Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-7-1

DYNAMIC RESPONSE OF A SETBACK BUILDING WITH A FLEXIBLE FLOOR DIAPHRAGM

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SUMMARY

This paper investigates the dynamic response of a setback building with long and narrow one storey base and symmetric slender tower, including in-plane flexibility of the floor diaphragm. A continuum model is developed to investigate the behaviour of such buildings. It is found that the floor displays significant in-plane flexibility and affects the overall dynamic behaviour. Special attention is needed for the design of columns in tower just above the setback level. Also, the ground storey columns beneath the tower must be designed for forces actually transferred by the flexible floor and not on the basis of overall base shear coefficient.

INTRODUCTION

Buildings with vertical setbacks require careful dynamic analysis. Depending on the structural properties (mass, stiffness, etc.) of the tower and the base, unusually high shear may result at the base of the tower. This high shear has to be transferred by the setback level floor to the frames or walls in the base of the structure. Thus, if setback level floor itself is not rigid in its own plane, further complexity arises. The building configuration studied in this paper consists of a long and narrow base of one storey and a slender tower of three storeys placed symmetrically at the centre of the base (Fig. 1). Thus, the setback level floor is fairly flexible.

Extensive studies have been carried out in the past on buildings with vertical setback (Refs. 1-7) but always with rigid floor diaphragm assumption. Of particular interest, in the present study, is the concept of vertical stepped shear beam (Refs. 1, 4) used for modelling setback buildings. Earlier contributions on buildings with flexible floor diaphragms have been summarized in Ref.(8).

ANALYTICAL MODEL

A continuum model is developed to investigate such buildings (Fig. 2). Similar models have been used earlier for study of other building configurations with flexible floor diaphragms (Refs. 9,10). In the model used here, the setback level floor, being long and narrow, has been modelled as bending (Bernoulli-Euler) beam and the slender tower as shear beam. The ground storey frames have been modelled as distributed shear beam system. Even though a single storey moment resisting frame does not behave like a shear beam, still the overall dynamics of the building can be correctly obtained as long as the frame is being approximated as shear beam of equivalent storey stiffness. As most of the mass is lumped at the floor levels, the only error will be in deflection shape of the ground storey columns.

The coordinate system (x,y,z) is shown in Fig.(2). Equations of motion for free vibration of the system can be written as:

$$k_1^* \, v_{1,yy}(x,y,t) - m_1^* \, v_{1,tt}(x,y,t) = 0 \qquad (1)$$

$$E_2 I_2 \, v_{2,xxxx}(x,t) + m_2 \, v_{2,tt}(x,t) = - k_1^* \, v_{1,y}(x,y = h_1,t) \qquad (2)$$

$$k_3 \, v_{3,yy}(y,t) - m_3 \, v_{3,tt}(y,t) = 0 \qquad (3)$$

in which E_2I_2 is flexural stiffness of the setback level floor; k_1^* is shear stiffness of the ground storey frames or walls per unit length of the building; k_3 is shear stiffness of the tower portion; m_1^* is mass per unit area (in x - y plane) of the ground storey frame system; m_2,m_3 are mass, per unit length, of setback level floor and tower, respectively; 2L is length of the building; h_1 is the height of setback level floor; and H is the total height of the building.

Using symmetry of the structure, only its right half needs to be analyzed. The boundary conditions for symmetric (translation) modes of vibration of the structure are:

(i) $v_1(x, y=0, t) = 0$ (zero displacement at the base)
(ii) $v_1(x,y=h_1,t) = v_2(x,t)$ (displacement compatibility)
(iii) $v_2(x=0,t) = v_3(y=h_1,t)$ (displacement compatibility)
(iv) $v_{2,x}(x=0,t) = 0$ (zero slope at mid-span)
(v) $v_{2,xx}(x=L,t) = 0$ (zero moment at free end)
(vii) $v_{2,xxx}(x=L,t) = 0$ (zero shear at free end)
(vii) $v_{3,y}(y=H,t) = 0$ (zero shear at free end)
(viii) $-E_2I_2 \, v_{2,xxx}(x=0,t) + \frac{1}{2} k_3 \, v_{3,y}(y = h_1,t) = 0$ (force equilibrium)

Eqs.(1,2,3) have been solved (Ref. 11) by the method of separation of variables for these boundary conditions to obtain characteristic equation and mode shape expressions.

EXAMPLE

As an example, consider the building configuration shown in Fig. (1). Following properties of this example structure have been used:

Ground storey distributed shear beam system:
mass (m_1^*) = 1545.6 kg/m^2
shear stiffness (k_1^*) = 2.975 x 10^7 N/m
height (h_1) = 3.50 m
Setback level floor:
mass (m_2) = 5186.0 kg/m
modulus of elasticity (E_2) = 2.21 x 10^{10} N/m^2
moment of inertia (I_2) = 7.29 m^4
length of the floor (2L) = 40.00 m
Tower:
mass (m_3) = 26846.0 kg/m
shear stiffness (k_3) = 3.245x10^8 N
height (H) = 14.0 m.

RESULTS

The results obtained by this model (flexible floor - FF) have been compared with those for rigid floor model (vertical stepped shear beam, VSSB). The periods of first three modes for FF (and VSSB) models are 0.435 sec (0.420 sec), 0.185 sec (0.159 sec) and 0.124 sec (0.114 sec), respectively. Due to floor flexibility, the FF model obviously gives higher periods. The first three mode shapes for FF model are given in Fig. (3). Even though from this figure it may appear that the setback level floor is not undergoing significant in-plane deformation, examination of numerical values clearly indicates that in fundamental mode floor displacement at mid-span is almost 2.25 times that at the end of the span. This, as will be seen subsequently, affects distribution of seismic shear in ground storey frames significantly.

Seismic shear has been calculated for a uniform ground motion characterized by a constant acceleration spectrum value of 0.20g. Table (1) gives tower base shear and total base shear in the structure in first three modes of vibration and the square root of sum of squares (SRSS) values, for FF and VSSB models. Also given in the table are TBSC (Tower Base Shear Coefficient, i.e., ratio of shear at the tower base to total weight of tower) and BSC (Base Shear Coefficient, i.e., ratio of total base shear in the building to total weight of the building). One can see that FF model gives higher tower base shear and total base shear than what is expected from VSSB model. TBSC is much higher than BSC in both FF and VSSB models which indicates that the usual practice of treating tower as a separate structure is very unconservative. If one treats the tower as a separate structure, the base shear coefficient for tower will be of the order of 0.15 for a spectral acceleration of 0.20 g. However, here it is seen that tower base shear coefficient is of the order of 0.20. This warrants for a careful dynamic analysis of setback buildings.

Table (2) gives values of mid frame base shear, MFSC, side frame base shear and SFSC. MFSC is defined as the ratio of shear in centre frame at ground storey times total number of frames in ground storey to total weight of the building and SFSC is the ratio of base shear in end frame times total number of frames in ground storey to total weight of the building. Thus, MFSC and SFSC when compared with BSC indicate the shear being transferred to the middle and the end frames by flexible floor as compared to that due to a rigid floor. SRSS value of MFSC is 0.147 which is about 50% higher than the average value (BSC) of 0.097 for rigid floor model and about 26% higher than the average value of 0.117 for FF model. This result suggests that using total shear to be borne by ground storey and distributing it to the ground storey frames in proportion to their stiffness will lead to unconservative design especially for the centre frame. Thus one can see that it is very important to incorporate floor flexibility for such buildings.

It is also seen in Tables (1,2) that the higher mode contribution is relatively more significant than in a regular building. Also, three modes seem to be adequate for most practical purposes.

CONCLUSIONS

The floor displays significant in-plane flexibility and affects the overall dynamic behaviour. The flexible floor model shows significant in-plane floor deformation in first and third modes of vibration. The columns at the base of tower (just above the setback level) are found to have most severe shear, even more than that in the ground storey columns. This requires special attention of the designer. Also, the ground storey columns just under the tower suffer much larger shear than will be predicted on the basis of rigid floor diaphragm analysis.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the Department of Science and Technology, Government of India.

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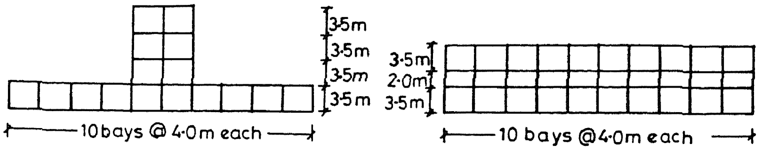
TABLE 1. TOWER BASE SHEAR AND TOTAL BASE SHEAR

Mode No.	Flexible Floor Model				Vertical Stepped Shear Beam Model			
	Tower Base Shear (N)	TBSC	Total Base Shear (N)	BSC	Tower Base Shear (N)	TBSC	Total Base Shear (N)	BSC
I	5.50×10^{5}	0.195	6.90×10^{5}	0.098	5.10×10^{5}	0.181	6.06×10^{5}	0.086
II	5.31×10^{4}	0.019	4.42×10^{5}	0.063	2.87×10^{1}	0.000	3.03×10^{5}	0.043
III	2.79×10^{4}	0.010	3.82×10^{4}	0.005	5.08×10^{4}	0.018	6.74×10^{4}	0.010
SRSS value	5.53×10^{5}	0.196	8.20×10^{5}	0.117	5.13×10^{5}	0.182	6.81×10^{5}	0.097

TABLE 2. SHEAR IN CENTRE AND SIDE FRAMES

Mode No.	Mid Frame Base Shear (N)	MFSC	Side Frame Base Shear (N)	SFSC
I	8.44×10^4	0.132	3.76×10^4	0.059
II	4.08×10^4	0.064	3.94×10^4	0.061
III	9.19×10^2	0.001	6.55×10^3	0.010
SRSS value	9.38×10^4	0.147	5.49×10^5	0.085



Elevation

Plan

Fig. 1 Building Configuration

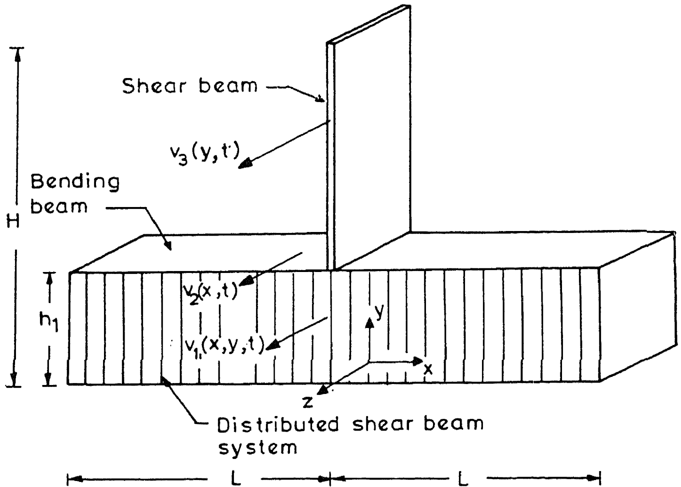
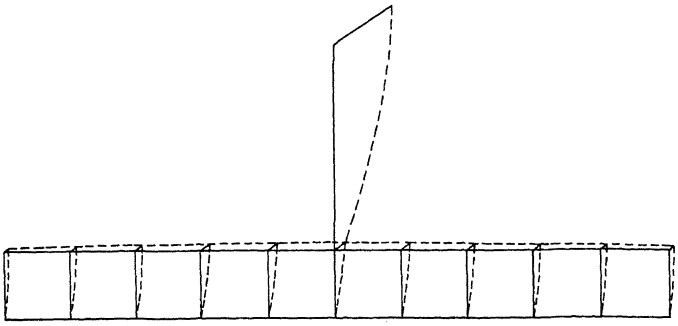
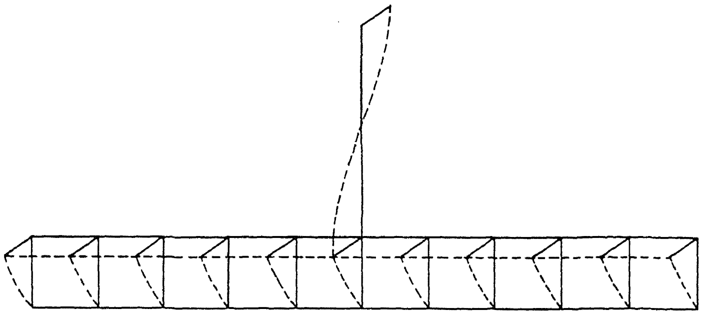


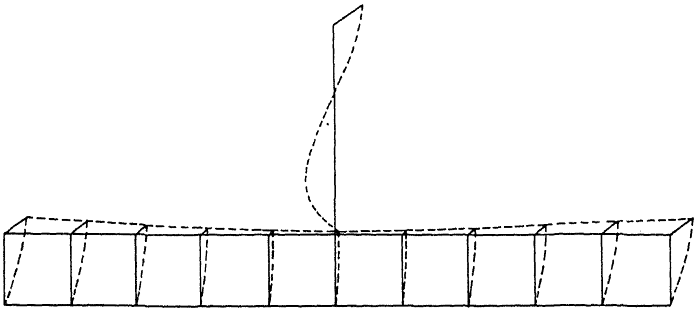
Fig. 2 Analytical Model



FIRST TRANSLATIONAL MODE (T = 0.435 Sec)



SECOND TRANSLATIONAL MODE (T = 0.185 Sec)



THIRD TRANSLATIONAL MODE (T = 0.124 Sec)

Fig. 3 Mode Shapes of the Building