ELASTIC ANALYSIS OF PILOT BUILDING

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The pilot building for the optimum seismic protection study is a 13-story steel frame building. In order to understand the reasons for the odd behavior of this building (increasing the strength and stiffness of this very flexible building generally led to a decrease in the strength of the earthquake that would cause yielding in the building, as indicated in an earlier study), this report presents a number of results from the elastic analysis of the building including discussions on: ideal building (uniform properties, strength proportional to stiffness) with smooth response spectrum input; actual building with smooth response spectrum input; and actual building with time-history input. Three main conclusions are as follows: (1) for very flexible buildings, only modest increases in yield acceleration can be achieved by stiffening of the building; (2) unless actual designs are checked by dynamic analysis (and then redesigned), there may be considerable variation in the resistance of the designs; (3) analysis using a single time-history, even an artificial time-history for a smoothed response spectra, can introduce considerable variation in yield displacement. The time-history used for analysis of the pilot building is not adequate for very flexible buildings.

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1. R.V. Whitman, "Preliminary Work Plans and Schedules," August, 1971.
2. E. H. Vanmarcke and R.V. Whitman, "Background for Preliminary Expected Future Loss Computations," October, 1971.
3. P.J. Trudeau, "Identification of Typical Soil Profiles in the Boston Basin Area," November, 1971.
4. J.M. Biggs, "Comparison of Wind and Seismic Forces on Tall Buildings," December, 1971.
5. R.V. Whitman, "Contribution to State-of-the-Art Report of the Earthquake Committee of the IABSE-ASCE Tall Buildings Committee--Economic and Social Aspects," March, 1972.
6. J.E. Brennan and R.J. McNamara, "Optimum Seismic Protection for New Building Construction in Eastern Metropolitan Areas," April, 1972.
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11. R.V. Whitman, et al., "1964 Alaskan Earthquake Tall Building Damage Review," July, 1972.
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INTRODUCTION

The pilot building for the optimum seismic protection study is a 13-story steel frame building. The building is described in Report 2 (Leslie thesis) and in the thesis by Anagnostopoulos. The latter thesis presents a dynamic analysis for the building, with emphasis upon results in the non-linear range. The results are rather unsatisfactory from the standpoint of the optimization study, since increasing the strength (and stiffness) of this very flexible building generally led to a decrease in the strength of the earthquake that would cause yielding in the building.

In order to understand better the reasons for the odd behavior of this building, this report presents a number of results from the elastic analysis of the building. The order of discussion is:

1. Ideal building (uniform properties, strength proportional to stiffness) with smooth response spectrum input.
2. Actual building with smooth response spectrum input.
3. Actual building with time-history input.

RESPONSE OF IDEAL BUILDING

To have some idea as to how much the yield acceleration might be affected by increased strength and stiffness, let us first consider in an approximate way the behavior of a uniform shear beam where strength and stiffness are proportional so that the yield distortion is the same in all designs.

From the theory for dynamic response of a uniform shear beam, the distortion (du/dx) of the beam in the nth mode is:

$$\frac{2S_{dn}}{H} \cos \frac{n\pi x}{2H} \tag{1}$$

where S_{dn} is the spectral displacement for the nth mode and H is the length of the beam. The maximum distortion in each mode is at the bottom of the beam (as well, for modes higher than the first, at some higher point in the beam) and is $2S_{dn}/H$. Thus, if three modes are included in modal analysis using response spectrum input, the maximum distortion might be taken as either

$$\Sigma = \frac{2}{H} (S_{d1} + S_{d2} + S_{d3}) \tag{2}$$

$$\mathrm{SRSS} = \frac{2}{H} \sqrt{S_{d1}^2 + S_{d2}^2 + S_{d3}^2} \tag{3}$$

Now let us assume that the response spectrum consists of two straight lines on log-log paper, with one line of constant S_v and the other of constant S_d. Further, assume that the lines intersect at a period of 3 seconds, so that $S_v + \frac{2\pi}{3} S_d$. Then, if the fundamental period T_1 lies on the line of constant S_d while the two higher modes having periods T_2 and T_3 lie on the line of constant S_v, then:

$$\Sigma = \frac{2S_d}{H} \left(1 + \frac{T_2 + T_3}{3}\right) \tag{4}$$

$$SRSS = \frac{2S_d}{H}\sqrt{1 + \frac{1}{9}\left(T_2^2 + T_3^2\right)} \qquad (5)$$

For the uniform shear beam, $T_2 = T_1/3$ and $T_3 = T_1/5$. Hence,

$$\Sigma = \frac{2S_d}{H}\left(1 + 0.179T_1\right) \qquad (6)$$

$$SRSS = \frac{2S_d}{H}\sqrt{1 + 0.0168T_1^2} \qquad (7)$$

Suppose then that we start with a fundamental period of 6 seconds for the 0 level design. If we increase the stiffness by a factor of 4 while keeping the yield distortion constant, then we increase the yield acceleration (proportional to S_d) by:

$$\text{using } \Sigma: \quad (1 + 1.074)/(1 + 0.537) = 1.35$$

$$\text{using SRSS:} \quad \sqrt{1 + 0.607}/\sqrt{1 + 0.152} = 1.19$$

Thus, the 4-fold increase in stiffness and associated 4-fold increase in strength only increases the yield acceleration by 19% to 35%.

Using the periods for the several designs of the pilot building gives the results in Table 2. Going from the periods for level 2 to those for level 3 increases the yield acceleration from 8% to 14%, while going from the periods for level 2 to those for level 5 increases the yield acceleration from 11% to 26%.

Thus, for a flexible uniform shear beam, with strength proportional to stiffness so that the yield distortion is fixed, large increases in strength and stiffness mean only small increases in the yield acceleration.

RESPONSE OF PILOT BUILDING TO SMOOTH SPECTRA INPUT

For an actual building designed in accordance with the code, the strength and stiffness may not change in a consistent way when the design base shear is changed. This effect may be examined by using a smooth response spectra input to the actual designs made for the pilot building. Table 3 gives the yield distortions* and modal responses (participation factor x mode shape) for the various designs, for key floor levels. The input was taken as $S_d = 5$ inches and $S_v = 10.5$ in/sec, which correspond roughly to the time-history used for analysis of the pilot building normalized to a peak acceleration of 0.11g.

Results of the analysis are given in Table 4. These results were obtained by using the average of the Σ and SRSS results. It is seen that the trend for each direction is erratic: in each case there is an example of increased strength leading to decreased yield level. In the case of the X-direction, this is because the top story of design level S is unusually flexible and has a large distortion in the 1st mode; if this top story were ignored in this design, the yield acceleration would be 0.90g. In the Y-direction, the design of the first floor for level 3 appears to provide more stiffness than strength.

These results show that designs which fulfill the code but

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*Note: The term yield displacement as used here refers to a rough estimate of interstory distortion that will cause first yielding somewhere in the story. Since, however, it is computed in the same way for all three designs, the conclusions drawn are valid, independent of actual local yields.

which are not checked by dynamic analysis may have considerable variation in actual resistance. The average resistance (last column of Table 3) does show an increase with design level.

It may be noted that the 2nd and 3rd modes contribute very strongly to distortions at the top of the building. The UBC does not give an adequate design of the upper stories in the transverse direction.

RESPONSE OF PILOT BUILDING TO TIME HISTORY INPUT

Response computed using a time-history input (an artificial time-history corresponding to a smoothed response spectra) are presented in the thesis by Anagnostopoulos. The yield accelerations are summarized in Table 5. Now the yield acceleration varies even more widely as the strength of the building is increased. There are several reasons for this:

1. The spectral displacements for the fundamental mode increase as the building is strengthened. For example:

Design level	S_{d1} in X direction
2	2.4 inches
3	3.1
3	5.9

2. The spectral displacements of the higher modes jump around erratically depending upon the relation of the periods to the peaks and valleys of the response spectrum.
3. The phasing of the maxima of the modes. For example, consider the following results for interstory displacements, in inches, in the X direction:

Design	Story	Σ	SRSS	Time-history
2	11	0.094	0.062	0.094
3	13	0.065	0.040	0.042
5	1	0.112	0.081	0.091
5	13	0.100	0.058	0.073

These results apply for a peak acceleration 0.007g, and were computed using the spectral displacements from the response spectrum for the time-history. For the last three entries, the time-history maximum is between those obtained by the Σ and SRSS methods. For the first entry, however, the time-history response is equal to the result by the Σ method.

SUMMARY

The results of this study are compared in Table 3. There are three main conclusions to be drawn.

1. For very flexible buildings, only modest increases in yield acceleration can be achieved by stiffening of the building.
2. Unless actual designs are checked by dynamic analysis (and then redesigned), there may be considerable variation in the resistance of the designs.
3. Analysis using a single time-history, even an artificial time-history for a smoothed response spectra, can introduce considerable variation in yield displacement. The time-history used for analysis of the pilot building is not adequate for very flexible buildings.

TABLE 1

PERIODS OF PILOT BUILDING IN SECONDS

Design Level	X-direction Mode 1	X-direction Mode 2	X-direction Mode 3	Y-direction Mode 1	Y-direction Mode 2	Y-direction Mode 3
2	5.27	1.96	1.14	4.50	3.31	2.95
3	4.20	1.53	0.91	3.31	1.17	0.68
S	3.08	1.14	0.71	2.95	1.02	0.61

TABLE 2

RESPONSE FOR IDEAL BUILDING TO SMOOTH RESPONSE SPECTRUM INPUT

Direction	Design Level	max. dist. x $H/2S_d$ Σ	max. dist. x $H/2S_d$ SRSS	Ratio to Level 2 Σ	Ratio to Level 2 SRSS
X	2	2.04	1.26	1.00	1.00
	3	1.81	1.16	0.89	0.92
	S	1.62	1.10	0.79	0.87
Y	2	1.85	1.20	1.00	1.00
	3	1.62	1.10	0.88	0.92
	S	1.54	1.08	0.84	0.90

TABLE 4

YIELD ACCELERATION FOR PILOT BUILDING USING SMOOTH RESPONSE SPECTRA INPUT

Design Level	Earthquake to Yield		Yield at Floor		Ratio to Level 0		
	X	Y	X	Y	X	Y	Ave.
2	0.064g	0.076g	11	11	1.00	1.00	1.00
3	0.080g	0.064g	1	1	1.25	0.84	1.03
S	0.077g	0.084g	13*	1	1.20	1.11	1.15

*Followed closely by stories 1 and 9.

TABLE 5

YIELD ACCELERATION FOR PILOT BUILDING USING TIME-HISTORY INPUT

Design Level	Earthquake to Yield		Yield at Floor		Ratio to Level 0		
	X	Y	X	Y	X	Y	Ave.
2	0.061g	0.071g	11	11	1.00	1.00	1.00
3	0.106g	0.082g	13	1	1.74	1.15	1.42
S	0.078g	0.060g	13	1	1.28	0.84	1.04

TABLE 3

MODAL FACTORS AND YIELD DISTORTIONS FOR PILOT BUILDING

Direction	Design Level	Story	$\Gamma_1\Phi_1$	$\Gamma_2\Phi_2$	$\Gamma_3\Phi_3$	Yield Disp-in.
X	2	1	0.127	0.184	0.149	1.16
		9	0.139	0.143	0.123	0.82
		11	0.132	0.254	0.147	0.82
		13	0.055	0.148	0.287	1.02
	3	1	0.178	0.191	0.141	0.95
		9	0.104	0.130	0.064	0.85
		11	0.092	0.179	0.082	1.02
		13	0.062	0.176	0.342	0.94
	S	1	0.206	0.198	0.113	1.08
		9	0.096	0.105	0.060	0.62
		11	0.088	0.163	0.024	0.79
		13	0.086	0.258	0.439	0.80
Y	2	1	0.117	0.179	0.150	0.82
		9	0.131	0.165	0.076	0.71
		11	0.105	0.227	0.170	0.78
		13	0.046	0.133	0.248	0.68
	3	1	0.183	0.202	0.175	0.73
		9	0.104	0.138	0.040	0.70
		11	0.089	0.182	0.140	0.81
		13	0.039	0.102	0.177	0.86
	S	1	0.142	0.183	0.155	0.75
		9	0.110	0.153	0.039	1.04
		11	0.082	0.181	0.141	0.77
		13	0.043	0.124	0.228	0.75

TABLE 6

INCREASE IN YIELD ACCELERATION FOR VARIOUS CASES

Design Level	Ave. values			Range		
	Ideal	Spectra	Time-history	Ideal	Spectra	Time-history
2	1.00	1.00	1.00	1.00	1.00	1.00
3	1.11	1.03	1.42	1.10-1.11	0.84-1.25	1.15-1.74
S	1.18	1.15	1.04	1.15-1.20	1.11-1.20	0.84-1.28

For "ideal" and "spectra" columns, average of Σ and SRSS was used.