

STUDYING THE EFFECT OF EARTHQUAKE EXCITATION ANGLE ON THE INTERNAL FORCES OF STEEL BUILDING'S ELEMENTS BY USING NONLINEAR TIME HISTORY ANALYSES

Mahmood Hosseini¹ and Ali Salemi²

 ¹ Associate Professor, Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, Email: <u>hosseini@iiees.ac.ir</u>
² Graduate Student, Earthquake Engineering Department, Engineering School, Science and Research Branch of the Islamic Azad University (IAU), Tehran, Iran, Email: <u>ali.saalemi@gmail.com</u>

ABSTRACT :

It has been claimed by many researchers that the direction of dominant excitation might be none of the main directions of the building axes. However, the researches performed in this regard are mostly limited to buildings with elastic behavior. In this paper two 5-story steel buildings with moment frames, one with square and the other with rectangular plan, have been designed base on the seismic design code for steel buildings, and then have been analyzed by a Nonlinear Time History Analysis (NLTHA) program using simultaneously the accelerograms of two horizontal components of some earthquakes. The used earthquakes are almost of the same PGA level, but have different frequency contents. A set of values from 0 to 90 degrees, with an increment of 10 degrees, have been used for angle of excitation. Buildings' columns have been divided into three main categories, including corner, side, and internal columns, and axial force and bending moment values in different columns, and moment values in girders, as well as the total base shear forces of the buildings, have been investigated in all cases. The results show that the columns' axial forces may exceed the ordinary cases up to 50% by varying the angle of excitation, and that this variation is more in buildings with rectangular plans. Furthermore, each column gets its maximum axial force with a specific angle of excitation, which is not 0 or 90 necessarily, and is different from column to column, and that specific angle is not the same for different earthquakes.

KEYWORDS:

Angle of Excitation, Columns' Axial Forces, Corner and Side Columns.

1. INTRODUCTION

In almost all seismic design codes consideration of simultaneous effects of two horizontal components of earthquake excitations is taken into account by applying 100% of earthquake lateral forces in the direction of one of the building main axes and 30% of those forces in the direction of other main axis. This is while in reality the direction of the dominant component of excitations might not be one of the main directions of the building axes, and applying the main component in a direction other than main axes direction may lead to higher internal forces and stresses in the building's structural elements. Some researchers have worked on the effect of angle of excitation on the response values since mid 80s.

Smeby and Der Kiureghian (1985) have presented some modal combination rules for buildings systems with linear behavior subjected to multicomponent earthquake excitations based on spectral analyses. They have assumed that there is a kind of main reference system of coordinates for the ground motion in which the components of ground motion are un-correlated. They have presented a relation for calculating the mean of maximum response of the system subjected to two horizontal components of ground motion with the same spectra, which gives two angles or directions of excitations one for minimum and the other for maximum response values. The calculated critical angles are not usually the same for various kinds of responses. They have claimed that the response spectra should be obtained for un-correlated direction to give proper results.

The "mass perturbation procedure" and the "critical excitation direction" have been used also to analyze the



three-dimensional response of multistory buildings (Bicanic et al 1986). They have used perturbation by operating the system lumped mass matrix only, and have defined it as the shift of the center or mass for the required distance, expressed as the percentage of the gyration radius along the perturbation axis. They have claimed that once the perturbation axis is defined, the critical excitation directions follow automatically and a series of distinct excitations can be analyzed, each corresponding to the critical direction for one of the modes of vibration.

The effect of six-component seismic input and the input direction on the response of three-dimensional structures by using time history analysis, the translational-torsional spectral method (TTSM), and the maximum response method (MSM) have been studied (Cheng and Ger 1990). They have claimed that for MSM, the critical seismic input direction must be determined; TTSM, however, does not depend on seismic input direction, and that both methods yield similar results. They have described mathematical derivations, and have shown by numerical examples that the structural response is significantly influenced by seismic components and their input directions.

Lopez and Torres (1997) have tried to present a simple method, which can be applied in building codes to determine the critical angle of seismic incidence and the corresponding peak response of structures subjected to two horizontal components applied along any arbitrary directions and to the vertical component of earthquake ground motion. In their method the seismic components are given in terms of response spectra that may be equal or have different spectral shapes. In that study the structures are discrete, linear systems with viscous damping. Their method, which is based on the response spectrum method of analysis, requires the solution of standard cases of seismic analysis and therefore can be easily implemented in standard computer programs. For the general case of three arbitrary response spectra, their method requires the solution of five seismic loading cases, two for each horizontal component and one for the vertical component. If the horizontal response spectra have the same shape or if there is only one horizontal component, it is then required to solve just two seismic loading cases for the horizontal components and one for the vertical component. They have claimed that it can be shown that the formulas derived for the critical angles and the peak response are essentially identical to the ones obtained earlier by Smeby and Der Kiureghian using random vibration theory.

Lopez and his colleagues (2000) have tried later to develop an improved understanding of the critical response of structures to multicomponent seismic motion characterized by three uncorrelated components that are defined along its principal axes: two horizontal and the vertical component. They have derived an explicit formula (claimed to be convenient for code applications) to calculate the critical value of structural response to the two principal horizontal components acting along any incident angle with respect to the structural axes, and the vertical component of ground motion. They have defined the critical response as the largest value of response for all possible incident angles. They have shown that the ratio $r_{\rm cr}/r_{\rm srss}$ between the critical value of response and the SRSS response - corresponding to the principal components of ground acceleration applied along the structure axes - depend on three dimensionless parameters: the spectrum intensity ratio Y between the two principal components of horizontal ground motion characterized by design spectra $A(T_n)$ and $\mathbb{Y}A(T_n)$; the correlation coefficient α of responses r_x and r_y due to design spectrum $A(T_n)$ applied in the x- and y-directions, respectively; and $\beta = r_y/r_x$. They have demonstrated that the ratio r_{cr}/r_{srss} is bounded by 1 and $\sqrt{(2/1 + \gamma^2)}$, thus the largest value of the ratio is $\sqrt{2}$, 1.26, 1.13 and 1.08 for Y = 0, 0.5, 0.75 and 0.85, respectively. This implies that the critical response never exceeds $\sqrt{2}$ times the result of the SRSS analysis, and this ratio is about 1.13 for typical values of Υ , say 0.75. They have discussed that the correlation coefficient α depends on the structural properties but is always bounded between -1 and 1. For a fixed value of Υ , the ratio $r_{\rm cr}/r_{\rm srss}$ is largest if $\beta=1$ and $\alpha=\pm 1$. In that study the parametric variations presented for one-storey buildings indicate that this condition can be satisfied by axial forces in columns of symmetric-plan buildings or can be approximated by lateral displacements in resisting elements of unsymmetrical-plan buildings.

It is seen that the previous researches with regard to the effect of angle of excitation are mostly limited to buildings with elastic behavior. In this study two sets of 5-story steel buildings with moment frames, one set with square and the other with rectangular plan, have been designed base on the seismic design code for steel



buildings, and then have been analyzed by a Nonlinear Time History Analysis (NLTHA) program using simultaneously the accelerograms of two horizontal components of some earthquakes. The used earthquakes are almost of the same PGA level, but have different frequency contents. A set of values from 0 to 90 degrees, with an increment of 10 degrees, have been used for angle of excitation. The details of the study and its results are described briefly in the following sections of the paper.

2. INTRODUCING THE STUDIED BUILDINGS

Two regular and symmetric plans have been considered for the buildings as shown in Figure 1.



Figure 1. The square and rectangular plans of the considered buildings for the study

The direction of joists has been considered orthogonal in adjacent bays as shown in Figure 1 to make the distribution of vertical static loads more uniform on columns. The story height has been considered to be 3.00 meters in all cases. All buildings have been designed based on IBC 2008, considering ST37 steel for the structural material and soil type II as the most common soil type in most parts of the country. All columns have been designed by using box sections and all beams by IPE sections. It has been assumed that the infill walls are constructed such that can not have any adverse effect in seismic behavior of frames, as recommended by the code.

3. NONLINEAR TIME HISTORY ANALYSES OF THE BUILDINGS

The accelerograms of three well-known earthquakes, whose specifications are given in Table 1, have been used for Nonlinear Time History Analyses (NLTHA) of the designed buildings.

Earthquake	Place and Date	Recording Station	PGA values of the two components (g)		
Northridge	US, 1994	90014 Beverly Hills – 12520 Mulhl	0.617 – 0.444		
Manjil-Rudbar	Iran, 1990	Abbar	0.520 - 0.500		
Victoria	Mexico, 1980	6604 Cerro Prieto	0.621 - 0.587		

Table 1. The specifications of selected earthquakes for NLTHA



All of these accelerograms have been recorded on soil type II to be compatible with the soil type used in design of buildings. Figure 2 to 7 show the acceleration spectra of the two horizontal components of these earthquakes for 5% of critical damping.



Figure 3. Acceleration spectrum of second component of Northridge earthquake

It is seen in Figures 2 and 3 that the dominant periods of the Northridge earthquake are in the range of 0.15 sec to 0.60 sec. Figures 4 and 5 shows the range of dominant periods of Manjil-Rudbar as 0.10 sec to 0.70 sec.



Figures 6 and 7 depict the dominant period of Victoria earthquake in range of 0.10 sec to 1.0 sec. These ranges are all suitable for exciting the considered 5-story buildings whose natural periods are about 0.6 sec based on the seismic design code.



Figure 5. Acceleration spectrum of second component of Manjil-Rudbar earthquake

It is also noticeable in these Figures that the maximum spectral accelerations of Northridge and Manjil-Rudbar earthquakes are both around 2.0 m/s^2 while that of Victoria earthquake is around 1.0 m/s^2 . This difference should show itself in the response values to some extent.





Figure 6. Acceleration spectrum of first component of Victoria earthquake



Figure 7. Acceleration spectrum of second component of Victoria earthquake

The three accelerograms pairs have been applied to both buildings, with various angles of incidence with respect to the main axis (assumed here to be X axis) with an increment of 10 degrees. The buildings' columns have been divided into three corner, side, and middle columns, and variation of maximum values of axial and shear forces as well as bending moment in columns of each category and the bending moments of girders in various frames have been investigated with varying the degree of incidence. To simplify the comparison of results all



values in each case have been normalized to the values corresponding to degree of incidence equal to zero degree, which is called the "base case" from now on.

4. NUMERICAL RESULTS AND DISCUSSION

Among different internal forces most variations were observed firstly in axial forces of columns, and secondly in bending moments of columns. Also, least variations were observed in bending moments of girders. Table 2 shows the percent of variation of axial forces of columns of the first story for various maximizing cases with respect to the base case.

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Earthquake name		Northridge		Manjil-Rudbar		Victoria	
Building	Column	Critical	Variation	Critical	Variation	Critical	Variation
plan shape	category	angle	percent	angle	percent	angle	Percent
Square	Corner	70	41%	50	40%	90	11%
	Side	30	11%	60	15%	0	-
	Middle	30, 70	5%	50	13%	60	7%
Rectangular	Corner	50	53%	30	34%	30	19%
	Side	90	18%	90	17%	70	2%
	Middle	60	39%	50	54%	70	43%

Table 2. Percent of variation of axial forces in columns in various cases

It is seen in Table 2 that the maximum axial force in each column may occur by a specific angle of incidence, which is different from the critical angle for other columns. It should be mentioned that the maximum variations does not necessarily belong to the same column in each category. It is also worth mentioning that the variation percents given in Table 2 are just with regard to the base case, and in some cases the variation percent is not so much with respect to the other main axis, namely Y. As the other set of important numerical results, Table 3 shows the percent of variation of bending moments in columns of the first story for various maximizing cases with respect to the base case.

Earthquake name		Northridge		Manjil-Rudbar		Victoria	
Building	Column	Critical	Variation	Critical	Variation	Critical	Variation
plan shape	category	Angle	percent	angle	percent	angle	percent
Square	Corner	0	-	70	7%	0	-
	Side	0	-	0	-	0	-
	Middle	0	-	0	-	0	-
Rectangular	Corner	90	?	70	56%	90	?
	Side	90	72%	70	56%	0	-
	Middle	0	0	70	52%	0	-

Table 3. Percent of variation of bending moments in columns in various cases

It is seen in Table 3 that the maximum bending moment in columns occurs mainly by angle of incidence of either 0 or 90 degrees, however, for some earthquakes it may occur by some other angle.

5. CONCLUSIONS

Based on the numerical results it can be concluded that:

- The internal forces of structural elements depend on the angle of incidence of seismic wave with respect to the axes of building plan.
- Among various internal forces the axial forces of columns are more sensitive to the angle of incidence.



- The columns' axial forces may exceed the ordinary cases up to 50% by varying the angle of excitation, and this variation is more in buildings with rectangular plans than in those with square plans.
- The maximum bending moment in columns occurs mainly by angle of incidence of either 0 or 90 degrees, however, for some earthquakes it may occur by some other angle.
- The difference between maximum moments due to various angles of incidence is more remarkable in building with rectangular plans and may reach to 60%.
- The base shear forces of buildings due to various angles of incidence may be different to 10%.
- Each of the internal forces of column gets its maximum value with a specific angle of excitation, which is not 0 or 90 necessarily, and is different from column to column, and that specific angle is not the same for different earthquakes.
- There is not a single specific angle of incidence for each building which maximize the internal forces of all structural members together, and each member gets it's the maximum value of each of its internal forces by a specific angle of incidence. This angle is not the same for various earthquakes.

Finally, it should be mentioned that this study was limited to regular symmetric buildings, and it seems that the variations of internal forces by varying the angle of incidence become much more in irregular and asymmetric buildings. Further studies are required for these cases.

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