

---

Asteris PG, Cavaleri L, Di Trapani F, Sarhosis V. [A macro-modelling approach for the analysis of infilled frame structures considering the effects of openings and vertical loads](#). *Structure and Infrastructure Engineering* 2016, 12(5), 551-566.

**Copyright:**

This is an Accepted Manuscript of an article published by Taylor & Francis in *Structure and Infrastructure Engineering* on 28/04/2015, available online:

<http://www.tandfonline.com/10.1080/15732479.2015.1030761>

**DOI link to article:**

<http://dx.doi.org/10.1080/15732479.2015.1030761>

**Date deposited:**

16/02/2016

**Embargo release date:**

28 April 2016



This work is licensed under a [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International licence](#)

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

# A macro-modelling approach for the analysis of infilled frame structures

Cavaleri L.<sup>1</sup>, Di Trapani F.<sup>1</sup>, Asteris P.<sup>2</sup>, V. Sarhosis<sup>3</sup>

<sup>1</sup>*Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale e dei Materiali (DICAM), University of Palermo, Italy.*

<sup>2</sup>*School of Pedagogical & Technological Education, University of Athens, Greece*

<sup>3</sup>*School of Civil Engineering, Cardiff University, CF23 3AA, Cardiff, UK*

## Abstract

An approach towards the assessment of the in-plane horizontal capacity of infilled frames consists of the substitution of each infill with an equivalent diagonal strut. While several studies have been focused on the in-plane horizontal behavior of full infills, limited work has been carried out to investigate the behavior of infills with openings. Also, in most of the studies, the influence of the vertical load is not present. In this paper, an approach for the identification of an equivalent strut which takes into account the effects of the opening at the infill is presented. An extended FE analysis considering the infilled frames containing different sizes of opening under various amounts of vertical loads have been developed. The model is used to identify the mechanical characteristics of an equivalent strut. From the results analysis, a relationship between the width of an equivalent strut and the reduction coefficient ( $\lambda^*$ ) representing the mechanical characteristics of frame and infill has been obtained.

**Keywords:** Infilled frames, equivalent strut, masonry, FE analysis

---

\*Corresponding author ..... E-mail:.....

## 26 **1. Introduction**

27 Infill walls subjected to lateral loads are radically affecting the behaviour of infilled framed  
28 structures under lateral loads(Stafford Smith 1968, Stafford Smith and Carter 1969, Cavaleri et al.  
29 2005, Asteris et al. 2003, Asteris et al. 2011, Wang et al. 2011, Willam et al. 2010, Yang et al.  
30 2010, Sarhosis et al. 2014). The stiffness and strength variation of an in-filled frame depends on the  
31 geometrical and mechanical properties of the masonry infill wall and surrounding frame;the frame  
32 to masonry infill wall stiffness ratio as well as the interaction between the infill panel and the  
33 surrounding frame. Among these factors the level of vertical load transferred from the frame to the  
34 infill and the presence of openings have to be considered (e.g. NCEER 1994) in the analysis.

35 For the analysis of the masonry infill frames, the macro-modelling approach, which replaces the  
36 infill with one or more equivalent struts have extensively been used in the past by various  
37 researchers including Asteris (2003), Cavaleri and Papia (2003), Crisafulli and Carr (2007), Zhai et  
38 al. (2011), Chrysostomou and Asteris (2012), Moghaddam and Dowling (1987) and Asteris et al.  
39 (2011). However, as far as the authors' knowledge is concerned, there are limited studies on the  
40 influence of the combination of vertical and horizontal loads on the masonry in-fills containing  
41 openings.

42 Stafford & Smith (1968) investigated the influence of a uniformly distributed vertical load  
43 observing a considerable increase in the lateral stiffness and lateral strength. More recently, Papia et  
44 al. (2004) studied the mechanical behaviour of RC frames infilled with brick masonry wallsand  
45 observed a similar effect. Also, Stafford & Smith (1968) and Valiasis & Stylianidis (1989)  
46 considered the vertical load effect to be conservative and did not take it into account, among the  
47 variables affecting, the evaluation of the cross-section of the equivalent strut. Nevertheless, while  
48 this conclusion can be valid for a single frame, it may not be conservative for complex structures  
49 with such as partially infilled frame structures.

50 Also, according to Mosalam et al. (1997) and Holmes (1961), infill panels containing openings will  
51 normally characterised by a reduced stiffness and strength when compared to the full infill panels.  
52 The effect of openings on the masonry infill panels have also been studied experimentally. In 1971,  
53 Mallick and Garg (1971) carried out studies on the position of the opening. Next year, Liauw  
54 (1972) undertook several experiments and formulated a simplified model, Also, Schneider et al.  
55 (1998) investigated the case of large windows on the behaviour of infilled steel frames. More  
56 recently, Kakaletsis and Karayannis (2007) conducted an experimental program to investigate the  
57 effect of window and door openings on the hysteretic characteristics of infilled RC frames and  
58 understand the relative merits of the position of the window and door openings in the frame.  
59 Furthermore, Kakaletsis and Karayannis (2008, 2009) and Kakaletsis (2009) investigated  
60 experimentally the compressive strength, the modes of failure, the stiffness and the energy  
61 dissipation of infilled RC frames containing openings and subjected to cyclic loading. Moreover,  
62 Mosalam et al. (1997) carried out a series of experimental tests on gravity load–designed steel  
63 frames with semi-rigid connections infilled with unreinforced masonry walls subjected to cyclic  
64 lateral loads. The experimental tests were conducted to evaluate the effects of the relative strength  
65 of the concrete blocks and mortar joints, the number of bays, and the opening configuration of the  
66 infill on the performance of single-story reduced-scale infilled frames. A simple iterative FEM  
67 model was proposed by Achyutha et al. (1986) to investigate the infilled frames containing  
68 openings with or without stiffeners around the openings. From the results, it was found that when  
69 the percentage of window opening is greater than 50%, the contribution of the infill panels can be  
70 neglected. Asteris (2003) proposed graphs to estimate the stiffness-reduction factor corresponding  
71 to the size and location of the opening. The analytical results demonstrated that for the samples  
72 considered, a 20–30% opening reduces the stiffness of the solid-infilled frame by about 70–80%.  
73 Tasnimi and Mohebkhah (2011) studied the behaviour of steel frames with masonry-infill panels by  
74 examining six full-scale one-story, one-bay specimens with central openings. Cyclic tests

75 demonstrated that partially infilled frames do not always increase the ductility of the frames, since  
76 ductility depends on the failure mode of the infill material. Moreover, a relation to determine the  
77 equivalent strut's width- reduction factor has been proposed.

78 The effects of openings on stiffness and strength of infilled frames are primarily taken into  
79 consideration by reduction factors (Tasnimi and Mohebkhah 2011; Al-Chaar et al. 2003; Al-Chaar  
80 2002; New Zealand Society for Earthquake Engineering 2006; Durrani and Luo 1994; Mondal and  
81 Jain 2008; Asteris 2003, Papia et al. 2003). The reduction factor shows the ratio of stiffness or  
82 strength of partially infilled frame to that of a similar solid one. For the aforementioned studies, the  
83 contribution of the vertical loads to the strength of the infill wall panels is not taken into account  
84 leading to inaccurate results since the influence of vertical load is a critical parameter which affects  
85 the contact lengths (Fig. 1) between the infill wall and the surrounding frame.

86 In this paper, an analytical equation for the determination of the reduction factor of the infill wall  
87 (equivalent compressive strut) stiffness taking into account the percentage opening of the infill wall  
88 (area of opening to the area of infill wall) as well as the vertical load distribution is proposed. The  
89 proposed equation based on similar previous proposal proposed by Asteris (2003) (for taking into  
90 account the effect of the openings) and by Amato et al. (2008, 2009) for taking into account the  
91 vertical loads. To validate the proposed equation an in-depth analytical investigation using a micro-  
92 modelling Finite Element method was conducted. The numerical procedure provides the "exact"  
93 response of a series of infilled frames under horizontal and vertical loads by modelling the  
94 compressive stress transmitted by the frame to the infill through contact surface elements governed  
95 by the Coulomb friction law. The term "exact" is referring to an infill which is modelled by a  
96 detailed FE micro-modelling approach and the regions in which frame and infill transmit  
97 compressive stress to each other are modelled by contact surface elements.

98

## 99 2. Identification of the width of an equivalent strut

100 The cross-section of the pin-jointed strut equivalent to an infill (Fig. 2-a) can be obtained by  
101 imposing the initial lateral stiffness to be equal to the initial stiffness of the equivalent braced frame  
102 (see Fig. 2-b). Denoting  $\bar{D}_i$  the stiffness of the actual system (Fig.2-a) solved by the Finite Element  
103 Method (micro-modelling approach) and  $D_i$  the stiffness corresponds to the simplified model (Fig.  
104 2-b), their equivalence can be written as:

$$D_i = \bar{D}_i \quad (1)$$

105 The dimensionless value of the lateral stiffness  $D_i$  of the infill frame (Fig. 2-b equivalent to Fig. 3-  
106 a), , for the case of lateral top displacement  $\delta = 1$ , is equal to the sum of the dimensionless values of  
107 the two horizontal forces  $D_d, D_f$  to be applied to the schemes in Fig. 3-b and Fig. 3-c, (obtained as  
108 the decomposition of the scheme in Fig.3-a based on the principle of superposition).The  
109 dimensionless value of the lateral stiffness  $D_i$  of the infill frame is equal to::

$$D_i = D_d + D_f \quad (2)$$

110 For the scheme in Fig. 3-b the lateral stiffness  $D_d$  can be calculated as follows:

$$D_d = \frac{k_d \cos^2 \theta}{1 + \frac{k_d}{k_c} \sin^2 \theta + \frac{1}{4} \frac{k_d}{k_b} \cos^2 \theta} \quad (3)$$

111 where  $k_d$ ,  $k_c$  and  $k_b$  are the axial stiffness of the diagonal strut, column and beam respectively:

$$k_d = \frac{E_d t w}{d}; \quad k_c = \frac{E_f A_c}{h}; \quad k_b = \frac{E_f A_b}{\ell'} \quad (4)$$

112 In Eq. (4),  $E_d$  and  $E_f$  are the Young's modulus of the infill along the diagonal direction and the  
113 Young's modulus of the concrete constituting the frame;  $t$  is the thickness of the infill;  $A_c$  and  $A_b$   
114 are the column and beam cross-sectional areas; the angle  $\theta$  defines the diagonal direction of the

115 strut and  $h'$  and  $\ell'$  are the height and the length of the infill frame (all the above parameters are  
116 explained in Fig. 2).

117 The Young's modulus of the infill along the diagonal can be estimated by combining the masonry  
118 elastic moduli along the horizontal and vertical directions as suggested in (Jones 1975), or by using  
119 the simplified approach discussed by Cavaleri et al. (2013) on the basis of the experimental studies  
120 reported in (Cavaleri et al., 2012).

121 The lateral stiffness corresponding to the frame  $D_f$  (Fig. 3-c), for the case of columns having the  
122 same cross-section, can be estimated using the following expression:

$$D_f = K \left[ 24 \frac{E_f I_c}{h'^3} \left( 1 - 1.5 \left( 3 \frac{I_b}{I_c} \frac{h'}{\ell'} + 2 \right)^{-1} \right) \right] \quad (5)$$

123 where  $I_c$  and  $I_b$  are the moments of inertia of column and beam sections respectively and  $K$  is a  
124 constant depending on the aspect ratio of the infill ( $K = 0.7$  for  $\frac{\ell}{h} = 1$ ,  $K = 0.5$  for  $\frac{\ell}{h} = 2$ ). In the  
125 case where columns are of different cross-sections, a mean value of their axial stiffness can be used.

## 126 **2.1 “Exact” infilled frame stiffness**

127 For the evaluation of the lateral stiffness by means of the micro-modelling approach, the FE  
128 program SAP 2000 has been used. Both the frame and the infill have been modelled using four node  
129 plane stress solid elements assuming elastic, isotropic and homogeneous elastic materials  
130 behaviour. The frame-infill interaction have been modeled using interface elements acting only in  
131 compression (zero tensile strength). The mechanical characteristics calibrated in such a way to  
132 simulate the presence of a mortar having an assigned elastic modulus. The zero tensile strength  
133 assumption enables the simulation of the detachment between the frame and the infill. Because the  
134 interaction between the frame and the infill is strictly associated with the frame to infill contact

135 length, which is influenced by the vertical load, the model allows the evaluation of the system's  
 136 lateral stiffness  $\bar{D}_i$  in relation to the vertical load.

## 137 2.2 Equivalent strut cross-section

138 By substituting the value of  $D_i$  obtained from Eq. (2) in Eq. (1), one obtains:

$$\bar{D}_i = D_d + D_f \quad (6)$$

139 Furthermore, by substituting Eq.(3) in Eq.(6), the ratio  $w/d$  can be expressed as a function of the  
 140 “exact” lateral stiffness  $\bar{D}_i$  of an infilled frame given by the FE model previously described and  
 141 the bare frame stiffness  $D_f$  given in Eq. (5):

$$\frac{w}{d} = \frac{\bar{D}_i - D_f}{E_d t \cos^2 \theta} \left( 1 - \frac{\bar{D}_i - D_f}{k_c} \left( \frac{h'^2}{\ell'^2} + \frac{I}{4} \frac{k_c}{k_b} \right) \right)^{-1} \quad (7)$$

142  
 143 From eq. (7), the ratio of the width of equivalent pin-jointed diagonal strut to the length of the  
 144 diagonal strut ( $w/d$ ) can be represented as a function of  $\lambda^*$ ,  $w/d = f(\lambda^*)$ , which can take into  
 145 account the influence of vertical loads and the size of the openings.

146 By running a number of simulations for infilled frames characterized by different mechanical and  
 147 geometrical values and different loading conditions, a set of points representing the global frame-  
 148 infill behaviour ( $\lambda^*$ ) and the characteristics of each equivalent strut ( $w/d$ ) can be obtained.

149 In this study, in agreement with the conclusions of Papia et al. (2003) the parameter  $\lambda^*$  has been  
 150 taken as:

$$\lambda^* = \frac{E_d}{E_f} \frac{t}{A_c} \frac{h'}{A_c} \left( \frac{h'^2}{\ell'^2} + \frac{I}{4} \frac{A_c}{A_b} \frac{\ell'}{h'} \right) \quad (8)$$



151 **3. Numerical investigation**

152 The numerical analysis was carried out for different values of mechanical and geometrical  
153 properties of an infilled frame and for four vertical load levels. For each analysis, the lateral  
154 stiffness  $\bar{D}_i$  of the system was calculated as the ratio between the applied horizontal load and the  
155 inter storey average displacement. The horizontal and vertical forces acting on the frame were  
156 applied on the initial and final section of the upper beam at middle depth, while the vertical load  
157 was concentrated on the top nodes of the upper beam-column joints. Values of the elastic modulus  
158  $E_f$  of the concrete frame were varied from 10,000 to 25,000 MPa while the Poisson's ratio kept  
159 constant and equal to  $\nu_f = 0.15$ . The diagonal elastic modulus  $E_d$  was in the range 3,000 to 10,000  
160 MPa and the diagonal Poisson ratio  $\nu_d$  was equal to 0.2.

161 The interface elements used to model the interaction between surrounding frame and infill panel  
162 were calibrated and an elastic modulus in compression of the mortar equal to 3,000 MPa obtained.  
163 Two different values of the aspect ratio  $\ell/h$ , namely 1 and 2, were investigated. Different  
164 dimensions for the openings (centered and homothetic with respect of the boundary of the infill)  
165 were considered.

166 The size of each opening was defined by the dimensionless parameter  $\xi = h_v/h = \ell_v/\ell$ ,  $h_v$  and  $\ell_v$   
167 being the dimensions of the opening itself, see Fig.(2).

168 The analyses were repeated for four dimensionless vertical load levels:  $\varepsilon_v = 0$ ,  $\varepsilon_v = 0.00016$ ,  
169  $\varepsilon_v = 0.00032$ ,  $\varepsilon_v = 0.00080$  where  $\varepsilon_v$  is defined as

$$\varepsilon_v = \frac{F_v}{2A_c E_f} \quad (9)$$

170  $A_c$  being the mean cross section area of the columns and  $F_v$  the total vertical load acting on the  
171 frame.

172 In Figs. 4 &5, the influence of the lateral load and the size of the opening to the contact lengths  
173 (beam-infill and column-infill) is clearly depicted. Especially, the greater the opening size, the  
174 greater the beam-infill and column-infill contact length. In agreement with previous experimental  
175 (Smith 1968) and analytical (Asteris 2003) works, large openings result the curvature of the infill to  
176 follow the curvature of the frame. In Fig. 6 the results of the numerical investigation in the case of  
177 aspect ratio of infills  $\ell/h=1$  are inserted showing the correlation between the dimensionless width  
178 of the equivalent strut and the parameter  $\lambda^*$ . Fig. 7 refers to the case were  $\ell/h$  equals to 2.

179 From the results analysis, it was found that the effect of vertical loads reduces as the ratio between  
180 the dimensions of the opening and the dimensions of the infill increases. This is proved by the fact  
181 that for a fixed  $\lambda^*$ , the values of  $w/d$  correspond to different levels of the vertical load which tends  
182 to become similar. Furthermore, it can be observed that as the area of openings increases, the  
183 variation of  $w/d$  (i.e.  $\lambda^*$ ), becomes smaller.

184 Fig. 8 shows the reduction factor ( $r$ ) of  $w/d$  against the opening ratio  $\xi$  for square infills ( $\ell/h=1$ )  
185 and rectangular infills ( $\ell/h=2$ ) **without vertical loads** ( $\epsilon_v = 0$ ). From Fig.8 and for low values of  
186  $\xi = h_v/h = \ell_v/\ell$  (i.e. up to 0.2), the ratio  $\ell/h$  have a minimal effect on ....., while for values  
187 of  $\xi$  greater than 0.2 a reduction of the dimensionless strut width is obtained. Also, for each value  
188 of the opening ratio, to a contained range of values for the factor  $r$  can be obtained. **The different**  
189 **values of  $r$  for assigned  $\xi$  correspond to different values of  $\lambda^*$  in the range assigned for this**  
190 **parameter**. Considering the contained range of values for  $r$  for assigned  $\xi$  and that this fact is more  
191 prevalent for high values of the opening ratio  $\xi$  when the reduction of  $w/d$  is strongly pronounced,  
192 that is infills have not more a significant effect on the behaviour of the frame, surely a unique value  
193 of  $r$  can be associated to each value of the opening ratio  $\xi$ . On the basis of this consideration, the  
194 numerical results can be fitted by the analytical expression:

$$r = 1 + 0.24\xi - 4.23\xi^2 - 2.6\xi^3 + 12.73\xi^4 - 7.15\xi^5 \quad (10)$$

195 It is important to note that eq. 10 does not depend on the aspect ratio  $\ell / h$ .

196 In Figs. 9 and 10 the reduction factor of the dimensionless strut width due to openings is combined  
 197 with the amplification factor ( $k$ ) due to vertical loads. The numerical results show that it is not  
 198 possible to add the effects of openings and vertical loads since there is an interaction between the  
 199 two phenomena which controls the behaviour. As a consequence the resulting  
 200 amplification/reduction factor is obtained as a nonlinear function of  $r$  and  $k$  as it will be discussed  
 201 below.

202

#### 203 **4. Model for the identification of the equivalent strut**

204 Results of numerical investigations presented here, show that the loss of stiffness due to the  
 205 openings and the gain of stiffness due to vertical loads can be correlated with the characteristics of  
 206 an infilled frame ( $\lambda^*$ ). The results show that the effects of openings and vertical loads depends on  
 207 the parameter  $\xi$  defining the size of the opening:  $\xi = hv / h = \ell v / \ell$ , the parameter  $\lambda^*$   
 208 characterizing the infilled frame and the parameter  $\varepsilon_v$  characterizing the level of vertical loads  
 209 defined in Eq.(9). Imposing that the Eq. (7) assumes the form:

$$w/d = r \cdot g'(k) \cdot g''(\ell/h) \cdot g'''(\lambda^*) \quad (11)$$

210 where  $r$  is the reduction factor  $0 < r < 1$  taking the openings in the infills into account, while  $k$  is  
 211 the amplification factor taking the effect of the vertical load into account in absence of openings,  
 212 the problem is to find an expression for the functions  $g'(k)$ ,  $g''(\ell/h)$ ,  $g'''(\lambda^*)$ . This problem can  
 213 be solved by observing the results of the numerical investigation.

214 In Papia et al (2003) it has been proved that the function  $g'''(\lambda^*)$  can be expressed as

$$g^m(\lambda^*) = \frac{c}{(\lambda^*)^\beta} \quad (12)$$

Where

$$c = 0.249 - 0.0116 v_d + 0.567 v_d^2 \quad (13)$$

$$\beta = 0.146 + 0.0073 v_d + 0.126 v_d^2 \quad (14)$$

215 The numerical investigation carried out in this work showed that there is a non-linear relationship  
 216 between the parameters  $k$  and  $r$  . Therefore , the following equation can be used

$$r \cdot g'(k) \cdot g''(l/h) = rk^\gamma \frac{h}{\ell} \quad (15)$$

217 where

$$k = [1 + (18\lambda^* + 200)\varepsilon_v] \quad (16)$$

218 and

$$\gamma = 1 + \frac{0.5r}{(h/\ell)^4} \quad (17)$$

219 The Eq. (16) for  $k$  was previously proposed by Amato et al. (2009) for the case of infills without  
 220 opening and verified for square infilled frame while here it is proposed for square and rectangular  
 221 infills in general.

222 In Figs.9-10 it is possible to note as the analytical proposal Eq. (15) fits the numerical results. Eq.  
 223 (15) takes into account the variation of the dimensionless width due to  $\lambda^*$  for a high value of the  
 224 opening ratio (i.e. close to 1) and neglects the influence of  $\lambda^*$  for the lowest values of  $\xi$  where the  
 225 influence of the infills themselves becomes negligible.

226 To this point observe that the strong interaction between openings and vertical loads is expressed by  
 227 the exponent  $\gamma$  applied to the parameter  $k$  . In fact, while  $k$  was generated to take the influence of

228 vertical loads into account,  $\gamma$  depends on the reduction factor  $r$  that, conversely, was generated to  
 229 take the influence of openings into account. Considering Eqs. (16 &17) allows one to conclude that  
 230 if there are no vertical loads the following equation is valid:

$$k^\gamma = k \quad (18)$$

231 The above formulation is an extension of the one proposed by Amato et al. (2009).

232 In Fig.11 the values assumed by  $k^\gamma$  varying the vertical loads and the opening ratio can be  
 233 observed, evidencing vertical loads seems to assume a more strong role in the case of square infills.

234 The equation (15) for the reduction factor  $r$  can be considered as an updating of the expression  
 235 proposed by Asteris (2003), Asteris et al. (2013), Asteris et al. (2012) obtained from the FE model.

236 However as concluded by Asteris (2003), the reduction factor  $r$  here proposed does not depend on  
 237 the aspect ratio of infills but assumes slightly different values especially for the cases of low levels  
 238 of the opening ratio.

239 Asteris (2003) proposed the following expression for the calculation of  $r$ :

$$r = 1 - 2\alpha_w^{0.54} + \alpha_w^{1.14} \quad (19)$$

240 where,  $\alpha_w$  is the infill wall opening ratio (area of opening to the area of infill wall).

241 Considering that  $\alpha_w = \xi$  eq.(19) can be rewritten as

$$r = 1 - 2\left(\frac{\ell_v h_v}{\ell \cdot h}\right)^{0.54} + \left(\frac{\ell_v h_v}{\ell \cdot h}\right)^{1.14} = 1 - 2(\xi)^{1.08} + (\xi)^{2.28} \quad (20)$$

242 In Fig. 12, a comparison between the function (10) and the function (20) is presented evidencing  
 243 that the two proposals converge for the highest values of  $\xi$ . Hence, the differences result from the  
 244 low values of  $\xi$ .

245

## 246 **Conclusions**

247

248 The presence of masonry infill wall panels within a framed structure will strongly affect its  
249 structural response under horizontal actions and seismic loads. Recent developments have shown  
250 that such interaction can be expressed by replacing the characteristics of the panel with that of an  
251 equivalent diagonal strut. Also, research has shown that there are several parameters influencing the  
252 definition of the diagonal strut and its equivalent width. The latter depends on the degree of  
253 coupling between geometrical and mechanical features of the frame and masonry infill.

254  
255 In this paper, an analytical expression for the identification of the equivalent strut dimensionless  
256 width  $w/d$ , and therefore of its stiffness, has been proposed by means of an extensive numerical  
257 investigation which was carried out using a series of FE models representative of the “exact”  
258 response. The expression derived involves the product of a reduction factor function  $r(\xi)$ , where  
259  $(0 \leq r(\xi) \leq 1)$ , and takes into account the stiffness reduction due to the openings, taking the  
260 effect due to vertical load, the infill aspect ratio and the geometrical-mechanical features of the  
261 overall system.

262  
263 A good fit of results obtained between the analytical predictions and the numerical investigation.

264 Also, from the results analysis it was found that::

- 265 • The presence of opening strongly reduces the stiffness of the infill panel and this reduction  
266 does not depend on the aspect ratio of the infill;
- 267 • The greater the opening size, the greater the beam-infill and column-infill contact length
- 268 • Vertical loads increase the contact infill-frame lengths, thus increase the overall stiffness of  
269 the infill panel;
- 270 • The influence of vertical loads is significant for solid infills. In contrast is almost negligible  
271 for infill panels with large openings; The capacity of vertical loads to increase the stiffness is  
272 maximum for square infills and it slightly reduces increasing their aspect ratio. From the

273 analytical results, it was found that all the functions composing the final expression of  $w/d$   
274 are not independent one by each other and moreover their combination is nonlinear. This  
275 should be interpreted as natural consequence of *strong* coupling affecting the infill-frame  
276 interaction mechanic.

277 The proposed expression is a reliable tool for the determination of equivalent compressive pin  
278 jointed strut width since it simultaneously accounts for a large number of parameters not generally  
279 accounted for by already available models in the literature. The proposed expression is also  
280 increasing predictive accuracy and reliability of the analysis.

281

## 282 **References**

- 283 Achyutha, H., Jagadish, R., Rao, P. S., and Shakeebur Rahman, S. (1986). "Finite element simulation of the  
284 elastic behaviour of infilled frames with openings." *Comput. Struct.*, 23(5), 685–696.
- 285 Amato G, Cavaleri L, Fossetti M, Papia M (2008) Infilled frames: influence of vertical loads on the  
286 equivalent diagonal strut model. Proc. of 14th WCEE, Beijing, China, CD-ROM, Paper 05-01-0479.
- 287 Amato G, Fossetti M, Cavaleri L, Papia M (2009) An updated model of equivalent diagonal strut for infill  
288 panels. Proc. of Eurocode 8, Perspectives from the Italian standpoint Workshop. Doppiavoce Editor.  
289 Napoli, Italy, 119-128.
- 290 Asteris PG (2003) Lateral Stiffness of Brick Masonry Infilled Plane Frames. *J Struct Eng ASCE*  
291 129(8):1071-1079.
- 292 Asteris, P.G., Cotsovos, D.M., Chrysostomou, C.Z., Mohebkhah, A., Al-Chaar, G.K. (2013). Mathematical  
293 micromodeling of infilled frames: State of the Art, *Engineering Structures*, ELSEVIER, Volume 56,  
294 Pages 1905-1921.
- 295 P.G. Asteris, I.P. Giannopoulos, and C.Z. Chrysostomou, "Modeling of infilled frames with openings", *Open*  
296 *Construction and Building Technology Journal*, 6, pp. 81-91, 2012.
- 297 Asteris PG, Antoniou ST, Sophianopoulos DS, Chrysostomou CZ (2011) Mathematical Macromodeling of  
298 Infilled Frames: State of the Art. *J Struct Eng ASCE* 137(12): 1508-1517.
- 299 Baran M, Sevil T (2010) Analytical and experimental studies on infilled RC frames. *Int J Phys*  
300 *Sciences* 5(13): 1981-1998.
- 301 Cavaleri L, Di Trapani F, Macaluso G, Papia M (2012) Reliability of code-proposed models for assessment  
302 of masonry elastic moduli. *Ingegneria Sismica* 1: 38-59.

303 Cavaleri L, Fossetti M, Papia M (2005) Infilled frames: developments in the evaluation of cyclic behaviour  
304 under lateral loads. *Struct Eng Mech* 21(4): 469-494.

305 Cavaleri L, Papia M (2003) A new dynamic identification technique: application to the evaluation of the  
306 equivalent strut for infilled frames. *Eng Struct* 25: 889–901.

307 Cavaleri L, Papia M, Macaluso G, Di Trapani F, Colajanni P. (2013) Definition of diagonal Poisson's ratio  
308 and elastic modulus for infill masonry walls. *Materials and Structures*, doi 10.1617/s11527-013-0058-9.

309 Chrysostomou CZ, Asteris PG (2012) On the in-plane properties and capacities of infilled frames. *Eng Struct*  
310 41: 385–402.

311 Crisafulli FJ, Carr AJ (2007) Proposed macro-model for the analysis of infilled frame structures. *Bull New*  
312 *Zealand Soc Earthquake Eng* 40(2): 69–77.

313 Jones RM (1975) *Mechanics of composite materials*. McGraw-Hill, Tokio.

314 Holmes, M. (1961). "Steel frames with brickwork and concrete infilling." *ICE Proc.*, 19(4), 473–478.

315 Liauw, T. C. (1972). "An approximate method of analysis for infilled frames with or without opening." *Build.*  
316 *Sci.*, 7(4), 233–238.

317 Mainstone RJ (1971) On stiffness and strength of infilled frames. *Proceedings of Institution of Civil*  
318 *Engineers* 7360s: 57-90.

319 Mainstone RJ (1974) Supplementary note on the stiffness and strength of infilled frames. Building Research  
320 Station, U.K, CP 13/74.

321 Mallick, D. V., and Garg, R. P. (1971). "Effect of openings on the lateral stiffness of infilled frames." *ICE*  
322 *Proc.*, 49(2), 193–209

323 Moghaddam HA, Dowling PJ (1987) The state-of-art in infilled frames. ESEE research report 87-2. Imperial  
324 College of Science and Technology, London.

325 Mosalam, K. M., White, R. N., and Gergely, P. (1997). "Static response of infilled frames using quasi-static  
326 experimentation." *J. Struct. Eng.*,  
327 123(11), 1462–1469.

328 NCEER (1994), Workshop on "Seismic response of masonry infills", Technical report NCEER-94-0004, San  
329 Francisco.

330 Papia M, Cavaleri L, Fossetti M (2003) Infilled frames: developments in the evaluation of the stiffening  
331 effect of infills. *Structural Engineering and Mechanics* 16(6): 675-693.

332 Papia M, Cavaleri L, Fossetti M (2004) Effect of vertical loads on lateral response of infilled frames.  
333 *Proceedings 13th World Conference on Earthquake Engineering*, Vancouver, Canada, No.2931  
334

335 Sarhosis V., Tsavdaridis K., Giannopoulos G. (2014). Discrete Element Modelling of masonry in-filled steel  
336 frames with multiple window openings subjected to lateral load variations, *Open Construction and*  
337 *Building Technology Journal*, 8, XX-XX.



339 Schneider, S. P., Zagers, B. R., and Abrams, D. P. (1998). "Lateral strength of steel frames with masonry  
340 infills having large openings." *J. Struct. Eng.*, 124(8), 896–904.

341 Stafford Smith B (1968) Model tests results of vertical and horizontal loading of infilled frames. *Proceedings*  
342 *of American Concrete Institute* 65(8):618-625.

343 Stafford Smith B, Carter C (1969) A method for analysis for infilled frames. *Proceedings of Institution of*  
344 *Civil Engineers* 7218: 31-48.

345 Tasnimi, A. A., and Mohebkah, A. (2011). "Investigation on the behavior of brick-infilled steel frames with  
346 openings, experimental and analytical approaches." *Eng. Struct.*, 33(3), 968–980.

347 Valiasis TN, Stylianidis KC (1989) Masonry infills in R/C frames under horizontal loading, *Experimental*  
348 *results. European Earthquake Engineering* 3: 10-20.

349 Wang M, He M, Lu J, Huang W (2011) Study on finite element model of infilled walls of steel frames.  
350 *Advanced Materials Research* 250-253: 2424-2427.

351 Willam KJ, Citto C, Shing PB (2010) Recent results on masonry infill walls. *Advanced Materials Research*  
352 *133-134: 27-30.*

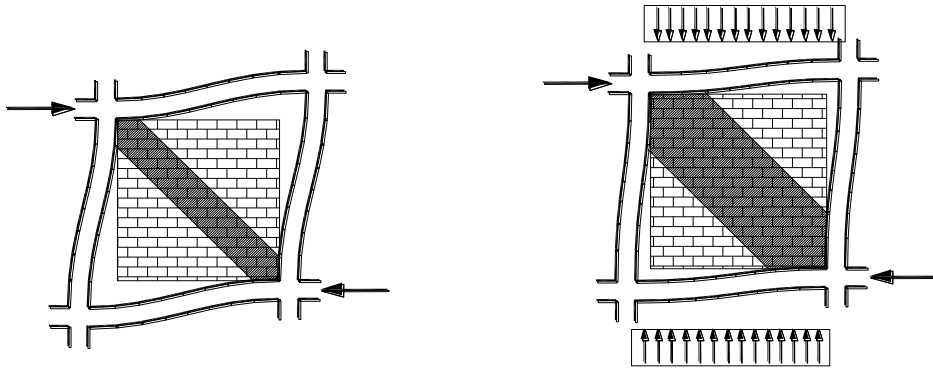
353 Yang W, Ou JP (2010) Finite-element modeling of nonlinear behavior of masonry-infilled RC frames.  
354 *Journal of Structural Engineering* 136(3): 285-296.

355 Zhai C, Wang X, Li S, Xie L (2011) An improved three-strut model for masonry infills in RC frame  
356 *structures. Advanced Materials Research* 163-167: 4129-4132.

357

358

359



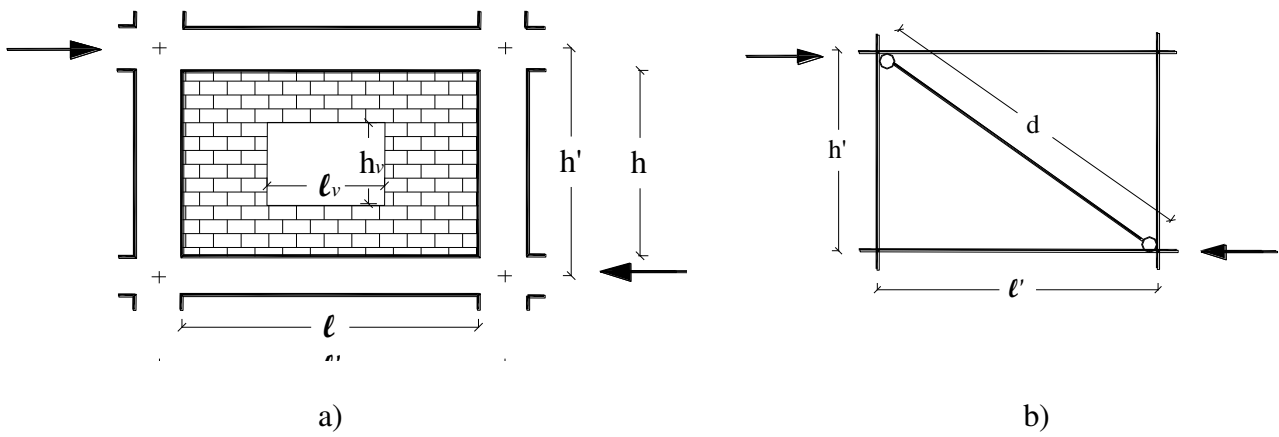
360

361

Fig.1 Effect of vertical load on the frame infill contact region under lateral load.

362

363



364

365

366

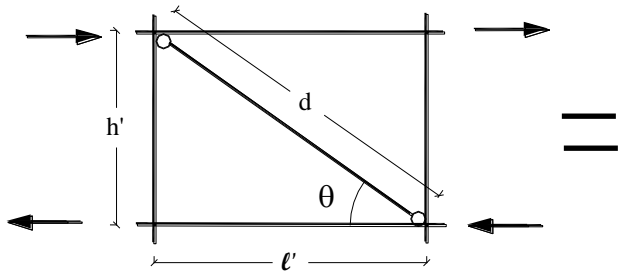
367

Fig.2 An infilled frame under horizontal load: (a) actual system; (b) macro-model.

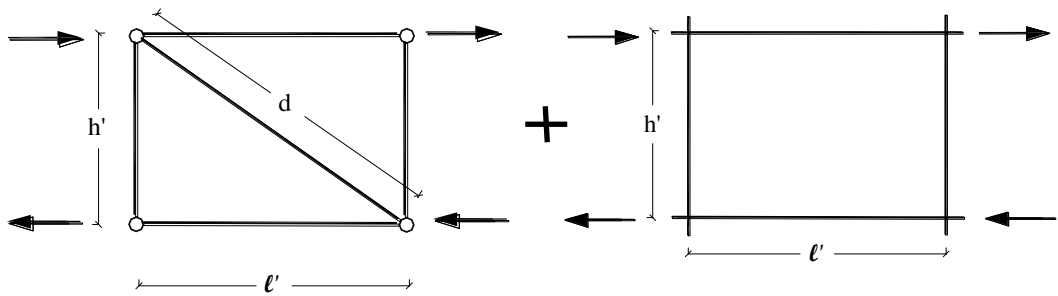
368

369

370



371 a)



b)

c)

372

373

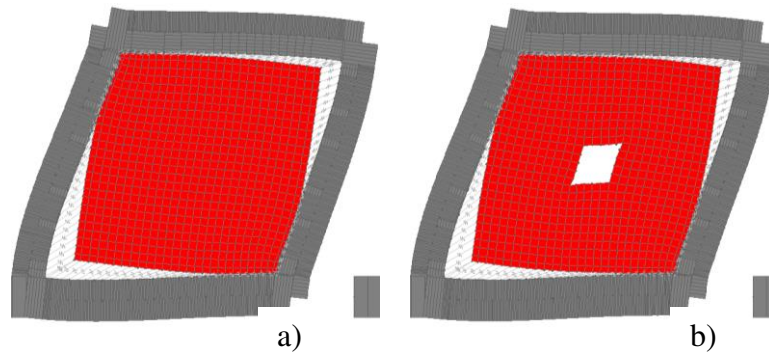
374

375

Fig. 3 Decomposition of the macro-model in two schemes

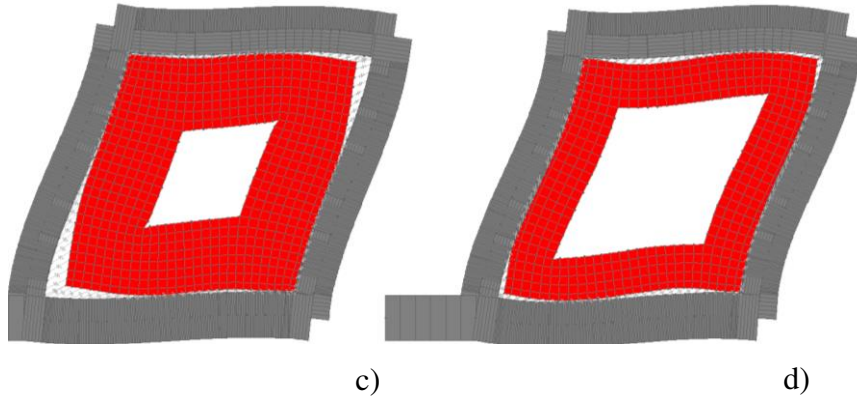
376

377



378

379



380

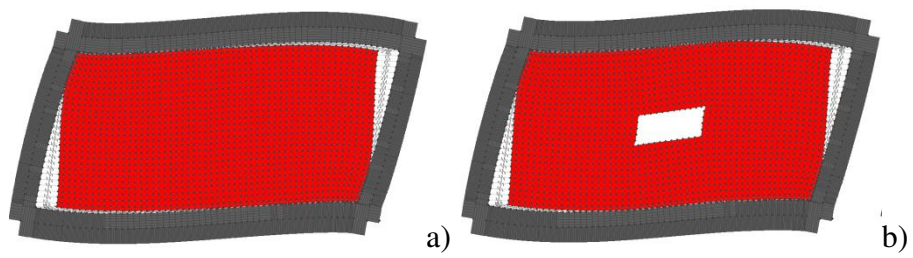
381 Fig. 4. Qualitative infilled frame deformed shape under lateral load for different opening extensions

382 -  $\frac{\ell}{h} = 1$

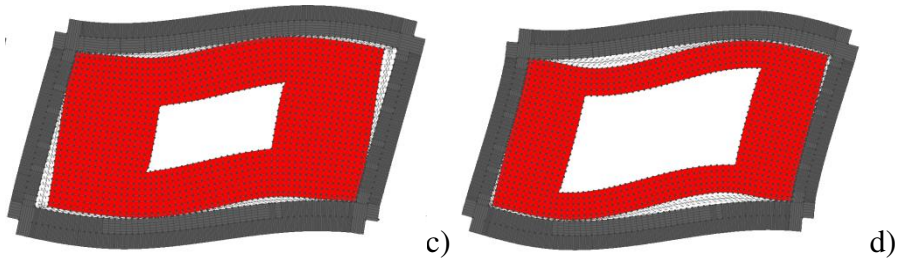
383

384

385



386



387

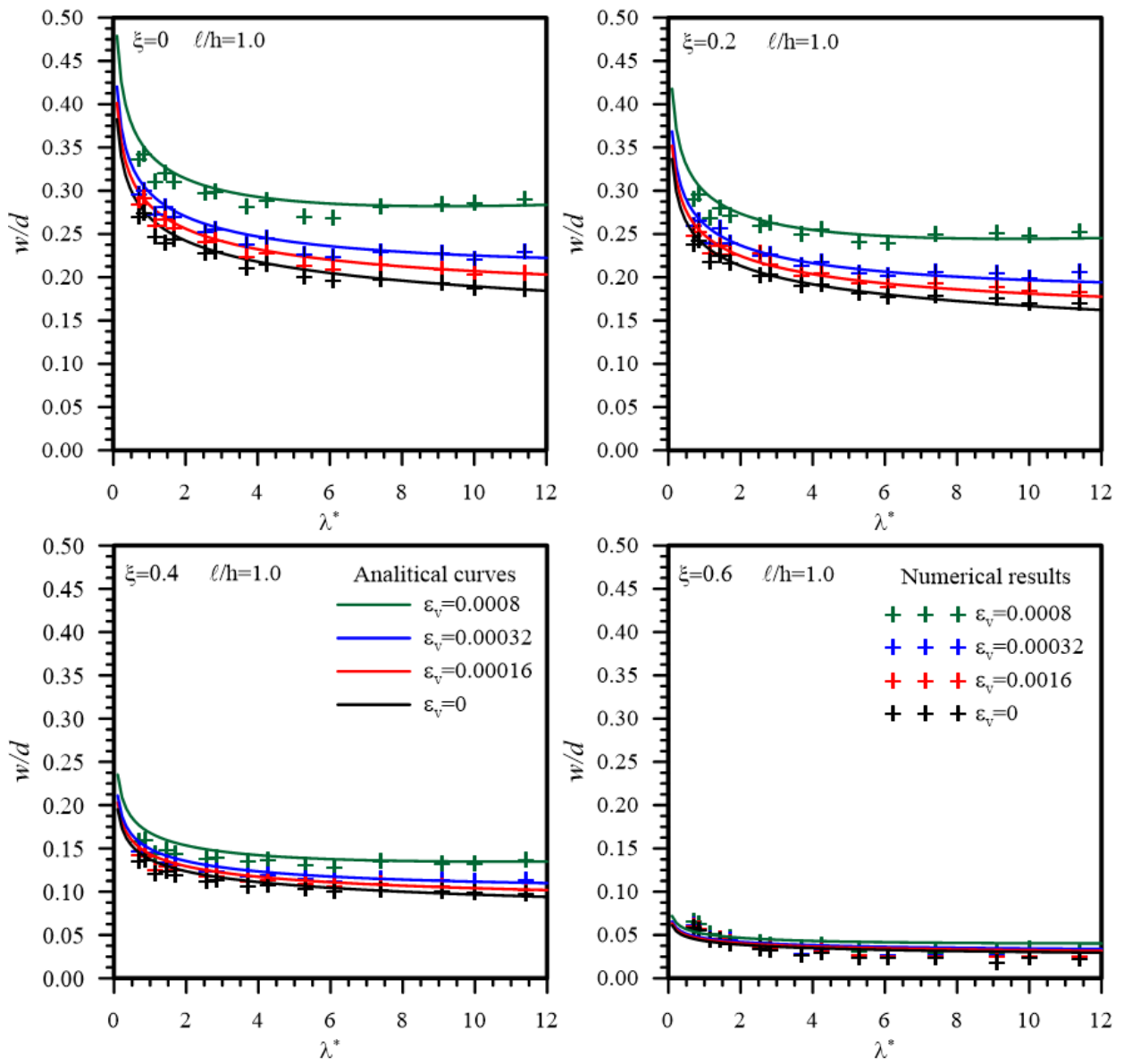
388

389

390 Fig. 5. Qualitative infilled frame deformed shape under lateral load for different opening extensions

391 -  $\frac{\ell}{h} = 2$

392



394

395

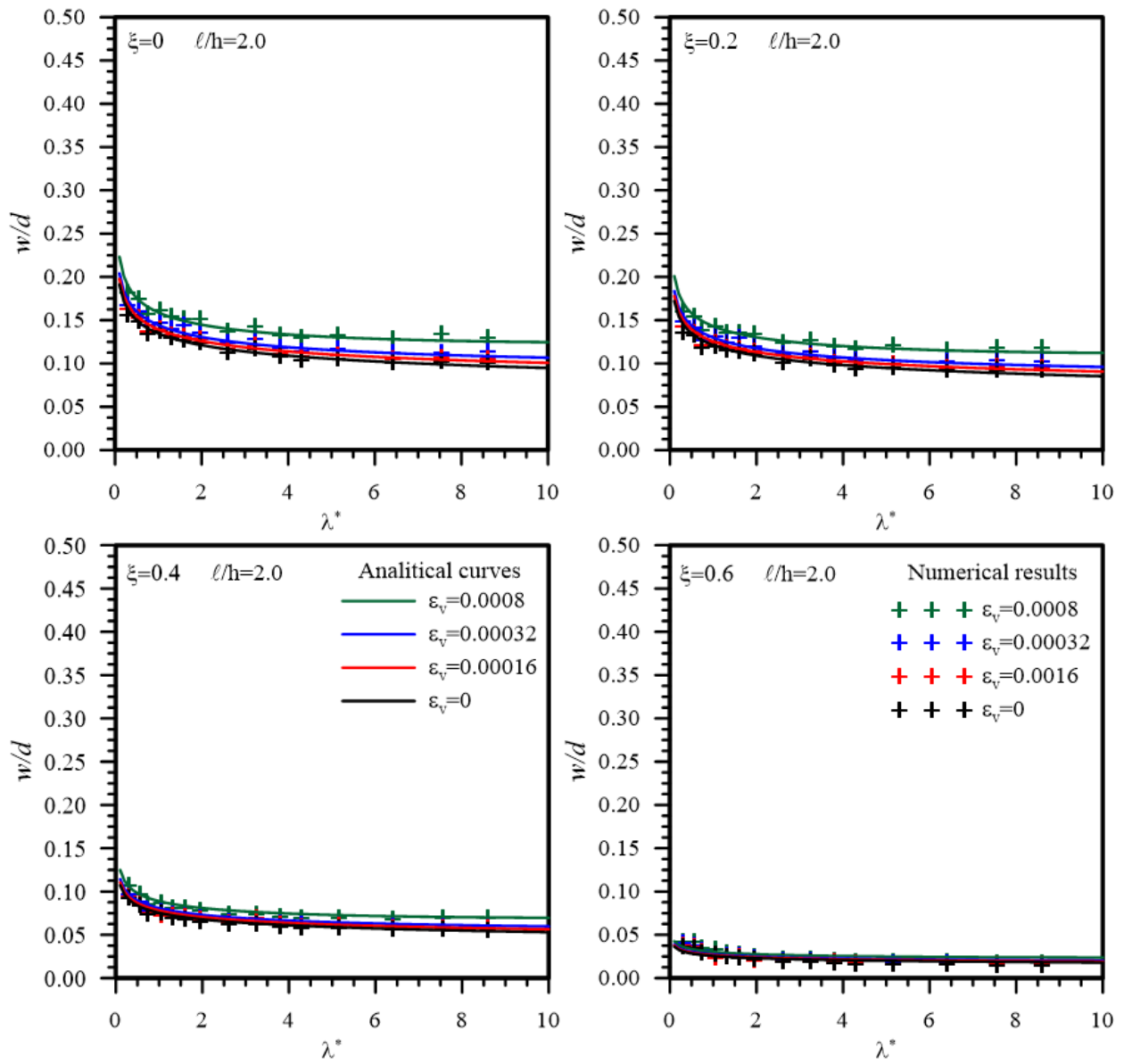
396 Fig. 6. Values of  $w/d$  varying the vertical load and the opening ratio: experimental points and fitting

397 curves –  $\frac{\ell}{h} = 1$

398

399

400



401

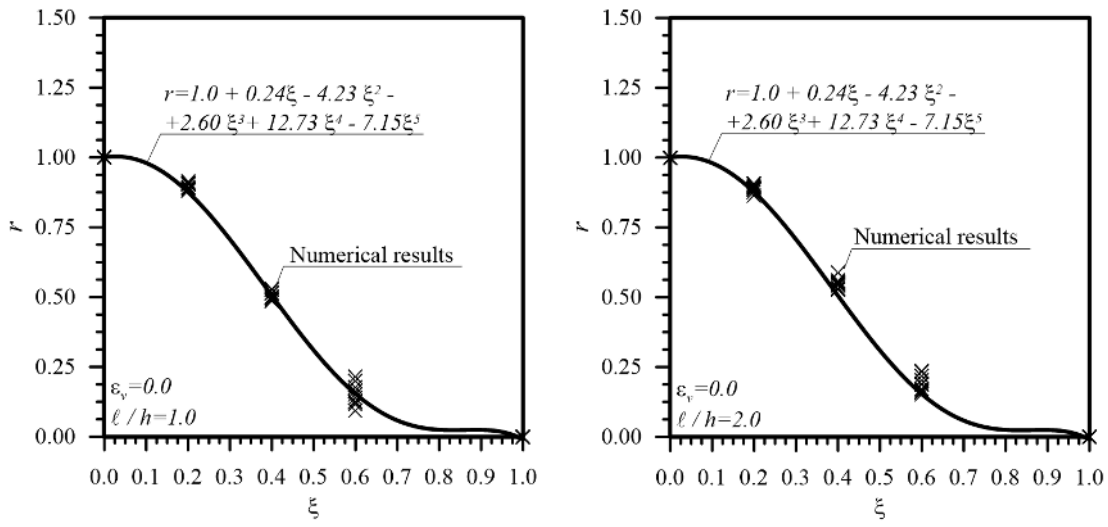
402

403 Fig. 7. Values of  $w/d$  varying the vertical load and the opening ratio: experimental points and fitting

404 curves -  $\frac{\ell}{h} = 2$

405

406



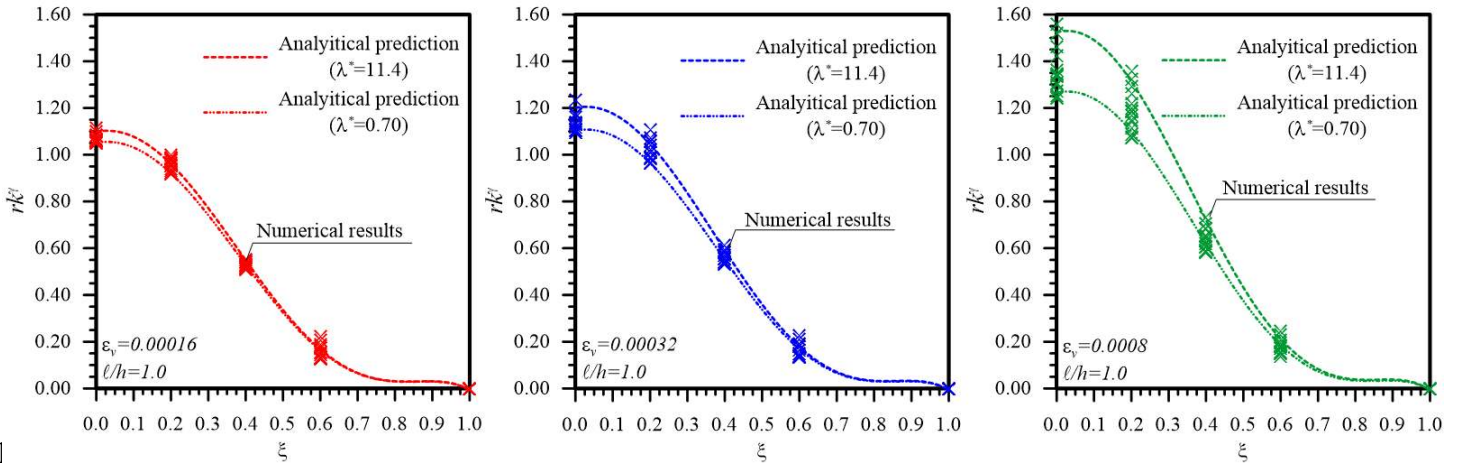
407

408

409 Fig. 8. Reduction factor (numerical points and fitting curve) of the dimensionless strut width (w/d)  
410 varying the opening ratio  $\xi$  : a) square infills, b) rectangular infills

411





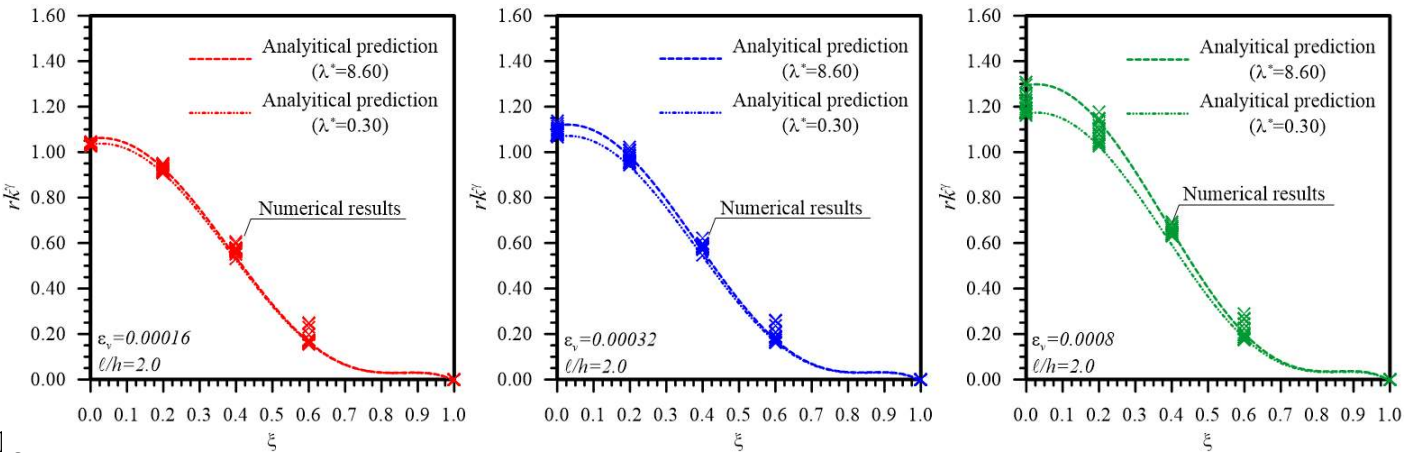
41

414 Fig. 9. Reduction factor of w/d due to openings combined with the amplification factor due to

415 vertical loads for different levels of vertical loads (numerical points and fitting curves) -  $\frac{l}{h} = 1$

416

417



41

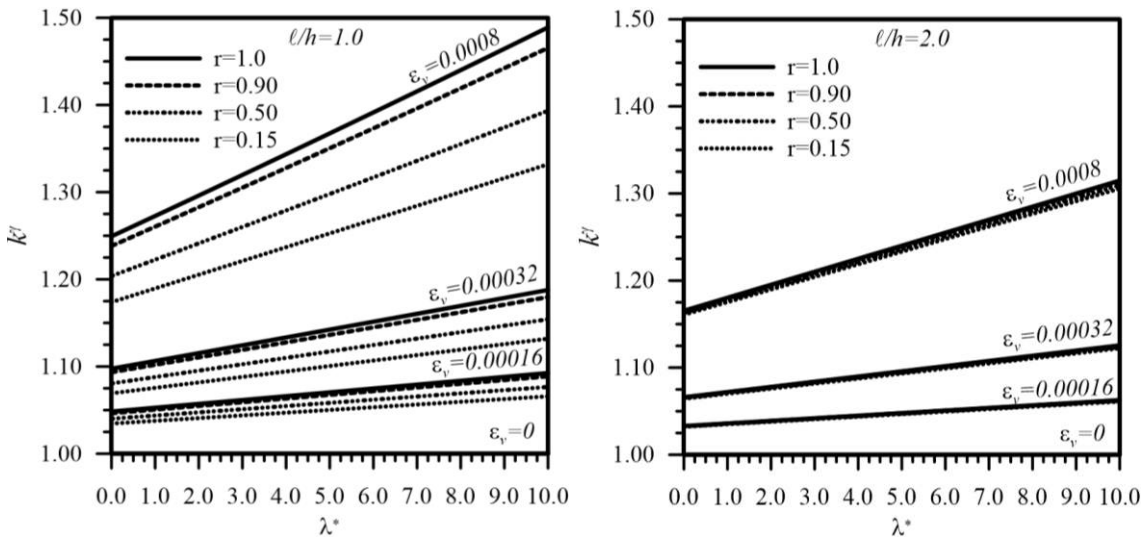
419

420 Fig.10. Reduction factor of w/d due to openings combined with the amplification factor due to

421 vertical loads for different levels of vertical loads (numerical points and fitting curves) -  $\frac{l}{h} = 2$

422

423



424

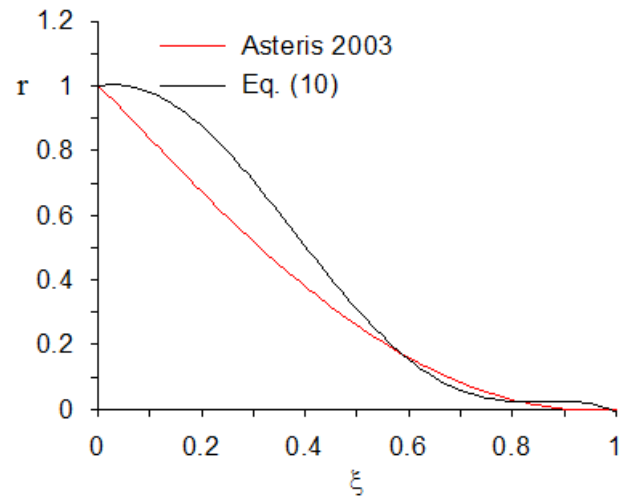
425

426 Fig.11. Values assumed by  $k_g$  varying the aspect ratio, the vertical loads and the opening ratio.

427

428

429



430

431

432 Fig. 12. Comparison between the proposed analytical expression of the reduction factor  $r$  and the  
433 that obtained from Asteris (2003).