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THE EFFECT OF STIFFNESS DEGRADATION OF SHEAR WALL AND FLOOR HORIZONTAL DEFORMATION ON THE FRAME-SHEAR WALL BUILDINGS

Cuiru YANG and Dahai LIU

China Northwest Building Design Institute
173 West 7th Road , Xi'an , Shaanxi
P. R. CHINA

SUMMARY

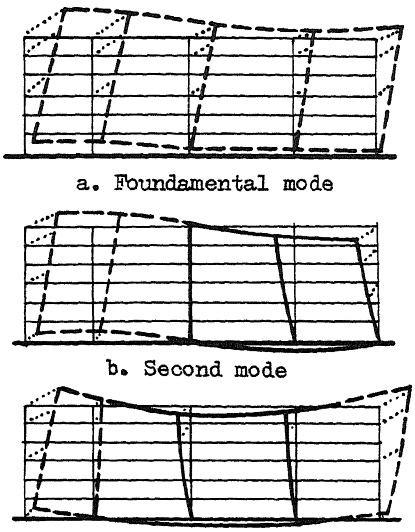
For multistory buildings, based on the ambient vibration modes and earthquake damages a spatial structural mechanical model in consideration of the horizontal deformation of floor slabs is established, and a grid multiple mass system is used in seismic analysis. Because the actual deformation of the frame-shear wall structure far exceeds the elastic limit of the wall during a strong earthquake, the actual stiffness of walls at different strain stages are determined from experimental data. And through the distribution of lateral load, the precise values of maximum seismic forces acting on frames and walls are thus obtained.

INTRODUCTION

During a strong earthquake, the actual deformations of a frame-shear wall structure far exceeds those according to elastic limits of the shear wall, and the reduction of wall stiffness will lead to a corresponding increase of seismic stresses of the frames. Furthermore, it was observed that during the Tangshan Earthquake of 1976, the degree of damage of frames were closely correlated to the distances between shear walls, manifesting the influence of the floor horizontal deformation. All these facts warrant attention in the analysis of frame-shear wall structures.

MECHANICAL MODEL

Recently in seismic response analysis of multistory buildings, the floor slabs are assumed as rigid diaphragms, i.e. the horizontal stiffness of the floorings are assumed to be unlimited. However, it has been verified by the ambient vibration modes, the measurements of the horizontal deflection of the floor slabs and the earthquake damages of the multistory buildings, that the horizontal rigidity of floor slab is not unlimited. The first three vibration modes of the 6-storied building by means of ambient surveying are shown as figure 1. We may find that the floor slabs are also deformable in the horizontal direction from the curves of these modes. Referred to the eleven multistory buildings with fabricated reinforce concrete floor slabs, by surveying the horizontal deformation curves of the slabs under the action of one 10 kN horizontal force and analysing the spatial structure, the equivalent horizontal shear stiffness of the floor slab per unit area is obtained and it is about 1×10^5 kN. In the experimental study of seismic behaviour of 3-storied R/C frame structure, one 40 kN horizontal force is applied on the center of the top floor slab, surveying of the horizontal deflection of the top floor slab is shown as figure 2, the horizontal stiffness of the floor slab obtained from those datas is about 0.95×10^5 kN



a. Foundamental mode

b. Second mode

c. 3rd mode

Fig. 1 Ambient vibration modes of 6-storied building

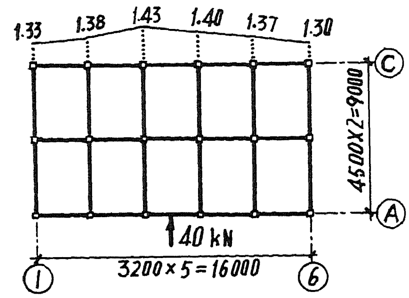


Fig.2 Horizontal deformation of top floor slab

Based on the empirical datas mentioned above, for the seismic response analysis of the frame-shear wall structures, the sketch of the spatial structure as shown in figure 3 should be adopted, and the corresponding "Multi-mass-point Grid System" as shown in figure 4 is employed as the mechanical model.

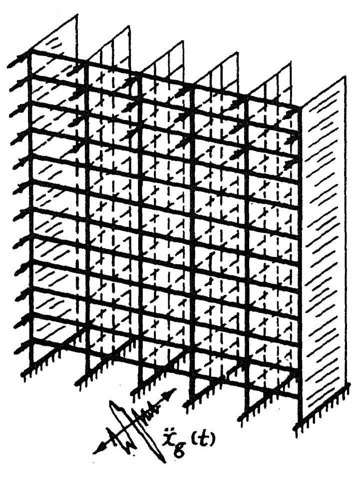


Fig.3 Sketch of spatial structure

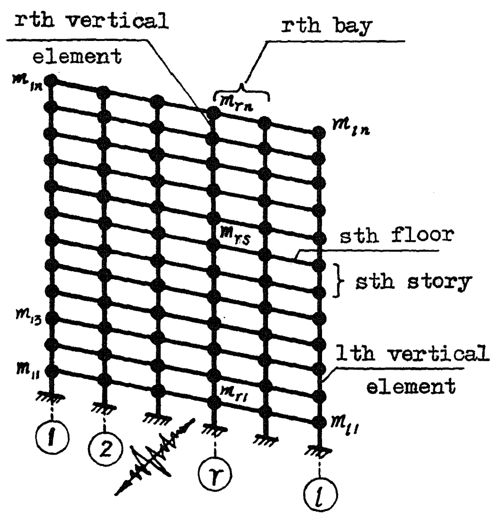


Fig.4 Mechanical model

EQUATION OF MOTION

Under the action of a single component $\ddot{x}_g$ of ground motion, the equation of motion of a "Multi-mass-point Grid System" is

$$[m]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[m]\{\ddot{x}_g\} \quad (1)$$

The equation of motion for the undamped free vibration of a system becomes

$$-\omega^2[m]\{\ddot{x}\} + [K]\{x\} = 0 \quad (2)$$

where

$\{x\}$, $\{\dot{x}\}$ and $\{\ddot{x}\}$ — column vectors of respectively relative displacements, velocities and accelerations of the masses;

$$\{x\} = [\ \{x_1\}^T \quad \{x_2\}^T \ \cdots \ \{x_r\}^T \ \cdots \ \{x_l\}^T\ ]^T$$

$\{x_r\}$ — displacement column vector of rth vertical element,

$$\{x_r\} = [\ x_{r1} \quad x_{r2} \cdots \ x_{rs} \cdots \ x_{rn}]^T$$

$\{\ddot{x}_g\}$ — acceleration column vector of ground motion,

$$\{\ddot{x}_g\} = \{1\}_N \ddot{x}_g \quad , \quad N = nl$$

ω — circular frequency of spatial structure's natural vibration,

$[m]$ — mass matrix, being a diagonal matrix of submatrices of the masses of the vertical elements,

$$[m] = \text{diag}\,[[m_1] \quad [m_2] \cdots [m_r] \cdots [m_l]]$$

$$[m_r] = \text{diag}\,[\ m_{r1} \quad m_{r2} \ \cdots \ m_{rs} \ \cdots \ m_{rn}\ ]$$

$[K]$ — sidesway or deflection stiffness matrix of the spatial structure, being the matrix sum of the vertical element's sidesway stiffness matrix $[K']$ and floor (roof) horizontal stiffness matrix $[k]$, i.e.

$$[K] = [K'] + [k]$$

$$[K'] = \text{diag}\,[[K_1] \quad [K_2] \cdots [K_r] \cdots [K_l]]$$

$$[k] = \begin{bmatrix} [k_{11}] & [k_{12}] & & & & & & \\ [k_{21}] & [k_{22}] & [k_{23}] & & & & 0 & \\ & \cdots & \cdots & \cdots & & & & \\ & & & [k_{r,r-1}] & [k_{r,r}] & [k_{r,r+1}] & & \\ & & & & \cdots & \cdots & \cdots & \\ & 0 & & & & & [k_{l,l-1}] & [k_{l,l}] \end{bmatrix}$$

$[k_r]$ — sidesway stiffness sub-matrix of rth vertical element,

$[k_{r,r+1}]$ — coupling stiffness submatrix involving the stiffnesses of adjacent floors of the same bay for rth and (r+1)th vertical elements.

COMPUTATIONAL PROCEDURE

By utilizing equation (2) and its derived dynamic equation with its eigenvalues, thus obtaining the complete spatial modes $[X_{jl}]$ and corresponding natural periods $\{T_j\}$, it is possible to obtain the structure's earthquake response. The lateral forces of the frames and shear walls may be determined as follows:

1) From the obtained modes $[X_{jl}]$ and periods $\{T_j\}$, and by means of the response spectrum, calculate the earthquake loads on the mass points corresponding to the first several (usually five are needed) modes.

$$[P_{jl}] = Cg[m][X_{jl}][\alpha_j][\gamma_j] \quad (3)$$

$[\alpha_j] = \mathrm{diag}[\ \alpha_1 \quad \alpha_2 \ \cdots \ \alpha_N\ ]$

$[\gamma_j] = \mathrm{diag}[\ \gamma_1 \quad \gamma_2 \ \cdots \ \gamma_N\ ]$

2) The sidesway of the structure corresponding to the first 5 modes are obtained by the sidesway flexibility matrix,

$$[\Delta_{ji}] = [K]^{-1}[P_{ji}] \qquad (4)$$

3) For the jth mode in $[\Delta_{ji}]$, list out the sidesway column vector of the rth vertical element, and post-multiply it by the sidesway stiffness submatrix $[K_r]$ of the rth vertical element (as a free body), the horizontal earthquake loads on the rth vertical element is

$$\{F_{ji}\} = [K_r]\{\Delta_{jr}\} \qquad (j = 1, 2, \cdots, 5; \ \ r = 1, 2, \cdots, l) \qquad (5)$$

4) Superpose the first five modal story shears and moments by the conventional "SRSS" method, thus obtaining the design internal forces of the members for checking purpose.

RESULTS OF SPATIAL ANALYSIS

106 frame-shear wall structures of various storeys, shear wall spacings and earthquake intensities are taken as case study. The results obtained have been systematically examined, and the following points are presented for reference of the engineer.

SPATIAL MODES The first four vibration modes of 8-storied and 30-storied frame-shear wall buildings are shown respectively in figure 5 and figure 6. Their figurations are similar to those as shown in figure 1.

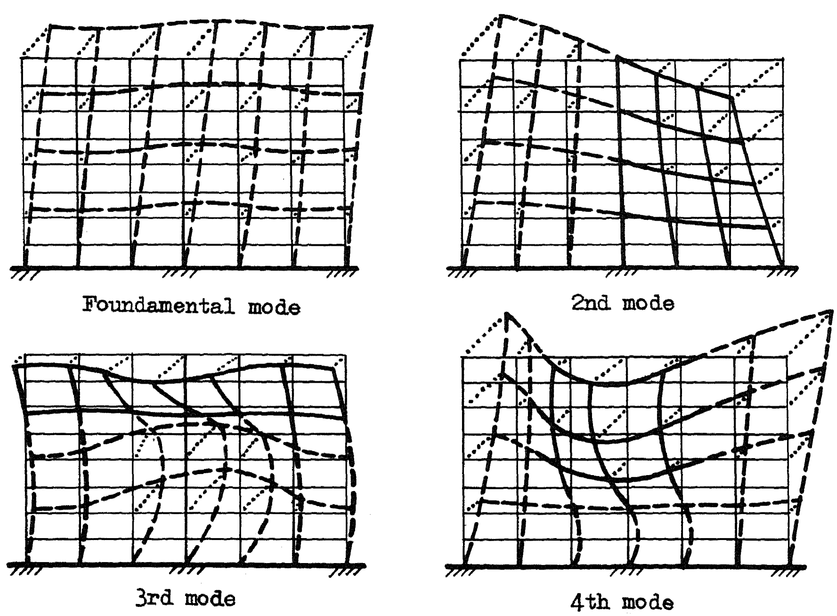


Fig.5 Calculated modes of 8-storied building

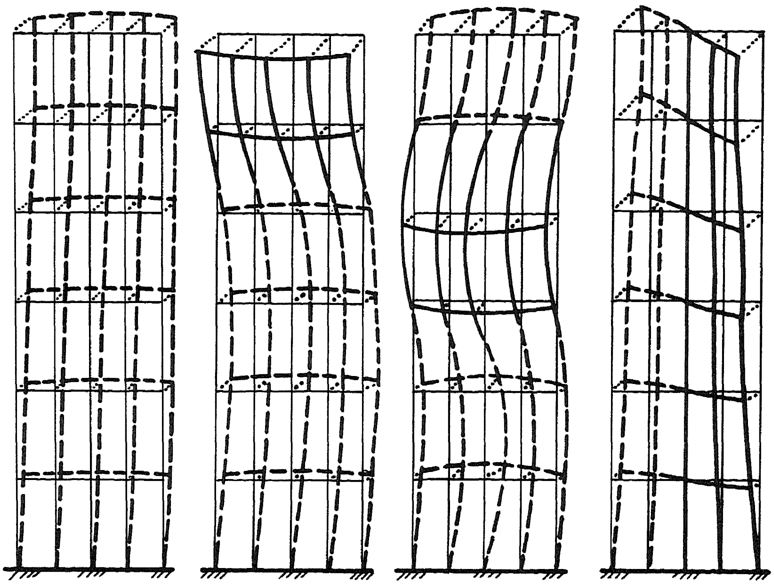


Fig.6 Calculated modes of 30-storied building

STORY SHEAR OF FRAMES Results obtained for 10-storied to 30-storied frame-shear wall buildings under an earthquake of intensity scale 8 show that for shear wall spacing/building width ratio equal to 2, the maximum increases of seismic stress at the middle frame are listed in table 1.

Table 1 Increase of story shear force due to horizontal deformation of floorings

No. of story	Stories of building				
	10	15	20	25	30
Top story	113 %	118 %	114 %	103 %	95 %
Middle story	116 %	107 %	103 %	102 %	102 %
2nd story	106 %	103 %	101 %	101 %	101 %
1st story	236 %	228 %	216 %	200 %	190 %

STIFFNESS DEGRADATION OF SHEAR WALL

During a strong earthquake, the actual deformations of a frame-shear wall structure far exceeds those according to elastic limits of the shear wall, and the reduction of wall stiffness will lead to a considerable increase of seismic stresses of frames. In seismic analysis of highrise frame-shear wall structures, the current specification stipulated that the story shear forces of the frame resulting from elastic deformation compatibility shoud be adjusted by multiplying a factor of 1.5 . From the point of view of inelastic strain of wall, this stipulation seems to be rather rough and unsafe.

Matrix displacement method is used for seismic analysis of highrise frame-wall structures with different stories, different wall spacings and different earthquake intensities. The actual stiffness of aseismic walls at different deformation stages are determined from experimental data. Through the distribution of lateral load, the precise values of maximum seismic forces acting on frame and on walls at each story are thus obtained.

The lateral load-displacement relationships of the shear wall and the frame are shown respectively as figure 7 and figure 8. By comparising these two pictures, it is evident that for R/C shear wall and frame the elastic limit of the angle of story drift are respectively about 0.25×10^{-3} and 2×10^{-3}. While the actual angle of story drift of a frame-shear wall structure approaches 2×10^{-3} under the action of strong earthquake ground motion, the strain of the frame is still located at the elastic range, but the strain of the shear wall far exceed its elastic limit and its lateral stiffness has a great degradation. According to these actual stiffness of walls and frames, the story seismic shear force of the frame is increased to be three times that the stiffness degradation of wall is not considered. Taking into account the stiffness degradation of the walls, for 8∼30 storied buildings with frame-shear wall structure the increase of story seismic shear force of frames are shown as table 2.

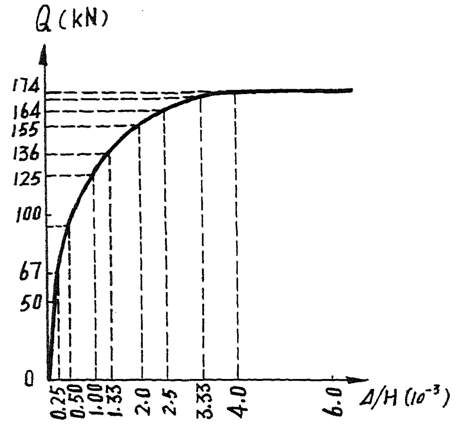


Fig.7 Lateral load-displacement relationship of shear wall

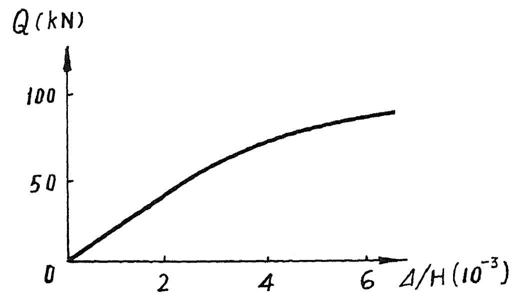


Fig.8 Lateral load-displacement relationship of frame

Table 2 Increase of story shear force due to stiffness degradation of shear wall

Angle of story drift (Δ/H)		1/1000	1/750	1/500	1/300
Stiffness degrading factor C_w		0.5	0.4	0.3	0.2
No. of story	Top story	170 %	200 %	240 %	300 %
	Middle story	180 %	220 %	260 %	350 %
	1st story	190 %	240 %	300 %	420 %

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