

REDUNDANCY AND RELATIVE EARTHQUAKE RESISTANCE OF TALL BUILDINGS

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SUMMARY

Redundancy and resistance of various types of buildings are compared. Typical story distortions for each type of building are used to estimate relative energy and strength capacities. Although the buildings with larger code "K" factors are strong, they are subject to failure at small story distortions. Multistory, box-type systems are vulnerable to damage and collapse unless their strength is sufficient to cope with real earthquake demands. A combination of redundancy and ductility is indicated for all tall or slender buildings in active seismic areas.

INTRODUCTION

The word "redundant" is defined in Webster's dictionary as "exceeding what is necessary or normal; characterized by or containing an excess; serving as a duplicate for preventing failure of an entire system (as a spacecraft) upon failure of a single component." The last definition is the one most appropriate for describing a means to increase the earthquake resistance of tall buildings. Unfortunately, many designers and builders of tall buildings consider only the other, inappropriate definitions: "exceeding what is necessary or normal, or containing an excess." Still another concept of redundancy pertains to a structural system that is indeterminate or incapable of analysis by the simple equations for static equilibrium. Redundancy is defined in many dictionaries as "superfluous or needless repetition," a definition that is rejected here for tall buildings; in most cases, redundancy is by no means superfluous or needless for survival. Redundancy in buildings may be of two basic types: one provides material beyond that required to meet a code, and the other holds different systems or elements in reserve, allowing them to come into action as the distortion increases. The latter type is of particular interest here.

A ductile moment-resisting frame with infill walls is a doubly redundant system that has been found to be especially effective for earthquake resistance. Many designers have been confused, if not disturbed, by modern code requirements for combined space frames and walls. They have noted that, because of relative rigidity, the frames could not function much, if at all, unless the walls first cracked and yielded. This is precisely what the original authors of such code requirements had in mind: redundancy and reserve ductility, an ideal combination, especially for tall, slender buildings responding to severe ground motion. Redundancy is not to be confused with ductility, although they are often coupled; together they are synergistic. Ductility and reserve energy capacity are much to be desired, especially in tall, narrow structures. When these qualities are provided together with redundant elements, benefits and safety margins are enhanced. Most building codes also permit (if higher lateral forces are used in the design) nonredun-

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dancy in tall, slender buildings, with or without ductility. These buildings should be cause for concern in instances where actual response may exceed -- as well it can -- a level equivalent to the response that is the basis for code requirements. In such cases, there is no redundancy to prevent severe damage or collapse.

In the study reported here, the relative energy-absorption values and story-shear values of various types of buildings, with and without redundancy, are obtained from idealized but realistic models of story-shear distortion.

BUILDING SYSTEMS AND THEIR MODELS

Table I is a list of typical tall building systems and their assumed bi-linear V- Δ data, wherein V is relative story shear and Δ is story distortion. The type of building idealized as model A is a ductile moment-resisting frame, of steel or ductile concrete, with no walls. The frame provides all of the structure's lateral strength and rigidity. This type of building may be subject to considerable drift, but its long fundamental period could place it in a favorable range of the response spectrum, away from the spectrum hump of typical earthquake acceleration spectra. The building is redundant to the extent that its frame can sustain loadings beyond design levels. The K factors listed in Table I are taken from the 1982 *Uniform Building Code* (Ref. 1).

TABLE I - MATHEMATICAL MODEL DATA*

V- Δ Model	Building Type**	Yield Point		Peak Value		K
		V	Δ	V	Δ	
A1	DMR Steel Frame	1.0	0.5	1.0	5	0.67
A2	DMR Concrete Frame	1.0	0.4	1.4	4	0.67
B	Braced Frame	1.0	0.15	1.0	2	1.33
C	Braced Frame & DMR Steel Frame	1.0	0.15	1.0	2	0.80
		0.25	0.5	0.25	5	
D	Eccentric Bracing & DMR Steel Frame	1.0	0.5	1.0	2	0.80
		0.25	0.5	0.25	5	
E	Shear Walls & DMR Steel Frame	1.0	0.1	1.25	0.4	0.80
		0.25	0.5	0.25	5	
F	Shear Walls & Frame	1.0	0.1	1.25	0.4	1.00
		0.1	0.5	0.1	5	
G1	Box, Shear	1.0	0.1	1.25	0.4	1.33
G2	Box, Flexure	1.0	0.1	1.50	0.6	1.33

*Values of V are relative; values of Δ are in inches.

**DMR = ductile moment-resisting.

The building analyzed in model B relies upon braces of some type for horizontal strength. The frame joints are considered to be pinned. If the braces are slender, they function only in tension, and there is no indeterminacy or redundancy. Model C represents buildings with both a moment-resisting frame and a bracing system; thus, there is redundancy and reserve ductility for emergency demands. Model D represents a fairly new type of building; the brace connections are purposely made eccentric to induce more ductility and energy-absorbing capacity into the system. With moment capacity in the frame joints, there is redundancy as well as ductility. This type can also have filler walls.

The building treated in model E has a moment-resisting frame and shear walls. If the walls are well tied to the frame, there is excellent initial resistance, with reserve ductility and redundancy. The tall buildings in San Francisco in 1906 had steel frames, designed to resist wind force, and heavy plain brick walls; a few also had diagonal bracing. Although not designed for seismic loading, the buildings of this type survived the 1906 earthquake without collapse; however, walls cracked and braces failed. Model F is like model E except that it assumes little or no moment resistance in the frame; thus, there is little redundancy for earthquake resistance other than what the walls can provide. The frame, however, may delay or prevent collapse.

Model G represents a box system consisting of walls with no frame at all. The system has no redundancy and has little or no ductility if crushing or shear governs, as in model G1. If failure is in a flexural mode, model G2 would apply. Examples of buildings represented by model G, up to 160 feet in height, do exist in earthquake regions such as Nevada and California. Models E, F, and G are rigid and tend to have short initial fundamental periods which can correspond to typical spectral acceleration peaks. However, because this study is concerned with capacity, variations in spectral demand are not considered here.

The models used in this study are bilinear plots of story shear versus story-shear distortions for the data shown in Table I. The inelastic domain beyond yield is vitally important to the survival of tall buildings in strong earthquakes. The V- Δ performance characteristics can be developed from empirical data and from the results of tests of materials, elements, and scaled or full-size structures. Unless the V- Δ characteristics can be estimated, it is not feasible to predict a building's inelastic response or the risks associated with that response. Table I shows data for the undamaged state, with the initial yield shear in each case normalized to unity. Adjustments for the K factors are made subsequently. Where two or more elements provide shear resistance, there is redundancy, and the sum of those shears at any distortion provides the total shear resistance at that distortion on the first cycle prior to any deterioration. It is assumed in this study that the 1982 *Uniform Building Code* (Ref. 1) applies in design and that, in the base shear formula $V = ZIKCSW$, $ZICS = 1.0$, so that design base shear varies as KW .

It is well recognized by the author that the V- Δ values shown in Table I are estimates involving judgment and that they could vary from case to case or from one person to another. However, in this study, only relative values are used, and the results obtained are intended to be essentially qualitative rather than quantitative. The results for various models vary so much that alternative V- Δ characteristics would not significantly affect the relative findings.

ANALYSIS PROCEDURE AND RESULTS

The procedure used here is an application of the reserve energy technique, RET (Ref. 2, 3, 4), wherein the energy demand, or kinetic energy, based upon 5%-damped spectral velocity, S_v , is related to the work done in building distortion, and the work done is related to the effective area under the shear-distortion, or V- Δ , plots. The areas determined from the bilinear models are multiplied by the applicable K factors, and they are also reduced for inelastic deterioration under reversals and cycling. The deterioration factor, γ_i , varies with distortion, Δ_i , and with the characteristics and geometry of the model; it was estimated from those data and from the shapes of the V- Δ plots. From the RET, and with allowance for K, the effective energy, or work capacity, out to story distortion, Δ_i , is $K(U_i - \gamma_i H_i)$ wherein the subscript i represents the stage of story distortion; U_i is the gross area under the curves to Δ_i ; and H_i is the "hump" area to Δ_i , or the area above a straight line from the origin of the V- Δ plot to the curve at Δ_i . The kinetic energy, which is taken as $(WS_{v_i}^2)/2g$, is equated to $K(U_i - \gamma_i H_i)$. With S_{v_i} taken as a constant value, the story shear capacity is proportional to $[K(U_i - \gamma_i H_i)]^{1/2}$. These two terms are investigated for various models and various degrees and types of redundancy and ductility. In all cases the *total* value, based upon the sum of all values of nondeteriorated resistance at each Δ_i , were used to obtain the relative energy and shear values.

Figure 1 shows, for the model of each building type, the relative value of energy capacity versus story distortion. By energy capacity is meant the ability to store energy and to do work. In each case, allowance has been made for the K factor and for deterioration under cycling. Figure 2 is the square root of the energy value plotted against distortion; this plot is therefore relative to shear value or lateral-force capacity. All distortion values shown should be truncated for P- Δ effects, clearances, or other secondary conditions.

Table II is a sample of computation. The deterioration factors were varied with distortion and also from model to model.

TABLE II - MODEL A2: DMR CONCRETE FRAME (K = 0.67)

Δ_i	γ_i	U_i	H_i	$(U_i - \gamma_i H_i)$	$K(U_i - \gamma_i H_i)$	$[K(U_i - \gamma_i H_i)]^{1/2}$
0.10	0	0.0125	0	0.0125	0.0084	0.092
0.25	0	0.0781	0	0.0781	0.0523	0.229
0.40	0	0.200	0	0.200	0.134	0.366
0.50	0.02	0.300	0.05	0.299	0.200	0.448
1.00	0.05	0.820	0.287	0.806	0.540	0.735
2.00	0.10	1.942	0.764	1.866	1.250	1.118
3.00	0.15	3.176	1.242	2.990	2.003	1.415
4.00	0.20	4.520	1.720	4.176	2.798	1.673

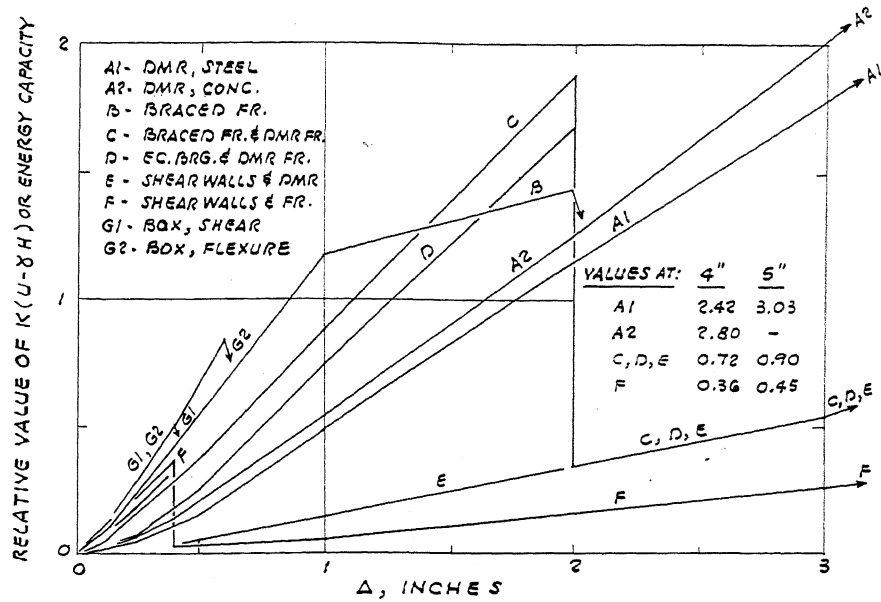


Fig. 1 - Relative Energy Capacities

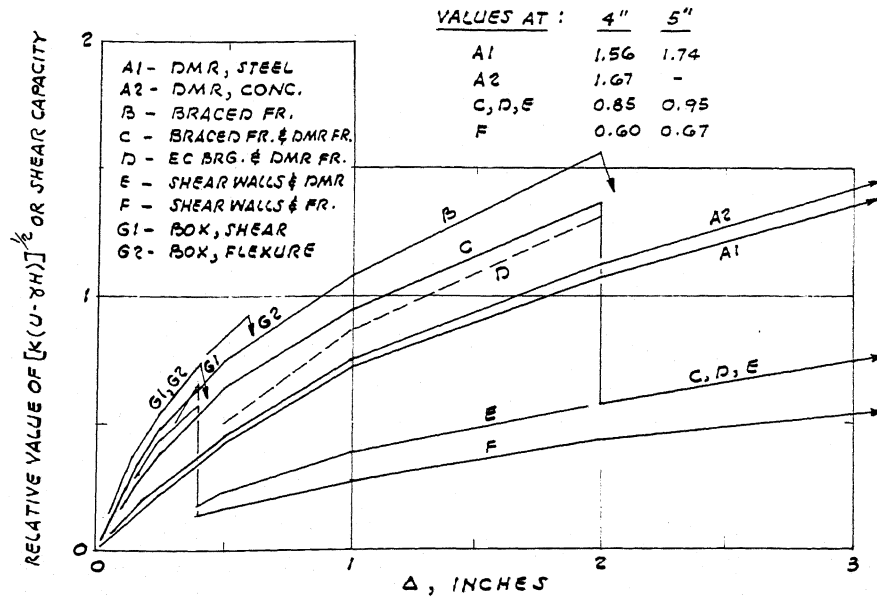


Fig. 2 - Relative Shear Capacities

Table III shows peak relative energy values and peak relative shear values with corresponding peak story distortion.

TABLE III - PEAK RELATIVE ENERGY AND SHEAR VALUES*

V-A Model	Maximum Distortion (inches)	Peak Relative Energy Value	Peak Relative Shear Value
A1	5	3.03	1.74
A2	4	2.80	1.67
B	2	1.43	1.56
C	5	0.90	0.95
D	5	0.90	0.95
E	5	0.90	0.95
F	5	0.45	0.67
G1	0.4	0.50	0.71
G2	0.6	0.85	0.92

*Where these distortions are limited by P-A or other effects, the full relative values are not developed but are to be truncated to the limiting distortion (see Figures 1 and 2).

DISCUSSION OF RESULTS

The reason for the survival of many tall buildings, and the failure of some, is evident from Figures 1 and 2. Also obvious is the fact that some types of buildings require considerable distortion, and probable cosmetic damage, to develop the energy (work) capacity needed to avoid failure. The box-type buildings (models G1 and G2) are strong at small distortions but can suddenly reach failure at distortions far below those of the other types. The types of buildings represented by models E and F, having redundancy, are apt to be damaged rather heavily, but collapse is not likely. Because of their redundant elements, buildings represented by models C and D offer more initial resistance, up to a point, than those of model A1 or model A2. Beyond that point, they depend solely upon the reserve frame capacity. Figures 1 and 2 and Table III show much about building capacity and require considerable study. The building code K factors do not provide equality of resistance. Much more than strength is involved in the earthquake problem.

REFERENCES

1. *Uniform Building Code*, 1982 edition, International Conference of Building Officials, Pasadena, California, USA.
2. John A. Blume, "A Reserve Energy Technique for the Earthquake Design and Rating of Structures in the Inelastic Range," *Proceedings*, Second World Conference on Earthquake Engineering, Tokyo, Japan, 1960, Vol. 2, pages 1061-1084.

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APPENDIX

Fig. A shows the general geometry for the reserve energy technique.

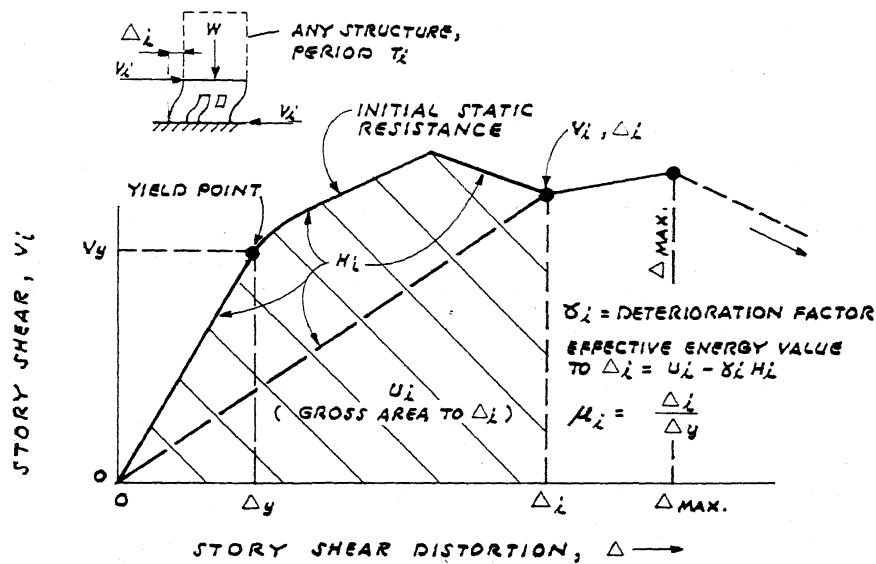


Fig. A - Reserve Energy Geometry

