An Investigation of Serviceability Requirements of the 1988 UBC Seismic Provisions

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ABSTRACT

The Uniform Building Code (UBC) serviceability requirements to control story drift and member forces for the ''moderate'' design earthquake are examined. It is shown from the UBC drift limits that the intensity of the UBC-implied moderate design earthquake for buildings taller than 65 ft. is only one-sixth that of the severe design earthquake. Recorded responses of one steel and one reinforced concrete building frames which were subjected to ground excitations with an intensity similar to the UBC moderate design earthquakes are studied. The results show that, for certain ductile building systems, the UBC one-phase design procedure cannot avoid excessive story drifts and structural yielding.

INTRODUCTION

Modern building seismic design provisions generally require that a well designed building should be able to (i) resist minor earthquakes without damage, (ii) resist moderate earthquakes without structural damage, but probably experience some nonstructural damage, and (iii) resist major earthquakes without collapse (6). The 1988 UBC (9) seismic design provisions focus mainly on the third criterion, which is commonly referred to as the ultimate limit state. The first two criteria can be referred to as the serviceability limit state — a limit state which is overlooked in the UBC. While the ultimate limit state deals with the life-safety considerations for severe earthquakes, the serviceability limit state attempts to reduce economic losses by minimizing nonstructural damage and by avoiding structural yielding in moderate earthquakes.

For design purposes UBC specifies an elastic design spectrum (C_{eu}) for the severe design earthquake. The design base shear ratio (C_w) for working stress design is computed as follows (see Fig. 1):

$$C_w = \frac{C_{eu}}{R_w} \tag{1}$$

where R_w = system performance factor. Since the R_w factor is a force reduction factor to account for structural ductility, structural overstrength, and the difference between the working stress and strength design formats (7), the C_w spectrum in Fig. 1 represents the *inelastic* design spectrum for the severe design earthquake. Note that the level of the C_w spectrum varies with the R_w factor. To consider the serviceability limit state, it is necessary to know the elastic design spectrum (C_{es}) for the moderate design earthquake. In this study it is assumed that the levels between the severe and moderate design earthquakes differ by a factor R_{ser}

$$C_{es} = \frac{C_{eu}}{R_{ser}} \tag{2}$$

Fig. 1 shows the C_{eu}, C_{es}, and C_w spectra. Note that the C_w spectrum is the inelastic design spectrum for the severe design earthquake, while the C_{es} spectrum is the *elastic* design spectrum for the moderate design earthquake.

To determine the R_{ser} value implied by UBC, it is necessary to consider the UBC drift limits. For buildings with an R_w value greater than 7.5 and a height taller than 65 ft., UBC requires that the design story drifts ratio not exceed $0.03/R_w$ (see point A in Fig. 2). Accepting a limit of story drift ratio equal to 0.005 in order to control nonstructural damage, the ordinate of point B in Fig. 2 can be determined by proportions

$$R_{ser} = \frac{0.03/R_w}{0.005} R_w = 6 \tag{3}$$

Since UBC uses an effective peak acceleration (EPA) equal to 0.4 g in high seismic regions, Eq. 3 implies that the EPA for the UBC moderate design earthquake is about 0.07 g — a level of excitations which has been experienced by many buildings in the Bay Area during the Loma Prieta earthquake.

For steel design the allowable stress for seismic load combinations is equal to $0.88F_y$ (= $0.66\ F_y \times$ 4/3). The UBC-implied allowable stress, $F_a^{(es)}$, for the moderate design earthquake can be computed by proportions (see Fig. 2)

$$\frac{F_a^{(es)}}{0.88F_y} = \frac{C_{es}}{C_w} = \frac{C_{eu}/R_{ser}}{C_{eu}/R_w} = \frac{R_w}{R_{ser}} \tag{4}$$

that is,

$$F_a^{(es)} = \frac{R_w}{R_{ser}} \times 0.88F_y = \frac{R_w}{6} \times 0.88F_y \tag{5}$$

The above equation shows that the UBC-implied allowable stress at the moderate design earthquake level is excessive for ductile frame systems. For example, $F_a^{(es)}$ is equal to $1.76F_y$ for $R_w = 12$. When the gravity load effects are considered, a general expression for $F_a^{(es)}$ can be derived (8). Gravity load effects can reduce but cannot eliminate member overstress in moderate earthquakes.

OBJECTIVE AND SCOPE

The main objective of this research is to study the serviceability performance (i.e., control of story drift and member forces) of multistory buildings. Two buildings (CSMIP Station Nos. 57355 and 57357) have been selected for this study because the recorded base motions of these buildings have an intensity similar to that of the UBC-implied moderate design earthquake.

METHOD OF ANALYSIS

For each building it is necessary to compute member forces and story drift ratios. Since only a limited number of floors were instrumented to measure the lateral motions, and no member force measurements were made by CDMG (2), a static analysis procedure using the computer program ETABS (4) has been developed. For each building the analysis procedure involves the following steps.

1. Establish a 3-dimensional finite element model based on the design drawings.
2. Estimate dead loads and realistic live loads.
3. Based on the analytical mode shapes and the relative displacements of the instrumented floors, compute the relative displacements of the other uninstrumented floors. Fig. 3 shows schematically the procedure for a 10-story building which is instrumented at the fifth floor and roof.
4. Perform structural analyses at peak responses by applying the gravity loads and by imposing the relative displacements obtained from step 3 to the model. Detailed structural responses are thus obtained.

SUMMARY OF RESULTS

CSMIP Station No. 57357 — This is a 13-story office building located in San Jose (see Fig. 4b). It was designed in 1972. The lateral force resisting system is a steel moment-resisting space frame. The fundamental periods predicted by the 1988 UBC empirical formula is 1.77 sec. The reactive weight of the building is estimated to be 25,200 kips. The building is founded on alluvial soil with a mat foundation. The 1988 UBC design base shear ratio is 0.043 for R_w = 12. A review of the design based on the 1988 UBC (see Fig. 5a) indicates that the maximum story drift ratio is 90% of the UBC limit (= $0.03/R_w$ = 0.025), and the member stress ratios are low (≈ 0.4).

Table 1 shows the natural periods computed from the responses recorded during the 1984 Morgan Hill earthquake (3) and the 1989 Loma Prieta earthquake. The elongation of the natural period is insignificant (less than 10%), which is typical for steel structures.

The EPA of the base horizontal motion is 0.08 g. The ETABS analysis shows that the maximum story drift ratio is 1.28% (see Fig. 5b). Fig. 5b shows that the stress ratio produced by the Loma Prieta earthquake can be as high as 2.1 if the structure were to respond elastically. Apparently this type of building does not satisfy the serviceability requirements to minimize nonstructural component damage and to avoid significant member yielding even under minor to moderate earthquake excitations.

CSMIP Station No. 57355 — The building was designed in 1964 and constructed in 1967 (Fig. 4a). This reinforced concrete office building consists of 10 stories above grade and one story below the ground level. The lateral force resisting system consists of two end reinforced concrete shear walls and six interior frames in the E-W direction, and four frames in the N-S direction. The building is founded on alluvial soil with a mat foundation. The reactive weight of the building is estimated to be 24,500 kips. The R_w value in the N-S (moment frame) direction could be taken as either 12, 7, or 5, depending on the ductility (or detailing) provided. Except for the UBC detailing requirements, this building satisfy the UBC strength and stiffness requirements for an R_w value equal to 12.

The stress ratios of the structural elements (see Fig. 6) show that the beams control the design and the columns are under-stressed. The gravity load effect is significant on these beams. The design story drift ratios produced by the 1988 UBC design seismic forces are much smaller than the UBC limits.

A comparison of the measured periods (see Table 1) during the 1984 Morgan Hill earthquake (5), and the 1989 Loma Prieta earthquake shows some elongation of fundamental periods in the longitudinal and transverse directions. The elongation of the periods suggests a loss of stiffness of about 23% in the E-W direction and 40% in the N-S direction. Considering that the rocking motion is significant in the E-W direction during the Morgan Hill earthquake (1), the N-S direction was judged to be critical in resisting ground excitations.

Because of the large lateral stiffness, which is a characteristic of reinforced concrete buildings in general, the maximum story drift ratio (= 0.17%) during the Loma Prieta earthquake did not exceed the serviceability limit of 0.5%.

The member forces obtained at the peak responses of the building show that a number of beams have exceeded the yield moment, which is defined by the initial yielding of the longitudinal reinforcements. The ratios between the actual member forces produced by the earthquake and the UBC required strength have reached 1.05 in the beams and 1.7 in the columns (Fig. 6). Significant structural yielding might have occurred had these members been proportioned to just satisfy the UBC strength requirement.

CONCLUSIONS

The Uniform Building Code seismic design procedure does not address the serviceability limit state explicitly. Therefore a building structure which satisfy the UBC might experience significant nonstructural and structural damages. The serviceability problem is more pronounced for ductile frames with less gravity loads. A simple analytical study shows that the intensity of the UBC-implied moderate design earthquake for buildings taller than 65 ft. is only one-sixth that of the severe design earthquake. For ductile frame systems the member forces may exceed member capacity significantly if the structure were to respond elastically. This is confirmed by the study of a 13-story steel frame; the actual stress ratio may be as high as 2.1, and the maximum story drift ratio is 1.28%. Because of the large lateral stiffness, the serviceability performance tends to be satisfactory for the type of reinforced concrete structures studied.

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Building	Direction	Morgan Hill	Loma Prieta	Model
CSMIP-57355	N-S	0.91 (5)	1.08	1.08
	E-W	0.64	0.71	0.70
	torsion	0.39	0.47	0.37
CSMIP-57357	N-S	2.1 (3)	2.28	2.01
	E-W	2.2	2.24	2.17
	torsion	1.7	1.75	1.62

Table 1 Comparison of Natural Periods

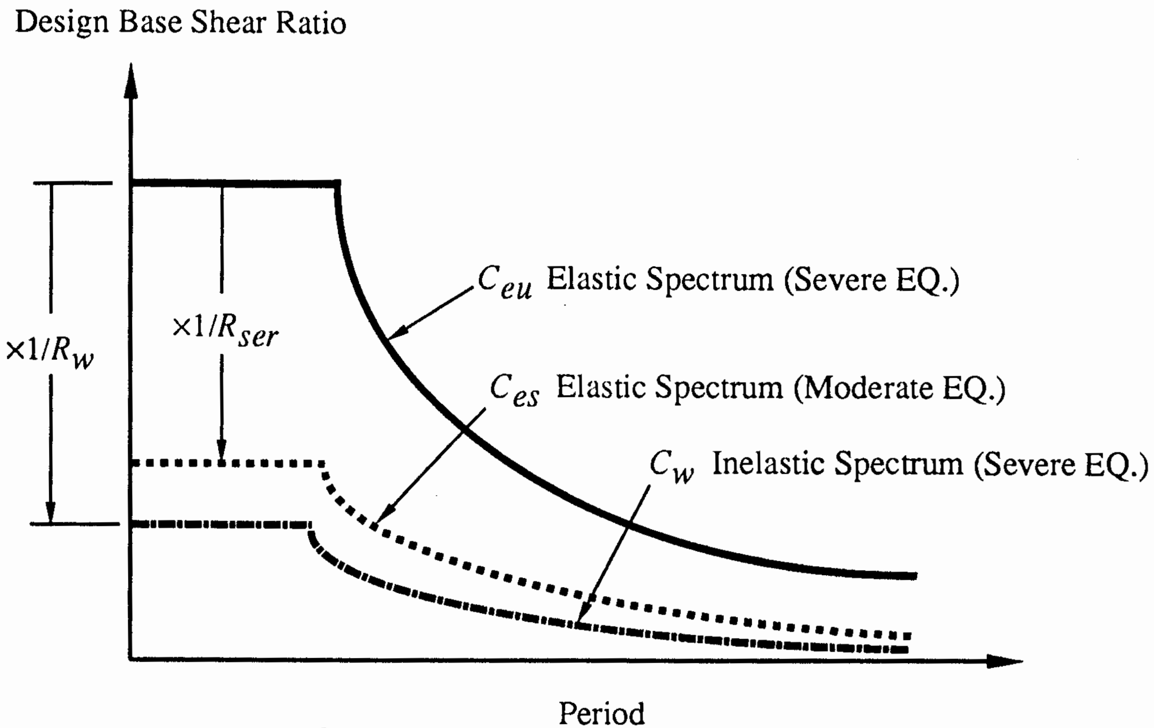


Fig. 1 Comparison of Design Spectra for Different Limit States

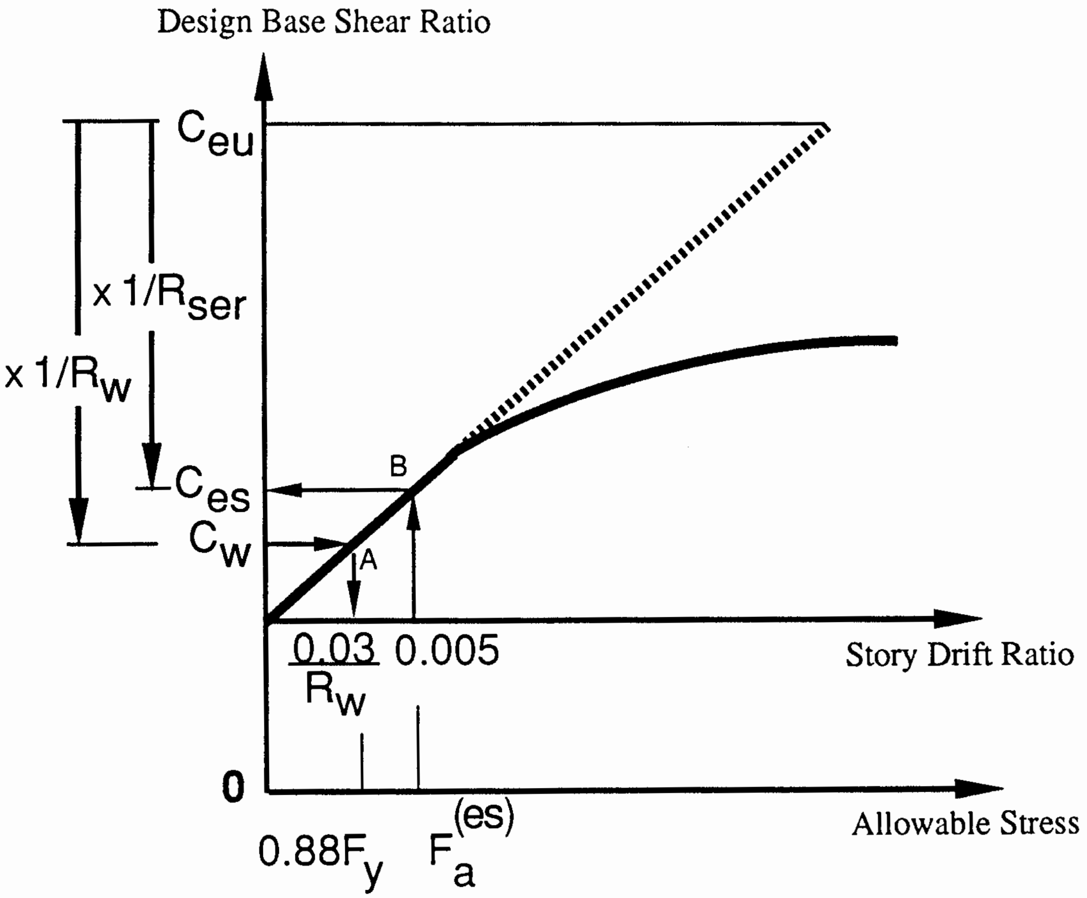


Fig. 2 Relationship between UBC Inelastic Design Force Level and Moderate Earthquake Design Force Level

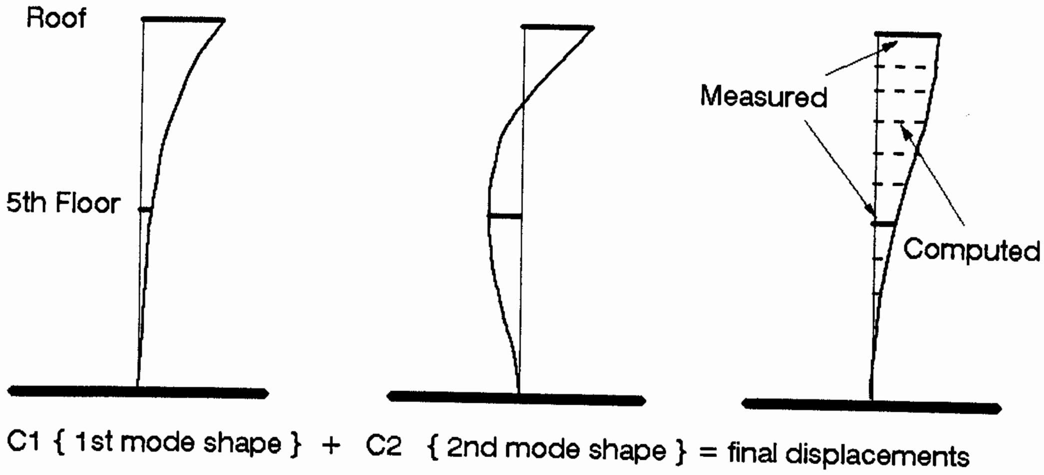
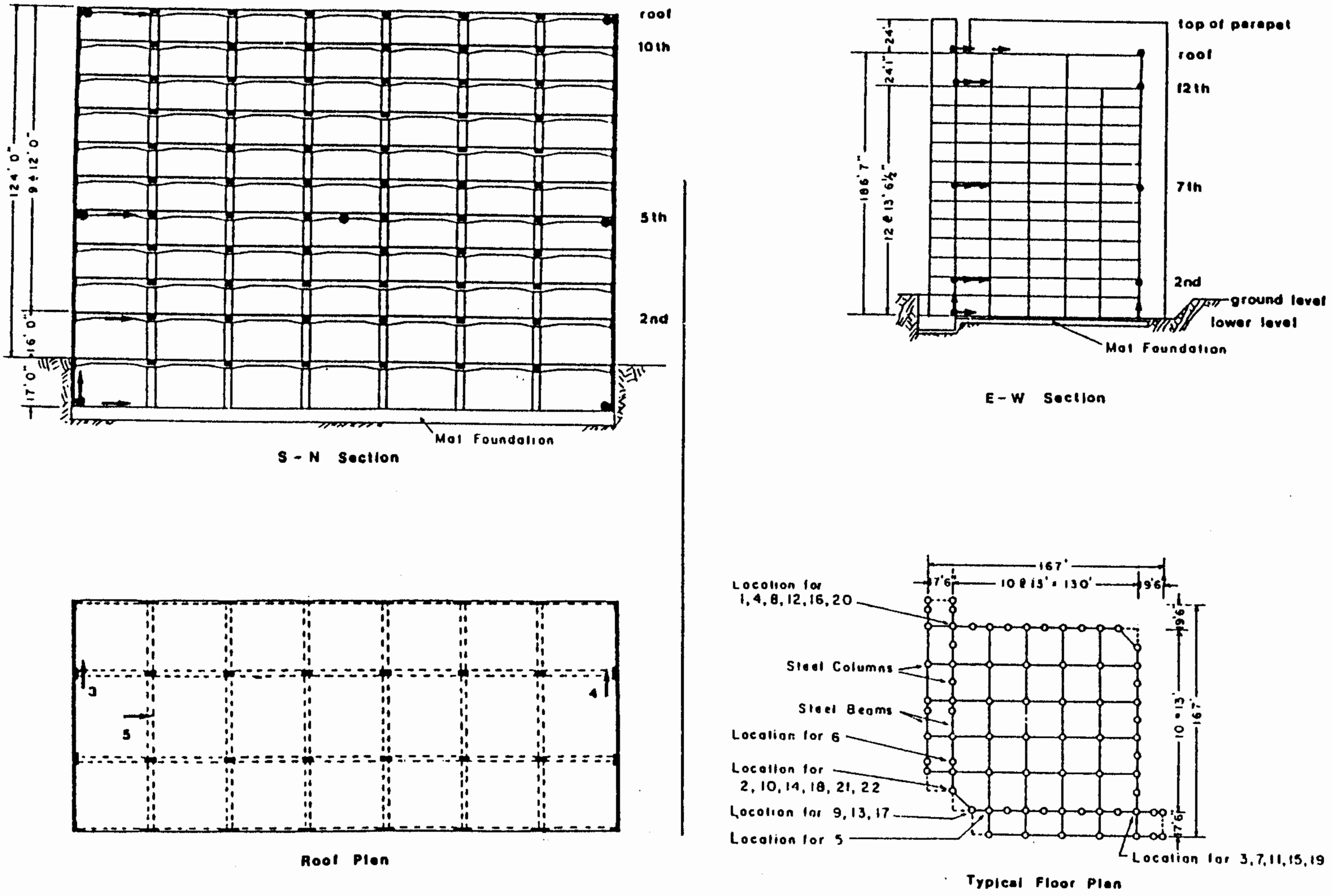


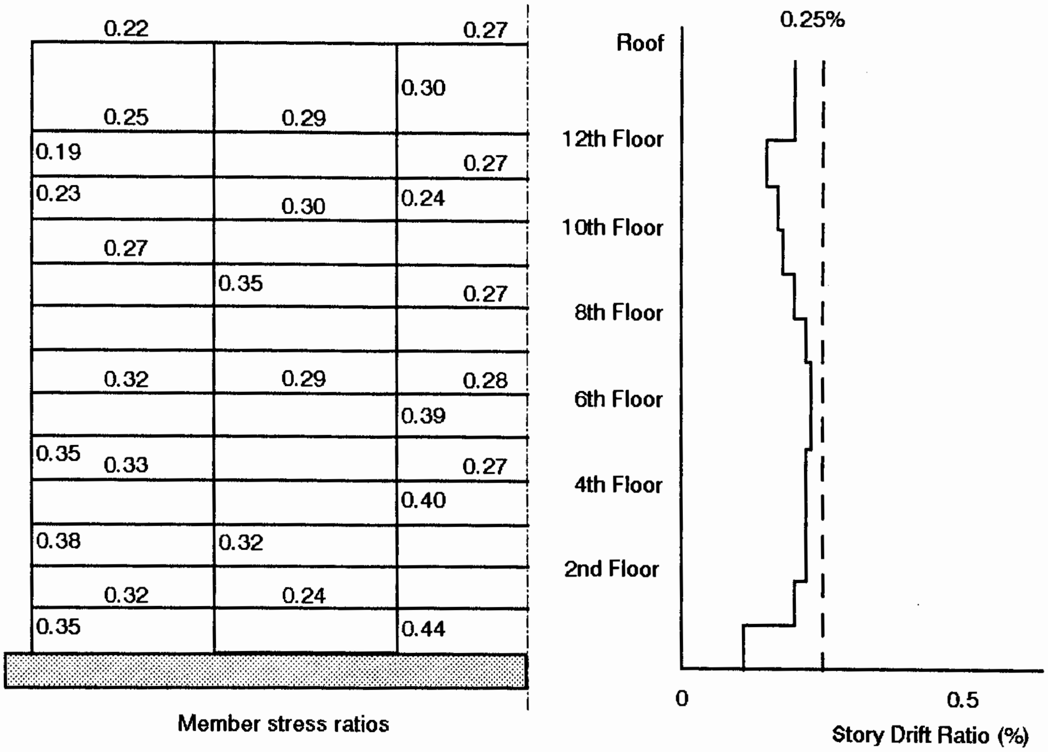
Fig. 3 Procedure to Compute Relative Displacements



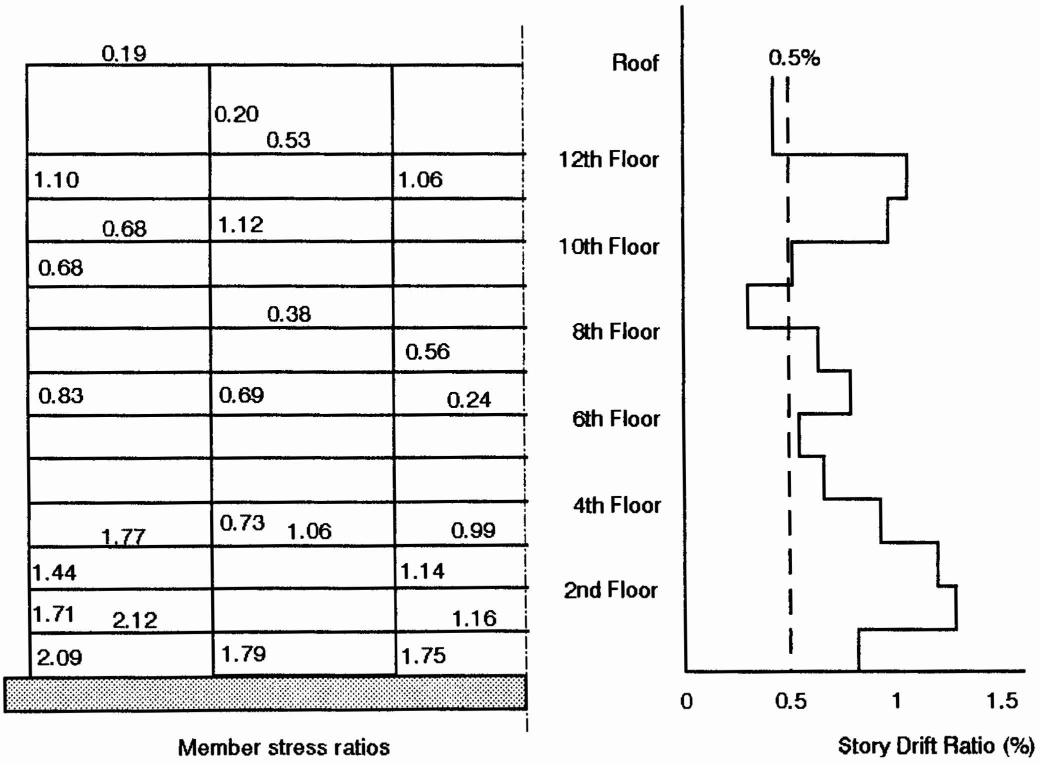
a- CSMIP355

b- CSMIP357

Fig. 4 Plan and Elevations of Buildings



(a) 1988 UBC Design



(b) 1989 Loma Prieta Earthquake

Fig. 5 Member Stress Ratios and Story Drift Ratios (CSMIP No. 57357)

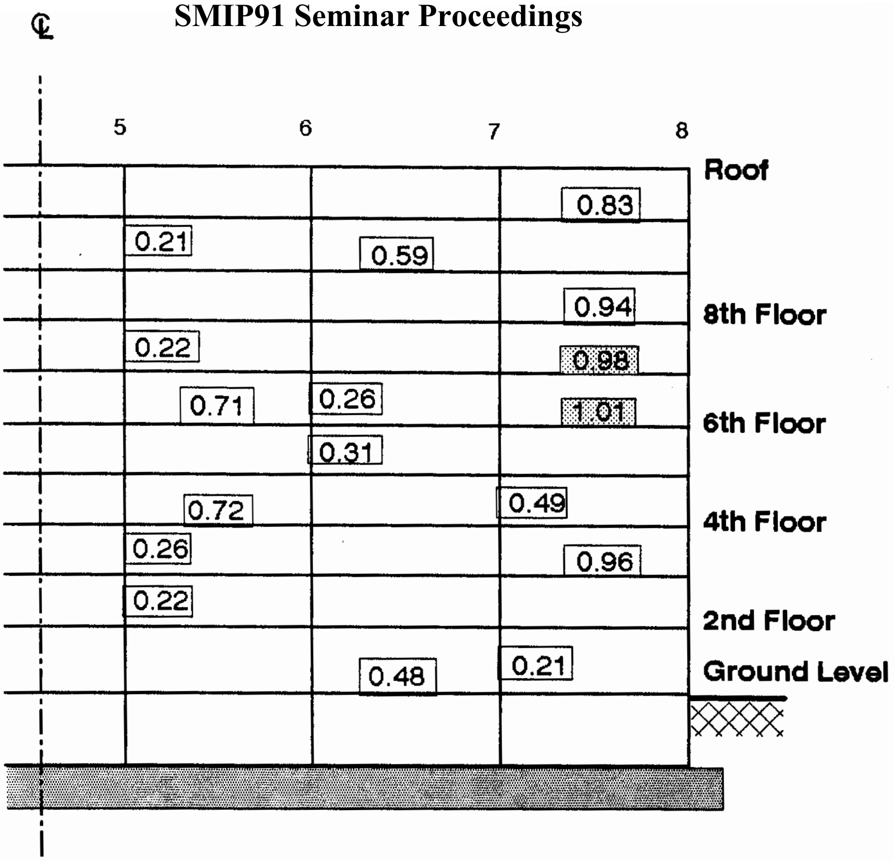


Fig. 6 Member Stress Ratios for 1988 UBC Design (CSMIP No. 57355)

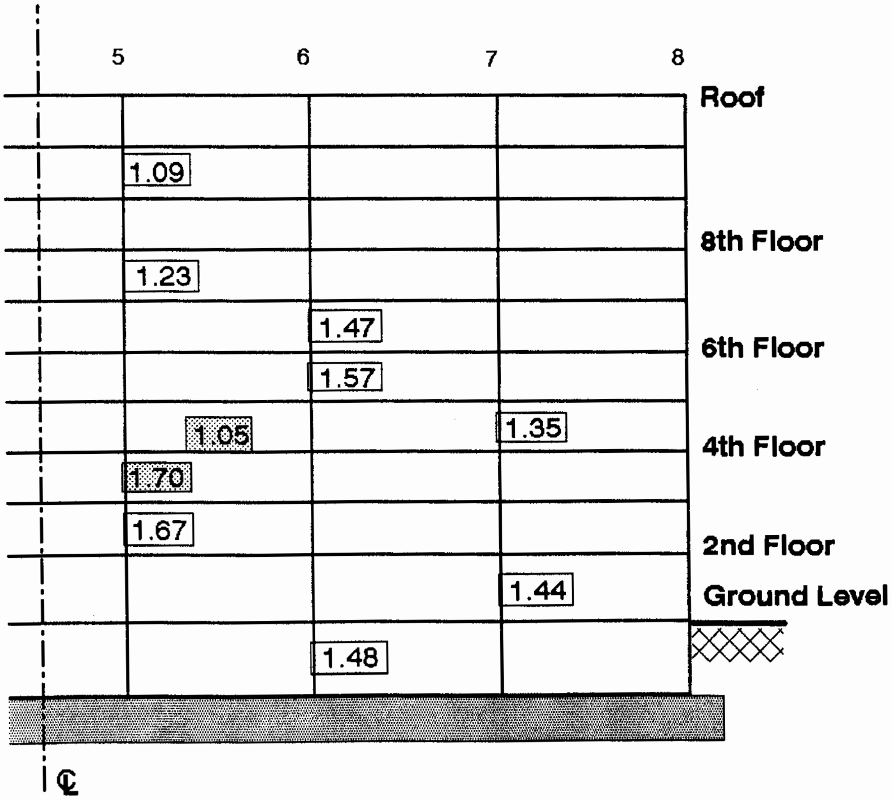


Fig. 7 Ratios between Member Forces Produced by Loma Prieta Earthquake and UBC Design Seismic Forces (CSMIP No. 57355)