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AN ANALYTICAL APPROACH FOR ASSESSMENT OF THE EFFECTS OF INFILL PANELS IN RC FRAMES

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Abstract. *The use of macro-modeling approaches based on the concept of the equivalent strut for simulating infill panels presents a number of critical aspects, mainly related to the variability of the results from the parameters adopted (for example: width of the strut, non-linear constitutive law under cyclic actions, assignment of strut mechanical properties in multiple strut models). It should also be observed that it is particularly difficult to identify and calibrate the above mentioned quantities, even if the mechanical parameters of the masonry components (mortar and bricks) are known. It is thence highly desirable to define numerical procedures for aimed at this task, in order to reduce the variability of results due to the characteristics of the equivalent strut. In the present paper, the first results of a procedure aimed at the calibration of the macro-models of infill panels are presented. The adopted methodology directly considers the heterogeneity of materials and the texture effects at the micro-scale, exploiting a "Rigid Body and Spring Model"(RSBM), in which the masonry panel is described as a set of unitary cells constituted by rigid blocks and elasto-plastic springs. The non-linear cyclic law of the equivalent strut is then obtained by a simple numerical identification procedure. The approach has been validated on the basis of some reference experimental tests available in the technical literature, by comparing the experimental results and those obtained respectively by RBSM model and the strut model previously calibrated with the proposed procedure.*

1 INTRODUCTION

In RC framed buildings, infill panels are usually made by hollow masonry brickwork built within the frame mesh in contact with the surrounding structural RC elements (beams and columns), but without any reliable connecting device. For these reasons, in the common practice and technical standards [1,2], the infilled panels are considered as non-structural elements. It is commonly – but incorrectly – believed that neglecting the stiffness and strength contribution provided by infill walls is a conservative assumption, with regard to the structural safety. The observation of the damages caused by recent earthquakes on existing RC buildings has pointed out that the presence of infill panels modifies the behaviour of the frame under seismic loads. Furthermore, the effects induced can be very variable depending on the distribution of the infill panels and the interaction between panels and RC frames [3]. In some cases these aspects play a crucial role in the seismic assessment, and can void the complex procedures for the evaluation of the mechanical strength of the materials [4].

Actually, the increasing awareness of the crucial role played by infill is orienting the current research threads towards studies aimed at incorporating this aspect into the seismic vulnerability assessment of existing structures. In this sense, existing procedures like the N2 Method for the pushover analysis have been recently extended in order to account for the infill contribution [5].

Over the past years, the variability exhibited by the behaviour of infilled frames (in particular for buildings designed under vertical loads only) has strongly stimulated researchers to investigate the interaction between masonry panels and RC by means of experimental tests [6,7]. The results of these research studies have pointed out a great dispersion of the parameters which characterize the seismic response of the infilled frames. The main source of the scattering in the numerical results is, indeed, the high variability of the significant model parameters. Among these, the mechanical characteristics of the constituent materials (mortar and bricks) and of the overall masonry panel (intended as a continuous material) are crucial. But another fundamental aspect is represented by the model adopted for simulating the infills within the computational model of the building. In this context, there are several approaches, in the literature. The approaches based on the macro-modeling of the panel are surely the most popular. The composite panel is replaced by an equivalent beam element reacting only to compressive axial loads (strut), in which the material is an homogeneous continuum. The advantage of the approach is surely represented by a great reduction of the involved parameters – and thence of the computational burden (the only variables at stake are the geometrical and mechanical parameters of the equivalent strut: width b_W, stiffness, non-linear cyclic law). On the other side, it should be observed that the advantages related to the simplicity and versatility of the model are counterbalanced by the great uncertainty about the definition of these parameters, which actually varies in a wide range, making the results very disperse [8,9]. The availability of many different models further contributes to increase the uncertainty of the results: several numerical relationships have been recently proposed in order to calibrate the equivalent strut by considering the effects of the failure modes (which is very difficult to predict in the preliminary design phase) and of local effects (weakness at the ends of columns) [10].

Within this framework, the present study proposes a procedure aimed at calibrating the parameters of the equivalent strut on the basis of detailed meso-scale analyses of the infilled frame performed by a rigid elements approach. The basic idea is to define an automatic procedure in which, once the geometrical and mechanical parameters of the infilled frame are given as input data, the non-linear cyclic law of equivalent strut is provided as the output.

The procedure, is not intended to be used as an alternative to more refined models, but as a valid tool for obtaining reliable results within the framework of the equivalent strut method. In fact, it is of simple and rapid application, and able to reduce computational burden, especially when the global behaviour of a whole building has to be assessed. In the meso-scale model, the masonry panel is described as a periodical assembly of unitary cells constituted by rigid elements and elasto-plastic springs (RBSM) [11]. In the paper, after outlining the whole procedure and its theoretical basis, some preliminary results are presented, which are useful in order to validate the fundamental steps of the whole procedure. The current format of the procedure is actually a preview of a work which is presently in progress, and will involve the implementation of further refined analyses at the meso-scale level, as well as further validations performing laboratory tests with the use of modern technologies for stress and strain measurement [12,13].

2 STATE OF ART

As previously mentioned, many difficulties arise when trying to characterize the seismic response of infilled frames. These are due in part to the variability of the different parameters that govern the overall mechanical behaviour, in part to the problems encountered in the experimental testing, and also to the difficulties associated to the numerical modeling of masonry structures. The last aspect is particularly important, and will be briefly discussed in the following paragraph, with the aim of providing an overview of the available analytical models and modeling techniques. Two large categories are identified: finite element models (micro-modeling) and simplified or phenomenological models (macro-modeling).

2.1 Micro-modeling

Micro-models are aimed at simulating the non-linear nature of the masonry panel, taking into account the behavior of the individual constituents: brick and mortar. The analysis becomes quite complex, as a result of the kinematic induced by horizontal joints, that represent the weak point of the panel [14].

These approaches can be further subdivided into four categories, depending on the level of sophistication of the model adopted for the masonry components and, most of all, for the contact surfaces between the elements of the panel and between them and the structures of the boundary frame. The first group includes coarser methods, in which masonry is considered as a homogeneous material, and the effects induced by the presence of mortar joints are accounted at a global level, by introducing proper parameters. They are usefully applied to appraise the global structural behaviour without entering into the detail of the local tensional response of individual panels. The mechanical properties of the masonry are defined by a stress-strain law and a failure criterion (Von Mises, Drucker-Prager) is specifically assigned to the material [15]. The second group includes models in which masonry is considered as a two phase material, and both brick and mortar joints are modeled with continuous elements [16]. The contact surfaces between the elements are represented by a bed of springs (interface elements) in order to account for local debonding, sliding or detachment. This kind of models involve a large number of finite elements and parameters and thence require a heavy computational effort, which limits the applications to the analysis of small panels. The models belonging to the third group are in the mid between the previous ones, since they model the blocks with continuous elements and the mortar joints with springs, in which both the of elasto-plastic deformation of the mortar and the block-interface interaction is incorporated. The reference model, proposed by Page, provided only an elastic behaviour for the blocks [17].

Finally, the last group includes numerical models created as an extension of Page model. The distinguishing feature is the possibility of considering the post-elastic behavior of the blocks up to failure [18]. Actually, these approaches are not able to precisely identify the collapse mode, but allow to determine the failure condition thanks to the accurate reproduction of the stress (and hence the stiffness) associated to the generic node of the mesh. However, these methods often involve problems related to a strong mesh sensitivity, since many authors use triangular shape mesh. In this sense, Liaw and Kwan [19] have used three different types of element for studying the behavior of the infilled frame subject to monotonic loads. In particular, they used a one-dimensional element able to simulate the creep and debonding for the frame-infill contact surface, triangular planes elements (2 DoF nodes) for the panel, and a brittle material with an ideally linear elastic behaviour under tension. The distinguishing feature of the model is to consider an isotropic material before cracking, and an anisotropic material after cracking.

It should be noted that all the described models are characterized by a relevant computational burden, as the consequence of the micro-scale modeling of the mechanical behavior of heterogeneous materials (i.e., masonry infills). In continuous approaches, the effects due to the heterogeneity of the constituent materials is considered by means of homogenization procedures [20] aimed to the definition of an equivalent continuum to be used in the finite element analysis.

As an alternative to continuum models combined with homogenisation techniques, it is possible to adopt discrete models [21]. In the present work, indeed, this class of approaches is adopted, according to which the masonry panel (which is a heterogeneous periodic body) is macroscopically described as a "mechanism" composed by "periodic cells" connected by springs (RSBM, [11,22]).

Through this approach, it is possible to model the masonry panels at the "macro-scale" through a kinematic that take into account, in a simplified manner, also of the specific effects of masonry texture. These approach has have been fruitfully applied, in the last few years, for modeling the behaviour of masonry structures both in-plane and out-of-plane [23,24,25,26], allowing to perform the vulnerability assessment for whole masonry buildings [27,28,29,30].

2.2 Macro-modeling

In macro-modeling approaches, the simulation of the frame-infill interaction is based on the solution of simplified mechanical problems. Among them, it is worth mentioning the "equivalent strut" method [31,32]. It is based on the experimental observation that under horizontal actions, is the compressive stress substantially follows the diagonal path, and thence adopts one or more equivalent diagonal struts in order to simulate the infill masonry panel. This method is indeed one of the most used, thanks to easy and flexible application possibilities. On the other hand, it should be observed that the advantages related to the simplicity and versatility of the model are counterbalanced by the difficulties rising in the interpretation of the numerical results. Indeed, the most critical problem in the use of macro-models consists in the difficulty of correctly identifying the mechanical properties and the geometrical features of the equivalent diagonal struts, which haven't a direct correspondence with the actual frame-panel system.

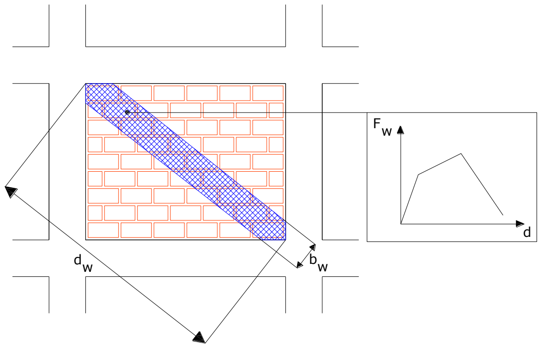

Figure 1: Modeling infilled frame using the "equivalent strut" method.

It must be underlined, however, that the opportunity of properly considering the role of in-fill panels in the structural seismic response, especially in the case of existing structures designed for vertical loads only [8,9] is, nowadays, widely acknowledged. Moreover the use of simplified models is a modern approach also for more complex problems [33].

The fundamental parameters of the methods are represented by the geometric features of the strut (length d_W, thickness t_W and width b_W), the stiffness λ, the hysteretic constitutive law F_W-d which governs the non linear cyclic behaviour of the panel (Figure 1).

Depending on the objectives of the analysis (whether the effect of the infills on the global behavior of the structure are to be appraised, or attention is focused on the local response of the structural elements), it could be necessary to adopt multi-strut systems to simulate the presence of the panel. This approach allows to evaluate the effects of shear induced by the panels on the ends of the reinforced concrete elements, highlight possible brittle behaviours [34]. There is an extensive literature in this field, that shows the interest of the scientific community for the topic, and but reveal also that there is a great variability of the results, depending on the formulation and application of the proposed procedures [10].

It's also important investigate the aspects relate to the hysteretic law that defines the equivalent strut response. Among the different proposals, examples can be found in which the law is expressed in terms of axial strain/stress [34], and formulations in which, regardless of the geometrical and mechanical characteristics of the infill, a predominant failure mode (which can consist in the crushing at the center or at the corners of the panel) is a-priori defined [35].

Anyway, the experimental evidence has pointed out that crushing represents only one of the possible failure modes of the infill panel. Thence, it should be first necessary to evaluate the ultimate load associated to each of the possible failure, and then to calculate the strength of the panel as the minimum of these loads [36].
Two other closely related factors that complicate the calibration of macro-models for simulating masonry infill panels are: *(i)* the large dispersion of the mechanical properties of the materials, that being intended for non structural elements, are usually scarcely qualified, *(ii)* the unreliability of the predictive methods available in this field.

The equivalent strut is a very effective and practical method but presents many drawbacks that may affect its reliability. For these reasons, this paper proposes a methodology based on a simplified analysis of the infill panels at the "meso-scale", that allows to calibrate the parameters that govern the method of the equivalent strut, in order to properly characterize the panel and reduce the differences observed with the experimental response.

3 RIGID BODY AND SPRING MODEL (RBSM)

The basic idea of the method (Figure 2) consists in describing the masonry (intended as a composite periodic material) as a mechanism composed of the unitary cells constituted by of rigid blocks and elasto-plastic springs (RBSM) [11] The elastic features of the springs are defined by means of a specific identification procedure with the objective of transferring the information about the main characteristics of the masonry texture from the "*meso-scale*" to "*macro-scale*" [37].

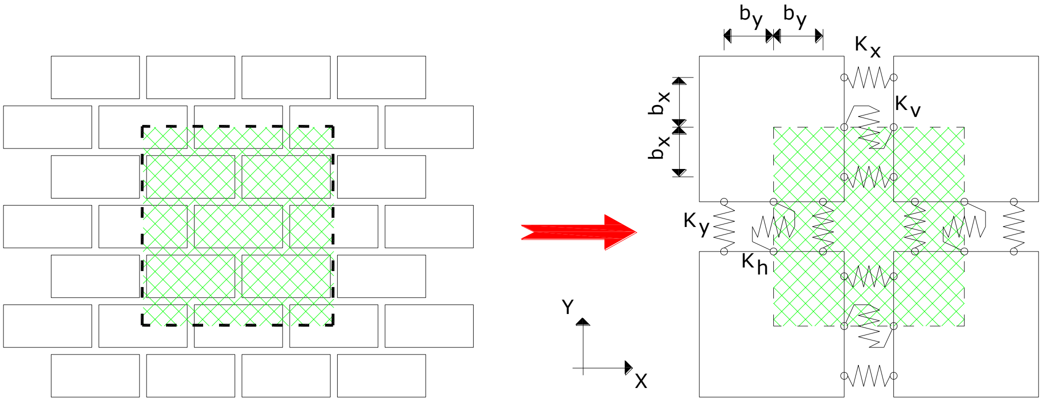

Figure 2: Scheme of a regular masonry texture and an example of the unit cell consists of four rigid blocks connected by elasto-plastic springs.

The connection between the rigid blocks occurs by means of two axial springs (indicated with K_x or K_y, depending on the direction) and a shear spring (K_h, K_v , depending on configuration) arranged along each of the common sides between the blocks at a distance equal, respectively, to b_x and b_y. The hysteretic behavior of the springs is obtained on the basis of the mechanical parameters of the constituents of the panel (mortar and blocks) and takes account of the mechanical degradation of mortar joints in the cycles of loading and unloading.

3.1 Discrete formulation of the kinematics

The masonry-like composite material is modelled as a plane solid body partitioned into m quadrilateral mass-elements Ω^i such that no vertex of one quadrilateral lies on the edge of another quadrilateral. Given a global reference frame $\{O, x, y\}$ the deformed configuration of the discrete model is described by the displacements and rotation $\{u_i\ v_i\ \psi_i\}$ of the local reference frames $\{o^i, \xi^i, \eta^i\}$ fixed in each element's barycentre o^i. These 3m variables are assembled into the vector of Lagrangian coordinates $\{u\}$ that is conjugated in virtual work with the corresponding vector of external loads $\{p\}$ (*see Figure 3*):

$$\{u\}^T = \{u_1, v_1, \psi_1, u_2, v_2, \psi_2, \dots\dots\dots, u_m, v_m, \psi_m\} \tag{1}$$

$$\{p\}^T = \{p_1, q_1, \mu_1, p_2, q_2, \mu_2, \dots\dots\dots, p_m, q_m, \mu_m\} \tag{2}$$

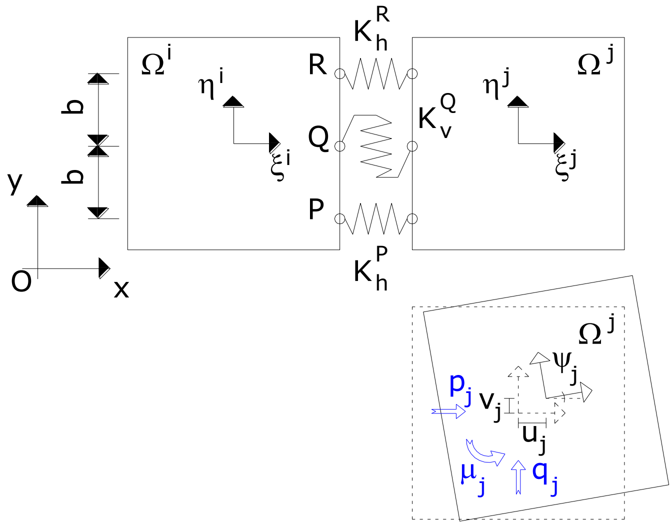

Figure 3: Kinematics of the j-th rigid body with the notation adopted [22].

The three points P, Q, and R, positioned on the sides of each rigid block, define the positions of the connection springs. These have the elastic force function of the deformation associated with the corresponding connection points. In detail, the average strain "shear" ε^Q is associated to the point Q, while the average axial deformations ε^P and ε^R are associated respectively to the points P and R. Under the assumption of small displacements, and denoting by r the number of sides of the connection between all the elements of the discrete model, the relationship between displacements and deformations can be expressed by defining the matrix *3r x 3m* $[B]$ as follows:

$$\{\varepsilon\} = [B]\{u\} \tag{3}$$

3.2 Elasto-plastic effects

A stress vector $\{\sigma\}$ is correspondingly assembled together with the diagonal matrices $[V]$ and $[D]$ which contain the reference volumes of the corresponding three-dimensional solid and the elastic stiffness of the springs:

$$\{\sigma\}^T = \{\sigma_1^P, \sigma_1^Q, \sigma_1^R, \sigma_2^P, \sigma_2^Q, \sigma_2^R, \dots\dots\dots, \sigma_r^P, \sigma_r^Q, \sigma_r^R\} \tag{4}$$

$$[V] = diag\{V_1^P, V_1^Q, V_1^R, V_2^P, V_2^Q, V_2^R, \dots\dots\dots, V_r^P, V_r^Q, V_r^R\} \tag{5}$$

$$[D] = diag\{k_1^P, k_1^Q, k_1^R, k_2^P, k_2^Q, k_2^R, \dots\dots\dots, k_r^P, k_r^Q, k_r^R\} \tag{6}$$

Consequently, given the constitutive laws of the springs, $\{\sigma\}=[D]\{\varepsilon\}$, and denoting with W_E and W_I respectively, the virtual work done by external loads and the internal virtual work done by the springs, the principle of virtual work is rewritten as follows:

$$\{\bar{u}\}^T\{p\} = W_E = W_I = \{\bar{\varepsilon}\}^T[V]\{\sigma\} = \{\bar{u}\}^T[B]^T[V][D][B]\{u\} \tag{7}$$

So for every arbitrary virtual displacement is valid the following expression:

$$\{p\} = [B]^T[V][D][B]\{u\} = [K]\{u\} \tag{8}$$

With $[K]$ generalized stiffness matrix of discrete system

3.3 Equation of motion and constitutive laws

In order to consider inertial effects, the mass of each element and the rotational inertia around its own local center of gravity are collected and assembled in the following diagonal matrix:

$$[M] = diag\{m_1, m_1, t_1, m_2, m_2, t_2, \dots \dots \dots, m_m, m_m, t_m,\} \tag{9}$$

Viscous damping is evaluated mainly on the first vibrational modes and is attributed through the definition of the damping matrix [C] assumed proportional to mass matrix. In the general case of material with non-linear constitutive law, the system of equations of motion of the discrete system, during a single time step, takes the following form [22]:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + \{f^*\} + [K^*]\{\Delta u\} = \{p\} \tag{10}$$

with $\{f^*\}$ the vector of generalized internal forces, and $[K^*]$ generalized tangent stiffness matrix. The system of equations of motion is integrated using the Newmark implicit method and iterating within individual steps according to the Newton-Raphson algorithm, until it reaches the desired degree of convergence. The stiffness of the springs and the distance between the connection points are assigned with the criterion to approximate the average strain energy in correspondence of the reference volume of each spring. Assigning to the shear springs different stiffnesses in horizontal and vertical direction, together with a calibration of the distances between the connections, it is possible to model the effects of some masonry texture (for example, stone blocks interlocking often present in the case of significant degradation of the masonry that significantly changes the resistance of the panel). The constitutive laws for elastic-plastic behaviour are assigned using a phenomenological approach [11], based on the results of cyclic tests available in the technical literature.

The next section illustrates the procedure for defining the characteristic points of the cyclic law F_W-d_W of the equivalent strut macro-scale level) on the basis of the afore mentioned meso-modeling of the masonry panel.

4 FROM THE MESO-SCALE TO THE MACRO-SCALE (EQUIVALENTI STRUT METHOD)

The aim of the research work is to use a meso-scale modeling to define the parameters of the equivalent strut through which infill panels are usually simulated. From an operational point of view, the sequence of operations that allow to link a meso-scale approach to a macro-modeling system can be summarized in the diagram shown in Figure 4.

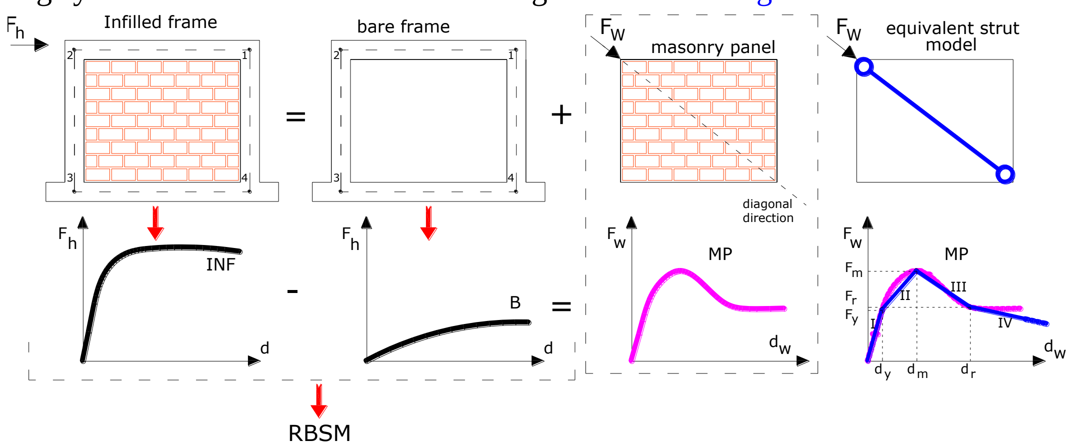

Figure 4: From meso-scale to the equivalent strut model

The procedure starts by evaluating the behaviour of the infilled frame using the RBSM approach. The parameters of blocks and springs, components of the periodic unit cell (*see Figure 2* and *§ 3*), are calibrated on mechanical parameters of bricks and mortar of the panel. The interactions between the unit cell and the elements of the frame are simulated by means of elasto-plastic springs, while the elements of the frame are modeled by means of rigid blocks having the mechanical characteristics of reinforced concrete.

A pushover analysis is then performed for the numerical model, obtaining the response curve, in which the total applied force F_h is plotted against the displacement d of the control node (which is chosen as the upper corner node). The F_h-d curve of the infilled frame (hereinafter indicated with the abbreviation INF) is intended as the “sum” of two contributions, respectively, due to the bare frame (B) and to the masonry panel (MP). The first contribution is always evaluated through RBSM approach, while the second is directly obtainable by eliminating the contribution of the bare frame (B) from the infilled frame configuration (INF).

By expressing the response of the masonry (MP) through the components directed along the diagonal of the panel, the non-linear law to be assigned to the equivalent strut F_W-d_W is defined once 3 characteristic points (in correspondence of significant stiffness variations) are identified. In detail, the associated points are, respectively: the yield strength, the maximum strength and the residual strength of the system, directly evaluated on the curve of the MP configuration.

This points single out a force-displacement law consisting of four branches: (I) initial elastic behavior of the panel, from zero up to the yield point; (II) formation of the strut in the panel (separation of infill from the frame), from yield strength point up to the maximum value; (III) force drop, due to exceeding the maximum threshold in terms of displacement. The last part (IV) corresponds to the final state of the panel after the collapse, with constant decrease of the resistance, which is necessary in order to improve the numerical stability of the analysis.

The width of the equivalent strut is evaluated assuming absence of degradation and uncracked conditions, deduced directly from the response of MP model. Therefore, considering the yield point, the width b_W is obtained by the following balance equation:

$$\frac{E \cdot t_W \cdot b_W}{d} = \frac{F_y}{d_y} \tag{11}$$

with E elastic modulus of the equivalent strut; F_y and D_y, respectively, force and displacement at yield.

5 BENCHMARK

5.1 Description of the structural scheme and of the experimental results

The proposed procedure has been validated on the basis of the results of experimental tests performed over a real scale infilled frame [38], which were specifically developed as part of a more general experimental study aimed to investigate the out of plane behaviour in relation to the damage level [39]. The geometry of the case study is shown in Figure 5, while the mechanical characteristics of the elements of the portal, of brick and mortar are collected in Table 1.

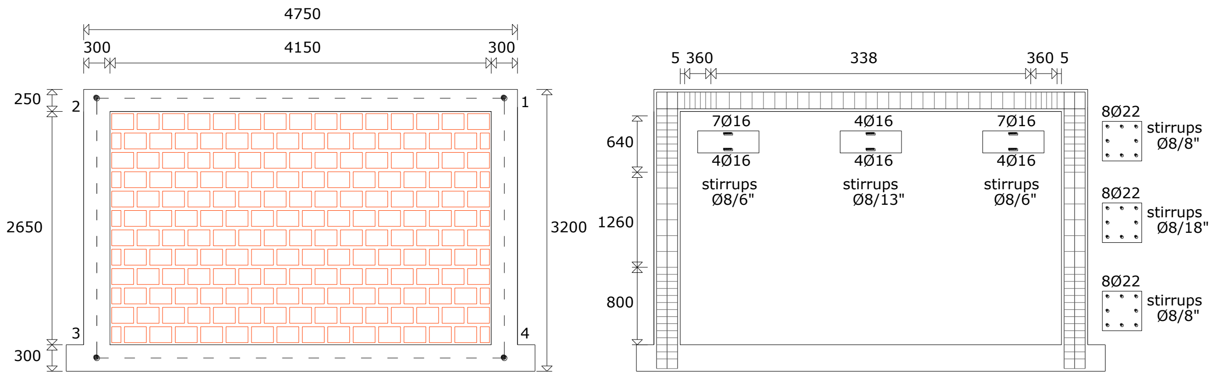

Figure 5: Infilled frame: geometry and amounts of reinforcing rebars

	BRICK		
Nominal size	*Length*	250	*mm*
	Width	300	*mm*
	Height	190	*mm*
Unit weight		10.6	*kg*
Hole percentage		55	*%*
Compression strength parallel to hole *(UNI EN 772-1)*		13	*MPa*
Compression strength orthogonal to hole *(UNI EN 772-1)*		2.6	*MPa*
	MORTAR - M10 [1]		
Compression strength		10	*MPa*
	REINFORCED CONCRETE		
Average cylindrical compression strength $f_{cm,beam}$		34.54	*MPa*
Average cylindrical compression strength $f_{cm,column}$		29.32	*MPa*
	MASONRY PANEL		
Vertical elasticity modulus		3238	*MPa*

Table 1: Mechanical and geometrical parameters of the components

The laboratory tests were carried out on several samples of infilled frames having the characteristics of Table 1, under a constant vertical load of *400 kN* in correspondence of the columns, in order to simulate the gravity loads at the ground floor of a building with 3 floors. The in-plane cyclic tests showed a non-linear behavior for a *0.1% -0.2%* value of the drift, in correspondence of the detachment between the columns and the infill. Between *0.2%* and *0.4*%, mortar joints' cracking occurs, with the rigid rotation of individual blocks, and the development of the damage is mainly concentrated at the center of the panel.

Afterwards, the cracking state increases, until reaches the maximum resistance of the panel in the range *0.8% -1.0%* of the drift. The load remains substantially constant after that a state of severe damage of the infill (indicative of the ultimate limit state of infill) is reached, due to crushing of the blocks in correspondence with a drift of *1.2%*.

By comparing the envelope curves of the in plane hysteresis cycles (Figure 6) in the two configurations: bare (B) and infilled (INF), a marked increase of shear at the base can be noticed, due to the strong contribution in resistance of the panel. At the range *0.8% -1.0%*, the maximum resistance of the infilled frame is more than *2.5* times the value found for the bare frame.

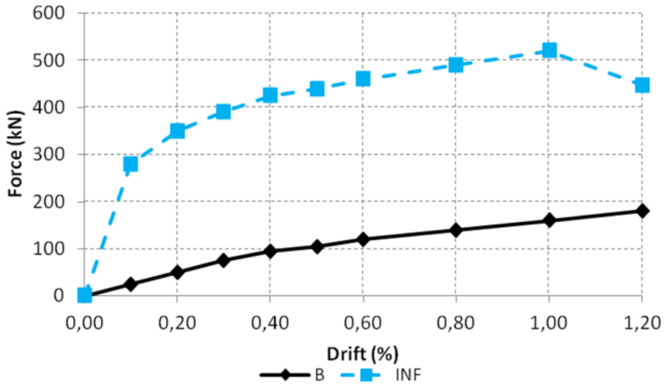

Figure 6: Envelope curves of the hysteresis cycle relative to the in plane test of the frame in the two configurations: bare (B) and infilled (INF).

5.2 From "*meso*" to *macro-modeling*

The infilled frame described in the previous section has been numerically implemented using the RBSM model (*see § 3*), in order to describe the structures at the "macro-scale" through a cinematic which allows to take into account, in a simplified way, also the effects of the masonry texture. The numerical analysis have shown a damage mechanics that reflects in large part the one shown by the reference experimental tests. In particular, Figure 7 shows the deformed configurations of the numerical model in correspondence of two drifts' values: *0.05%* (left) and *0.94%* (right). In particular, the two considered time instants identify the kinematic in correspondence of the first variation of stiffness of the system, and of collapse at a late stage.

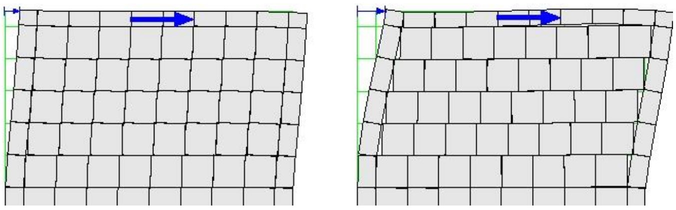

Figure 7: Kinematics of the infilled frame at 0.05% of drift (left) and at 0.94% of drift (right).

The incipient collapse condition, for the drift equal to *0.94%*, shows that the rotational component of the rigid blocks (present for low values of displacement) is predominant on the sliding mechanism along the horizontal joints, and as a result an evident detachment between frame and panel occurs.

For the aims of this paper, it is particularly interesting to express the response of the infilled frame as the trend of the F_h –D curve, where F_h is the horizontal resultant force and D is the horizontal drift. As described in *§ 4*, the response of the panel (MP) can be obtained, in a simplified way, by deducting from the behavior of the infilled frame (INF) the contribution of the bare frame (B). Figure 8 shows, respectively, the functions $F_h=F_h(Drift)$ for the configurations INF, B and MP_h (the letter *h* indicates the configuration associated with the kinematic mechanism in the horizontal direction).

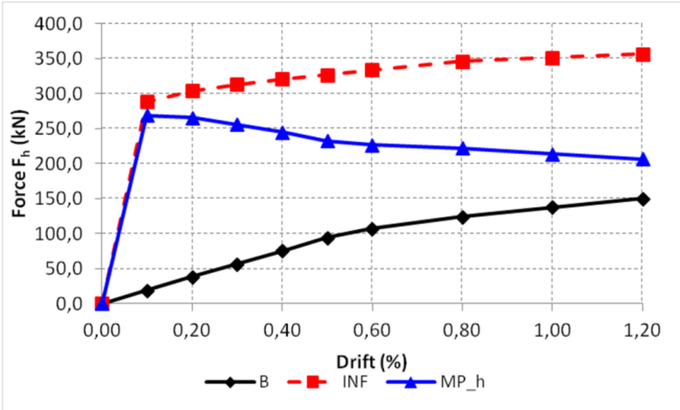

Figure 8: Force-drift curves obtained by RBSM modeling.

In accordance with the experimental results, the infill contribution is *2.4* times the strength of the bare frame. Obviously, the contribution of the panel (MP) (i.e., in the absence of the boundary frame) lays between the two configurations. For low drifts values, the response is very close to the infilled frame's one (INF), while at collapse is approaches the bare frame, demonstrating that the under conditions of non-cracked panel, the horizontal action is almost entirely absorbed by the masonry panel.

By representing the response of masonry (MP) with the diagonal components (F_W and d_W) along the diagonal direction of the panel, it is possible to build the non-linear law to be assigned to the equivalent strut. To this aim, 3 representative points should be identified (yield strength, maximum strength and minimum residual stress) corresponding to the main changes in the stiffness shown by the panel during development and propagation of damage. For the case under consideration, Figure 9 shows the adopted non-linear law of the equivalent strut in terms of F_W and d_W, compared with numerical response of the panel (MP).

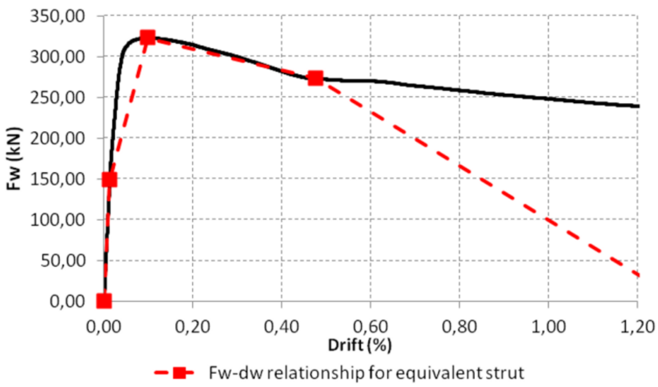

Figure 9: Graphic definition of the non-linear law of the equivalent strut.

Finally, once that the elastic response of the panel is obtained, by means of Eq. 11, it is possible to evaluate the width of the equivalent strut. In this case, b_W assumes a value of *1.92 m* which is to be understood as a measure of a geometric parameter derived by mechanical homogenization between panel (two-dimensional element) and strut (one-dimensional element).

5.3 Comparison between meso-scale, macro modeling and experimental tests

A further comparison has been performed in order to assess the quality of the results obtained by the macro-modeling calibrated on an meso-scale approach. To this purpose, the infilled frame has been implemented within a finite element solver [40]. The non-linear behavior of the frame has been evaluated by means of a "fibers" model, locating the non-linearity in the end sections of the structural elements by means of plastic hinges having a proper length. The constitutive laws assigned to the fibers are the Mander stress-strain law [41] for concrete, whereas an elastic perfectly plastic law with hardening has been assumed for steel. Both laws have been properly adapted on the basis of investigations carried on materials presented in [38]. As already mentioned, the non-linear law of the equivalent strut is obtained by deducting the dynamic behavior of the bare frame from that of the infilled frame, both evaluated with RBSM approach. Therefore, it is useful to compare the response of the bare frame obtained through the different modeling, meso-scale (RBSM) and macro-scale (by fiber model), with the experimental results (Figure 10).

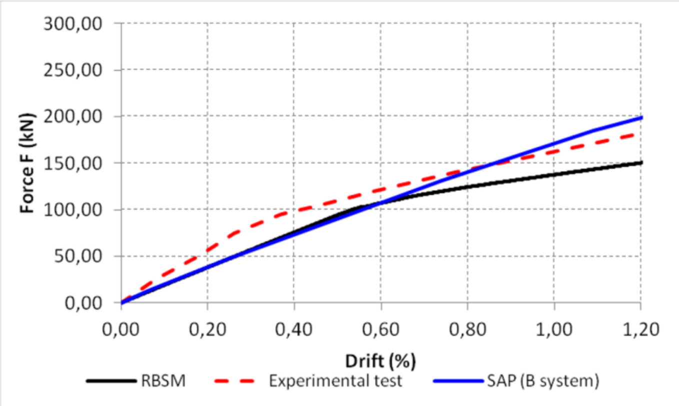

Figure 10: Bare frame (B): comparison of results..

Looking at the result, it is evident a good matching of the performance obtained by the different approaches considered. This is confirmed by evaluating the percentage errors E_r of horizontal force compared with the experimental results, reported in Table 2 in correspondence of significant *Drift* of the test (*0.2%*, *0.5%*, *1.0%* and *1.2%*)

drift *[%]*	Exp. test F_h *[kN]*	RBSM F_h *[kN]*	SAP (*B model*) F_h *[kN]*	RBSM E_r *[%]*	SAP (*B model*) E_r *[%]*
0.2	*56.0*	*40.7*	*47.8*	*27.2*	*14.7*
0.5	*111.0*	*88.4*	*95.2*	*20.4*	*14.2*
1.0	*165.4*	*140.9*	*159.1*	*14.8*	*4.1*
1.2	*181.7*	*154.3*	*179.8*	*15.1*	*1.0*

Table 2: Results provided by the different approaches for the bare configuration B: horizontal force and errors.

In Figure 11 and Table 3, similarly , the comparisons of the results for the infilled frame (INF) are compared.

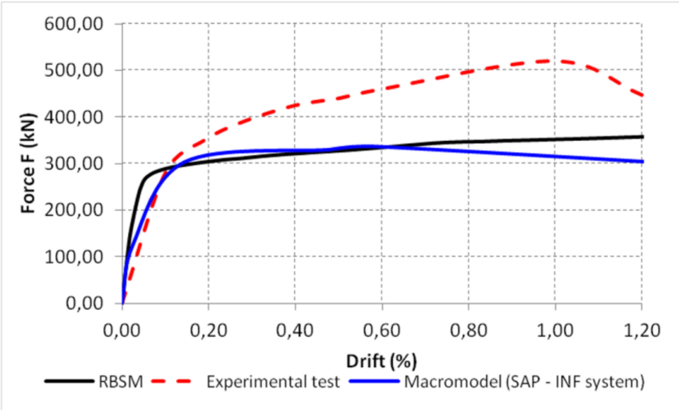

Figure 11. Infilled frame (INF): comparison of results

drift *[%]*	Exp. test F_h *[kN]*	RBSM F_h *[kN]*	Macro-model *(SAP - INFmodel)* F_h *[kN]*	RBSM E_r *[%]*	Macro-model *(SAP - INFmodel)* E_r *[%]*
0.2	*363.2*	*309.8*	*308.0*	*14.7*	*15.2*
0.5	*438.5*	*319.8*	*331.2*	*27.1*	*24.5*
1.0	*527.2*	*336.6*	*362.7*	*36.2*	*31.2*
1.2	*444.7*	*343.3*	*308.2*	*22.8*	*30.7*

Table 3: Results provided by the different approaches for the configuration INF: horizontal force and errors

6 FINAL REMARKS

The great interest of the scientific community about the issue of infilled frame modelling is testified by the presence of a vast literature produced. In the wide range of proposals developed over the past years, there is a relevant thread about the development of simplified models of a rapid application, such as the method of equivalent strut, which are clearly aimed at allowing the solution of real problems (analysis of whole, real buildings).

However, the method is basically a very simplified abstraction of the physical reality aimed at assessing the effects of the infill on the global response of the structure, but, also when are a specific mechanical characterization of masonry is available, the reliability of the numerical simulations is limited. It is very useful, therefore, to have a simple automatic procedure able to derive the parameters governing the definition of the equivalent strut, taking into account the interaction effects between the individual constituents (bricks and mortar) and the reinforce concrete frame.

To this end, this paper presents the preliminary results of an original procedure aimed at calibrating the constitutive non-linear law of the equivalent strut by a meso-scale modeling (RBSM model) of the infilled frame. An experimental analysis of the literature has allowed a first validation of the proposed procedure, which showed a substantial coherence with the experimental behavior.

The present study highlights, anyway, the need for further validation tests based on the direct availability of experimental analyses, and a refinement in the definition of the cyclic law of equivalent strut.

In the future, moreover, it is provided to perform dynamic analysis at the meso-scale, and the definition of an optimization process for deriving the mechanical parameters of the elasto-plastic springs starting from characteristics of the materials constituting the masonry texture.

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