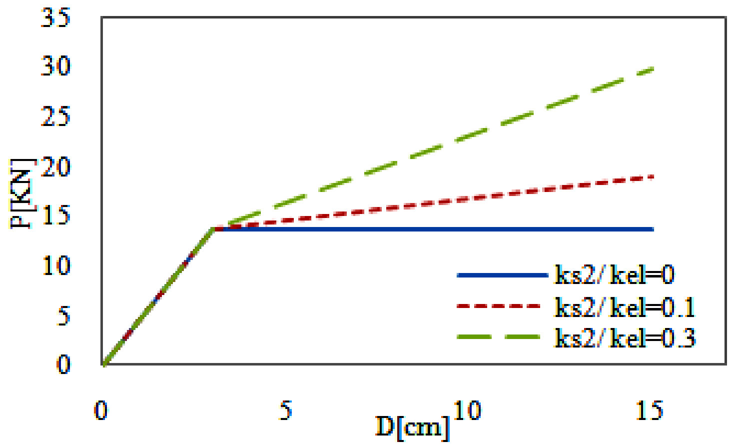
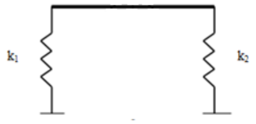


Fig. 6. Force-Deflection characteristics of springs in group A.

Table 5. Springs properties in group B.



	Spring 1 properties			**Spring 2 properties**			
Group	k_{el}	P_y	k_s	k_{el}	P_y	k_s	k_{s2}/k_{el}
I	0.045	-	-	0.045	-	-	-
II	0.045	13.6	0	0.045	13.6	0	0
B_1	0.045	13.6	0	0.045	13.6	-0.0045	-0.1
B_2	0.045	13.6	0	0.045	13.6	-0.0136	-0.3

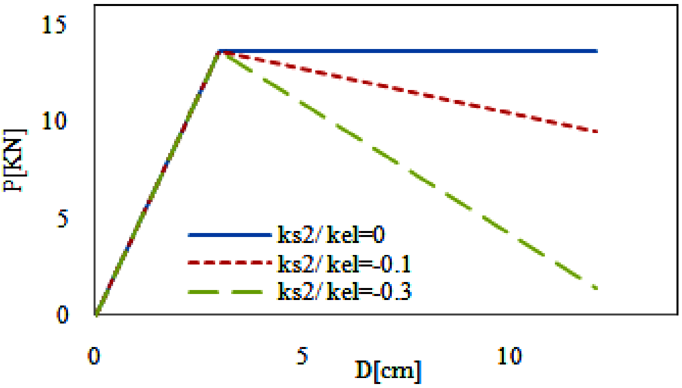
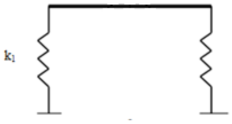


Fig. 7. Force -Deflection characteristics of springs in group B.

Table 6. Springs properties in group C.



	Spring 1 properties			**Spring 2 properties**			
Group	k_{el}	P_y	k_s	k_{el}	P_y	k_s	P_{y2}/P_{yl}
I	0.045	-	-	0.045	-	-	-
II	0.045	13.6	0	0.045	13.6	0	1
C_1	0.045	13.6	0	0.045	18.9	0	1.4
C_2	0.045	13.6	0	0.045	24.4	0	1.8

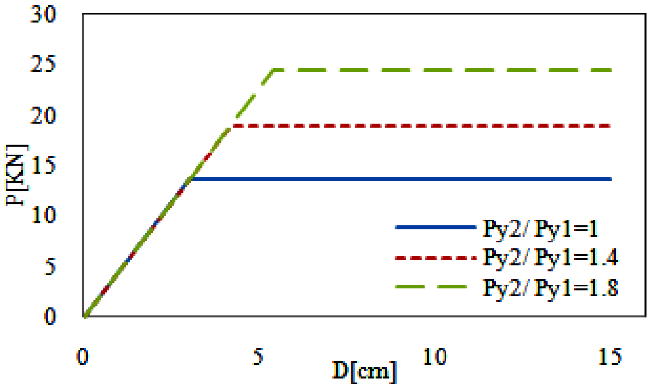
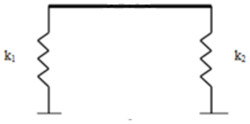


Fig. 8. Force-Deflection characteristics of springs in group C.

Table 7. Springs properties in group D.



	Spring 1 properties			**Spring 2 properties**			
Group	k_{el}	P_y	k_s	k_{el}	P_y	k_s	k_{el2}/ k_{el1}
I	0.045	-	-	0.045	-	-	1
II	0.045	13.6	0	0.045	13.6	0	1
D_1	0.045	13.6	0	0.009	13.6	0	0.2
D_2	0.045	13.6	0	0.018	13.6	0	0.4

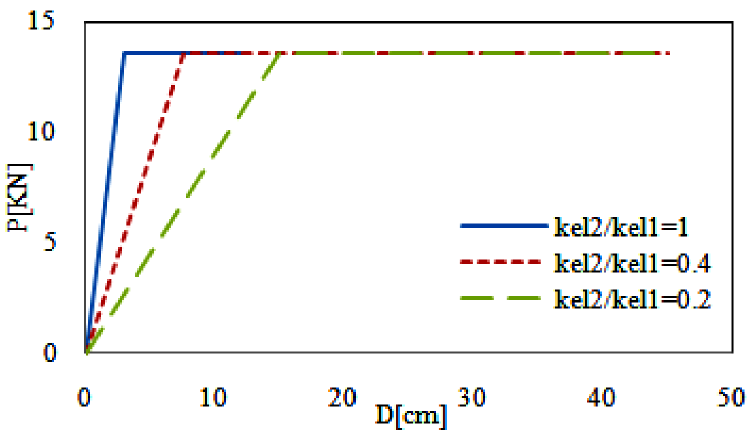


Fig. 9. Force-Deflection characteristics of springs in group D.

ANALYSIS RESULTS

To study the nonlinear behavior of the aforementioned systems in different groups and to investigate the effect of asymmetricity induced by the properties changes of the spring “2” in two elastic and inelastic ranges, the models were analyzed for different conditions i.e., performing 60 nonlinear time history analyses subjected to 6 aforementioned earthquake records and 10 pushover analyses.

The overall behavior of generic structure with different nonlinear irregularity can be observed through these pushover analyses. A couple of time history analysis results are shown in Figures 10 to 17. Base-shear-displacement relationships obtained by dynamic analyses of structural system C on class-C and class-E type soils are also shown in Figure 18.

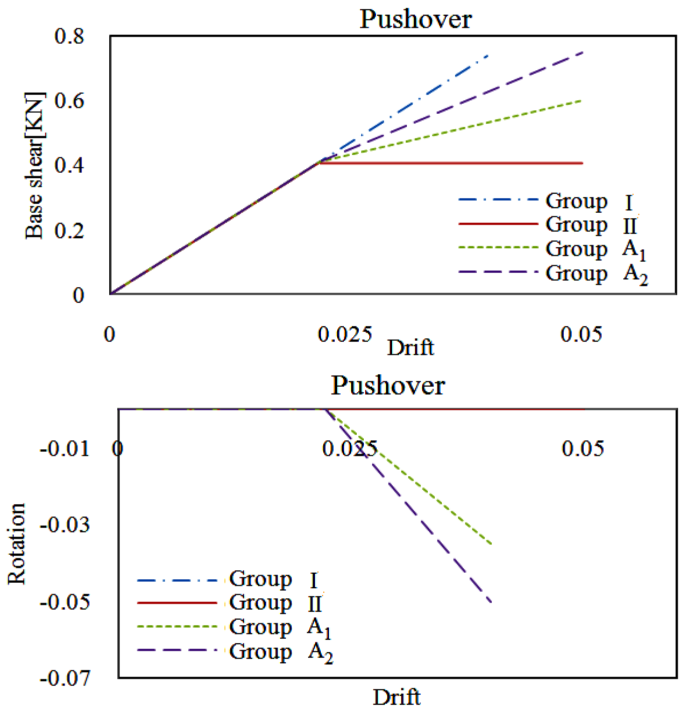


Fig. 10. Base-shear and rotation vs. drift curves obtained by pushover analysis of group A.

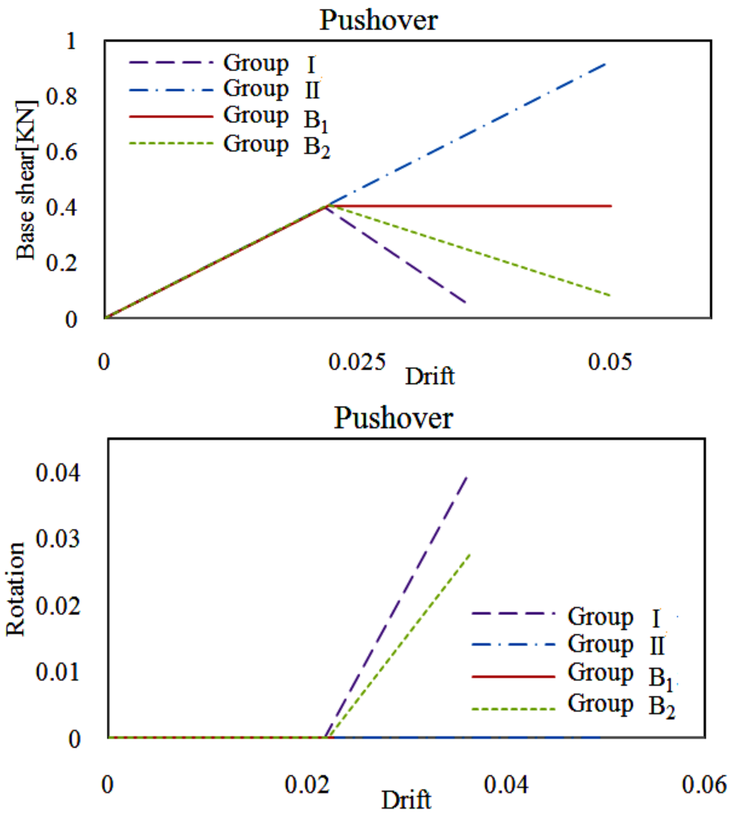


Fig. 11. Base-shear and rotation vs. drift curves obtained by pushover analysis of group B.

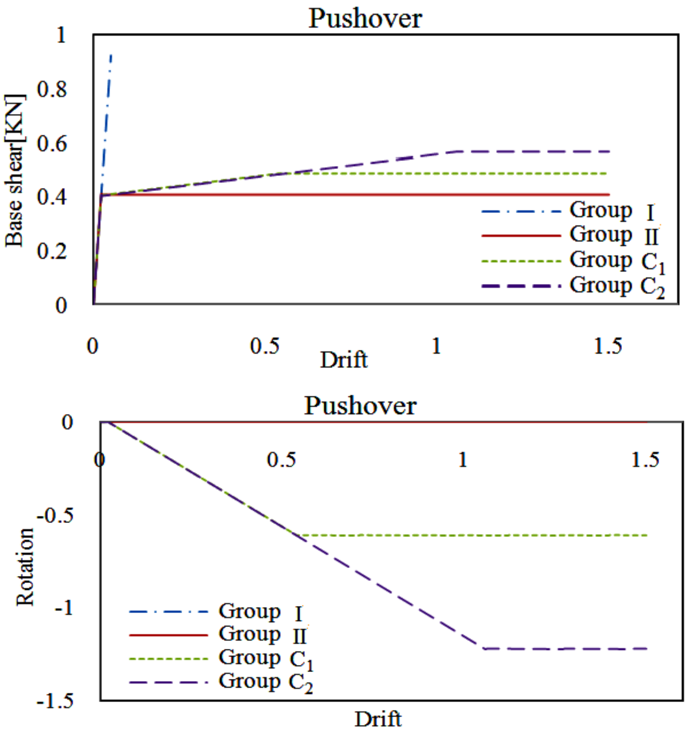


Fig. 12. Base-shear and rotation vs. drift curves obtained by pushover analysis of group C.

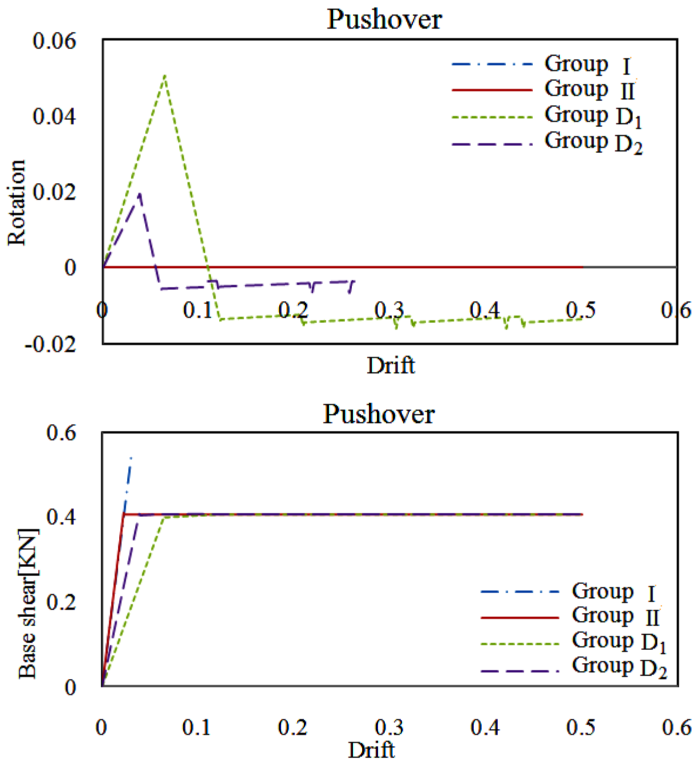


Fig. 13. Base-Shear and rotation vs. drift curves obtained by pushover analysis of group D.

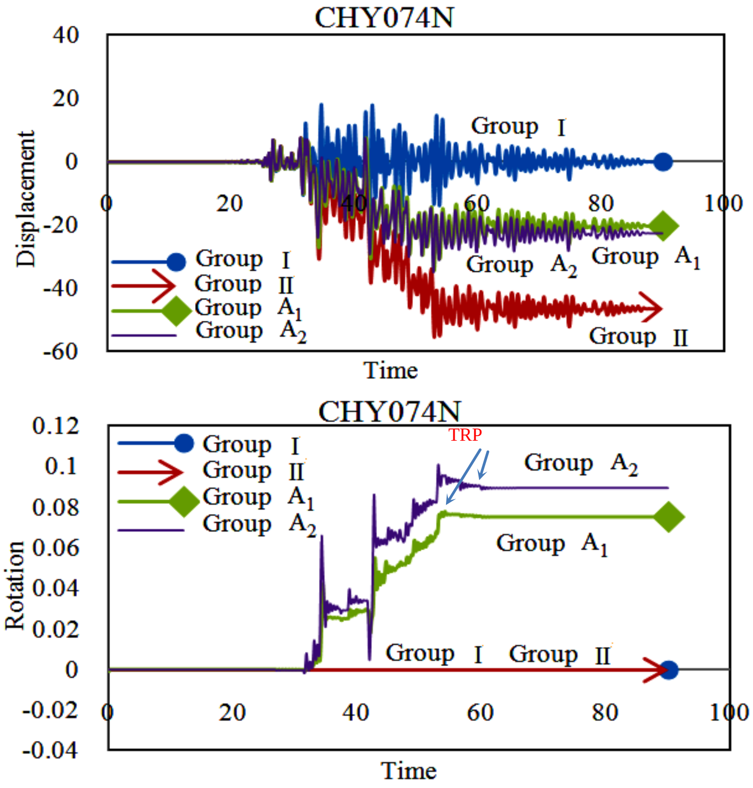


Fig. 14. Displacement and rotation time-history obtained by application of CHY074N earthquake load (class-C type soil) of group A.

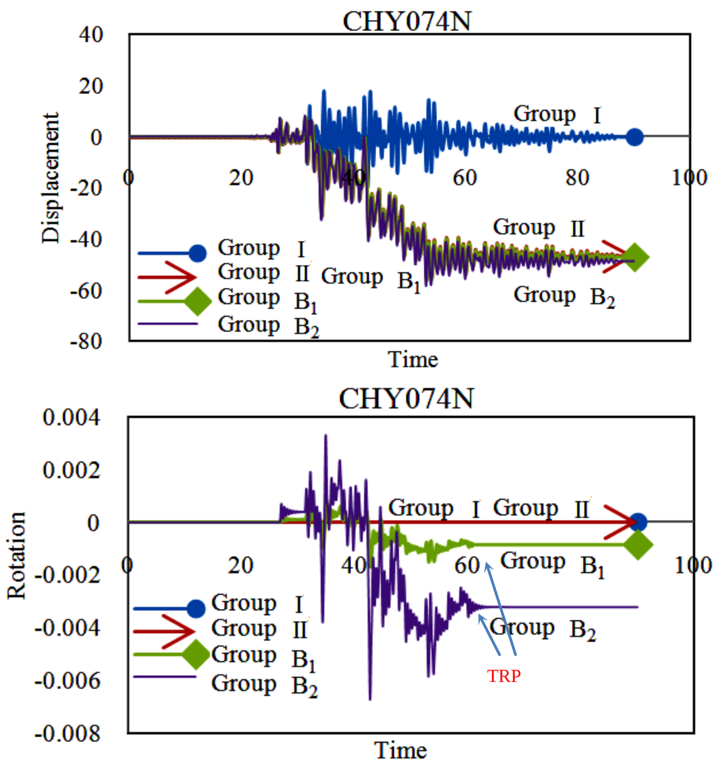


Fig. 15. Displacement and rotation time-history obtained by application of CHY074N earthquake load (class-C type soil) of group B.

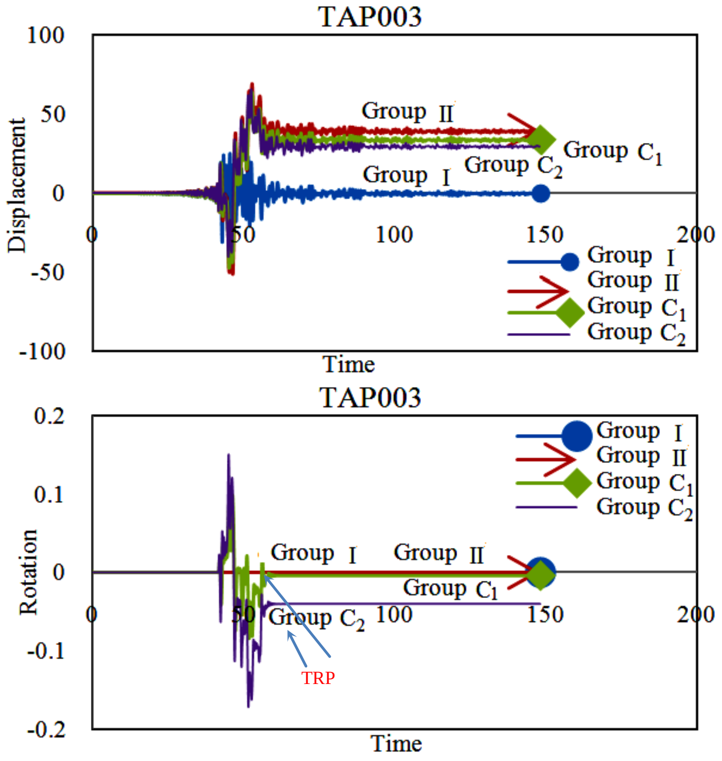


Fig. 16. Displacement and rotation time-history obtained by application of TAP003 earthquake load (class-E type soil) of group C.

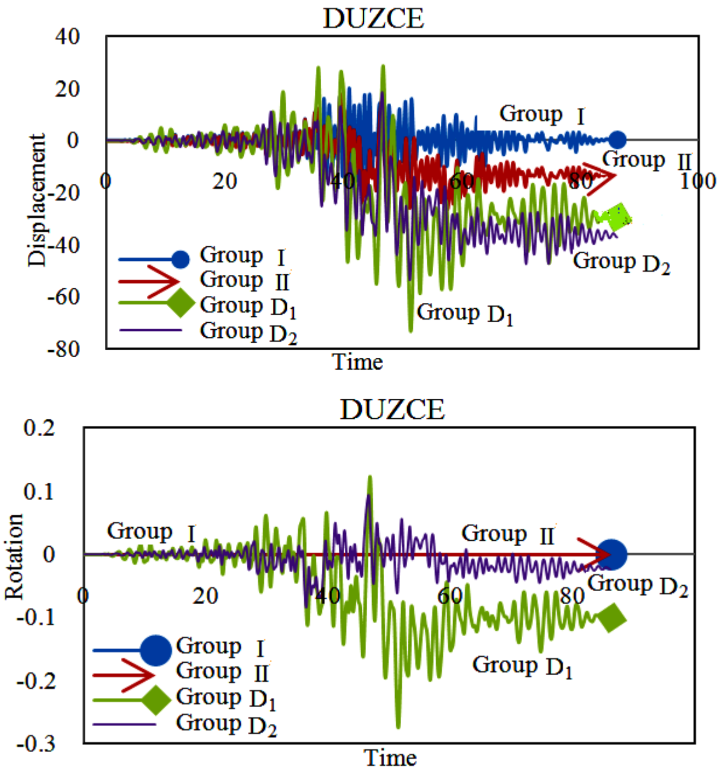


Fig. 17. Displacement and rotation time-history obtained by application of DUZCE earthquake load (class-E type soil) of group D.

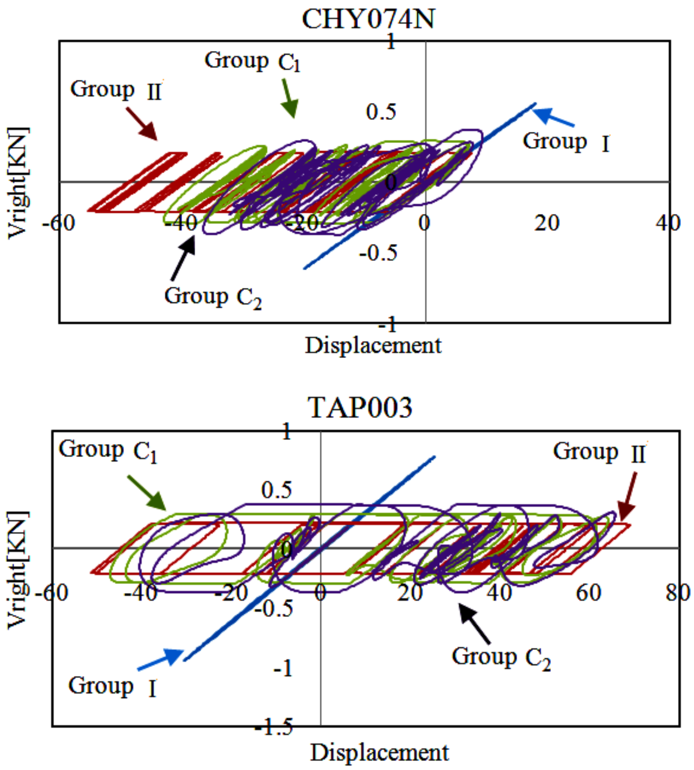


Fig. 18. Base-shear-displacement obtained by application of CHY074N and TAP003 earthquake loads of group C.

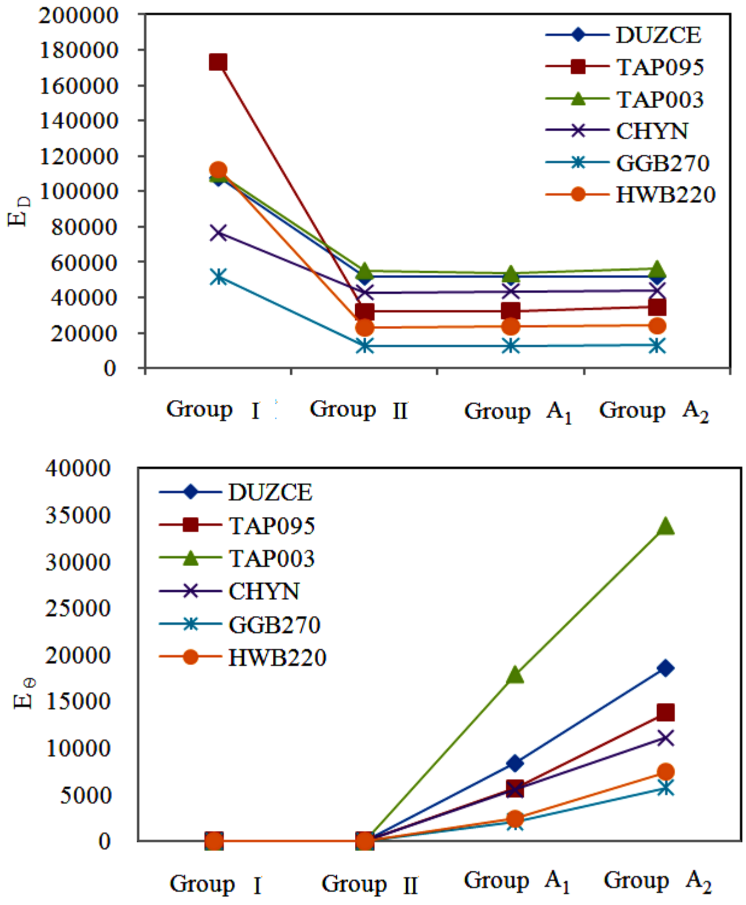


Fig. 19. E_D and E_θ energy of group A.

The energy quantities dissipated in translational and rotational movements can be calculated. E_D and E_θ are shown in Figure 19 for the group A. These curves can be used for determination and comparison of energy dissipation method in each asymmetric case.

DISCUSSION

The following illustrations may be concluded from comparing the results of the different linear and nonlinear torsion induced to four-group structures:

From Figures 10-13 in the groups where the induced torsion is inelastic, the rotation obtained by pushover analysis is zero, since before yielding, the elastic stiffness of the springs are the same. After entering the post-yield behavior range, the rotation begins and whatever the difference between two springs behavior be higher (i.e., the higher asymmetricity), the rotation becomes more severe.

Results of the analysis carried out on different structure groups under the applied excitation (Figures 14-17) conclude that the structure initially oscillate about the initial equilibrium point. If the structure enters the nonlinear behavior range, the structure will again vibrate about its new equilibrium point, after a severe initial translation. If the rotation and translation curves of the beam gravity center are being compared for symmetric and asymmetric structures, it is observed that in asymmetric structures the system rotation was stopped after reaching the new equilibrium point and the beam only experience transitional movements. Thus, the point where new equilibrium begins called as terminal rotation point (TRP). These points are shown in rotation history of Figures 14-16.

One of the differences between elastic and inelastic asymmetric structures is the existence of constant rotation after the stabilizing of rotation gravity center in inelastic structure, whereas for an elastic asymmetric structure, the rotation continues until the end of excitation. For an inelastic asymmetric counterpart, the structure becomes symmetric after passing the terminal rotation point and the structure only experience translational movements. Thus, one of the prerequisites for reaching the terminal rotation point is the formation of large inelastic deformations in the structure at the beginning of seismic excitations.

In the fourth group, where the induced torsion is elastic, since before yielding, the elastic stiffness of the springs are different, the rotation resulted by pushover analysis begins and it is proportional to the elastic stiffness difference between the springs. In other words, whatever the difference between the behavior of the springs be higher, (i.e., the higher the asymmetricity), the rotation becomes more severe.

Displacement time-history in fact is the horizontal displacement quantity time-history at the beam gravity center. In the groups where the induced torsion is inelastic, it is observed that the displacements are the same before the yield of springs and once yielding occurs; their displacement time-histories become different.

From the resulted time-history analysis of Figure 14, it can be seen that the effect of difference in post-yield stiffness and difference in elastic stiffness is similar before reaching the terminal rotation point, i.e., higher the post-yield stiffness, lower the displacement is. After attaining the terminal rotation point, it seems that in addition to the relation between stiffness and displacement, the degree and type of asymmetricity and the excitation type are also affect the displacement quantity. However, this conclusion is not true for the elastic asymmetric structures and as it can be seen in the time-history curves shown in Figure 17, the increase in elastic stiffness reduces the displacement both in elastic and inelastic ranges. It should be noted that in asymmetric structure with elastic torsion, due to the closeness of the elastic strength and slight difference with inelastic range, these displacements are approached to each other. It can be anticipated that in the case of asymmetric structures with elastic torsion, if the structure enters in inelastic range, the stiffness changes of elastic part has slight effect on reaction of structure compared to that of inelastic asymmetric structure.

Comparison of displacement time history shown in Figure 14 with Figure 15 gives that the inelastic asymmetry from unequal positive post-elastic stiffness (hardening) has more influence on responses with respect to negative post-elastic stiffness (softening).

From the resulted time-histories depicted in Figure 16, it is concluded that the displacements due to earthquake load are the same since the elastic stiffness of the springs are equal before the yield of the springs. However, once yielding occurs, the displacements are proportional to yield strength, i.e., higher the yield strength of the system, lower the displacements are.

The rotation induced by dynamic loads show that the higher eccentricity due to differences between elastic, post-yield stiffness, and strength of the springs are higher, the structures experience more rotational movements.

In group D (Figure 17), since the elastic stiffness of the springs is different, the rotation in dynamic analysis begins before yielding occurs and its value is proportional to the difference between elastic stiffness of the two springs. Nevertheless, the rotation is equal to zero in other groups before yielding occurs and then system rotation begins while yielding occurs. It is pertaining to elastic symmetricity.

It is very interesting to note that in spite of other groups, there is no terminal rotation point for structures included elastic eccentricity. In this type of eccentricity, rotation oscillates throughout whole earthquake excitation.

As can be seen in figures 18, the base shear-displacement curves of asymmetric structures depended on seismic excitation properties related to local soil types. Where the excitation related to class-C type soil, the shear-displacement curves for group C are occupied in one side of coordinate axes, while in the case of class-E type soil the shear-displacement curves are concentrated on both sides of coordinate axes. In fact, in all inelastic asymmetric structures the amount of displacement domain of gravity center is wider in the case of the excitation of class-E type soil than that of class-C type soil. It is concluded that the excitation type affects the inelastic displacement amplitude of the asymmetric structures.

The earthquake energy induced to structures having inelastic eccentricity is mainly rotational energy in comparison with translational one. The amount of rotational energy in this type of eccentricity depends highly on records selected in each bin type as can be seen in Figure 19. The E-type records induced more rotational energy in comparison with C-type records to structures.

For more resolution, the bird's eye view of the displaced structure at different time during excitation are shown in Figure 20. The definition of terminal rotation point is a much more elucidated in this figure. Once entrance to inelastic deformation and bear large translation movement at the same time (T=53 Sec), both structures with different eccentricity reach terminal rotation point where no rotation experienced by structures and it means structures forgot any eccentricity induced by lateral loading. This is major difference between elastic and inelastic eccentric structures. For elastic eccentric structures up to end of excitation, structures experience rotation oscillation.

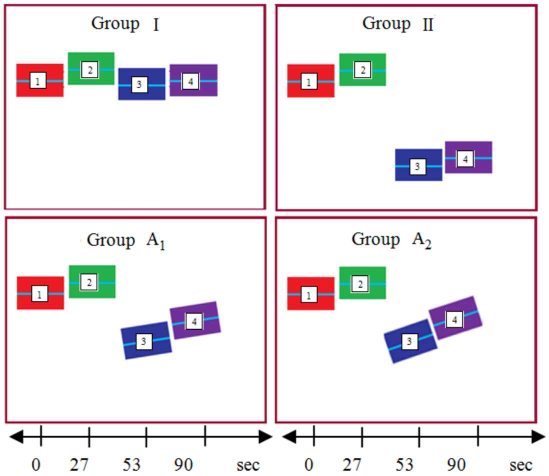


Fig. 20. The bird's eye view of structure at different key time points subjected to CHY074N earthquake.

It seems elastic eccentricity to be more destructive in comparison with eccentricity in inelastic range in view of more rotation imposed on structure that observed in elastic range.

CONCLUSIONS

It is well known that the existing structural members exhibit nonlinear behavior under strong earthquakes and if they are assumed to behave linearly, the calculated displacements and rotations are far from real ones. Consequently, it is obvious that for accurate prediction of structure behavior, the real behavior of structural elements especially for inelastic eccentricity should be considered. This way, the collapse of many structures in past earthquakes that were assumed symmetric according to the criteria of structural codes can be justified.

In this paper, a new concept called "terminal rotation point" is recognized. Once structure reaches this point, this nonlinear asymmetric structure alters its behavior from asymmetricity to symmetricity during excitation.

In inelastic asymmetric structures, the translational and rotational vibrations were uncoupled before the yield of springs and then these oscillations became coupled once before achieving the terminal rotation point. Having passed this point, the vibrations become uncoupled again. However, the translational and rotational movements are always coupled throughout whole excitation in elastic asymmetric structures.

It should be noted that these results are limited to the finite number of analyses on two types of soils i.e. C and E types under far-field earthquake records. Other affecting factors including near-fault earthquakes and other soil types as well as the increase of the number of structural degree of freedom should be further studied to prove the existence of terminal rotation point for all types of eccentric-plan buildings in future.

It is noteworthy to mention that the validity of the conclusions of all these fundamental studies in case of one-story one-bay building needs to be examined for other generic structures. So, this idea should be implemented to the numerous multistory buildings, which will be a research area for future works.

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