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FURTHER DEVELOPMENTS OF A SIMPLIFIED MODELLING OF INFILLED FRAMES FOR REINFORCED CONCRETE BUILDINGS

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Abstract.
The main proposals for the modelling of the infilled frames are calibrated on the results deriving from experimental testing data. In many cases, the experimental laws acquired that concern samples packaged with materials and executive methods (for frame-panel interface conditions, for mechanical properties ...) are extended to different with several uncertainties. Several researchers suggest approaches that ranging from the macro-scale to micro-scale analysis. The different proposals confirm the complexity to simulate the kinematic mechanism between constitutive elements (mortar and bricks) and between masonry panel and surrounding frame. Therefore, the great variability of models and available studies do not allow to apply a univocal model adaptable in all cases, (Except by adopting, micro-modelling approaches, increasing the computational effort). This raises the need to define simplified models that take into account the geometry, mechanical properties of the masonry walls and elements of the surrounding frame. For these purposes, the present study proposes a Rigid Blocks Method in a simplified format for simulating of the infilled frames in order to define the main parameters that characterize the simplified "Equivalent Strut model" (i.e. the macro-modelling of the infill walls). The method falls in the meso-scale approaches commonly used for analysis of masonry structures. The use of an equivalent rod for modelling the infill panels is simple and reduces the computational costs when it is need to evaluate the global behavior on building scale. In order to demonstrate its multiple advantages, the method is presented. The opportunity to simulate the behavior of the infilled frame varying the mechanical properties and modality to derive ad hoc constitutive laws in presence of openings are just some the potential of the method. With the help of numerical benchmarks having similar characteristics to those widespread into building heritage these results are widely discussed.

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1 INTRODUCTION

The numerical modelling of the infilled frames is affected by several variables, which makes the different models existing in the technical literature very variable and uncertain. For many years, in fact, the research goal of many researchers has been to reduce the influence of the many factors involved in the problem [1, 17]. Among the variables, first of all, it should be recalled the heterogeneity of the mechanical properties of the constituents (bricks and mortar) and the difficulty to obtain information and data about the masonry used in the infilled panels [26], the difficulty to simulate the frame-infill interaction or the impossibility to predict, at the design phase, the exact failure mode of the generic infilled frame.

A model that is particularly easy to use for this typology of studies is the "*Equivalent Strut Method*". In the field of the approaches of *macro* modelling, the Equivalent Strut is widely used to simulate the effects of infill panels on the global response of individual frames and / or buildings [2, 4, 11, 15, 19, 27]. These studies are important in order to establish the retrofit interventions needed to ensure the seismic safety to the deficient buildings [9, 10].

The model is based on the behaviour exhibited by an infilled frame subject to a horizontal load. In particular, by increasing the load, because of the detachment of masonry from the boundary reinforced concrete frame, the panel no longer behaves as a two-dimensional shear resistant element but as a "*one-dimensional equivalent beam*" element. The strut follows the distribution of the compressive forces along the diagonal of the panel and it acts as a strut in opposition to the horizontal action [3, 16, 18].

The described model is defined by the geometrical and mechanical characteristics and by the force-displacement constitutive law that governs the behaviour of the equivalent strut during the non-linear phase. The above parameters depend by models and experimental tests reported in the literature, which especially in the case of existing structures, cannot be generalized to all the possible cases, but are reliable only in few cases that are similar to those on which they were defined [4]. The laboratory tests cannot be generalized because are expensive. Therefore, it is necessary to employ computational procedures, more or less refined, by which the experimental tests on specimens of infilled frames are simulated numerically.

The aim of the present work is to define the Force-Displacement constitutive law of the *equivalent strut*. A simplified discrete model (falling within the family of the models, for *Rigid Block-analysis*) is used in this work and was implemented within a common commercial finite element software [5]. The definition of the *Rigid Blocks and Springs Model* (RBSM), in a simplified format, requires as input a few data on the geometry of the infilled frame and the mechanical parameters of the masonry panel. The purely numerical findings consist of capacity curves, in terms of shear base – interstorey drift. The characteristic branches of the constitutive law of the equivalent strut (the force-displacement relationship "F_w - d_w") which regulates the elastic and plastic behaviour of the rod are obtained by means of a simplified procedure divided into three operating phases briefly recalled inside. The application of which, for the purposes of the present work only affect the third phase.

The procedure on a sampling of *#17* RBSM models with variable geometry was applied. For each of which the constitutive law of the equivalent rod was determined. With the seventeen force-displacement relationships, by means of numerical processing, the formulations for the parametric evaluation of the characteristic points of a single constitutive law of the entire sampling were defined. The generalized law so defined can be used to define an equivalent strut for building scale applications without having to resort to sophisticated modelling (having high computational costs) for each single infilled frame. Thence, the aim of this paper is to demonstrate how to perform extensive numerical experiments by RBSM models allows to obtain results useful for calibrating macro-models when it changes not only the geometry (as briefly shown in this paper) but also, as future scenarios, when they change the mechanical characteristics of the panels. These results in terms of "approximate" laws are expressed. These laws define the parameters regulating the behaviour of the equivalent rods in non-linear field.

2 THE MESO-MODELING AND SIMPLIFIED PROCEDURE

The "*meso-scale*" models are usually referred to as "*discrete models*". If they are applied to structural systems that require a limited number of elements, they allow to reduce the computational burden required by the continuous or discontinuous approaches. The *Rigid Body Spring Model* (RBSM), consists in describing the masonry as a mechanism composed of the unitary cells constituted by of rigid blocks and elastic-plastic springs [6, 20] (Figure 1). Through this approach, it is possible to model the masonry panels at the "macro-scale" through a kinematic that takes into account the specific effects of masonry texture. It has been fruitfully applied, in the last few years, for modeling the behavior of masonry structures both in-plane and out-of-plane [21,22], allowing to perform the vulnerability assessment for whole masonry buildings [23,24,25].

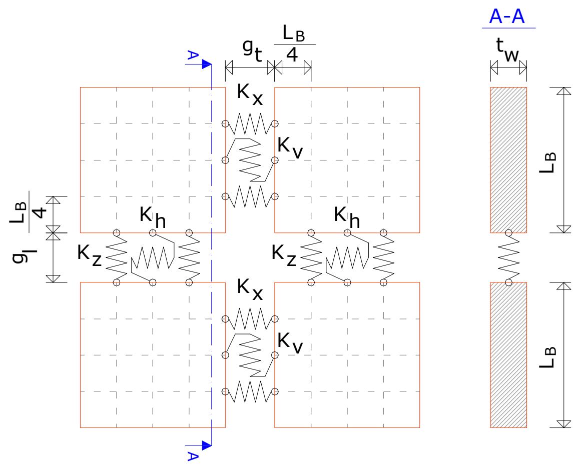

Figure 1: Simplified periodical cell describing the masonry texture.

The connection between the rigid blocks occurs by means of two axial springs (indicated with K_x or K_z, 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_z. The hysteretic behaviour of the springs is obtained on the basis of the mechanical parameters of the constitutive elements of the panel (mortar and blocks) and takes account of the mechanical degradation of mortar joints in the cycles of loading and unloading.

In the simplified format, the use of a *meso-scale* modelling is an easy and quick step within the proposed procedure, aimed at defining some characteristic features of the global response of the infilled frame. For these reasons, the properties of the springs are defined according to a simplified approach. The elastic stiffness of each spring is estimated through the geometrical and mechanical properties of the infill, such as the *modulus of elasticity* of the masonry panel in horizontal and vertical direction (E_{wh}, E_{wv}), *shear modulus* (G), areas of influence of the axial spring (A), areas of influence of the shear spring (A_T), thickness of the head joint (g_t), thickness of the bed joint (g_l) and thickness of the masonry panel (t_w).

When the kinematic of the model is such as to engage the springs over the elastic response, force-displacement laws regulate the plastic behaviour of the system. As with the elastic behaviour, also for the decreasing behaviour of the stiffness has been adopted a simplified approach. Figure 2 shows the constitutive laws of the springs, respectively, axial and shear, used in the present work. For both, three branches constitute the force-displacement law. In the figures, the subscript "*as*" indicates the axial spring, while "*ss*" the shear spring. The fundamental variables of the laws are calibrated with an approach depending on the material strengths: compression strength of the masonry in horizontal direction (σ_{wh}), compression strength of the masonry in vertical direction (σ_{wv}), tensile strength of the masonry (σ_{wt}), shear strength of the masonry along the bed joints (τ_{wh}), shear strength of the masonry along the head joints (τ_{wv}).

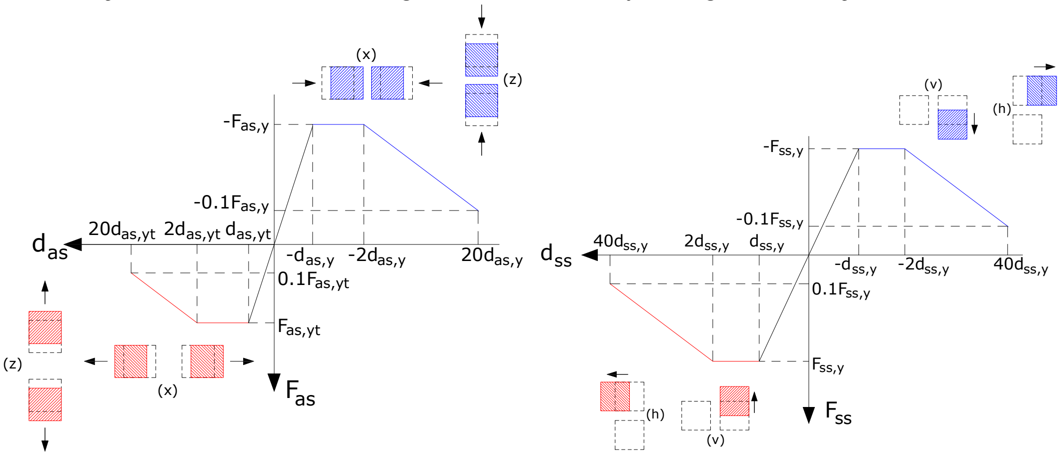

Figure 2: Constitutive laws of the axial and shear springs.

Three consequential step forms the simplified procedure (Figure 3).

1st step: *"meso-analysis of the infilled frame"*

The first step of the procedure is to assess the response of the infilled frame by a nonlinear static analysis (pushover). The model described in the previous section simulates the behaviour of the masonry panel. A *lumped-plasticity model* evaluated with plastic hinges arranged in five sections along the length of each element (beam and columns) describes the nonlinear behaviour of the concrete. The constitutive law adopted for the plastic hinges is in according to FEMA 273 [12]. In the case of existing structures, the evaluation of plastic hinges should take into account the effective strength values of materials in according to numerical approaches (in this context, the research developed by authors [13,14] are particularly interesting.)

2nd step: *"evaluation of the infill conribution without RC frame"*

The F_h-d_h curve of the INF configuration is intended as the "*sum*" of two distinct contributions, respectively, due to the bare frame (B) and the masonry panel (MP). The first contribution is evaluated using a nonlinear static analysis on the model without infill panel. The second, however, is obtained by subtracting (in correspondence with each displacement value) from the response of the INF configuration, the share due to the bare frame B.

3rd step: *"Evaluation of the constitutive law of the Equivalent Strut"*

Once the response F_w^{MP}- d_w^{MP} for masonry panel has been obtained, the constitutive law of the equivalent strut is built on the backbone of MP curve in order to define the ESM model. The law consists of four branches delimited by four characteristic points identified on the MP curve. The first branch describes the elastic response up to the yield point "*S*". The second branch describes the behaviour of the equivalent strut from when begins the plastic deformation up to achieve the point of maximum strength capacity "*M*". This is followed by the descending branch due to the propagation of crack in the panel such that induce a significant decrease of resistance until to the point "*D*". Finally, the fourth branch describes the force-displacement relation until the failure (point "*R*") with a residual resistance maintained in order to ensure stability and convergence to the numerical solution. The *M* and *R* points are preliminarily identified. They coincide, respectively, with the maximum point and last point of the MP curve. While, *S* and *D* points are directly evaluated by an iterative approach that minimizes the difference between the subtended areas of the MP curve and the defined constitutive law.

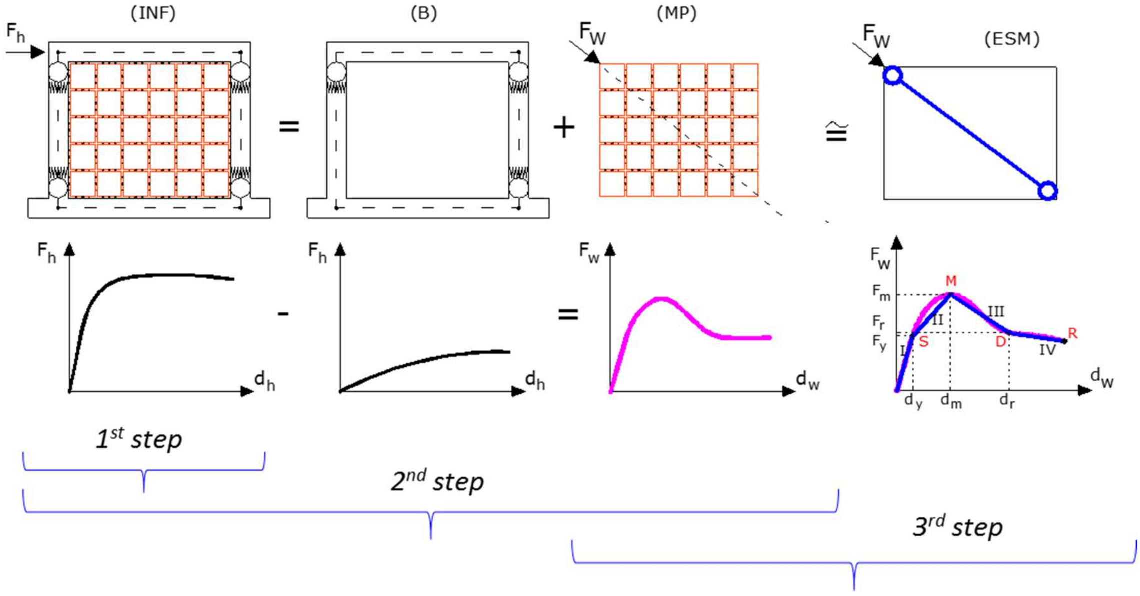

Figure 3: Graphical description of the simplified evaluation of the masonry panel response.

3 NUMERICAL TESTS

3.1 Description of the sampling and modeling

For the purposes of this study in software Sap2000 *#17* RBSM plane models were implemented. All models are listed in ascending order in Table 1 as a function of the *slenderness* "λ" equal to the ratio of height *H* and width *B* (defined in Figure 4) of the infilled frame (both measured than to the middle line of the sections). The thickness of the panel is equal to 30cm for all samples.

n.	B [m]	L [m]	λ	n.	B [m]	L [m]	λ
01	5.0	2.5	0.500	10	5.0	4.5	0.900
02	4.5	2.5	0.555	11	3.0	3.0	1.000
03	5.0	3.0	0.600	12	4.5	4.5	1.000
04	4.0	2.5	0.625	13	4.0	4.5	1.125
05	5.0	3.5	0.700	14	3.5	4.0	1.143
06	3.5	2.5	0.714	15	2.0	2.5	1.250
07	4.5	3.5	0.777	16	3.0	4.0	1.333
08	5.0	4.0	0.800	17	2.5	3.5	1.400
09	4.0	3.5	0.875				

Table 1: Characteristics of sampling.

The boundary frame (the same for each sample) is reinforced concrete with conglomerate having class of resistance *C25/30*. It is constituted by two square columns with side equal to *30cm* and one beam with width *b=30cm* and height *h=50cm*. The longitudinal reinforcement of the columns is equal to $8\phi16$ symmetrically along the sides distributed, while the beam presents in the centre span, longitudinal tension reinforcement *As* equal to $4\phi14$ and in compression reinforcement *As'* equal to $3\phi16$. Those quantities are inverted at the supports. The masonry panel is assumed made of brick blocks P700 type. They are characterized by a weight per unit of volume of about $700\text{-}760\ kg/m^3$. Their physical and geometric characteristics are comply with the requirements established by Eurocode 6 [7] and fall among the elements classified as hollow bricks, with φ drilling percentage between 45% and 55%. Eurocode 6 provided the compression strength along the vertical direction, in the case of hollow blocks and ordinary mortar, with the Eq.1.

$$f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \tag{1}$$

where:

- f_k is the characteristic compressive strength, expressed in *MPa*. In the present treatment the average values of the resistances have been adopted. From experimental tests carried out on similar typologies of the blocks used, it is the average value obtained by multiplying the characteristic value by a factor equal to *0.8*.
- K is a constante qual to *0.45*.
- f_b is the average compression resistance along the direction of loads, expressed in MPa.
- f_m is the mortar compression strength, expressed in *MPa*.

As regards the compression strength in the horizontal direction, EC6 proposes the Eq.1, putting in place of K a coefficient $K_h = 0.5K$. The shear strength ($\tau_{wh} = \tau_{wv}$), with no vertical loads, it is assumed to *0.2MPa* assuming a mortar with bad features having M2.5 resistance class. The average value of the resistance, for non-linear analysis, is obtained by dividing the characteristic value to *0.7*. The mechanical characteristics are determined with the usual relations provided by the Italian Technical Standards [8]: $E=1000f_k$, $G=0.4E$ e $\nu=E(2G)^{-1}-1$.

The single RBSM model is constituted by a regular discretization of *n* two-dimensional plane elements (*4*-nodes *shell* elements) enclosed by a contour of the beam elements. The total degrees of freedom are *4n*. The behaviour perfectly rigid of blocks is guaranteed by assigning to *4*-nodes of each *shell* a "*Diaphragm*" internal constraint with Y rotational axis perpendicular to the OXZ reference system. The internal costraint connects the nodes of the shell element by means of ideal rigid rods devoid of mass and stiffness. The connections between rigid blocks is with "*NLlink*" elements of "*multilinear plastic*" typology (Figure 4). The nonlinear behaviour of *NLlink* elements is in according to constitutive laws shown in Figure 2, respectively, for the axial (F_{as} - d_{as}) and shear (F_{ss} - d_{ss}) springs.

At the interface between frame and masonry panel (i.e. between beam and *NLink* elements along the sides of the rigid blocks adjacent to the frame), are arranged *Rigid N*Link elements. The *rigid NLlink* maintain unchanged the relative distances between the nodes on axis line of the reinforced concrete element and the boundary line of the concrete, in order to simulate the material between them. The model is constrained to the ground by means of interlocking constraints at the base columns. In addition, the hinge constraints at the end nodes of the *rigid NLlink* elements simulate the position of specimen in the test device.

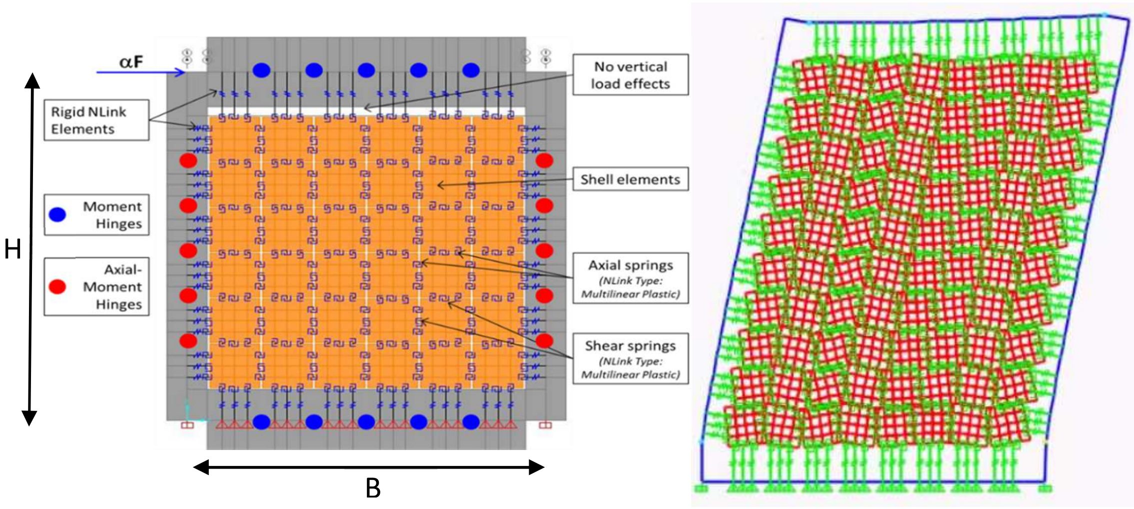

Figure 4: Extrude view of the finite element model with rigid blocks and springs implemented in Sap2000 (on the left); Deformed configuration for generic RBSM model (on the right).

3.2 Analysis by simplified procedure

The procedure described in §2 has been applied to the models listed in Table 1. For each model by starting from the nonlinear static analysis and its processing, the steps 2 and 3 lead to the definition of the law of the equivalent strut for the geometry of infilled frame considered. For example, the law of the equivalent rod for the model number 15 ($\lambda=1.25$) is represented in Figure 5.

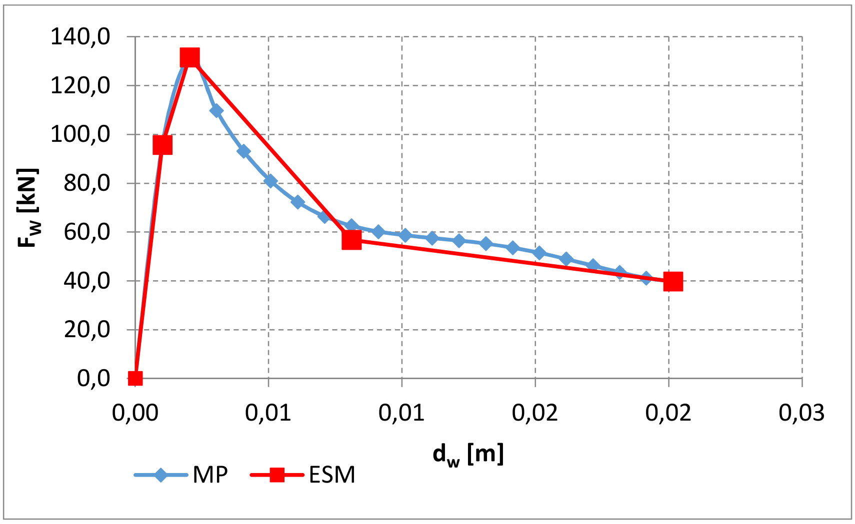

Figure 5: Force - displacement law for the sample with geometry 2,0m x 2,5m.

After determining the constitutive laws for all *17* models of the sampling, a numerical study was performed in order to obtain, as a function of the slenderness "λ", a univocal law of the entire sample. The aim is to define parametric formulations for the infill panels having similar mechanical properties to those of the sampling, which allow to determine the constitutive law of the equivalent rod, once known only the geometry of the infilled frame. To this end, bringing together the *17* constitutive laws, they were built of graphics to correlate the yield strength (F_y), the displacement at yield (d_y), the maximum strength (F_{max}) and the maximum displacement (d_{max}) to the shape parameter (in Figure 6 for the force F_y).

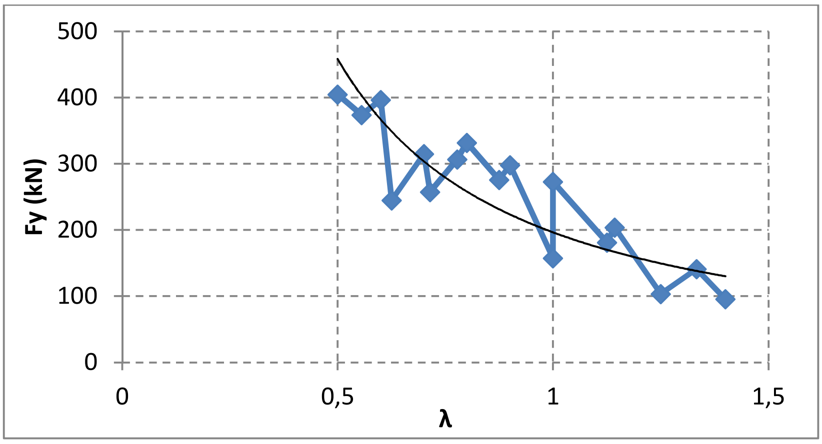

Figure 6: Exponential regression for the evaluation of F_y as a function of the slenderness

The numerical regressions that approximate with lower margins of error are functions in the format, respectively, exponential and linear. The formulations obtained for the analysed sampling are shown below. The Eqs. 2 and 3 in exponential form, while Eqs. 4 and 5 in two variables linear.

$$F_y = 196.42 \cdot \lambda^{-1.223} \quad \& \quad d_y = 0.0012 \cdot \lambda^{-0.039} \tag{2}$$

$$F_{max} = 223.93 \cdot \lambda^{-1.039} \quad \& \quad d_{max} = 0.002 \cdot \lambda^{0.4183} \tag{3}$$

$$F_y = 11.389 + 99.667B - 44.97H \quad \& \quad d_y = -0.000105 + 0.000143B + 0.000233H \tag{4}$$

$$F_{max} = 52.384 + 91.45B - 41.09H \quad \& \quad d_{max} = -0.00147 + 0.000019B + 0.00034H \tag{5}$$

The D point that represents the maximum loss of strength of the panel when it is in the plastic phase is definable by the coordinates $\{3d_{max}; 0.3F_{max}\}$.

4 RESULTS

In order to validate the whole procedure, the results of the nonlinear analyses on *macro*-models and meso-models (RBSM) were compared. The geometries taken as a reference for the comparison are those having slenderness λ equal, respectively, to *0.5*, *0.9* and *1.25*.

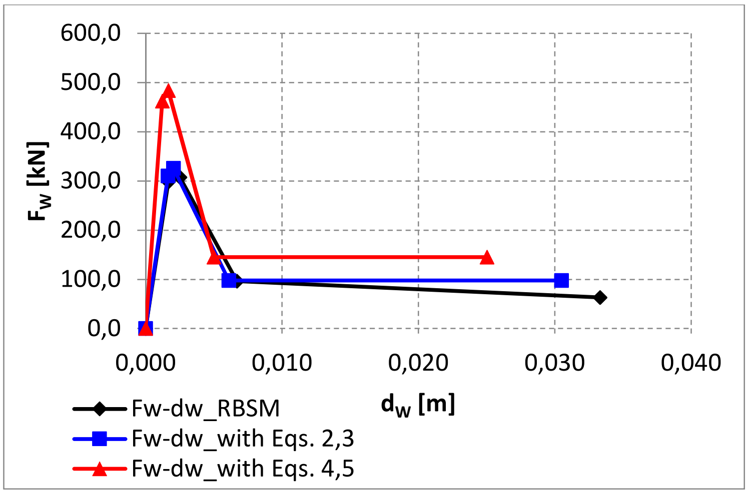

Figure 7: F_w-d_w laws compared for sample having λ=0.9.

For all the three samples, the points of the force-displacement law of the equivalent strut was derived by applying the Eqs 2-5. For the geometry having $\lambda = 0.9$ in Figure 7 the F_w-d_w laws are compared.

Subsequently, for each geometry under consideration for comparative purposes, two models with the Equivalent Strut Method (ESM) were implemented. The first with the equivalent rod having the F_w-d_w law having main points defined by the eqs. 2 and 3. The second with strut that has F_w-d_w law given by eqs. 4 and 5. For both models pushover analysis was performed. The capacity curves obtained from both models, in terms of *Base shear - Drift [%]* were compared with, respectively, the curves obtained with the RBSM models and the model relative to the bare frame. As an example, in Figure 8, the comparisons between results obtained for a geometry characterized by $\lambda=1.25$ are summarized.

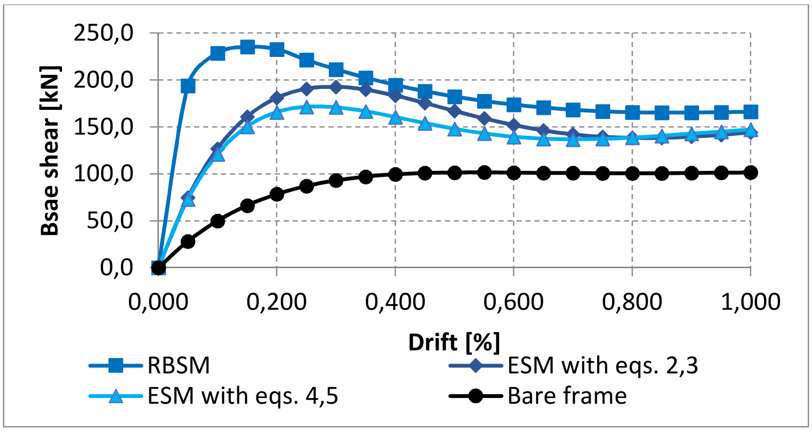

Figure 8: Comparison of results for geometry having $\lambda=1.25$.

The *macro*-models differ from the *meso*-scale model (RBSM), on average, by about *25%* in the range of $0<drift[\%]<1$. In addition to the difference between the above models, the comparison between the models in terms of resistance increase with respect to the model representative of bare configuration (without infill) is very attractive. An increment of the base shear between *1.48* and *2.32* times the resistance explicated by the bare frame was encountered.

5 CONCLUSIONS

The main aim of this work is the calibration of the Equivalent Strut Method for modelling of infilled frames in *building*-scale application. The above calibration is proposed by means numerical experimental tests on discrete models (*Rigid Block and Spring Model* - RBSM), commonly used in the analysis of masonry structures, and subsequent application of a simplified procedure proposed by the authors.

The procedure aims to define the points of the nonlinear constitutive law of equivalent connecting rod by means of the use of numerical formulations expressed as a function of a geometrical shape parameter of the buffered frame. The formulations through the implementation of *#17* RBSM models having fixed mechanical characteristics and λ that it varies between *0.5* and *1.4* were obtained.

By applying the procedure on the entire sampling and whereas for comparative purposes the results obtained for the geometries having the equal, respectively, to *0.5*, *0.9* to *1.25*, the following conclusions can be derived:

- The differences between RBSM models and models with equivalent struts having non-linear law obtained with generalized approximate formulations are equal to about 25%.
- The use of approximate formulations of exponential type for the definition of the non-linear law of the struts is closest to the results obtained with refined modelling RBSM, compared to the models with the struts defined with polynomial formulations.
- The results obtained, both preliminarily on the RBSM in its simplified form, both on the model with equivalent strut, show the significant contribution in strength provided by in-fills.

In the future, the definition of approximate laws for the calibration of the *macro*-models can be extended to infilled frames having different mechanical properties.

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REFERENCES

[1] D. Celarec, P. Ricci, M. Dolšek. The sensitivity of seismic response parameters to the uncertain modelling variables of masonry-infilled reinforced concrete frames. *Engineering Structures*, **35**:165–177, 2012.

[2] A. Fiore, F. Porco, G. Uva. Effects of the yield and ultimate strengths of the equivalent strut models on the response of existing buildings with infill panels. *International Journal of Structural Engineering*, **6**(2):140-157, 2015. doi:10.1504/IJSTRUCTE.2015.069690

[3] B. Stafford Smith. Lateral Stiffness of infilled frames. Journal of Structural Division, ASCE, 6, 183-99, 1963.

[4] G. Uva, F. Porco, D. Raffaele, A. Fiore. On the role of equivalent strut models in the seismic assessment of infilled RC buildings. *Engineering Structures*, **42**, 83-94, 2012. doi:10.1016/j.engstruct.2012.04.005

[5] A. Fiore, F. Porco, A Multiscale approach for modelling of infilled frames. COMPDYN 2015 - 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.). Crete Island, Greece, 25–27 May 2015.

[6] S. Casolo, Macroscale modelling of microstructure damage evolution by a Rigid Body and Spring model. *Journal of Mechanics of Materials and Structures*, **4**(3), pp. 551-570, 2009. doi:10.2140/jomms.2009.4.551

[7] CEN. Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures. Brussels. Belgium; 2005.

[8] DM 14/01/2008. Norme Tecniche per le Costruzioni (NTC 2008). Gazzetta Ufficiale n.29. Roma; 2008 *(in Italian)*.

[9] F. Porco, A. Fiore, S. Casolo. Comparison between seismic retrofitting solutions for existing reinforced concrete buildings: a case study. *International Journal of Structural Engineering,* **5**(3), 242-261, 2014. doi:10.1504/IJSTRUCTE.2014.063035

[10] F. Porco, A. Fiore, G. Uva, D. Raffaele. The influence of infilled panels in retrofitting interventions of existing reinforced concrete buildings: a case study. *Structure and Infrastructure Engineering*, **11**(2), 162-175, 2015. doi:10.1080/15732479.2013.862726

[11] A. Fiore, F. Porco, G. Uva, M. Sangirardi. The influence of uncertainties of infill panels relative to the seismic response of RC existing buildings, *WIT Transactions on the Built Environment*, **141**, 479–490, 2014. doi:10.2495/SUSI140411

[12] FEMA. Nerph guidelines for the seismic rehabilitation of buildings. FEMA-273, Washington, DC. 1997.

[13] G. Uva, F. Porco, A. Fiore, M. Mezzina, The assessment of structural concretes during construction phases", *Structural Survey,* **32**(3), 189-208, 2014. doi:10.1108/SS-06-2013-0023

[14] F. Porco, G. Uva, A. Fiore, M. Mezzina, Assessment of concrete degradation in existing structures: a practical procedure, *Structural Engineering and Mechanics,* **52**(4), 701-721, 2014. doi:10.12989/sem.2014.52.4.701

[15] P.G. Asteris, S.T. Antoniou, D.S. Sophianopoulos, C.Z. Chrysostomou, Mathematical macromodelling of infilled frames: state of the art. *Journal of Structural Engineering*, **137**(12), 1508–1517, 2011.

[16] G. Campione, L. Cavaleri, G. Macaluso, G. Amato, F. Di Trapani. Evaluation of infilled frames: an updated in-plane-stiffness macro-model considering the effects of vertical loads. *Bulletin of Earthquake Engineering*, **13**(8):2265-2281, 2014.

[17] M. Ercolino, P. Ricci, G. Magliulo, G. Verderame. Influence of infill panels on an irregular RC building designed according to seismic codes. *Earthquakes and Structures* **10**(2):261-291, 2016.

[18] R.J. Mainstone. Supplementary note on the stiffness and strength of infilled frames. Current paper CP13/74. *Building Research Establishment*. London, 1974.

[19] F.J. Crisafulli, A.J. Carr, R. Park, Analytical modelling of infilled frame structures - a general review. *Bulletin of the New Zealand Society for Earthquake Engineering* **33**(1), 30-47, 2000.

[20] S. Casolo and F. Peña, Modelling micro-structure aspects of masonry walls by a simplified approach, *Advances in Architecture* **15**, pp. 337-346, 2003.

[21] S. Casolo, G. Uva, Nonlinear analysis of out-of-plane masonry façades: Full dynamic versus pushover methods by rigid body and spring model, *Earthquake Engineering and Structural Dynamics*, 42: 499–521, 2013 - DOI: 10.1002/eqe.2224.

[22] S. Casolo, G. Uva, Out-of-plane seismic response of masonry façades: some comparisons among full dynamic and pushover analysis, *Ingegneria Sismica*, ISSN: 03931420, **27**:3, 33-54, 2010.

[23] S. Casolo, C.A. Sanjust, Seismic investigation on the Cathedral of Syracuse by finite elements and by a specific rigid body and spring model, *WIT Transactions on the Built Environment*, pp. 535, 2007. doi:10.2495/STR070501

[24] S. Casolo, A. Fiore, F. Porco, F., D. Raffaele, C.A. Sanjust, G. Uva. A multi-level approach for the numerical modelling of complex monumental buildings: Seismic assessment of the "Maniace Castle" of Syracuse. *Civil and environmental engineering:*

Concepts, methodologies, tools, and applications, pp. 1352-1379, 2016. doi:10.4018/978-1-4666-9619-8.ch061

[25] S. Casolo, G. Milani, C.A. Sanjust, A. Taliercio. Maniace castle in Syracuse, Italy: Comparison between present structural situation and hypothetical original configuration by means of full 3D FE models. *Open Civil Engineering Journal*, 6(SPEC.ISS.1), 173-187, 2012. doi:10.2174/1874149501206010173

[26] Porco, F., Porco, G., Uva, G., M. Sangirardi, Experimental characterization of "non-engineered" masonry systems in a highly seismic prone area. *Construction and Building Materials* **48**, pp. 406-416. 2013. doi:10.1016/j.conbuildmat.2013.07.028

[27] Perrone, D., Leone, M., Aiello, M. A. Evaluation of the infill influence on the elastic period of existing RC frames. *Engineering Structures*, 123, 419-433, 2016. doi:10.1016/j.engstruct.2016.05.050