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RESPONSES OF THREE DIMENSIONAL BUILDINGS UNDER BI-DIRECTIONAL AND UNIDIRECTIONAL SEISMIC EXCITATIONS

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SUMMARY

In seismic analysis of buildings the major (longitudinal) component of earthquake is usually considered separately in reference directions of building. In fact, the transversal component of earthquake exists with first component simultaneously. In this paper, the simultaneous effect of two horizontal components of earthquake on buildings under arbitrary angle of excitation will be analyzed and the practice code recommendations will be discussed. Also the critical angle of seismic excitation and the increase of maximum responses under two components with respect to one component in linear and nonlinear behavior will be determined. In linear behavior, 14 models of 5 storey 3-D steel buildings with moment resistant frame (MRF) and eccentric braced frame (EBF) systems and in nonlinear behavior 3 models of moment resistant buildings will be analyzed. The studied methods for considering of two components effect are: 1) the combination method of 30%; 2) the SRSS combination 3)the 20% method. The results show that these combination methods are often non-conservative with respect to maximum response under two components. The maximum response under two components is usually more than one component in linear and nonlinear behavior. The difference of maximum responses under two and one components in nonlinear behavior is often less than corresponding values in linear behavior.

INTRODUCTION

In seismic design of buildings, the earthquake motions are considered in principle directions of building. But the main direction of earthquake and principle axes of structure are not identical and the response of structure will change with variation of earthquake excitation angle. Therefore, the structure should be resistant under different excitation angles of earthquake. [1] It is usually proposed that the members are designed for 100% of the prescribed seismic forces in one direction plus 30% of the prescribed forces in the orthogonal direction. Some practice codes propose SRSS combination alternatively [2]. Also in some papers it has been advised that two prior combinations underestimate the seismic response with respect to exact response. A better estimate is obtained upon amplifying in 20% the response that results upon applying the longitudinal horizontal component of the seismic in each one of the two principal directions of the building [3]. In some studies it has been shown that the

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response of structure under bi-directional earthquake is higher than the uni-directional one.[4]. Also the critical angle and the associated maximum structural response, for the general case of three ground motion components have been determined by [5]. In this paper we will study combinations proposed by practice codes and compare them with exact response(maximum response under two components). The critical angles under two and one components and the difference percent of maximum responses under two and one components will be determined in linear and nonlinear behaviors. Also if the seismic excitation angle changes from 0º to 180º the variation of the structural response will be manifested.

MODELS

In this paper, 14 models of 5 storey steel buildings are studied that the first seven models (1-7) have moment resistant frame (MRF) and the last six ones (9-14) models posses eccentric braced frame (EBF) system in both directions x and y. They are designed in accordance with prescriptions of ASCE for medium ductility class structures. Story heights are 3.2m. All structures have 5 five equal spans of 5m in x direction and three equal spans of 4m in y direction. Model 1 is regular that plan view has been shown in figure 1. Model 2 is an un-symmetric in plan that has overhang in y direction (figure 2), model 3 is irregular in height (figures 3 and 4), because the mass of 2 and 3 stories differ more than 50%[6] In models 4-7 the eccentricity varies gradually with changing the center of mass location.

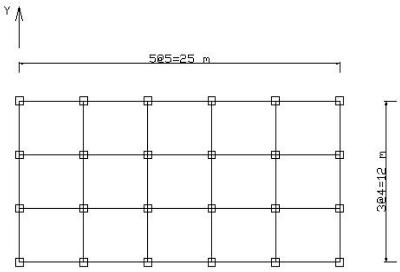

Figure 1- Model 1

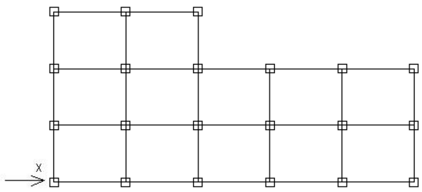

Figure 2- Model 2

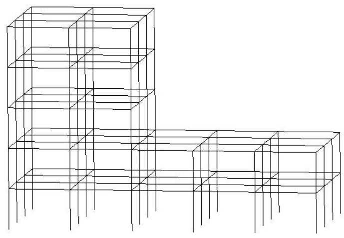

Figure 3-Perspective view of model 3

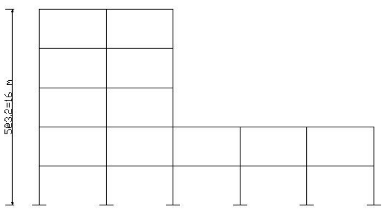

Figure4-Side view of model 3

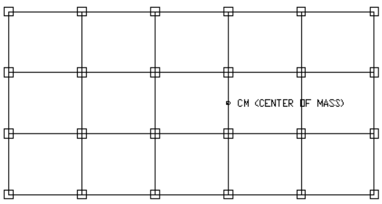

Figure 5- Model 4

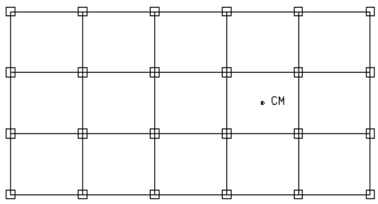

Figure 6- Model 5

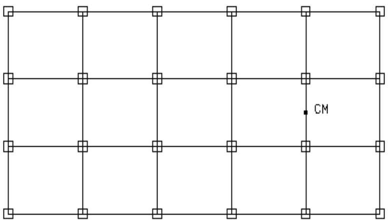

Figure 7- Model 6

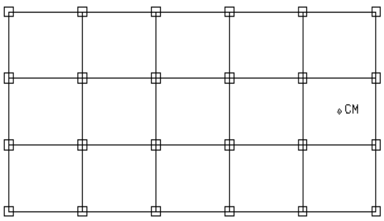

Figure 8- Model 7

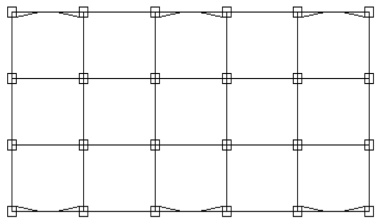

Figure 9- Model 8

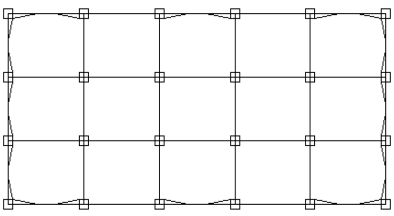

Figure 10- Model 9

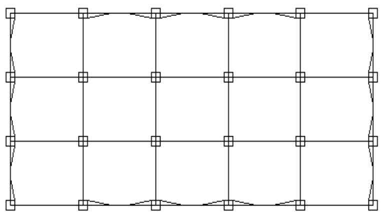

Figure 11- Model 10

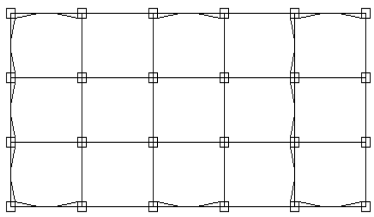

Figure 12- Model 11

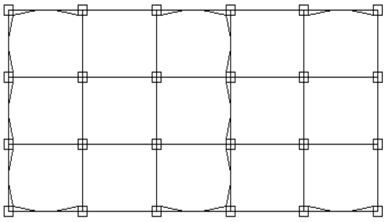

Figure 13- Model 12

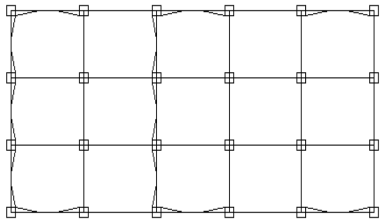

Figure 14- Model 13

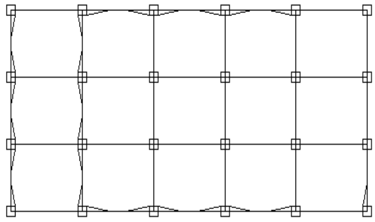

Figure 15- Model 14

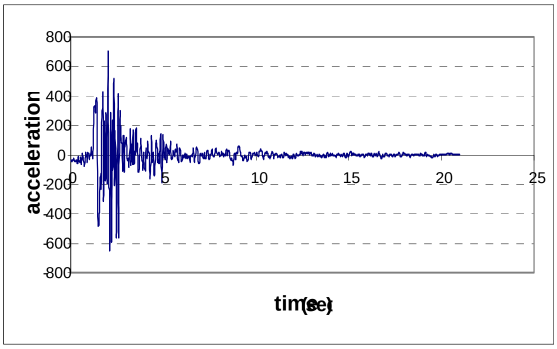

Figure 16- longitudinal component of naghan earthquake

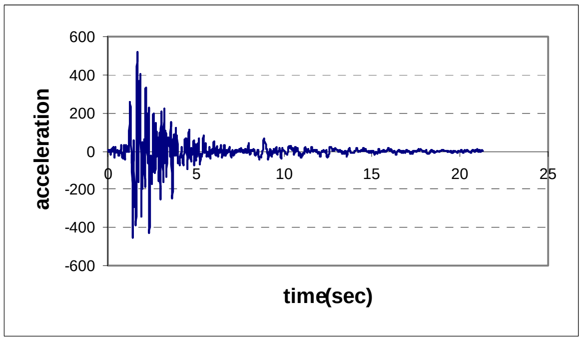

Figure 17- transverse component of naghan earthquake

(figures 5-8). Model 8 has combined system in plan that lateral resistant system in x and y directions are respectively EBF and MRF(figure 9). Models 9,10 are regular braced in both direction x and y that model 9 has corner column (figure 10) and model 10 has no corner column (figure 11). It‘s noted that the corner column is the column that locates at intersection of two braced frames. Models 11-14 are irregular in plan that eccentricity increase with changing the location of bracings in direction y (figures 12-15). The two horizontal components of naghan acceleration are used as seismic loads. (figures 16,17) The maximum acceleration peaks of principal and secondary components are 0.7g and 0.5g respectively. The components with the maximum acceleration peak are normalized to 0.35g. The second acceleration values are normalized with the same scale factor applied to the corresponding first component in order to ensure that the relative intensities of both components of the original record are maintained.

LINEAR BEHAVIOR

Earthquake has an arbitrary excitation angle and may affect the structure from any direction. Therefore a program has been developed that determines any response of the structure under two and one component with any excitation angle from 0º to 180º using four response histories ($R^{2y}, R^{2x}, R^{1y}, R^{1x}$) obtained from SAP2000 Program. For example R^{1x} is the response of the structure when the first component of earthquake is applied in x direction and other parameters are described like this. The response of the structure under two and one components with the excitation angle of θ are calculated respectively from (1) and (2):

$$R_1 = R^{1x}\cos\theta + R^{1y}\sin\theta \tag{1}$$

$$R = (R^{1x} + R^{2y})\cos\theta + (R^{1y} - R^{2x})\sin\theta \tag{2}$$

Herein the 30%, SRSS and 20% combinations and methods are considered respectively according to the following relations:

$$\begin{cases} R = R_0 + 0.3R_{90} \\ R = R_{90} + 0.3R_0 \end{cases} \tag{3}$$

$$R = \sqrt{(R_0)^2 + (R_{90})^2} \tag{4}$$

$$R_{\%20} = 1.2 \times \max\{R_0, R_{90}\} \tag{5}$$

R_0 and R_{90} are the responses of structure under longitudinal component of earthquake when excitation angles of earthquake are 0º and 90º respectively. These combinations are compared with Rmax (bi) that is the maximum response under two components with critical excitation angle. The results of analyses in some models are presented in tables (3-8) and the columns and beam 221 locations have been manifested in table 1 and figure 18. Also the symbols used in tables have been explained in table 2. The results show that the combinations underestimate the responses with respect to the maximum responses under two components of earthquake. However the 20% method often gives the answers better than SRSS and 30% combinations, though 20% method has considerable errors. It is noted that if we ignore of –11.8% error for shear base, we can use 20% method only for base shear response in these 14 models. Also 30% combination has error in regular building. The difference percent of maximum responses under two and one components (ΔR) in irregular in height building (model 3) is more than the corresponding values in regular building. It indicates that the buildings are irregular in height have more sensibility to influence of two earthquake components. In eccentric MRF building, ΔR for axial force of columns located at the rigid side of building is more than flexible side and it indicates the high sensibility of rigid side columns to two components of earthquake. Also if the eccentricity increases gradually in MRF and EBF system buildings (models 4-7, 11-14), the difference percent of maximum responses will not always increase. The critical angle of shear base and displacement under one component is in X or Y direction, but under two components it has not been seen the same results. The critical angles of axial force in columns under two and one components are often provided in directions except of reference ones. Maximum difference percent of axial forces in columns under two and one components are smaller if the gravitational loads are considered (ΔR_g), because the seismic axial force is only a fraction of the total force. But ΔR for storey displacement doesn't vary if gravitational loads are considered or not. In eccentric braced frame buildings that has corner column (model 9), the maximum difference percent of axial forces under two and one components in corner column is more than the corresponding values in same location columns in braced building that hasn't any corner columns. This difference percent in model 9 is less than the

Table 1- location of columns according to figure 16

column	number of columns considering their locations				
	storey 1	storey 2	storey 3	storey 4	storey 5
C1	1	2	3	4	5
C2	21	22	23	24	25
C3	41	42	43	44	45
C6	101	102	103	104	105
C8	26	27	28	29	30
C14	31	32	33	34	35
C15	51	52	53	54	55

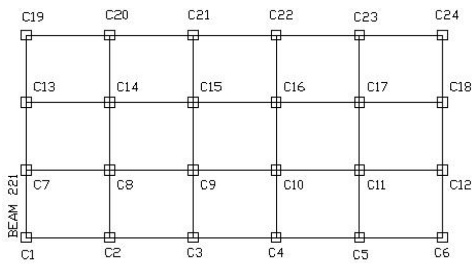

Figure 18-location of columns and beam 221

Table 2 –Explain of symbols

Explain	Symbol
difference percent between combinations and maximum responses under two components	$\Delta R_{combination}$
maximum response under two components and one component respectively	Rmax (bi) , Rmax (uni)
maximum responses difference percent under two and one components considering and not considering gravitational loads	ΔR g , ΔR
critical angle under two components and one component respectively	$\theta\ cr_{bi}$, $\theta\ cr_{uni}$
building shear base in x and y direction respectively	Shear base x, shear base y
displacement of storey i in x and y direction	displacement x i, displacement y i
Axial force, shear force and bending moment of column i respectively	f column i , V beam i , M beam i
shear force of column i along global y axis and bending moment about y axis	Vy column i , My column i

Table 3- Results of model 1

Response of structure	ΔR combination			Rmax (bi) ton, m	Rmax (uni) ton , m	ΔR	ΔR_g	$\theta\ cr_{bi}$	$\theta\ cr_{uni}$
	30%	SRSS	20%						
Shear base x	-8.4	-8.4	9.9	78.99	72.32	8.44	8.44	125	0
Shear base y	-17.3	-17.3	-0.7	85.184	70.468	17.28	17.28	38	90
displacement x 5	-2.2	-2.2	17.3	0.026	0.025	2.22	2.22	125	0
displacement y 5	-18.4	-18.4	-2.1	0.030	0.025	18.40	18.40	28	90
f column 1	-18.6	-19.7	-16.9	12.385	9.943	19.72	4.95	0	60
F column 31	-21.6	-15.6	-26.9	1.210	0.970	19.83	0.28	74	134
F column 101	-16.4	-16.8	-15.9	12.233	9.943	18.72	4.65	59	120
M beam 221	-13.0	-13.0	4.4	3.626	3.155	13.00	6.49	180	90
My column 1	-25.8	-25.9	-11.0	7.938	6.463	18.58	17.73	128	180
V beam 221	-12.8	-12.8	4.6	1.792	1.562	12.82	3.04	180	90
Vy column 1	-13.2	-13.2	4.1	2.908	2.524	13.22	10.00	34	90

Table 4- Results of model 3

Response of structure	ΔR combination			Rmax(bi) ton, m	Rmax (uni) ton , m	ΔR	ΔR_g	$\theta\ cr_{bi}$	$\theta\ cr_{uni}$
	30%	SRSS	20%						
Shear base x	-26.5	-26.5	-11.8	87.03	63.94	26.53	26.53	119	0
Shear base y	-24.0	-24.0	-8.8	83.11	63.15	24.02	24.02	21	90
displacement x 5	4.7	0.5	17.6	0.033	0.032	1.98	1.99	130	0
displacement y 5	-26.6	-22.1	-22.1	0.040	0.031	22.07	22.07	37	90
f column 1	-30.9	-31.9	-29.5	16.39	10.85	33.76	10.37	10	63
F column 41	-36.2	-35.3	-37.0	12.48	9.04	27.59	5.55	77	135
F column 101	-16.3	-17.0	-15.2	5.25	4.12	21.50	5.34	90	116
M beam 221	-20.7	-20.7	-4.9	4.12	3.27	20.73	11.01	180	90
My column 1	-44.7	-46.1	-42.4	9.66	5.61	41.94	40.29	110	177
V beam 221	-20.5	-20.5	-4.6	2.04	1.62	20.51	5.36	180	90
Vy column 1	-24.2	-24.3	-9.1	3.36	2.54	24.26	18.97	180	90

Table 5- Results of model 4

Response of structure	ΔR combination			Rmax(bi) ton, m	Rmax(uni) ton , m	ΔR	ΔR_g	$\theta\ cr_{bi}$	$\theta\ cr_{uni}$
	30%	SRSS	20%						
Shear base x	-3.4	-3.4	15.9	79.272	79.272	0.00	0.00	180	180
Shear base y	-1.3	-1.3	18.4	77.49	76.45	1.33	1.33	74	90
displacement x 5	-1.6	-5.5	10.6	0.026	0.024	7.68	7.66	145	3
displacement y 5	-16.5	-16.5	0.3	0.027	0.022	16.46	16.46	56	90
f column 1	-11.6	-12.5	-10.3	10.335	8.791	14.94	3.26	9	62
F column 101	-28.2	-30.5	-24.2	17.638	12.077	31.53	10.00	56	113
M beam 221	-23.2	-23.2	-7.9	2.89	2.22	23.25	10.27	48	90
My column 1	-18.6	-21.9	-11.5	4.46	3.29	26.22	23.88	112	0
V beam 221	-23.6	-23.6	-8.3	1.45	1.10	23.62	4.74	48	90
Vy column 1	-11.2	-11.2	6.5	1.90	1.69	11.24	7.45	45	90

Table 6- Results of model 7

Response of structure	ΔR combination			Rmax (bi) ton, m	Rmax (uni) ton , m	ΔR	ΔR_g	$\theta\ cr_{bi}$	$\theta\ cr_{uni}$
	30%	SRSS	20%						
Shear base x	-10.7	-10.7	7.2	84.324	84.324	0.00	0.00	180	180
Shear base y	-10.3	-10.3	7.6	118.341	106.147	10.30	10.30	64	90
Displacement x 5	-3.7	-7.6	4.4	0.028	0.025	12.98	12.95	0	0
Displacement y 5	-8.2	-8.2	10.1	0.045	0.041	8.22	8.22	67	90
F column 1	-4.2	-7.8	2.6	14.051	12.354	12.08	3.33	92	77
f column 101	-15.2	-18.3	-9.4	16.093	12.162	24.42	7.27	95	93

Table 7- Results of model 8

Response of structure	ΔR combination			Rmax (bi)	Rmax(uni)	ΔR	ΔR_g	θ cr_{bi}	θ cr_{uni}
	30%	SRSS	20%	ton, m	ton , m				
Shear base x	-15.1	-15.1	1.9	160.72	160.54	0.11	0.11	177	180
Shear base y	-16.7	-16.7	-0.1	82.64	68.82	16.72	16.72	22	90
displacement x 5	-6.0	-6.0	12.8	0.022	0.022	0.00	0.00	180	180
displacement y 5	-21.3	-21.3	-5.5	0.031	0.025	21.27	21.27	29	90
F column 1	-18.3	-21.7	-11.6	32.986	25.317	23.25	10.84	21	170
F column 2	-19.5	-22.3	-14.7	25.511	19.009	25.49	11.95	22	169
f column 26	-23.0	-17.5	-28.1	1.281	0.906	29.27	0.44	180	58

Table 8- Results of model 9

response of structure	ΔR combination			Rmax (bi)	Rmax (uni)	ΔR	ΔR_g	θ cr_{bi}	θ cr_{uni}
	0.3	SRSS	0.2	ton, m	ton , m				
Shear base x	-23.87	-23.91	-8.70	174.68	163.58	6.36	6.36	159	180
Shear base y	-10.11	-10.16	7.81	144.71	130.00	10.16	10.16	57	90
displacement x 5	-15.73	-15.78	1.06	0.02	0.02	7.73	7.73	151	180
displacement y 5	-14.76	-14.88	2.14	0.02	0.02	14.89	14.88	57	90
f column 1	-23.04	-19.50	-26.42	45.29	36.32	19.80	10.90	17	49
f column 2	-20.70	-16.48	-24.66	27.84	23.10	17.03	8.61	16	49
f column 101	-15.61	-9.55	-21.09	42.16	36.25	14.02	7.47	95	131

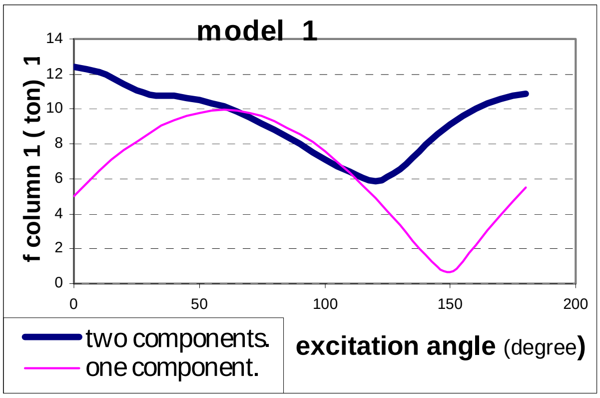

Figure 19-Axial force of column diagram

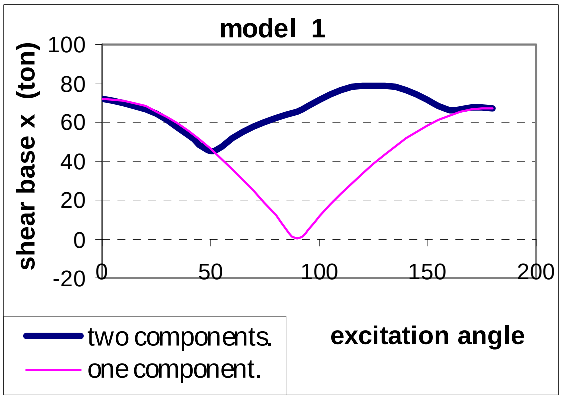

Figure 20-Axial force of column diagram

corresponding values in same location columns in building that has combined system in plan (model 8). Thus in buildings that lateral stiffness is considerably different in both directions of structure, the sensibility of columns axial force to simultaneous effect of two components of earthquake is more than other buildings. However there is no recommendation for these combined system buildings in practice codes. Also the maximum difference percent of axial forces in braced building that has corner column is less than regular MRF building. According to the less stiffness of moment resistant buildings with respect to braced ones in these models, it is concluded that flexible buildings are more sensible to influence of two components. The axial force of column and shear base diagrams in model 1 have been shown respectively in figures (19,20) when the excitation angle varies from 0º to 180º.

NONLINEAR BEHAVIOR

The non-linear analysis allows the response in each time step to be known considering the stiffness variations experienced when some critical sections yield.[7] The non-linear behavior is due to nonlinear relation between stress and strain. The stress-strain relationship behavior curve is equal to the elastic modules (E=2.1*10^6 kg/cm^2) and the curve slope in the second branch is 3% of first branch (Figure 21). Models 1-3 are taken for nonlinear analyses are employed for nonlinear time history analyses. Beam 188 element is used for modeling of beams and columns. For definition of damping, the Rayleigh damping is used it is related to mass and stiffness ($C = \alpha M + \beta K$). For nonlinear time history analyses, the special case of newmark method has been used. $(\beta = 0.252506,\ \gamma = 0.505)$. Two and one components of naghan earthquake are applied separately that the earthquake excitation angle varies from 0º to 180º. The results according to tables (9-11) show that the maximum displacement difference percent under two and one components between displacements in X and Y directions in nonlinear behavior is less than the linear one. Other Maximum responses difference percent under two and one components in nonlinear behavior is less than the linear ones. But this point isn't always valid about the axial forces of columns in non-linear

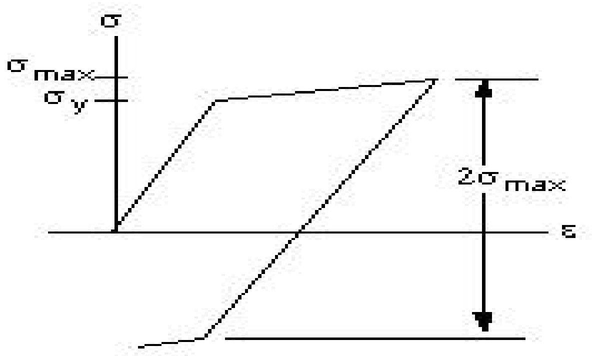

Figure 21- Bilinear model behavior

Table 9 – Results of nonlinear analysis for model 1

Response	Nonlinear			linear		
	ΔR g %	θ cr_{bi}	θ cr_{uni}	ΔRg $_{non}$ /ΔRg $_{linear}$	θ cr_{bi}	θ cr_{uni}
displacement x 5	4.14	110	0	1.86	125	0
displacement y 5	2.28	70	90	0.16	28	90
f column 1	1.5	180	50	0.13	0	60
f column 2	2.98	180	50	0.24	0	61
f column 5	12.94	180	50	1.29	22	55
f column 31	4.04	10	170	3.37	74	134
V beam 221	1.53	80	90	0.5	180	90
Vy column 1	-0.03	80	90	0	34	90
M beam 221	1.49	80	90	0.23	180	90
My column 1	-0.62	170	0	-0.03	128	180

Table 10– Results of nonlinear analysis for model 2

Response	Nonlinear			linear		
	ΔR g %	θ cr_{bi}	θ cr_{uni}	ΔRg $_{non}$ /ΔRg $_{linear}$	θ cr_{bi}	θ cr_{uni}
displacement x 5	1.47	170	180	0.38	128	0
displacement y 5	2.92	80	90	0.17	28	90
f column 1	1.28	40	50	0.11	0	59
f column 2	0.47	40	60	0.04	0	60
f column 101	0.05	110	130	0.01	133	152
f column 58	17.57	0	50	1.01	165	49
f column 59	12.54	0	40	0.69	180	45
V beam 221	1.79	80	90	0.66	180	90
Vy column 1	-0.37	80	90	-0.06	180	91
M beam 221	1.8	80	90	0.31	180	90
My column 1	-0.68	170	180	-0.04	131	180

Table 11– Results of nonlinear analysis for model 3

Response	Nonlinear			Linear		
	ΔR g %	θ cr_{bi}	θ cr_{uni}	$\Delta Rg_{non}/\Delta Rg_{linear}$	θ cr_{bi}	θ cr_{uni}
displacement x 5	7.67	110	180	3.86	130	0
displacement y 5	3.19	80	90	0.14	37	90
f column 1	3.37	30	50	0.16	10	63
f column 41	5.86	110	130	0.42	77	135
f column 101	1.89	120	130	0.15	90	116
V beam 221	1.62	80	90	0.3	180	90
Vy column 1	1.02	50	90	0.05	180	90
M beam 221	1.68	80	90	0.15	180	90
My column 1	5.98	140	0	0.15	110	177

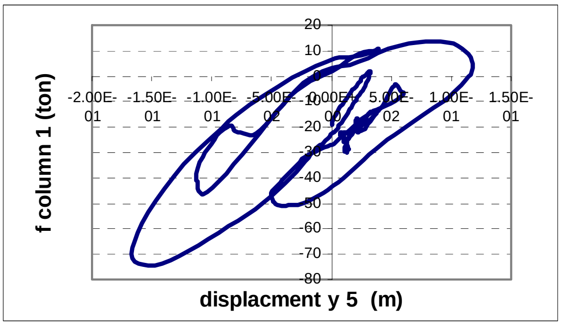

Figure 22-column axial force diagram versus displacement under two components with excitation angle of 50º in model 1

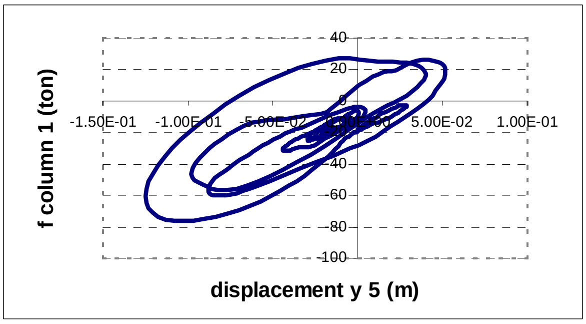

Figure 23-column axial force diagram versus displacement under one component with excitation angle of 50º in model 3

behavior. Maximum difference percent of axial force in several columns often decreases in non-linear behavior with respect to linear behavior and in other columns increases.

It's noted that the non-linear criteria for column is that if the maximum strain of column exceeds the yield strain of steel (εy =.001143) it it would be concluded that the column has entered in nonlinear region. Figures 22,23 show respectively axial force of column 1 in models 1,3 versus the lateral displacement of storey 5. The axial force of column increases with the displacement increases very slowly, therefore the column has entered in non-linear region.

The maximum difference percent displacements for irregular in height building (model 3)is considerable with respect to models 1 and 2 in nonlinear behavior. This point shows the sensibility of irregular in height buildings to influence of two simultaneous components. The critical angles under one component in non-linear behavior is close to corresponding values in linear behavior but critical angles under two components in non-linear behavior differ from corresponding values in linear behavior. [8]

The critical angle for displacement under one component is along the same displacement but under two components is not in direction of reference axes. Also the critical angles of axial forces in columns under two and one components aren't in direction of reference axes. The responses of structure under two and one components don't get to their maximum values in same critical angle in non-linear behavior like linear behavior.[8]

RESULTS

a) In linear and nonlinear behavior, maximum response under two components is more than maximum response under one component, although in some range of excitation angles in linear and non-linear behavior, the response of structure under two components might be less than one component.
b) In non-linear behavior, the maximum difference percent of responses under two and one components in regular, irregular in plan and irregular in height buildings are less than linear

behavior, as well as, the sensibility of structural response to simultaneous influence of two horizontal components in nonlinear behavior is less than linear behavior.

c) Simultaneous influence of two components on regular and irregular in height buildings is considerable. Also influence of two components in irregular in height buildings are more than regular buildings. It shows the sensibility of irregular in height buildings to two simultaneous components. However, in practice codes for seismic resistant design of buildings there is no advice for irregular in height buildings under two components.

d) SRSS and 30% combinations in the studied buildings underestimate the response of structure with respect to maximum response under two components. 20% method is more realistic than two prior combinations. The 20% method can be used, if –11.8% error is ignored. We prefer to apply simultaneous influence of two components in dynamic analysis of buildings.

e) The critical angle is a property of the structure and critical angle isn't always in direction of reference axes. The critical angle under one component in non-linear and in linear behavior are close, but critical angle under two components in non-linear behavior often differs from linear behavior. Also critical angle of columns axial force isn't always in direction of reference axes.

f) In buildings that lateral stiffness is mainly different in both directions of structure (like buildings that have combined system in plan), the sensibility of the structure to simultaneous effect of two horizontal components of earthquake is more than the braced building that has corner column and this sensibility is more than the braced one that has no corner column.

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