EARTHQUAKE RESISTANCE OF STRUCTURAL SYSTEMS FOR TALL BUILDINGS

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SUMMARY

This paper presents a qualitative study of the behaviour of some of the commonly used structural systems for the high rise buildings subjected to earthquake forces. The systems analysed are: frame-shear core interactive system,framed-tube system and tube-in-tube system. The percentage of lateral load resisted by each of the constituent systems has been determined for buildings of various heights. The characteristics of the core as a load carrying element and its efficiency as a bracing element have been studied. Recommendations are made regarding the suitability of a system for buildings of various heights.

INTRODUCTION

A pure rigid-frame system, resisting lateral loads primarily through flexure of beams and columns, is unsuitable for concrete buildings higher than 60 m. Beyond this height the sway begins to control the design. The sway can be controlled by the provision of shear walls which interact with the frames and increase the total stiffness of the building beyond the sum of two individual components. This arrangement enhances the suitability of the system to 40 storeys (Ref. 1). For higher buildings, the framed-tube system can be used. In its simplest form the system consists of a closely spaced grid of exterior columns forming the periphery of the building and connected with deep spandrel beams at the floor levels, thereby creating an effect of hollow tube perforated by openings for the windows (Ref. 2). Beyond certain height interior or exterior bracings become necessary for the suitability of the system. One such method of the interior bracing is the provision of interior cores. The resulting system called tube-in-tube system beside possessing necessary stiffness for lateral loads also possesses excellent torsional qualities (Ref. 3).

STRUCTURAL BEHAVIOUR OF SYSTEMS

The framed-tube may be visualized as resisting loads like a huge box section beam cantilevering out of the ground. The stiff floors act as diaphragms distributing the lateral forces to the periphery walls. The overturning due to lateral loads is resisted by the tube causing compression and tension in columns, while the shear due to lateral loads

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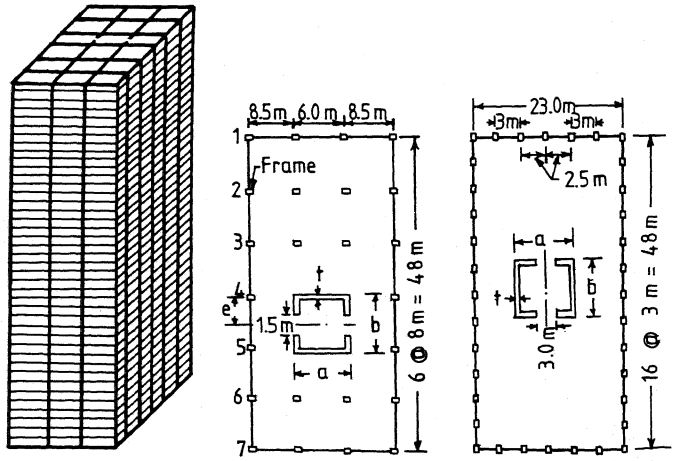
is resisted by flexural action in columns and beams,primarily in two rigid frames parallel to the direction of lateral loads. Therefore, for all practical purposes the bending moments in these columns can be determined by judicious choice of points of contraflexure in each storey. The total deflection of the framed-tube system,therefore, comprises of deflection due to frame action and deflection due to tube action.

The tube-in-tube system has the advantages of both the framed-tube as well as shear-wall type structure. The inner core is designed not only to take gravity load but also a portion of lateral loads. The floor structure tie the exterior and interior tubes together to make them act as a single unit. The response of the core to lateral loads is dependent on its shape, degree of homogeneity and rigidity,direction of lateral load and its location. In general a core has to carry torsion as well as bending and direct shear. The optimal torsional resistance is obtained with closed core sections. At every floor level there are openings in the core, and the amount of continuity provided by spandrels determines the behaviour of the core.



(a)Frame-shear core System (b)Tube-in-tube System

Figure 1. Typical plans for the systems analysed

The total deflection of the frame-shear core interactive system and of tube-in-tube system is obtained by superimposing the individual modes of deformations of constituent systems.

To estimate the optimum range and usage of the three systems to resist earthquake forces, buildings having 20 to 100 storeys on a typical plan with a fixed core area have been analysed.

ANALYSIS OF CORE

Based on translational and rotational shears the wall thickness, t, of the core is given by (Ref. 1):

$$t = \frac{F}{2\, v_c a} \left(1 + \frac{e}{b}\right) \tag{1}$$

where v_c is the permissible shear stress for the concrete mix used and e is the eccentricity of the lateral force, F, with respect to the core centroid; a and b are the core dimensions.

Considering the core to behave as a free standing box section cantilever of variable thickness, the maximum deflection, Δ_c, at the top is computed by using the Newmark's numerical integration technique. The flexural stiffness is given by:

$$k_c = F/\Delta_c \tag{2}$$

ANALYSIS OF FRAME

For a N_s - storey building with B as frame dimension parallel to the direction of lateral force, the base shear, V_B is given by (Ref. 4) as:

$$V_B = I\, \alpha_o\, B\, C\, W \tag{3}$$

The distribution of total lateral force $F = V_B$, along the height of the building, i.e., lateral force Q_i at any floor level, i, is given by:

$$Q_i = V_B \frac{w_i\, h_i^2}{\sum_{j=1}^{N_s} w_j\, h_j^2} \tag{4}$$

For a constant storey height, h, and constant storey weight, w:

$$Q_i = \frac{6\, V_B \cdot i^2}{N_s\, (N_s + 1)\, (2N_s + 1)} \tag{5}$$

Using the approximate portal method of analysis the axial force, N_{ck}, in the column of (k+1)th storey can be shown to be:

$$N_{ck} = \frac{h}{2B} \sum_{i=1}^{N_s - k} Q_{i+k}\, (2i-1) \tag{6}$$

For the axial force in the bottom storey column, k = 0 and

$$N_c = \frac{V_B\, h}{2B\, (2N_s + 1)} \, (3N_s^2 + N_s - 1) \qquad (7)$$

The shear force at any particular level is the sum of all forces above that level:

$$V_{tk} = \sum_{i=k+1}^{N_s} Q_i = V_B \left[1 - \frac{k(k+1)(2k+1)}{N_s(N_s+1)(2N_s+1)} \right] \qquad (8)$$

Moment at kth storey level is given by:

$$M_k = h \left[\sum_{i=1}^{m} Q_{i+k} \cdot i \right]$$

$$= \frac{h.m(m+1)}{12} \left[3m\,(m+1) + 4k\,(2m+1) + 6k^2 \right] \qquad (9)$$

where $m = N_s - k$ = number of storeys above kth storey.

Once the forces are known the sections of the members are designed by limit state method (Ref. 5). The total building sway i.e. the maximum deflection of the rigid frame at the top can be expressed as:

Δ_f = deflection due to bending of beams + deflection due to bending of columns + deflection due to axial deformation of columns

$$= \frac{H\, V_c\, h^2}{12\, E\, I_c} + \frac{H\, V_b\, L^2}{12\, E\, I_b} + \frac{2\, N_c\, H^2}{3\, E\, A_c\, B} \qquad (10)$$

where A_c is the cross-sectional area of external column at the building base subjected to axial force, N_c.

In case of framed-tube, the rigid frame is a part of the tube which itself deforms because of lateral loads. Therefore, the deflection due to axial deformation of column is accounted for while calculating the deflection of the tube, Δ_t, as a whole. However, the deflections, Δ_b and Δ_c, due to deformations of beams and columns, respectively, cause further deflection of entire tube frame.

$$\Delta_{tube} = \Delta_t + \Delta_c + \Delta_b = \Delta_t + \frac{V_c\, h^2\, H}{12\, E\, I_c} + \frac{V_b\, L^2\, H}{12\, E\, I_b} \qquad (11)$$

Therefore, the stiffness of the outer tube $k_{tube} = F/\Delta_{tube}$.

If the total deflection of the inner tube (core) as an independent unit is Δ_{core}, its stiffness is given by:

$$k_{core} = F/\Delta_{core} \qquad (12)$$

The lateral load shared by two constituent systems is proportional to their stiffnesses :

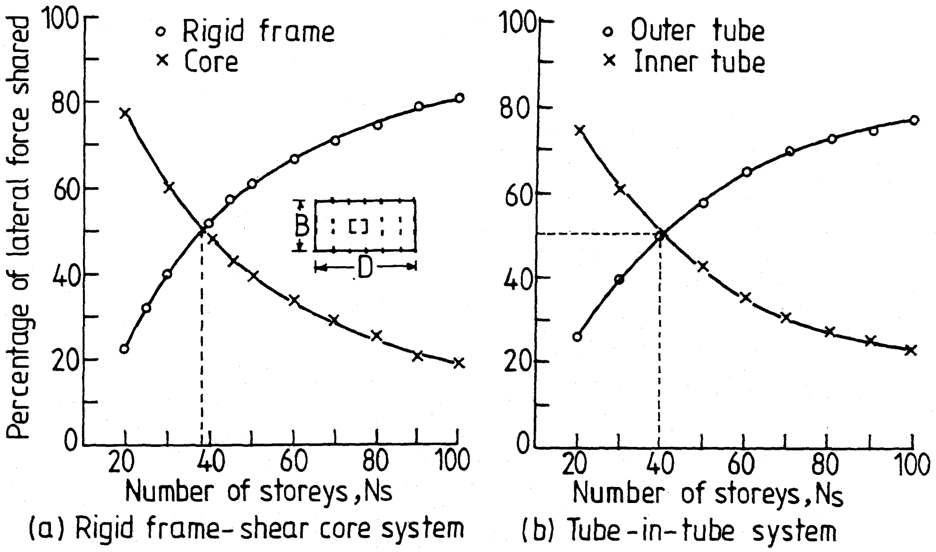
$$F_{tube} = \frac{k_{tube}}{k_{tube} + k_{core}} \quad \text{and} \quad F_{core} = \frac{k_{core}}{k_{tube} + k_{core}} \qquad (13)$$

The total stiffness of the tube-in-tube system is given by:

$$k_{tc} = k_{tube} + k_{core} = \frac{F}{\Delta_{core}} + \frac{F}{\Delta_{tube}} \qquad (14)$$

The deflection of tube-in-tube system is given by:

$$\Delta_{tc} = \frac{F}{k_{tc}} = \frac{1}{1/\Delta_{tube} + 1/\Delta_{core}} \qquad (15)$$



(a) Rigid frame-shear core system (b) Tube-in-tube system

Figure 2: Load shared by constitutent systems

The percentage of load carried by each of the two constituent systems based on rigid diaphragm action of floor structures are given in Figs.(2a) and (2b),respectively. The maximum drifts of two systems are compared with permissible values in Figs. (3) and (5), respectively. Whereas drift of a framed-tube system is given in Fig. (4).

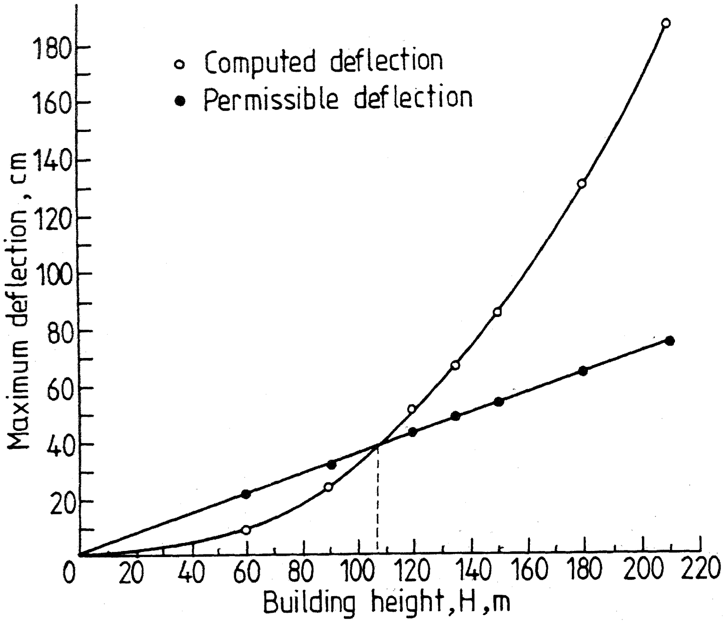
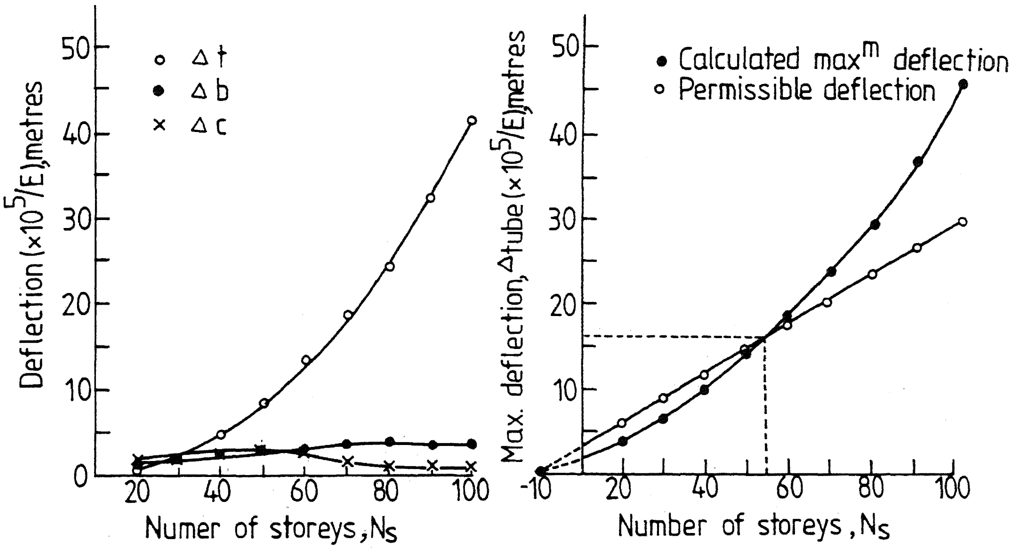


Figure 3. Drift vs height for frame-shear core system

For smaller height buildings using frame-shear core system, the core is stiffer than the rigid frames and resists larger portion of lateral load as indicated in Fig. (2a). The relative stiffness of core decreases with increase in number of storeys. For very high buildings the frames are stiffer than cores and their stiffness ratio varies slowly. The optimal number of storeys in the buildings using this system may be taken as 35, i.e. no additional advantage is gained by the provision of the shear cores in the framed buildings with more than 35 storeys and the design is governed by drift criteria.

In buildings using framed-tube system, upto 30 storeys the major part of the total deflection is due to the bending deformations of columns and beams. For higher buildings, the deflection due to bending of tube as single unit is major contributor as shown in Fig. (4), while contribution due to deformation of columns and beams remain almost constant. Figure (4) reveals that an unbraced framed-tube system is suitable upto 55 storeys (165 m).



(a) Deflection components of framed-tube (b) Maximum total deflection

Figure 4. Drift vs number of storeys for framed-tube system.

For the buildings higher than 60 storeys, the provision of tube-in-tube system should be considered. Upto 40 storey (120 m) height, the inner tube (core) deflection is less than that of exterior framed-tube and the inner tube carries more load. Beyond 40 storey, the load shared by exterior tube increases. Figure (5) indicates that the tube-in-tube system is suitable for buildings upto 90 storeys, beyond which the total deflection exceeds the permissible value (0.0035 H). For still higher buildings the modular or bundled-tube system should be considered.

CONCLUSIONS

The study indicates that the relative stiffness of the cores decreases with increase in number of storeys. Beyond a certain height, the frames are stiffer than the core. This condition differs from the general belief that the cores are always stiffer than the rigid frames. The core-frame interactive system may be recommended upto 35 storeys, whereas framed-tube system is efficient upto 55 storeys and tube-in-tube system upto 90 storeys.

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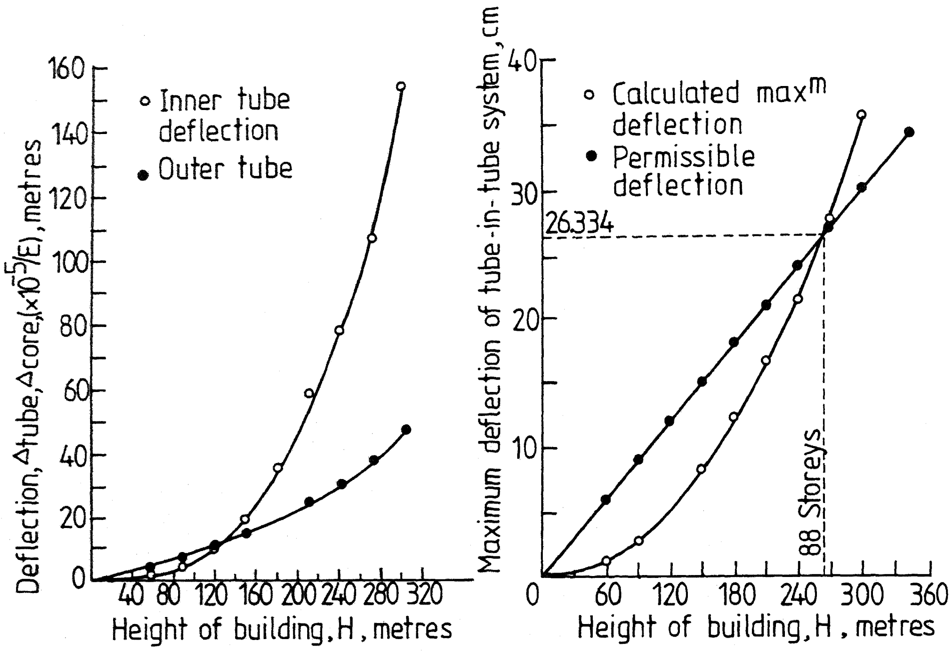

(a). Deflection of outer and inner tubes (b) Maximum total deflection

Figure 5. Drift vs height for tube-in-tube system.

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