Investigating the Effect of Inelastic Behavior on Seismic Design lateral Force Distribution of Steel Moment Frames

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SUMMARY:
In recent earthquakes, most of the observed collapses have been related to inappropriate distributions of strength and stiffness of structural elements. Since most building structures designed according to current code procedures are expected to undergo large deformations in the inelastic range when subjected to major earthquakes, lateral force distributions can be quite different from those given by the code formulas. In this paper, design lateral force distribution of the SAC-3, -9 and -20 located in Los Angeles, has been investigated using dynamic time-history analyses results. The maximum story shear at each level, under ground motion records at 10% and 2% probability of exceedance in 50 years, obtained from nonlinear time history dynamic analyses, and compared with the code lateral load pattern. It is concluded that code lateral force distribution does not able to accurately predict deformation and force demands that may be induced during nonlinear phase; causing structures to behave in a rather unpredictable and undesirable manner.

Keywords: Steel moment frame, Inelastic behavior, Lateral force distribution

1. INSTRUCTION

Since most building structures designed according to current code procedures are expected to undergo large deformations in the inelastic range when subjected to major earthquakes, lateral force distributions can be quite different from those given by the code formulas. This is due to current seismic design approach which is generally based on elastic analysis and considered inelastic behavior in an indirect manner (Goel et al., 2010). For example, according to International Building Code (IBC, 2006) provisions, after selecting the member sizes for required strengths, as obtained from elastic analysis, effect of inelastic behavior is considered by multiplying the calculated drift at design force by a deflection amplification factor and limiting that to specified value.

In recent earthquakes, most of the observed collapses have been related to inappropriate distributions of strength and stiffness of structural elements. The seismic codes are generally considering the seismic effects as lateral inertia forces according to the force-based approach that was inception in the early 1900s and has not changed significantly yet (Hajirasouliha and Moghaddam, 2009). The height wise distribution of these static forces and therefore, stiffness and strength seems to be based implicitly on the elastic vibration modes (Green, 1981) and (Hart, 2000). As structures exceed their elastic limits in severe earthquakes, the use of inertia forces corresponding to elastic modes may not lead to the optimum distribution of structural properties; consequently, the structure does not response in a desirable and predictable manner.

One of the essential elements of performance-based seismic design of structures should be to use more realistic design lateral force distribution, which represents peak lateral force distribution in a structure in the inelastic state and includes the higher mode effects (Chao et al., 2007). In this paper, shear forces that induced from earthquake excitation and the forces determined by code patterns is investigated for 3-, 9- and 20-story steel moment resistant frames (located in Los Angeles) that was the subject of an extensive analytical study as part of the SAC steel research program (Gupta, 1999) based on nonlinear dynamic time history analyses results.

2. LATERAL LOADING PATTERNS

In most seismic building codes, lateral-load resisting systems for regular structures may be designed based on the Equivalent Lateral Force (ELF) procedure (UBC 1997; NEHRP 2003; IBC 2006). A principal component of the ELF procedure is the utilization of design lateral load patterns to determine the strength and the stiffness characteristics of the structure. These code-compliant design lateral load patterns were established based on the dynamic behavior of elastic structural systems. Thus, the design lateral load patterns of the ELF procedure do not explicitly account for the inelastic response of the structural system. If the structure is expected to experience significant levels of inelastic behavior, code-compliant lateral load distributions may not provide an accurate representation of the story shear demands imposed on the structural system. Therefore, this design approach is especially suitable for relatively small but frequent earthquakes to limit damage to acceptable levels once the system experiences relatively small levels of inelastic behavior. However, when structures are exposed to severe ground shaking, structural elements may be prone to yielding, and consequently, experience significant levels of inelastic behavior.

The current lateral seismic-force distributions in building codes are generally based on first-mode dynamic solution of lumped multiple-degree-of-freedom elastic systems, which can be determined from following typical relationship:

$$\frac{w_i h_i^k}{\sum_{j=1}^{n} w_j h_j^k} V \tag{1.1}$$

Where w_i and h_i are the weight and height of the ith floor above the base, respectively; n is the number of stories; and k is an exponent related to the effective fundamental period of the structure that differs from one seismic code to another.

According to NEHRP 2003 provisions, k = 1 for structures having a period of 0.5 s. or less, k = 2 for structures having a period of 2.5 s. or more and k is determined by linear interpolation between 1 and 2 for structures having a period between 0.5 and 2.5 s. When k is equal to 1, this lateral force pattern corresponds to an inverted triangular lateral load distribution and the response of the building is assumed to be controlled primarily by the first mode. While k = 2, it corresponds to a parabolic lateral load distribution and the response is assumed to be influenced by higher mode effects. The distribution of seismic lateral forces based on the IBC 2006 is identical to that obtained following the NEHRP 2003 provisions.

The lateral load pattern for UBC 1997 is quite different from NEHRP 2003 and IBC 2006 because of the concentrated load at the top floor. The force at the top floor computed from Eqn. 1.1. is increased by adding an additional force Ft=0.07TV for a fundamental period T of greater than 0.7 s. In such a case, the base shear V in Eqn. 1.1. is replaced by (V−Ft).

3. MODELING AND ASUMPTIONS

SAC buildings are the perimeter steel moment resistant frame (SMRF) buildings designed by consulting structural engineers as part of the SAC project. These structures are compliant with provisions of the UBC 1994 for the Los Angeles, California region. In this paper, The SAC-3, -9 and -20 (M1 post-Northridge model) are modelled as 2-dimensional frame that represent half of the structure in the north-south direction. The effects of top and bottom plate are considered in modelling of girders. The frame is given half the seismic mass of the structure at each floor level and the effects of the gravity loads are neglected in the analysis. However, the effect of geometric nonlinearity (P-Δ) is considered in analysis.

In order to investigate the effects of inelastic behavior of structure on accuracy of code lateral load pattern in predicting the strength distribution along the height, nonlinear time-history (NTH) analysis were conducted at two seismic hazard levels. A total of 40 SAC Los Angeles–region ground motions records (Somerville et al. 1997; twenty at 10% and twenty at 2% probability of exceedance in 50 years) were used to obtain the maximum story shear at each level as a benchmark values. The characteristics of the selected SAC ground motions are given in Table 3.1. and 3.2.

Analyses were carried out by using the OpenSees software. Modelling of steel material is based on "Steel02" in material library of the software which have a bilinear stress-strain relationship with 3% stiffness hardening.

Table 3.1. Characteristics of ground motions used in this study (10% in 50 years)

SAC Name	Record	Earthquake Magnitude	Distance (km)	PGA (cm/sec^2)
LA01	Imperial Valley, 1940, El Centro	6.9	10	452.03
LA02	Imperial Valley, 1940, El Centro	6.9	10	662.88
LA03	Imperial Valley, 1979, Array #05	6.5	4.1	386.04
LA04	Imperial Valley, 1979, Array #05	6.5	4.1	478.65
LA05	Imperial Valley, 1979, Array #06	6.5	1.2	295.69
LA06	Imperial Valley, 1979, Array #06	6.5	1.2	230.08
LA07	Landers, 1992, Barstow	7.3	36	412.98
LA08	Landers, 1992, Barstow	7.3	36	417.49
LA09	Landers, 1992, Yermo	7.3	25	509.7
LA10	Landers, 1992, Yermo	7.3	25	353.35
LA11	Loma Prieta, 1989, Gilroy	7	12	652.49
LA12	Loma Prieta, 1989, Gilroy	7	12	950.93
LA13	Northridge, 1994, Newhall	6.7	6.7	664.93
LA14	Northridge, 1994, Newhall	6.7	6.7	644.49
LA15	Northridge, 1994, Rinaldi RS	6.7	7.5	523.3
LA16	Northridge, 1994, Rinaldi RS	6.7	7.5	568.58
LA17	Northridge, 1994, Sylmar	6.7	6.4	558.43
LA18	Northridge, 1994, Sylmar	6.7	6.4	801.44
LA19	North Palm Springs, 1986	6	6.7	999.43
LA20	North Palm Springs, 1986	6	6.7	967.61

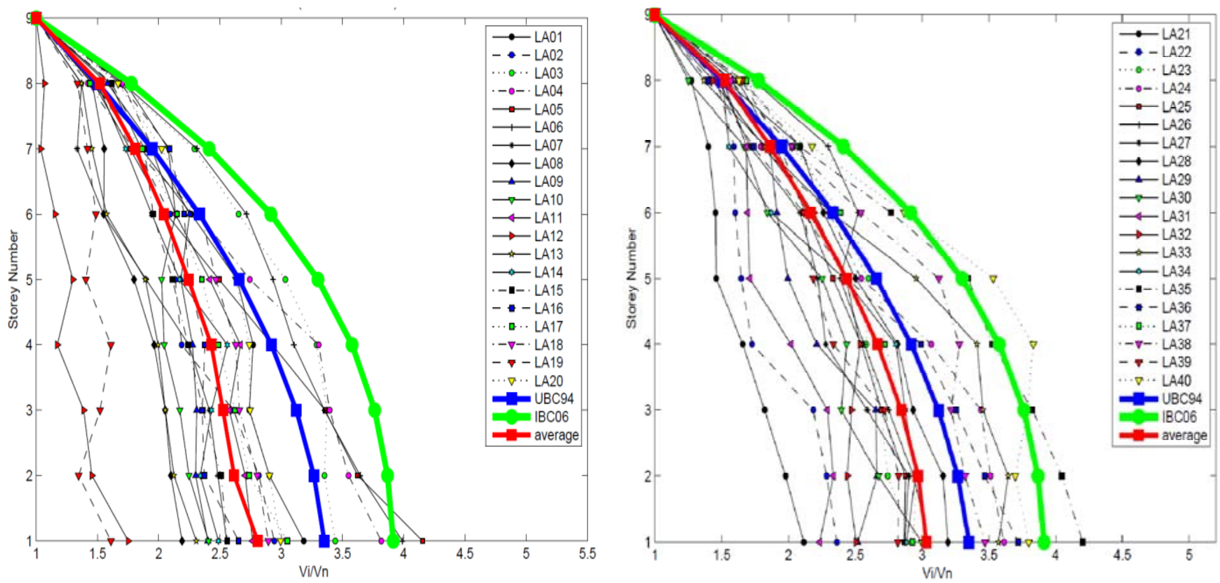
Table 3.2. Characteristics of ground motions used in this study (2% in 50 years)

SAC Name	Record	Earthquake Magnitude	Distance (km)	PGA (cm/sec2)
LA21	1995 Kobe	6.9	3.4	1258
LA22	1995 Kobe	6.9	3.4	902.75
LA23	1989 Loma Prieta	7	3.5	409.95
LA24	1989 Loma Prieta	7	3.5	463.76
LA25	1994 Northridge	6.7	7.5	851.62
LA26	1994 Northridge	6.7	7.5	925.29
LA27	1994 Northridge	6.7	6.4	908.7
LA28	1994 Northridge	6.7	6.4	1304.1
LA29	1974 Tabas	7.4	1.2	793.45
LA30	1974 Tabas	7.4	1.2	972.58
LA31	Elysian Park (simulated)	7.1	17.5	1271.2
LA32	Elysian Park (simulated)	7.1	17.5	1163.5
LA33	Elysian Park (simulated)	7.1	10.7	767.26
LA34	Elysian Park (simulated)	7.1	10.7	667.59
LA35	Elysian Park (simulated)	7.1	11.2	973.16
LA36	Elysian Park (simulated)	7.1	11.2	1079.3
LA37	Palos Verdes (simulated)	7.1	1.5	697.84
LA38	Palos Verdes (simulated)	7.1	1.5	761.31
LA39	Palos Verdes (simulated)	7.1	1.5	490.58
LA40	Palos Verdes (simulated)	7.1	1.5	613.28

4. ANALYTICAL RESULTS

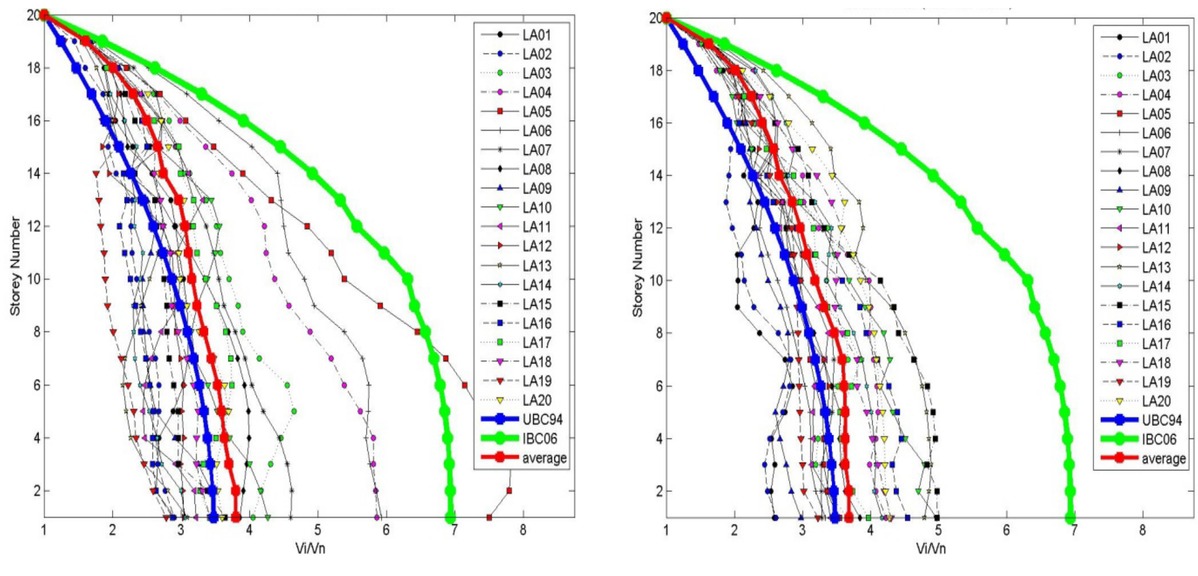
As described in previews section, the peak story shear resulting from NTH analysis is considered as benchmark responses. In order to convenience in comparing the results of nonlinear analysis with different seismic hazard levels, a dimensionless parameter called "relative story shear" is used in this study (Chao, 2007). Relative story shear is defined as the ratio of maximum story shear force at level i to that at top level n; i.e. Vi/Vn.

Relative story shear distributions diagrams are presented for SAC-9 and -20 structures under DBE and MCE earthquake in Figure 4.1. and 4.2. respectively. As can be seen in these figures, IBC lateral force distribution considerably differs from NTH analysis results. According to IBC load pattern, design story shear forces at upper levels are much smaller than those given by nonlinear dynamic analysis. This lead to inappropriate distribution of strength in upper level and generally resulted in smaller member sizes and therefore larger story drifts at those levels.



(a) (b)

Figure 4.1. Relative story shear distributions from nonlinear dynamic analyses and code formulas for SAC-9; (a) Under DBE level excitations; (b) Under MCE level excitations



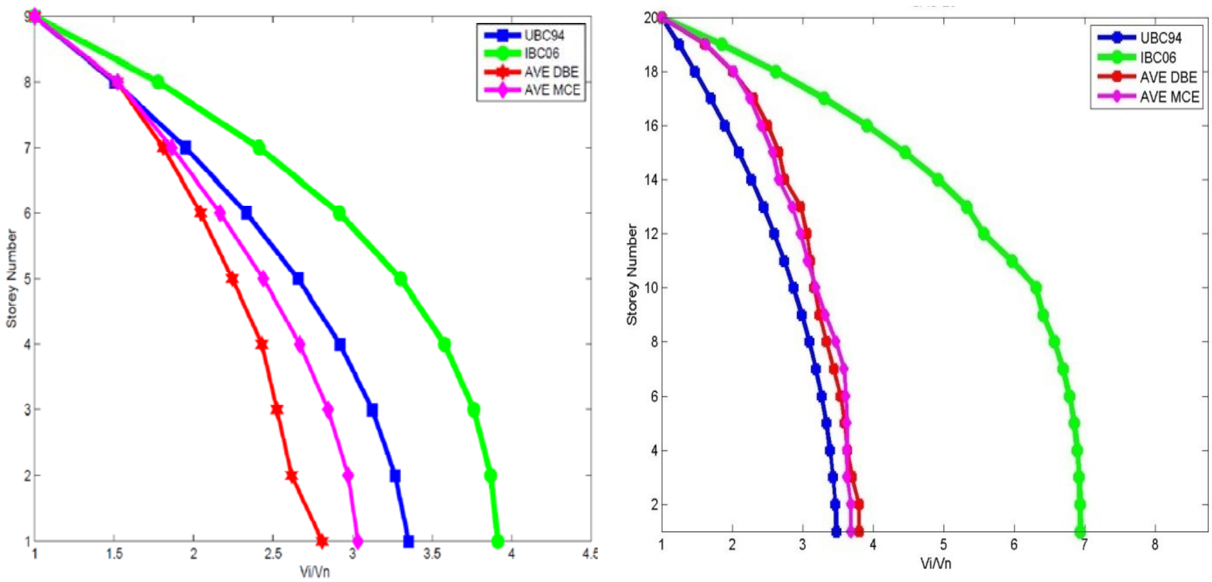
(a) (b)

Figure 4.2. Relative story shear distributions from nonlinear dynamic analyses and code formulas for SAC-20; (a) Under DBE level excitations; (b) Under MCE level excitations

In contrast to IBC lateral load distribution pattern analytical results showed that, by applying an additional lateral force at top level, the UBC equation gives better prediction than the IBC equation. However UBC equation is underestimating in compare with average results of NTH analysis. Based on some researcher's opinion, the reason that the IBC does not include the additional top force can be attributed to the concern that an underestimation of story shears in the lower stories might be more risky than those in the top stories. This is interesting to note that, despite of SAC-9, for the SAC-20 structure by increasing in seismic hazard level, shear forces at upper levels is not decreased (Figure

4.3). This is due to concentration of inelastic deformation at the lower levels which caused by soft story mechanism under both DBE and MCE levels.

To investigate the effect of inelastic behavior of structure on distribution of seismic loading along the height, the ratio of lateral force at level i to the base shear (F_i/V_b) is determined for average results of NTH analysis with DBE and MCE levels. This ratio is representing the lateral load pattern as shown in figure 4.4. to 4.6. for SAC-3, -9 and -20 respectively.



(a) (b)

Figure 4.3. Relative story shear distributions from nonlinear dynamic analyses and code formulas under DBE and MCE level excitations; (a) SAC-9; (b) SAC-20

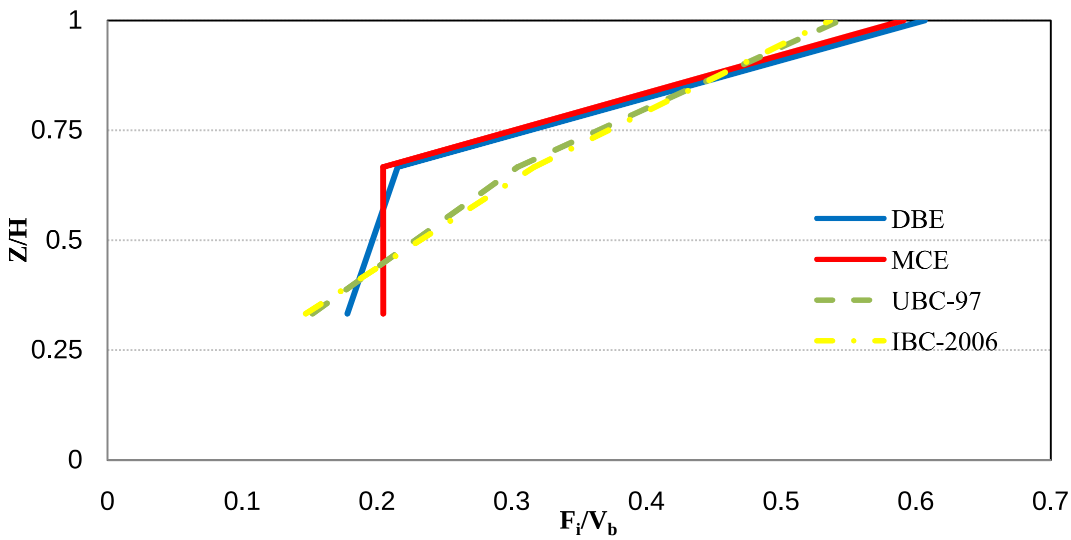


Figure 4.4. Seismic lateral load pattern of SAC-3 based on NTH analysis and code formulas

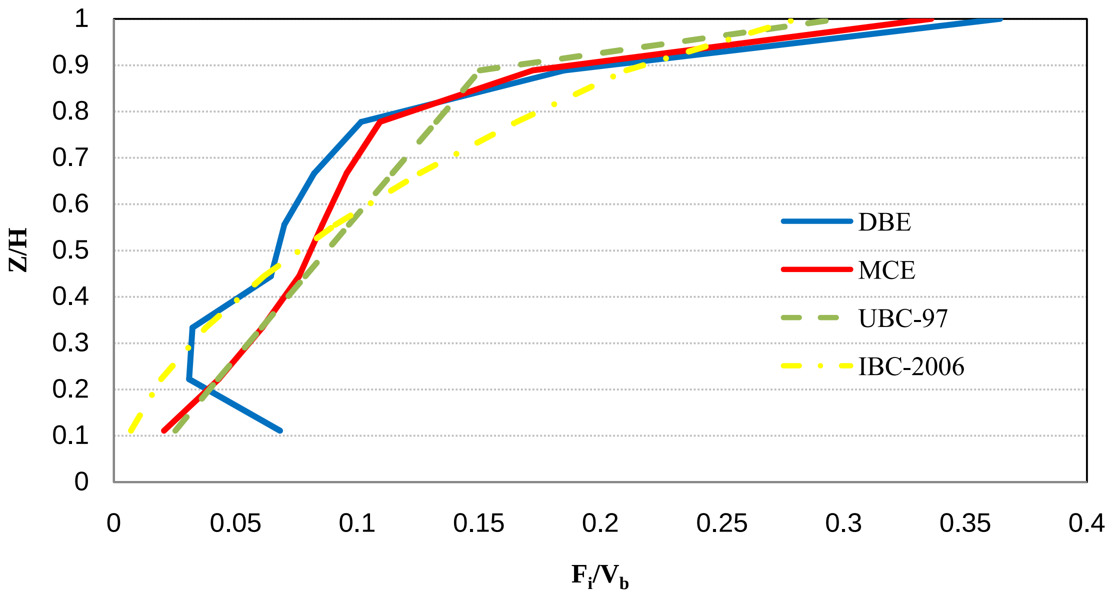


Figure 4.5. Seismic lateral load pattern of SAC-9 based on NTH analysis and code formulas

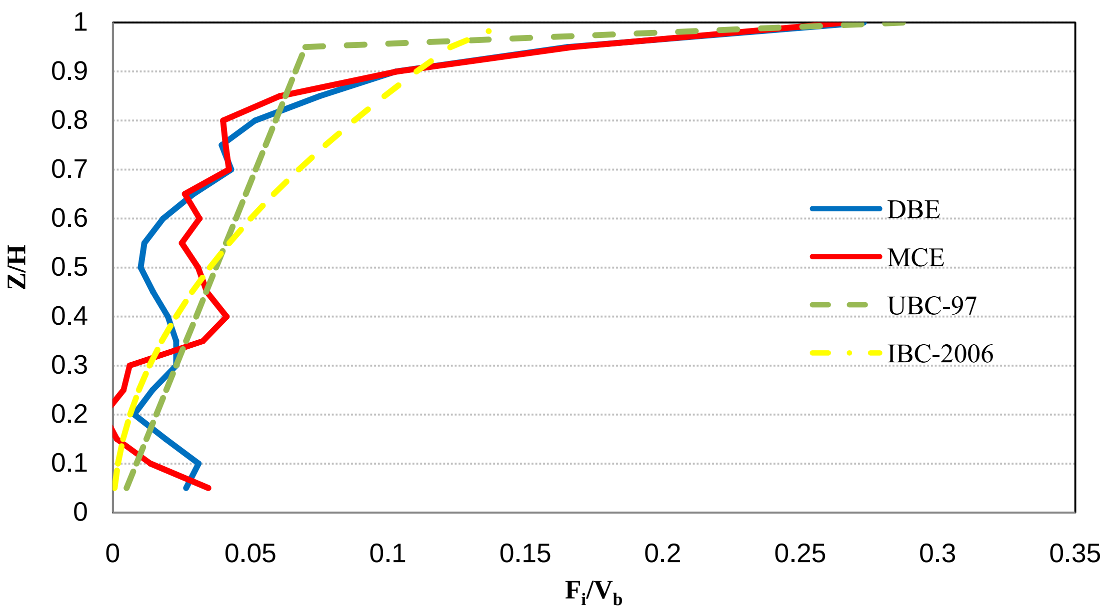


Figure 4.6. Seismic lateral load pattern of SAC-20 based on NTH analysis and code formulas

As represented in above figures, from base to approximately 0.4H, IBC equation is underestimating in compare with average results of NTH analysis, specially for tall buildings under MCE level excitation. From 0.4H to 0.9H, IBC equation is far overestimating in compare with average results of NTH analysis. While above this range, UBC equation with additional lateral force at top level, gives better prediction than the IBC equation.

5. CONCLUSION

This paper present a study aimed at evaluating the accuracy of code design lateral force distribution considering inelastic behavior of structures when subjected to major earthquake. The SAC-3, -9 and -20 structures is investigated by conducting nonlinear time history analysis with SAC ground motions prepared for Los Angeles region at two level of seismicity. Analytical results showed that, maximum story shear distributions as given in the codes, which are based on first-mode elastic behavior, deviate significantly from the time-history dynamic analysis results regardless of whether the structures respond in the elastic or inelastic range.

Design story shear forces that predicted by IBC load pattern are smaller than those given by nonlinear dynamic analysis at upper levels. Although the UBC equation gives better prediction than the IBC equation, this is not accurate enough to predict benchmark responses. Use of a realistic force distribution based on inelastic response is one of the essential elements of performance-based seismic design if accurate representation of expected structural response is to be realized.

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