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A RATIONAL ELF DYNAMIC ANALYSIS FOR IBC 2000

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ABSTRACT:

A rational procedure to calculate static seismic Equivalent Lateral Forces (ELF) in a building, using basic principles of structural analysis, is presented in this paper. This procedure will be submitted for consideration/adoption in the International Building Code (IBC). The IBC is the proposed combined International Conference of Building Officials - Uniform Building Code, Building Officials & Code Administrators International - National Building Code and Southern Building Code Congress International - Standard Building Code. The first edition of the IBC is scheduled for publication in the year 2000 (Phillips et al., 1995). The paper also compares, utilizing the proposed procedure, the seismic force demand/capacity ratios for various components in a building with the demand/capacity ratios calculated using performance based criteria. The proposed procedure calculates the seismic force demand using a two-factored approach to construct a four region free-field acceleration response spectra (Working, 1995). The proposed spectra correspond to the current rock spectra, but are modified by two spectral site coefficients. One coefficient corresponds to short period motion, while the other corresponds to long period motion. In addition, the response spectra are adjusted by a special factor at lower periods. The acceptability of various components in a building, and overall stability of a building, can subsequently be addressed by comparing demand/capacity ratios of the various components. Actual displacements are computed and compared to allowable serviceability limits and performance based criteria.

KEY WORDS:

Equivalent Lateral Force Procedure, Ground Motion, Response Spectra, Global System Base Shear, Member Joint Distributed Force, Inelastic Demand Ratio, Force-Deflection Shape.

INTRODUCTION:

The basic premise is that all structures subject to seismic earthquake motion shall be designed/analyzed to account for numerical force-equilibrium and deflection compatibility analysis in a dynamic environment (i.e. a three (3) dimensional finite element computer analysis), EXCEPT certain regular low rise structures. The statistical reality is that most structures constructed today fall within the latter exceptions.

The purpose of an Equivalent Lateral Force (ELF) procedure is to permit the design of certain regular low rise structures without the requirement of a computerized finite element analysis. ELF procedures require a force-equilibrium analysis (i.e. resolution of external and internal forces) but do not require a deflection compatibility analysis. Deflections are checked for individual members and overall interstory drift limits. The primary use of an ELF procedure is for the design or retrofit of one (1) to three (3) story wood and regular low rise concrete or masonry shear wall structures. ELF procedures may also be used for preliminary design of all structures of any height or material.

There are two basic ELF procedures - the Global System Base Shear (GSBS) procedure and the Member Joint Distributed Force (MJDF) procedure. The first procedure, and by far the most common, is a Global System Base Shear (GSBS) procedure (International, 1994). The GSBS procedure is the procedure currently prescribed in the 1994 Uniform Building Code (International, 1994) and in the National Earthquake Hazard Reduction Program publications including the 1994 provisions (Federal, 1995), and has the following four (4) major attributes. The first attribute is to assume/select a variety of coefficients. A numerical coefficient R (R_w, R_d, R_o, ... R) of some kind is selected to represent the global system energy dissipation capacity of the structure. This single coefficient or product of coefficients is used in virtually all structural calculations for equivalent lateral forces or deflections. In addition to R, values for a seismic zone factor (Z), an importance factor (I), and a site coefficient for soil characteristics (S) are selected. The second attribute is the concept of a Base Shear which is another traditional number calculated to represent the maximum total equivalent lateral force acting on the structure at the base level. The third attribute is the concept of a vertical distribution of this Base Shear upward from the base level to the roof using a linear straight line proportioning; a quadratic distribution is even being considered as an additional refinement to account for the effects of higher modes. The fourth and final major attribute is that the fundamental period (T) of the structure is determined from empirical based statistical data and is used in the computation of the magnitude of the equivalent lateral force base shear.

The second procedure, and by far the most rational, is a Member Joint Distributed Force (MJDF) procedure. The MJDF procedure is not presented in the literature and will be developed herein for the first time as a rational alternative to the GSBS procedure discussed above. The MJDF procedure has the following five attributes. First, the MJDF procedure requires that the equivalent lateral forces at each level (F_x) are determined based on an assumed deflected shape (a non-linear shape may be selected to account for the effects of higher modes). Second, a free-field ground motion response spectrum is utilized (which accounts for the soil profile). Third, the fundamental period of vibration (T) is calculated the same as the GSBS procedure. Fourth, the total equivalent lateral force acting at the base level (i.e. base shear) is the summation of the equivalent lateral forces acting at each level above the base. This is consistent with the principles of basic structural dynamics, and fundamentally different than the GSBS procedure. The fifth and final major attribute is that the capacities of individual members and joints are then calculated using the applicable sections of the UBC 94, and using the nominal material properties and a capacity reduction factor of 1.0 (i.e. $\phi = 1.0$). The Inelastic Demand Ratio (IDR) are thus calculated as the demand divided by the capacity. A structure shall be deemed to comply, if all the structural members and joints IDR's and the drift ratios are less than specified limits. Note that there are different limits for various performance based criteria.

THEORY AND EQUATIONS FOR MJDF PROCEDURE:

The primary function of the MJDF procedure is to generate equivalent lateral forces and deflections for a given structure on a specific site for a specified performance based criteria. The performance objective is thus addressed using selected IDR and performance criteria inlieu of an increase in lateral force via an importance factor (I) (Department, 1995). A four (4) Region Site Specific Spectra (4RS) may be used in lieu of a site spectrum to account for the effective peak accelerations and soil profile; see the following section for development of theory and equations. Entry into the 4RS requires only the fundamental period (T), which shall be determined from the standard UBC 94 equations. Knowing T, select the spectral acceleration (S_a) from the 4RS.

The next, and only other quasi new, ingredient is the selection of a force-deflection shape (ϕ) to determine the equivalent lateral forces at each level. Pending additional research and comparisons of actual shapes, a straight line shape $\phi = x/L$ may be used to represent the force-deflection shape for shear wall type buildings and a sine shape $\phi = \sin(\pi x/2L)$ may be used to represent the force-deflection shape for moment frame type buildings.

The following relationships are developed from equations of basic structural dynamics and are presented for reference and clarity (Chopra, 1995).

- Participation Factor (Γ):
  $\Gamma = (\Sigma W_x \phi_x)/(\Sigma W_x \phi_x^2)$
- Equivalent Lateral Force (F_x):
  $F_x = (\Gamma \phi_x) S_a W_x/g = \Gamma (S_a/g) W_x \phi_x$
- Story Shear (V_x):
  $V_x = \Sigma F_x = \sum_{i=x}^{i=n} F_i$
- Base Shear (V_1):
  $V_1 = \sum_{i=1}^{i=n} F_i$
- Story/Level Acceleration (C):
  $C = F_x/W_x = [\Gamma (S_a/g) W_x \phi_x]/W_x$
  $= \Gamma (S_a/g) \phi_x$

  C = Equivalent Seismic Coeff. for Non-Structural items
  = Story/level spectral acceleration - used to design rigid equipment or non-structural light secondary items anchored on a floor.
- Spectral Displacement (S_d):
  $S_d = S_v T/(2\pi) = S_a/w^2$
  $= T/(2\pi)*T/(2\pi) S_a$
  $= (T/(2\pi))^2 S_a$

  Recall:
  $S_v = T/(2\pi) S_a$ = Spectral Velocity
  $\omega^2 = K/M = (2\pi/T)^2$ = circular frequency
  K = System Stiffness
  M = System Mass = w/g
  W = System Weight = ΣW_x

  Thus: $T = 2\pi/w = 2\pi(M/K)^{1/2} = 2\pi(W/(gK))^{1/2}$
  Also: $T^2 = (2\pi)^2 S_d/S_a$
  Now: $T = 2\pi(S_d/S_a)^{1/2}$
- Lateral Displacement (d_x):
  $d_x = \Gamma S_d \phi_x = \Gamma (T/(2\pi))^2 S_a \phi_x$

Compare d_x to interstory drift limits for performance based criteria.

- Effective Stiffness (K):

  Recall: $T = 2\pi(W/(gK))^{1/2}$

  Thus: $K = (2\pi/T)^2 W/g = (2\pi/T)^2 \Sigma W_x/g$
  K = measure of overall resistance to deflection
- Overturning Moment (M_x):
  $M_x = M_{(x+1)} + V_x(\Delta h_x)$

  Where: x=1 at first floor (i.e. ground/base level)
- Effective Weight (E_w):
  $E_w = \Gamma^2 (\Sigma W_x \phi_x^2)$

  E_w = portion of total weight that is participating in computation for equivalent lateral forces.
- Percentage of Weight Participating (W_p):
  $W_p = E_w/\Sigma W_x$ = analogous to active mass (should be greater than 90%).

Once the equivalent lateral forces and displacements have been calculated, the distribution to the various vertical lateral force resisting elements must be determined. Under prime conditions, the correct procedure would be to degrade the cementicious and wood elements based on their IDR's and iterate on the dynamic analysis with a revised period and loading until convergence (City, 1995, Krawinkler, 1990, Seismic, 1995). With an ELF procedure, an adjustment to the period cannot be made because a dynamic analysis is not being performed. Furthermore, by the very nature of structures appropriate for an analysis using an ELF procedure (regular low rise buildings), the periods are normally short and it is slightly conservative to design a structure using a higher equivalent lateral force than to try and reduce this force based on a subjective assessment of a reduced period corresponding to a degradation of the vertical lateral force resisting elements. It is, however, appropriate and necessary to distribute the equivalent lateral force to the vertical, lateral force resisting elements based on their relative rigidities. Their relative rigidities requires using the effective stiffness (k). Thus, a rigid diaphragm analysis is normally required to distribute the lateral forces to the vertical lateral force resisting elements. Only under the simplest conditions would flexible diaphragm assumptions be appropriate. In any event, the lateral force distribution to resisting elements in the same line must be distributed based on their effective stiffness. IDR's can then be calculated to determine the current performance level and/or provide guidance for additional strengthening to satisfy a given performance criteria.

GROUND MOTION RESPONSE SPECTRA:

This procedure requires a rational, realistic appraisal of the seismic demands imposed by the earthquake. A two-factored four-region (4RS) approach to construct a free-field acceleration response spectra, similar to that proposed by the Seismology Committee of the Structural Engineers Association of California for the 1997 Uniform Building Code, is recommended (Seismic, 1995, Structural, 1995).

The response spectra can be constructed for five soil profile types, which are defined for the average soil shear wave velocity in the top 100 feet of the soil profile, as shown in Table 1 (Kircher, 1995, Working, 1995).

There is a sixth soil profile type, S_F, which requires a site-specific evaluation to establish the site coefficients. In addition to the shear wave velocity, there are relations for average standard penetration test blowcount or undrained shear strength in the upper 100 feet of soil profile for each soil profile type (Kircher, 1995). The seismic coefficients C_A and C_V are used to define the constant acceleration and constant velocity regions of the response spectra and are given in Tables 2 and 3. Note that both C_A and C_V are significantly greater than the ZN factor for soft soil sites in low seismic zones. The coefficients are based on (but not identical to) the 1994 NEHRP provisions. The values of the coefficients are a function of the soil profile type and the product of the Seismic Zone Factor (Z) and Near Source Factor (N). Recall that the repeatable high ground acceleration aka effective peak ground acceleration or Seismic Zone Factor (Z) typically averages 65 percent of the peak ground accelerations for sites within 20+ miles (32 kilometers) of the epicenter (Ploessel et al., 1974). At greater distance from the epicenter, the peak acceleration attenuates faster than Z and Z approaches 100 percent of the peak acceleration, see Table 2.

The Seismic Zone Factor (Z) is recommended to be similar to that used in the UBC 94 or NEHRP 94. The values of Z are shown below to be used with Tables 2 and 3:

Seismic Zone Factor Z					
Zone	1	2A	2B	3	4
Z	0.075	0.15	0.20	0.30	0.40

Performance levels are directly related to the permitted maximum inelastic demand ratios, drift and maximum parameter values, see Tables 2 and 3 for preliminary/draft values. Additional work is required to finalize and correlate these values.

The Near Source Factor (N) is a recognition that recent earthquakes, such as the 1994 Northridge and 1995 Hyogo-Ken Nanbu (Kobe) earthquakes, have demonstrated that near-source ground motions can significantly exceed the level of ground motion assumed by present building codes (Comartin, 1995). Near-source factors, which are a function of proximity to a seismic source and earthquake magnitude, have been proposed for the UBC 97. These factors are also based on the activity rate of the faults. These near-fault factors apply where the closest distance to the seismic source is less than 10 km. For the most active faults, referred to as Type A faults, having maximum moment magnitude of greater than 7.0 and slip rates of at least 5 mm/year, the Near Source Factor (N) has a value of unity (1.0) at a distance of 10 km, a value of 1.5 for a distance of 5 km, and 1.9 for 2 km or less. For faults with slip rates between 2 and 5 mm/yr and maximum moment magnitude of 6.5 or greater, referred to as Type B faults, the N factor is 1.0 at a distance of 10 km, 1.2 at a distance of 5 km. and 1.5 at a distance of 2 km or less. For distances of 2 km or less, the N factor value at 2 km may be used; for intermediate distances between 2 and 10 km, the N factor may be linearly interpolated between the values specified at 2, 5, and 10 km. Faults not meeting the Type A or B descriptions are considered as Type C faults, and the Near Source Factor for Type C faults is 1.0 regardless of distance, see Table 4 and Table 5.

This 4RS procedure may not adequately address the issue of the near field effects of the "blind" thrust faults that are believed to be underlying the Los Angeles Basin. Because of the uncertainty in the locations, orientations, slip rates, and other important fault parameters, the Near-Fault Factor concept may not be able to account for these important seismogenic structures until more definitive information about these "blind" thrust faults is available. The combined product of the zone and near-source factors, ZN, is used with the appropriate soil profile type to determine the C_A and C_V coefficients. The C_A and C_V coefficients are used to construct the 5% damped response spectra. There is a constant acceleration plateau having a value of 0.8 C_A whenever $N > 1.0$ for periods greater than $T_V = C_V/0.8C_A$ seconds, and beyond a period of $T_D = 3.0$ to 4.2 seconds, the response spectra decreases with in the acceleration values having a constant displacement.

EXAMPLE PROBLEM: ONE-STORY TILT-UP BUILDING

A one-story concrete tilt-up building is analyzed (see Figure 1) to show the relationship between the two ELF procedures (see Figure 2).

GSBS procedure: $S = 1.2$

$T = 0.05*h / (L)^{1/2} = 0.05 *20 / (170)^{1/2} = 0.0767$ sec

$C = 1.25 * 1.2 / T^{2/3} = 8.3 > 2.75$

Thus: $C = 2.75$

$V_I = ZICW/R_w$

$= 0.40*1.0*2.75*W/6 = 0.183*W$

Thus: $V_I = 0.183*730$ kips = 134 kips

Where: $W = 12\text{psf}*(170\text{ft}*170\text{ft}) + 94\text{psf}*(10\text{ft}+2\text{ft})*170\text{ft}*2 = 730$ kips

MJDF procedure:

Soil Profile Type S_D: $ZN = 0.40$, $C_A = 0.40$, $C_V = 0.64$

Building Height = 20 feet

$T = 0.0767$ sec

Thus: $V_2 = 730$ kips, see Figure1

In order to obtain an equivalent comparison, it is necessary to adjust the MJDF value as follows:

Procedure	Load Factor	ϕ Factor	IDR
GSBS	1.4	0.60	1.00
MJDF	1.0	1.00	1.50

Now: $V'_2 = 730$ kips $*(1/1.4)*(0.60/1.00)*(1.00/1.50) = 208.6$ kips

Also to be considered is the pending discussions on the proper force level for low rise buildings with very short periods. This could be accomplished by applying a redundancy reliability factor (ρ) as proposed for the UBC 97 or by adjusting the value of R_w. When the effective R_w is revised from 6 to 4, the new value for V_I can be calculated as follows:

$V'_I = 134$ kips $*(6/4) = 201$ kips

Thus: $V'_I \sim V'_2$ Note: MJDF > GSBS

CONCLUSION:

An equivalent lateral force procedure and example problems are presented for the design or retrofit of wood and low rise concrete or masonry shear wall structures utilizing the basic principle of structural dynamics. A two (2) factor-four (4) region free-field ground motion spectrum combined with a assumed deflection shape and empirical period computation, is used to generate equivalent lateral forces, deflections and strength demands on members consistent with results from finite element computer based dynamic modal spectrum analysis. Inelastic demand ratios are computed as the demand divided by the capacity and are compared to limit values based on performance based criteria. Values for building interstory drift are also computed and compared to performance based criteria drift limits.

RECOMMENDATIONS:

Additional research is required to finalize the shape of the assumed deflected shape and to verify the empirical formulation presented in the UBC 94 for the determination of the building period. Further research is also required to reach a consensus position within the structural community of the appropriate performance based criteria IDR values for the various materials and structural systems. The final formulation of the two factor, four region free-field ground motion spectra is scheduled for completion by the end of 1999. Pending resolution of these items, it is recommended that the MJDF-ELF procedure be submitted as an appendix to the IBC 2000 as an alternate to the GSBS-ELF procedure with the intention to consolidate the two procedures by the next printing of the IBC.

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Table 1: Soil Profile Types / Average Shear Wave Velocity

Soil Profile Type	Soil Profile Description	Average Shear Wave Velocity (feet/second)
S_A	Hard Rock	> 5,000
S_B	Rock	5,500 to 5,000
S_C	Very Dense Soil and Soft Rock	1,200 to 2,500
S_D	Stiff Soil	600 to 1,200
S_E	Soft Soil	< 600
S_F	Site Specific Evaluation Required	

Table 2: Seismic Coefficient, C_A (site-dependent effective peak acceleration (EPA) at grade)

Soil Profile Type	Shaking Intensity, ZN					
	0.075	0.15	0.20	0.30	0.40	> 0.40
S_A	0.06	0.12	0.16	0.24	0.32	0.8ZN
S_B	0.08	0.15	0.20	0.30	0.40	1.0ZN
S_C	0.09	0.18	0.24	0.33	0.40	1.0ZN
S_D	0.12	0.22	0.28	0.36	0.40	1.0ZN
S_E	0.19	0.32	0.34	0.36	0.40	1.0ZN
S_F	-	-	-	-	-	-

Table 3: Seismic Coefficient, C_V (controls the constant velocity portion of the response spectra)

Soil Profile Type	Shaking Intensity, ZN					
	0.075	0.15	0.20	0.30	0.40	> 0.40
SA	0.06	0.12	0.16	0.24	0.32	0.8ZN
SB	0.08	0.15	0.20	0.30	0.40	1.0ZN
SC	0.13	0.25	0.32	0.45	0.56	1.4ZN
SD	0.18	0.33	0.40	0.54	0.64	1.6ZN
SE	0.26	0.50	0.64	0.84	0.96	2.4ZN
SF	-	-	-	-	-	-

Table 4: Fault type versus N value

Fault Type	Moment Magnitude	Slip Rate	N value - Distance from Fault		
A	> 7.0	> 5 mm/year	1.0	1.5	1.9
B	> 6.5	2-5 mm/year	1.0	1.2	1.5
C	All other Faults		1.0	1.0	1.0

Table 5: Faults in California

Fault Type	Name	Location
A	San Andreas	Northern Cal. / Southern Cal.
A	Haward	Northern California
A	San Jacinto, Garlock and Imperial	Southern California
B	Sierra-Madre and Palos Verdes	Southern California
B	Whittier-Elsinore	Southern California
B	Cucamonga	Southern California
C	Newport-Inglewood	Southern California

Figure 2: MJDF - ELF PROCEDURE SPREADSHEET

Project: One-story concrete tilt-up building. $T =$ 0.0767 sec $S_a =$ 1.00 **Date:** 1/10/96

Story / Level (1)	Elevation (ft) (1)	h_x (ft) (2)	Δh_x (ft) (3)	W_x (kips) (4)	ϕ_x (5)	$W_x\phi_x$ (kips) (6)	$W_x\phi_x^2$ (kips) (7)	F_x (kips) (8)	C_x (9)	V_x (kips) (10)	M_x (kip-ft) (11)	d_x (in.) (12)	δ_x (13)
Roof	20.00	20.00		730.0	1.000	730.0	730.0	730.0	1.00			0.06	0.0002
			20.00							730.0	14600		
Ground	0.00	0.00		0.0	0.000	0.0	0.0	0.0	0.00			0.00	
			Totals	730.0		730.0	730.0						

T (sec) (a)	S_a coeff.*g (b)	Γ (c)	E_w (kips) (d)	W_p % (e)	K (kips/in.) (f)
0.0767	1.00	1.00	730.0	1.00	12678.1

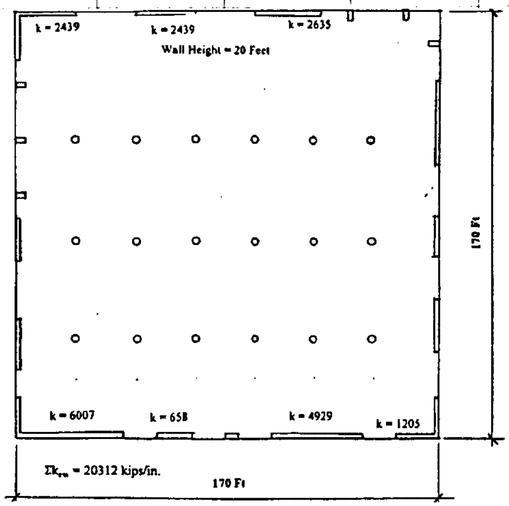

Figure 1: Floor Plan for Tilt-up Building

(1)	From Drawings	(11)	Overturning moment = $M_{(x+1)} + V_x(\Delta h_x)$; x=1 @ 1st Floor
(2)	Height above base normalized to Elevation 0.00	(12)	Deflection at story / level = $\Gamma(T/(2\pi))^2 S_a\phi_x$
(3)	Height of story / level	(13)	Drift / Ratio = d_x/h_x ..... compare to allowable
(4)	Weight of story / level		
(5)	Displaced / Deformed shape = x /L [alternatively $\phi = \sin(\pi x)/(2L)$]	(a)	Period from UBC 94 i.e. $T = C_t * (h_n)^{3/4}$
(6)	(4) * (5) x = 0 at base ; x=1 at roof / top	(b)	Spectral acceleration from spectra = Coeff. * g
(7)	(5) * (6)	(c)	Participation factor = $\Sigma W_x\phi_x / \Sigma W_x\phi_x^2$
(8)	Horizontal force = $\Gamma(S_a/g)W_x\phi_x$	(d)	Effective weight = $\Gamma^2(\Sigma W_x\phi_x^2)$ (similar to effective mass)
(9)	Horizontal acceleration at story / level = $\Gamma(S_a/g)\phi_x$	(e)	Percent of weight participation = $E_w/\Sigma W_x$ (should be > 90%)
(10)	Shear at story / level = ΣF_x above	(f)	Effective stiffness = $(2\pi/T)^2(\Sigma W_x/g)$