ELEMENTS OF A DYNAMIC-INELASTIC DESIGN CODE

by

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SYNOPSIS

The need for a dynamic-inelastic design code that provides greater utilization of available knowledge than the current earthquake codes is discussed followed by the philosophy of such a code including the requirement for reasonable simplicity and workability. Elements of the code are presented as a supplementary section to existing static-elastic requirements. Two levels of earthquake intensity are specified. The dynamic-inelastic provisions are based upon kinetic energy reconciliation with energy stored, converted to heat, and used to do work in the inelastic range as in the reserve energy technique.

INTRODUCTION

It has become increasingly clear that static or pseudo-static seismic design codes are not adequate for the design of important, unusual or high risk structures. Even where elastic dynamic analyses are conducted using earthquake records there is a problem of what to do with the results which generally greatly exceed those from code-specified lateral forces. Rigorous inelastic modeling and analyses are complex, often costly, and the results are highly dependent upon both the elastic and inelastic model characteristics selected for analysis.

It is proposed that seismic building codes have two basic parts -- the first consisting of the most desirable procedures and requirements for a static-elastic type design such as now generally practiced, and the second be a dynamic-inelastic part which would also be required for buildings of certain types. This would in effect create a "plateau" (1) of initial resistance for the most probable earthquake demands and an ultimate-resistance control against collapse under a less probable but still possible extreme earthquake demand. This paper is concerned only with the second, dynamic-inelastic part and it is not intended to be a complete code and commentary but a presentation of key elements. Some of the material on which this code is based has been presented previously (1, 2, 3, 4, 5, 6).

A basic factor is not the dynamic analysis, whether with elastic or inelastic models, but what the real resistance values of buildings are as compared to the probable and possible demands. No analysis, per se, improves a building unless something worthwhile is done with the results of that analysis. In addition, the analysis must be based upon realistic models and conditions. The question may be raised as to which model is proper for dynamic analysis -- the one before damage or the one after damage has allowed the structural frame to act essentially alone. This code approach is that both are needed -- the first to determine the response that might lead to damage and inelasticity and the second to check the structure for survival should the strong motion continue. The

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natural periods and other properties of these two models may be quite different (6, 7, 8).

There will be two extreme points of view to any dynamic-inelastic design code -- one that it is complicated and extra work for the designer, and the other that it lacks scientific rigor and is too simplified for the real problem. Obviously both can't be right, although both may have valid points. Discussion has been going on for many years while the tools have been available, and while thousands of new buildings are being constructed each year -- built to exist hopefully for 50 or more years without all the benefits of available knowledge. The Southern California hospital failures of 1971, for example, were not only predictable but preventable, but not under any then existing code. Moreover, codes rather than available knowledge seem to determine building properties. In view of these considerations the elements of a dynamic-inelastic code are presented in the following text.

BASIC REQUIREMENTS

For a dynamic-inelastic design code to be feasible and useful it must be simple, clear, and in terms and procedures with which the designer is familiar or with which he could readily become familiar. In addition, it should not depart from the good features of established practices and codes. The basic objective of such a code is to provide adequately for the effects of time and of energy which are largely lacking in existing seismic provisions. The subject is so complex that complete rigor can not be included in a code; nor is that necessary. Certain assumptions and some generalizations are therefore required. In spite of these, the code should provide for the effects of: complex realistic ground motion; damping; natural periods; changes in natural periods; mode shapes; dynamic amplification; inelastic as well as elastic properties; response of an inelastic system; force-deformation characteristics; deterioration under repeated cycles; capacity to do work; modal combinations; soil-structure interaction; energy conservation and reconciliation; all materials and elements that participate in the response; probabilistic variations in ground motion; and probabilistic variations in resistance.

Current seismic codes specify equivalent static horizontal forces from which the designer computes shears, moments, axial forces and finally stresses. However, the element of time is not included adequately and the element of energy is largely neglected. Certainly earthquake response involves time to a major degree, and the basic problem is one of mobilizing resistance to severe energy demands. The energy transmitted to the structure has to be dissipated in such manner that the structure will survive. Unless buildings are made much stronger than most codes require, this energy must be absorbed by doing work far beyond the minor amount of energy converted to heat by damping and friction and stored as elastic strain.

The Reserve Energy Technique (RET) was developed in the 1950's and presented in a series of publications (1, 2, 3) as a practical means of analysis or design in the inelastic range. It was published somewhat apologetically in view of lack of rigor and the need for more data. However, in today's state of great need for a workable dynamic design code, and in view of what has happened, it seems that RET offers a sound basis on which to accomplish the above noted objectives. It introduces energy and the resistance of nonstructural elements as the current missing link in design procedures for earthquake resistance and it does this in such a way as to keep the analysis tractable.

PHILOSOPHY

The philosophy of RET is really quite simple and includes consideration of: (a) the extreme demands of the earthquake that can cause the greatest damage or collapse; (b) peak spectral velocity at the period of interest can be used to compute the critical kinetic energy demand; (c) there is energy reconciliation between the kinetic energy and damping (heat), strain (stored) and damage (work done); (d) some structures have characteristics in the inelastic range which must be utilized for survival and these should be evaluated and utilized; (e) any deterioration or softening from repeated cycles can be estimated; (f) changes in dynamic properties from initial response must be considered in the later stages of the earthquake when survival may be in the balance; (g) all elements of resistance and work capacity (reserve energy absorption) should be utilized in the computations as they are in the real structures; and (h) the procedures in design must sacrifice rigor for the benefit of reasonable simplicity but must be reasonably conservative.

The elements of the proposed code are presented with the full understanding that with these "key elements" there still must be extensive work done in refining numerical values, and also that local conditions vary. However, it has been found that the application of these tentative requirements would have prevented the serious damage in Southern California in 1971 and that their application after the event seems to reliably reproduce the effects of the earthquake on all of the structures investigated (6).

PROPOSED CODE ELEMENTS

DYNAMIC-INELASTIC PROVISIONS

Sec. 100. (a) General. Every building of public assembly of more than ___ persons; of public function such as hospitals, police stations, fire stations, jails; other government buildings; of community housing of more than ___ family units; for basic communications or utility purposes; of more than ___ square feet of total floor area; of height greater than ___stories or with a height to width ratio greater than ___; or as may be specifically set forth; shall be first designed as per Section 99 and then be reviewed for performance under this Section and revised as necessary to comply with or exceed the minimum requirements of both Section 99 and this Section.[II]

The provisions of this Section apply to the structure as a unit and also to all stories and parts thereof unless otherwise specifically excepted herein.

The intent of this Section is to provide for the probability that the stress levels of Section 99 may be considerably exceeded because of strong ground motion and to insure a reasonable degree of resistance against collapse under such circumstances.

[II] "Section 99" refers to an improved static-elastic code such as UBC.

(b) Definitions. The following definitions apply only to the provisions of this Section.

Damping. As used herein related only to the kinetic energy loss without damage, or further damage; assumed to be viscous.

Deterioration. The decrease or softening in stiffness, strength or both due to repeated or reversed cycles.

Elastic Response. Response computed on the basis that the structure has elastic properties regardless of the extent of response.

Inelastic Response. Response in the inelastic range between yield point and ultimate value.

Time-history. Record showing the complete plot of ground motion as a function of time.

(c) Symbols and Notations. The following symbols and notations apply only to the provisions of this Section.

b = A subscript referring to base story.

C'_j = The static story shear coefficient actually provided, using all elements of story j with Section 99 stresses; $C'_j = (\beta V_{yj})/W_j$.

C_b = The fundamental mode dynamic base shear coefficient based on S_a and a ratio from Fig. 100-4.

DV_j = The dynamic shear in story j; at base story, DV_b per Eq. 100-1.

F = A force applied at the roof level of buildings over 7 stories; used solely to increase DV_j in the upper stories.

f = A factor based on mode shape; given in Fig. 100-4.

j = A subscript referring to story j, starting at the base story.

N, n = The total number of stories.

p_j = Ratio of effective energy absorption capacity in story j to the sum of same for that story plus all superimposed stories; Eq.100-3.

R_j = Reserve energy reduction factor for story j; to reduce elastic values to inelastic values; from RET.

RET = Reserve energy technique.

S_a = Spectral acceleration; g units.

T = The natural period of vibration of the fundamental mode, sec.

ult = A subscript indicating ultimate; the point on a V-Δ diagram beyond which the slope is always negative.

V_{yj} = The yield shear or yield force of story j.

V-Δ = Symbol for shear-distortion diagram of a story.

W_j = The seismic weight of the building at and above story j.

Z = Number of stories above plus the one under consideration.

α = A factor to convert elastoplastic to bilinear softening values; see Fig. 100-5.

materials after any damage has been done by the initial earthquake. Any change in stiffness from cracking or failure of partitions, filler walls, structural walls, beams, columns, or other elements shall be taken into account as well as expected deterioration due to repeated cycles (to be assumed as 10 in number for the initial phase and also for the final phase). Each period may be assumed to change by a factor equal to the square root of the ratio of the "initial" effective stiffness to the "final" effective stiffness of the first story.

3. Mode Shapes. The fundamental mode shape shall be assumed to be the most likely idealized shape in Figure 100-3 based upon the structure's framing, walls and geometry. Should there be significant ground rocking and/or translation the "rigid" bases shown in Figure 100-3 shall be rotated and/or translated accordingly.

4. Base Shear Coefficient Ratio. The ratio of the fundamental mode dynamic base shear coefficient to spectral acceleration, C_b/S_a, shall be obtained from Figure 100-4 using the appropriate number of stories and the selected model from Figure 100-3.

5. Shear-Distortion Models. Each story, j, to be investigated shall have an appropriate idealized shear-distortion (V-Δ) model selected from Figure 100-5 to best represent the actual conditions in the story based upon static test results of materials and elements similar to those proposed. If conditions require, other V-Δ types than those shown may be used but in all cases the type selected shall be justified on the basis of reliable test results. Numerical values shall be developed to define the diagram. Should there be deterioration in the model from the "initial" earthquake, the model for the "final" earthquake shall be appropriately altered from that of the initial phase. In no case shall μ'_I and μ'_F exceed the values in Table 100-C nor any other controlling criterion such as buckling, secondary effects, overall building stability or stress combinations. The first story shall always be investigated. For buildings of over 5 stories other stories shall also be investigated so that no more than 4 typical stories fall between those investigated. In determining V_y and Δ_y the average yield value may be used in lieu of the specified (minimum) yield value.

(f) Analysis.

1. General. The analysis for both initial and final earthquakes shall be conducted as though the structure remained elastic and then those results shall be adjusted to the inelastic state by the use of the reserve energy reduction factor, R. The computed ductility excursions μ_I and μ_F must not exceed the model values μ'_I and μ'_F respectively.

2. Base Shear and Story Shears. Only the fundamental mode shall be used in the spectral analyses but the dynamic base shear shall be increased for higher mode participation as follows:

$$DV_b = \frac{C_b}{S_a}\left[1 + \frac{N-1}{100}\right] S_a W_b \qquad (100\text{-}1)$$

DV_b shall be equal to the sum of assumed horizontal forces on the building which shall be applied to the story levels (for the purpose of obtaining story shears DV_j) in proportion to the modal deformations of the model selected from Figure 100-3 with the base rotated and/or translated as indicated for foundation compliance. DV_j shall also include additional shear from a force F applied horizontally at the roof level of all buildings over 7 stories in height for the purpose of increasing story shears for higher mode response in the upper half of the building. This force F need not be carried into the lower-half stories or to base shear, but it shall be additive in the upper stories to the forces distributed from dynamic base shear, DV_b. The force F shall be equal to 0.2 DV_b.

3. Relationships. Story j shall be checked using the following equations to see if the energy can be absorbed without the ductility excursions μ_{jI} and μ_{jF} exceeding the limiting values established for that story. If the limiting values are exceeded the story framing (and that of adjacent stories) shall be redesigned as necessary to meet these requirements.

$$R_j = \frac{\alpha \beta \sqrt{p_j}}{\sqrt{2\mu_j - 1}} = \frac{C'_j W_j}{DV_j} \qquad (100\text{-}2)$$

$$p_j = \frac{f}{\sqrt{Z}} \text{ ; but not} > 1.0 \qquad (100\text{-}3)$$

$$\mu_j = \frac{p_j \alpha^2 \beta^2}{2(R_j)^2} + \frac{1}{2} \qquad (100\text{-}4)$$

or,

$$\mu_j = \frac{p_j \alpha^2 (DV_j)^2}{2(V_{yj})^2} + \frac{1}{2} \qquad (100\text{-}5)$$

The above relationships apply to the initial and the final earthquakes with the appropriate values of DV_j obtained under paragraph (f)2 with the appropriate values of S_a and C_b. The coefficient α may also vary between the two earthquakes if the model changes from damage or deterioration. Using subscripts, the requirements for all stories in each direction are:

$$\mu_{jI} \leq \mu'_{jI} \qquad (100\text{-}6)$$

and,

$$\mu_{jF} \leq \mu'_{jF} \qquad (100\text{-}7)$$

In no story shall the sum of the ratios of μ_{jF}/μ'_{jF} for the transverse and longitudinal directions exceed 1.6.

(g) Redesign. If design changes are made for any reason including the results of analysis under this Section, they shall be done so as to meet (or exceed) all minimum requirements of Section 99, and the design as finally developed must also meet (or exceed) all minimum requirements of this Section.

(h) Connections. All joints and connections shall be capable of resisting the stresses and strains caused by the ductility excursions of the dynamic-inelastic analyses under this Section.

(i) Stability. The overall stability of the building shall be adequate under all the extreme story ductilities μ_{jF} assumed to exist simultaneously or in any other combination.

(j) Safety Factor. The intent of this Section as outlined in 100(a) is expected to be met in general by this Section. However, there are by necessity some averaged values and some assumptions included, some of which may involve minor conservatism and some none. On the whole, no planned safety factors for the given earthquake spectra have been provided. If and as such may be desired -- and this is recommended -- the values of μ_{jF} should be less than the maximum values allowed by the story models.

CONCLUSION

The tables and figures for the dynamic-inelastic "code" need considerable work to be completed, and the code itself should be considered a draft until these are completed and the whole document is reconciled. In addition, a commentary with examples would be essential. Although more research is needed in such matters as the effective mass of a building and the effective energy absorption on various stories simultaneously, the interim assumptions are generally conservative and the code is possible today. It is also simple to use. It would greatly improve the survival characteristics of proposed buildings and it would reveal existing buildings of high risk.

REFERENCES

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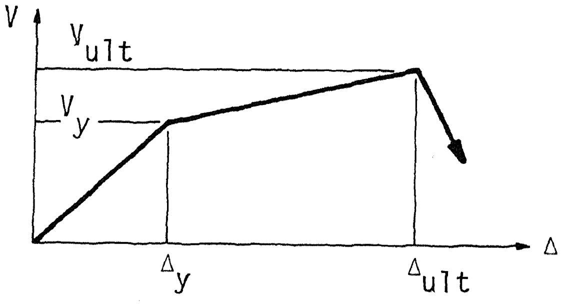
TABLE 100-A would provide (a) factors to change from 5% damped S_a values at various period bands to other damping values such as 2, 3, 4, 6, 7 and 8%; and (b) similar factors except to change from 7% to 4, 5, 6, 8, 9 or 10% damping.

TABLE 100-B would provide data for adjusting the response spectra beyond the 0.5 sec period for dominant site periods associated with deep soil layers over rock. (Shorter site periods would be covered statistically in Figures 100-1 and 100-2.)

TABLE 100-C would provide ductility factor limitations, for the "initial" earthquake and for the "final" earthquake, based on the material and the type of stress, as for example shear in concrete, bar tension in ductile concrete, steel in compression, etc.

FIGURE 100-1 would be a smoothed plot of 5% damped S_a spectra versus period T for the median conditions (50% probability of exceedance) in each region. Each seismic zone would have its own spectral curve, based upon intensive studies of actual earthquake records.

FIGURE 100-2 would be like Figure 100-1 except it would be for 7% damping and be for only 16% probability of exceedance in a 100-year period.



Model	Δ_{ult}/Δ_y	V_{ult}/V_y	α
I	1	1	1
II	2	1	1
III	4	1	1
IV	6	1	1
V	4	1.5	0.90
VI	6	1.5	0.90
VII	8	1.5	0.90
VIII	4	2	0.83
IX	6	2	0.83
X	8	2	0.83
XI	11	1	1
XII	11	2	0.83

FIG. 100-5 Inelastic Story Shear Models