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INFLUENCE OF MASONRY INFILLS ON DYNAMIC BEHAVIOUR OF REINFORCED CONCRETE FRAMED STRUCTURE

Emilio SCHIAVO[1], Luca MARTINELLI[2], Claudio CHESI[3]

ABSTRACT

Presence of masonry infill walls in R.C. buildings is very common. For horizontal loading, infill panels can drastically modify the response, attracting forces to parts of the structure that have not been designed to resist to them. However, in the design of new buildings and in the assessment of existing ones, even today these infill walls are usually considered as non-structural elements and their influence in the structural response is generally ignored, even though modeling tools, familiar to structural designers, are well able to take care of them with reasonable computational costs. This work aims to show the effects of non-structural masonry infills on the dynamic behaviour of reinforced concrete framed structures. As a first step, a recent macro-model from the literature is selected and a state of the art of the main structural identification issues involving this modeling approach is discussed. The macro model is adopted to simulate, by means of a widely available commercial finite element computer code, an experimental campaign on a four-storey full scale reinforced concrete frame, carried out at the European Laboratory for Structural Assessment (ELSA) of the Joint Research Center of the European Commission in Ispra (VA) Italy. A comparison between the outcome from numerical simulations with code prescribed performance levels and the outcome of the physical testing is presented and discussed.

Keywords: Masonry infills; infilled R.C. frame; non-linear infills behaviour; infills macromodel.

1. INTRODUCTION

In framed structures, such as buildings, it is very common in Italy to make use of lightweight masonry, consisting of hollow bricks and mortar, to build outer walls and internal partitions. As a matter of simplicity and economy of construction, infill panels are always built in simple contact with frame elements, without any joint or link that guarantee a reliable connection with columns and beams, also in relation to the possibility of out of plane falling. Recent earthquake events clearly showed that the dynamic behaviour of this type of structures is strictly related to the presence of partitions and infills. Unreinforced masonry panels are able to considerably stiffen the main frame structure while more than compensating for the increasing in inertial forces with their own resistance. Furthermore, the role of infills is fundamental in constructions not designed for seismic loads in order to prevent collapse.
On the other hand, it has been shown that, due to stiffness increase, infills might lead to irregularities in elevation, potentially compromising a totally correct structural arrangement. Torsional modes and soft storey mechanism induced by infills are well known. Furthermore, such behaviour can be also induced by a regular arrangement of infill panels, due to the sudden brittle failure of some of them. This happens because of the intrinsic weak material properties or often because of the loss of out-of-plane stability, due to an ineffective link with the frame or second order effects caused by the thickness, if smaller than the in-plane dimensions. Neglecting infills during the structural analysis might lead to underestimate the actions stressing structural elements, causing not proper design.

[1]Arup Italia, Corso Italia, 1 - 20122 Milan, Italy, emilio.schiavo@arup.com
[2]Politecnico di Milano, Department of Civil and Environmental Engineering (DICA), Piazza Leonardo da Vinci, 32 - 20133 Milan, Italy, luca.martinelli@polimi.it
[3]Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering (DABC), Piazza Leonardo da Vinci, 32 - 20133 Milan, Italy, claudio.chesi@polimi.it

This work aims at showing the effects of non-structural masonry infills on the dynamic behaviour of reinforced concrete framed structures. To this purpose, a general overview of the macro-models present in the literature is discussed and a state of the art of the main structural identification issues involving this modelling approach is presented. The experimental campaign on a four-storey full scale reinforced concrete frame, which was aimed at gathering information on the global dynamic response of bare and infilled frames by comparing their structural behaviour, will serve as the base for a comparison with numerical results coming from non-linear time history analyses. These last have been performed by the wide spread computer code Sap2000, developing a non-linear numerical model of the structure which implements a simplified macro-modelling approach recently proposed.

2. STATE OF THE ART

Since the first attempts to model the response of the composite infilled frame structures, experimental and conceptual observations have indicated that a diagonal strut with appropriate geometrical and mechanical characteristics could possibly provide a solution to the problem. In the early 1960s, Holmes (1961) replaced the infill with an equivalent pin-jointed diagonal strut made of the same material and having the same thickness as the infill panel and a width *w* defined by

$$\frac{w}{d} = \frac{1}{3} \tag{1}$$

where d = diagonal length of the masonry panel. Smith and Carter (1969) proposed the evaluation of the equivalent width, as a function of the relative panel-to-frame-stiffness parameter, λ_h :

$$\lambda_h = h \sqrt[4]{\frac{E_w t_w \sin 2\vartheta}{4 E I h_w}} \tag{2}$$

where E_w = modulus of elasticity of the masonry panel; EI = flexural rigidity of the columns; t_w = thickness of the infill panel and equivalent strut; h = column height between centerlines of beams; h_w = height of infill panel; θ = the angle for which the trigonometric tangent equals the infill height-to-length aspect ratio:

$\vartheta = \tan^{-1} h_w / L_w$ with L_w = length of infill panel (see Figure 1).

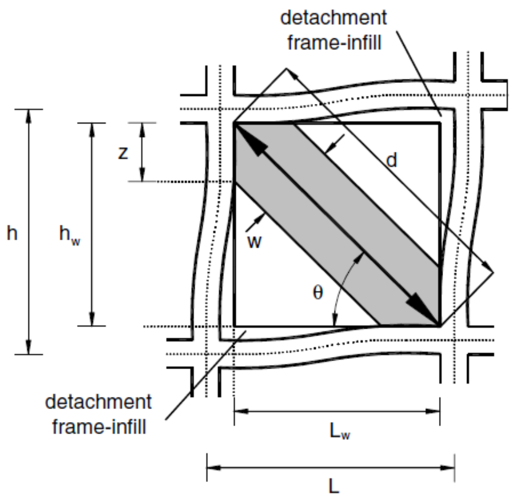

Figure 1. Diagonal strut geometric characteristics (from Asteris et al.,2011)

Mainstone (1974) proposed an empirical equation for the evaluation of the equivalent strut width on the basis of experimental and analytical data, given by

$$\frac{w}{d} = 0{,}175\ \lambda_h^{-0{,}4} \tag{3}$$

This formula was included in FEMA-274 (FEMA 1997) for the analysis and rehabilitation of buildings, and in FEMA-306 (FEMA 1998) because it has been proved to be the most popular over the years. This equation was accepted by the majority of researchers dealing with the analysis of infilled frames (Klingner and Bertero 1978; Negro and Colombo 1997; Fardis and Panagiotakos 1997). Paulay and Pristley (1992) pointed out that a high value for the diagonal strut width will result in a stiffer structure, and therefore a potentially higher seismic response. They proposed a conservative value, useful for the seismic design of masonry-infilled frames, given by 0.25*d*.
In order to extend the use of macro-models to perform nonlinear time history analyses, several hysteretic models have been developed through the years. Klingner and Bertero (1978) cyclic law has an historical importance, as a matter of fact it is the first hysteretic model ever proposed for the diagonal strut equivalent to infill panel. Panagiotakos and Fardis (1996), by means of experimental cyclic tests on scale samples of frames with brick infill panels defined a simplified tetra-linear relationship (see Figure 2).

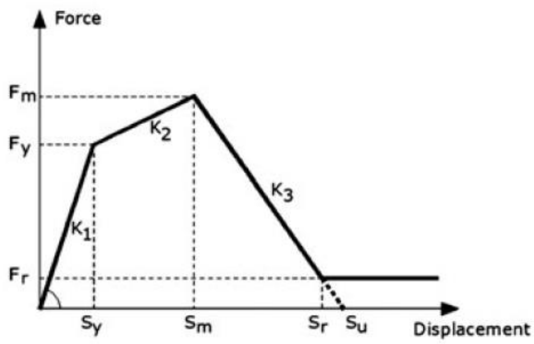

Figure 2. Force-Displacement relationship proposed by Panagiotakos and Fardis (1996)

In relation to the cyclic behaviour, the first characteristic is providing degradation of the envelope curve. In detail, the strengths, such as the ultimate load and the residual load, indicated by F_j, exponentially decreases as a function of cumulative displacements ΔS_j over the cracking displacement. Chrysostomou (1991) aimed at obtaining the response of infilled frames under earthquake loading by taking into account both stiffness and strength degradation of infills. He proposed to model each infill panel by multiple compression only inclined struts. Three parallel struts were used in each diagonal direction, and the off-diagonal ones, i.e. eccentric with respect to the frame nodes, were positioned at critical locations along the frame members, thus allowing to model the interaction between the infill and the surrounding frame.
The macro-model proposed by Rodrigues H., Varum H., Costa A. (2008) is an improvement of the commonly used equivalent bi-diagonal strut model. It takes into account the interaction of the masonry panel behaviour in the two directions. In order to represent a masonry panel they considered four support strut-elements with rigid-linear behaviour; and a central element, where the nonlinear hysteretic behaviour is concentrated (see Figure 3).

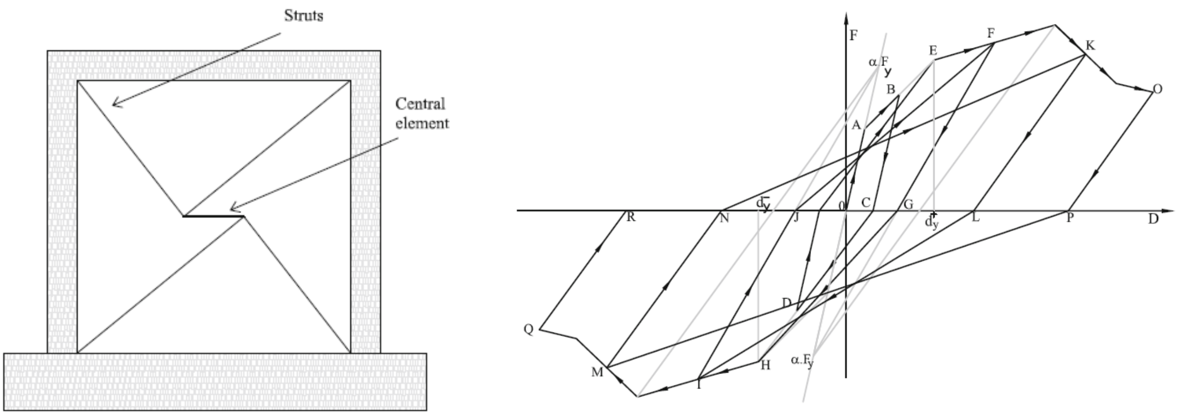

Figure 3. Hysteretic rules for the central link element (from Rodrigues et al., 2008)

Recently a flexible model requiring few parameters and a low computational effort, with sufficient reliability in the results, has been proposed by Cavaleri and Di Trapani (2014). The advantage of using this “Pivot model” is essentially due to the fact that it is based mainly on geometrical rules that define loading and unloading branches rather than analytical laws, but it is nevertheless capable to represent observed features of real hysteresis cycles. This reduces not only the computational effort but also the number of hysteretic parameters involved. Moreover, the Pivot model has great flexibility in modeling unsymmetrical tension–compression behaviour, as in the case of infill equivalent struts which are considered to resist only compression stresses.

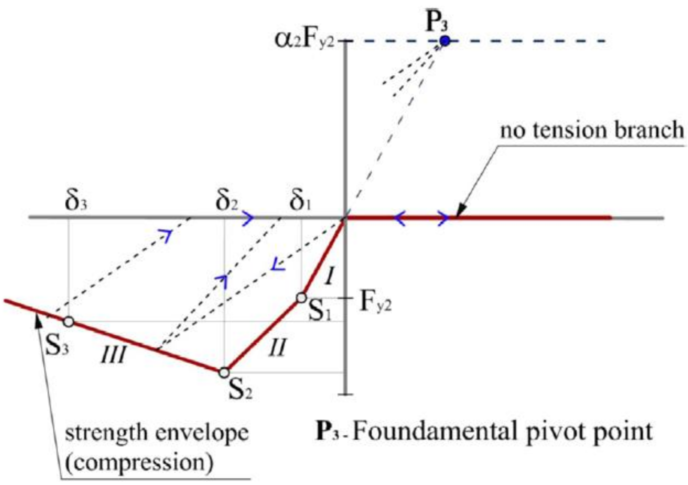

Figure 4. Hysteretic Pivot law particularization for the equivalent diagonal strut (from Cavaleri L. et al., 2014))

About macro-models, it is also worth mentioning that calibration of the parameters is particularly affected by the extreme variability of the mechanical parameters of the infill (non-structural materials are typically scarcely inspected and tested) and by the model of the equivalent strut; calibration, therefore, is quite effective and simple, but presents a number of critical aspects that, if not properly managed, can compromise the reliability of the results.

3. EXPERIMENTAL TESTS

Experimental campaigns, present in the literature since the early ’70s, were mainly concerned with tests on infilled one storey one bay frames, often at a reduced scale. If these tests, on the one hand, guarantee an excellent basis for the calibration of numerical models, on the other, by nature, they are not able to provide information on the global behaviour of real structures. To this purpose, an experimental campaign on a four-storey full scale reinforced concrete frame has been carried out in the European Laboratory for Structural Assessment (ELSA) at the Joint Research Center of the European Commission in Ispra (VA) Italy (Negro, P. et al, 1994), aiming at gathering information on the global dynamic response by comparing the structural behaviour of a Bare Frame and of an Infilled Frame. The full-scale reinforced concrete test structure (Figure 5) corresponds to a four storey, high-ductility, frame. In plane dimensions are 10m x 10m, referred to the column axes. Interstorey heights are 3.0m, except for the ground storey, 3.5m. The structure is symmetric in one direction (that of testing), with two equal spans of 5.0m, whilst in the other direction it is slightly irregular due to the different span lengths (6.0 and 4.0m).

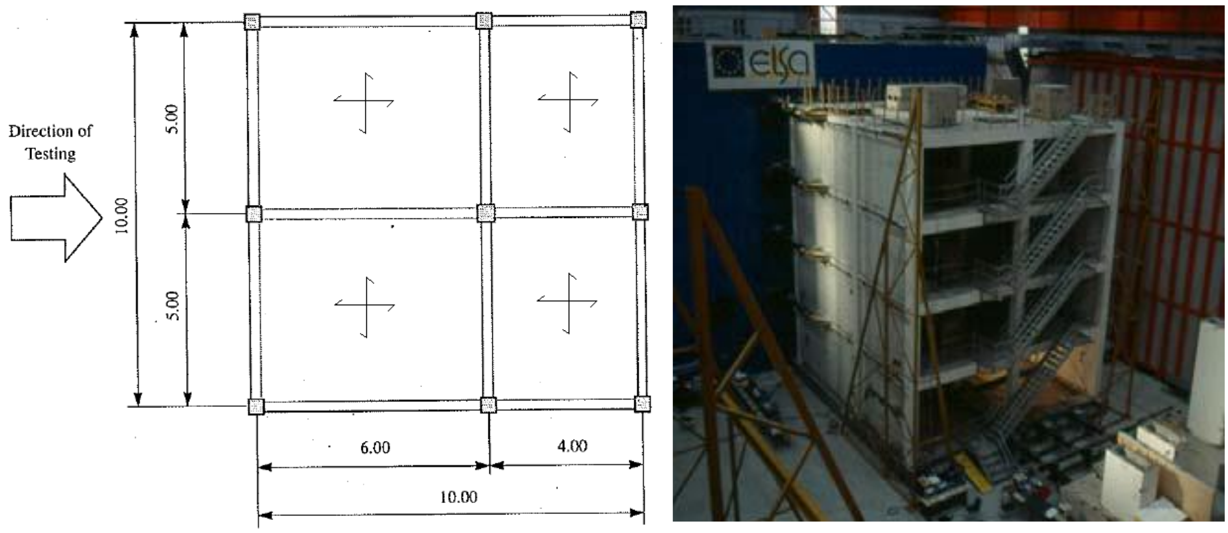

Figure 5. R.C. frame with uniformly infills distribution (from. Negro P. et al, 1994)

All columns have a square cross section with 400mm side, except for the interior column which is 450x450mm. All beams have a rectangular cross section, with total height of 450mm and width of 300mm. A solid slab, with thickness of 150mm has been adopted for all the floors.
In order to define the pseudo-dynamic test, a set of artificial accelerograms were generated, matching the response spectrum given by Eurocode 8 considering 0.3g peak ground acceleration, soil profile B and 5% damping. The artificial accelerograms were generated by using the waveforms derived from a real signal, the 1976 Friuli Earthquake (Figure 6).

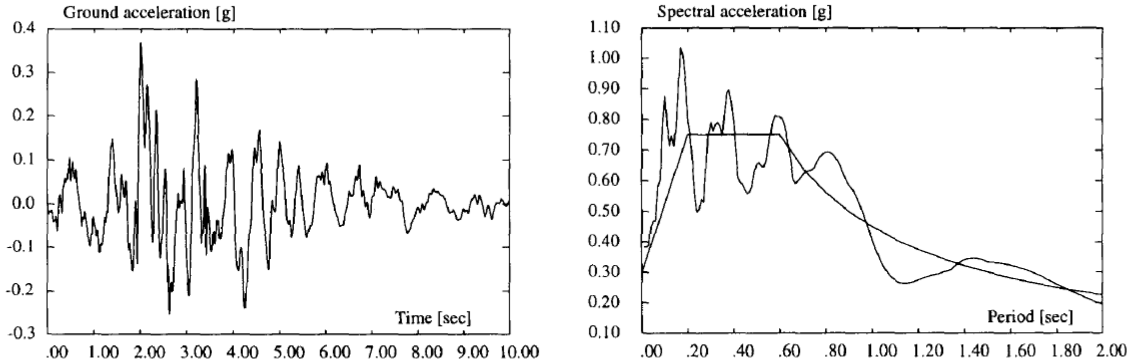

Figure 6. Reference accelerogram (from. Negro P. et al, 1994)

The first test was carried out on the Bare Frame (with no infills). A second test was performed in the Uniformly Infilled Frame configuration. Due to the relatively low damage suffered by the structure as a result of the Bare-Frame tests, no repair actions were taken. The materials used for the construction of the infill panels were selected as representative of typical light weight non-structural masonry. To facilitate construction, blocks commonly available in Italy were adopted. The blocks had dimensions of 245 x 112 x 190 (h) mm, with vertical holes taking 42% of the cross-section. After the second test, all the masonry panels were demolished and replaced with new ones, leaving the first storey bare. The latter test configuration was expected to lead to a soft-storey mechanism, and corresponded to the case of "*drastic reduction of infills in one or more storeys*" in Eurocode 8. For such cases, the Eurocode 8 requires a local increase of the forces to be used in design, as well as an increase in the portion of the columns of the ground floor to be detailed as for critical regions, up to the entire length of the column. However, none of these requirements was considered in the design of the specimen.

4. NUMERICAL RESULTS

The aim of the numerical models is to predict the dynamic behaviour of the four-storey structure in the experimental pseudo-dynamic tests. To this purpose, a lumped plasticity non-linear model has been implemented using Sap2000 software. The main reason for this choice is to suggest a simple and reliable modelling technique for infilled R.C. framed structures, easy to implement on commercial structural software tools, widely used in design practice. As a matter of fact, despite lumped plasticity models require lower computational effort than more complex models (e.g. smeard plasticity), a good level of prediction can be achieved.

R.C. frame non-linearites have been lumped at elements end sections by using "P-M2-M3 Fiber Hinges" while the equivalent struts representing the infills have been modelled using multilinear plastic link elements combined with the Pivot hysteretic law, as suggested by Cavaleri and Di Trapani (2014).

It is worth mentioning that, since no repair has been performed on the specimen during the experimental test stages, a staged construction analysis has been found necessary to account for the damages accumulated in the structure during the testing sequence. This has been implemented in the numerical model. A sensitivity study on the α_2 pivot parameter (see Figure 4 for the parameter definition) made possible the calibration of the model, as depicted in the next Figure 7.

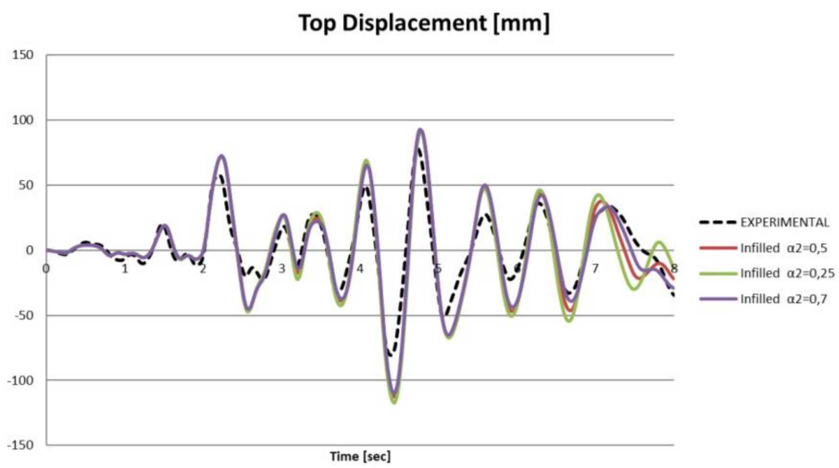

Figure 7. Comparison of the results for the Uniformly Infilled Frame model for different α_2 values.

The last test stage, i.e. the soft storey frame test, has been reproduced numerically by removing the links at the ground floor. The results for the analysis are shown in the next Figure 8.

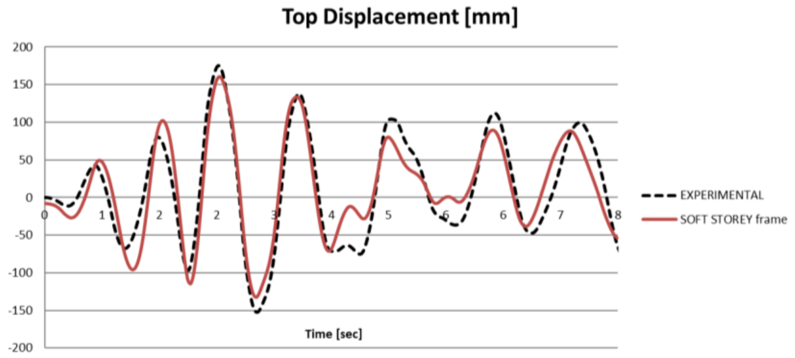

Figure 8. Comparison of the displacements of storey 4 for the Soft Storey Frame model

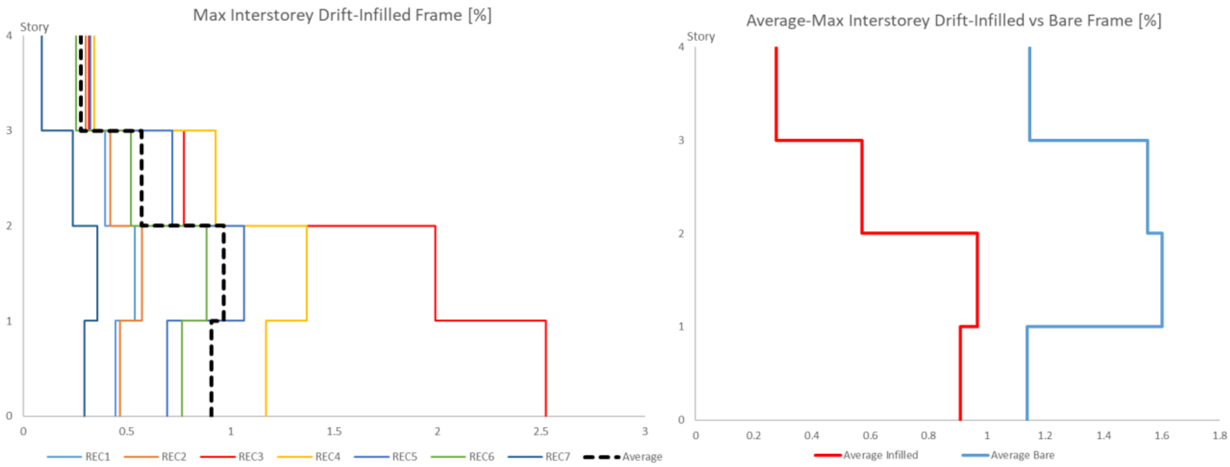

Figure 9. Interstorey drifts results

The response of the structure, uniformly infilled at all the levels, in terms of interstorey drifts to an additional set of seven ground motions is presented in Figure 9. These results show, in average terms (dashed line), the global tendency of the infilled framed structure to concentrate the drift in lower storeys. This represents a crucial point, to keep in mind for the next considerations.

From Figure 9 it can be noticed that the presence of infills might lead to a dual behaviour. In six cases, out of the seven analysed, (i.e. except for the record number three) this would result in a strong reduction, with respect to the bare frame configuration, of storey displacements and interstorey drifts in the order of at least 15-20%.

Additional remarks, related to this series of time histories, can be done by observing the results for record number four (depicted in Figure 10), which happens to be very severe for both structural models: the bare frame and the infilled one.

Figure 10(a) depicts for storey 1 the resultant of the story shear for the columns and the infills; Figure 10(b) that for the columns for Bare Frame and Uniformly Infilled Frame models; Figure 10(c) the input accelerogram for time history number four.

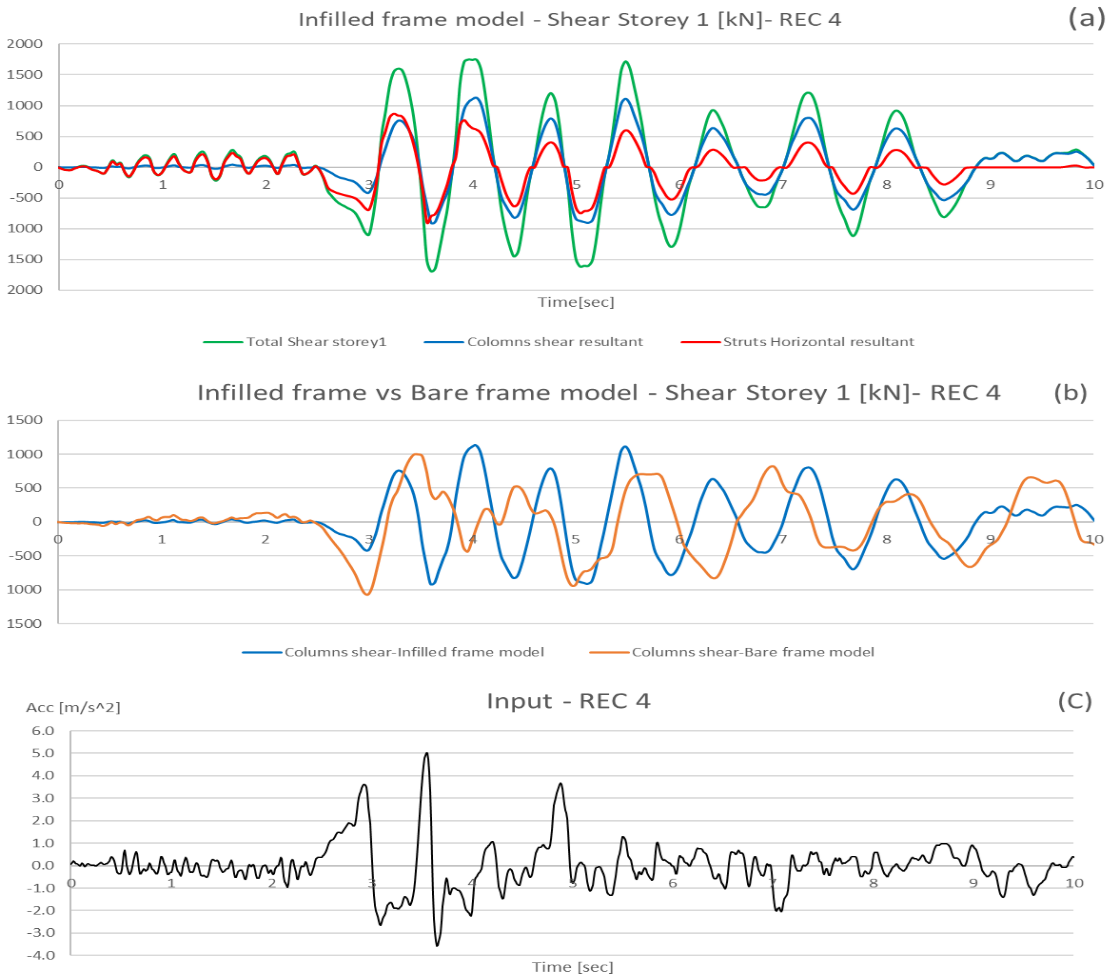

Figure 10. storey1 shear Rec4- (a) infilled frame columns shear resultant and struts horizontal resultant; (b) columns resultant shear for Bare frame and Infilled frame models; (c) input accelerogram

From Figure 10(a) it can be noticed that, within the first 2.5 seconds of the time history, struts bear all the storey shear. This means that, in this time range, the struts pre-cracking axial stiffness is much higher than the columns lateral one. When the ground acceleration increases from 3 to 3.8sec, columns and struts resist almost the same amount of shear. Subsequently, from 4sec until the end of the analysis, the struts give a lower and lower contribution because of the increasing internal damage. The maximum storey shear coming from the combined effect of the columns and the infills, for the Uniformly Infilled Frame, results to be about 50% larger than that of the Bare Frame (compare Figure 10(a) with Figure 10(b)), nevertheless the peak values of the columns shear come out to be very similar in both models.

5. CONCLUSIONS

The primary objective of this work was to assess if, and how much, a numerical model, implemented into a computer code widely used in design shops, could be representative of the effects of non-structural masonry infills on the dynamic behaviour of reinforced concrete framed structures.
The direct observation of the damage suffered by buildings during earthquakes has greatly contributed to clarify the role of non-structural infills, both in the seismic response and in the definition of the structural damage. A brief summary of the main parameters affecting the behaviour of infilled frames, that should be taken into account in setting-up mathematical models, has been presented and shows the complexity of the problem at hand. Additional complexities arise whereas non-structural masonry does not meet standard requirements and, in general, is subjected to poor quality control, leading to

very different material mechanical properties and construction techniques. Moreover, the presence of openings considerably affects the behaviour of infilled frames and hence their modeling (this issue has not been pursued in this work though).
Several numerical analyses were conducted on the bare frame, as well as on the infilled frame configuration showing that a good level of prediction can be achieved even with simplified modelling techniques (the equivalent strut macro-model). Obtained results demonstrate that the presence of light non-structural masonry infills can change the response of the structure to a large extent. The presence of a regular distribution of infills considerably prevents energy dissipation from taking place in the frame, resulting in a stiffer response, while good energy dissipation properties can be achieved by the infill itself. On the other hand, it must be stressed that in infilled framed structures, as a general trend, interstorey drifts concentrate at the lower storeys. As a matter of fact, irregularities in the panel distribution would result in unacceptably larger damage in the frame. The calibrated model of the structure has been subjected to additional analyses in order to deeply investigate its behaviour. It has been assessed that in the great majority of cases the presence of masonry panels is able to considerably stiffen the main frame structure and to more than compensate for the ensuing increase in inertial forces with the infills own resistance. By contrast, in one out of seven cases, it has been shown that the infills might lead to irregularities in elevation, compromising an otherwise totally correct structural arrangement. Indeed, soft storey behaviour can be induced by a regular arrangement of infill panels due to a sudden brittle failure of some of them. This may happen because of intrinsic weak material properties and strain softening.

6. ACKNOWLEDGMENTS

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