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Evaluation of Diagonal Strut Models for Different Masonry Infill Conditions inside R/C Frames

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Abstract-The influence of the masonry infills inside R/C frame structures under seismic type loadings is a subject that many modern seismic codes and provisions are newly focusing. Various researchers have proposed analytical expressions that accompanied the evolution of seismic codes in an effort to determine both the initial stiffness of the infill panels and their bearing capacity. However, in most of these provisions the influence of the joint interface between the masonry infill and the surrounding frame is ignored. In this study the ability of various proposed methodologies to predict the influence of the masonry infills is examined. Numerical simulations of the masonry infilled R/C frames are proposed that are evaluated against experimental results of a number of 1: 3 scaled masonry infilled R/C frame specimens tested at the Laboratory of Strength of Materials and Structures (LSMS) of Aristotle University under seismic-type loading. In these cases the predicted numerical behaviour of the masonry infilled R/C frames includes various significant non-linear mechanisms that develop in this complex problem, as the influence of the joint interface in the perimeter of the masonry infill and the influence of the masonry infill itself. An additional numerical technique is also 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. This diagonal strut simplification is a usual technique employed by many researchers and many methodologies. 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, Modeling*

I. INTRODUCTION

Masonry infilled reinforced concrete frame is a construction technique that is encountered in countries with relatively high seismic vulnerability. The seismic vulnerability of these structures has been demonstrated by the damages suffered after significant seismic events. Therefore, the necessity to deal with the impact of strong earthquake on masonry infilled R/C frames by particular seismic design provisions has been recognized. This is done in the relatively new updates of the seismic design provisions as the ones included in EC8 [1], American FEMA-306[2] and the newest Greek Regulation for Interventions (GRI [3]).

Several techniques have been proposed to take into account the influence of masonry infills on the overall behavior of masonry infilled R/C frame structures when these are subjected to horizontal seismic loads. These techniques can be grouped into two main categories; macro-modelling technique and micro-modelling technique. In the macro-modelling technique the simulation of masonry infills is approximated based either on the equivalent diagonal strut model or on homogenized plane elements ignoring any separation between masonry units and the mortar joints. In the micro-modelling technique the behavior of the masonry infills is numerically simulated by treating separately the masonry units and the mortar joints by finite elements with different properties. This is done employing various numerical tools.

The main advantage of macro-modeling is the computational simplicity. The diagonal strut is the most popular simulation of the masonry infill stiffness contribution when the R/C frames are subjected to horizontal seismic loads. This simplification allows the numerical simulation of the behavior of masonry infills in multi-story structures. An important parameter is the assignment of appropriate mechanical properties in these numerical representations of masonry infills that is based on the actual properties of the materials and construction details that are present in the structure. Relevant experimental confirmation of the masonry infilled R/C frame behavior is regarded significant.

Holmes [4] demonstrated that the stiffness of the masonry infill panel can be simply approximated by an equivalent diagonal strut. This was done assuming a modulus of elasticity and a thickness equal to the modulus of elasticity and the thickness of the masonry infill and a width of strut equal to one third of the length of the diagonal of the masonry infilled panel.

Stafford Smith and Carter [5] later suggested that the width of the equivalent diagonal strut depends on the relationship between the stiffness of the surrounding frame and the masonry infill. This method calculates the equivalent active width “w” of masonry panel that interacts with the surrounding frame. Alternative suggestions were provided by Mainstone [6], Liaw and Kwan [7] and Buonopane and White [8]. In recent decades, it became clear that a single diagonal strut was not adequate to model the complex behavior of the masonry infilled frame. These simulations cannot accurately account for the stress conditions that develop inside the masonry infill panel, the interaction between the surrounding frame and the masonry infill. More complex models of equivalent diagonal struts were proposed by Crisafulli and Carr [9] based on two, three or multiple diagonal struts. The simulation of masonry infills with diagonal strut elements is mainly used to describe the stiffness of masonry infills mainly in elastic analyses. P.G Asteris [10] in order to overcome the problem of the ever-changing contact conditions between the masonry infill and the surrounding frame proposed a finite element technique for the modeling of infilled frames. The adopted method is an extension of the method of contact points following that a criterion for the separation of masonry panel from the surrounding frame, and a finite element to model the in-plane anisotropic behavior of masonry infill panel were implemented.

The approach of simulating masonry infill panels with macro-models incorporating plane finite elements was developed by Mallick and Severn [11] using the finite element method for the analysis of two-dimensional masonry infilled frames. Since then, various alternatives have been proposed adopting the finite element method. These include the proposals of Riddington and Stafford Smith [12], Liaw and Kwan [7], Dhanaskar and Page [13], Mehrabi, Shing [14] and Manos, Soulis, Thauampteh [15].

Micro-modeling is a complex method that demands accurate computational representation of both material and geometry of masonry infilled R/C frames, but it is too time-consuming and computationally demanding to be used in large and applied structural configurations. Thauampteh [16], through a series of experiments carried out in the Laboratory of Strength of Materials and Structures at the Aristotle University (LSMS), examined the influence of the boundary conditions between the infill and the surrounding R/C frame. It was shown that these boundary conditions are of significance both in terms of total stiffness as well as of the bearing capacity and modes of failure of the infill and of the surrounding R/C frame. Manos, Soulis, Thauampteh [15] and Soulis [17], [18] developed a numerical macro-model for the masonry infill. This numerical simulation also included the non-linear numerical representation of the interface between the masonry infill and the surrounding R/C frame in an explicit way. The realism of this methodology was validated by the measured behavior of single-story, single bay, masonry infilled R/C frames tested by Thauampteh [16]. Soulis [17] proposed a numerical simulation where the surrounding R/C frame was simulated by elastic thick beam elements. The possibility of the development of plastic hinges at the ends of either the R/C beams or the R/C columns was also included in this methodology. A number of non-linear 2-D joint elements were employed at the ends of each R/C column and R/C beam to numerically simulate the formation of possible plastic hinges. Plane stress elements were used for the simulation of the masonry infill; these plane stress elements were connected to the R/C frame by two series of 2-D joint elements that simulated the masonry infill to R/C frame interface (peripheral mortar joint). In section 2 analytical expressions are used, as proposed by different investigators for the determination of the diagonal strut width “w” and the stiffness for masonry infills. The measured behavior of the single-story masonry infilled R/C frames, tested by Thauampteh [16] is used for comparison. The diagonal strut width “w” and the subsequent stiffness properties of the diagonal strut as calculated by the different expressions (EC8 [1], American FEMA-306[2], Greek Structural Intervention Regulation-GRI [3], Stafford Smith and Carter [5], Mainstone [6], Liaw and Kwan [7] were compared against the measured recordings. This research demonstrates the deviation observed in some masonry infilled frames. It was shown that considerable differences are reported between the predicted and the observed stiffness properties particularly in the case whereby the influence of the perimeter mortar joint was ignored. A parametric numerical analysis was carried out in section 3, following the initial evaluation of the proposed macro-model to extend the initial findings of the research. Equations for the determination of the diagonal strut width “w” for masonry infilled R/C frames were derived assuming different masonry infill configurations and different joint elements between the masonry infill and the surrounding frame. These predictions are compared with the recordings extracted from the experimental procedure for the masonry infilled R/C frames tested by Thauampteh [16]. Finally, in section 4 a simplified numerical technique is proposed whereby the non-linear behavior of the masonry infill is simulated by the diagonal strut with non-linear properties. With this simplified numerical approximation one has the computational advantages of the equivalent diagonal strut methodology while retaining the realism of the behavioral features of the fully non-linear methodology. The proposed diagonal strut model can accommodate the fully non-linear behavior of the masonry infill including the crucial behavior of the joint interface between the masonry infill and the surrounding frame which can be implemented in multistory masonry infilled R/C structures.

II. DIAGONAL STRUT WIDTH EVALUATION THROUGH CODE PROVISIONS AND ANALYTICAL EXPRESSIONS

Estimates of the diagonal strut width “w” can be found using a series of expressions given by different investigators as well as code provisions mentioned before. The analytical expressions that are considered in the present investigation were derived from the texts of the European Seismic Regulation EC 8 [1], the American Earthquake Regulation FEMA-306[2], the Greek Regulation of Interventions [3] and the ones proposed by Stafford Smith and Carter [5], Mainstone [6], Liaw and Kwan [7]. For the purposes of the current study the analytical expressions proposed by the aforementioned researchers and regulations were applied on a series of single-bay, single-storey masonry infilled R/C frames (Figure 1) that were tested by Thauampteh [16] at the Laboratory of strength of materials and structures(LSMS) at the Aristotle University of Thessaloniki. All the frames that have been utilized in this study were of 1:3 scale (Figure 1, Table 1) with l/h ratio equal to 1.7. The cross-section of the columns was 110mmx110mm and that of the beam 100mmx155mm with a reinforcement ratio equal to 0.00785 (ρ=0.785%). The infill thickness was 58,5mm for the original masonry infill configuration and

78,5mm for the repaired and strengthened masonry infill configuration. An axial load equal to 50KN was applied at the top of each column. The analytical expressions for the estimation of diagonal strut width were applied and the horizontal load–horizontal displacement curves were recorded for the series of masonry infilled frames tested by Thuaumpteh [16]. The masonry infill stiffness resulting from the methodologies mentioned before is compared with the corresponding horizontal load-horizontal displacement experimental behavior as recorded by Thauampteh [16] for the initial "elastic" part of this behavior. The observed behavior of the "bare" R/C frames without the infills was numerically approximated with sufficient accuracy in the study of Soulis [17]. From this comparison conclusions are drawn related to the degree of agreement or deviation between the observed and the predicted infilled frame behavior. This is naturally attributed to the corresponding infill stiffness approximation that is achieved by the examined methodologies. As mentioned before, a fully non-linear macro-model is also described in section 3 together with a corresponding simplified macro-model in section 4. Both these approaches addressed successfully the weaknesses of the diagonal strut stiffness approximation predicted by the examined methodologies. The numerical simulations, presented in sections 2, 3 and 4 took into account the influence of the mortar joint at the interface between the masonry infill and the surrounding frame. This was done both at the initial elastic range and at the post-elastic range of the analysis.

Table 1, shows the masonry infill panels with their code names used in both experimental and numerical investigations. In the same table a brief description of the joint interface between the masonry infill and the surrounding frame is given. The first specimen employed a very flexible material (cork) in this interface. Mortars of compressive stress 1.125MPa (type V1) or 0.64MPa (type H) were used for this interface for the other two specimens. From unconfined compression tests the corresponding Young's modulus values were obtained: 150MPa (mortar type V1), 60MPa (mortar type H) and 5MPa (cork). The mortar types V1, H were used for the construction of the masonry infills. Masonry units of the typical Greek constructions practice were used.

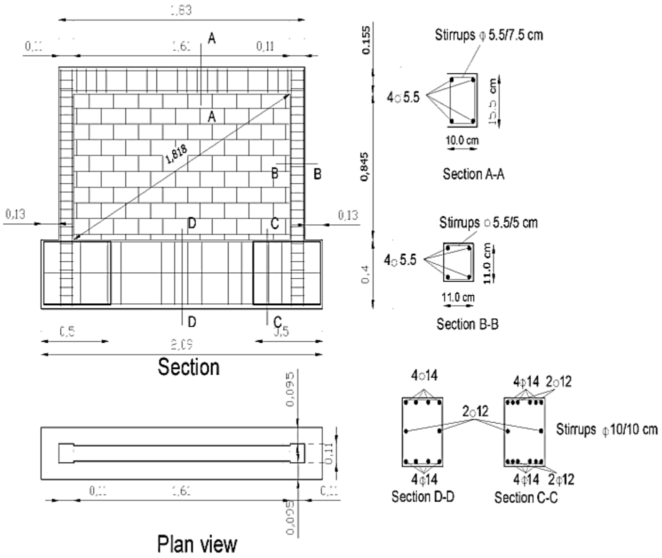

Figure 1. Masonry infilled R/C frame specimen and design details F2N

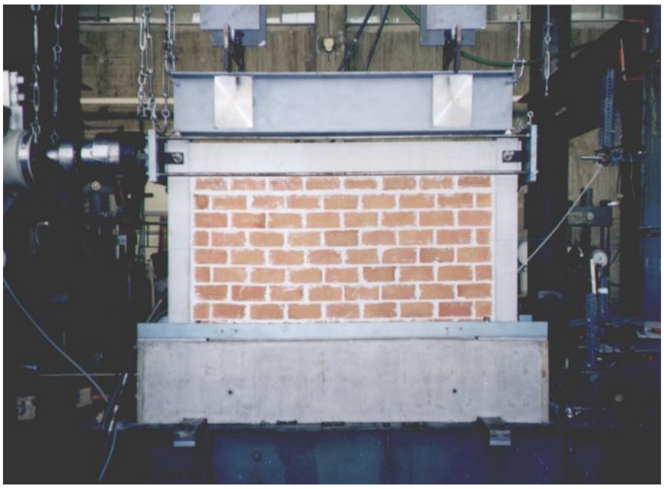

Figure 2. Experimental set up of masonry infilled frame F2N

TABLE I. DESCRIPTION OF THE SPECIMENS TESTED EXPERIMENTALLY BY THAUAMPTEH (2009)

No. Specimen	Code name of specimen	Technical description of the infilled frame	Axial load on each column (KN)	Technical description of the masonry infill	Description of the joint interface between the masonry infill and the surrounding frame
1	F1N(R2f,0w)s	Virgin Masonry+ Rep. R/C frame	50	Mortar type V1 for bed and head joints	Cork thickness 5mm
2	F2N	Virgin Masonry+ Vir. R/C frame	50	Mortar type V1 for bed and head joints	Mortar V1 thickness 10mm.
3	F3N(R1f,0w)*s	Virgin Masonry+ Rep. R/C frame	50	Mortar type V1 for bed and head joints	Mortar H thickness 15mm.
4	F2N(R1f,R1ww)s	Repaired and strengthened Masonry+ Rep. R/C frame	50	Masonry infill with mortar type H, strengthened with R/C plaster and transverse reinforcement type Π.	Mortar H thickness 10mm.

Two different macro-modeling numerical simulations are presented here aiming to predict the elastic behavior of the masonry infills of table 1. The first employed the equivalent diagonal strut approximation, where the width of the diagonal strut was approximated with the previously stated analytical expressions and code provisions (Figure 3), while the second employed a numerical macro-model simulation of the masonry infill. In this case the joint interface between the masonry infill and the surrounding frame was also numerically simulated (Soulis [17], [18], Figure 4). This later numerical simulation approximated the sliding or separation of the infill from the surrounding R/C frame when this was dictated by the level and nature of the stress field that developed at this interface. Figures 5, 6, 7, 8 show the comparisons between the corresponding numerical predictions of all the studied methodologies when applied to the specimens of table 1. For comparison purposes the corresponding observed behavior as recorded during the relevant tests of the masonry infilled R/C frames specimens F1N(R2f,0w)s, F2N, F3N(R1f,0w)*s, F2N(R1f,R1w)s was also included in these figures.

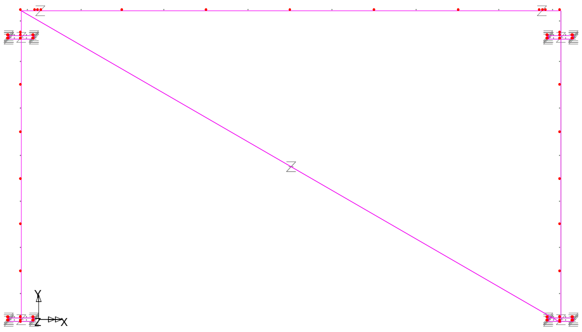

Figure 3. Equivalent diagonal strut model

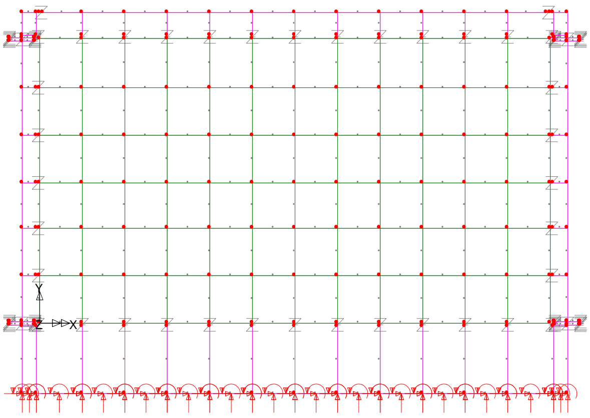

Figure 4. Analytical macro-model for the masonry infilled R/C frame

As already explained, the predicted-plotted behavior was obtained by calculating the width of the equivalent diagonal strut "w" each time from the corresponding analytical expressions proposed by the different researchers and code provisions. The resulting stiffness property was assigned to the diagonal strut. In this way the influence of the masonry infill (figure 3) was simulated. In addition, the mechanical properties of the masonry infill and the joint interface were derived from the constituent materials properties measured during the experimental investigation by Thauampteh[16].

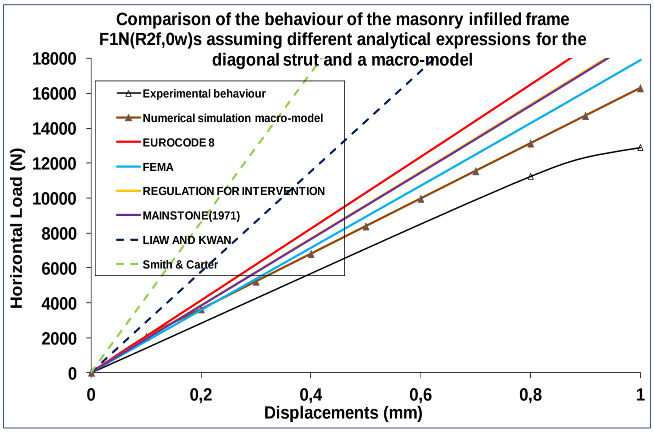

Figure 5. Comparison of elastic analysis of masonry infilled R/C frame F1N(R1f,0w)s assuming different expressions for the diagonal strut and a macro-model. *Mainstone curve coincides with Greek Regulation for Interventions(GRI) curve

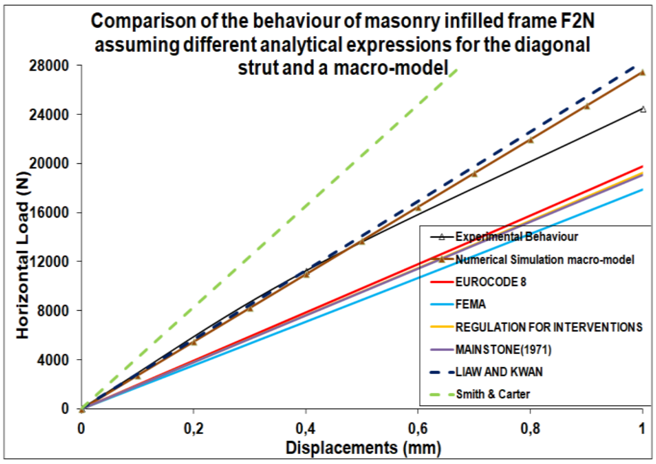

Figure 6. Comparison of elastic analysis of masonry infilled R/C frame F2N assuming different expressions for the diagonal strut and a macro-model. *Mainstone curve coincides with Greek Regulation for Interventions (GRI) curve

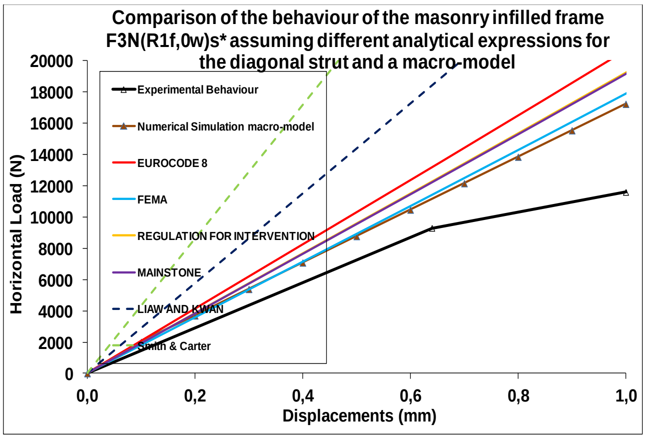

Figure 7. Comparison of elastic analysis of masonry infilled R/C frame F3N(R1f,0w)s* assuming different expressions for the diagonal strut and a macro-model. *Mainstone curve coincides with Greek Regulation for Interventions (GRI)curve

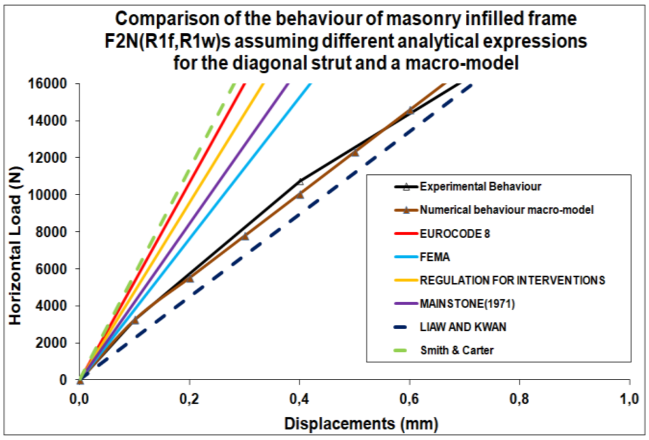

Figure 8. Comparison of elastic analysis of masonry infilled R/C frame F2N(R1f,R1w)s assuming different expressions for the diagonal strut and a macro-model

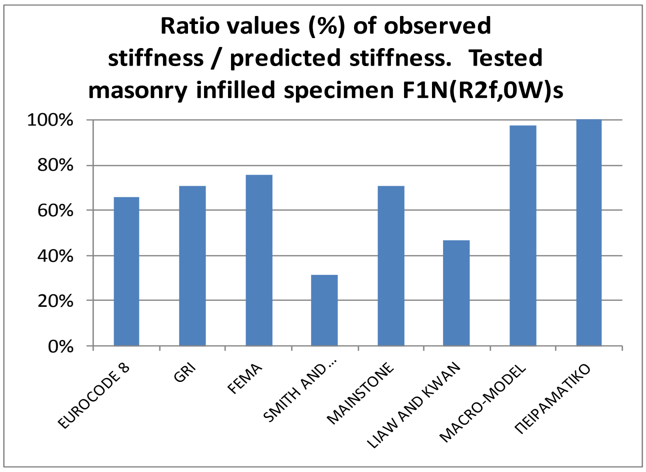

Figure 9. Evaluation of the behaviour of masonry infilled R/C frame F1N(R1f,0w)s assuming analytical expressions for the diagonal strut and a macro-model. Greek Regulation for Interventions = GRI

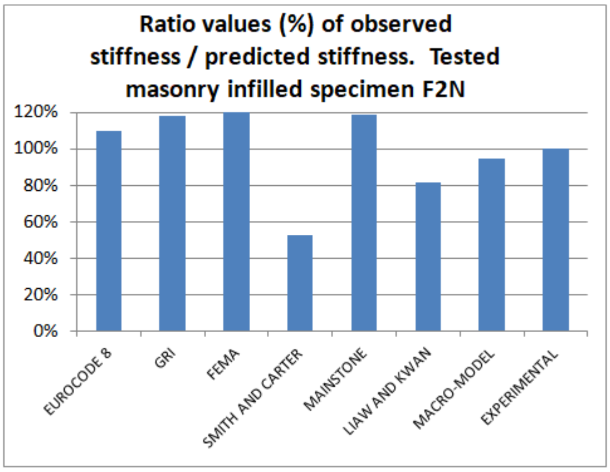

Figure 10. Evaluation of the behavior of masonry infilled R/C frame F2N assuming analytical expressions for the diagonal strut and a macro-model. Greek Regulation for Interventions = GRI

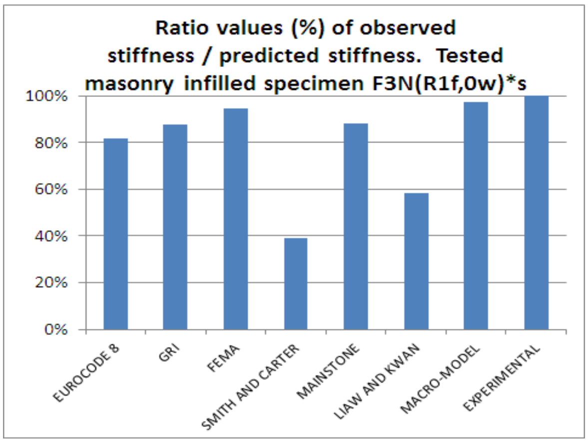

Figure 11. Evaluation of the behavior of masonry infilled R/C frame F3N(R1f,0w)*s assuming analytical expressions for the diagonal strut and a macro-model. Greek Regulation for Interventions = GRI

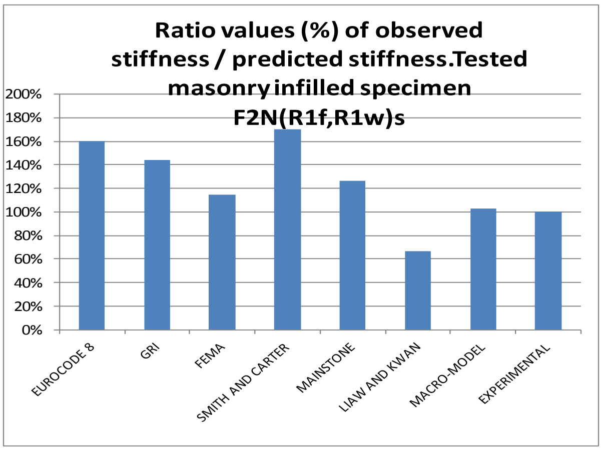

Figure 12. Evaluation of the behavior of masonry infilled R/C frame F2N(R1f,R1w)s assuming analytical expressions for the diagonal strut and a macro-model. Greek Regulation for Interventions = GRI

The predicted behavior from all numerical approximations is plotted together with the observed behavior in figures 5, 6, 7 and 8 for the four infilled R/C specimens F1N(R2f,0w)s, F2N, F3N(R1f,0w)*s, F2N(R1f,R1w)s. From the comparison of the obtained results the agreement or the deviation between predicted and observed behavior could be established.

In figures 9,10,11,12 the ratio of the observed stiffness over the predicted stiffness is plotted for the four masonry infilled R/C specimens F1N(R2f,0w)s, F2N, F3N(R1f,0w)*s, F2N(R1f,R1w)s. The ratio values smaller than 100% indicate that the predicted stiffness of the diagonal strut is overestimated. On the other hand, ratio values larger than 100% indicate instead that the observed stiffness of the masonry infill is underestimated by the predicted diagonal strut stiffness.

It was shown that the macro-model employed by Soulis [17],[18] exhibited the best degree of agreement with the observed behavior for the four specimens tested by Thauampteh[16]. This resulted from the capability of the proposed model to account for the differences in the joint interface between the masonry infill and the surrounding R/C frame. The FEMA[2] predictions although could not account for variations of the joint interface between the masonry infill and the surrounding frame, exhibited acceptable comparison with the experimental recordings especially for non-typical joint interfaces. However, for typical joint interfaces between the masonry infill and the surrounding frame that is identical to the joint of masonry infills as in the case of masonry infill frame F2N, discrepancies are reported. The predictions employed by the EC-8[1], Greek Regulations for Interventions (GRI)[3], and Mainstone [6] predicted ratios that followed the satisfactory FEMA[2] prediction, although they differentiated even more from the experimental recordings. Finally, the experimental recordings differed considerably from the predictions based on the expressions proposed by Stafford-Smith et.al [5] or Liaw et al. [7].

III. PROPOSED EQUATIONS FOR THE DETERMINATION OF THE DIAGONAL STRUT WIDTH

A numerical parametric analysis was carried out to determine the change of the equivalent diagonal strut width “w” when different stiffness ratios for the joint interface between the masonry infill and the surrounding frame and the masonry infill itself are introduced. This analysis follows the initial validation of the elastic behaviour of the masonry infilled R/C frames as presented in section 2 of the current study. The aim of this study is to prove the significance of the joint interface between the masonry infill and the surrounding frame on the contribution of the masonry infill in the overall lateral behaviour of the masonry infill frame. Three characteristic masonry infilled R/C frames were examined based on the masonry infilled R/C frame originally tested by Thauampteh [16] at LSMS of the Aristotle University of Thessaloniki. All the frames utilized the same surrounding frame as experimentally tested by Thauampteh [16]. Three different masonry infills were examined as shown in the table 2, together with 7 different ratios of joint interface between the masonry infill and the surrounding frame. These ratios were stiffness ratios of the joint interface (perimeter of infill) in respect to the masonry infill as described in table 2. The masonry infills considered in the analysis are characteristic masonry infills used by Thauampteh [16] assuming a weak, moderate and a strong masonry infill which corresponded to the masonry infills of F2N(R2f,0w)s, F2N, F2N(R1f,R1w)s frames.The thickness of the joint interface between the masonry infill and the surrounding frame was considered 10mm, while the thickness of the masonry infill was 58,5mm for the frames F2N(R2f,0w)s, F2N and 78,5mm for the frame F2N(R1f,R1w)s. The contribution of the different joint interfaces on the behavior of the masonry infill and subsequently the determination of the diagonal strut width is approached following four steps:

a) An elastic numerical macro-model for the masonry infilled R/C frame similar to the one used in the analysis of the previous sections is utilized and a numerical analysis is performed under combination of vertical and monotonic horizontal loading.

b) An elastic numerical analysis is also performed for the “bare” frame under the same load combination.

c) The subsequent stiffness of the masonry infill is approximated by subtracting the predicted stiffness of the masonry infilled frame by the stiffness of the “bare” frame.

d) For every combination of joint interface stiffness in respect to masonry infill stiffness a diagonal strut width is estimated.

TABLE II. PARAMETRIC NUMERICAL ANALYSIS FOR THE DETERMINATION OF THE DIAGONAL STRUT WIDTH

Frame specimen origin	Masonry Infill specimen origin	Masonry Infill Young Modulus (N/mm^2)	Masonry Infill Thickness (mm)	Stiffness ratios adopted between the joint interface and the masonry infill						
F2N	Wall F2N(R2f,0w)s	800	58,5	200	120	80	40	20	4	1
	Wall F2N	1000	58,5							
	Wall F2N(R1f,R1w)s	3000	78,5							

In the table 3, the results of the parametric analysis are presented for the three different masonry infills under investigation and the combination of different stiffness ratio between the joint interface and masonry infill. In figures 13, 14, 15 the diagonal strut width in respect to the stiffness ratio between the joint interface (perimeter of infill) and the masonry infill can be depicted. The three figures correspond to the three masonry infill configurations examined; weak, moderate and strong. In the same figures the diagonal strut width as resulted from the initial elastic behavior of the masonry infilled R/C frames tested by Thauampteh [16] are also included. The extracted equations can prognosticate the experimentally measured diagonal strut width, especially when the joint interface between the masonry infill and the surrounding frame and the masonry itself doesn't present extreme variations. When the stiffness ratio of the joint interface between the masonry infill and the surrounding frame and the masonry infill itself is increased then the contribution of the masonry infill as structural member in the overall behavior of the masonry infilled R/C frame increases. Frames F1N(R2F,0w)s and F1N(R2F,R1w)s with very flexible joint interfaces between the masonry infill and the surrounding frame show discrepancy from the linear equation predictions.

TABLE III. DIAGONAL STRUT WIDTH FOR DIFFERENT COMBINATIONS OF STIFFNESS RATIO BETWEEN JOINT INTERFACE AND MASONRY INFILL

Wall F2N(R2f,0w)s		Wall F2N		Wall F2N(R1f,R1w)s	
K joint/ K infill	Diagonal strut width "w"	K joint/ K infill	Diagonal strut width "w"	K joint/ K infill	Diagonal strut width "w"
200	966,25	200	861,06	200	293,71
120	775,26	120	753,23	120	272,54
80	737,65	80	718,11	80	270,32
40	735,67	40	726,13	40	269,81
20	725,49	20	725,45	20	264,53
4	697,01	4	721,19	4	258,77
1	609,63	1	703,16	1	249,93

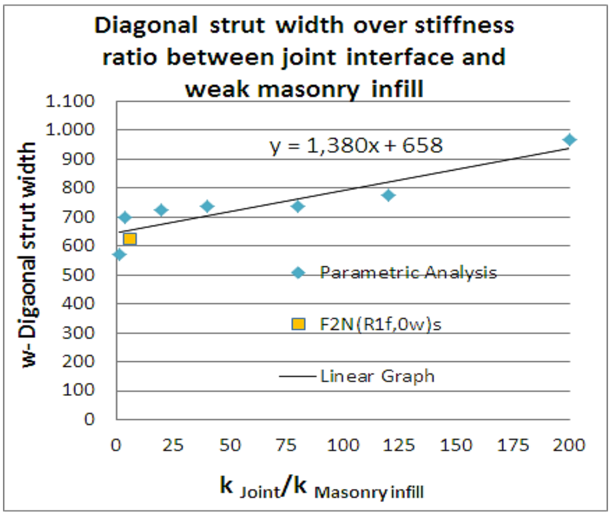

Figure 13. Diagonal strut width over stiffness ratio between joint interface and weak masonry infill

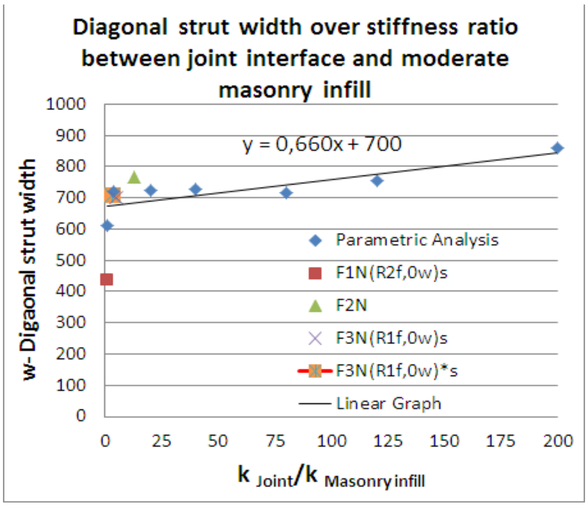

Figure 14. Diagonal strut width over stiffness ratio between joint interface and moderate masonry infill

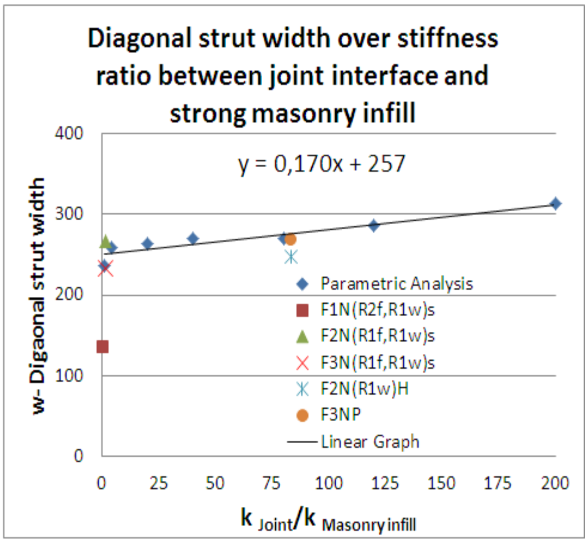

Figure 15. Diagonal strut width over stiffness ratio between joint interface and strong masonry infill

IV. NON-LINEAR RESPONCE OF THE MASONRY INFILLED R/C FRAME ADOPTING AN EQUVALENT DIAGONAL STRUT FOR THE MASONRY INFILL

In this section a non-linear numerical simulation of a single bay, single story masonry infilled R/C frame will be proposed utilizing the equivalent diagonal strut for the representation of the masonry infill. This numerical simulation will have the following characteristics:

The interface between the masonry infill and the surrounding frame will not be simulated in a straightforward fashion but by adopting the equivalent diagonal strut model (Figure 3). In contrast, the simulation of the surrounding frame remains the same as described by Manos, Soulis, Thauambteh [15].

The model of the equivalent diagonal strut adopts multi-linear properties for the simulation of the diagonal strut that is active only on compression (figure 3). Their non-linear properties are determined by a “push over” analysis in such a way that the overall behavior in terms of horizontal load-horizontal displacements of the masonry infilled frame using the equivalent diagonal strut is as close as possible to the same problem where this time the masonry infill and the interface between the masonry infill and the surrounding frame are simulated separately according to analytical macro-model (figure 4) described in the studies of Soulis[17], Manos, Soulis, Thauambteh [15] and Soulis [18].

The non-linear properties of the surrounding frame remain the same in the two different numerical models. The non-linear behavior of the joint interface between the masonry infill and the surrounding frame and the non-linear behavior of the masonry infill are approximated this time through multi linear properties that are assigned in the diagonal strut. It is obvious that this simplified process loses the immediacy of the exact representation of the individual structural elements (masonry infill, joint at the masonry-surrounding frame interface), as well as their individual non-linear behavior. In addition, the degree of approximation of the non-linear behavior of the masonry infill and the joint interface between the masonry infill and the surrounding frame is based on the validity of the analytical simulation of the masonry infill.

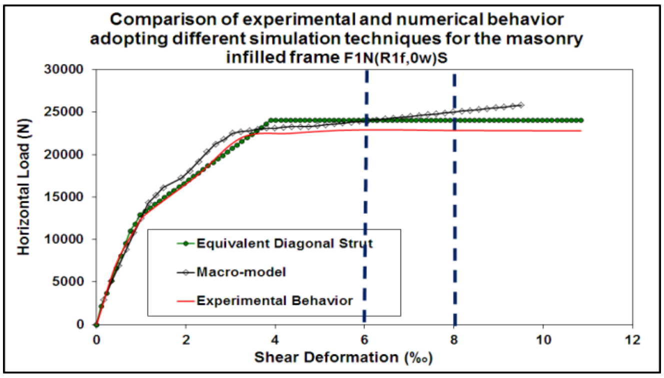

Figure 16. Envelope curve for the masonry infilled R/C frame F1N(R1f,0w)s

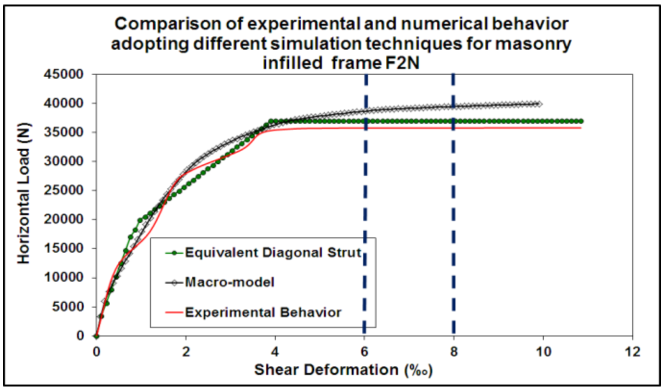

Figure 17. Envelope curve for the masonry infilled R/C frame F2N

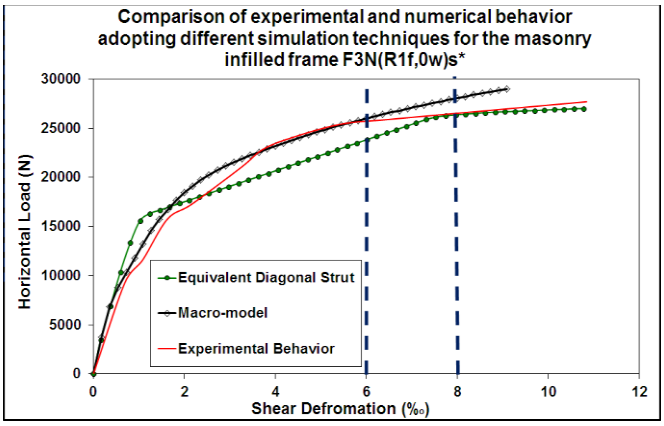

Figure 18. Envelope curve for the masonry infilled R/C frame F3N(R1f,0w)s*

The verification of the level of agreement between the model with the equivalent diagonal strut and the analytical numerical simulation of the masonry infilled R/C frame was done utilizing the results from three specimens tested by Thauampteh [16]. Namely, the masonry infilled frames with code names F1N(R2f,0w)s, F2N, F3N(R1f,0w)s*,were numerically simulated. In figures 16, 17, 18 the comparison between the envelope curves for the masonry infilled R/C frames F1N(R1f,0w)s , F2N, F3N(R1f,0w)s* for the two numerical simulations and the relative experimental curves, present a satisfactory level of agreement. In the same figures, the shear deformation levels γ=6‰ and γ=8‰ for the masonry infilled frames are presented. By corresponding each time, the behavioral curve of the model that adopts the equivalent diagonal strut with the behavioral curve of the simulation that adopts the analytical simulation with the use of a macro-model, for the desired each time shear deformation level, it is possible to capture the failure surface as this propagates. In figures 19a,b,20a,b,21a,b the failure surfaces that are predicted utilizing the macro-model simulation for masonry infilled frames F1N(R2f,0w)s, F2N, F3N(R1f,0w)s* are presented for shear deformation levels γ=6‰ , και γ=8‰. The damage pattern as it was experimentally recorded for each masonry infilled frame for shear deformation level γ=8‰ is also presented in the figures 19c, 20c, 21c.

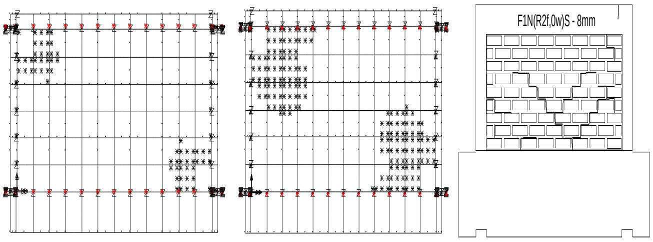

Figure 19. Failure surface for the masonry infilled R/C frame F1N(R2f,0w)s for shear deformation levels a) γ= 6‰,b) γ=8‰ c) Experimental damage pattern for γ=8‰

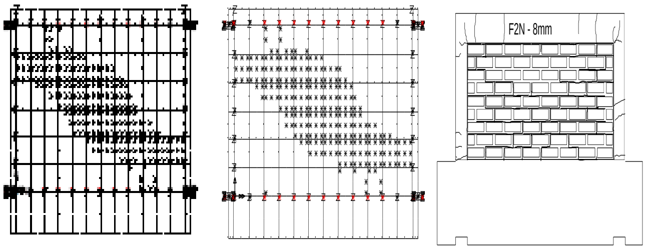

Figure 20. Failure surface for the masonry infilled frame R/C F2N for shear deformation levels a) γ= 6%o,b) γ=8%o c) Experimental damage pattern for γ=8%o

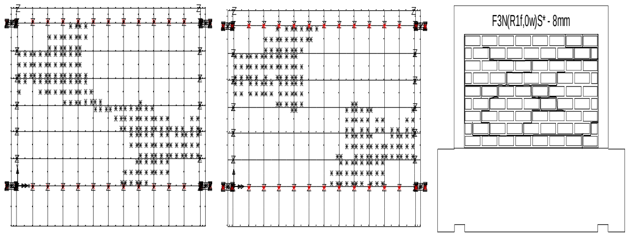

Figure 21. Failure surface for the masonry infilled frame R/C F3N(R1f,0w)s* for shear deformation levels a) γ= 6%o,b) γ=8%o c) Experimental damage pattern for γ=8%o

V. CONCLUSIONS

1. The comparative study of different methodologies aimed to predict the stiffness of the masonry infill though the calculation of the width of the diagonal strut was initially presented. This was done by employing analytical expressions of regulatory provisions (EC8 [1],FEMA [2],Greek Regulation for Interventions GRI [3]) as well as expressions proposed by a number of researchers e.g. Stafford Smith and Carter's [5], Mainstone [6], as well as Liaw and Kwan [7]. In all these diagonal strut approximations the influence of the flexibility of the interface between the masonry infill and the surrounding R/C frame is ignored. This influence is highlighted in this study when the observed masonry stiffness behavior from four tested masonry infill R/C frame specimens is presented. These four specimens were of the same geometry for the R/C and masonry parts and were subjected to the same vertical and horizontal loads. The flexibility of the interface joint between the masonry infill and the surrounding frame in these three specimens was varied employing initially a very flexible material (cork) or mortar joints of variable stiffness (mortar H or V1). The macro-model employed by Soulis [17], [18] exhibits the best degree of agreement with the observed behaviour for all four specimens. FEMA[2] expression showed the second best correlation in respect to the experimental measurements for the three of the four specimens under examination. In addition, there is considerable deviation between the predicted diagonal strut stiffness and the experimental when the expressions of EC-8[1], Greek Regulations for Interventions (GRI)[3], and Mainstone [6] are employed. However, these predictions show better agreement to the measured stiffness, when compared to the predictions based on the expressions proposed by Stafford-Smith et al [5] or Liaw and Kwan [7].

2. A parametric analysis performed that led to equations that can determine the diagonal strut width in respect to the stiffness of joint interface between the masonry infill and the surrounding frame and the stiffness of the masonry infill itself. A good approximation was recorded between the experimental diagonal strut width for different masonry infilled frames tested by Thauampteh [16] and the equations that resulted from the parametric analysis.

3. Based on this fully non-linear numerical simulation a simplification is next proposed by the authors. This consists of a multi-linear constitutive law which is derived from the fully non-linear analysis of single-story mutli-bay infilled R/C frames. This constitutive law is used to dictate the behaviour of equivalent diagonal struts that eventually simulate the masonry infills in multi-story multi-bay R/C infilled frames.

4. The comparison between the numerical simulations and the experimental behavior showed that:

a) The strength and the monotonic load-displacement behavior observed during the experiments of Thauampteh [16] on single-storey, single-bay masonry-infilled R/C frames were successfully predicted by the proposed numerical simulation that adopted the equivalent diagonal strut model and by the numerical simulation that adopted the macro-modeling technique.

b) The predicted accumulation of failures in the masonry infills and the development of plastic hinges in the R/C frame were predicted successfully with the proposed analytical numerical macro-model.

c) Some practical guidance for the design of masonry infill R/C frames can be proposed taking into account the results of the experimental measurements. In the experimental sequence a progressive increase of the stiffness and strength of the joint between the masonry and the surrounding frame was selected. It was shown that this progressive increase leads to the change of the contribution of the masonry infill in the overall performance of the masonry infilled R/C frame and mitigation of failure from corner crushing to failure along the diagonal of the masonry infill. In the cases where the joint interface between the masonry infill and the surrounding frame was weaker than the mortar joint between masonry units, failure occurred in the corners of the masonry infill (Cork) or a narrow zone of failures developed along the diagonal (Mortar type H). The masonry infilled R/C frame F2N, that utilized masonry infill with joint interface between the masonry infill and the surrounding frame with identical mechanical properties (Mortar type V1) with the mortar joint between the masonry units, showed higher stiffness, higher bearing capacity and failure propagation along the diagonal of the masonry infill.

5. The comparison of the behavior of the masonry infilled R/C frame model that adopted the equivalent diagonal strut can be calibrated against the masonry infilled R/C frame model that adopted the macro-model. In that way the propagation of failure in the joint interface between the masonry infill and the

surrounding frame and the masonry infill itself can be predicted in predefined deformation levels.

6. In conclusion, the model that adopted the multi-linear equivalent diagonal strut can be used in push over nonlinear analyses of multi-story masonry infilled structures due to its low computational demands. Furthermore, in combination with the proposed macro-model it is possible to determine the local effects (stress concentrations, failure surfaces, etc.) in the masonry infills, and study the interaction of the masonry infills with the surrounding frame, which takes into account the presence of the joint between the masonry infill and the surrounding frame.

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