INFILLED FRAMES: INFLUENCE OF VERTICAL LOAD ON THE EQUIVALENT DIAGONAL STRUT MODEL

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ABSTRACT :

The influence of masonry infills on framed structures behaviour is a central topic in the seismic design procedures and in the hazard evaluation of existing buildings.
Many models use equivalent strut elements in order to represent the infill but among the several parameters influencing the interaction between frame and infill the level of vertical loads is hardly considered. Nevertheless, neglecting this effect may produce inaccuracy because the axial deformations of the loaded columns can produce non-negligible variation in the contact region between infill and surrounding frame, influencing the seismic response of the infilled frame. It can easily been observed that, when this regions extends, the infill behaviour switches from that of a strut element to the one of a plate-shell.
An equivalent diagonal pin-jointed strut model, able to represent the stiffening effect of the infill in presence of vertical loads, is given in this paper.
By a numerical experimentation based on a FEM discretization of the frame-infill system, the lateral stiffness of some infilled frames is evaluated; then the ideal cross-section of the strut equivalent to the infill is obtained for different levels of vertical loads by imposing the equivalence between the frame containing the infill and the frame containing the diagonal strut. This way a correlation available in the literature between a parameter depending on the characteristics of the infilled frame and the equivalent strut width is generalized here to consider the vertical load presence. This correlation is provided in an analytical approximated form of immediate use in the practical applications.

KEYWORDS: Infilled frames, equivalent diagonal pin-jointed strut model, vertical loads influence.

1. INTRODUCTION

Infill panels, though considered non-structural, radically modify the frames response under lateral loads. The lateral stiffness can become ten times higher and the strength can increase four times if compared with the conventionally designed ones in which the presence of the infill is not considered. The interaction between infill and frame may or may not be beneficial to the performance of the structure under seismic loads; especially the stiffness growth can improve the global performance but, if the infill panels are not uniformly horizontally and/or vertically distributed it can also anticipate the structure collapse as numerous debates and experiences in recent earthquakes have demonstrated.

The stiffness and strength variations in an infilled mesh are due to several variables like geometrical and mechanical properties of infill and frame members, details of frame members, frame-infill stiffness ratio and the technique used for making the infill. But an other important factor, usually neglected, is the level of vertical load transferred from the frame to the infill. In the analysis of the infilled frames, referring to the macromodel approach, consisting of replacing the infill panel with an equivalent strut made of the same material of the infill, very few authors have studied the influence of the vertical loads. In 1968 Stafford Smith investigated the influence of a uniformly distributed vertical load imposed on the upper beam of a single store-single bay steel frame on the lateral stiffness and the lateral resistance of the infilled frame itself; he found a considerable increase in the lateral stiffness and lateral strength of the structure. More recently, Valiasis (1989), studying RC frames infilled with brick masonry walls, observed that the presence of a compressive axial load on the columns considerably improves the lateral strength of the system investigated. In spite of their conclusions, Stafford Smith and Valiasis have not inserted the effects of vertical loads in the criteria postulated for the evaluation of the cross-section of the equivalent strut, because they considered this effect to be conservative. Nevertheless, while this conclusion can be valid for a single mesh of infilled frame, it may not be conservative for a more complex framed structure with a non-uniform distribution of infills.

In spite of the conclusions of the above authors and of some others interested in the problem, considering the effect of vertical loads may be basic as it was also pointed out in NCEER (1994). For this reason, in the present paper, a general tool is obtained for modelling the elastic behaviour of the infill by an equivalent strut having a cross-section width w evaluated taking into account the vertical load influence . This work is connected to two previous papers. In the first one Papia et al. (2003) provide a family of curves for estimating the width of the equivalent strut in absence of vertical loads. In the second one, Papia et al. (2004) analyze the mechanism governing the variation in behaviour of the framed structure in relation with the variation in the vertical load.

The present equivalent strut model calibration is made by a micromodel approach procedure. The frame-infill system is modelled by a refined FEM discretization under fixed horizontal load and for different vertical load levels. The regions in which frame and infill transmit compressive stress to each other are modelled by contact surface elements governed by the Coulomb friction law. In the next sections the details of the above procedure are discussed.

2. IDENTIFICATION OF THE EQUIVALENT PIN-JOINTED STRUT

Referring to a single infilled mesh, the identification of the section of the equivalent pin-jointed strut can be performed by imposing the condition that the initial stiffness of the actual system in Fig. 1-a is equal to the initial stiffness of the equivalent braced frame in Fig. 1-b.

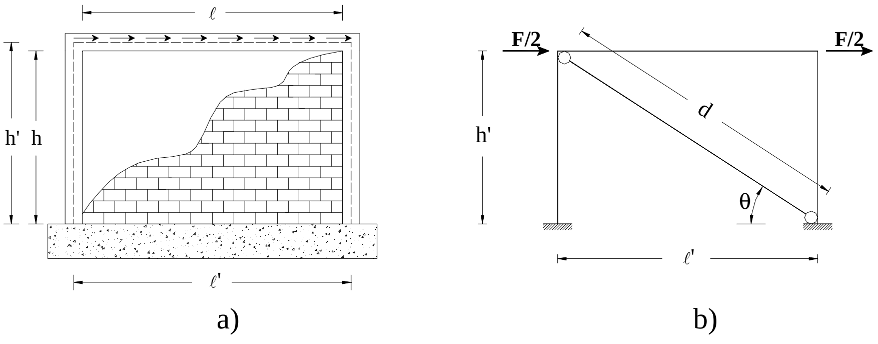


Figure 1 Infilled mesh under horizontal load: (a)actual system; (b) simplified model.

Note that in both schemes the bases of the columns are constrained. Hence these schemes do not exactly represent a generic mesh of a framed structure because the lower beam is assumed to be rigid. Nevertheless, this assumption is in agreement with the conclusions of many experimental tests, showing that the flexural stiffness of the beam does not influence the lateral stiffness of the infilled mesh (Mainstone 1971, 1974, Stafford Smith and Carter 1969).

Denoting as $\overline{D}_i$ be the stiffness of the actual system solved by the Finite Element Method and D_i the one corresponding to the simplified model, the equivalence condition can be written as

$$D_i = \overline{D}_i \tag{2.1}$$

When this equivalence is imposed, assuming the Young modulus and the thickness of the strut to be the same as for the infill, the width w of the strut can be determined, it being the only unknown quantity.

It can be observed that the results which will be shown later have been obtained by considering the panel made of elastic homogenous and isotropic material affected by the Young modulus value derived from compression diagonal tests or correlated to that derived from a compression load acting orthogonally to the bed joint direction by using an adequate reduction coefficient (Jones 1975).

3. LATERAL STIFFNESS OF THE EQUIVALENT BRACED FRAME

The lateral stiffness of the scheme in Fig. 1-b, equivalent to the scheme in Fig. 1-a, can be evaluated with good approximation by imposing the condition that the horizontal forces to be applied to the schemes in Fig. 2-b and Fig. 2-c produce unitary displacement of the point P in the middle span of the beam.

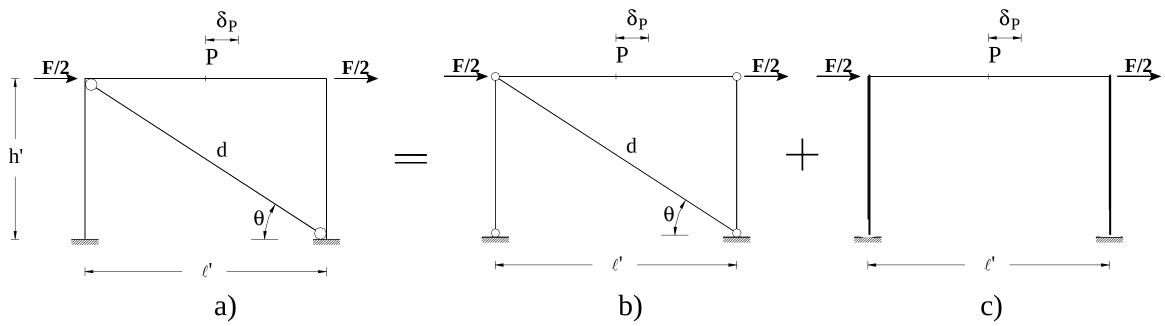


Figure 2 Decomposition of the macromodel

It can be easily found that the following value D_d of lateral stiffness is obtained for the scheme in Fig. 2-b:

$$D_d = \frac{k_d \cos^2\theta}{1 + \frac{k_d}{k_c} sen^2\theta + \frac{1}{4}\frac{k_d}{k_b}\cos^2\theta} \tag{3.1}$$

where the following equivalencies hold:

$$k_d = \frac{E_d\, t\, w}{d}; \quad k_c = \frac{E_f\, A_c}{h'}; \quad k_b = \frac{E_f\, A_b}{\ell'} \tag{3.2}$$

In Eqn. 3.2 k_d, k_c and k_b are the axial stiffnesses of the diagonal strut, of the columns and of the beam, respectively; E_d, E_f are the Young modulus of the infill along the diagonal direction and the Young modulus of the frame material; t is the thickness of the infill; A_c and A_b are the cross-section areas of the columns and of the beam; θ defines the diagonal direction as specified before; finally, h' and ℓ' are the height and the length of the frame in agreement with Fig. 1. The lateral stiffness D_f of the frame in Fig. 2-c can be simply evaluated using the expression:

$$D_f = 24\,\frac{E_f\,I_c}{h'^3}\left(1 - 1.5\left(3\,\frac{I_b}{I_c}\,\frac{h'}{\ell'} + 2\right)^{-1}\right) \tag{3.3}$$

where I_c and I_b are the moments of inertia of columns and beam sections respectively. Hence the global stiffness D_i of the simplified scheme constituting the braced frame in Fig. 2-a can be assumed to be

$$D_i = D_d + D_f \tag{3.4}$$

4. LATERAL STIFFNESS OF THE INFILLED FRAME BY A MICROMODEL APPROACH

For the evaluation of the lateral stiffness by means of the micromodel approach, the FEM program ADINA has been used. Both the frame and the infill have been discretizated by plane stress solid elements having each four nodes. The nodes at the bases of the columns have been fully constrained while two degrees of freedom have been assigned to all the other nodes. The infill panel and the frame have been modelled by means of elastic homogeneous and isotropic materials having elastic moduli E_d, E_f and Poisson ratios ν_d, ν_f respectively.

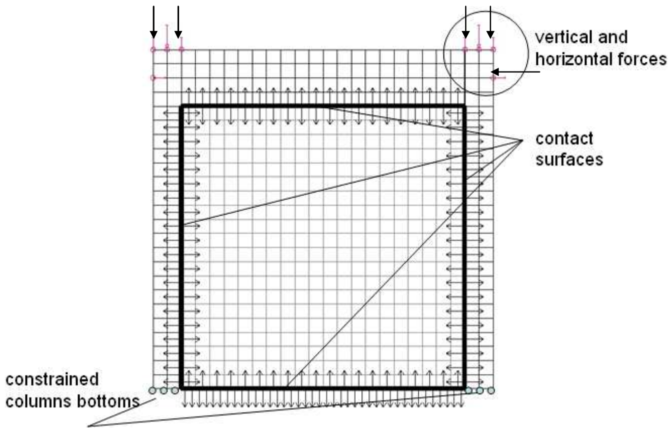


Figure 3 Finite element discretization of the infilled frame mesh

The frame-infill interaction has been modelled by axisymmetric 2D contact surface elements. Each interface element is composed of two contact surfaces that may come into contact during the loading process. One of the two contact surfaces in the pair is selected to be the “contactor surface” and the other one the “target surface”. Two main features of these elements are that the nodes of the contactor surface cannot penetrate the target surface and that no tensile strength is associated with the joint. This way modelling the detachment between frame and infill is possible. Because the interaction between the frame and the infill panel is strictly linked to the length of the contact zone, and this length is influenced by the vertical load level, this kind of FEM elements allows the evaluation of the system lateral stiffness $\overline{D}_i$ in relation with the vertical load. The contact algorithm used for the contact surface element is the constraint function method by K. J. Bathe et al. (1997).

The numerical analysis has been carried out for different values of mechanical and geometrical properties of the system and, what is more important, for various vertical load levels. From each analysis the lateral stiffness $\overline{D}_i$ of the system can be calculated as ratio between the applied horizontal load and the beam average displacements. The horizontal forces acting on the frame are applied on the initial and final section of the beam at middle depth, while the vertical load is concentrated on the beam-column joints. Fig. 3 shows a typical FEM discretization of the infilled frame mesh.

5. EQUIVALENT STRUT CROSS-SECTION

By substituting the value of D_i obtained from Eqn. 3.4 into Eqn. 2.1, one obtains

$$\overline{D}_i = D_d + D_f \tag{5.1}$$

Further, by substituting Eqn. 3.1 into Eqn. 5.1 the w/d ratio proves to be expressed by

$$\frac{w}{d} = \frac{\overline{D}_i - D_f}{E_d\, t\, \cos^2\theta}\left(1 - \frac{\overline{D}_i - D_f}{k_c}\left(\frac{h'^2}{\ell'^2} + \frac{1}{4}\frac{k_c}{k_b}\right)\right)^{-1} \tag{5.2}$$

By evaluating the "exact" lateral stiffness of the system $\overline{D}_i$ through the FEM model previously described, and the bare frame stiffness D_f (Eqn. 3.3), the *w/d* value can be obtained by means of Eqn. 5.2. The bare frame stiffness D_f can be evaluated once the geometrical features of the frame elements and the mechanical characteristics of the materials are known. If the procedure is repeated several times for different elastic and geometrical values, a correspondence between the actual features of the generic infilled frame and the characteristics of the equivalent strut can be found.

Since the procedure is based on the two columns having the same cross-section and orientation, when this condition is not verified, average values of moment of inertia and area of the columns have to be assigned in order to obtain a structurally symmetrical ideal scheme like the one considered in the proposed approach. In this case the level of approximation in the results can be considered of the same order as that achievable by other models available in the literature.

Once the investigation described before is concluded, the direct evaluation of the width w of the strut, in agreement with the most widespread tendencies in the literature, requires the definition of a parameter λ^* depending on the elastic and the geometrical features of the system in such a way that a function $w/d = f(\lambda^*)$ can be defined. This function must take the influence of verticals loads into account. In conclusion, the numerical investigation carried out by means of an "exact" model must give the possibility of defining a direct relation between the infilled frame and its loading condition and the equivalent braced frame, with a strong reduction in the computational effort for practical use in the structural analysis.

6. THE PARAMETER λ^*

The definition of a parameter that, concisely and with good reliability, univocally defines the ratio w/d to be adopted for the simplified model, can be obtained by imposing the condition that the difference $\overline{D}_i - D_f$ on the right side of Eqn. 5.2 is the true lateral stiffness of the infill panel, obtainable from the true load condition on the panel itself.

Once the Poisson ratio, the vertical loads level and the ℓ/h ratio are fixed, the lateral stiffness of the infill can be approximately written as

$$\overline{D}_i - D_f = D_d = \psi\, E_d\, t \tag{6.1}$$

where ψ depends on the unknown extension of the frame-infill contact regions. On the other hand, setting

$$\lambda^{*} = \frac{E_d}{E_f}\frac{t\,h'}{A_c}\left(\frac{h'^2}{\ell'^2} + \frac{1}{4}\frac{A_c}{A_b}\frac{\ell'}{h'}\right) \tag{6.2}$$

and considering Eqn. 6.1, Eqn. 5.2 can be written in the form

$$\frac{w}{d} = \frac{1}{\cos^2\theta}\,\frac{1}{\psi^{-1} - \lambda^{*}} \tag{6.3}$$

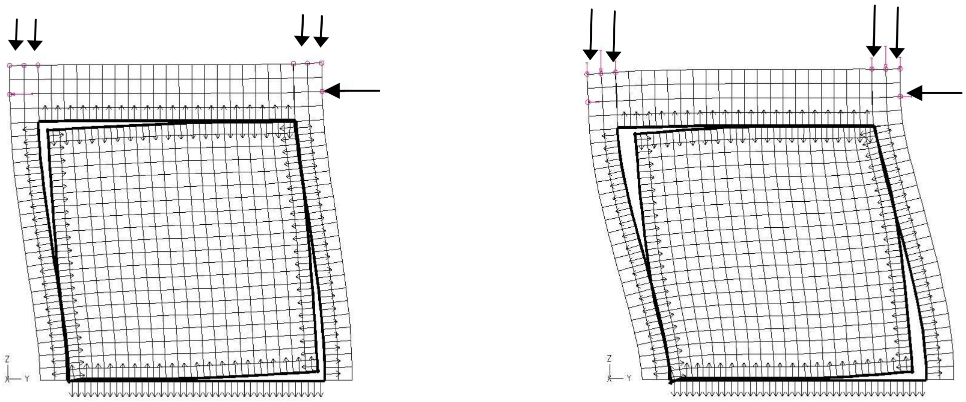
Eqn. 6.3 shows that, for assigned values of ℓ / h, ν_d and F_V (on which ψ depends) a curve $w/d = f(\lambda^{*})$ can be searched. In order to obtain this curve, different infilled frames models have been analyzed by the “exact” procedure, considering different values of the terms that define the parameter λ^{*}. In this first study the aspect ratio ℓ / h has been assumed to be equal to 1, while two different values of the Poisson ratios ν_d = 0.15, and ν_d = 0.25 have been considered. Once the frame-infill system has been fixed, the analysis has been carried out for four adimensional vertical loads levels: ε_V = 0, ε_V = 0.00016, ε_V = 0.00032, ε_V = 0.00080 where the used symbol stands for

$$\varepsilon_v = \frac{F_v}{2A_c E_c} \tag{6.4}$$

A_c and E_c being the section area and Young modulus of the column and F_v the total vertical load acting on the frame.

Once the values of the stiffness $\overline{D}_i$ have been computed by means of an “exact” numerical analysis, the values of w/d are obtained by Eqn. 5.2, for fixed ν_d. The results confirm the close dependence of the strut width on the parameter λ^{*} also in the presence of vertical load as previously shown in Papia et al. (2003).

They also show that when the vertical load and consequently the axial strain of the columns increases, the frame-infill contact length (Fig. 4) grows too, modifying the mechanical behaviour of the whole system, the panel switching from a strut element behaviour to a plate one. The lateral stiffness of the whole system is so enhanced. In other words for a fixed λ^{*} the strut width ratio w/d grows as F_V increases.



a) b)

Figure 4 Deformed mesh under horizontal force for two different vertical load levels: variation of the infill-frame contact area

In order to obtain a useful design tool, the w/d values obtained by the numerical investigation have been fitted by the analytical expressions proposed in Cavaleri et al. (2005)

$$\frac{w}{d} = k \frac{c}{\left(\lambda^*\right)^{\beta}} \tag{6.5}$$

$$c = 0.249 - 0.0116\,\nu + 0.567\,\nu^2 \tag{6.6}$$

$$\beta = 0.146 + 0.0073\,\nu + 0.126\,\nu^2 \tag{6.7}$$

where k is a coefficient taking the effect of vertical loads into account. For $k=1$ (no vertical load acting) the function fits very well the results of the numerical investigation shown in Papia et al. (2003). On the other hand, the numerical investigation carried out in this work has shown quite a linear dependence of the coefficient k on the vertical load and axial strains of the columns level, which can be approached by the expression

$$k = 1 + \left(18\,\lambda + 200\right)\varepsilon_v \tag{6.8}$$

Fig. 5 shows the comparison between the results obtained by the numerical analysis and the analytical curves provided by Eqs. 6.5 and 6.8.

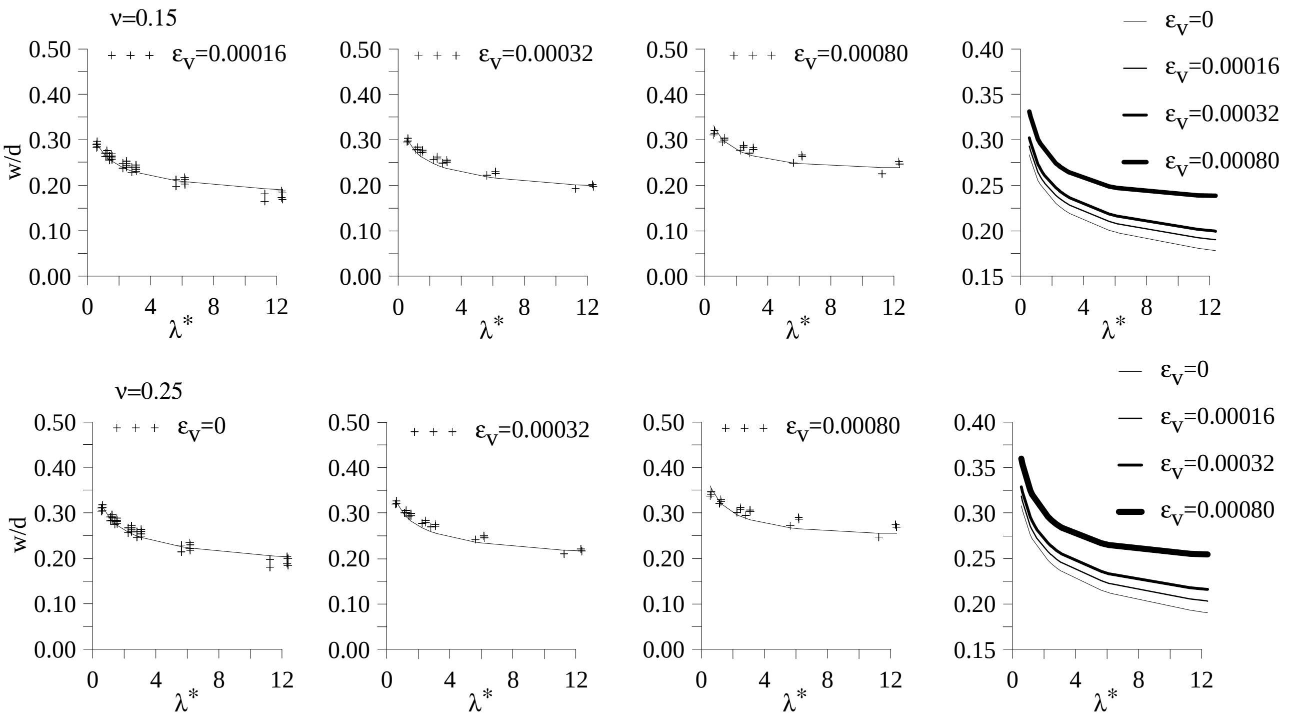


Figure 5 Comparison between results obtained by the numerical analysis and the analytical curves

For practical applications, Eqn. 6.5 allows the evaluation of the contribution of the infill to the lateral stiffness of the generic mesh of a framed structure with a low computational effort.

6. CONCLUSIONS

In this paper the mechanical behaviour of single store – single bay infilled meshes has been discussed and an analytical procedure available in the literature for the identification of a pin-jointed strut equivalent to the infill has been generalized to take the influence of vertical loads into account.

In details a numerical investigation on infilled meshes has proved that also in the presence of vertical load it is possible a strong correlation between the dimension of the equivalent diagonal strut model and a single parameter which depends on the characteristics of the system. Moreover the numerical results can be fitted by a law derived by the one proposed by Papia et al. (2003) using a multiplier which is a linear function of the vertical load acting on the system. A family of curves has so been obtained for different values of vertical load.

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