FACTORS INFLUENCING THE INELASTIC RESPONSE OF MULTI-STOREY FRAMES SUBJECTED TO STRONG MOTION EARTHQUAKES

by

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SYNOPSIS

The effects of various factors which may influence the inelastic response of multi-storey frames subjected to strong motion earthquakes has been studied analytically. The factors studied are: a) contribution of live load as a pure load on the girders, b) positions of live load, c) contribution of live load to floor mass, d) stiffness distribution between columns and girders, e) various levels and kinds of damping, f) earthquake intensities, and g) earthquake characteristics. The results are considered in terms of understanding which factors have significant influence on the response and how such information can be incorporated into the design criteria.

GLOSSARY OF TERMS

C, C_c - damping and critical damping factors;

DL, LL - dead and live loads;

E - modulus of elasticity;

F - multiplying factor for intensity of acceleration of accelerogram records;

I - moment of inertia of the member;

K - multiplying factor for stiffness of girders;

L - length of a member of the frame;

M_p - plastic moment of a member of the frame;

α - multiplying factor for inclusion of live load as pure load on the girder;

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β - multiplying factor for inclusion of live load mass to floor mass due to dead load;

γ - factor which defines the position of live load on the girder;

ζ - fraction of critical damping;

μ - ductility factor;

ϕ^y - yield deformation;

ϕ^p - total plastic hinge rotation.

INTRODUCTION

A rational basis for the design of earthquake resistant structures has been the subject of considerable study for some time. Despite a large number of investigations[1,2,3,4,5], into and observations[6] of the behaviour of structures subjected to strong motion earthquakes, there are still many aspects of the problem which have not been studied. Of some interest and importance is the interacting effect of some of the system parameters on the dynamic response of inelastic multi-storey frames. An engineer working in this field is faced with the complexities of non-linear behaviour, random excitation, and multi-degree of freedom systems with poorly defined behaviour characteristics. From these complexities must be obtained suitable and realistic mathematical models, methods of dynamic analysis, and finally a realization of the relative effects of the system parameters on the dynamic behaviour of structures.

There has been a large amount of activity in the last two decades towards developing suitable analytical methods for the dynamic analysis of multi-storey frames subjected to strong motion earthquakes and stressed in the inelastic range. Such efforts have normally been concentrated either on the development of a particular method of analysis or on the application of a method of analysis to one or more particular structures. Many of the previous efforts in this direction have been limited to the analysis of one or two degree of freedom systems due to the complex nature of the problem and large amount of storage and computer time necessary for the analysis[7,8,9,10]. Attempts to extend these studies to systems with more degrees of freedom have normally been made by utilizing simplifying assumptions with regard to defining a mathematical model[5,11,12]. The authors have recently developed a method[13] which can be used for the analysis of multi-storey building frames in which significant increase in capacity is obtained by optimal use of computer storage space.

In order to understand the importance of some of the system parameters on dynamic response, the analytical method developed by the authors has been used to study the effect of factors influencing the inelastic response of multi-storey frames subjected to strong motion earthquakes. The analysis is based on a mathematical model in which the mass of the frame is assumed to be concentrated at floor levels, and whose behaviour is governed by an idealized elastic perfectly plastic moment curvature relationship. A resultant of the dead load and live load is allowed to act on the girders as a concentrated load. Its position may depend on the amount and position of dead and live loads. Plastic hinges may form at all possible locations of maximum moment.

The factors or system parameters whose effect on the dynamic response is studied are the following:

a) the amount of live load included as vertical load on the girders,
b) different positions of the live loads,
c) varying live load contribution to floor mass,
d) varying stiffness distribution between girders and columns,
e) varying levels and kinds of damping,
f) varying relative earthquake intensities, and
g) varying earthquake characteristics.

The study of the above system parameters is of much interest with regard to ensuring economical and safe earthquake resistant design of the structure. Therefore, it seems logical and realistic to assess their effects and accordingly make recommendations for modification of design specifications.

FEATURES OF THE INVESTIGATION

Response Parameters

1) Ductility Factor

Aseismic design of any multi-storey building frame must consider the basic question of maximum inelastic flexural deformation in each member of the frame during the time history of the earthquake. This is determined by the member ductility factor, which has been defined as the ratio of the total flexural deformation (including the inelastic portion) to the flexural yield deformation. This is represented by

$$\mu = \frac{\phi^y + \phi^p_{max.}}{\phi^y} \qquad (1)$$

in which μ, ϕ^y and ϕ^p are member ductility factor, yield deformation and total plastic hinge rotation respectively. The yield deformation is given by

$$\phi^y = \frac{M_p L}{6EI} \qquad (2)$$

in which Mp, L, E and I are respectively the plastic moment, length, modulus of elasticity and moment of inertia of the member.

2) Maximum Displacement

Maximum displacement of any floor during the course of the earthquake is evaluated. This is of interest with regard to structural stability, strength and human comfort.

3) Maximum Acceleration

During the course of the earthquake different floors of the multi-storey structure receive accelerations which may be magnified considerably above the maximum ground acceleration. This is important from the point of view of human comfort and safety. The maximum acceleration is evaluated during the response.

SYSTEM PARAMETERS

The factors which influence the inelastic response and the related response parameters (defined earlier) are defined as the "system parameters". The following system parameters are being considered in this investigation:

a) the amount of live load included as vertical load on the girders: It is necessary to study the effect of variation of this parameter on the response of the structure as the constant stresses due to dead load must be superimposed on those due to live load and the maximum seismic forces generated by earthquake excitation. In addition, the stresses due to live load may result in early yielding of members.

b) different positions of the live loads: The position of live load is also important for the same reasons as in a), rather this may have far worse effect on the response than a) due to the initial sway of the structure.

c) varying live load contribution to floor mass: In addition to the effect of parameter a) the contribution of live load mass to the mass of each floor results in a different dynamical system. It is of interest to investigate the effect of this variation on response parameters.

d) varying stiffness distribution between girders and columns: In the lower stories of a multi-storey building, the stiffnesses of the columns govern the design while in the uppermost few stories the stiffnesses of the girders govern. Moreover the stiffness of girders is increased by the floor system. Thus it is of interest to know the effect of increasing the stiffness of the girders on the response parameters of the changed dynamical system. Such investigation is certainly of interest with regard to the aseismic design of structures insofar as the evaluation of the relative contribution of different floor systems to girder stiffnesses.

e) varying levels and kinds of damping: Undoubtedly this is one of the most important factors governing the behaviour of dynamical systems. Apart from the hysteretic damping due to inelastic behaviour, the variation of the percentage of critical damping of close and far coupled viscously damped systems is considered in this investigation.

f) varying relative earthquake intensities: The effect of variation of intensity of the amplitude of base acceleration due to an earthquake is investigated. For this purpose the amplitudes of base acceleration for a given earthquake are multiplied by constant factors such that the maximum acceleration amplitude varies from 0.32g to 0.50g. The effect of the variation of this factor may provide information about the probable effect of intensity on the damage of structures.

g) varying earthquake characteristics: The effect of this factor has been assessed by using several different earthquake records. In each case the base acceleration was multiplied by a constant factor so that the maximum base acceleration for each earthquake has an "intensified" value of 0.5g. This study may provide information as to the reliability of using the maximum base acceleration as a measure of probable damage to structures.

BASIC STRUCTURE

For the purpose of evaluating the effect of the various parameters, a basic multi-storey structure having ten stories and a single bay is used for the computation as shown in Fig. 1. The storey height is 12'0" and the bay width is 21'0". Corresponding to the frame spacing of 28'0" and a dead load of 100 psf acting on each floor of the finished structure, a concentrated dead load of 59 kips is assumed to act at the mid span of each girder. The relative stiffnesses of the members as shown in Table 1 are chosen so that the load deflection curve (under a monotonically increasing static horizontal load proportional to floor masses) has a nearly flat plateau in the inelastic range. The ratio of maximum deflection at collapse to the maximum deflection at first hinge formation is 4.77. This is defined as the static ductility factor.

The effects of the variation of the various system parameters detailed earlier in items a) through g), except d), on the response parameters of this basic structure have been evaluated and are discussed in this paper. In case of item d), in which the relative stiffness between girders and columns is varied, the stiffnesses of the columns are the same as those of the basic structure, but the stiffnesses of the girders of the basic structure are multiplied by a constant factor K. Values of K between 1 and 10 are considered.

STANDARD EARTHQUAKE

The effects of parameter a) through e) are determined by exciting the base of the structure with an acceleration equalling that of the El Centro California, earthquake of May 18, 1940, N-S component multiplied by a constant factor F so that the peak acceleration is 0.5g. In the subsequent text of this paper the above "intensified" earthquake is referred to as the "standard earthquake". When studying the effect of parameter f), the above earthquake has been used except that the multiplying factor F is varied as shown in Table 7. Table 8 lists the earthquakes used in studying the effect of parameter g).

OUTLINE OF THE PROCEDURE

In order to assess the effect of each of the aforementioned system parameters on the inelastic response of multi-storey frame subjected to strong motion earthquake, the system parameter in question is allowed to vary within a certain realistic range, while all other system parameters are kept constant at their normal values. During the response of the structure to an earthquake the plastic hinges are allowed to form at all possible locations of maximum moments equal to the plastic moment of the corresponding member. During each time history of the response of the structure, the response parameters are evaluated.

RESULTS

Figure 2 shows a portion of a typical inelastic response history. Typical response parameter variations are also shown in Figure 3, 4, and 5.

The observations and conclusions for each system parameter varied are described in the following paragraphs.

The effect of the value of the live load as a pure vertical load on the girders is shown in Table 2. An increase in the load on the girders due to contribution of live load results in a slight decrease in maximum displacements, negligible change in maximum accelerations and in the member ductility factors for any storey. The characteristics of the response do not change except that the amplitude of displacements is mildly affected.

It is concluded that inclusion of live load as a pure load on the girders has very little effect on response parameters. Thus the practice of neglecting the live load as a load on the girders is conservative in the sense that predicted deflections are slightly larger than would be expected.

The effect of the position of live load is described in Table 3. The movement of live load towards the extreme end of the girders results in the increase in maximum displacements, insignificant increase in maximum accelerations, increase in girder ductility factors and reduction in column ductility factors. It is interesting to note that the maximum ductility in columns occurs in the tenth storey while the maximum beam ductility has moved from the seventh to eighth storey. There is no change in response characteristics except that the magnitude of the displacement is increased due to movement of live load towards the end of girders.

It is concluded that position of live load appreciably affects the maximum ductility factors and accelerations. Its effect on maximum displacements is less severe. Response characteristics remain unchanged. Only amplitude of displacement is affected.

The effects of the live load contribution to floor mass are given in Table 4. An increase in live load contribution to floor mass and load on the girder results in an increase in maximum displacements, a decrease in maximum accelerations, and an increase in beam and girder ductility factors. The response characteristics have changed due to a change in the natural period as a consequence of change in floor mass. It is interesting to note that most of the inelastic activity takes place in seventh and eighth stories and a lesser amount in the second and third stories. Also maximum acceleration has moved from the tenth to the second floor when contribution of live load mass and load has increased from zero to 60% of maximum.

It is concluded that contribution of live load to floor mass and floor load severely affects the maximum displacements and ductility factors. However, the maximum accelerations are reduced due to increase in mass and load but response characteristics are significantly changed.

The effect of the variations of the girder stiffnesses is given in Table 5. As a result of a relative increase in the girder stiffness, the period of the structure decreases. This results in an increase in maximum displacement until a peak is reached at a period of 0.9277 secs. Further increase in girder stiffness and resulting increase in period results in the reduction of displacements. This trend seems to be consistent with the displacement spectrum of the standard earthquake used. The maximum ductility factors of columns obviously follow the same pattern as displacements. Also an increase in girder stiffness results in the increase in column ductility factors. In this case most of the inelastic activity takes place in the seventh storey.

It is concluded that the changes of girder stiffness should be viewed as changes in dynamic characteristics of the system. Changes in stiffness of girders may severely affect the ductility factors of the columns.

The effect of damping is described in Table 6. An increase in percentage of critical damping (close coupled) results in the reduction of maximum deflections, maximum ductility factors and maximum acceleration in a consistent manner. Also the response characteristics remain similar except for changes in the amplitude of displacement. Also maximum acceleration and maximum ductility factors are not confined to the same floor and storey respectively. Most of the inelastic activity is concentrated in seventh and second storey, the former being more severe. With low damping of two percent of critical, and changing of damping from close coupled to far coupled, there is negligible affect on response parameters except the maximum acceleration which has been doubled in the latter case and has moved from tenth to fourth floor.

It is concluded that damping has a significant effect on the response parameters.

The effects of earthquake intensity are described in Table 7. Proportional magnification of earthquake acceleration intensity results in the increase in maximum displacements and maximum ductility factors for beams and columns in a consistent manner. The characteristics of the response remain unchanged except for the increase in amplitude of displacement with increase in intensity.

It is interesting to note that increase in earthquake intensity may not necessarily amplify the maximum acceleration in a consistent manner. The increase in maximum acceleration is consistent till about 1.4 times the initial intensity. After this there is a decrease in the maximum acceleration which has shifted from fourth or fifth floor to the tenth floor. This is due to additional absorption of energy as a result of inelastic acitivity. The majority of inelastic activity in girders is concentrated in the seventh and second floors, that in the former being more severe.

It is concluded that change in earthquake intensity results in change in the maximum displacements and ductility factors. The relation between the intensity and damage to the structure may be said to be non-proportional due to inelastic behaviour of the structure. The increase in displacements is obviously less compared to increase in intensity of acceleration due to absorption of energy as a result of inelastic behaviour. Similarly the maximum acceleration may increase up to a certain peak value and may drop off thereafter.

Table 8 summarizes the effect of different earthquakes on the response parameters of the basic structure. In this case most of the ductility occurs in seventh and eighth stories. The response characteristics are obviously different for different earthquakes.

No definite conclusions can be derived except bounds for various response parameters could be established after more study in this area. Roughly an upper bound of 140% of that due to intensified El Centro December 30, 1934, E-W component could be said to be reasonably conservative for the group of earthquakes considered. It is worth noting that intensity of acceleration is not the only appropriate basis for assessing the damage on the structure, but characteristics of the earthquakes are important as well.

CONCLUSIONS

The results of this investigation indicate that some very general conclusions can be drawn which are of interest and importance in structural analysis and design for dynamic loads.

The effects of the live load as pure girder load and the live load position are of minor importance. An eccentrically positioned live load counteracts the effect of the additional pure girder load. Therefore all live load acting as pure girder load can be neglected without significantly affecting the reliability of the response data.

In contrast, the effect of live load contribution towards the mass at the floor levels has a significant effect on the response of the structure. This contribution changes the dynamic characteristics of the structure and can therefore produce effects which are not a simple function of the amount of live load included in the mass. It is recommended that the natural period be computed for both zero and full live load contribution. The response spectra for the particular earthquake can be examined in this region as a rough indication of the expected variation in behaviour.

Damping has a significant effect on the response, as would be expected. It is important, however, to consider the damping characteristics of both the structural and non-structural elements of the building in evaluating the relative value of damping and the strength of the coupling.

The relative response to different earthquake types with the same maximum base acceleration indicates that maximum base acceleration does not give a consistent indication of expected damage, i.e. maximum displacements, when inelastic behaviour is considered. The effect of varying the maximum base acceleration level for a given earthquake type also indicates that the relationship between damage and relative maximum base acceleration is non-linear. It can be concluded that both the intensity of acceleration and frequency response spectra for the earthquake type interact in a non-linear manner in influencing the dynamic response of the structure.

The above conclusions show that it is very important to be aware of all of the factors that influence response and that simple design and analysis methods which neglect some of these factors can be in gross error in predicting the response.

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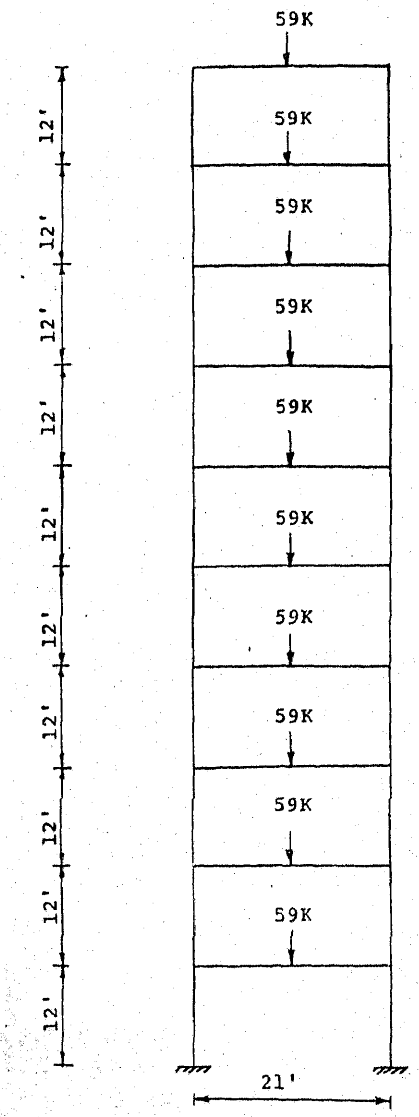


FIG. 1 THE BASIC STRUCTURE

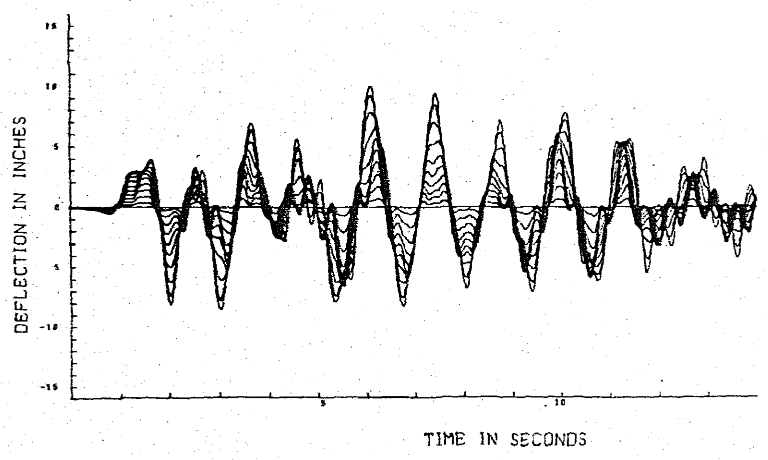


FIG. 2 TYPICAL INELASTIC RESPONSE HISTORY

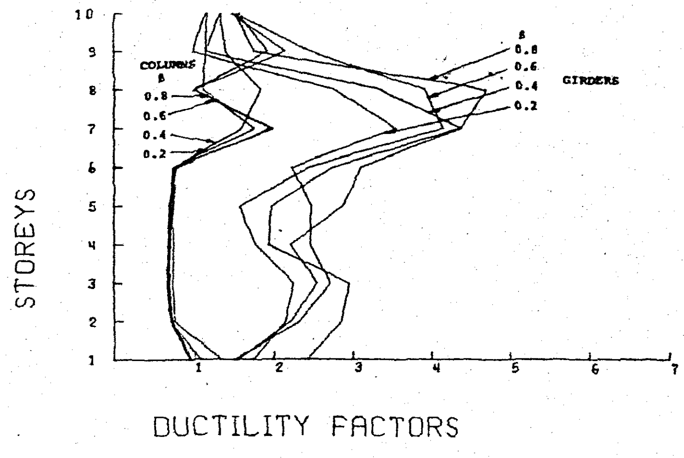


FIG. 3 TYPICAL RESPONSE PARAMETER VARIATION

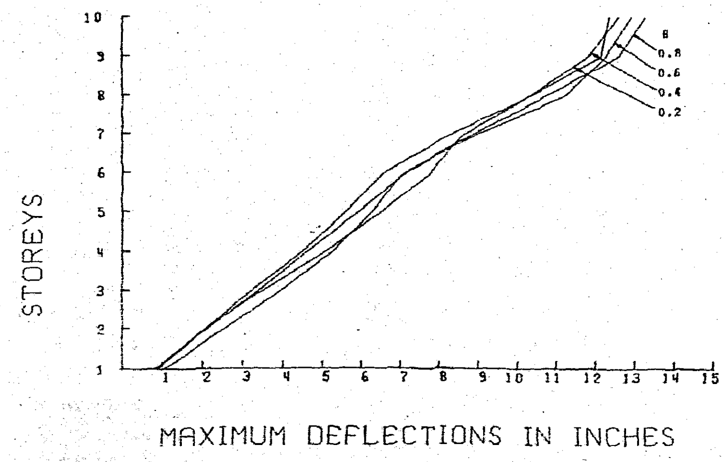


FIG. 4 TYPICAL RESPONSE PARAMETER VARIATION

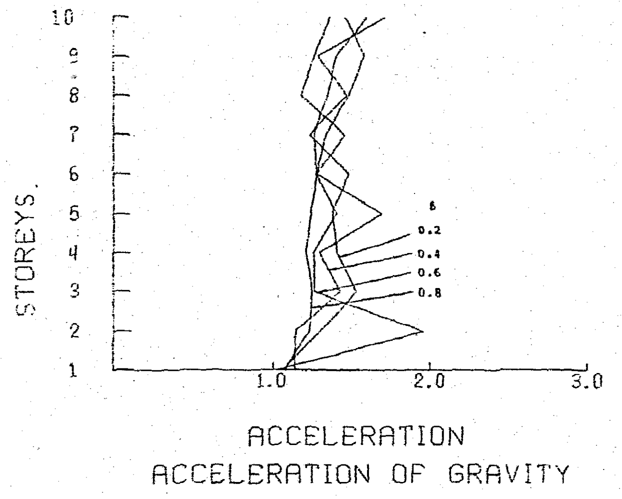


FIG. 5 TYPICAL RESPONSE PARAMETER VARIATION

TABLE 1 - RELATIVE STIFFNESSES OF THE MEMBERS OF BASIC TEN STOREY SINGLE BAY FRAME

Stories	Columns		Girders	
	Size	Relative Stiffness	Size	Relative Stiffness
10	14 WF 95	1.00	14 WF 158	1.02
9	" 103	1.10	" 167	1.09
8	" 127	1.39	" 167	1.09
7	" 136	1.50	" 167	1.09
6	" 184	2.14	" 219	1.50
5	" 193	2.26	" 219	1.50
4	" 211	2.51	228	1.58
3	" 219	2.63	" 228	1.58
2	" 228	2.77	" 237	1.65
1	" 246	3.03	" 237	1.65

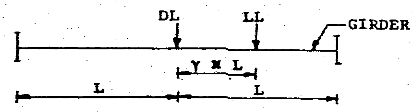
TABLE 2 - EFFECT OF VARIATION OF LIVE LOAD AS A PURE LOAD ON THE GIRDERS

LOAD ON THE GIRDER = DL + α x LL

System Parameter α	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Ductility Factor	
				Column	Girders
0	10.00	6.070	2.190 (X)*	1.31 (X)	3.3 (VII)
0.2	9.79	6.070	2.155 (X)	1.42 (X)	3.27 (VII)
0.4	9.51	6.070	2.170 (X)	1.33 (X)	3.29 (VII)
0.6	9.25	6.075	2.160 (X)	1.44 (X)	3.35 (VII)
0.8	8.98	6.750	2.150 (X)	1.46 (X)	3.36 (VII)

*Roman number enclosed by parentheses refers to storey number of the frame.

TABLE 3 - EFFECT OF THE CHANGE OF LIVE LOAD POSITION



System Parameter γ	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors	
				Columns	Girders
1.0	10.26	6.070	3.810 (IV)	1.36 (X)	4.28 (VIII)
0.5	9.44	6.072	3.840 (IV)	1.44 (X)	3.60 (VIII)
0.0	8.98	6.750	2.150 (X)	1.46 (X)	3.36 (VII)

TABLE 4 - EFFECT OF LIVE LOAD CONTRIBUTION TO FLOOR MASS

MASS OF EACH FLOOR = (DL + β x LL)/g

LOAD ON THE GIRDER = DL + β x LL

System Parameter β	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors		Period
				Columns	Girders	
0.0	10.00	6.070	2.190 (X)	1.31 (X)	3.30 (VII)	1.2812
0.2	12.57	12.430	1.720 (X)	1.76 (VII)	3.56 (VIII)	1.3739
0.4	12.90	12.070	1.700 (V)	1.83 (VIII)	4.39 (VII)	1.4608
0.6	12.35	8.730	1.960 (II)	1.97 (VII)	4.16 (VII)	1.5282
0.8	13.26	5.640	1.460 (VII)	2.15 (IX)	4.70 (VIII)	1.6207

TABLE 5 - EFFECT OF RELATIVE STIFFNESS BETWEEN GIRDERS AND COLUMNS

GIRDER STIFFNESS = GIRDER STIFFNESS x K

COLUMN STIFFNESS IS NOT CHANGED

System Parameter K	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors		Period
				Columns	Girders	
1.0	10.00	6.070	2.190 (X)	1.31 (X)	3.30 (VII)	1.2812
2.0	11.99	4.420	2.330 (VI)	2.97 (I)	0.99 (X)	1.0295
3.0	15.29	9.315	2.230 (X)	7.18 (VII)	0.97 (X)	0.9277
6.0	8.17	11.020	1.810 (IX)	1.69 (VII)	0.91 (X)	0.8110
10.0	6.99	11.900	2.550 (X)	2.07 (VII)	1.03 (X)	0.7990

TABLE 6 - EFFECT OF DAMPING

$$\zeta = \frac{c}{c_c}$$

Kind of Damping	System Parameter ζ	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors	
					Columns	Girders
	0.0	10.08	6.070	4.120 (IV)	1.28 (X)	3.33 (VII)
Close Coupled	0.01	9.96	6.070	3.940 (III)	1.29 (X)	3.25 (VII)
	0.02	10.00	6.070	2.190 (X)	1.31 (X)	3.30 (VII)
$C_{ij} = \delta_{ij} \zeta$ where δ_{ij} = kronecker delta	0.05	9.96	6.067	3.620 (V)	1.16 (VII)	3.10 (VII)
	0.10	9.86	6.095	3.260 (V)	1.15 (IX)	2.91 (VII)
Far Coupled $C_{ij} = \zeta$	0.02	9.70	6.06	4.570 (IV)	1.37 (X)	3.12 (VII)

TABLE 7 - EFFECT OF EARTHQUAKE INTENSITY

INTENSITY OF ACCELERATION = Y x ACTUAL INTENSITY

Maximum Base Acceleration /g	System Parameter Y	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors	
					Columns	Girders
0.319	1.000	8.53	7.390	2.580 (IV)	1.08 (IX)	2.60 (VII)
0.352	1.100	9.11	6.050	2.820 (IV)	1.13 (IX)	2.90 (VII)
0.383	1.200	9.36	6.050	3.010 (IV)	1.16 (IX)	2.89 (VII)
0.415	1.300	9.56	6.060	3.240 (V)	1.18 (IX)	3.17 (VII)
0.447	1.400	9.64	6.060	3.340 (V)	1.27 (X)	3.12 (VII)
0.500	1.567	10.00	6.070	2.190 (X)	1.31 (X)	3.30 (VII)

TABLE 8 - EFFECT OF EARTHQUAKE CHARACTERISTICS

Different Earthquakes	Maximum Displacement of 10th floor in inches	Time for Maximum Displacements	Maximum Acceleration /g	Maximum Ductility Factors	
				Columns	Girders
El Centro Dec. 30, 1934, N-S x 1.960	10.88	11.26	1.81 (X)	1.1 (IX)	2.4 (VII)
El Centro May 18, 1940, N-S x 1.567	10.00	6.07	2.19 (X)	1.3 (X)	3.3 (VII)
Olympia Apr. 13, 1949, N80E x 1.815	11.61	21.50	2.36 (X)	2.4 (IX)	3.6 (VIII)
El Centro Dec. 30, 1934, E-W x 2.838	12.24	18.13	2.16 (VIII)	1.8 (IX	3.3 (VIII)
El Centro May 18, 1940, E-W x 2.200	14.19	12.66	2.11 (X)	1.3 (IX,	3.4 (V)
Olympia Apr. 13, 1949, N10W x 2.660	14.61	16.04	2.07 (X)	1.8 (IX	3.7 (VIII)