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The Seismic Behavior of Single and Three Story Masonry Infilled R/C Frames Utilizing Non-linear Numerical Models

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Abstract- This paper deals with the applicability of a non-linear masonry-infill concrete-frame numerical simulation to predict realistically the seismic behaviour of model three story R/C frame structural formations with masonry infills. The major obstacle here is the computational time and memory requirements needed for the completion of such a numerical analysis including all the non-linear mechanisms which were employed in the preceding simulation of the single-story one-bay R/C frame with masonry infills. A numerical technique is proposed that draws information from the fully inelastic numerical simulation of the masonry infilled R/C frame in order to define the mechanical properties of an equivalent diagonal strut that represents the masonry infill. In order to overcome this obstacle, use was made of an equivalent non-linear diagonal strut model that draws information on the stiffness and strength variation from one-bay, one-story R/C masonry infilled unit. This simplified methodology includes the realism of the fully inelastic numerical simulation which was extensively validated utilizing existing experimental results.

Keywords- *Masonry Infill, Diagonal Strut, Three Story Frame*

I. INTRODUCTION

Significant research effort has taken place in the past by many researchers proposing valid numerical models of the non-linear behaviour of masonry infilled R/C/frames employing non-commercial or commercial software. Manos, Soulis and Thauampteh [1] presented a valid, fully non-linear 2-D numerical model that can capture realistically the in-plane hysteretic behaviour of reinforced concrete (R/C) frames with masonry infills when they are subjected to combined vertical and cyclic horizontal loads in order to predict their post-elastic seismic-type behavior. The effectiveness of this simulation was validated by comparing the numerically predicted behaviour with results from a series of pseudo-dynamic tests whereby a number of 1:3 scale, one-bay, one-story R/C frame specimens, including relatively weak masonry infills, were subjected to combined vertical and cyclic horizontal seismic-type loads (Thauampteh [2]). The role of the interface between the masonry infills and the surrounding concrete frame was also included in this simulation, which has been revealed that was crucial. Manos Soulis and Thauampteh [1] examined the applicability of the proposed non-linear model for the masonry-infilled concrete-frame numerical simulation to predict realistically the seismic behaviour of prototype multi-story R/C frame structural formations with masonry infills. Asteris [3] investigated the use of micro-modelling in predicting the behaviour of infilled frames whereas Soulis [4] validated a micro-modelling as well as a macro-modelling numerical approach capable of capturing the behaviour of masonry assemblages and masonry-infilled R/C frames subjected to combined vertical and cyclic horizontal loading. Penava, Sigmund and Kozar [5] tested 10 framed-masonry specimens of 1:2:5 scale. These test specimens were divided into three groups. The first group consisted of four R/C infilled frames with an unconfined opening, e.g. a door or window, either in the center of the infill or offset from the center. The specimens of the second group had a vertical tie element around the opening. The third group consisted of two R/C infilled frames, one without an opening and one "bare" reinforced concrete frame. Penava [6] proposed a micro-model numerical approach and calibrated the assigned numerical parameters in order to obtain the best correlation between experimental and numerical results. The concrete parts were simulated employing plane stress elements. For the reinforced concrete frame (Columns and lintel) were modeled adopting the fracture-plastic constitutive law, known as the Non-Lin-Cementitious material model. The longitudinal and transverse steel reinforcement of the reinforced concrete frame were modeled utilizing truss elements. Stylianides[7], conducted an extensive experimental program which included sixteen single-story one bay 1/3 scaled masonry infilled R/C frame models. Two of these specimens are used here for the validation of the numerical model proposed in this study. The influence of the important parameter concerning the level of interaction between the masonry infill and the surrounding R/C frame was also examined by Stylianides [7].

In the first part of the current study, presented in section II, a macro-modeling technique for the numerical simulation of masonry infill panels is adopted. Prior to simulating the behaviour of these masonry infill panels, this technique was validated with experimental results obtained either from diagonal compression tests on square masonry panels or from racking tests with masonry piers (Manos, Soulis and Thauampteh [1], Thauampteh [2]). Both the square masonry panels, tested under diagonal compression, and the masonry piers, tested under simultaneously vertical compression and horizontal racking cyclic forces, had the same mechanical characteristics as the masonry infills used for the construction of masonry-infilled R/C frames that are included in this paper. The experimental results from these tests compare reasonably well with the predictions from the numerical simulation. This provided the necessary confidence that the proposed numerical simulation can successfully capture the non-linear behaviour of masonry-infilled R/C frames. In this effort the same macro-model validated before is selected to be used in the numerical simulation of the masonry infill R/C frame behaviour including stiffness and strength degradation. This is done by numerically simulating the non-linear behaviour of the masonry infill itself, the formation of plastic hinges for the R/C frame at pre-defined locations and the sliding or the separation of the masonry infill from the surrounding R/C frame. A number of single-story one-bay R/C frame scaled specimens with masonry infills were constructed and tested at the strong reaction frame of the Laboratory of Strength of Materials of Aristotle University of Thessaloniki ([2]). The emphasis in the first part of this paper, presented in section II, is to employ the proposed numerical simulation for approximating the observed in-plane cyclic response of masonry infilled R/C specimens from this experimental sequence as well as of the experimental sequences conducted by Stylianides [7]. The validation of the proposed numerical approach was done through: a) the comparison between the numerical and experimental cyclic response of the infilled R/C frames under the combination of vertical cyclic horizontal loads, b) the comparison of the damage patterns predicted numerically and observed experimentally, c) the comparison of the shear behaviour of masonry infills themselves, assuming different interface and levels of interaction between the infills and the surrounding R/C frame.

The significance of the out-of-plane behaviour of the masonry infills is also observed after strong earthquake events. However, in the present investigation only the in-plane behaviour is examined. Moreover, the possibility of the R/C structural elements developing shear mode of failure should also be investigated. The shear modes of failure have been studied for masonry infilled R/C frames by Manos and Soulis [8]. However all the examined R/C infilled frames have failed under a flexural mode of failure, so the shear failure mechanism was not attributed to the numerical simulations under study. As the validation of the proposed numerical simulation was performed by Soulis [9] directly with the results obtained from the 1/3 scaled specimens tested either by Thauampteh [2], or Stylianides [7] any influences arising from scaling were ignored. It is expected that such influences cannot be significant as the used masonry infills were constructed with prototype burnt clay units, together with prototype mortar mixes. The mortar joints were approximately 9mm to 10mm thick, which is close to the thickness of prototype mortar joints. This type of weak masonry employed as masonry infill was dominated by the compression-shear (frictional) non-linear mechanism that developed at these joints.

Soulis [9] also studied the capability of the proposed numerical simulation of capturing the experimental behavior of multi-story 2-D frames. The numerical simulation proposed in the first part was used to simulate the behavior of such three-story structural formations including masonry infills; in particular a multi-story planar R/C frame structure, that was constructed and tested at the University of California, Berkeley by Klingner and Bertero [10]. Reasonably good agreement was observed between the numerical results and the experimental measurements regarding the hysteretic behavior of the "bare" and infilled three-story specimens. This analysis was satisfactory despite the significant number of finite elements utilized in the numerical simulation and the high computational requirements. In order to overcome this difficulty a diagonal strut model is proposed and validated, aiming to incorporate the influence of the masonry infills for multi-story structural formations. For this purpose, the previously mentioned planar 3-story structural formation is selected for the validation. More specifically, as will be described in section V of this paper, the masonry infills of this planar 3-story, R/C structure are modeled as diagonal strut members as proposed by Holmes [11], Stafford Smith B, Carter C[12], Campione, Cavaleri, Macaluso et al [13]; however, these are modeled with multi-linear properties Cavaleri, Fossetti, Papia [14]. The numerical response obtained from a "pushover" analysis employing these "multi-linear" diagonal struts is compared with the corresponding predictions employing the fully non-linear approach presented in the first part of this paper.

II. NUMERICAL SIMULATION OF THE BEHAVIOUR OF MASONRY-INFILLED R/C FRAMES SUBJECTED TO CYCLIC HORIZONTAL AND VERTICAL IN-PLANE LOADS

A series of reinforced concrete infilled frames were subjected to cyclic horizontal loading during the experimental investigation that took place in the Laboratory of Concrete and Strength of Materials of the University of Thessaloniki (Sylianides[7]). The first group of one-bay one-story frames were 1/3 scaled models with height over length ratio equal to 1.5 (l/h=1.5, figure 1). The cross-section of the columns was 150mmx150mm and that of the beam 100mmx200mmm and reinforcement ratio equal to 0.01 (ρ=1,01%). An axial load level of 80KN was applied at the top of each column by a hydraulic actuator. This was kept constant during the cyclic horizontal loading. Lateral load was applied by placing two single hydraulic actuators at the level of the horizontal axis of the R/C beam. The thickness of the masonry infills was 63mm.

The second group of one-bay one-story frames was also subjected to cyclic horizontal loading during the experimental investigation that took place in the Laboratory of Strength of Materials and Structures of the University of Thessaloniki (Thauampteh [2]). This group of specimens included 10 one-bay one-story 1/3-scale models with overall external dimensions 1720mm (length) x 1000mm (height) and a length over height ratio equal to 1.7 (l/h=1.7, figure 2). The cross-section of the columns was 110mmx110mm and that of the beam 100mmx155mmm. The reinforcement ratio was equal to 0.00785 (ρ=0.785%). Axial load equal to 50KN was applied at the top of each column by a hydraulic actuator. This was also kept constant during the cyclic horizontal loading.

The results of the study were included in the work by Thauampteh [2], where the behaviour of ten "bare" and masonry infilled specimens is examined in detail. Moreover, the extensive comparison of various numerical simulations with the behaviour observed by Thauampteh [2], as well as by Stylianides [7], for the masonry infilled R/C frames is included in the work by Soulis[9], where the conclusions of the corresponding extensive validations were also presented. Finally, a summary of the most important conclusions of this validation between the proposed numerical simulation of the masonry is presented in a recent publication of Manos and Soulis [15].

Due to space limitations, the validation of the proposed numerical simulations presented here is limited to the masonry infills utilising only one specimen (F3N(R1f,R1w)s) investigated by Thauampteh [2] as well as two specimens (F1N) and (F2N) investigated by Stylianides [7]. Brief information on the selected masonry infilled R/C specimens is listed in table I. Tables II and III list the mechanical properties of the materials used in the construction of these R/C masonry infilled frames.

TABLE I. DESCRIPTION OF THE SPECIMENS TESTED EXPERIMENTALLY BY THAUAMPTEH [2]

Frame Code name	Length over Height ratio	Vertical load on Columns (KN)	Technical description of masonry infill	Masonry Infill thickness (mm)	Technical description of the interface between frame and infill
1st group of specimens					
F1N [12]	1.5	80	mortar S	63	mortar S thickness 10mm (without plaster)
F2N [12]	1.5	80	mortar O	63	mortar O thickness 10mm (without plaster)
F3N(R1f,R1w)s (Repaired) [16]	1.7	50	Infill with mortar V1, reinforced with reinforced plaster, and transverse reinforcement type Π	78.5	Mortar H thickness 15mm. The reinforced plaster is not in contact with the surrounding frame

As already mentioned, the influence exerted by the interface between the masonry infill and the surrounding frame was examined extensively in both studies by Thauampteh [2] and by Soulis[9].

TABLE II. STRENGTHS OF MASONRY INFILLS AND CONCRETE FOR THE 1ST AND 2ND GROUP OF SPECIMENS[2], [7]

Masonry infill	Masonry Infill thickness (mm)	Compressive strength of masonry (N/mm^2)	Shear strength of masonry under diagonal compression (N/mm^2)	Compressive strength of masonry units (N/mm^2)	Compressive strength of concrete (N/mm^2)	Compressive strength of mortar cylinders (N/mm^2)
1st group of specimens Virgin infill [12]						
S	63	2.94	0.32	5.96	27.9	11.87
O	63	1.86	0.26	5.96	27.9	2.74
2nd group of specimens Reinforced infill						
Infill with mortar V1, reinforced with reinforced plaster	78.5	3.75	0.44	6.50	25.9	1.125

TABLE III. TENSILE STRENGTH OF THE REINFORCEMENT USED IN 1ST AND 2ND GROUP OF SPECIMENS [2], [7]

A/α	Yield stress f_{sy} (N/mm^2)	Ultimate strength f_{su} (N/mm^2)	Strain at yield ε_{sy} (%)	Strain at ultimate stress ε_{su} (%)	Young Modulus (N/mm^2)
Φ 6 (1st group)	348.0	457.0	0.174	18.0	$2.0x10^5$
Φ 2.7 (1st group)	271.0	395.0	0.135	19.0	$2.0x10^5$
Φ5.5 (2nd group)	311	425	0.8	22.0	6.5X104
Φ5.5 (2nd group)	360	542	0.6	20.0	6.5X104

III. NUMERICAL SIMULATION OF THE SINGLE STORY MASONRY INFILLED R/C FRAME

The finite element simulation employed for the R/C frame with the masonry infill is shown in figure 1. In the numerical model of the surrounding R/C frame the beam and the two columns are simulated, together with the locations of possible plastic hinge formation at the ends of each element (figure 1). Plane stress elements are used for simulating the masonry infill (Figure 1 detail No 1); they are connected to the surrounding frame by a different series of 2-D joint elements that simulate the masonry infill to R/C frame interface (peripheral mortar joint), as described below. It is assumed that a single material law including an isotropic modified Von Mises failure criterion governs the behaviour of the masonry infill. The mechanical elastic and post-elastic properties of the different masonry panels that are utilized in this numerical simulation are listed in table IV.

The interaction between the R/C frame and the masonry infill has a critical role, as it asserts an important influence on the resulting state of stress of the masonry infill and contributes to the development of the various masonry failure modes. For this purpose, two sets of non-linear 2-D joint elements are placed in the perimeter of the masonry infill – R/C interface used to simulate the separation and slip between frame and infill as well as the transfer of compression and shear for the different types of interface. The first set of these 2-D joint elements (figure 1 details No 2 and No 3) is active in the direction transverse to the interface; it is of a frictional type, where the value of friction coefficient is introduced (Table V) . The second set of non-linear joint elements (figure 1 details No 2 and No 3) is active in both the transverse and the normal to the interface directions simulating in this way the shear, compressive and tensile behavior of the interface.

Thick beam elements, able to deform and rotate in plane, were employed for both the columns and the beam. Rigid beam elements were also employed to simulate the corner connection between the beam and the column (figure 1, detail No. 4). A number of non-linear 2-D joint elements were also employed at the ends of each column (figure 1, detail No. 5). The formation of plastic hinges at each end of the beam is achieved by a number of flexural non-linear 2-D joint elements simulating the flexural moment against the elastic/plastic rotation at this location (figure 1, detail No. 4,). This time not only the flexural behaviour is simulated, by the moment versus the elastic/plastic rotation (with the presence of axial load) relationship, but also the slip of the reinforcement. These non-linear 2-D joint elements are represented by the “z” symbol. The measured mechanical properties of the concrete and reinforcement for the tested specimens are utilized to obtain the necessary values for the properties of these non-linear 2-D joint elements.

The moment-rotation relationship for the beam and column cross-section was calculated by specialized software (RCCOLA [16]) and based on its particular detailing and material properties. The total flexural behaviour of the beam and column hinge is compared satisfactorily with the corresponding behaviour produced by this non-linear 2-D joint element simulation of Manos, Soulis and Thauampteh [1].

TABLE IV. MECHANICAL PROPERTIES OF INFILLS USED IN THE NUMERICAL SIMULATIONS

Test No.	Frame Code name	E Young Modulus(N/mm^2)	f_k Measured Compressive strength of masonry (N/mm^2)	f_t Assumed Tensile strength of masonry (N/mm^2)	E_{sc} Softening Modulus under compression(N/mm^2)	E_{st} Softening Modulus under tension(N/mm^2)
1	F1N	2000	3.0	0.5	-20	-20
2	F2N	1500	1.8	0.35	-20	-20
3	F3N(R1f,R1w)s	3500	4.5 *	0.8	-5	-5

TABLE V. MECHANICAL PROPERTIES OF THE INTERFACE USED TO SIMULATE THE MORTAR JOINT BETWEEN INFILL AND SURROUNDING FRAME (S, O, H)

Simulation of joint interface between frame and infill	E Young Modulus (N/mm^2)	G Shear Modulus (N/mm^2)	f_k Measured Compressive Strength of mortar (N/mm^2)	f_{tn} Assumed Tensile Strength of mortar (N/mm^2)	τo Local bond shear strength of mortar (N/mm^2)	μ friction coefficient
S mortar	430	180	2.60	0.6	0.26	0.20
O mortar	100	59	1.50	0.15	0.20	0.20
H mortar	60	26	0.60	0.0	0.078	0.58

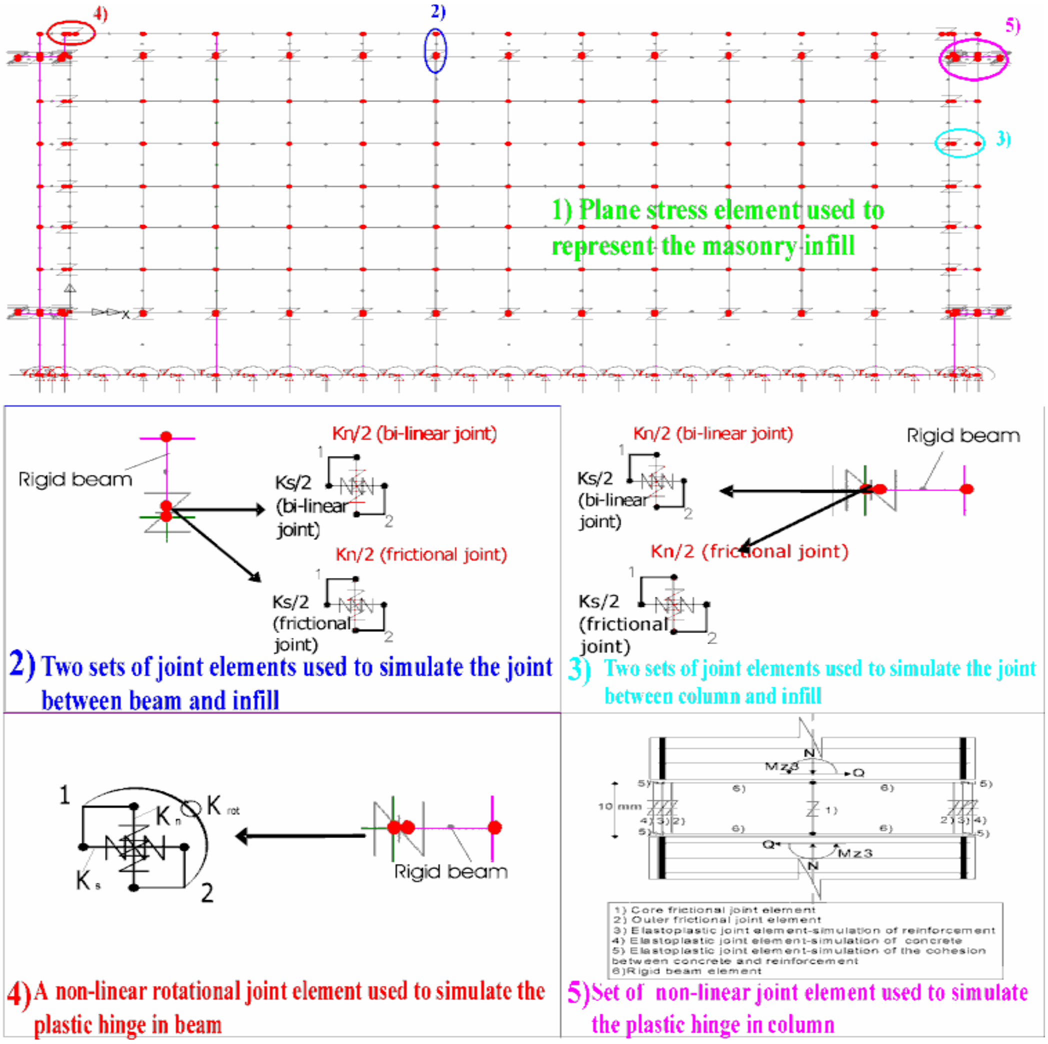

Figure 1. Fully non-linear numerical simulation of masonry infilled R/C model

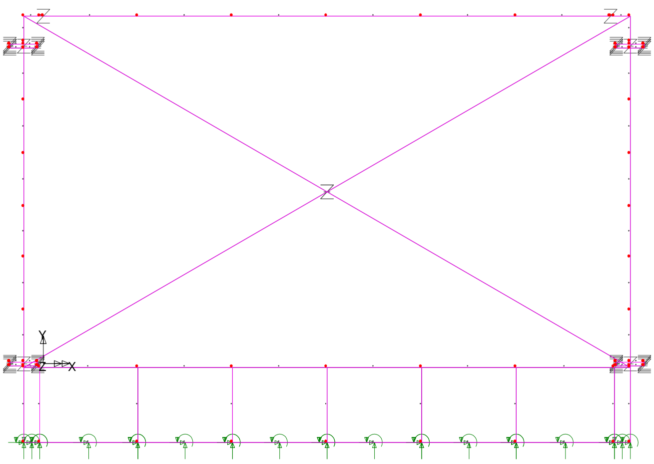

Figure 2. Equivalent diagonal strut model

IV. Simplification of the Numerical Simulation of the Masonry Infill Frame Response for a Single-Bay One-Story Infilled Frame.

In this section, a simplification of the masonry infill frame response for a single-bay one story infilled frame will be examined. This simplification will have the following characteristics:

1. The contact interface of the masonry with the surrounding frame will not be represented in the direct way employed before in section III. As a result, the masonry infill 2-D representation, as outlined in section III, will also be replaced by the well known equivalent diagonal strut model (figure 2). On the contrary, all the aspects of the reinforced concrete frame representation, described in section III, will be retained.

2. The equivalent diagonal strut will be a multi-linear model, active in compression only. Its force – displacement properties are defined by a "pushover" type of analysis in such a way that the total force – displacement response of the R/C infill frame, with the diagonal strut in-place, in terms of envelope curve, is as close as possible to the envelope curve of the numerical simulation of the same problem whereby the contact interface and the masonry infill were simulated separately.

3. Because the non-linear mechanisms and its properties of the R/C frame standing alone remain the same the non-linear response that arises at either the interface or at the masonry infill, which were addressed separately by the simulation of section III, is approximated this time in a combined way, utilizing the multi-linear equivalent diagonal strut approximation. It is obvious that through this simplified numerical treatment one loses the directness of treating this problem with a clear representation of the various non-linear mechanisms as they physically occur at either the contact interface or the masonry infill. Moreover, the degree of approximation of the masonry infill – contact interface – R/C frame interaction by the equivalent diagonal strut is based on the validity of the full non-linear treatment of the masonry infill – contact interface – R/C frame problem, which was demonstrated in section III. The validation of this proposed numerical simulation of the masonry infill – R/C frame behavior is presented here by comparing the numerically-predicted with the observed behavior in terms of: load-displacement hysteretic curves.

The numerical results obtained by employing either the tri-linear diagonal strut simulation for the masonry infill or the fully non-linear treatment are compared in figures 3,4 and 5 for specimens F1N F2N and F3N(R1f,R1w)s, respectively. In these figures, the experimental load-displacement (P-δ) curves, recorded during testing, are also plotted. As can be seen, the (P-δ) cycling curves predicted with the tri-linear diagonal strut compare quite well to both the corresponding (P-δ) curves obtained from the experiments as well as with the ones resulting from the fully non-linear treatment (section III). Good comparison between the experimental testing and the numerical simulation is observed in terms of the failure pattern. In figure 6 the experimental failure of masonry infilled frame F2N is presented. A diagonal cracking failure pattern is observed. The same failure pattern is predicted in the numerical simulation utilizing the macro-model (figure 7). In the figure 8 the observed failure of F3N(R1f,R1w)s is shown. The reinforced masonry infill exhibits crushing in its corners. The same failure is predicted through the macro-modeling technique (Figure 9). It must also be underlined again that the degree of approximation of the masonry infill – contact interface – R/C frame interaction by the equivalent diagonal strut is based on the validity of the full non-linear treatment of the masonry infill – contact interface – R/C frame problem, which was demonstrated in the current section.

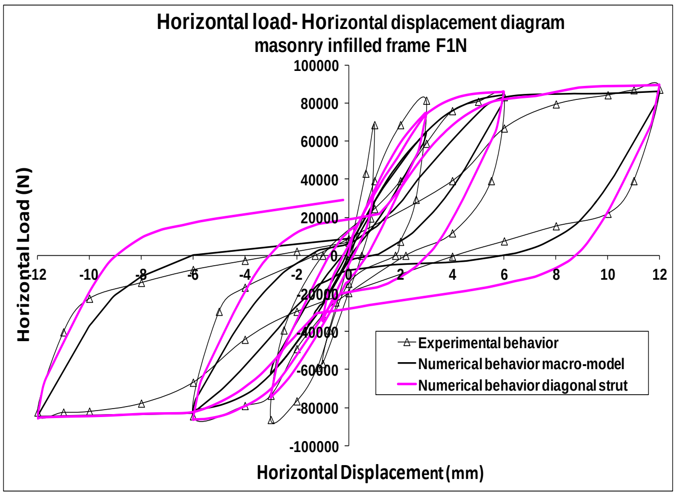

Figure 3. Comparison of cyclic response for specimen F1N

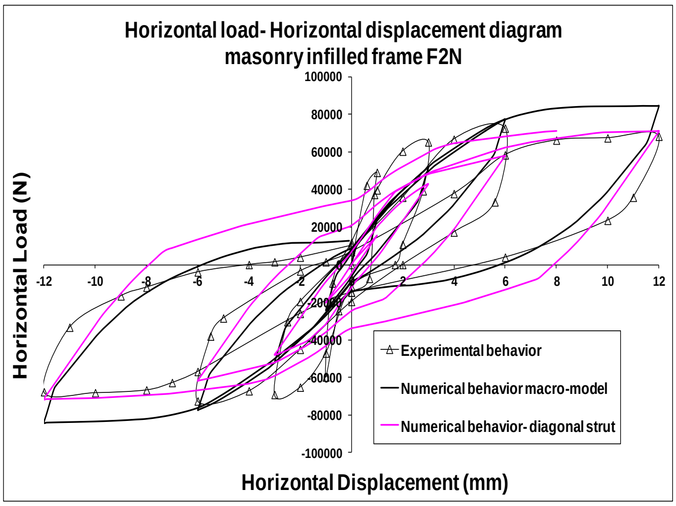

Figure 4. Comparison of cyclic response for specinmen F2N

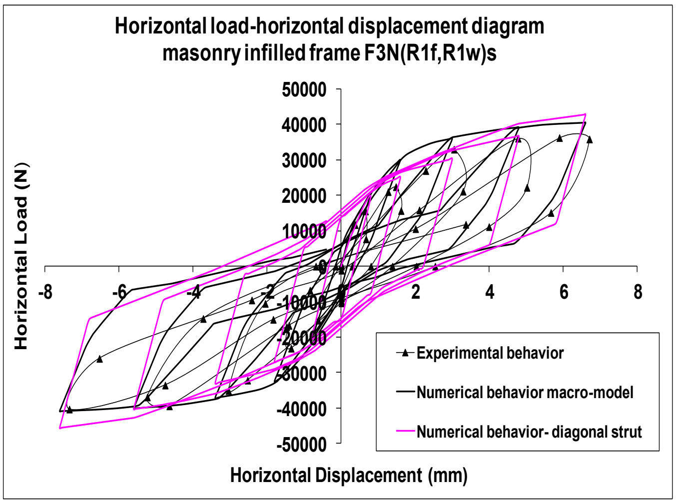

Figure 5. Comparison of cyclic response for specimen F3N(R1f,R1w)s

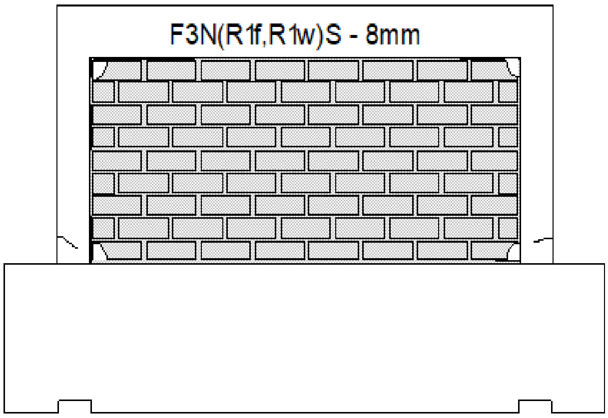

Figure 8. Experimental failure of masonry infilled frame F3N(R1f,R1w)s (Corner crushing)

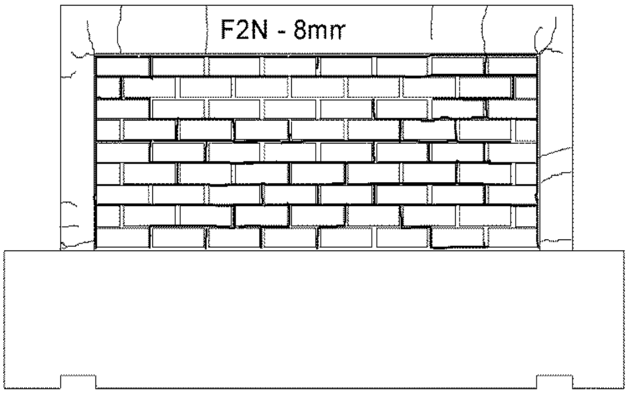

Figure 6. Experimental failure of masonry infilled frame F2N (DIAGONAL CRACKING)

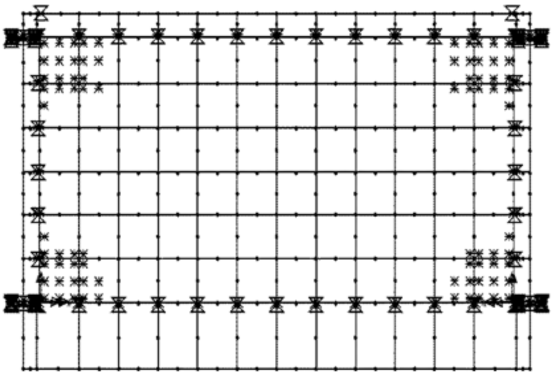

Figure 9. Failure predicted through macro-modeling technique

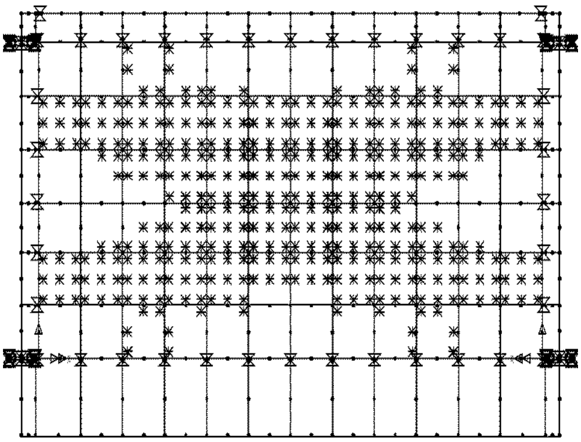

Figure 7. Failure predicted through macro-modeling technique

V. VALIDATION OF THE PROPOSED NUMERICAL SIMULATIONS FOR A 2-D , THREE STORY MASONRY INFILLED R/C FRAME

In the previous paragraph a successful numerical model for a 2-d single story R/C infilled frame subjected to cyclic horizontal loading was presented. It was shown that the presented model can describe and simulate the dominant non-linear mechanisms that develop in a single story R/C infilled frame. It is believed that all these dominant non-linear mechanisms that develop in a single-story masonry infilled R/C frame, as described in the first part of this paper, can also develop in the same way in a multi-story R/C frame structure with masonry infills when subjected to "seismic type" loading. For the examination of the capability of the proposed model to capture the dominant non-linear mechanisms that can be developed in a three story, single bay, R/C infilled frame a 1/3 scaled model of an eleven story prototype was selected. The design of the scale model and the experimental investigation took place in the Structural Engineering Laboratory of the Department of Civil Engineering, University of California by Klingner and Bertero[10].

There were four, three-story, one-bay, 1/3 scaled frame specimens tested experimentally by Klingner and Bertero [10]. These specimens included four different types of configurations: a) a bare frame (Figure 10), b) the same frame, infilled with clay blocks after test a, c) a virgin frame, infilled with clay blocks, d) a virgin frame, infilled with concrete blocks (figure 11). For the scope of validation of the proposed model only the configurations of: a) bare frame, b) virgin frame, infilled with concrete blocks will be utilized. Two numerical models will be examined for the masonry infilled R/C frame with concrete blocks one considering the fully non-linear configuration and one considering the diagonal strut model for the masonry infill.

The height over length ratio was equal to 1 (l/h=1, figure 10, 11). The cross-section of the columns was 152.4mmx152.4mm and that of the beam 203.2mmx101.6 mm and reinforcement ratio equal to 0.017 (ρ=1.7%, figures 12). Masonry infills were 51mm thick each, reinforced in a single-wythe horizontally and vertically, every 10cm by deformed #2 bars, spliced to dowels anchored in the frame members (figure 13). Lateral loads simulating the effects of in-plane shear due to lateral inertial forces, were applied at the third and one half story level using a hydraulic actuator with a capacity of 1560 KN. Column loads simulating the effects of gravity loads and the overturning moment associated with the lateral load. The total vertical force that was applied was 222KN. The ratio between lateral force and corresponding overturning moment was calculated by elastic analysis of the entire frame. To account for any changes due to panel degradation during the course of the test, the proportion of axial to lateral loads was changed, based on the amount of panel damage observed. Brief information on the selected masonry infilled R/C specimens together with the experimental arrangement and the loading sequence can be depicted in figures 10 and 11. Tables VI and VII list the mechanical properties of the materials used in the construction of these R/C masonry infilled frames. The mechanical properties of the masonry infills and the joint interface between the infill and the surrounding frame in the numerical simulation were derived from the constituent materials properties measured during the experimental investigation of Klingner and Bertero[10].In figure 14, the numerical simulation of the “bare” frame model is presented. It uses the same concept used in the numerical simaulation of the surrounding frame used in section III. In figure 15, the numerical simulation using the macro-modelling technique for the masonry infilled 3-story frame studied by Klingner and Bertero [10] is also shown. Finally, in figure 16 the numerical approximation utilizing equivalent diagonal struts for the masonry infills is reported. The stiffness and strength properties that were assigned to the diagonal strut are shown in figure 17. In this way the influence of the masonry infill was simulated.

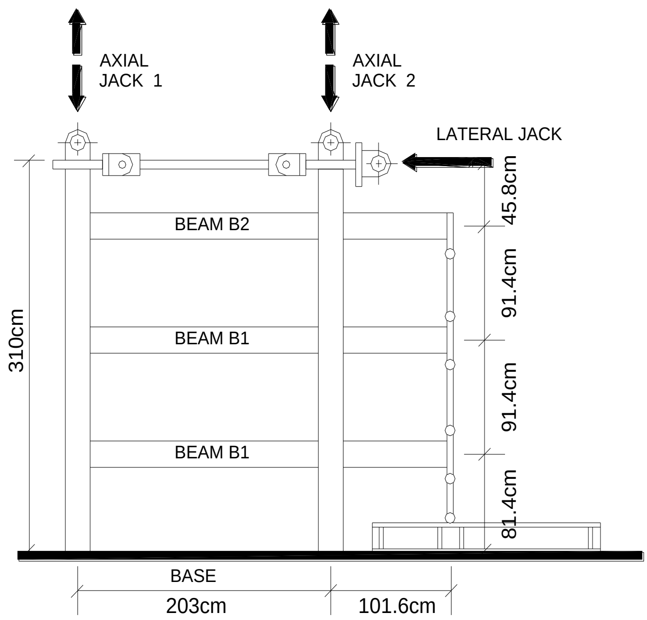

Figure 10. Bare frame specimen[10].

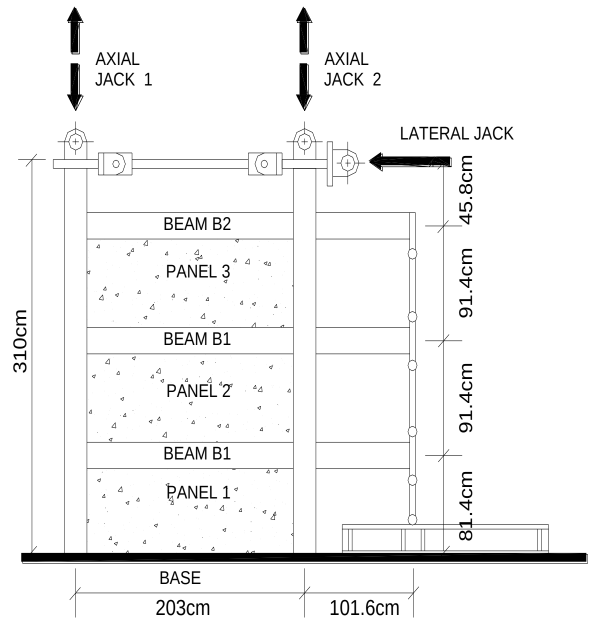

Figure 11. Masonry infilled R/C frame specimen [10]

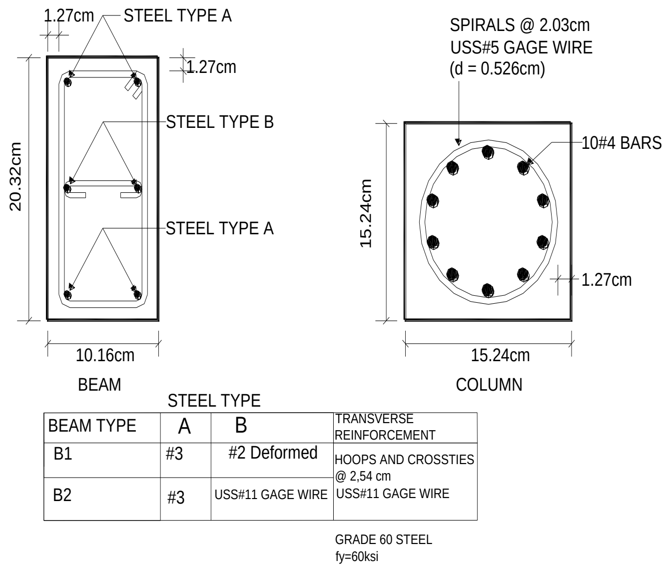

Figure 12. Column and beam design details (American reinforcement details)

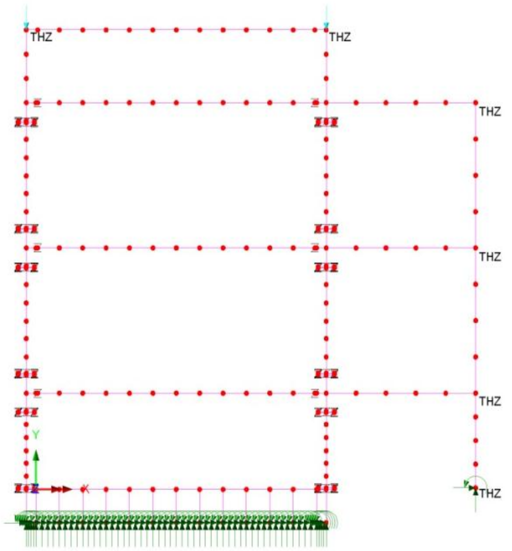

Figure 14. Numerical Simulation of the “bare” three story R/C frame

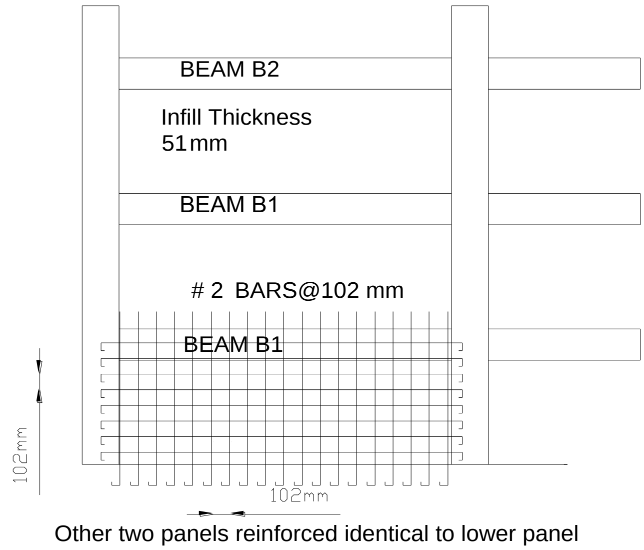

Figure 13. Masonry infill reinforcement

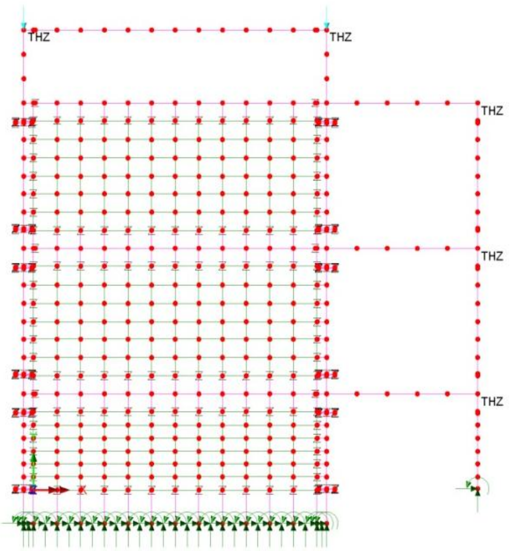

Figure 15. Numerical simulation of the three story masonry infilled R/C frame

TABLE VI. TENSILE STRENGTH OF THE REINFORCEMENT USED IN THE FRAME SPECIMENS [10]

Type of reinforcement	fy lower (N/mm^2)	fy maximum (N/mm^2)
#4(12,7mm)	512	741
#3(9,52mm)	470	652
#2 deformed(6,35mm)	506	729
USS #5 Wire(5,557mm)	670	678
USS #11 Wire(2,175mm)	703	759

TABLE VII. STRENGTHS OF MASONRY INFILLS AND CONCRETE FOR THE FRAME SPECIMENS[10]

Masonry infill	Masonry Infill thickness (mm)	Compressive strength of masonry (N/mm^2)	Young modulus (N/mm^2)	Compressive strength of concrete (N/mm^2)	Compressive strength of mortar cylinders (N/mm^2)	Compressive strength of grout cylinders (N/mm^2)
"Bare" Frame, test 1				25.9		
A virgin frame, infilled with clay blocks ,test 2	51	23.5 ground floor masonry infill	8343	22.0	26.5	24.57
		22.5 story masonry infill	7722			
A virgin frame, infilled with concrete blocks, test 3	51	18.96	9653	27.6	34.8	20.23

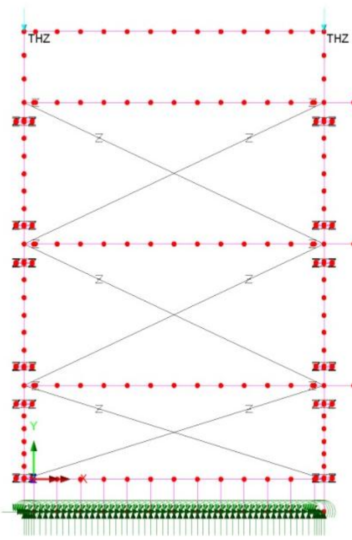

Figure 16. Numerical simulation of the three story masonry infilled R/C frame with equivalent diagonal struts

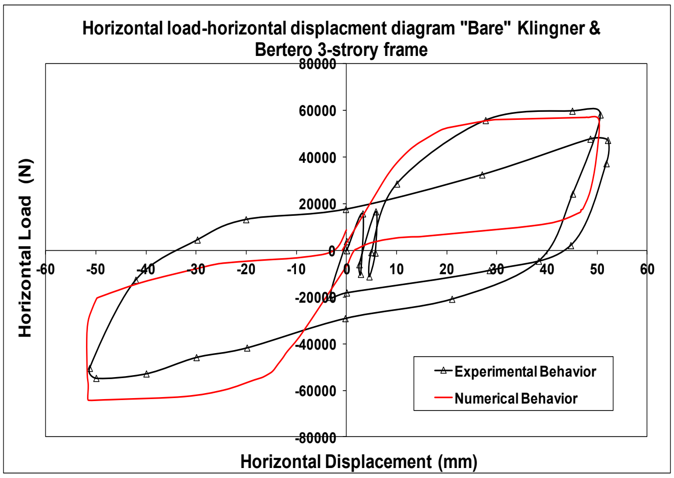

Figure 18. Comparison of cyclic response for Klingner & Bertero[10] 3-story "bare" frame

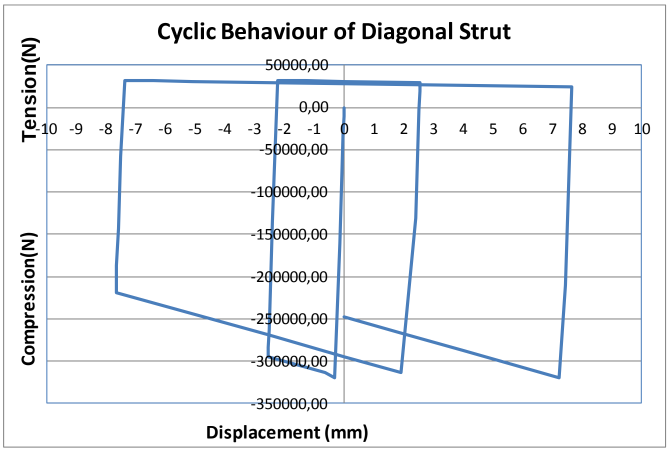

Figure 17. Hysteretic behaviour for the Klingner nad Bertero [10] equivalent diagonal strut

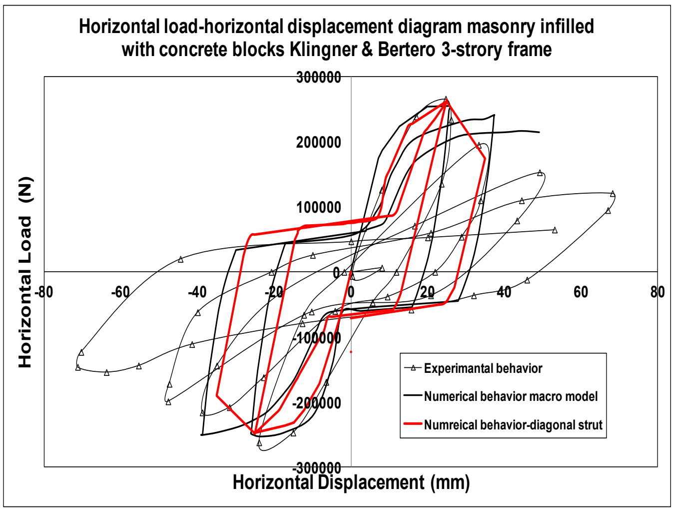

Figure 19. Comparison of cyclic response for Klingner & Bertero[10] 3-story masonry infilled frame with concrete blocks

The mechanical properties of the diagonal strut are determined in the study of Klingner and Bertero[10]. In the experimental study the crushing of some of the equivalent struts occurred at loads in the range of 280 kN to 320 kN. The tensile part of the diagonal strut behaviour is integrated in an effort to simulate the total tensile resistance produced when the masonry infill is joined by dowels with the surrounding frame. The post-elastic behavior incorporates a light softening behaviour. In figure 18 the experimental behaviour of the 3-story "bare" frame is compared with the numerical behavior. Both the initial stiffness and the bearing load were predicted successfully by the numerical simulation, however discrepancy was observed in terms of the hysteretic behaviour. In figure 19, the experimental behavior of the 3-story masonry infilled frame with concrete blocks is compared with the behavior of the fully non-linear treatment (macro-model), and the behavior of the simulation that utilizes the diagonal strut for the masonry infill. As can be seen, the cycling curve predicted with the diagonal strut compares in relative success to the corresponding curves obtained from the experiment as well as with the curve resulting from the numerical macro-model (section III). Both the macro-model and the diagonal-strut model capture satisfactorily the bearing capacity and the softening branch of the bearing capacity. However, the diagonal-strut model has slightly overestimated the hysteretic behaviour of the masonry infilled 3-story frame.

VI. CONCLUSIONS

1. The strength and load-displacement hysteretic behaviour observed during the experiments of single-story one-bay masonry-infilled R/C frames examined in this study is successfully predicted by the proposed numerical simulation. Some discrepancies are observed in the initial stiffness and the bearing capacity of the F1N and F2N strut models.

2. The damage patterns for the masonry infill, in terms of crack propagation are also successfully predicted.

3. The dissipated energy during the experimental "seismic-type" cyclic-loading sequence is in good agreement with the results of the proposed numerical simulation.

4. The employed numerical simulation of masonry-infilled R/C frame F3N (R1f,R1w)s predicted successfully the stiffness, strength and energy dissipation due to the presence of the partially reinforced masonry infill of the tested specimen.

5. The proposed numerical simulations of masonry infills incorporates influences arising from the interface between the masonry infill and the surrounding R/C frame, as these are found to be important in obtaining realistic predictions of the masonry infill to frame interaction. Thus, the proposed numerical simulation seems to represent in a reasonable way the most important influences that the interface between masonry infill and the surrounding frame could exert on the cyclic behavior of such structural assemblies. The behavior of the masonry infilled frames is examined in terms of stiffness, strength and modes of failure as demonstrated from the observed behavior.

6. Based on the successful validation of the proposed numerical simulation of the non-linear response of single-story one-bay masonry-infilled R/C frames a numerical model is proposed for the prediction of the behavior of a three story masonry infilled R/C frame under seismic type lateral loading.

7. By comparing the response of a planar three-story R/C masonry-infilled frame, as predicted by the fully-nonlinear simulation and the simulation adopting the equivalent diagonal strut model, it can be demonstrated that the proposed "equivalent diagonal strut model" is quite successful in predicting reasonably well the hysteretic behaviour of the three-story masonry infilled R/C frame.

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