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INELASTIC DESIGN OF BUILDING FRAMES TO RESIST EARTHQUAKES

by

John E. Isbell

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Department of Civil Engineering

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Typical apartment house structures designed according to Uniform Building Code standards were subjected to earthquake motions and analyzed. The main objective was to evaluate the ductility ratios and interstory displacements which result when the buildings are subjected to a severe earthquake. Three sets of building designs were studied: six story concrete moment resisting frame (CMRF) buildings; eleven story concrete moment resisting frame buildings; and eleven story steel moment resisting frame buildings (SMRF). Within each of these sets there was one design for each earthquake zone, 0 to 3 (zone 0 and 1 are the same) and a design for a "super" zone (4), which had a zone factor twice as large as that in zone 3. These buildings were subjected to an artificially generated earthquake with a maximum acceleration of 0.27g. This earthquake was generated to match the response spectrum developed for the Boston, Massachusetts area.

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INTRODUCTION

This report is a supplement to Inelastic Design of Building Frames to Resist Earthquakes. The main thrust here is to evaluate more completely some code designed buildings as to their response during an earthquake motion. In the parent report a few cases are mentioned briefly. The main objective is to evaluate the ductility ratios and interstory displacements which result when the buildings are subjected a severe earthquake. These parameters are important because in some way the interstory displacements are a measure of the damage that will occur in the building and the story ductility ratios are an indication of possible collapse of the building. Some other observations, concerning Newmark's inelastic response spectra and estimating ductility ratios will also be made.

BUILDING AND EARTHQUAKE CHARACTERISTICS

For a previous study a number of typical apartment house structures were designed by the Cambridge firm of Le Messurier Associates, Consulting Engineers. These buildings were designed according to Uniform Building Code standards and are representative of conventional engineering practices. No specific earthquake considerations were made, beyond those given in the code. The designs were reviewed by a firm in California as a check. A complete report of the design methods used and considerations made is given in reference 1.

These building designs were subjected to earthquake motions and analyzed in reference 2. Here some further observations will be made. Three sets of building designs were studied; 6 story concrete moment resisting frame (CMRF) buildings, 11 story concrete moment resisting frame buildings, and 11 story steel moment resisting frame buildings (SMRF). Within each of these sets there was one design for each earthquake zone, 0 to 3 and a design for a "super" zone (4), which had a zone factor twice as large as that in zone 3. Actually, designs for zone 0 and 1 are the same, so there are 4 designs in each set, resulting in a total of 12 designs.

These buildings were subjected to an artificially generated earthquake with a maximum acceleration of 0.27g. This earthquake was generated to match the response spectrum developed for the Boston area. Further discussion of the development of the response spectrum and artificial earthquake is given in references 3 and 4. The buildings were analyzed with a computer program developed by S. Anagnostopoulus. Further information concerning this program can be found in reference 4.

INTERSTORY DISPLACEMENTS AND DUCTILITY RATIOS FOR CODE DESIGN

The interstory displacements and ductility ratios for the 6 story CMRF designs are shown in Figures 1 to 4. The stiffness, resistance, elastic limit interstory displacements, maximum interstory displacements, and story ductility ratios are given in Table 1. For all of the zones, the ductility ratios remain basically the same. The average in each case is approximately 2 and the maximum in any of the 4 designs is 4.6. Thus there is very little inelastic action occurring in any of these buildings, even in the zone 0 design. The primary reason for this is that the buildings are very flexible, with periods ranging from 2.81 sec. for zones 0 & 1 to 1.38 sec. for zone 4. Comparing these with the 0.1 N or 0.6 sec. rule of thumb, illustrates their extreme flexibility.

Looking at the elastic limit interstory displacements and maximum interstory displacements further illustrates the flexibility of these buildings. The maximum displacements for zones 0 to 3 are very large and erratic. Those in zone 4 are somewhat reduced but are still rather large. Such large interstory displacements would probably cause significant damage if such an earthquake were to occur. An interesting point brought out in a previous report is that increasing the design zone does little to control these important parameters.

Another reason for rather low ductility ratios observed in these code designs can be obtained by comparing the elastic response spectrum for the Boston area with the response spectrum upon which the code is based. A figure showing these two is given in reference 2. The difference between the two spectra is a measure of the inelastic action incorporated in the code. It is clear that in the period range of these buildings, the difference between the two spectra is rather small, thus the low ductility ratios are expected.

The interstory displacements and ductility ratios for the 11 story CMRF designs are shown in Figures 5 to 8. The design and response characteristics are given in Table 2. In general the same points made about the 6 story designs concerning flexibility and the design spectrum apply to the eleven story designs. For all zones the story ductility ratios were small and the average ductility ratios for the buildings were between 1.2 and 1.4. Thus there was even less inelastic action in these than in the 6 story designs.

The interstory displacements for zones 0 to 2 are rather large (average values 0.087' and 0.09'), but not nearly as large as those from the 6 story designs. This occurs because even though these buildings are taller they are somewhat stiffer than the 6 story buildings. The interstory displacements for zone 3 and 4 are less because of the increased stiffness of these designs and the ductility ratios remain essentially the same because the elastic limit interstory displacements decrease in proportion with the decrease in maximum interstory displacements.

From Figures 5 through 8 it is clear that the largest response occurs in the bottom stories. This is due, principally, to the fact that the stiffnesses are uniform (except for the bottom story because of its assumed fixity) and the shear resistances taper only slightly from bottom to top. Thus the elastic limit interstory displacements are essentially uniform. But the shear forces generated by the earthquake increase from top to bottom. Therefore first yielding occurs in the lower stories and subsequent response is concentrated in that area.

The interstory displacements and ductility ratios for the 11 story SMRF designs are given in Figures 9 to 12. The design and response characteristics are given in Table 3. The stiffnesses are tapering and the resistances vary in 2, 3, and 4 story jumps. In the first four stories the columns remained the same, 5 and 6 were the same, 7 and 8 were the same, and 9 through 11 were the same. The response parameters show a similar pattern for all the zones. In zones 2 to 4 the values of the parameters are much the same also. The design for zone 0 and 1 yielded large interstory displacements and ductility ratios in some of the stories. In all cases the maximum response occurs in the 9th story. This seems to be due to the change in strength from the 8th story to the 9th story. The 8th story is relatively strong because it has the same design as the 7th story and therefore could take the force that the 7th story was designed for. Since the 9th to the 11th stories have the same design, the 9th is designed more near the limit of its capacity than the other two. Therefore the greatest change in strength occurs between the 8th and 9th story and this change is reflected in the response of the building.

Even with the rather high ductility ratos in some of the stories, the average ductility ratios for the buildings were low (2.1 to 3.6). As with the concrete buildings, this results from the flexibility of the designs. The elastic limit interstory displacements are so large that they are not greatly exceeded by the displacements caused by the earthquake.

OTHER OBSERVATIONS

It is also interesting, with the data from these analyses, to check the validity of Newmark's inelastic displacement spectrum as was done in the report-Inelastic Design of Building Frames To Resist Earthquakes. Newmark states that the elastic and inelastic response spectra should be the same in the range of periods we are considering here, for a one DOF system. To check this with respect to these MDOF systems, two approaches were taken. The first was to compute a spectral displacement based on the maximum interstory displacement in the building. The second was to compute a spectral displacement using the maximum displacement at the top of the building. This corresponds to using an average interstory displacement.

Table 4 gives the values of the spectral displacements for the various approaches in each design case studied. These values show that Newmark's spectrum is conservative with respect to average interstory displacements, but quite unconservative with respect to maximum interstory displacements. This further verifies the results found in the parent report.

The final observation concerns the ability to estimate the magnitude of the ductility ratios that will develop in a code designed building when it is subjected to a severe earthquake. It would be desireable if the ductility ratio was incorporated in the design process so that it could be directly controlled. The code does not attempt this. Therefore the next best thing is to develop a means of estimating the probable ductility ratios once the design has been made.

In reference 2 it was found that a good estimate of the inelastic interstory displacements can be made using elastic, first mode interstory displacements. Dividing the average interstory displacement, obtained from this elastic, first mode approach, by the average elastic limit interstory displacement, gives an estimate of the average ductility ratio of the building. Figure 13 shows a plot of the estimated average ductility ratio vs. the actual average ductility ratio. The estimated value is quite close for most of the cases, but clearly unconservative for some.

TABLE 1

DESIGN AND RESPONSE CHARACTERISTICS OF 6 STORY CMRF BUILDINGS

6 STORY CMRF

ZONE 0 & 1 T_1= 2.81 sec

STORY	K	R	X_e	$X_{0.27}$	μ
1	8596	464	0.054	0.249	4.6
2	5082	496	0.098	.126	1.3
3	5082	480	0.0945	.100	1.1
4	5082	408	0.08	.258	3.2
5	5082	340	0.067	.102	1.5
6	5082	284	0.056	.062	1.1
		AVG.	0.0749	.149	2.2

ZONE 2 T_1 = 2.81 sec

STORY	K	R	X_e	$X_{0.27}$	μ
1	8596	462	0.054	0.248	4.6
2	5082	500	0.985	.125	1.3
3	5082	478	0.094	.100	1.1
4	5082	410	0.081	.252	3.1
5	5082	330	0.065	.126	1.9
6	5082	298	0.0586	.060	1.0
		AVG.	0.0752	.152	2.05

TABLE 1 (Continued)

DESIGN AND RESPONSE CHARACTERISTICS OF 6 STORY CMRF BUILDINGS

6 STORY CMRF

ZONE 3 $T_1 = 2.07$

STORY	K	R	X_e	$X_{0.27}$	μ
1	15624	1054	0.0675	0.069	1.0
2	9356	900	0.0962	.107	1.1
3	9356	682	0.073	.276	3.8
4	9356	572	0.061	.132	2.1
5	9356	496	0.053	.083	1.6
6	9356	304	0.0325	.079	2.4
		AVG.	0.0638	.124	2.0

ZONE 4 $T_1 = 1.38$ sec.

STORY	K	R	X_e	$X_{0.27}$	μ
1	34000	1462	0.043	0.118	2.8
2	20700	1438	0.0694	.075	1.1
3	20700	1386	0.067	.067	1.0
4	20700	1266	0.061	.062	1.1
5	20700	910	0.044	.112	2.7
6	20700	654	0.0316	.029	1.0
		AVG.	0.0527	.077	1.6

TABLE 2

DESIGN AND RESPONSE CHARACTERISTICS OF 11 STORY CMRF BUILDINGS

11 STORY CMRF

ZONE 0 & 1 $T_1 = 2.66$ sec.

STORY	K	R	X_e	$X_{0.27}$	μ
1	34877	1416	0.041	0.123	3.5
2	18523	1376	.074	.140	1.9
3	18523	1310	.071	.090	1.2
4	18523	1310	.071	.079	1.1
5	18523	1310	.071	.125	1.8
6	18523	1290	.070	.097	1.4
7	18523	1290	.070	.087	1.2
8	18523	1290	.070	.072	1.0
9	18523	1272	.069	.057	.8
10	18523	1272	.069	.051	.7
11	18069	1272	.070	.029	.4
		AVG.	.068	.087	1.4

ZONE 2 $T_1 = 2.66$ sec

STORY	K	R	X_e	$X_{0.27}$	μ
1	34876	1576	0.045	0.158	3.5
2	18523	1576	.085	.138	1.6
3	18523	1576	.085	.114	1.3
4	18523	1536	.083	.088	1.0
5	18523	1536	.083	.098	1.2
6	18523	1536	.083	.083	1.0
7	18523	1536	.083	.081	1.0
8	18523	1416	.076	.083	1.1
9	18523	1349	.073	.065	.9
10	18523	1349	.073	.051	.7
11	18523	1272	.069	.028	.4
		AVG.	.076	.090	1.2

TABLE 2 (Continued)

DESIGN AND RESPONSE CHARACTERISTICS OF 11 STORY CMRF BUILDINGS

11 STORY CMRF

ZONE 3 T_1 = 2.05 sec.

STORY	K	R	X_e	$X_{0.27}$	μ
1	57761	2206	0.038	0.103	2.7
2	31272	2206	.071	.092	1.3
3	31272	2206	.071	.097	1.4
4	31272	2206	.071	.081	1.2
5	31272	2206	.071	.069	1.0
6	31272	2101	.067	.071	1.1
7	31272	1969	.063	.093	1.5
8	31272	1933	.062	.064	1.0
9	31272	1933	.062	.052	.8
10	31272	1827	.058	.038	.7
11	31272	1615	.052	.021	.4
		AVG.	.062	.071	1.2

ZONE 4 T_1 = 1.47 sec.

STORY	K	R	X_e	$X_{0.27}$	μ
1	110291	3187	0.029	0.063	2.2
2	60335	3187	.053	.062	1.2
3	60335	3187	.053	.053	1.0
4	60335	3187	.053	.052	1.0
5	60335	3037	.050	.058	1.2
6	60335	3037	.050	.054	1.1
7	60335	2693	.045	.070	1.6
8	60335	2508	.042	.055	1.4
9	60335	2508	.042	.037	.9
10	60335	2508	.042	.027	.7
11	60335	2399	.040	.015	.4
		AVG.	.045	.050	1.2

TABLE 3 (Continued)

DESIGN AND RESPONSE CHARACTERISTICS OF 11 STORY SMRF BUILDINGS

11 STORY SMRF

ZONE 3 T_1 = 2.40 sec.

STORY	K	R	X_e	$X_{0.21}$	μ
1	27646	596	0.022	0.075	3.5
2	16684	596	.036	.102	2.9
3	15934	596	.037	.092	2.5
4	15934	596	.037	.056	1.5
5	15004	590	.039	.056	1.4
6	15004	590	.039	.041	1.0
7	10806	360	.033	.120	3.6
8	8800	360	.041	.099	2.4
9	6920	220	.032	.193	6.1
10	6422	220	.034	.113	3.3
11	6422	220	.034	.048	1.4
		AVG.	.035	.090	2.7

ZONE 4 T_1 = 1.71 sec.

STORY	K	R	X_e	$X_{0.21}$	μ
1	59144	1174	0.020	0.037	1.9
2	38248	1174	.031	.036	1.2
3	36022	1174	.033	.034	1.0
4	36022	1174	.033	.034	1.0
5	28854	894	.031	.072	2.3
6	26350	894	.034	.055	1.6
7	20138	636	.032	.094	2.9
8	17532	636	.036	.059	1.6
9	11094	360	.032	.179	5.5
10	8686	360	.041	.113	2.7
11	8686	360	.041	.050	1.2
		AVG.	.033	.069	2.1

TABLE 3 (Continued)

DESIGN AND RESPONSE CHARACTERISTICS OF 11 STORY SMRF BUILDINGS

11 STORY SMRF

ZONE 3 T_1 = 2.40 sec.

STORY	K	R	X_e	$X_{0.21}$	μ
1	27646	596	0.022	0.075	3.5
2	16684	596	.036	.102	2.9
3	15934	596	.037	.092	2.5
4	15934	596	.037	.056	1.5
5	15004	590	.039	.056	1.4
6	15004	590	.039	.041	1.0
7	10806	360	.033	.120	3.6
8	8800	360	.041	.099	2.4
9	6920	220	.032	.193	6.1
10	6422	220	.034	.113	3.3
11	6422	220	.034	.048	1.4
		AVG.	.035	.090	2.7

ZONE 4 T_1 = 1.71 sec.

STORY	K	R	X_e	$X_{0.21}$	μ
1	59144	1174	0.020	0.037	1.9
2	38248	1174	.031	.036	1.2
3	36022	1174	.033	.034	1.0
4	36022	1174	.033	.034	1.0
5	28854	894	.031	.072	2.3
6	26350	894	.034	.055	1.6
7	20138	636	.032	.094	2.9
8	17532	636	.036	.059	1.6
9	11094	360	.032	.179	5.5
10	8686	360	.041	.113	2.7
11	8686	360	.041	.050	1.2
		AVG.	.033	.069	2.1

TABLE 4

SPECTRAL DISPLACEMENTS COMPUTED FROM VARIOUS APPROACHES

11 STORY CMRF	ZONE 0 & 1	ZONE 2	ZONE 3	ZONE 4
$S = \frac{N\ X_{max}}{\Gamma \cdot \phi_{1,N}}$	1.22'	1.38'	1.13'	0.61'
$S = \frac{X_T}{\Gamma \cdot \phi_{1,N}}$	0.66'	0.70'	0.44'	0.31'
S(NEWMARK)	0.70	0.70'	0.52'	0.38'
6 STORY CMRF				
$S = \frac{N\ X_{max}}{\Gamma \cdot \phi_{1,N}}$	1.18'	1.18'	1.31'	0.56'
$S = \frac{X_T}{\Gamma \cdot \phi_{1,N}}$	0.61'	0.62'	0.48'	
S(NEWMARK)	0.71	0.71'	0.52'	0.36'
11 STORY SMRF				
$S = \frac{N\ X_{max}}{\Gamma \cdot \phi_{1,N}}$	2.05'	1.33'	1.54'	1.22'
$S = \frac{X_T}{\Gamma \cdot \phi_{1,N}}$	0.51'	0.47'	0.49'	
S(NEWMARK)	0.71	0.71	0.69'	0.46'

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