AN ASSESSMENT OF THE ADEQUACY OF THE INDIAN SEISMIC CODE

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ABSTRACT

The computation of the storey forces resulting from earthquake ground motion is the high point of the seismic analysis of multi-storey structures. From available literature, most of the national seismic codes assume the shear frame model for this purpose. This work proposes an improved structural model and shows how to use same to assess the adequacy of the Indian Seismic Code and by extension other national seismic codes that are formulated on the basis of the shear frame model. The improved model considers the effects of flexible horizontal members and column axial loads, two critical factors ignored by the shear frame model. The results show that the effect of flexible horizontal members and column axial loads on seismic response is quite significant and should be incorporated in the seismic codes.

NOTATION

MDOF - *Multi-degree of freedom*

$[M]$ - *Mass matrix*

$\{\ddot{U}\}$ - *Acceleration vector*

$[K]$ - *Stiffness matrix*

$\{U\}$ - *Displacement vector*

$[C]$ - *Damping matrix*

$\{\mathring{U}\}$ - *Velocity vector*

$[\phi]$ - *Mode shape matrix*

M_n - $\{\phi^T{}_n\}[M]\{\phi_n\}$ = *Generalized mass*

L_n $\{\phi^T{}_n\}[M]\{I\}$ = *Earthquake participation factor*

$\ddot{U}_g(t)$ - *Earthquake ground motion*

K - *Performance factor*

W_i - *Weight of floor i*

ϕ_i^r - *Mode shape coefficient at floor I obtained from free vibration analysis*

r - *Mode of vibration*

S_a - *Spectral acceleration value corresponding to the appropriate natural frequency of vibration and damping of the structure.*

β - *Coefficient depending on the soil foundation system*

I - *Importance factor*

F_o - *Seismic zone factor*

g - *Acceleration due to gravity*

N - *Number of storeys*

INTRODUCTION

Most national earthquake codes were formulated based on the shear frame model, [1]. Indeed, earlier works on seismic analysis of ideal frames employed mainly the shear frame (vertical pole) model, [2]. The type of model used in the dynamic analysis of rigid frames greatly influences the results obtained as the stiffness distribution of the frame is dependent on the model used, [3]. The shear frame model disregards the effect of joint rotations and column axial loads on dynamic response of the structure, [1]. The column axial loads may safely be ignored as long as they remain small compared to the critical loads of the columns. When the ratio of the axial loads to the critical loads becomes sizeable, as may be the case in the lower columns of tall rigid buildings, the bending stiffnesses are markedly reduced by the presence of axial compression, such that it may no longer be realistic to neglect the axial loads in determining the bending stiffnesses of the columns, [4]. Verbanov and Capitanov [5] and Osadebe [6, 7] improved on the vertical pole model by taking into consideration the axial load deformation in addition to the lumped masses. But the improved model still shared the deficiency that the rigidities of the horizontal members were not considered in the stiffness analysis. It merely summed up the rigidities of the vertical members at each storey level to give the rigidity of the vertical pole at that storey level.

This paper develops an improved structural model for seismic analysis that incorporates the effects of flexible horizontal members and column axial loads, and then compares the results from the Indian Seismic Code with those obtained using the improved model. Matrix displacement method of analysis is used on the basis of the stiffness coefficients of axially-loaded beam elements. These stiffness coefficients are obtained as a product of the conventional stiffness coefficients and relevant stability functions which serve as modification factors.

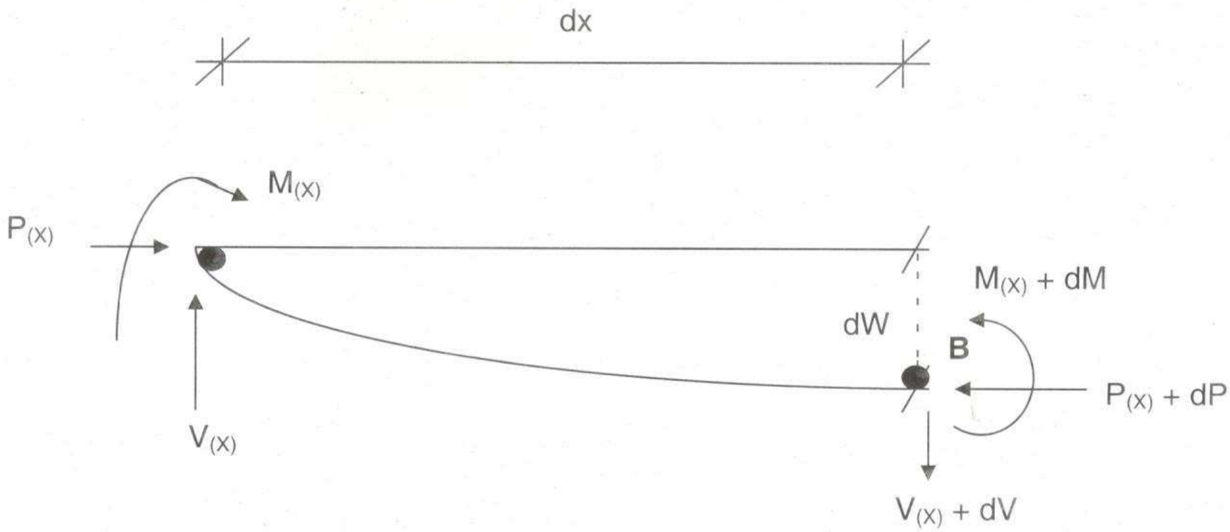

Fig 1: A Section of a Beam-Column.

By considering the equilibrium of the beam-column section shown in Fig. 1 above, the deflection curve is shown to be: [8]

$$W_{(x)} = W_o + \frac{\alpha_o}{k} \text{Sin } kx + \frac{M_o}{EIk^2} (\text{Cos } kx - 1) + \frac{V_o}{EIk^3} (\text{Sin } kx - kx) \qquad (1)$$

where $k^2 = P/(EI)$, and W_o, α_o, M_o and V_o are the initial values.

By applying relevant boundary conditions, the rotational stiffnesses for a fixed-ended beam-column of length L are shown to be:

$$V_o = -\frac{6EI}{L^2} \times F_2(A) = V_L \qquad (2)$$

where $F_2(A) = \dfrac{A^2}{6} \dfrac{(-\text{Cos } A)}{(2\text{-}2 \text{ Cos} A - A \text{ Sin} A)}$

and $A^2 = PL^2/(EI)$ $\quad M_o = 4EI \times F_1(A)$ (3)

where $F_1(A) = \dfrac{A}{4} \dfrac{(\text{Sin } A - A \text{ Cos } A)}{(2\text{-}2\text{Cos} A - A \text{ Sin } A)}$

$$M_L = -\frac{2EI}{L} \times F_3(A) \qquad (4)$$

where $F_3(A) = \dfrac{A}{2} \dfrac{(A - \text{Sin } A)}{(2\text{-}2\text{Cos}A - A\text{Sin}A)}$

For the same fixed-ended beam-column, the translational stiffnesses are shown to be:

$$V_o = -\frac{12EI}{L^3} \times F_5(A) = V_L \qquad (5)$$

where $F_5(A) = \dfrac{A^3 \operatorname{Sin} A}{12(2-2\operatorname{Cos} A - A\operatorname{Sin} A)}$

$$M_o = \frac{6EI}{L^2} \times F_4(A) \qquad (6)$$

where $F_4(A) = \dfrac{A^2 (1-\operatorname{Cos} A)}{6(2-2\operatorname{Cos}A - A\operatorname{Sin}A)}$

$$M_L = \frac{-6EI}{L^2} \times F_4(A) \qquad (7)$$

It is noted that all the stiffness coefficients derived above assume their conventional expressions if the stability functions $F_j(A)$ ($j = 1, 2,3,4,5$), which now serve as correction factors, are assigned unit value,

The actual beam and column stiffnesses are used in computing the stiffness matrix elements.

i.e. $F_j(A) = 1$.

SEISMIC RESPONSE

The equation of motion of the multi-storey building shown in Fig. 2 can be

written as: **[9]**

$$[M]\{\ddot{U}_t\}+[C]\{\mathring{U}\}+[K]\{U\}=\{0\} \qquad (8)$$

The effective earthquake force can be derived by expressing the total displacements as the sum of the relative motions and the displacements resulting directly from the support motions.

i.e $\{U_t\}=\{U\} + \{I\}U_g \qquad (9)$

in which $\{I\}$ represents a column of ones.

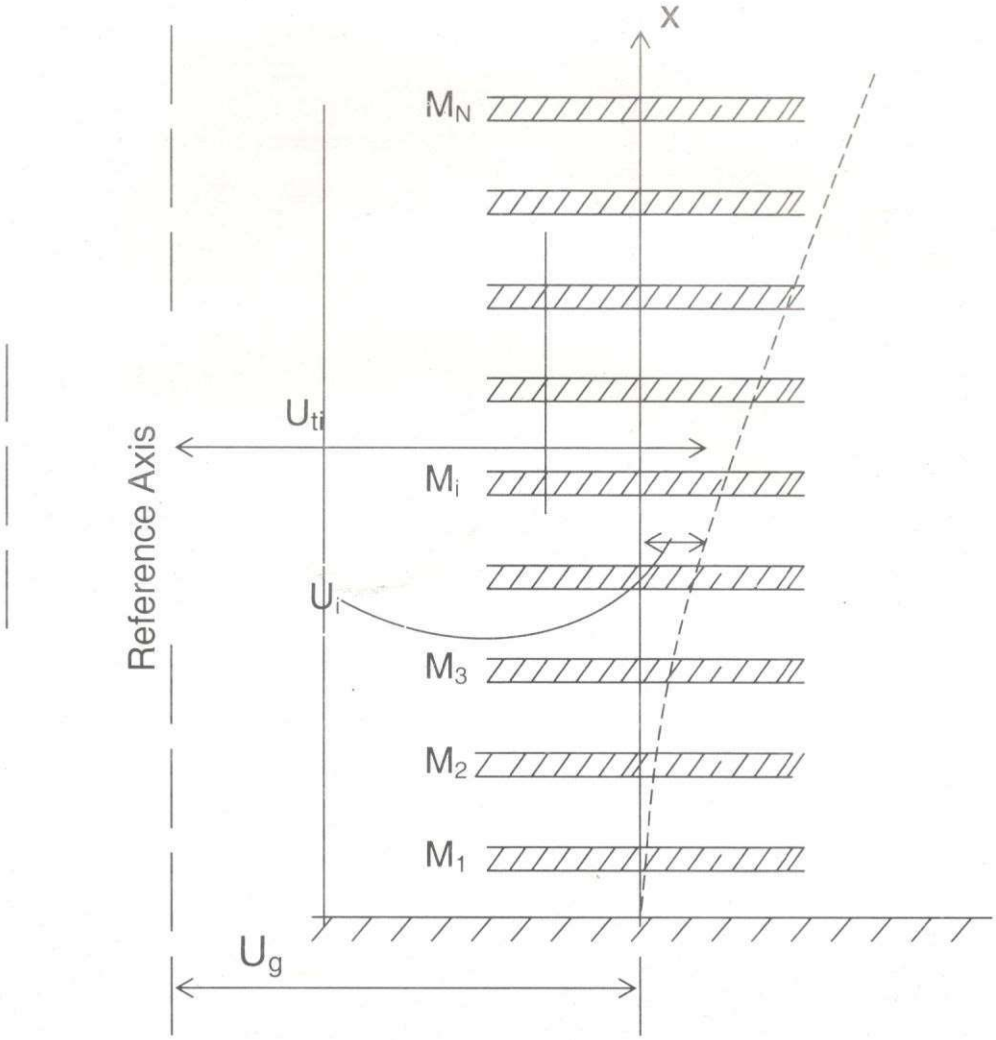

Fig. 2: Lumped MDOF System With Rigid Base Translation

Substituting equation (9) into (8) leads to the relative response equations of motion:

$$[M]\{\ddot{U}\}+[C]\{\mathring{U}\}+[K]\{U\} = \{F_{eff}(t)\} \qquad (10)$$

in which $\{F_{eff}(t)\} = -[M]\{I\}\ddot{U}_g(t)$

The transformation to normal coordinates leads to a set of N uncoupled modal equations of the form:

$$\ddot{Y}_n + 2\varepsilon_n \omega_n Y_n + \omega^2_n Y_n = \frac{\{\phi^T_n\}\{F_{eff}(t)\}}{\{\phi^T_n\}[M]\{\phi_n\}} \quad (11)$$

Y_n is the amplitude of this modal response.

The generalized force resulting from the earthquake excitation (neglecting the negative sign) is given by:

$$F_n(t) = \{\phi^T_n\}\{F_{eff}(t)\} = L_n\ddot{U}_g(t) \quad (12)$$

where the earthquake participation factor is

$$L_n = \{\phi^T_n\}[M]\{I\} \quad (13)$$

in which [I} is a unit column vector of dimension n. The earthquake participation factor is different for each mode because it contains the mode shape ϕ_n.

Thus, in terms of earthquake ground motion $\ddot{U}_g^{(t)}$,

$$\ddot{Y}_n + 2\varepsilon_n\omega_n Y_n + \omega^2_n Y_n = L_n \frac{\ddot{U}_g(t)}{\{\phi^T_n\}[M]\{\phi_n\}} \quad (14)$$

The response of the nth mode at any time t of the MDOF system demands the solution of this equation for Y_n. This may be done by evaluating the Duhamel integral:

$$Y_n(t) = \frac{L_n}{M_n\omega_n} .V_n(t) \quad (15)$$

where M_n is the generalized mass associated with mode n given by:

$$M_n = \{\phi^T_n\}[M]\{\phi_n\}$$

$V_n(t)$ is the modal earthquake-response integral given by:

$$V_n(t) = \int \ddot{U}_g(\tau)e^{-\varepsilon n\omega n(t-\tau)}\mathrm{Sin}\omega_n(t-\tau)d\tau \quad (16)$$

The relative displacement vector due to all modal responses is obtained by superposition, that is,

$$U(t)=[\phi]\{Y(t)\}=[\phi]\left\{\frac{L_n}{M_n\omega_n} V_n(t)\right\} \quad (17)$$

in which [ϕ] is made up of all mode shapes for which the modal response is excited significantly by the earthquake, and the term in braces represents a vector of such terms defined for each mode considered in the analysis.

The elastic forces associated with the relative displacements can be obtained directly by premutiplying by the stiffness matrix.

$$\{F_s(t)\} = [K]\{U(t)\} =[K][\phi]\{Y(t)\}$$

$$=[M][\phi]\left\{\frac{L_n \omega_n V_n(t)}{M_n}\right\} \quad (18)$$

Equation (18) is a completely forces developed in a damped general expression for the elastic structure subjected to arbitrarily varying ground motions.

INDIAN SEISMIC CODE REQUIREMENTS

The Indian Seismic Code recommends that for multi-storey buildings, the total earthquake response should be determined by using a spectrum curve.

According to this Code, the lateral force Q_i^r acting at any floor level i in the rth mode of vibration is given by the equation: [**10**].

$$Q_i^r = KW_i\,\phi_i^r \frac{\sum_{j=1}^{N} W_j\phi_j^r}{\sum_{j=1}^{N} W_j(\phi_j^r)^2} \cdot \frac{S_a^r\,\beta.I.F_0}{g} \qquad (19)$$

The modal participation factor C^r for mode r is:

$$C^r = \frac{\sum_{j=1}^{N} W_j\phi_j^r}{\sum_{j=1}^{N} W_j(\phi_j^r)^2} \qquad (20)$$

The horizontal force Q_i^r acting at any floor level i in the rth mode becomes:

$$Q_i^r = KW_i\,\phi_i^r\,C^r.\frac{S_a^r\,\beta.I.F_0}{g} \qquad (21)$$

NUMERICAL EXAMPLE

A computer program 'QUAKE', developed for seismic analysis of multi-storey frames possessing axially-loaded vertical and flexible horizontal members [**8**], is used. The storey forces resulting from an earthquake motion for frames of 6, 10 and 15 storeys respectively are computed using (1) the Indian Seismic Code procedure outlined above, and (2) the developed computer program 'QUAKE' based on the improved model. The North-South component of the El Centro (California) earthquake is used to simulate the input ground motion, [**11**].

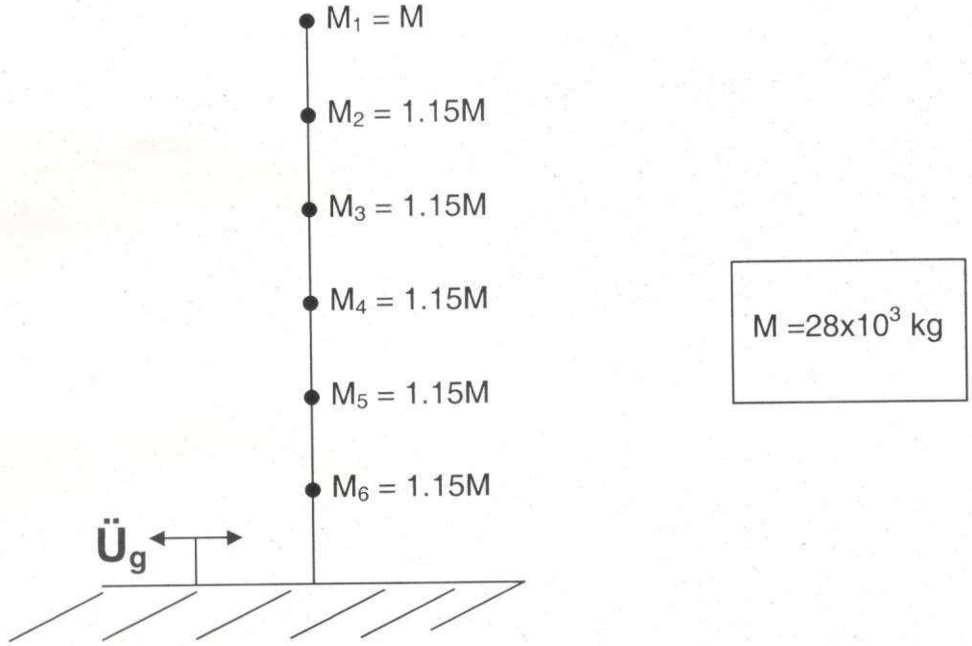

Fig. 3: A 6-DOF system subjected to ground motion

The results are shown in Table 1.

Table 1 : Maximum Storey Forces for 6-storey Frame

STOREY	MAXIMUM STOREY FORCE, KN			
	SHEAR FRAME MODEL	INDIAN SEISMIC CODE	IMPROVED MODEL (Flexible Joints + Axial Loads)	% DIFFERENCE
1	221.5455	221.4548	139.5340	37.0
2	222.9537	222.8795	123.3819	44.6
3	196.8679	196.8023	119.5900	39.2
4	179.5023	179.4239	111.5336	37.8
5	158.1743	158.0873	110.0669	30.4
6	104.1912	104.1120	68.1142	34.6

DISCUSSION OF RESULTS AND CONCLUSION

The validity of the developed computer program 'QUAKE' was first of all confirmed by manual solution of a 3-storey frame, using the improved model, i.e. with joint rotations allowed and column axial loads included, [**1,10,11**]. The results compared accurately with those obtained using 'QUAKE'.

Table 1: show that the results from the Indian Seismic Code procedure compare well with those obtained using the shear frame model, confirming that the Code is actually based on the shear frame model. However, the values obtained using the Code generally represents a lower bound compared to the shear frame model values (0.04% average difference). There is however a significant reduction in storey forces when joint rotations are allowed and axial loads included (generally more than 30% reduction for all the frames analysed).

It can be concluded that the effect of flexibility of horizontal members and column axial loads on seismic response of tall frames is quite significant and should therefore not be ignored by the Indian Seismic Code, and by extension other national seismic codes that are formulated based on the shear frame model. Since reduced storey forces generally imply reduced natural vibration frequencies [**8**], it follows that the adoption of the improved model as the basis for seismic codes will ensure that the vibrating structure is taken further off the resonance range, thereby reducing vulnerability in the event of an earthquake.

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