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BEHAVIOUR OF INFILLED FRAMES WITH OPENINGS STIFFENED BY SURROUNDING FRAMES

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SUMMARY

A method for evaluating the stiffness to horizontal forces of two-dimensional bracing systems with openings is presented. Panels stiffened by surrounding frames and/or by inner frames along the boundary of the opening are also considered. On the basis of numerical results obtained by the finite element method, analytical expressions for panels without stiffening frames have been deduced; for the other cases examined diagrams for practical use are presented. The behaviour of the systems is examined by varying the size, position and mechanical and geometrical properties of the opening. In particular, the results obtained make it possible to balance the stiffness loss of the panel due to the opening, by inserting a stiffening inner frame.

INTRODUCTION

The presence of brickwork or concrete panels in reinforced or steel frames can prove to be decisive in relation to the stiffness of a structure subjected to horizontal loads. This problem has been analysed by several researchers, mostly experimentally, in order to provide simplified models for the evaluation of stiffness and strength (Refs. 1 to 5). The determination of these models is more complex when an opening is present; in this case not many and not very general results are available (Refs. 6,7). The solution is obtained by means of numerical procedures, such as the finite element method (FEM) or the boundary element method (BEM) (Ref. 8).

In Refs. 9 and 10 it is shown that a stiffness loss of 60 to 70 percent can occur because of an opening.

The analysis of the behaviour of a frame stiffened by two-dimensional bracing systems can be carried out by determining first the stiffness and strength properties of the panel and subsequently by analysing the mutual interactions which occur in relation to the type of connection with the frame itself. As regards the first aspect of the problem, in Ref. 11 the phenomenon of the instability that may occur in steel diaphragms is analysed. In this paper, instead, the stiffness of the panel is analysed mostly with regard to systems with openings. In order to obtain very general results, we also consider cases in which the panel is stiffend by a stiffening surrounding frame and/or by an inner frame when an opening is present. These frames are linked to the panel itself along the whole boundary.

STIFFNESS OF PANELS WITH OPENINGS

The analysis of panels subjected to horizontal concentrated loads at the top has been carried out for the schemata shown in Fig. 1.

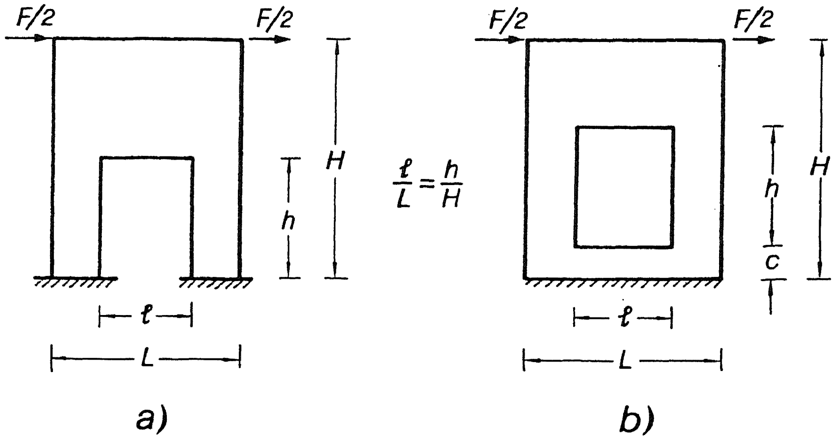

Fig. 1 Structural models of panels with openings

The value of the ratio h/ℓ has been assumed equal to the ratio H/L. Ratios $2/3 \leq H/L \leq 1.5$ have been considered. Therefore, the ratio between the size of the opening and the size of the panel is univocally defined by the parameter ℓ/L. The centroid of the opening is on the vertical symmetry axis of the panel.

Since the stiffness of the system depends on the position of the opening along the height, the parameter $c/(H-h)$, which univocally determines the scheme in Fig. 1, has been considered.

The numerical results obtained show that, given the ratios H/L and ℓ/L, the maximum stiffness values occur in cases in which

$$c/(H-h) = 0 \tag{1}$$

which corresponds to the configuration of Fig. 1a). For these configurations the stiffness D_0 behaves differently in relation to the values of the parameter ℓ/L. Precisely, if the ratio of opening is in the range $0 \leq \ell/L \leq 0.25$, then the presence of the opening has no influence and hence the stiffness of the actual system can be assumed to be equal to the stiffness of the solid panel, which depends only on the parameter H/L. If $0.25 \leq \ell/L \leq 2/3$, the stiffness decreases linearly when ℓ/L increases. In cases in which $\ell/L > 2/3$, the stiffness decreases exponentially. Denoting as t the thickness of the panel and as E_p the modulus of elasticity, the following expressions have been deduced:

$$D_0 = [36.21 \left(\frac{H}{L}\right)^2 - 228.149 \frac{H}{L} + 309.061] \cdot t\, E_p \times 10^{-3} \tag{2}$$

for $0 \leq \ell/L \leq 0.25$

$$D_0 = [36.21\,(\frac{H}{L})^2 - 297.744\,\frac{H}{L} + 438.661 - 518.4\,\frac{\ell}{L}\,(1 - 0.537)]\cdot t\,E_p \times 10^{-3} \quad (3)$$

$$\text{for } 0.25 \leqq \ell/L \leqq 2/3$$

$$D_0 = \{[-1.187\,(\frac{H}{L})^2 + 3.483\,\frac{H}{L} - 2.691][(\frac{\ell}{L})^{-15} - 1] + [1.907\,(\frac{H}{L})^2 +$$

$$- 5.616\,\frac{H}{L} + 4.361][(\frac{\ell}{L})^{-14} - 1]\}\cdot t\,E_p \times 10^{-3} \quad \text{for } 2/3 \leqq \ell/L \leqq 1 \quad (4)$$

Eqs. 2, 3 and 4 provide values which show good approximation, with a maximum error of 10 percent. The curves in nondimensional form deduced from the analytical expressions are compared with the numerical results (FEM) in the diagram shown in Fig. 2

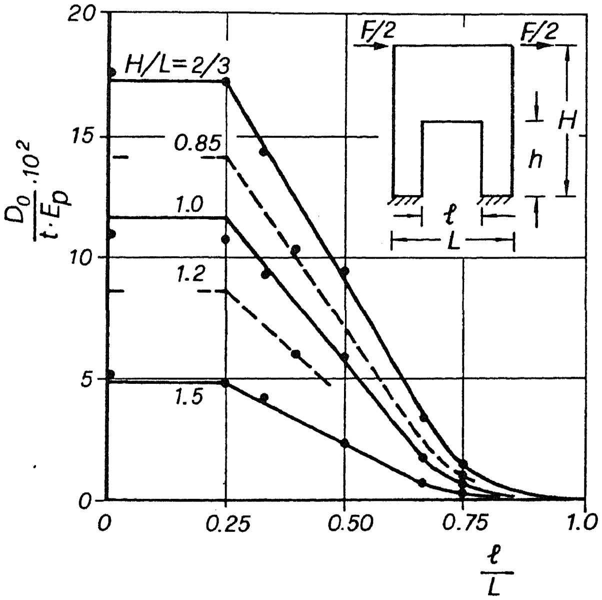

Fig. 2 Comparison between the analytical (———, - - -) and numerical (•) results.

With reference to systems with different positions of the openings (Fig. 1b), from the numerical analysis we have deduced that, given the value of the ratio ℓ/L, the stiffness behaves differently in relation to the parameter H/L. Therefore the ratio between the stiffnesses D and D_0 has been examined for the values H/L = 2/3, 1, 1.5. The analysis has been carried out for the opening ratios ℓ/L = 0,25, 1/3, 0.5, 2/3, 0.75, and the results are shown in Fig. 3. This figure shows that the position of the opening has a big influence on the stiffness of the panel: the loss of stiffness increases when the opening shifts towards the top, until the value c/(H-h) = 0.75 is achieved. On the other hand, this value represents a limiting configuration for the usual systems. Moreover, the influence of the position of the opening becomes more significant as the ratio ℓ/L increases, up to a limiting value of this parameter of order of 0.5 ÷ 0.6, beyond which the curves are almost coincident.

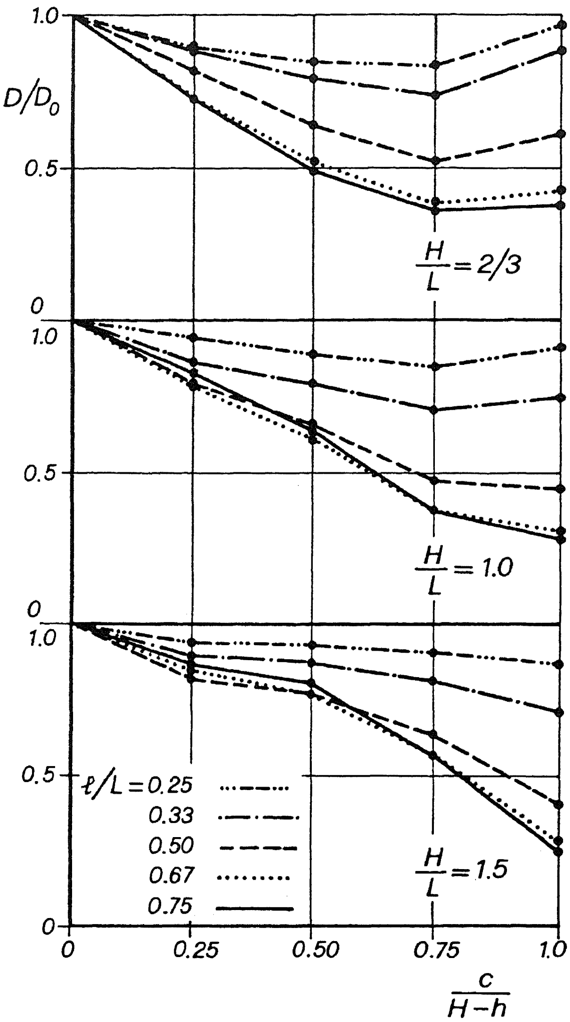

Fig. 3 Stiffness ratio between the systems shown in Fig. 1b) and those in Fig. 1a), versus the position of the opening

PANELS WITH STIFFENING FRAMES

The following systems have been considered: i) panels without openings stiffened by surrounding frames (Fig. 4a); ii) panels with openings and with stiffening frames along the boundaries of the openings (Fig. 4b); iii) panels with openings and with surrounding and inner frames (Fig. 4c).

In all cases the frame is assumed to be of thickness equal to that of the panel and both the frames, if present, to be made of the same material. Three different values of the ratio between the modulus of elasticity of the panel E_p and the modulus of elasticity E_f of the frame have been considered: $E_p/E_f = 0.1$, 0.2, 0.3. Square panels with square openings are considered; the opening is centered with respect to the panel. The curves which represent the stiffness of the system of Fig. 4a), with variations in the height of the cross-section of the surrounding frame, are shown in the diagram in Fig. 5.

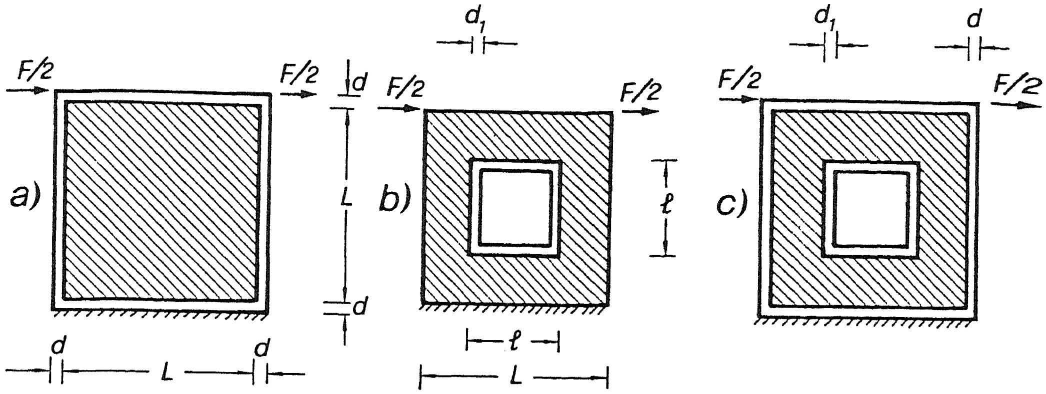

Fig. 4 Panels with stiffening frames

On account of the considerations in the previous section, it can be observed that the values corresponding to the ratio $d/L = 0$ can be obtained with good approximation from the following expression:

$$D/(t\,E_f) = [D_0/(t\,E_p)]\cdot E_p/E_f \tag{5}$$

where the first factor in the second member is deducible from Eq. 2.

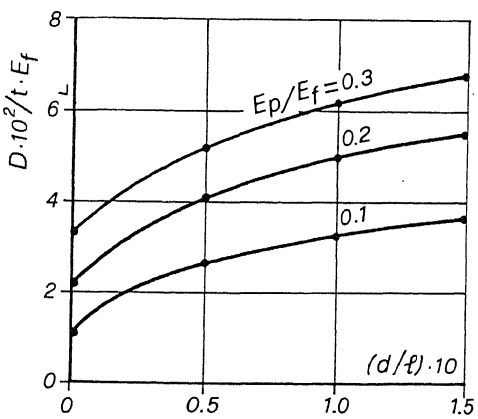

Fig. 5 Stiffness of solid panels with surrounding frames

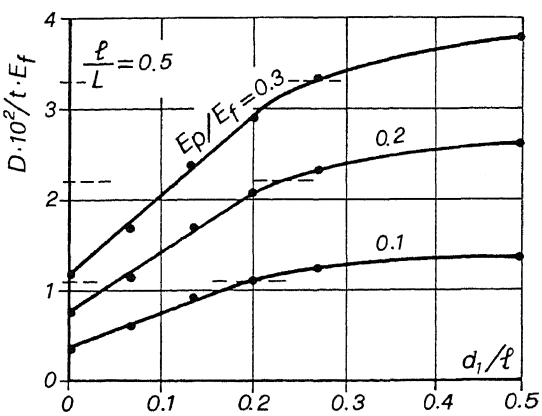

Fig. 6 Stiffness of the panels shown in Fig. 4b)

The results of the analysis of the systems in Fig. 4b) for the opening ratio $\ell/L = 0.5$ are shown in Fig. 6. It can be observed that the stiffness is nearly proportional to the height of the cross-section of the stiffening frame, until this height becomes equal to about 20 percent of the size of the opening. For the ratios E_p/E_f considered, the dashed lines in the diagram refer to the values of stiffness of the panels without openings. The results show that it is not advantageous to insert an inner frame with a cross-section height greater than $d_{1,0}$, which restores the solid panel stiffness, because the curves in Fig. 6, for $d_1/\ell > d_{1,0}/\ell$, become nearly horizontal. The values of stiffness of the systems shown in Fig. 4c) can be calculated utilizing the results obtained for the panels shown in Fig. 4a) and b). The value of stiffness corresponding to $d/L = 0$ in the diagram in Fig. 5 is equal to that in Fig. 6 corresponding to the value $d_{1,0}/\ell$ restoring the solid panel stiffness. Thus, the stiffness of the system in Fig. 4c) is obtained simply by adding to the value of Fig. 5 corresponding to the value d/L of the system the difference

$$\Delta D = D(d_1/\ell) - D(d_{1,0}/\ell) \qquad (6)$$

obtained from the diagram in Fig. 6.

CONCLUSIONS

Analytical expressions for evaluating the stiffness of panels with door ways (Eqs. 2, 3, 4) have been presented. The procedure proposed for the square panels with square openings and surrounding and/or inner stiffening frames can be considered a very general solution because the diagrams analogous to those in Fig. 6 for different values of the ratio ℓ/L can be simply obtained. The results of the analysis carried out make it possible to deduce the dimension of the stiffening frames to be inserted in apertures in panels resistant to horizontal action, so as to prevent the presence of doors on windows causing dangerous stiffness losses and high asymmetry in the behaviour of structures under seismic actions.

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