Micro and Macro-modeling Techniques for the Simulation of the Masonry Infilled R/C Frames under Earthquake Type Loading

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Abstract—Three types of numerical simulation techniques for the masonry infills are adopted in the current paper, namely a micro-modeling technique, a macro-modeling technique and a simulation whereby the masonry infill and the joint interface between the surrounding frame and the infill is represented by a diagonal strut model. Initially, the hysteretic behavior of three R/C frames with masonry infills tested at the Laboratory of Strength of Materials and Structures of the University of Thessaloniki are examined when they are subjected to horizontal cyclic loads. Non-linear finite simulations are employed, that can describe the reduction of strength and initial stiffness. The inelastic behavior of the frame is simulated including the non-linear simulations of the masonry infill, 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. The second part of the present work examines the effectiveness of the micro-modeling technique and that of the diagonal strut model for the numerical simulation of masonry infills inside R/C frame specimens when different types of openings are considered. The results from three framed masonry infill specimens that were tested under horizontal cyclic loading at the University of Osijek have been also utilized for the validation of the micro-model technique and the diagonal strut model that is proposed. Differences and similarities between the adopted numerical modeling techniques are commented and discussed.

Index Terms—Modeling Techniques; Masonry-Infilled R/C Frames; Numerical Simulation

I. INTRODUCTION

Distinct numerical modeling techniques have been proposed by different researchers in an effort to simulate masonry infills inside R/C frame structures. The main categories of masonry infill numerical modeling can be divided into macromodels models (simulation of masonry units and mortar joints as a single model with single material properties), micromodels (separate simulation of masonry units and mortar joints) and diagonal strut models (simulation of masonry infill as a diagonal strut). (Mohyeddin, Goldsworthy and Gad [1]). Chrysostomou et al. [2] proposed a new strut model where each infill panel was represented by six compression inclined struts. Three parallel struts were used in each diagonal direction, and the off-diagonal ones were positioned at critical locations along the frame members. Gosh and Amde [3], proposed a finite element simulation to study the failure modes of infilled frames. Different frame-infill strengths ratios were examined. The frames that have been utilized analytical by previous researchers (Riddington [4], Pook and Dawe [5]) were included in the Gosh and Amde [3] study. Two failure criteria were proposed for the masonry infill; the first includes a homogenization approach together with the Von Mises failure criterion for plane stress elements and a smeared crack model. In the smeared crack model the mortar joints of the masonry infill are modeled assuming a combination of the Mohr-Coulomb yield criterion together with a yield criterion in tension. Manos, Soulis, Thauampteh [6] and Soulis [7] validated a micro-modeling as well as a macro-modeling numerical approach capable of capturing the behavior of masonry assemblages and masonry-infilled R/C frames subjected to combined vertical and cyclic horizontal seismic-type loading. Relatively recent publication by Asteris et al [8], underlined distinct approaches for modeling the masonry infill that could be distinguished into macromodels (no discrete masonry units in the model), simplified micromodels (discrete masonry units with interface elements), and micromodels (discrete masonry units and mortar in the model). The proposed nonlinear micro-modeling technique has been utilized to capture the behavior of fully masonry infilled R/C frames and masonry infilled R/C frames with openings. Koutromanos, Stavridis, Benson Shing, Willam, [9] demonstrated the ability of a proposed nonlinear finite element models to capture the response of masonry-infilled R/C frames under cyclic loads. Distributed cracking and crushing in concrete and masonry elements are described by a smeared-crack continuum model, while dominant cracks as well as masonry mortar joints are modeled utilizing a cohesive crack interface model. Allouzi R, Irfanoglu A., Haikal [10] proposed a 3D non-linear micro-model having the capability to model strength and stiffness degradation. Their model managed to simulate various types of in-plane failure modes of infilled frames under monotonic and cyclic loading. A continuum concrete damage plasticity model with an elastoplastic model for steel reinforcement bars in combination with cohesive-friction interfaces along mid-thickness of mortar bed joints were used and it was demonstrated that they were capable of simulating the behavior of infilled frames under monotonic and cyclic loadings.

It was demonstrated by the experimental investigations of Stylianos [11] that the infill–frame interaction is significantly influenced in all its aspects (stiffness, strength,
energy dissipation characteristics, degradation, damage potential etc.) from the non-linear properties and behavior of the infill, the surrounding frame, and the contact surface at the interface between the frame and the infill.

In the first part of the current study as this is presented in section II the description of the single storey, single bay, masonry infilled R/C frames tested experimentally is taking place. In section III, the micro-modeling technique, and the macro-modeling technique were described and adopted. In section IV the diagonal strut model for the numerical simulation of the masonry infills is addressed. Three numerical simulations were proposed and validated utilizing masonry infilled R/C specimens namely F1N, F3N(R1f,0w)*s and F3N(R1f,R1w)ws. The one utilizing a simulation where the masonry units and mortar joint were simulated separately(micro-model), the second utilizing a homogenized plane stress simulation(macro-model) where the masonry infill behavior was governed by a single failure criterion and the third by the well known representation of the masonry infill with an equivalent diagonal strut. Before the simulation of the behavior of these masonry infill panels, the validation of the adopted modeling technique was carried out. This step involved verification of experimental results carried out on square masonry panels under diagonal compression tests or from racking tests on masonry piers under the combination of vertical and horizontal forces (Stylianides [11], Thauampteh [12], Manos, Soulis, Thauampteh [6]).

In section V the validation of the proposed numerical simulation (Soulis[7]) was performed by comparing the results obtained from the 1/3 scaled specimens tested by either Stylianides [11] or Thauampteh [12] and the numerical predictions. The weak type masonry that have been employed as masonry infills were dominated by the compression-shear (frictional) non-linear mechanism. In the same section the effectiveness of a micro-model technique for the numerical simulation of a masonry infill inside R/C frame specimens when different types of openings is investigated. Penava, Sigmund, Kozar [13], reviewed non-linear FEM modeling techniques for numerical simulation of framed-masonry structures under cyclic loading. The response of the diagonal strut model for masonry infill was also examined when incorporated into the simulations of Penava et al. [13] masonry infilled frames. Numerical results are validated utilizing experimental results of framed masonry specimens with or without openings. Penava et.al [14] tested 10 framed-masonry specimens of 1:2.5 scale. Penava et.al [13] proposed a micromodel and calibrated the assigned numerical parameters in order to obtain the best correlation between experimental and numerical results. The concrete section was simulated as plane stress elements. The reinforced concrete frame (Columns and lintel) were modelled adopting the fracture-plastic constitutive law, known as the Non-Lin-Cementitious plasticity model. The longitudinal and transversal steel reinforcements of the reinforced concrete frame were modeled utilizing truss elements. In their model the masonry units and the mortar-masonry interface were modeled as separate finite elements. The smeared crack method has been adopted for the crack modeling of the masonry units. The interface material model was used to simulate the contact between the masonry units, as well as between the masonry units and the frame (the mortar in the physical model). The model is based on the Mohr–Coulomb criterion with tension cut-off and requires the determination of the initial elastic normal and shear stiffness. Penava et al [13] showed that the best correlation between the numerical and experimental results was achieved when they combined measured material properties, with the addition of a cohesion hardening-softening function for bed joints to take into account the mortar interlocking within the unit’s hollows.

A numerical micro-model was also proposed by Lourenco and Rots [15] for masonry wall piers under combination of horizontal and vertical loads. In their simulation the masonry units were expanded by the masonry mortar thickness leaving all the non-linear behavior concentrated in the interface between units. In the current investigation the micromodel proposed for the masonry infill by Soulis[7] was utilized and validated against the experimental and numerical results of the frame masonry specimens tested by Penava et al [13]. The measured material properties as obtained by normative tests by Penava et.al [13] were used as input parameters for the numerical simulation proposed by the author in the current study. In section VI the differences and similarities between the micromodels proposed by Penava et.al [13] and that adopted by Soulis [7] were also discussed.

II. DESCRIPTION OF SINGLE-STOREY SINGLE-BAY MASONRY-INFILLED R/C FRAMES

In the Laboratory of Strength of Materials and Structures of the University of Thessaloniki a series of reinforced concrete infilled frames were subjected to cyclic horizontal loading during the experimental investigation that took place (Thauampteh [12]). Detailed description of the experimental specimens tested and of the consequent results adopted of the full study is included in the work of Stylianides [11] and Thauampteh [12]. Due to space limitations, the validation of the proposed numerical simulations presented here is limited to one specimen (F1N) tested by Stylianides [11], and two specimens F3N(R1f,0w)*s and (F3N(R1f,R1w)ws) tested by Thauampteh [12]. An outline of the design details and the technical description of specimen F1N, F3N(R1f,0w)*s and F3N(R1f,R1w)ws can be depicted in Fig. 1 and 2 and Table I, respectively. An outline of the technical description of specimen F1N, F3N(R1f,0w)*s and F3N(R1f,R1w)ws are reported in Table I. The cyclic loading was applied gradually through an imposed cyclic horizontal displacement sequence. The influence exerted by the interface between the masonry infill and the R/C frame was examined extensively in the studies of Thauampteh [12] and by Soulis [7]. The R/C frame and the masonry infill interaction involve an important mechanism on the resulting state of stress of the masonry infill and contribute to the development of the various masonry failure modes. Tables II, III and IV list the mechanical properties of the materials used in the construction of the first and second groups of specimens. The experimental behavior of ten masonry infilled R/C frames [14] under cyclic horizontal load was employed by Penava et. al [13] to calibrate their numerical model. Three of these masonry infilled frames, namely GI2, GI1, GI2, were also utilized by the author in the current

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study initially to validate the proposed numerical simulation of masonry infilled frames applying the micro-modeling strategy for the masonry infill and secondly to compare the monotonic numerical behaviour of the masonry infilled frame simulated by the micro-model proposed by Penava et al [13] with that micro-model proposed by Soulis [7].

A summary of the selected masonry infilled R/C specimens that have been adopted for the scope of the numerical validations are listed in Table I and Fig. 3, 4. The mechanical properties of the steel reinforcement, masonry infills, masonry units and mortar joints are shown in tables II to VII. Normative tests have been realized by Penava et al [13] in a similar effort as Manos et al [2] did to obtain the material properties. This investigation was significantly useful for the approximation of the mechanical properties assumed in the numerical part of both research efforts.

| Frame Code name | Length over Height ratio | Vertical load on Columns | Technical description of masonry infill | Masonry Infill thickness (mm) | Technical description of the interface between frame and infill |
|-----------------|--------------------------|--------------------------|----------------------------------------|-------------------------------|---------------------------------------------------------------|
| 1st group of specimens (Fig. 1) Stylianides [11] |
| FIN | 1.5 | 80 KN | mortar S | 63 | mortar S thickness 10mm |
| 2nd group of specimens (Fig. 2) Thauampteh [12] |
| F3N(R1H,0 w)*s(Repai red) | 1.7 | 50 KN | Infill with mortar V1, | 58.5 | mortar H thickness 15mm (without plaster) |
| F3N(R1f,R 1w/js (Repaired) | 1.7 | 50 KN | Infill with mortar V1, reinforced plaster, and transverse reinforce ment type II | 78.5 | mortar H thickness 15mm. Reinforced plaster is not in contact with frame |
| 3rd group of specimens (Fig. 3, 4) Penava [13] |
| GI1 | 1.5 | 365 KN | Infill with central door and mortar M5 | 120 | mortar M5 thickness 10mm |
| GI2 | 1.5 | 365 KN | Infill with central window and mortar M5 | 120 | mortar M5 thickness 10mm |

Fig. 1. Masonry infilled R/C frame 1st specimen and design details, Stylianides [11].

Fig. 2. Masonry infilled R/C frame 2nd specimen and design details, Thauampteh [12].

Fig. 3. Bare R/C frame 3rd group of specimens and design details [13].

Fig. 4. Masonry infilled R/C frames 3rd group of specimens Penava et al [13].

**TABLE I: OUTLINE OF ALL SPECIMENS**

- Door: $l_d/A_o = 0.35/0.90$ m
- $A_o = 0.32$ m$^2$
- $A_i/A_o = 0.14$
- Window: $l_i/h_i = 50.0/60.0$ cm
- $A_o = 0.30$ m$^2$
- $A_i/A_o = 0.13$
TABLE II: MECHANICAL PROPERTIES OF MASONRY INFILLS AND CONCRETE

| Masonry infill | Compressive strength of masonry (N/mm²) | Shear strength of masonry under diagonal compression (N/mm²) | Compressive strength of mortar cylinders (N/mm²) |
|----------------|----------------------------------------|-------------------------------------------------|----------------------------------|
| F1N specimen Virgin infill Stylianides [11] | 2.94 | 0.32 | 5.96 |
| Infill mortar | 3.75 | 0.18 | 6.50 |
| F3N(R1f,0w)s* specimen reinforced infill Thauampthe [12] | | | |
| Reinforced with reinforce d plaster GI1, GI2, GH2 specimens Virgin infill Penava et al. [13] | | | |
| | 120 | 17.2 | 2.80 |

TABLE III: MECHANICAL PROPERTIES OF THE REINFORCEMENT

| A/α | Yield stress fy (N/mm²) | Ultimate strength fsu (N/mm²) | Strain at yield esy (%) | Strain at ultimate stress εu (%) | Young Modulus E (N/mm²) |
|-----|-------------------------|-------------------------------|------------------------|-------------------------------|----------------------|
| Φ 5.5 (1st group) | 311 | 425 | 0.8 | 22.0 | 6.5X10⁶ |
| Φ 5.5 (1st group) | 360 | 542 | 0.6 | 20.0 | 6.5X10⁶ |
| Φ 8 (2nd group) | 340.0 | 467.1 | 0.170 | 20.5 | 2.0X10⁸ |
| Φ 6 (2nd group) | 348.0 | 457.0 | 0.174 | 18.0 | 2.0X10⁸ |
| Φ 2.7 (2nd group) | 271.0 | 395.0 | 0.135 | 19.0 | 2.0X10⁷ |
| Φ10 | 550 | 650 | 1.0 | 2.1X10⁷ |
| #stirrups | 550 | 650 | 1.0 | 2.1X10⁷ |

TABLE IV: MECHANICAL PROPERTIES OF THE INTERFACE USED TO SIMULATE THE MORTAR JOINT BETWEEN INFILL AND SURROUNDING FRAME (S, H, M5)

| Simulation of joint interface between frame and infill | You ng Modulus f fy (N/mm²) | Shear Modulus f fsu (N/mm²) | Measured Compressive Strength f f (N/mm²) | Assumed Bond Strength f f of mortar (N/mm²) | Friction coefficient β |
|--------------------------------------------------------|-----------------------------|----------------------------|----------------------------------|----------------------------------------|----------------------|
| S mortar | 430 | 180 | 2.6 | 0.26 | 0.26 |
| H mortar | 60 | 26 | 0.60 | 0.06 | 0.08 |
| M5 mortar | 5650 | 2570 | 2.70 | 0.2 | 0.35 |

TABLE V: MECHANICAL PROPERTIES OF THE MORTAR UNITS USED BY PENAVA ET AL. [13]

| Initial masonry units properties adopted by Penava, Sigmund, Kozar [13] | Young Modulus of masonry parallel to bed joints (N/mm²) | Young Modulus of masonry parallel to head joints (N/mm²) | Tensile strength of masonry units parallel to head joints (N/mm²) | Compressive strength of masonry units parallel to head joints (N/mm²) | Strain at ultimate compressive strength (μ) | Compressive strain at ultimate compressive strength (μ) |
|------------------------------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Infill GI1, GI2, GH2 | 5650 | 850 | 1.8 | 17.5 | 1.35 | 8.10 |

TABLE VI: MECHANICAL PROPERTIES OF THE MORTAR BED JOINTS USED BY PENAVA ET AL. [13]

| Properties of bed joint adopted by Penava Sigmund, Kozar [11] | Young Modulus f M (N/mm²) | Shear Modulus f F (N/mm²) | Tensile Strength f T (N/mm²) | Local bond shear strength f L (N/mm²) | Friction coefficient β |
|--------------------------------------------------------------|---------------------------|---------------------------|-------------------------------|------------------------------------|----------------------|
| M5 mortar | 5650 | 2570 | 2.70 | 0.2 | 0.35 |

TABLE VII: MECHANICAL PROPERTIES OF THE MORTAR HEAD JOINTS USED BY PENAVA SIGMUND, KOZAR [13]

| Simulation of head joint for masonry infilled R/C frames GI1, GI2, GH2 | Young Modulus f M (N/mm²) | Shear Modulus f F (N/mm²) | Tensile Strength f T (N/mm²) | Local bond shear strength f L (N/mm²) | Friction coefficient β |
|------------------------------------------------------------------------|---------------------------|---------------------------|-------------------------------|------------------------------------|----------------------|
| M5 mortar | 850 | 386 | 2.70 | 0.2 | 1.05 |

*Cohesion hardening – softening function

III. THE NUMERICAL SIMULATION OF THE BEHAVIOR OF SINGLE-STOREY, SINGLE-BAY MASONRY-INFILLED R/C FRAMES

An extensive study of various numerical simulations of the behaviour observed for masonry infilled R/C one-bay one-storey frame specimens tested by Stylianides [11], and by Thauampthe [12] was included in the thesis of Soulis[7] together with an extensive validation process, utilizing the results of all these experimental studies ([11], [12]). Three different modeling strategies are applied for the numerical simulation of the masonry infills. In macro-modelling strategy the masonry infills are simulated as plane stress elements with homogenized, single material properties (Fig. 5a). In micro-modelling strategy the constituents of the masonry infill are simulated separately (mortar bed mortar head joints, and mortar units, Fig. 5b), and different mechanical properties are assigned in each of these numerical representations. The macro-modelling strategy was adopted for the simulation of the masonry infills of masonry infilled frame specimens F1N, F3N(R1f,0w)s*, F3N(R1f,R1w)s (Fig. 5a). The micro-modelling strategy was adopted for the simulation of the masonry infills of masonry infilled frame specimens F1N, F3N(R1f,0w)s*, GI1, GI2, GH2 (Fig. 5b).

![Fig. 5 a) Masonry infill simulation with macro-modelling technique](image-url)
masonry infill as indicated by Fig. 7a, 7b) and Table VIII, are based on experimental measurements of masonry walls that have been subjected to diagonal compression tests together with the corresponding properties used for the successful numerical simulation of these wall specimens (Soulis [7]).

| Table VIII: Mechanical Properties of Infills Adopted in the Numerical Simulations |
|---------------------------------|---------------|----------------|-----------------|------------------|
| Frame Code Name | Young Modulus (N/mm²) | Poisson’s Ratio | Compressive Strength of Masonry (N/mm²) | Tensile Strength of Masonry (N/mm²) | Softening Modulus (N/mm²) |
| FIN | 2000 | 0.18 | 3.0 | 0.5 | -20 |
| F3N/R1H, 0w/j/s | 1000 | 0.2 | 1.2 | 0.2 | -10 |
| F3N/R1H, R1w/j/s | 3500 | 0.2 | 4.5 * | 0.8 | -5 |

B. Simulation of the Masonry Infill (Micro-model)

In the case of micro-model, the simulation of the masonry units and the mortar joint was done separately (Fig. 5b). The material properties for the masonry units and mortar were obtained by normative material tests conducted at the Laboratory of Material’s Strength d Structures in the Aristotle University of Thessaloniki. The masonry units were simulated with elastic plane stress elements assuming that they were expanded to the mortar thickness, leaving an interface for the simulation of the mortar of the physical model. Two sets of 2-D non-linear joint elements simulate the separation and slip of the bed joint interface. The first set of these 2-D joint elements is assigned in the direction transverse to the interface; it is of a frictional type, where the value of friction coefficient is introduced (Table IV). The second set of non-linear joint elements is assigned in both the transverse and the normal to the interface directions. The axial and transverse stiffness of the joint interface was calculated adopting the following expressions:

\[ K_n = \frac{E \times t \times b}{l} \]

(1)

\[ K_s = \frac{G \times t \times b}{l} \]

(2)
where E, G are the modulus of elasticity and the shear modulus of the mortar joint, t, b are the depth and influence length of the mortar joint respectively and I is the height of the mortar joint.

The tensile strength, the shear strength, the compressive strength of the joint interface was calculated adopting the material properties shown in Tables IV, VI, VII. The same simulation was adopted for the simulation of the head joint interface between masonry units.

The possible fracture of masonry units was also simulated introducing an interface in the middle of each masonry unit with the stiffness and strength values adopted from the experimental tests on masonry units.

C. Simulation of the beam/column R/C elements and the plastic hinge formation

In the numerical model of the R/C frame the beam member and the two columns members are simulated as thick beam elements. The locations of possible plastic hinge formations at the ends of each element (Fig. 6a, b, c) were also introduced in the model. They were able to deform and rotate in plane. A number of non-linear 2-D joint elements were employed at the ends of each column (Fig. 6, a,b,c) to render this plastic hinge formation. Rigid beam elements were also employed to simulate the corner connection between the beam and the column (Fig. 6, a,b,c) and the rigid connection between the columns' and beam's axis with the joint element representing the interface between the masonry infill and the surrounding R/C frame. More details for the simulation of the R/C frame are provided in the research efforts of Manos, Soulis, Thauamptieh [6] and Soulis [7]. The formation of beam plastic hinges is achieved by a number of flexural 2-D non-linear joint elements simulating the flexural moment against the elastic/plastic rotation at the ends of the beam. Not only the flexural behavior 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 also represented in Fig. 6a, b, c 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.

D. Simulation of interface between the R/C frame and the masonry infill

Two sets of non-linear 2-D joint elements are used to simulate the separation and friction between frame and infill as well as the compression and shear for the three different types of interface. The first set of these 2-D joint elements (Fig. 6a, b, c) is of frictional type. The value of friction coefficient that is introduced (Table IV) was shown to yield reasonably good behavior during the numerical simulations of the diagonal compression tests (Soulis [7]). The second set of non-linear joint elements (Fig. 6a, b, c) is active in both the normal and the transverse to the interface directions. In the normal to the interface direction these joint elements have elastic and post-elastic force/displacement properties based on measured compressive strength values listed in Table IV (resulting from the corresponding interface area) together with an assumed post-elastic softening behavior. Similarly, the elastic and post-elastic force/displacement properties of these joint elements in the transverse direction are based on assumed bond shear strength with a softening nature. The numerical model was analytically described in the works of Manos, Soulis, Thauamptieh [6] and Soulis [7].

IV. SIMPLIFICATION OF THE NUMERICAL SIMULATION OF THE MASONRY INFILL FRAME RESPONSE USING DIAGONAL STRUT ELEMENTS

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 masonry infill 2-D representation, as outlined in Fig. 6a, 6b and sections IIIA, III.B, will be replaced by the well known equivalent diagonal strut model (Fig. 6c). All the aspects of the reinforced concrete frame representation, described in section III.C, will be retained. The contact interface of the masonry infill with the surrounding R/C frame will not be represented, as was described in Fig. 6a, 6b.

2. The equivalent diagonal strut will be a multi-linear model, active in compression only. Its behavior is 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 approaches the total force – displacement response of the numerical simulation of the same problem whereby the contact interface and the masonry infill were simulated separately (Fig. 6a, 6b respectively).

3. The non-linear mechanisms and the R/C frame properties remain the same in the equivalent diagonal strut model. All the non-linear response that arises at either the interface or at the masonry infill, which were addressed separately in sections III B,D are approximated utilizing a multi-linear equivalent diagonal strut model. It is obvious that with the proposed simplified numerical treatment 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 is lost. 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 sections III.

The purpose of this simplification is to numerically simulate the response of such single storey masonry infilled R/C frames, where different construction characteristics are employed such as openings in the infills, reinforcement in the infills. In order to verify the degree of approximation of this simplified approach it will be applied in three distinct cases, namely specimen F1N (Fig. 1), specimens F3N(R1f,R1w)s*, F3N(R1f,R1w)s (Fig. 2). The results from the simplified approach utilizing a tri-linear diagonal strut model will be compared to the corresponding numerical results of the more detailed numerical simulations (macro-modeling technique, and micro-modeling technique) presented in section III as well as with the corresponding experimental results.

Fig. 8a, 8b and 8c depict the comparison of the predicted behavior, in terms of force – displacement, envelope curves.
resulting from a “pushover” type of loading, whereby the infill was simulated with the macro-modeling technique, the micro-modeling technique and a tri-linear equivalent strut with the corresponding experimental behavior of the infill R/C frame. This is done for specimen F1N in Fig. 8a and for specimens F3N(R1f,0w) s*, and F3N (R1f, R1w) s in Fig. 8b, 8c respectively. The envelope curve predicted with the tri-linear diagonal strut compares quite well to both the experimental envelope curve as well as to the two numerical modeling techniques that have been employed. Relatively small number of trials has been realized for the properties of the diagonal struts. In Fig. 9a the failure of the masonry infill observed experimentally is shown, while in Fig. 9b (black *), and 9c (red *) the failure patterns of the numerically predicted behavior of numerical simulations adopting the macro-modeling and micro-modeling technique for the masonry infill are also shown for shear strain levels of 8%.

V. VALIDATION OF THE PROPOSED NUMERICAL SIMULATION FOR THE MASONRY INFILLED R/C FRAME

The numerical results obtained either by the tri-linear diagonal strut simulation for the masonry infill or by the two non-linear modeling techniques (micro-modeling and macro-modeling) are compared in Fig. 10a 10b and 10c for specimens F1N, F3N(R1f,0w) s and F3N(R1f,R1w) s, respectively. The micro-modeling technique wasn’t applied in the case of F3N(R1f, R1w) s as in this experimental specimen reinforced masonry infill has been utilized with homogenized properties. The experimental behavior in terms of load-displacement (P-δ) curves, recorded during testing, are also plotted these figures. 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 adopting the two non-linear modeling techniques (sections III.A to III.B). The degree of approximation of the masonry infill – contact interface – R/C frame interaction by the 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 sections III.

The duration of the cyclic macro-modeling numerical simulation is 30minutes with 424Mbytes memory requirements. The duration of the corresponding cyclic micro-modeling numerical simulation is 58minutes with memory requirements of the order of 1,274Mbytes, whereas the simulation of the cyclic response with the equivalent diagonal strut lasts 20minutes with 221Mbytes memory requirements. The “pushover” analysis for the definition of the multi-linear properties of the equivalent diagonal strut lasts less than 50seconds with relatively low memory requirements. These computer time and computer memory demands were recorded with a computer with the following specifications: AMD Athlon (tm) 64x2 dual, core processor 4200+2.20GHz, 896 MB Ram. Thus, considerable advantages in terms of computer time as well as computer memory requirements results from adopting the multi-linear diagonal strut approximation together with a “pushover” type of analysis.
The comparison and the validation of the monotonic behavior of the proposed simulations were also performed for three masonry frames tested by Penava et.al [13]. In this case the corresponding envelope curves resulting from the relevant experiments on masonry infilled frame specimens GII, GI1 and GI2 are adopted. In Fig. 11a, 11b, 11c this comparison can be depicted for the three, different masonry infilled R/C frames. In the case of masonry infilled frame with a central window opening GI2, both numerical simulations underestimate the level of horizontal load that is obtained experimentally.

The damage patterns as observed experimentally are compared with the damage patterns predicted by the numerical simulations proposed by the author in the current study and by Penava et.al [13]. In Fig. 12a), the damage pattern for masonry infill frame GII2 is shown that is agreement with the failure patterns observed numerically by the simulations presented here and Penava et.al [13] (Fig. 12b, 12c). The main characteristic is the diagonal failure of masonry infills and masonry piers. However, both numerical simulations show a wider distribution of failures that is not confirmed in that extent experimentally especially in the model proposed by Soulis. Good agreement in the damage patterns is also confirmed between the experimental and numerical investigation for the masonry infilled frame with a door opening GI1, and a window opening GI2 as shown in Fig. 13a, b, c and 14 a, b, c respectively.
VI. DIFFERENCES AND SIMILARITIES OF THE MICRO-MODELING STRATEGIES

The main differences and similarities in the modeling strategies as adopted by the two research groups (Soulis and Penava et al [13]) can be depicted as follows for different structural members:

A. Reinforced concrete frame

The modeling strategy adopted in this article in consistency with that proposed by Soulis [7] utilizes linear elements for the simulation of the surrounding frame. The total nonlinear behavior of the surrounding frame is concentrated on predefined positions where plastic hinge formation is allowed. A series of non-linear joint elements are mobilized to model the possible plastic hinge formation as proposed by Soulis [7]. There is no separate numerical simulation of the concrete section and longitudinal and transverse reinforcement. On the other hand Penava et al [13] utilizes plane elements to represent concrete members. The non-linear behavior of concrete was simulated adopting the fracture-plastic constitutive law that was assumed that was spread throughout the surrounding frame.

Truss elements are used to model the longitudinal and transversal reinforcements in the numerical simulation of Penava et al [13]. Additionally Penava et al [13] assumed that the transverse reinforcement bar closest to the joint had to be moved further away from the joint edge, while its area was increased by about 100 times in order to prevent unrealistic tension softening. The numerical simulation adopted by Soulis and Manos doesn't simulate separately longitudinal and transverse reinforcement but the total flexural behavior of the joint adopting the construction details and material properties of R/C cross section.

B. Masonry infill

a) Both modeling strategies for the masonry infill utilized the micro-modeling technique. Masonry units and the mortar-masonry interface were considered separately. The mortar between masonry units was not modeled either in the numerical simulation of Penava et al [13] or the numerical simulation proposed here. The masonry units are modeled as elastic plane stress elements with a non-linear joint interface in their center in an effort to describe their quasi-brittle behavior. This was done manually by introducing series of joint elements in the center of a masonry unit element. Penava et al [13] incorporated the SBeta material model that introduces automatically a rotated crack inside the simulation of plane masonry unit.

b) The contact between the masonry units, as well as between the masonry units and the surrounding frame was described by non-linear joint elements in the research effort of Soulis and by non-linear interface elements in the effort of Penava et. al [13]. These elements combine the Mohr-Coulomb failure criterion with a tension cut-off in both strategies. The bed and head joints were modeled adopting the mechanical properties defined by Penava et.al [13]. Normal and tangential stiffness of the bed joints in Soulis model [7] were calculated using the modulus of elasticity, the shear modulus and the poison ratio as measured by Penava et.al [13]. The mortal interlocking in the hollow clay masonry units was simulated in both numerical simulations applying the cohesion-hardening-softening function as proposed by Penava et.al [13].

c) The micro-modeling technique cannot be used for reinforced masonry infills or with infills with homogenized mechanical properties(R/C panels). In this case as the one described in the numerical simulation of F3N[R1f,R1W]s the macro-modeling modeling technique is used.

C. Joint interface between the masonry infill and the surrounding frame

Non-linear joint elements were used for the simulation of the interface between the masonry units and the surrounding frame in the investigation carried out by Soulis. The same mechanical properties that were used for the simulation of bed and head joints were also used for the simulation of the interface between masonry units and the surrounding frame. This selection was mutual for both models that were proposed by the two researchers (Soulis, and Penava et.al [13]). The non-linear behavior of joint elements in the interface between the masonry infill and the surrounding frame were based on the Mohr-Coulomb criterion with tension cut off.

VII. CONCLUSIONS

The strength, load-displacement hysteretic behavior and failure patterns observed during the experiments of Styliamides [11], Thlaampteh [12] for the single-story, one-bay, masonry-infilled R/C frames examined in this study are successfully predicted by the proposed numerical simulation that utilize different modeling techniques for the simulation of the masonry infill (micro-modeling technique , macro-modeling technique, diagonal strut model).

The employed numerical simulation of masonry-infilled R/C frames predicts successfully the experimental behavior due to the presence of the partially reinforced masonry infill (reinforced plaster).

The influences arising from the modeling of interface between the masonry infill and the surrounding R/C frame was incorporated in the performed numerical analyses. The importance of this modeling strategy in obtaining realistic predictions in terms of the load-displacement behaviors and failure modes for masonry infilled R/C frames under horizontal actions was addressed. Thus, the numerical simulations adopted represent reasonably the most important influences that arise from the interface between masonry infill and surrounding frame in terms of stiffness, strength,
and modes of failure, of such masonry infilled frames as it is demonstrated from the comparison with the experimental behavior.

The monotonic load-displacement behavior produced experimentally by Penava et al. [14] on single-storey one-bay masonry-infilled R/C frames including openings in their infills, are satisfactorily predicted by the numerical simulations proposed in the current study. However, there is a discrepancy in the case of masonry infilled R/C frame with central window opening (G12), where the horizontal bearing strength measured numerically is underestimated by the numerical simulation proposed.

The damage patterns predicted numerically are in agreement with the damage patterns observed experimentally by Penava et al. [14]. However, there is an overestimation of the shear failure predicted numerically in the bed joints in the model proposed here. In the current study a micro-modeling approach was applied for the simulation of the masonry infills including openings. The differences and similarities with the micro-modeling technique adopted by Penava et al. [13] are commented and discussed. Both micro-modeling simulations predict comparable results in terms of the horizontal load-displacement curves and the predicted damage patterns.

The proposed diagonal strut model can successively simulate the hysteretic and monotonic behavior observed experimentally for the three groups of specimens tested. It was also shown that it can be a valuable tool because it can incorporate the influence of the openings, the influence of the joint between masonry infill and surrounding frame and the different masonry infill characteristics in a macroscopic way. Considerable advantages in terms of computer time as well as computer memory requirements results were recorded adopting the multi-linear diagonal strut model. Thus, this model can be employed in the numerical simulation of masonry infills in multi-storey structural formations.

REFERENCES

[1] Mohyeddin-Kermani Alirez  , Goldsworthy Helen M,Gad Emad (2015), "A Review of the Seismic Behavior of RC Frames with Masonry Infill", Research Gate publication, 2015.

[2] Chrysostomou, C. Z., Gergely, P., Abel, J. F. (2002). “A six-strut model for nonlinear dynamic analysis of steel infilled frames.” Int. J. Struct. Stab. Dyn., 2(3), 335–353.

[3] Ghosh K. and Amde, A.M, (2002), “Finite Element Analysis of Infilled Frame”, ASCE, Journal of Structural Engineering, Vol. 128, No 7, July 2002, pp. 881-889.

[4] Riddington, J.R (1984), “The Influence of Initial Gaps on Infilled Frame Behavior”, Proceedings of Inst. Civ. Eng, Part 2, Vol. 77, Sep. 1984, pp. 295-310.

[5] Pook L.L. and Davie J.L.,(1986), “Effects of Interface Conditions Between a Masonry Shear Panel and Surrounding Steel Frame”, in Proceedings of 4th Canadian Masonry Symposium, University of New Brunswick Press, Fredericton, N.B., Canada,1986, pp. 910-921.

[6] Manos, G.C, Soulis V.J. and Thaumampth, J. (2001), “The Behavior of Masonry Assemblies and Masonry-infilled R/C Frames Subjected to Combined Vertical and Cyclic Horizontal Seismic-type Loading”, Journal of Advances in Engineering (Software, Vol. 45, pp. 213-231.

[7] Soulis V.J. (2009), “Investigation of the Numerical Simulation of Masonry Infilled R/C Frame Structures under Seismic-type Loading”, Ph.D. Thesis, Department of Civil Engineering, Aristotle University of Thessaloniki.

[8] Asteris PG. Cotsovos DM, Cryso Romero cz et al. “Mathematical micromodeling of infilled frames: state of the art. Eng Struct 56:1905-1921

[9] Koutromanos I., Stavridis A., Benson Shg P., Willam K., (2011),“Numerical modeling of masonry-infilled RC frames subjected to seismic loads”, Computers and Structures 89 (2011) 1026–1037.

[10] Allozzi R., Irfanoglu A., Haikal G,(2014), "Non-linear finite element modeling of RC frame-masonry wall interaction under cyclic loadings", Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering, July 21-25, 2014, Anchorage, Alaska.

[11] Styliandides K. (1985), “Experimental Investigation of the Behavior of Single-story Masonry R/C Frames using 3D Finite Element Model,” Journal of Structural Engineering, Vol. 111, No. 1, pp. 130-140.

[12] Thaumampth. J.(2009), “Experimental Investigation of the Behavior of Single-story R/C Frames with Masonry Infills, Virgin and Repaired, under Cyclic Horizontal Loading”, Ph.D. Thesis, Department of Civil Engineering, Aristotle University of Thessaloniki.

[13] Penava D. Sigmund V., Kojar. I., “Validation of a simplified micromodel for analysis of infilled RC frames exposed to cyclic lateral loads”, Bull Earthquake Eng (2016) 14:2779–2804 DOI 10.1007/s10518-015-9700-7.

[14] Penava D, “Influence of openings on seismic response of masonry infilled reinforced concrete frames”, Josip Juraj Strossmayer University of Osijek, Osijek.

[15] Lourenco P. Rots J.G, “On the use of micro-models for the analysis of masonry shear-walls” eds Pande G.N, Middleton J, Computer Methods in Structural Masonry-2, Swansea, UK, 1993, pp. 14-25.

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