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PERFORMANCE BASED DESIGN METODOLOGY FOR STRUCTURES

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INTRODUCTION

Design Issues for Structures The traditional approach for structural design is based on a consideration of strength. Factored loads are used to establish the required strength capacity of the structural components. The appropriate component "sizes" are chosen so as to meet these requirements with an additional safety margin included to allow for material strength variation. Once the structure is fully defined, its performance under service loadings is checked. The displacements corresponding to service loadings are usually the primary quantities of interest.

The dominant loading for a structure depends on the function, configuration, and location of the structure. Buildings are subjected to two general types of loadings, "gravity" and "lateral". Wind and earthquake are the most frequently occurring lateral loads. Gravity loads consist of the actual weight of the structure and the material, equipment and people contained in the building. As the building height increases, the lateral loading becomes more important in comparison to the gravity loading, and eventually becomes the dominant design loading. The relative importance of wind vs earthquake depends on the location, building height, and structural makeup. For steel buildings, the transition from "earthquake dominant" to "wind dominant" loading occurs when the building height reaches approximately 100m. Concrete buildings, because of their larger mass, are controlled by earthquake loading up to at least 250m, height. In regions where the earthquake action is low, e.g., the Chicago area of the US, the transition occurs at a much lower height and the design is governed primarily by the wind loading.

Both wind and earthquake loadings are dynamic in nature and produce time varying response. The critical performance measures are related to the motion of the building and pertain to human (and equipment) comfort and structural damage. For service load conditions, the structural performance measure is expressed as a constraint on inter-story displacement; human comfort is defined by a limiting value for the peak acceleration. For extreme load conditions, inelastic deformation of the structure is the primary design constraint; structural performance is expressed as a "desired" distribution and magnitude of structural damage (inelastic deformation) throughout the building height. Structural damage is the key measure for earthquake dominant design; peak acceleration tends to be the controlling criterion for wind-dominant design. Table 1 shows the variation of peak acceleration with structural damping for a "typical" building and different wind conditions. The design specification for acceleration is in the region of 1-2% for service wind loading. Substantial structural damping is required to meet this constraint.

A Motion Based Design Approach The normal design approach generates an initial estimate of the structural components using strength requirements based on factored loads, and then checks for the inter-story displacement and peak acceleration under service loads. Iteration is usually required to satisfy the drift (inter-story displacement) and acceleration constraints for tall buildings. Drift under service loads depends mainly on the structural stiffness. The acceleration is governed primarily by the energy dissipation capacity of the structure (i.e., structural damping). Drift under the extreme loading is influenced somewhat by stiffness and damping, but is largely controlled by the inelastic energy adsorption capacity of the structure. A strength-based approach to preliminary design lacks the ability to deal with drift, acceleration, and damage in an effective manner. A more rational design approach is needed, especially for building heights in the range where wind and earthquake effects are of equal importance. Such an approach must support the integration of multiple performance objectives such as drift, acceleration, and damage with the more traditional concern of structural integrity (strength).

	Frequency of Occurrence			
	1/100 in one year		1/10 in one year	
	max. acceleration	fraction of critical damping required	max. acceleration	fraction of critical damping required
across-wind response	1%g 2%g 3%g 8.8%g	77.6% 19.4% 8.6% 1%	1%g 2%g 3%g 4.5%g	20.7% 5.2% 2.3% 1%
along-wind response	1%g 2%g 3%g 5.7%g	32.8% 8.2% 3.6% 1%	1%g 2%g 3%g 3.12%g	9.8% 2.4% 1.1% 1%

Table 1

Notes:

- 200 x 50 x 30 m. building located in suburban area
- average density of building = 176 kg/m^3, fundamental frequency = 0.17 Hz
- meterology data is of Toronto, Canada
- calculation based on the National Building Code of Canada

A framework for performance based design has been presented by Albano (1). The methodology combined systems theory with Suh's Principles of Axiomatic Design to synthesize and evaluate design alternatives in a rational manner. The starting point of the approach is the identification of the performance objectives, which are treated as the functional requirements for the product. Design variables are then chosen to satisfy the functional requirements. Selection of the design variables is the key step. Experience has shown that "good" designs are characterized by a one-to-one correspondence between the functional requirements and the design variables, i.e., each functional requirement is satisfied by a single distinct design variable. Coupling between the functional requirements and the design variables generally makes it more difficult to accommodate changes in the functional requirements and to converge on an acceptable design. Applying the performance based approach to the building design problem leads to the following set of functional requirements and their corresponding design variables:

Functional Requirements
1. Limit inter-story displacement under service load
2. Limit acceleration under service load.
3. Limit inter-story displacement under extreme load

Design Variables
1. Magnitude and distribution of structural stiffness
2. Energy dissipation capacity.
3. Energy adsorption capacity

The design strategy is as follows. Firstly, the distribution of stiffness, which involves the choice of material stiffness and cross-sectional properties, is established by enforcing the requirements on the magnitude of inter-story deformation corresponding to service loading. The ideal state is "uniform" inter-story deformation throughout the building height. With the stiffness defined, the requirement on acceleration is met by incorporating energy dissipation mechanisms over the height. One possible choice is viscous damping distributed in a manner similar to the distribution of stiffness, i.e., to take damping proportional to stiffness. The last step is to provide for energy adsorption over the height through hysteretic damping. Ideally, one wold like to have uniform "inelastic" inter-story deformation under the extreme load as well as uniform "elastic" inter-story deformation under service load. Hysteretic damping depends on the yield force level and magnitude of inelastic deformation. In this approach, the yield force level is adjusted throughout the height so as to produce the desired "uniform" inelastic inter-story deformation state.

The essential difference between this design approach and the conventional "strength-based" approach is that the structural design parameters are determined by deformation rather than strength requirements. Providing sufficient strength capacity is viewed as a constraint; the actual design requirement is "limiting" the deformation to a specified range.

In the following sections, we apply this design approach to a simple beam, and develop approximate analytical relations for the key design parameters.

A STRAIN BASED APPROACH FOR STIFFNESS

<u>Kinematic relations</u> The expressions for transverse shear and bending deformation are:

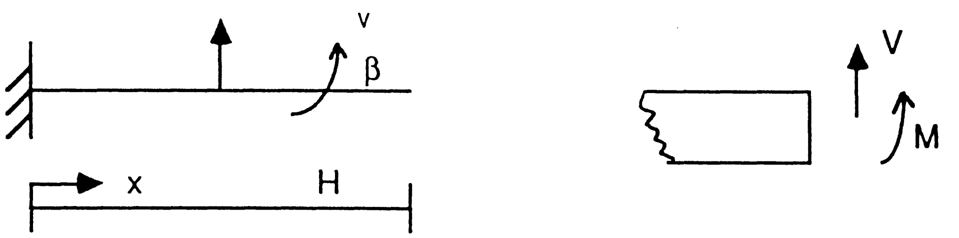

Figure 1

We consider the simple cantilever beam shown in Figure 1. The expressions for transverse shear and bending deformation are:

$$\gamma = v_{,x} - \beta \quad (1)$$

$$k = \beta_{,x}$$

where v,β are the translation and rotation measures. We are interested in the case where γ and k are constant. Setting

$$\gamma = \gamma^* \qquad k = k^* \qquad \gamma^*, k^* \text{ constant} \tag{2}$$

in (1), integrating and enforcing the fixity conditions leads to:

$$v = \gamma^* x + \frac{1}{2}k^* x^2$$
$$\beta = k^* x \tag{3}$$

The deflection at the top of the beam is given by (total length = H)

$$(v)_{shear} = \gamma^* H = v_s \tag{4}$$

$$(v)_{bending} = \frac{1}{2}k^* H^2 = v_b$$

The relative importance of transverse shear vs bending deformation depends on the ratio of γ^* to k^*.

We assume the cross-section consists of a pair of columns with diagonal bracing (see Fig. 2).

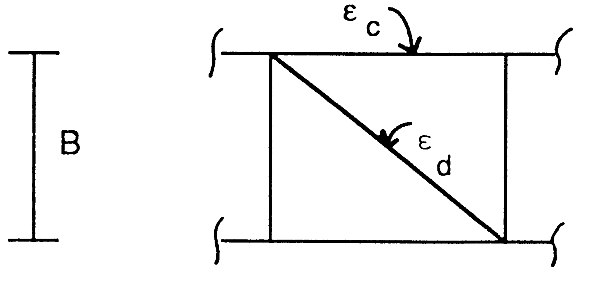

Figure 2

The extensional deformation measures for the column (ε_c) and diagonal (ε_d) are related to γ and k by

$$\varepsilon_c^* = \frac{B}{2}k^*$$
$$\varepsilon_d^* = \frac{1}{2}\gamma^* \quad \text{(for } 45^o \text{ direction)} \tag{5}$$

We introduce a constraint between the column and diagonal extensional strains,

$$\varepsilon_d^* = f\,\varepsilon_c^* \tag{6}$$

where f is a constraint. Typical values of f range from ≈ 3 (elastic) to 6 (inelastic). Substituting (5) in (6) results in :

$$\gamma^* = fBk^* \tag{7}$$

Returning to equation (4), the ratio of the displacement contributions from shear and bending becomes

$$\frac{v_s}{v_b} = 2f\,\frac{B}{H} \tag{8}$$

For tall buildings, (H/B) $\approx 5 \rightarrow 7$ and v_s/v_b is of order unity.

Force - deformation relations We assume linear visco-elastics relations for shear and moment

$$V = D_T\,\gamma + D_T'\gamma_{,t}$$
$$M = D_B\,k + D_B'\,k_{,t} \tag{9}$$

For periodic response, we work with complex stiffness measures

$$V = \widetilde{D_T}\,\gamma$$
$$M = \widetilde{D_B}\,k \tag{10}$$

Equilibrium Equations

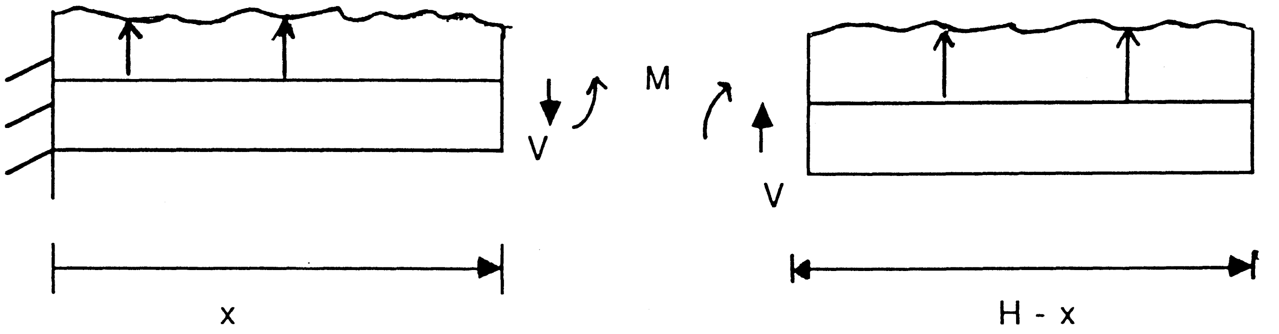

Figure 3

The integral forms of the equilibrium equations are (see Fig. 4 for notation)

$$V = \int_x^H b\,dx$$
$$M = \int_x^H V\,dx \tag{11}$$

where

$$b = \bar{b} - mv_{,tt} - cv_{,t} \tag{12}$$

We are assuming a linear viscous drag force.

Strategy for static loading

Once the loading, $\bar{b}$, is specified, we can determine the transverse shear and bending moment distributions using (11). Then, we can determine the required stiffness distributions throughout the beam length by specializing (9) for static loading and constant deformation. The resulting relations are:

$$D_T = \frac{V}{\gamma^*}$$

$$D_B = \frac{M}{k^*} \tag{13}$$

For example, taking a uniform loading which is reasonable for simulating the wind action on a tall building,

$$V = b_0 (H - x)$$

$$M = \frac{b_0}{2} (H - x)^2 \tag{14}$$

and

$$D_T = \frac{b_0(H-x)}{\gamma^*} = \frac{b_0 H}{\gamma^*} \left(1 - \frac{x}{H}\right)$$

$$D_B = \frac{b_0 (H-x)^2}{2k^*} = \frac{b_0 H}{2\gamma^*} \left(1 - \frac{x}{H}\right)^2 H^2 \left[f\frac{B}{H}\right] \tag{15}$$

Typical values for γ^*, f, and aspect ratio are:

$$\gamma^* \approx \frac{1}{400} \qquad f \approx 3 \qquad \frac{B}{H} \sim \frac{1}{6}$$

They correspond to

$$v_{top} \approx \frac{H}{200} \qquad \text{(service load displacement)}$$

One would use these typical values together with b_0 and H to establish the appropriate value for D_T at x = 0. We discuss later how to modify the stiffness distributions near x = H.

<u>Strategy - Free Vibration Case</u> We work with elastic force-deformation relations (neglect damping) and consider only the inertia term in the external loading.

$$b = - m v_{,tt} \tag{16}$$

Then, the equations for D_T and D_B reduce to

$$V = -m \int_x^H v_{,tt}\, dx = D_T \gamma \tag{17}$$

$$M = \int_x^H V\,dx = D_B\,k$$

We specify the deformation measures to be constant along the x direction and vary periodically with time.

$$\gamma = \bar{\gamma}^* e^{i\Omega t} \qquad k = \bar{k}^* e^{i\Omega t} \tag{18}$$

where $i = \sqrt{-1}$ and Ω is the circular frequency in radians. The displacement measures follow from (3)

$$v = e^{i\Omega t}\,\phi(x) \qquad \beta = e^{i\Omega t}\,\psi(x) \tag{19}$$

where

$$\phi(x) = H\bar{\gamma}^*\left[\frac{x}{H} + \frac{1}{2}\left(\frac{\bar{k}^* H}{\bar{\gamma}^*}\right)\left(\frac{x}{H}\right)^2\right]$$

$$\psi(x) = H\bar{\gamma}^*\left[\frac{1}{H}\left(\frac{\bar{k}^* H}{\bar{\gamma}^*}\right)\frac{x}{H}\right] \tag{20}$$

$$\frac{\bar{k}^* H}{\bar{\gamma}^*} = \frac{1}{f}\left(\frac{H}{B}\right)$$

Using Equations (17 - 20), one obtains

$$D_T = \frac{m\Omega^2 H^2}{2}\left\{1 - \left(\frac{x}{H}\right)^2 + \frac{1}{3}\left(\frac{\bar{k}^* H}{\bar{\gamma}^*}\right)\left[1 - \left(\frac{x}{H}\right)^3\right]\right\}$$

$$D_B = \frac{m\Omega^2 H^2}{2}\,H^2\left\{\frac{1}{4}\left[1 - \frac{4}{3}\frac{x}{H} + \frac{1}{3}\left(\frac{x}{H}\right)^4\right] + \frac{1}{3}\left(\frac{\bar{\gamma}^*}{\bar{k}^* H}\right)\left[2 - 3\frac{x}{H} + \left(\frac{x}{H}\right)^3\right]\right\} \tag{21}$$

We determine D_T at x = 0 by specifying a "representative" load value, V_R, and a "representative" deformation value, γ_R.

$$D_T\big|_{x=0} = \frac{V_R}{\gamma_R} \equiv D_{T,0} \tag{22}$$

Then, the fundamental frequency is given by

$$\frac{m\Omega_N^2 H^2}{2}\left\{1+\frac{1}{3}\left(\frac{H}{fB}\right)\right\}=D_{T,0} \tag{23}$$

It should be noted that this solution is the <u>exact</u> solution for the fundamental mode shape and frequency.

Equations (21) requires zero stiffness at the top (x=H). Although this result is theoreticaly correct, one would normally incorporate some stiffness in this region. Numerical studies were carried out for modified stiffness distributions based on including a fraction of the base stiffness, ranging from 0 to .25. Results show that the effect on the deformation distribution is small away from the top zone.

A DAMPING BASED APPROACH FOR ACCELERATION

<u>Weighted Residual Formulation - Modal Equations</u> We need first to establish a set of modal equations which incorporates viscous and inelastic effects. Our starting point is the Principle of Virtual Displacements specialized for the beam problem,

$$\int_0^H \left(M\delta k + V\delta\gamma\right) dx = \int_0^H \left(b - mv_{,tt} - cv_{,t}\right)\delta v dx \tag{24}$$

We express the displacements in terms of a generalized coordinate, q, and spatial distributions corresponding to "constant" bending and shear deformations.

$$v = q\phi$$
$$\beta = q\psi \tag{25}$$

where

$$\phi = \frac{x}{H}+\frac{1}{2}a\left(\frac{x}{H}\right)^2 \tag{26}$$

$$\psi = a\frac{x}{H^2}$$

The strains are determined with

$$\gamma = q\left(\frac{1}{H}\right)$$

$$k = q\left(\frac{a}{H^2}\right) \tag{27}$$

where

$$a = \frac{kH}{\gamma} = \frac{1}{f}\frac{H}{B} \tag{28}$$

We use the distributions for D_T and D_B defined by (21), which we write below in a more compact form.

$$\bar{x} = \frac{x}{H}$$

$$D_T = D^* \left\{1 - \bar{x}^2 + \frac{1}{3} a \left(1 - \bar{x}^3\right)\right\}$$

$$D_B = H^2 D^* \left\{\frac{1}{4}\left[1 - \frac{4}{3}\bar{x} + \frac{1}{3}\bar{x}^4\right] + \frac{1}{3a}\left[2 - 3\bar{x} + \bar{x}^3\right]\right\} \qquad (29)$$

$$D^* = \frac{m\Omega_N^2 H^2}{2} = \frac{V_R/\gamma_R}{1 + \frac{1}{3}\left(\frac{H}{fB}\right)}$$

The relations for V,M in terms of stiffness are:

$$V = D_T \gamma + D_T^{\prime} \gamma_{,t}$$
$$M = D_B k + D_B^{\prime} k_{,t} \qquad (30)$$

Taking q as the independent variable, and requiring (24) to be satisfied for arbitrary δq yields the following

$$\left(\int_0^H \left[\frac{a^2}{H^4} D_B + \frac{1}{H^2} D_T\right] dx\right) q + \left(\int_0^H \left[\frac{a^2}{H^4} D_B^{\prime} + \frac{1}{H^2} D_T^{\prime}\right] dx\right) q_{,t}$$

$$= \int_0^H [\phi b]\, dx - \left(\int_0^H m\, \phi^2\, dx\right) q_{,tt} - \left(\int_0^H c\phi^2\, dx\right) q_{,t} \qquad (31)$$

We write (31) as

$$M q_{,tt} + C q_{,t} + K q = P \qquad (32)$$

where

$$M = \int_0^H m\phi^2\, dx = mH\left(\frac{1}{3} + \frac{a}{4} + \frac{a^2}{20}\right) = \Gamma_1\, m\, H$$

$$P_{\text{for b const.}} = \int_0^H \phi b\, dx = \frac{b_0 H}{2}\left(1 + \frac{a}{3}\right)$$

$$K = \int_0^H \left[\frac{a^2}{H^4} D_B + \frac{1}{H^2} D_T\right] dx$$

$$K = \frac{2D^*}{H}\left(\frac{1}{3} + \frac{a}{4} + \frac{a^2}{20}\right) = \frac{2D^*}{H}\Gamma_1 \tag{33}$$

$$C = \int_0^H c\phi^2 \, dx + \int_0^H \left[\frac{a^2}{H^4} D_B' + \frac{1}{H^2} D_T'\right] dx$$

<u>Distributed viscous damping</u> We take c = constant, and also specify the viscous stiffness terms to be linearly proportional to the elastic terms.

$$c = \alpha m$$
$$D_T' = \beta D_T$$
$$D_T = \beta D_T \tag{34}$$

The distribution of viscous damping (complex stiffness) has the <u>same</u> form as for the elastic stiffness (see eq. 29) For this choice, the C term simplifies to

$$C = \alpha M + \beta K \tag{35}$$

Introducing the definition of "damping" ratio

$$\zeta = \frac{C}{C_{crit}} = \frac{C}{2(MK)^{1/2}} = \frac{C}{2M\,\Omega_N} \tag{36}$$

and noting (35), results in

$$\zeta = \frac{1}{2}\left(\frac{\alpha}{\Omega_N} + \beta\Omega_N\right) \tag{37}$$

and

$$q_{,tt} + 2\zeta\,\Omega_N\, q_{,t} + \Omega_N^2\, q = \frac{P}{M} \tag{38}$$

For earthquake excitation

$$b_0 = -\,m a_g$$

and the loading term has the following form

$$\frac{P}{M} = \frac{-m a_g \frac{H}{2}\left(1 + \frac{a}{3}\right)}{mH\left(\frac{1}{3} + \frac{a}{4} + \frac{a^2}{20}\right)} = -a_g \frac{1 + \frac{a}{3}}{\frac{2}{3} + \frac{a}{2} + \frac{a^2}{10}} = -\,a_g\,\Gamma_3 \tag{39}$$

For $a = H/fB \approx 2,\ \Gamma_3 \approx 1.$

<u>Consideration of acceleration due to wind</u>

The accelerations are related to the fundamental period and damping ratio by [2]:

$$\text{Cross wind acceleration} \sim \frac{1}{T_{cw}^2} \frac{1}{\sqrt{\zeta_{cw}}} \tag{40}$$

$$\text{Along wind acceleration} \sim \frac{1}{T_{aw}^2} \frac{1}{\sqrt{\zeta_{aw}}}$$

Since the period is fixed by the deformation requirement, the only other design variable that is available for controlling the acceleration is the damping ratio. One decides on the appropriate value acceleration, determines ζ with (42), and selects the combination of α, β with (37). Numerical comparisons are presented in [2].

STRAIN BASED APPROACH FOR ENERGY ADSORPTION

Modal force for inelastic response We need to establish the strength level corresponding to a specified level of damage. Our strategy is to work with an equivalent single degree of freedom model, similar to how we treated damping. For the inelastic case, we take the strain allocation paramter, f, to be in the range of 6 when establishing the magnitude of a.

We take the shear strength distribution to be similar to the shear rigidity distribution

$$V_y = V_y^* f(\bar{x})$$
$$D_T = D^* f'(\bar{x})$$

$$f(\bar{x}) = 1 - \bar{x}^2 + \frac{1}{3} a \left(1 - \bar{x}^3\right) \tag{41}$$
$$f'(\bar{x}) = 1 - \bar{x}^2 + \frac{1}{3} a' \left(1 - \bar{x}^3\right)$$
$$a^* = \frac{1}{f} \frac{H}{b}$$

V_y = shear force at yield
a - inelastics ($f \approx 6$)
a′ - elastics ($f \approx 3$)

The ratio of V_y to D_T is the "yield" transverse shear deformation, γ_e

$$\gamma_e = \frac{V_y}{D_t} = \frac{V_y^*}{D^*} \frac{f(\bar{x})}{f'(\bar{x})} \approx \text{constant} \tag{42}$$

The moment relations are defined in a similar way.

$$D_B = D_B^* \, g'(\bar{x})$$

$$M_y = M^* \, g(\bar{x}) \tag{43}$$

$$g(\bar{x}) = \frac{1}{3}\left[2 - 3\bar{x} + \bar{x}^3\right] + \frac{1}{4} a \left[1 - \frac{4}{3}\bar{x} + \frac{1}{3}\bar{x}^4\right]$$

$$M^* = HV_y^* \qquad D_B^* = \frac{H^2}{a} D^*$$

The ratio of M_y to D_B is the "yield" bending deformation,

$$k_e = \frac{M_y}{D_B} = \frac{M^*}{D_B^*} \frac{g(\bar{x})}{g'(\bar{x})} \approx \text{constant} \tag{44}$$

The left hand side of (24) defines the equivalent generalized force associated with the internal force quantities, V and M. Substituting for V, M and γ, k, one obtains the following:

$$\int_0^H (V\,\delta\gamma + M\,\delta k)\,dx = \delta q \int_0^H \left[\frac{1}{H} V + \frac{a}{H^2} M\right] dx$$

$$= \delta q \int_0^H \left[V^* f(\bar{x}) + \frac{a}{H}\left(HV^*\right) g(\bar{x})\right] d\bar{x}$$

$$= \delta q \int_0^H \left\{V^* \left[f(\bar{x}) + ag(\bar{x})\right]\right\} d\bar{x} \tag{45}$$

$$\equiv \delta\, q\, F_{int}$$

Then

$$F_{int} = V_y^* \left\{\frac{2}{3} + \frac{a}{2} + \frac{a^2}{10}\right\} \equiv F_y \qquad \text{for inelastic behavior}$$

$$F_{int} = K\,q \qquad \text{for elastic behavior} \tag{46}$$

Energy Balance The equation of motion based on the assumed inelastic mode shape has the form

$$M\, q_{,tt} + F_{int} = P_{ext} \tag{47}$$

where

$$M = \Gamma_1\, m\, H$$

$$P_{ext\ for\ earthquake} = -\frac{m\,H}{2}\left(1 + \frac{a}{3}\right) a_g = -\Gamma_2\, M\, a_g \tag{48}$$

$$\Gamma_2 = \frac{1}{2\Gamma_1}\left(1 + \frac{a}{3}\right) \qquad \Gamma_1 = \frac{1}{3} + \frac{a}{4} + \frac{a^2}{20}$$

We define the elastic limit as q_e, and the total displacement as q_T.

$$q_e = H\,\gamma_e$$

$$q_T = (1+\mu)\, q_e = H\,(1+\mu)\,\gamma_e \tag{49}$$

Equating kinetic energy to internal work, we obtain the following relation.

$$\frac{1}{2} M \, |q_{,t}|^2_{max} = \frac{1}{2} K q_e^2 + F_y (\mu \, q_e) = \frac{1}{K} F_y^2 \left(\frac{1}{2} + \mu\right) \tag{50}$$

Following Akiyama's approach [4], the energy associated with an earthquake is expressed in terms of an equivalent velocity, v_{eq}, for a single degree of freedom system.

$$E = \int - M \, a_g \, \dot{v} dt = \frac{1}{2} M \, v_{eq}^2 \tag{51}$$

The appropriate definition for the "modal" equation is

$$q_{,t} \, |_{eq} = \left(\int - 2\Gamma_2 \, a_g \, q_{,t} \, dt \right)^{1/2} = \Gamma_2^{1/2} \, v_{eq} \tag{52}$$

Then, assuming the earthquake energy demand is met by a combination of elastic and inelastic energy capacity,

$$\frac{1}{2} M |q_{,t}|^2_{eq} = \frac{1}{K} F_y^2 \left(\frac{1}{2} + \mu\right) \tag{53}$$

and substituting for mass, stiffness, and modal yield force results in the following expression for the shear strength level as a function of the ductility.

$$V_y^* \approx \left[\Gamma_3 \frac{mD^*}{H} \frac{1}{\frac{1}{2} + \mu} \right]^{1/2} v_{eq} \tag{54}$$

$$\Gamma_3 = \frac{\frac{2}{3} + \frac{a'}{2} + \frac{a^2}{10}}{\left(\frac{2}{3} + \frac{a}{2} + \frac{a^2}{10}\right)^2} \left(1 + \frac{a}{3}\right) \approx (1)$$

Equation (54) gives an estimate of the upper bound on the required shear strength magnitude at the base. It accounts for different values of f as well as for μ.
One specifies μ and v_{eq}. Then, using (54), one obtains an estimate of the strength level required to provide the energy adsorption capacity needed to withstand the earthquake and have the maximum inelastic deformation at or below the specified level. The desired goal is constant inelastic deformation throughout the building height.

Ongoing studies, considering various stiffness and strength distributions, are presently being carried out to assess how close to the desired "inelastic" deformation state can be achieved [3]. Also, the analysis is being extended to handle other types of deformation states, e.g., the bending deformation remains elastic while the shear deformation behaves in an elastic-plastic manner. The above approach assumes elastic-perfectly plastic behavior for both bending and shear.

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