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OPTIMAL BRACING SCHEMES FOR STRUCTURAL SYSTEMS SUBJECT TO THE ATC-3-06, UBC, AND BOCA SEISMIC PROVISIONS

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SUMMARY

An optimality criterion approach is used as a consistent means for comparing the effectiveness of braced frames subject to the ATC-3-06, UBC and BOCA seismic provisions. The major points of interest are that the BOCA provisions are not consistent with the UBC and ATC provisions, ATC-3-06 modal analysis provisions provide lighter structures, K-bracing is the most efficient bracing system, and rigid frames are the least efficient systems.

INTRODUCTION

Structural designers are continually challenged to find the most cost effective means of providing a seismically safe structural system. In order to have an accurate means for comparing design alternatives, the designer needs a design methodology which will provide consistency. Nonlinear optimization procedures are an ideal tool for controlling the critical parameters such as drift, displacement, frequencies, stresses, and code provisions while providing a structure with the optimal weight or cost (Refs. 1,2).

An optimality criteria algorithm initiated by Cheng and Truman which included the ATC-03-06 provisions has been modified to include the BOCA and UBC seismic provisions (Refs. 3,4,5). Therefore, providing a consistent means for comparing the BOCA, UBC, and ATC-3-06 for different structural configurations.

SEISMIC CODES

In general, the three codes, BOCA, UBC, and ATC-3-06, provide formulae for finding a total base shear and a means for distributing this force to the different story levels. Although the procedures are similar, the actual applied forces can differ significantly.

BOCA Seismic Provisions The design shear, V, is determined from the formula:

$$V = Z\ K\ C\ W \tag{1}$$

where the coefficients Z represents the seismic zone, K represents the type of structural system, C represents the effects of the natural period, and W is the total weight of the loads and structure. The base shear is distributed according to this equation:

$$F_x = (V-F_t)(W_x h_x) \Big/ \sum_{i=1}^{n} W_i h_i \qquad (2)$$

where the subscript x represents the x^{th} floor, W is the floor weight, h is the height of the floor, above the base, F_t is a predetermined, additional force at the top level of the building, and n is the number of stories.

<u>UBC Seismic Provisions</u> The design base shear, V, is given as:

$$V = Z\ I\ K\ C\ S\ W \qquad (3)$$

where Z, K, C, and W are similar to the BOCA Code, I represents the importance of the structure, and S represents the site/soil characteristics. The lateral loads are distributed according to Eq. 2.

<u>ATC-3-06 Equivalent Lateral Force Procedure</u> The design base shear, V, is determined from the equation:

$$V = C_s W \qquad (4)$$

where C_s is determined from one of three equations which include the effects of the frame type, soil characteristics, effective peak accelerations, and effective peak velocity-related accelerations. The lateral force distribution is determined from an equation with the same form as Eq. 2 except $F_t = 0$ and each, h, term is replaced with h^k, where k relates to the natural period of building.

<u>ATC-3-06 Modal Analysis Procedure</u> The m^{th} modal base shear, V_m, is given as:

$$V_m = C_{sm} \overline{W}_m \qquad (5)$$

where C_{sm} is a coefficient similar to C_s from Eq. 4, and $\bar{W}_m$ is the effective modal gravity load which is based upon the m^{th} modal shape. The lateral force distribution is determined as:

$$F_{xm} = W_x \phi_{xm} \Big/ \left(\sum_{i=1}^{n} W_i \phi_{im} \right) \qquad (6)$$

where ϕ_{xm} is the mode shape and W_x is the gravity load for the x^{th} level.

OPTIMALITY CRITERIA METHOD

In structural optimization, a two step procedure is generally required. First, the structure is analyzed to find the response, and secondly, the materials are redistributed in a fashion which will continue to satisfy the constraints while reducing the weight or cost of the system. Each structure is represented by a set of primary and secondary design variables which consist of the member properties. The primary design variables, the major-axis moment of inertia, are the independent variables while the secondary design-variables, the crossectional area, are dependent variables statistically related to the primary design variables. The primary and secondary design variables are related through this equation:

$$A = C_1 I_x^p + C_2 \qquad (7)$$

where A is the crossectional area, I_x is the major-axis moment of inertia, and C_1, C_2 and p are constants determined from the statistical analysis of the appropriate crossections. The algorithm used is based on satisfying the Kuhn-Tucker conditions for optimality. (Ref.1,2) This algorithm is capable of constraining the displacements, drifts, and natural frequencies for two and three dimensional structures subject to static loads, coupled with dynamic modal analysis, UBC, BOCA and ATC-3-06 provisions.

NUMERICAL RESULTS

The examples presented have some common data. Each beam or column member is considered to be a wide flange steel section with Young's modulus of 29,000 ksi (204 kg/m^2) and a density of 7.34×10^{-4} $lb\text{-}s^2/in^4$ (8×10^{-14} $kg\text{-}s^2/m^4$). The moment of inertia I_x of each column and beam is related to the crossectional area, A, through Eq. (7) with C_1=0.5008, C_2=0.0, and p=0.487. Each bracing member is taken to be a double-angle section with C_1=0.2954, C_2=0, and p=1.0. Also, the following design variable linking was used: a) all of the columns in the same floor level are identical, b) all of the beams on the same floor level are identical, and c) all of the braces on the same floor level have identical crossections.

Seven Story, Two Bay Frames These braced frames, Fig. 1, were subjected to the UBC seismic provisions with the lateral displacements constrained to 0.234 in (5.94×10^{-3}m) times the level number and the intrastory drifts were constrained to 0.26 in (6.6×10^{-3}m). A uniformly distributed weight of 416.7 lb/in (7441 kg/m) has been applied as nonstructural weight on the floors.

Table 1 and Fig. 2 show the results for the various bracing schemes. As observed by the comparison in Fig. 2, the optimal structural weight produced by the uniformly K-braced frame is more economical than the other four cases. The use of either diagonal or K-bracing produces an effective means for earthquake resistant structures subjected to constrained conditions based on lateral displacements and story drifts. Rigid (unbraced) frames require the most steel with knee-braced frames requiring approximately ten percent less steel. The use of knee-braces induces additional bending moments in the beams, therefore, requiring large beams in order to resist those induced bending moments.

Twenty-Five Story, One Bay Frames Table 2 and Figs. 3 and 4 show the results from the optimal designs by the UBC seismic provisions for different bracing systems with both pinned and rigid beam to column connections. As observed by the comparison in Fig. 4, the optimal structural weight produced by uniformly K-braced with pinned connections is more economical than the other four cases. Again, it indicates that unbraced framing system produces the largest weight. Diagonally braced with rigid connection systems require more steel than diagonally braced with pinned connections. It demonstrates the effectiveness in using bracing systems to resist seismic forces.

Three-Story, Two Bay Diagonally Braced Frame This structure, Fig. 5, was subjected to the ATC-3-06 seismic provisions with the intrastory drift constrained to 0.234 in (5.94×10^{-3}m) and the overall displacements were constrained to 0.225in (5.72×10^{-3}m) times the level number (i.e., the second story displacement constraint is 0.225•2=.450 in). Secondly, the structure was subjected to the UBC and BOCA seismic provisions with the intrastory drift constrained to 0.052 in (1.32×10^{-3}m) and the lateral displacements constrained to 0.050 in (1.27×10^{-3}m) times the level number. A uniformly distributed weight of 260.4 lb/in (4650 kg/m) has been applied as nonstructural weight on the first and second level and 208.3 lb/in (3720 kg/m) on the third floor. The drifts and displacements for the ATC-3-06 have been modified to reflect the affects of the deflection amplification factor C_d which is used to simulate nonelastic effects. In both ATC-3-06 analysis procedures, values of A_a, A_v were based upon map area 7, soil profile group II, a regular configuration, a framing coefficient of 0.035, a response modification factor, R, of 5.0, and a deflection amplification factor, C_d, of 4.5.

As shown in Fig. 6, the results of the two ATC-3-06 analysis procedures show a similar stiffness distribution. From Table 3, the Equivalent Lateral Force procedure produces a heavier system than the Modal Analysis procedure. As observed by the comparison in Table 3, the optimal structural weight produced by BOCA code is much less than the other three provisions. The design base shear determined from the BOCA code is nearly one third of the design base shears from the other three provisions as shown in Table 3. Parameters provided in the BOCA code are normally less than those provided by the UBC code, but for the three-story structure, an approximate period of 0.3 seconds is suggested which changes the parameter C in Eqs. (1 and 3) to 0.075 for BOCA, but it gives 0.122 for the UBC. The Modal Analysis procedure provides the most ecomomical design compared to other approaches.

CONCLUSIONS

It is apparent that the optimal solutions obtained from the ATC-3-06, UBC, and BOCA seismic provisions indicate that the performance of BOCA is considerably different. The ATC-3-06 procedures produce lighter structures. Conventional bracing schemes such as K-bracing and diagonal bracing are the most effective. K-bracing provides the lightest structures. Its produces structures which are approximately ten percent lighter than the diagonal bracing. Rigid frames require the most steel with knee bracing requiring approximately ten percent less steel. Multi-story diagonal bracing provides a structure which requires less steel than a knee-braced system but more steel than single-story diagonal bracing. Rigid frames, purely based on weight without regards to ductility, provide the most inefficient configuration.

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Table 1 Frames Subject to UBC Seismic Provisions
(1 kip = 454 kg, 1" = 2.54 cm)

Scheme No.	1	2	3	4	5
Bracing	None	X	K	Knee	Cross
Cycles	8	8	8	10	2
Base Shear (kips)	325.5	413.2	410.7	410.7	408.4
Initial Structural Wt. (kips)	198.3	147.8	125.2	185.2	153.2
Optimum Structural Wt. (kips)	162.0	94.1	84.2	143.2	132.5
Maximum Drift (in) at Story No.	0.26 2,7	0.27 3,4	0.27 6	0.26 2	0.26 3

Table 2 Frames Using Both Pinned and Rigid Beam to Column Connections (1 kip = 454 kg, 1" = 2.54 cm)

Scheme No.	1	2	3	4	5
Bracing	None	X	K	X	K
Connection	Rigid	Rigid	Rigid	Pinned	Pinned
Cycles	2	10	10	10	10
Base Shear (kips)	447.6	612.3	590.3	611.9	590.2
Initial Structural Wt. (kips)	324.8	502.8	348.4	512.7	356.6
Optimum Structural Wt. (kips)	293.5	197.3	161.6	195.9	161.2
Maximum Drift (in) at Story No.	2.43 9	2.37 21,24	2.36 15	2.39 21,22	2.34 14,15 19-25

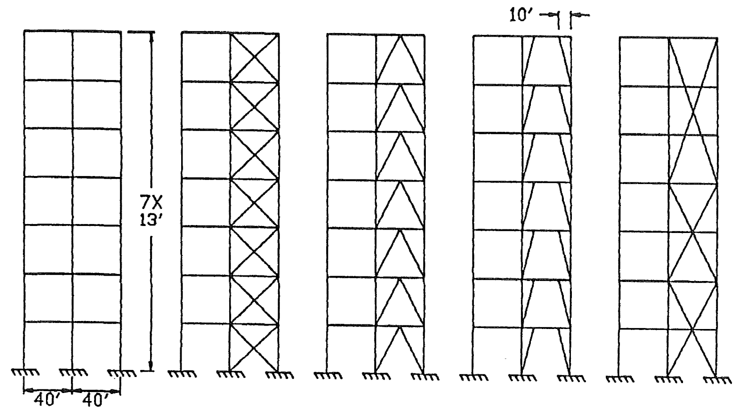

Fig. 1 Seven-Story, Two-Bay Frames (1' = .305 m)

Table 3 Frames Subject to ATC-03-06, UBC, and BOCA Seismic Provisions (1 kip = 454 kg, 1" = 2.54 cm)

Provisions	ELF	MA	UBC	BOCA
Cycles	6	5	8	4
Base Shear (kips)	123.6	101.9	132.1	40.6
Initial Structural Wt.(kips)	73.7	66.5	76.0	27.2
Optimum Structural Wt.(kips)	60.8	48.6	70.0	18.8
Maximum Drift (in) at Story No.	0.24 2	0.24 2	0.05 2	0.05 2

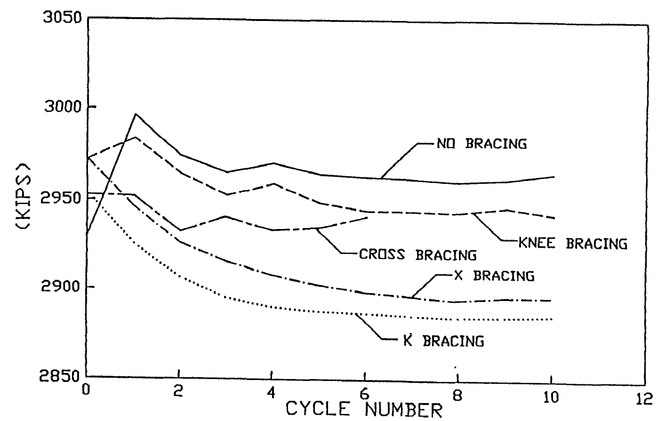

Fig. 2 Total Weight vs. Optimum Cycles (1 kip = 454 kg)

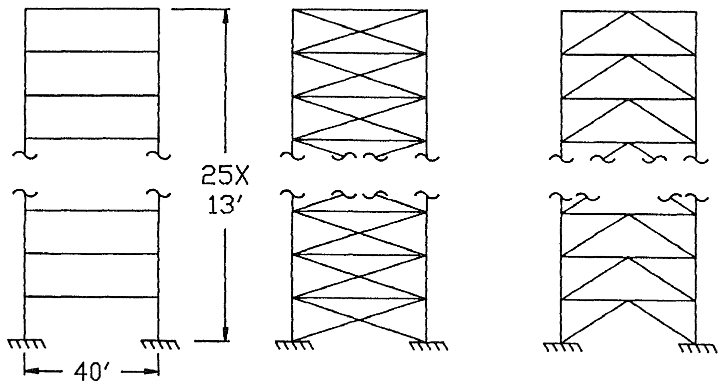

Fig. 3 Twenty-Five-Story, One-Bay Frames (1′ = .305 m)

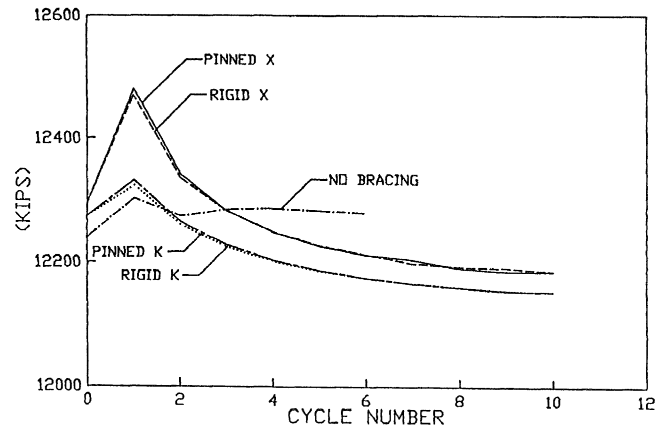

Fig. 4 Total Weight vs. Optimum Cycles (1 kip = 454 kg)

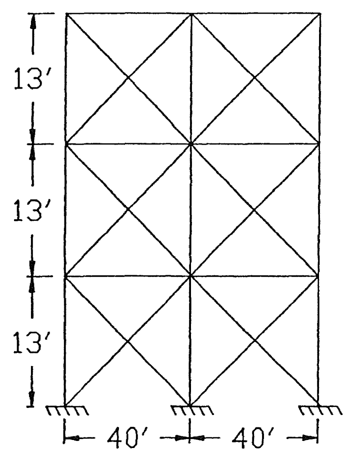

Fig. 5 Three-Story, Two Bay Frame (1′ = .305 m)

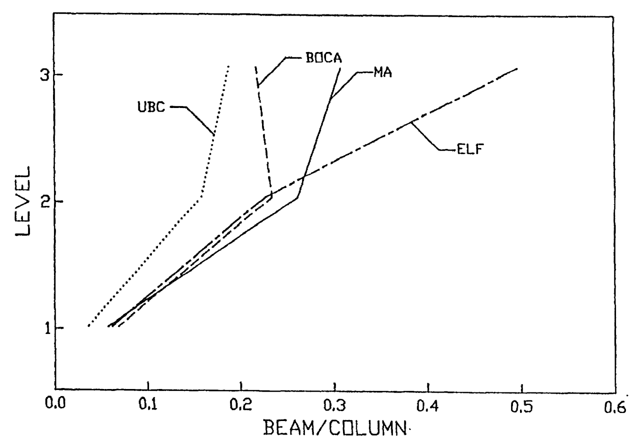

Fig. 6 Relative Stiffness Distribution (1 kip = 454 kg)