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# Influence of Opening Ratio and Position in Infill Wall on Constitutive Law of Equivalent Compression Strut

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## Abstract

Infill walls are widely used in any building to create a separation between spaces intended for different purposes. In general, partial openings exist in infill wall with different opening ratio and position due to architectural considerations, functional needs and aesthetic concerns. In current practice, buildings are considered as bare frames ignoring infills and openings. However, infill walls and partial openings may significantly affect the seismic behavior of structures. Equivalent compression strut model is frequently used in modelling of infill walls for structural analysis. Accordingly, the force-displacement (F–D) relationship of equivalent compression strut is quite important in nonlinear analysis of infilled frames. In particular, opening sizes and position are essential parameters in order to properly constitute F–D relationship of infill wall with openings simulated by means of an equivalent compression strut. In this study, F–D relationship of equivalent compression strut is determined for different opening ratios and positions in infill wall considering three different F–D relationship models available in the literature. The maximum strength of equivalent compression strut and the corresponding displacement, the compression cracking force and the corresponding displacement, the residual strength and the axial compressive stiffness of the strut are compared and discussed for different constitutive F–D laws. It is found that force values of F–D relationships decrease as opening ratio increases. However, displacement values are not generally effected by opening ratio or position. Furthermore, openings upon the diagonal are more influential on F–D relationships of equivalent compression strut in comparison to other opening positions.

## Key words

Infill walls with openings, Opening ratio and positions, force-displacement relationship, equivalent compression strut

## 1. INTRODUCTION

In current design practice the presence of infill walls is generally neglected due to the complex composite behavior of the bounding frame and the infill wall, and the lack of a rational design procedure for masonry infilled buildings. However, the field observations after destructive earthquakes clearly illustrate that infill walls may have significant influence on seismic performance of structures by drastically altering the strength and stiffness characteristics, as well as the expected failure mechanism. Therefore, neglecting the infill walls in practical structural analysis and design may lead to a substantial inaccuracy in estimating the seismic response of infilled structures in terms of both capacity and earthquake demand.

Numerical simulation of infill walls is essential to understand and evaluate the possible effects of infill walls on global seismic response of infilled structures during major seismic events. Accordingly, during the last decades, extensive experimental investigations and analytical studies have been performed to properly model the contribution of infill [1]–[13]. On the basis of available research works, the fundamental idea to incorporate the infill wall in numerical models is generally oriented at micro- and macro-modelling techniques. Although infill walls can be simulated more adequately using micro-models, this type of modelling technique generally requires more computational effort and found to be impractical for the analysis of three dimensional structures [9], [14]. Meanwhile, macro-models exhibit significant advantages by providing reasonable accuracy and efficiency in simulating the contribution of infill. Among these, the concept of single or multiple compressive equivalent diagonal struts has by far been the most favored one [7],[8], [10]–[18].

Estimation of nonlinear strength and stiffness characteristics of the infill during the inelastic response is the preliminary issue to be considered in nonlinear analysis. In this sense, it is essential to constitute realistic force–displacement relationships capable of representing the nonlinear behavior of the equivalent strut, which is not an easy task. Therefore, many different proposals have been made for determining the stiffness and strength characteristics of infill wall and several nonlinear constitutive F–D laws composed of three or four segments and mainly developed for solid infill walls are available in the literature [19]–[24]. The presence of prevalent openings, such as windows and doors, may possibly effect the adopted constitutive parameters causing a discontinuous load path within the infill wall. Furthermore, the variability of percentage and position of the opening reveals an important uncertainty in determination of the characteristic parameters assumed in the constitutive model.

Three different constitutive models all of which enable simulating infill walls by means of a single equivalent strut are considered. The influence of the opening in terms of both percentage and position is taken into consideration by using the derived stiffness reduction factors. The variation of stiffness reduction factor as a function of opening percentage for different positions of opening is obtained from finite element analysis considering infill wall-frame interaction. The modified F–D relationship models are constituted for specific opening percentages considering three different positions of opening as upon the diagonal, above the diagonal and under the diagonal. The stiffness and strength parameters calculated in the horizontal direction are precisely transformed to the direction of the equivalent diagonal. In order to investigate the influence of the infill wall opening percentage and the opening position on the constitutive law, the characteristic parameters assumed in constitutive models of the compressive equivalent diagonal strut in terms of strength, stiffness and displacement are compared for the reference F–D relationships.

## 2. STIFFNESS REDUCTION FACTORS FOR INFILL WALLS WITH OPENINGS

In order to account for the possible effects of openings on stiffness and strength of infill wall, stiffness reduction factors (k) varying between 0 (bare frame) and 1 (fully infilled frame) are introduced. Stiffness reduction factors are originally developed considering the position and the percentage of the opening within the infill wall. Infill walls are widely simulated by two-dimensional finite elements since their thickness is smaller in comparison to the length and the height. Accordingly, a modelling technique of plane finite elements is implemented to simulate infill wall. Dimension of finite elements (i.e. small pieces of shell elements) are accurately selected and openings within the wall are easily provided by erasing the related finite elements. The mutual interaction of the bounding frame and the masonry panel is modeled by means of gap elements that can only transform axial compression. The stiffness of gap element is determined as:

$$K_g = \frac{t_w \cdot a_w \cdot E_{me}}{r_w} \quad (1)$$

where $t_w$ and $E_{me}$ are the thickness and the elastic modulus of the infill wall, and $a_w$ and $r_w$ are the width and the length of the compressive equivalent diagonal strut, respectively. The implemented modelling technique is shown in Figure 1.

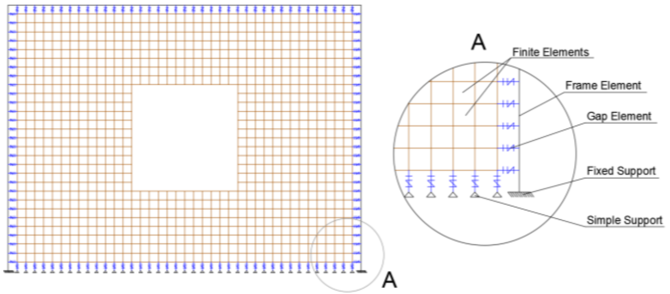


*Figure 1. Modelling of the bounding frame, the infill wall and the interaction*

Having completed the analytical model, a finite element analysis is conducted in elastic region for monotonic loading in order to determine stiffness reduction factors of infill walls with openings. Firstly, the lateral stiffness of one-story one-bay bare frame ($k_{bare}$) subjected to a horizontal load at the top level is obtained by dividing the applied load (P) to the lateral top displacement of the bare frame ($\Delta_{bare}$). Then, applying the same procedure for a fully infilled frame yields the lateral stiffness of the fully infilled one ($k_{full}$). Finally, openings are provided within the infill wall and the lateral stiffness of partially infilled frame ($k_{part}$) is calculated. Figure 2 describes the procedure used to determine the lateral stiffness one-story one-bay infilled frame with openings.

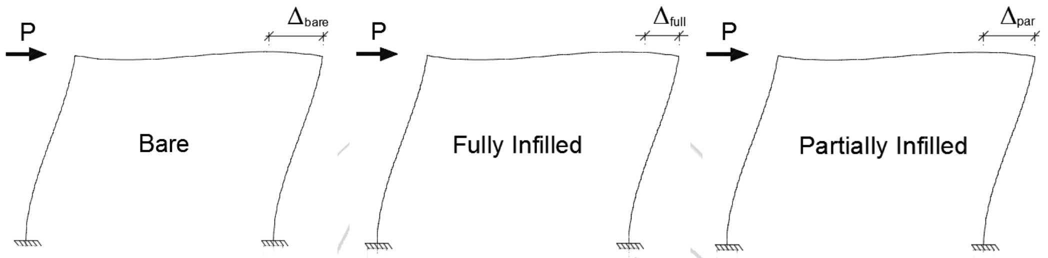


*Figure 2. Determination of lateral stiffness of frames*

The following equations yield the lateral stiffness of solid masonry infill panel (kfull,i) and the lateral stiffness of infill panel with openings (kpart,i), respectively:

$$k_{full,i} = k_{full} - k_{bare} \tag{2}$$

$$k_{part,i} = k_{part} - k_{bare} \tag{3}$$

Consequently, the stiffness reduction factor (k) accounting for the effect of the opening on the stiffness is obtained as the ratio of the lateral stiffness of infill wall with opening to the lateral stiffness of solid infill wall:

$$k = \frac{k_{part,i}}{k_{full,i}} \tag{4}$$

## 3. CONSTITUTIVE MODELLING OF INFILL WALLS

Infill walls with or without openings can significantly alter the seismic performance of structures by contributing to lateral resistance, interacting with the bounding frame and leading to different failure mechanisms expected for bare structures. In the field of nonlinear seismic analysis, the method of the compressive equivalent diagonal strut is widely used to simulate the behavior of infill panels since nonlinear micro-modelling technique requires high computational effort. The main problem containing large uncertainties is how to determine the F–D envelopes and hysteretic behavior of the diagonals. The following multi-linear constitutive models (i.e. F–D envelopes) which provide the simulation of infill wall by means of a single equivalent diagonal strut are adopted as a reference in the present study.

### *3.1. The Constitutive Law Proposed by Panagiotakos and Fardis*

The constitutive model proposed by Panagiatakos and Fardis is composed of four segments [20]. The slope of the first branch, i.e. the initial shear stiffness of the uncracked panel (K1), is specified as:

$$K_1 = \frac{G_w \cdot L_{in} \cdot t_w}{H_{in}} \tag{5}$$

where $G_w$ is the shear modulus of the wall, $L_{in}$ and $H_{in}$ are the length and the height of the infill, respectively, and $t_w$ is the thickness of the wall.

The yielding force ($F_y$) corresponding to the first cracking of infill wall (i.e. the cracking force) is associated with the tensile strength of the infill ($f_{tp}$) obtained from the diagonal compression test and is determined using the following equation:

$$F_y = f_{tp} \cdot L_{in} \cdot t_w \tag{6}$$

The second branch corresponds to the formation of a diagonal compressive path within the infill wall. Accordingly, the axial stiffness of the compressive equivalent diagonal strut ($K_2$) is:

$$K_2 = \frac{E_{me} \cdot t_w \cdot a_w}{r_w} \tag{7}$$

The ratio between the maximum force ($F_m$) and the cracking force is assumed to be 1.3. The displacement corresponding to the maximum force can easily be determined as:

$$\delta_m = \delta_y + \frac{F_m - F_y}{K_2} \tag{8}$$

where $\delta_y$ is the displacement at the cracking point.

The stiffness of the third branch representing the softening of the infill panel is assumed to range within $0.005 \cdot K_1 \leq K_3 \leq 0.1 \cdot K_1$. The residual force ($F_r$) is assumed $0.05 \cdot F_y \leq F_r \leq 0.1 \cdot F_y$ whereas the corresponding displacement ($\delta_r$) is calculated as:

$$\delta_r = \delta_m + \frac{F_m - F_r}{K_3} \tag{9}$$

The fourth branch characterized by a constant residual strength describes the ultimate state of the infill wall. The F–D relationship of Panagiotakos and Fardis is shown in Figure 3 (a).

### *3.2. The Constitutive Law Proposed by Dolsek and Fajfar*

A three-linear F–D envelope for the diagonal strut representing the masonry infill based on the results of some experimental tests is proposed by Dolsek and Fajfar [22]. The initial stiffness of the infill ($K_1$) is calculated according to Eq. (5). The strength of the infill ($F_m$) is determined as follows:

$$F_m = 0.818 \cdot \frac{L_{in} \cdot t_w \cdot f_{tp}}{C_I} \cdot \left(1 + \sqrt{{C_I}^2 + 1}\right) \tag{10}$$

where $C_I$ is estimated by:

$$C_I = 1.925 \cdot \frac{L_{in}}{H_{in}} \tag{11}$$

The cracking force ($F_y$) is assumed to be $0.6 \cdot F_m$. The story drift corresponding to the maximum force ($D_m$) is 0.2% in case of solid infill panel, 0.15% in case of window opening and 0.10% in case of door opening. The ratio between the story drift at collapse of the infill panel and that at the maximum force is arbitrarily assumed as 5 (Figure 3 (b)).

For the F–D envelope of the diagonal strut, both the initial stiffness and the strength in horizontal direction have to be transformed to the direction of the diagonal, as well as in the constitutive relationship proposed by Panagiotakos and Fardis.

### *3.3. The Constitutive Law Proposed by Tsai and Huang*

A multi-linear constitutive F–D law is used to simulate the nonlinear behavior of the compressive equivalent diagonal strut. The compressive strength of the infill ($R_m$) is evaluated through the following equation:

$$R_m = a_w \cdot t_w \cdot f'_{m90} \tag{12}$$

where $f'_{m90}$ is the horizontal expected strength of the infill panel and is assumed to be 65% of the compressive strength of the infill ($f'_m$) which is estimated in terms of the compressive strength of bricks ($f_b$) and the mortar strength ($f_j$) as follows [2]:

$$f'_m = 0.63 \cdot {f_b}^{0.49} \cdot {f_j}^{0.32} \tag{13}$$

The displacement corresponding to the compressive strength of the infill is:

$$\Delta_m = \varepsilon'_m \cdot r_w \tag{14}$$

where $\varepsilon'_m$ is the strain corresponding to the maximum compressive strength and is estimated by:

$$\varepsilon'_m = \frac{0.27}{{f_j}^{0.25}} \cdot \frac{f'_m}{{E_{me}}^{0.7}} \tag{15}$$

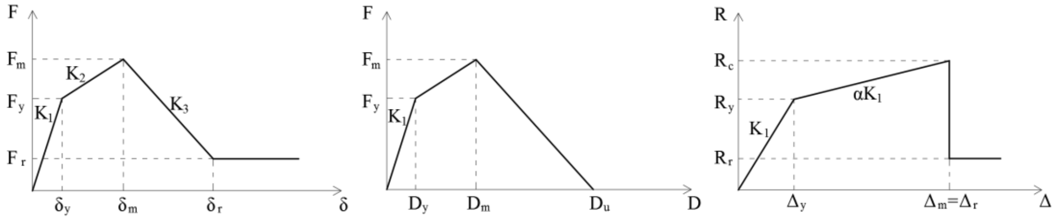
The cracking force ($R_y$) is given by:

$$R_y = \frac{R_m - \alpha \cdot K_1 \cdot \Delta_m}{1-\alpha} \tag{16}$$

The post-stiffness ratio ($\alpha$) is assumed as 0.2. The displacement at the cracking ($\Delta_y$) can be calculated as:

$$\Delta_y = \frac{R_y}{K_1} \tag{17}$$

Finally, the residual strength of the diagonal strut ($R_r$) is assumed to 30% of the cracking force. The model of Tsai and Huang, and the main involved parameters are shown in Figure 3 (c).



(a) Panagiotakos and Fardis (b) Dolsek and Fajfar (c) Tsai and Huang

*Figure 3. The adopted constitutive models*

## 4. CASE STUDY

In order to investigate the possible influence of opening percentage and position within the infill wall on the relevant parameters of the constitutive model of the compressive equivalent diagonal strut, one-story one-bay reinforced concrete (RC) frame is considered. The bay length is 5 m and the story height is 3 m. Rectangular beams and square columns are considered in the design. Rectangular beam dimensions are 25x50 cm and square columns dimensions are 40x40 cm. The compressive strength of concrete is assumed to be 20 MPa. The masonry infill consists of hollow bricks with a thickness of $t_w$ = 200 mm. The elastic modulus of infill wall is calculated as $E_{me}$ = 1661 MPa considering the stress–strain relations of brick infill and mortar [2]. Three different positions of window opening as opening upon the diagonal, opening above the diagonal and opening under the diagonal, and three opening percentages (the area of the opening to the total area of infill) as 22%, 32% and 45% are considered. The typical layout of the openings is shown in Figure 4.

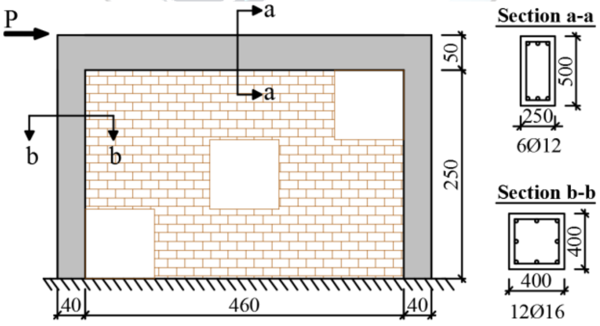


*Figure 4. Layout of the openings within the wall and the bounding RC frame*

### *4.1. Stiffness Reduction Factors*

The influence of the opening in terms of both percentage and position is taken into consideration by means of stiffness reduction factors. The variation of stiffness reduction factor as a function of opening percentage for different positions of opening is obtained from finite element analysis considering infill wall-frame interaction. The finite element analysis is conducted in the elastic region for the monotonic loading using the structural analysis tool SAP2000 [25]. Figure 5 shows the derived stiffness reduction factor of infilled frame with openings in relation to opening percentage for three different positions of opening. One can easily obtain the stiffness reduction factors entering in this graph. The stiffness reduction factors determined for the opening positions and percentages considered in this study are presented in Table 1.

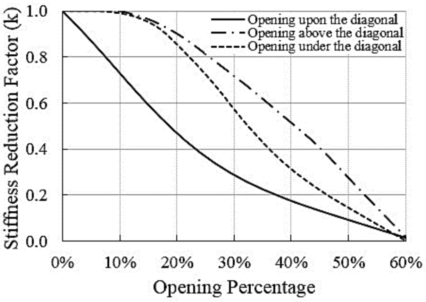


*Figure 5. Variation of stiffness reduction factor in relation to opening percentage*

*Table 1. Stiffness reduction factors*

| Opening percentage (%) | Position of the opening | | |
|---|---|---|---|
| | Upon the diagonal | Above the diagonal | Under the diagonal |
| 22 | 0.43 | 0.88 | 0.82 |
| 32 | 0.26 | 0.68 | 0.52 |
| 45 | 0.13 | 0.41 | 0.22 |

With reference to Figure 5, it can be concluded that stiffness reduction factors of all opening positions decrease as opening percentage increases. However, the position of opening substantially effects the variation of the stiffness reduction factor with respect to opening percentage. Opening upon the diagonal is more influential on reducing the stiffness of the infill wall, since it gives smaller stiffness reduction factors. This position of opening significantly reduces the stiffness even in case of small opening percentages. On the other hand, opening above the diagonal is the least influential position. For opening percentages smaller than 18 both opening positions above the diagonal and under the diagonal have the same influence on stiffness of infill and for opening percentages small than 10, the presence of the opening may be neglected for those positions of the opening. On the contrary, the contribution of the infill wall with opening can be ignored regardless of the position in case infill wall opening ratio exceeds 60%.

### *4.2. The Modified Constitutive Relationships*

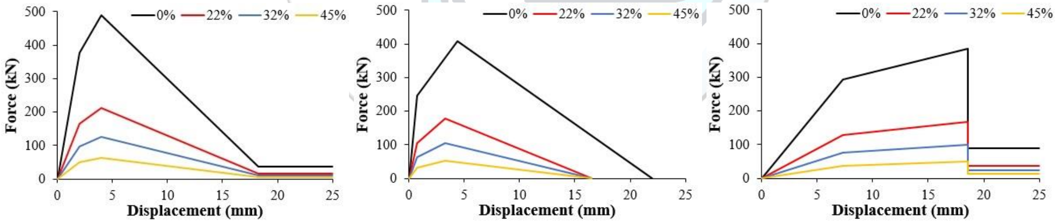
Since the influence of the opening in terms of both percentage and position is taken into consideration by using the stiffness reduction factors of the study, strength and stiffness parameters of the constitutive F–D law are conveniently reduced. Accordingly, modified F–D relationships reflecting the influence of the opening are constituted for infill walls with openings. The additional necessary parameters to constitute the reference F–D relationships are taken as $G_w$ = 664.4 MPa, $f_{tp}$ = 0.36 MPa and $f'_{m90}$ = 3.02 MPa. The width of the compressive equivalent diagonal strut is calculated as $a_w$ = 637 mm for the infill wall without opening [26]. In order to properly investigate the influence of opening percentage and position on the constitutive law of the compressive equivalent diagonal strut, stiffness and strength parameters applied to the horizontal direction in the models of Panagiotakos and Fardis, and Dolsek and Fajfar are transformed to the direction of the diagonal. Accordingly, summarized in Table 2 are the constitutive parameters of the diagonal strut.

The values of constitutive parameters in terms of both strength and stiffness decrease with increasing infill wall opening ratio in all the constitutive models. The highest strength and stiffness values are obtained when the opening is considered above the diagonal and the smallest ones are calculated for the central opening. The cracking and the maximum force values of the Panagiotakos and Fardis constitutive law are relatively higher than those values of the other two models. Although its higher strength, the cracking force of the constitutive law proposed by Fardis and Fajfar is smaller than the cracking force of the Tsai and Huang constitutive law. The initial stifness of the constitutive F–D laws of Panagiotakos and Fardis and Dolsek and Fajfar is equal while the initial stiffness of Tsai and Huang constitutive relationship is quite low. Accordingly, larger displacements are obtained in the case of the model of Tsai and Huang. $K_2$ stiffness of the Dolsek and Fajfar constitutive law is 60% higher than $K_2$ stiffness of the Panagiotakos and Fardis model, while the stiffness of the softening branch of the two model is almost the same. Displacement corresponding to the cracking point is not influenced by the infill wall opening ratio and the opening position. The displacement corresponding to the maximum force and the ultimate displacement of the infill panel with opening are found to be smaller than those values of the solid panel in the case of Dolsek and Fajfar constitutive law. However, the infill wall opening ratio does not affect these displacements. On the other hand, the constitutive displacements of the other two models do not change according to the infill wall opening ratio and the opening position.

*Table 2. Constitutive parameters of the diagonal strut*

| **Opening position** | **Opening percentage** | **$R_y$ (kN)** | **$\Delta_y$ (mm)** | **$R_m$ (kN)** | **$\Delta_m$ (mm)** | **$R_r$ (kN)** | **$\Delta_u$ (mm)** |
|---|---|---|---|---|---|---|---|
| **Panagiotakos and Fardis** | | | | | | | |
| Fully infilled | 0% | 377 | 1.19 | 490 | 3.99 | 38 | 18.27 |
| Upon the diagonal strut | 22% | 164 | 1.19 | 213 | 3.99 | 16 | 18.27 |
| | 32% | 97 | 1.19 | 126 | 3.99 | 10 | 18.27 |
| | 45% | 49 | 1.19 | 64 | 3.99 | 5 | 18.27 |
| Above the diagonal strut | 22% | 330 | 1.19 | 429 | 3.99 | 33 | 18.27 |
| | 32% | 254 | 1.19 | 331 | 3.99 | 25 | 18.27 |
| | 45% | 153 | 1.19 | 198 | 3.99 | 15 | 18.27 |
| Under the diagonal strut | 22% | 308 | 1.19 | 400 | 3.99 | 31 | 18.27 |
| | 32% | 196 | 1.19 | 255 | 3.99 | 20 | 18.27 |
| | 45% | 83 | 1.19 | 108 | 3.99 | 8 | 18.27 |
| **Dolsek and Fajfar** | | | | | | | |
| Fully infilled | 0% | 245 | 0.77 | 408 | 4.39 | - | 21.96 |
| Upon the diagonal strut | 22% | 106 | 0.77 | 177 | 3.29 | - | 16.47 |
| | 32% | 63 | 0.77 | 105 | 3.29 | - | 16.47 |
| | 45% | 32 | 0.77 | 53 | 3.29 | - | 16.47 |
| Above the diagonal strut | 22% | 214 | 0.77 | 357 | 3.29 | - | 16.47 |
| | 32% | 165 | 0.77 | 275 | 3.29 | - | 16.47 |
| | 45% | 99 | 0.77 | 165 | 3.29 | - | 16.47 |
| Under the diagonal strut | 22% | 200 | 0.77 | 333 | 3.29 | - | 16.47 |
| | 32% | 127 | 0.77 | 212 | 3.29 | - | 16.47 |
| | 45% | 54 | 0.77 | 90 | 3.29 | - | 16.47 |
| **Tsai and Huang** | | | | | | | |
| Fully infilled | 0% | 294 | 7.28 | 385 | 18.54 | 88 | - |
| Upon the diagonal strut | 22% | 128 | 7.28 | 168 | 18.54 | 38 | - |
| | 32% | 76 | 7.28 | 99 | 18.54 | 23 | - |
| | 45% | 38 | 7.28 | 50 | 18.54 | 12 | - |
| Above the diagonal strut | 22% | 258 | 7.28 | 337 | 18.54 | 77 | - |
| | 32% | 199 | 7.28 | 260 | 18.54 | 60 | - |
| | 45% | 119 | 7.28 | 156 | 18.54 | 36 | - |
| Under the diagonal strut | 22% | 240 | 7.28 | 314 | 18.54 | 72 | - |
| | 32% | 153 | 7.28 | 201 | 18.54 | 46 | - |
| | 45% | 65 | 7.28 | 85 | 18.54 | 19 | - |

In Figure 6, the F–D relationships obtained for the opening position upon the diagonal, which is found to be the most influential opening position, using the constitutive parameters of Table 2 is plotted.



*(a) Panagiotakos and Fardis* *(b) Dolsek and Fajfar* *(c) Tsai and Huang*

*Figure 6. F–D relationships for the opening position upon the diagonal strut*

## 5. CONCLUSIONS

The results of the study demonstrate that the stiffness and strength values of the constitutive relationships decrease as the opening ratio increases and the position of the opening has a substantial influence on those values. However, the displacements are not affected by the infill wall opening ratio and the opening position expect the displacement corresponding to the strength of the infill in the case of the constitutive law proposed by Dolsek and Fajfar. A relatively large displacement at the cracking point of the infill wall is obtained in the case of the Tsai and Huang constitutive law, while the cracking displacements of the other two models show quite close agreement. Although the constitutive law of Dolsek and Fajfar yields relatively smaller ultimate displacement, the ultimate displacements of the considered models agree quite well. Openings upon the diagonal are found to be more influential on the constitutive parameters of the considered F–D relationships of the compressive equivalent diagonal strut.

Considering the complexity of adopting a simple yet realistic constitutive law for masonry infill walls, it can be concluded that the agreement between the characteristic parameters of the different constitutive models is quite reasonable.

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