COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
G.C.Manos, V.Soulis, J.Thauampteh (eds.)
Kos Island, Greece, 12–14 June 2013

IN-PLANE BEHAVIOUR OF MASONRY INFILLS WITHIN MULTI-STOREY R/C FRAMES SUBJECTED TO SEISMIC TYPE LOADS AND THEIR UTILIZATION IN RETROFITTING

G.C. Manos[1], V. Soulis[1], J. Thauampteh[1]

[1]Laboratory of Strength of Materials and Structures, Dept. Civil Engineering, Aristotle University, Thessaloniki, GREECE

e-mail: gcmanos@civil.auth.gr

Keywords: Numerical simulation, Masonry-infilled R/C frames, Equivalent step-by-step analysis

Abstract. *Observations from past strong earthquake activity have shown that masonry infill panels can be damaged to a substantial degree.Under certain circumstances this interaction of masonry infills with the surrounding R/C frame during the seismic response may result in either beneficial effects, by increasing the stiffness, strength and seismic energy absorption of the structure, or in adverse consequences (damage) to the main R/C structural elements. Consequently, there is need first to understand this behavior resulting from the masonry infill to R/C frame interaction and next to have reliable tools to predict it in order to prohibit adverse consequences. These tools can then be utilized in the retrofitting of R/C multistorey structures designed and constructed according to old earthquake resistant design provisions. This paper presents first 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 load. The effectiveness of this simulation was validated by comparing the numerically predicted behaviour with results from an experimental sequence whereby a number of 1:3 scale, one-bay, one-storey R/C frame specimens, including weak and strengthened masonry infills, were subjected to combined vertical and cyclic horizontal seismic-type loads. Next, this paper deals with the applicability of this successful non-linear masonry-infill concrete-frame numerical simulation to predict realistically the seismic behaviour of a prototype multi-storey R/C frame structural formations with masonry infills. Further more the proposed numerical simulation of the same multi-storey R/C frame structural formation was utilized in an application of a retrofitting scheme. In order to overcome the obstace of computational time and computer memory requirements, use was made of an equivalent post-elastic "pushover" type of analysis that draws information on the stiffness and strength variation from one-bay, one-storey R/C masonry infilled unit frames that compose a given multistorey structural formation.*

1 INTRODUCTION

Many researchers in the past were involved in the effort to propose valid numerical simulation to capture the behaviour observed experimentally of multi-storey 2-D frames. The numerical simulation proposed by Soulis [1] was used to simulate the behaviour of three-storey structural formations including masonry infills; in particular a multi-storey planar R/C frame structure, that was constructed and tested at the University of California, Berkeley by Klingner and Bertero [2] was examined. Reasonably good agreement was observed between the numerical results and the experimental measurements regarding the hysteretic behaviour of the "bare", and infilled three-storey specimens. Next, a "pushover" analysis was performed for a planar 6-storey infilled RC building. This analysis was accomplished to a satisfactory degree despite the significant number of finite elements utilized in the numerical simulation and the high computational requirements. In order to overcome this difficulty a new equivalent analysis is proposed and validated, aiming to incorporate the influence of the masonry infills for multi-storey structural formations. For this purpose, the previously mentioned planar 6-storey structural formation is selected for the validation of the proposed equivalent method of analysis. More specifically, as will be described in section 3 of this paper, the masonry infills of this planar 6-storey, R/C structure are modeled as diagonal strut members as proposed by Holmes [3], [4]; however, these are modeled with multi-linear properties. 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.

Previous studies by Mainstone and Liauw [5],[6] as well as the extensive experimental and numerical investigation conducted before by the authors [1],[7],[8] and briefly reported here, demonstrated that the stiffness and strength added in single-storey R/C frames through the use of masonry infills can be affected by various non-linear mechanisms such as:

a) The non-linear behaviour of the R/C frame.

b) The non-linear mechanisms that develop at the interface between the R/C frame and the masonry infill with the individual mechanical properties and their interactions.

c) The level of shear deformation that develops in the masonry infill and consequently its non-linear behaviour for that level of shear deformation.

Consequently, the development of all these non-linear mechanisms dictates the total behaviour of masonry infill frames and renders an elastic type of analysis a crude approximation. In the first part of this paper (section 2) it is shown that all these (a to c) non-linear mechanisms are quite successfully simulated numerically by the proposed "fully non-linear" numerical treatment (Type A simulation). This type A simulation assumes that: a) the masonry infills are simulated with plane stress elements, having non-linear mechanical characteristics, b) the infill to frame interface is simulated by sets of non-linear joint element, whereas the R/C structural members have the capability of developing plastic hinges at their ends, as described in section 2.1. The major obstacle in extending this type of full non-linear numerical treatment to a multi–storey masonry-infilled R/C frame structure, in order to simulate separately all these non-linear mechanisms for the R/C frame members, the masonry infills, and the interfaces between the R/C frames and masonry infills, is the computational time and computer memory requirements needed for the completion of such numerical analysis. It is believed that all these dominant non-linear mechanisms that develop in a single-storey masonry infilled R/C frame, as described in the first part of this paper, can also develop in the same way in a multi-storey R/C frame structure with masonry infills when subjected to "seismic type" loading. In the second part of this paper, presented in section 3, the non-linear response of masonry infilled multi-storey framed R/C planar structural formations is addressed through an equivalent post-elastic *"pushover"* analysis to confront the obstacle of the high computational requirements of the fully non-linear approach; this is done by utilizing the full non-linear response of a number of "single-storey" infilled frame units that such a multi-storey structure can be decomposed to. It must be stressed that only in-plane stiffness and strength variation of these masonry infilled units is considered in this approximation whereas the out-of-plane behaviour and its possible effects, although important, are not addressed.

Pushover analysis is a nonlinear static procedure which validity and applicability have been extensively studied in literature. According to Eurocode 8 Part 3 (EN 1998-3)[9]: paragraph 4.4.4 (1) Nonlinear static ("pushover") analysis is a non-linear static analysis under constant gravity loads and monotonically increasing horizontal loads. (2) Buildings not complying with the criteria for regularity in plan shall be analysed using a spatial model. (3) For buildings complying with the regularity criteria the analysis may be performed using two planar models, one for each main direction.

According to Eurocode 8 Part 1 (EN 1998-1):4.3.3.4.2.3[9] (1), the relation between base shear force and the control displacement (the "capacity curve") should be determined by "pushover" analysis for values of the control displacement ranging between zero and the value corresponding to 150% of the target displacement. (2) The control displacement may be taken at the centre of mass of the roof of the building. The top of a penthouse should not be considered as the roof.

This approximate *"pushover"* analysis, outlined in the following steps a to h and summarized in Table 1, deals with the non-linear behaviour of masonry infilled multi-storey R/C frames, with respect to their in-plane stiffness and strength variation, utilising the findings of the in-depth research in the behaviour of the single-storey masonry infill R/C frame units; this was presented in the first part of this paper (section 2) and is also included in the work reported by Manos, Soulis and Thaumpteh ([8]). The objective of this section is to approximate the complex behaviour of multi-storey R/C infilled frames and retrofitted multi-storey R/C infilled frames by applying the simplified equivalent diagonal strut simulation briefly presented in section 3, so that a realistic solution of such practical problems becomes attainable in terms of computer time and computer memory requirements.

An equivalent post-elastic numerical simulation is proposed (Type B simulation) for multi-storey R/C frame structural formations that include masonry infills and retrofitted multi-storey R/C frame structural formations with strengthened masonry infills. This type B simulation is built assuming that the masonry infills are simulated with diagonal strut members, having multi-linear mechanical characteristics, whereas the R/C structural members have the capability of developing plastic hinges at their ends, as described in section 2.1. The steps that describe the methodology are extensively outlined by Manos et.al [8]. These steps are briefly outlined in Table 1 presented below:

Step a:	*Multi-storey frame.* Decompose the multi-storey structural formation to individual single-storey one-bay masonry infilled R/C frame units. Group these units according to their common geometric and mechanical characteristics of the R/C elements and masonry infills, in order to minimize the number of different units to be analysed in the next steps.
Step b:	*Single-storey units.* Prepare simulation type A for each one of these single-storey units in order to obtain their full non-linear response.
Step c:	*Single-storey units.* Perform a "pushover" analysis with simulation type A for each single-storey unit and obtain its full non-linear response together with the accumulation of damage of the masonry infills that can be linked to the increase of the shear strain

	levels.
Step d:	*Single-storey units.* Prepare a number of simulations type B for each one of these single-storey units by replacing the masonry infill with an equivalent multi-linear diagonal strut member whereas retaining the capability of the R/C members to develop plastic hinges at their ends.
Step e:	*Single-storey units.* For each single-storey unit obtain horizontal load (H) versus horizontal displacement (δ) or shear strain (γ) response curve from "pushover" analyses employing simulation type B. Adjust the diagonal strut properties in such a way that both type A and type B simulations result in approximately the same stiffness and strength variation for the chosen shear strain levels for the masonry infill (e.g. 0.1%, 0.15%, 0.2%, 0.25%, 0.3%, etc.).
Step f:	*Multi-storey frame.* Perform a "pushover" analysis with simulation type B for the multistorey structural formation having replaced the masonry infills with the equivalent multi-linear diagonal struts found from step e. For every interval (i+1) of this analysis a target top storey displacement is set. Each time the target displacement value is such that corresponds approximately to shear strain levels already examined in steps d) and e) (e.g. 0.1%, 0.15%, 0.2%, 0.25%, 0.3%, etc.)
Step g:	*Multi-storey frame* Record at pre-selected intervals (i+1) of step f) and for target top storey displacement that corresponds to shear strain levels (e.g. 0.1%, 0.15%, 0.2%, 0.25%, 0.3%) the actual storey displacements and forces as well as the shear-strain levels γ_{i+1} for each masonry infill as they result from the type B analysis.
Step h:	*Multi-storey frame* Assess the performance of each masonry infill of the multi-storey structure by using the corresponding full non-linear response type A simulation (step c) and the obtained shear strains γ_{i+1} values in the previous step (g) for each masonry infill of the multi-storey structure at interval i+1.

Table 1: Steps of equivalent post-elastic analysis for the examination of the ultimate state of masonry infills.

2 THE NUMERICAL SIMULATION OF THE BEHAVIOUR OF MASONRY-INFILLED R/C FRAMES EMPLOYING THE SIMULATION TYPE A AND SIMULATION TYPE B FOR THE MASONRY INFILL

In order to verify the degree of approximation of both the simulation types A and B, two scaled models that have been tested in the experimental study of Thauampteh [10] were utilized. Namely specimen F3N(R1f,0w)*s and specimen F3N(R1f,R1w)s will be simulated. In this case the results from the simplified approach utilizing a tri-linear diagonal strut model (Simulation type B) will be compared to the corresponding numerical results of the more explicit numerical simulation (fully non-linear, Simulation type A), as well as with the corresponding experimental results.

The single-storey one-bay R/C frame scaled specimens F3N(R1f,0w)*s and specimen F3N(R1f,R1w)s with masonry infills were constructed and tested at the strong reaction frame of the Laboratory of Strength of Materials of Aristotle University of Thessaloniki (Thauampteh [10]). These specimens include one-bay one-storey 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 1). The cross-section of the columns was 110mmx110mm and that of the beam 100mmx155mmm. These two scale masonry infilled frame models incorporate two different types of infills the one with relatively weak infill and one with reinforced infill.

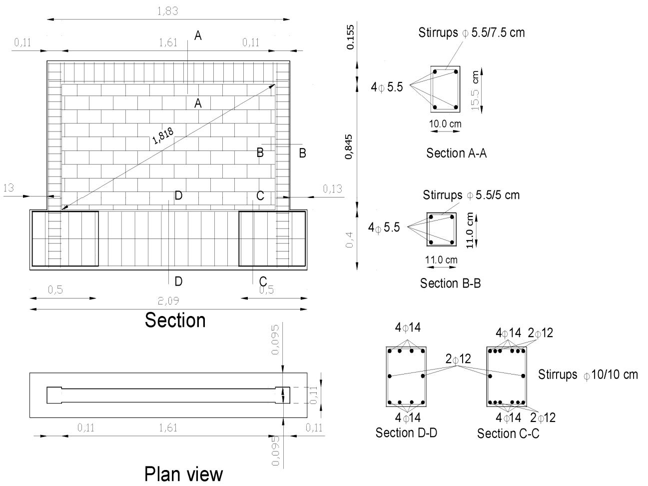


Figure 1a: Masonry infilled R/C frame specimen F3N(R1f,0w)*s and design details [10].

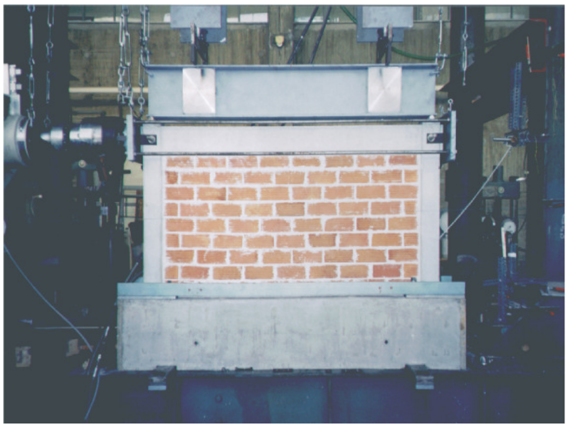


Figure 1b: Test set up of frame with repaired masonry infill F3N(R1f,0w)*s.

Brief information on the selected masonry infilled R/C specimens is listed in table 2 and described extensively by Thauampteh [10] and Soulis [1].

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
F3N(R1f,0w)*s (**Repaired**) [10]	1.7	50	mortar **V1**	58.5	mortar **H** thickness **15mm** (without plaster)
F3N(R1f,R1w)s (**Repaired**) [10]	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

Table 2: Outline of all specimens for the 1st and 2nd group of specimen.

As already mentioned, the influence exerted by the interface between the masonry infill and the surrounding frame was also examined in both studies by Thauampteh [10] and by Soulis[1]. Tables 3, 4 and 5 list the mechanical properties of the materials used in the construction of the specimens.

Masonry infill	Masonry Infill thickness (mm)	Compressive strength of masonry (N/mm^2)	Shear strength of masonry 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)
Virgin infill [10]						
V1	58,5	2,765	0.180	6.50	25.9	1.125
Reinforced infill[10]						
Infill with mortar **V1**, reinforced with reinforced plaster	78,5	3,75	0.44	6.50	25.9	1.125

Table 3**:** Strengths of masonry infills and concrete used in the specimens [10].

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)
Φ5.5	311	425	0.8	22.0	6.5X10^4
Φ5.5 stirrups	360	542	0.6	20.0	6.5X10^4

Table 4**:** Tensile strength of the reinforcement used in the specimens [10].

A/a	Simulation of joint interface between frame and infill	**E** Young Modulus (N/mm^2)	**G** Shear Modulus (N/mm^2)	$\mathbf{f_k}$ Measured Compressive Strength of mortar (N/mm^2)	$\mathbf{f_{tn}}$ Assumed Tensile Strength of mortar (N/mm^2) (as % of f_c)	**τo** Local bond shear strength of mortar (N/mm^2)	**μ** friction coefficient
1	**H** mortar	60	26	0.60	0.06(10%)	0.078	0.58

Table 5**:** Mechanical properties of the mortar joint located between the infill and the surrounding frame (mortar type H).

2.1 Simulation type A

Extensive comparison of various numerical simulations with the behaviour observed by Thauampteh [10], as well as by Stylianides [11], Valiasis [12], and Yasin [13] for the masonry infilled R/C frames is included in the work of Soulis[1] where the conclusions of the corresponding extensive validation, utilizing the results of all these experimental studies [10], [11], [12], [13] are presented. In the recent publications by Manos, V. J. Soulis, J. Thauampteh [7], [8] the numerical simulation of the behaviour of masonry-infilled R/C frames using plane stress elements for the simulation of the masonry infill (Simulation type A) is presented. This type of simulation is shown in figure 2.

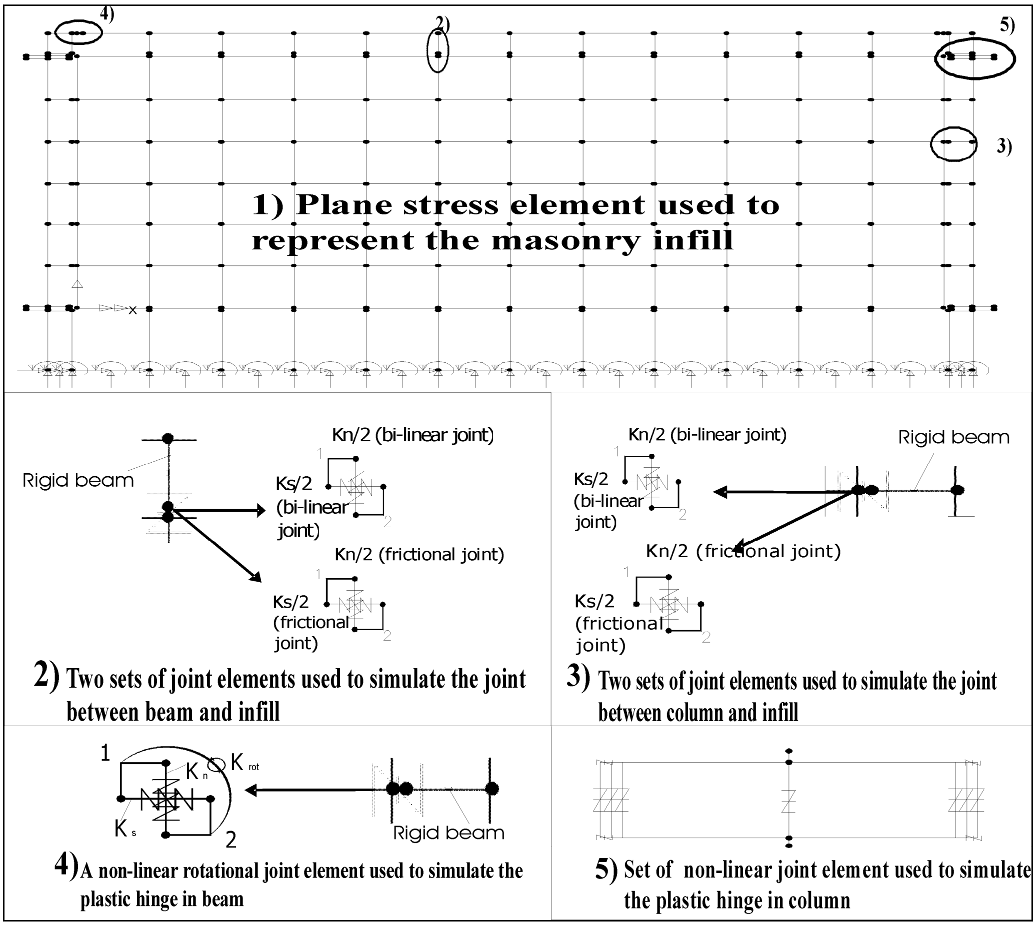


Figure 2: Finite element simulation of masonry infilled R/C model.

In this 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 2 detail No 4 and 5). 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 2, detail No. 4). A number of non-linear 2-D joint elements were also employed at the ends of each column (figure 2, detail No. 5). The selected numerical simulation showed that the non-linear moment-rotation relationships for the beam and column cross-sections could be simulated successfully. Plane stress elements are used for simulating the masonry infill (figure 2 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). Two sets of non-linear 2-D joint elements are used to simulate the separation and slip between frame and infill as well as the transfer of compression and shear for the specific type of interface that is simulated. The first set of these 2-D joint elements (figure 2 details No 2 and No 3) is active in the direction transverse to the interface; it is of a frictional type, while the second set of non-linear joint elements (figure 2 details No 2 and No 3) is active in both the transverse and the normal to the interface directions. In the current study the mechanical properties of the joint interface between the masonry infill and the surrounding frame can be depicted in table

5.The mechanical elastic and post-elastic properties of the unreinforced and reinforced masonry panels that are utilized in this numerical simulation are presented in the study of Soulis [1], and Manos et.al [7].

2.2 Simulation type B

The implementation of the simulation type B described in the previous section demands the simplification of the masonry infill frame response for a single-bay one storey infilled frame adopting an equivalent diagonal strut model. 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 2.1 As a result, the masonry infill 2-D representation, as outlined in section 2.1 will also be replaced by the well known equivalent diagonal strut model (figure 3). On the contrary, all the aspects of the reinforced concrete frame representation, described in section 2.1, will be retained.

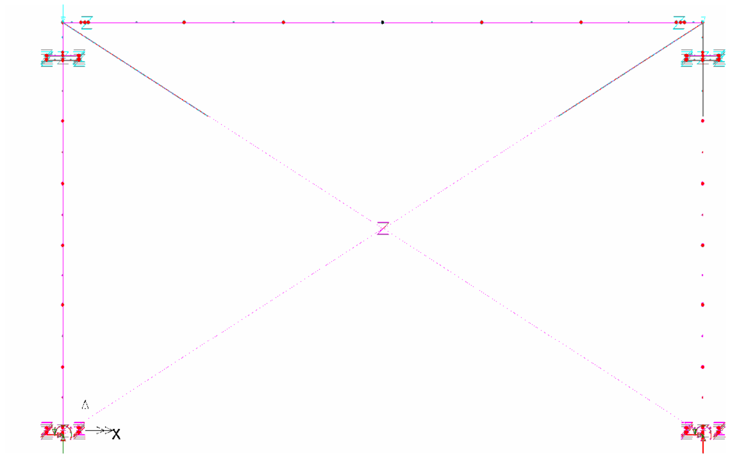


Figure 3: Equivalent diagonal strut model.

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 (sections 2.1 respectively).

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 sections 2.1 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 2.1.

2.3 Validation of the proposed equivalent diagonal strut model proposed by Simulation type B

Figures 4a and 4b depict the comparison of the predicted behavior, in terms of envelope curves resulting from a "pushover" type of loading, whereby the infill was simulated with a tri-linear equivalent diagonal strut(Simulation type B) with the corresponding behavior of the same infill frame that was simulated according to the fully non-linear treatment (Simulation type A). The envelope curves as resulted from the experiments are also plotted in these figures for masonry infilled model frames F3N(R1f,0w)*s and F3N(R1f,R1w)s. The tri-linear equivalent strut behaviour was obtained by a relatively small number of trials for the properties of the diagonal strut retaining the same numerical simulation for the surrounding R/C frame for both numerical simulations as the one described in section 2.1.

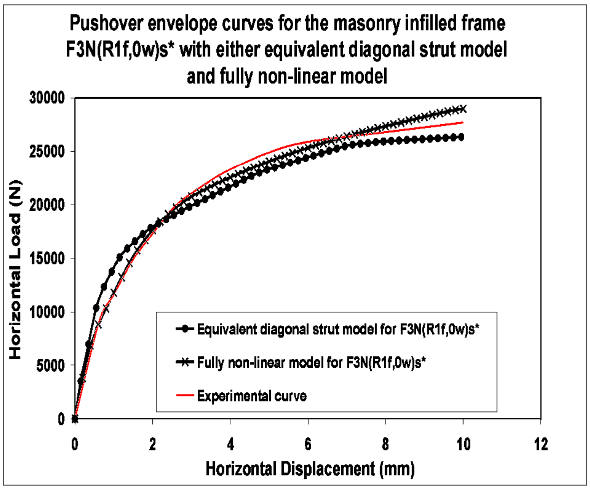


Figure 4a: Comparison of envelope curves for masonry infilled model frame F3N(R1f,0w)*s.

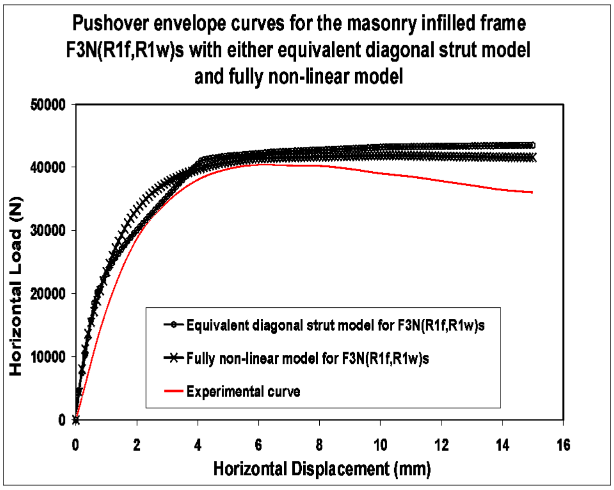


Figure 4b: Comparison of envelope curves for masonry infilled model frame F3N(R1f,R1w)s.

As can be seen, the envelope curve predicted with the tri-linear diagonal strut (Simulation type B) compares quite well to both the experimental envelope curve as well as to the one resulting from the fully non-linear treatment (Simulation type A). This comparison is extended for the case of cycling loading that was utilized during the experiments. The properties of the tri-linear diagonal strut model defined before were kept unaltered. The numerical results obtained this time by employing either the tri-linear diagonal strut simulation for the masonry infill or the fully non-linear treatment are compared in figures 5a and 5b for specimens F3N(R1f,0w)*s and F3N(R1f,R1w)s, respectively. As can be seen in figures 5a,b, 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 (sections 2.1. to 2.2).

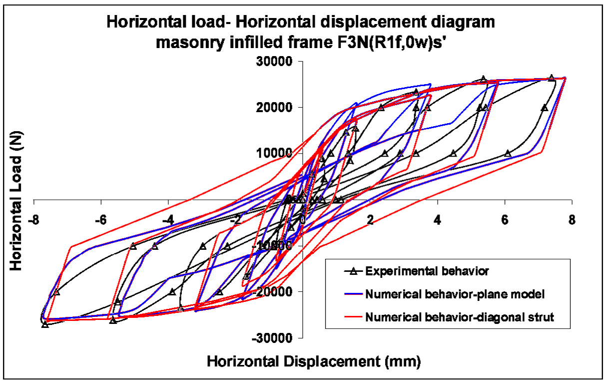


Figure 5a: Comparison of cyclic response for specimen F3N(R1f,0w)*s.

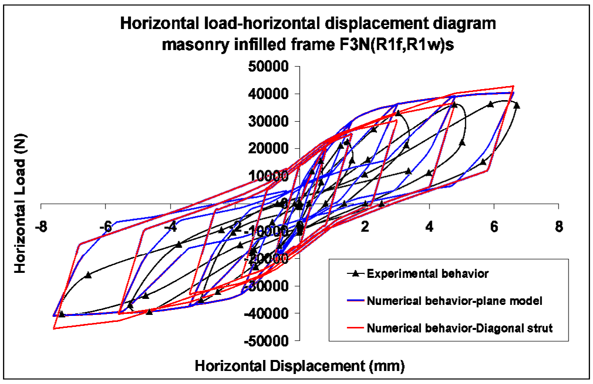


Figure 5b: Comparison of cyclic response for specimen F3N(R1f,R1w)s.

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 sections 2.1. Considerable gains 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 application of such a simplification for multi-storey R/C infilled frames is outlined in section 3.

3 APPLICATION OF THE PROPOSED EQUIVALENT STEP-BY-STEP ANALYSIS

A 6-storey masonry infilled planar frame structural formation is selected for the validation of the proposed method of analysis when this structure is subjected to seismic-type horizontal loading. More specifically an outer planar section of a 6-storey masonry infilled R/C building is studied. The results from the application of the proposed equivalent "pushover" type B analysis for this 6-storey R/C frame with masonry infills will be compared with the results from a "pushover" fully non-linear type A numerical simulation of the same structure. Additionally the proposed equivalent post-elastic analysis will be applied in the case of a retrofitted 6-storey jacked R/C frame with reinforced masonry infills.

3.1 Description of the 6- storey R/C building numerical simulation

A characteristic plan view of the 6-storey masonry infilled R/C building is shown in figure 6.The outer facade of this 6-storey building is shown in the figures 7. Only a section in the large dimension of the structure will be utilized for the application of the proposed analysis (figure 7). The retrofitted scheme for a typical base storey frame unit that was utilized in the current study includes both the jacketing of columns and the strengthening of the masonry infill panels with reinforced plaster(figure 8). The reinforced masonry infill panel was connected to the surrounding frame with weak mortar (type H) similar to the one used in the construction of F3N(R1f,R1w)s specimen.

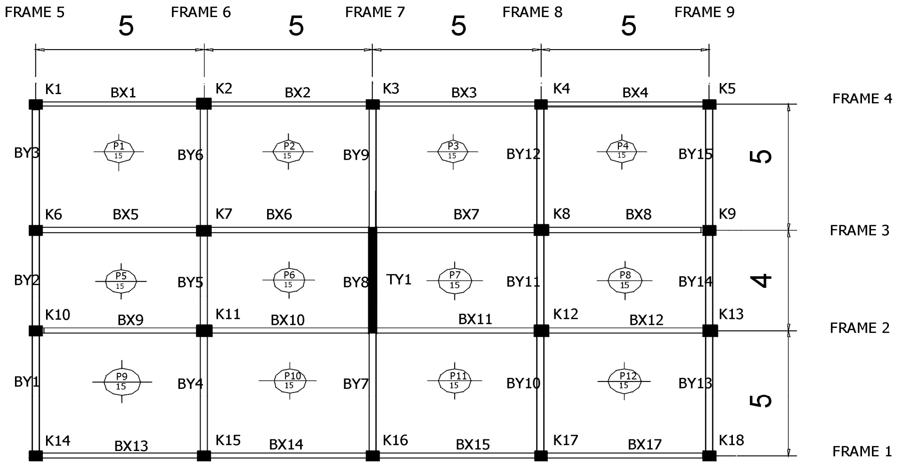


Figure 6: Plan of a typical floor level

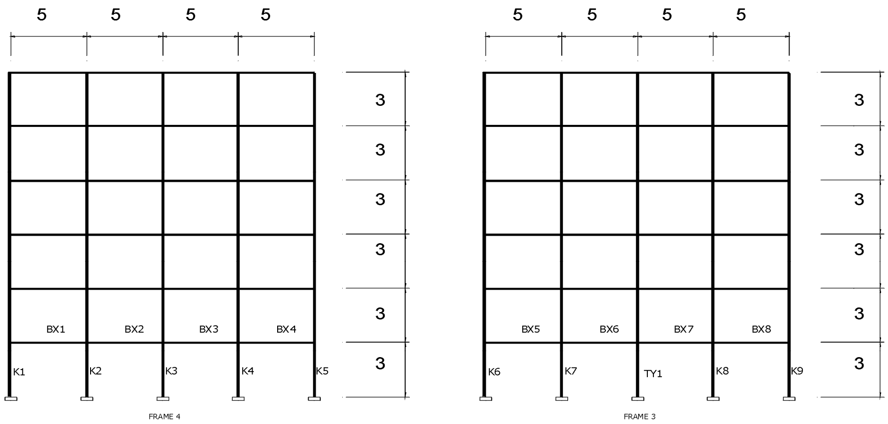


Figure 7: Typical section of structure, frames 4-3

The height of the structure is 18m. Table 6, lists the cross section areas of the columns and beams of the 6-storey structure. In the same table the cross section areas of the retrofitted elements are also shown.

The following vertical loads are imposed apart from the self-weight:

The self-weight of the masonry infills (3,6KN/m^2), applied at the perimeter of the structure

The marble coating of each floor 1,3kN/m^2

The imposed vertical liveload is assumed to be Q=2kN/m^2

	Storey	Columns K1-K5, K14-K18, K6,K9,K10,K13	Columns K7-K8-K11-K12	Shear Wall TYi	Beam $BXi_{(1,17)}$	Beam $BYi_{(1,7,9,15)}$	Beam BY8
Initial	$1^{ος}$ – $5^{ος}$	40/40	45/45	400/25	20/60	20/60	30/90
Retrofitted	$1^{ος}$ – $5^{ος}$	55/55	60/60	400/25	20/60	20/60	30/90

Table 6: Cross sections of columns, beams and wall of the 6-storey structure.

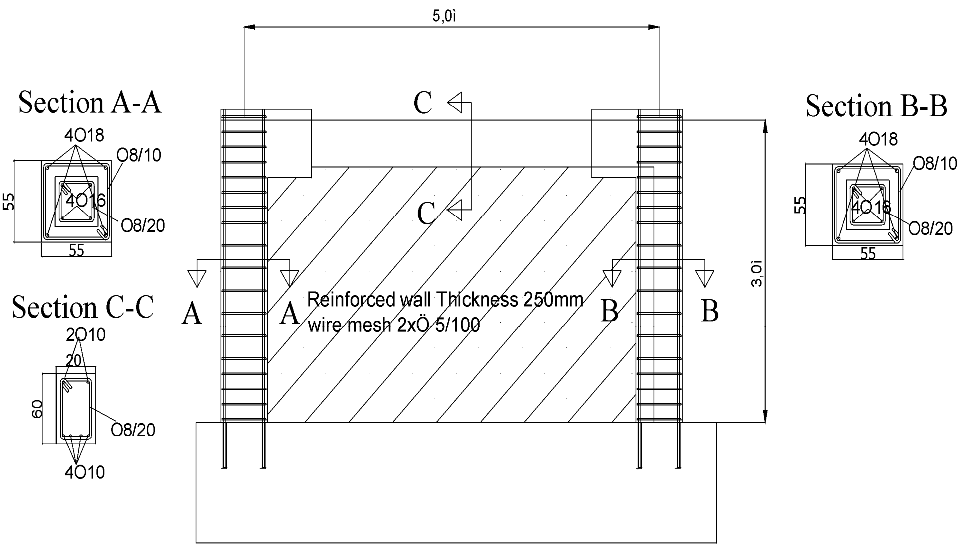


Figure 8: Typical base storey retrofitted frame with the columns' jackets and strengthened infill panel with reinforced plaster.

The validation of the proposed equivalent type B "pushover" analysis for frame No. 4 of the 6-storey structure will proceed according to the steps outlined in the table 1 provided in the introduction. Figure 9a depicts the numerical simulation of frame No. 4 whereby the masonry infills are simulated as nonlinear plane stress elements with their contact interfaces (simulation type A), whereas figure 9b depicts the simulation of frame No. 4 where the masonry infills are simulated as multi-linear diagonal strut members (Simulation type B).

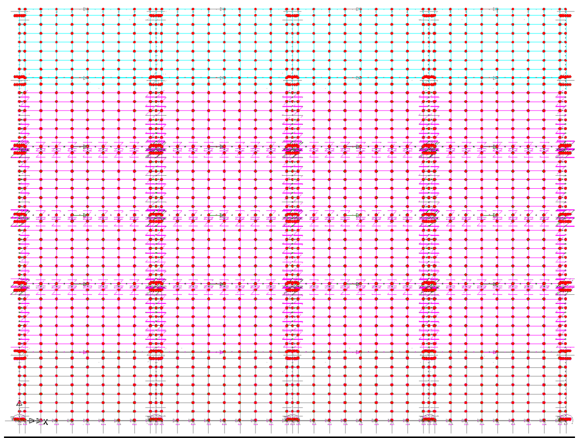


Figure 9a: Type B numerical simulation of 6-storey plane structure with masonry infills simulated as diagonal struts.

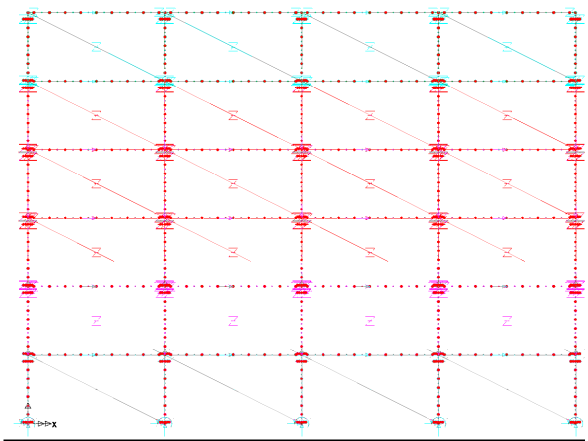


Figure 9b: Type A numerical simulation of 6-storey plane structure with masonry infills simulated as plane stress elements.

For the fully non-linear "pushover" type A analysis of the 6-storey structure, the maximum target displacement at the top was set equal to 54mm, with the displacement profile along the height of the building assumed to be triangular. The resulting in this way displacement was imposed at each floor level in a gradual increasing fashion. The corresponding lateral forces at each floor level resulting from this fully non-linear analysis were recorded especially for horizontal maximum top displacement levels of 18mm, 27mm, 36mm, 45mm, 54mm, 57,6mm. Both type A and type B simulations predicted the corresponding deformation pattern of the whole structure at each floor level. By comparing the load-deformation obtained through either the type A (fully non-linear approach) or the type B (equivalent post-elastic with multi-linear struts approach) the validity of the type B approximation of the masonry infill response will be assessed.

3.2 Numerical simulation of the single storey unit

The equivalent post-elastic analysis that was described in table 1 determines the decomposition of the multi-storey structural formation to individual single-storey one-bay masonry infilled R/C frame units. The numerical simulations of the fully non-linear masonry infilled R/C frame unit (simulation type A), and the non-linear R/C frame unit that utilizes the diagonal strut for the simulation of masonry infill (Simulation type B) is described below.

A) Fully non-linear masonry infilled R/C frame response (simulation type A): The successful numerical simulation that has been proposed in section 2 will be applied first for the whole 6-storey structure. The horizontal load-horizontal displacement fully non-linear response curve resulting from this simulation will include non-linear mechanisms for the masonry infill, the surrounding R/C frame, the interface between the masonry infill and the surrounding prototype frame. Described briefly in what follows is the numerical simulation of the masonry infill, that of the R/C frame and of the interface between the R/C frame and the masonry infill (figures 10a, 10b and 10c).

a) Simulation of the masonry infill. The simulation of the masonry infill, utilizing non-linear plane stress finite elements, was described extensively in section 2. This is also followed here (figure 10b). The isotropic nonlinear material law of Modified Von Mises was utilized. The adopted mechanical properties of the initial and the strengthened masonry infill panels are listed in Table 7.

Mechanical properties	**Initial**	**Strengthened**
Young Modulus (N/mm^2)	2500	3500
Poisson Ratio	0,20	0,20
Tensile strength (N/mm^2)	0,20	0,80
Compressive strength (N/mm^2)	2,50	4,50
Softening Modulus under compression (N/mm^2)	0	0
Softening Modulus under tension(N/mm^2)	0	0

Table 7: Mechanical properties used for the description of Von Mises failure criterion of the initial and strengthened masonry infills for the 6-storey structure.

b) *Simulation of the beam/column R/C elements and the plastic hinge formation.*The simulation of the surrounding R/C frame is done with linear elastic beam and column members together with predetermined locations of possible plastic hinge formation at the ends of each element the same way as described in section 2.1.

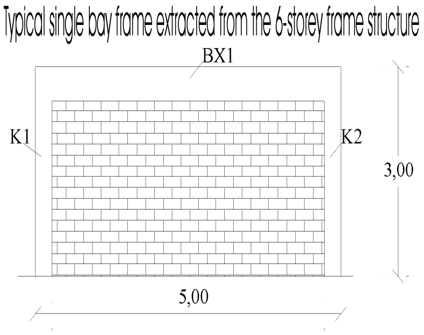


Figure 10a: Typical masonry infilled frame unit of the 6-storey building.

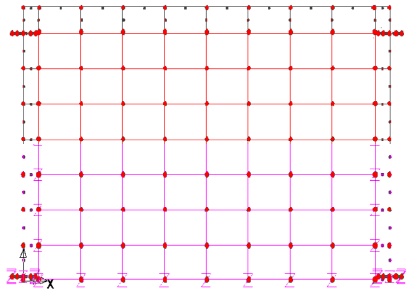


Figure 10b: Fully non-linear masonry infilled R/C frame simulation (type A).

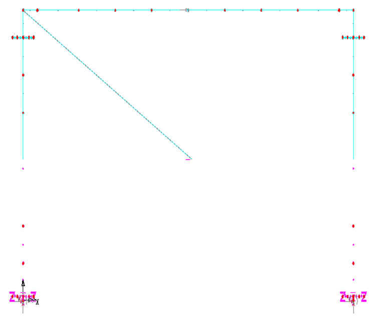


Figure 10c: Non-linear surrounding R/C frame- with multi-linear diagonal for masonry infill (type B).

c) *Simulation of interface between the R/C frame and the masonry infill* The numerical simulation of the interface between the prototype R/C frame and the masonry infill is done in the same way as described in section 2.1, utilizing non-linear joint elements in the axial and transverse direction. This interface is assumed that was built with mortar type H (see Thauampteh [10] and Table 5) with mechanical properties typical to the ones used in the Greek building practice.

B) Non-linear surrounding R/C frame with multi-linear diagonal struts (Simulation type B): Next, the proposed equivalent type B numerical simulation that has been proposed in section 2.2. will also be applied for the whole 6-storey structure. As was done in simulation type A here too the numerical simulation of R/C members will be done with linear elastic beam and column elements together with predetermined locations of possible plastic hinge formation at the ends of each element (figure 10c). The properties of each equivalent diagonal struts are determined with successive approximations as described in step e of Table 1.

For each one of these single-stories masonry infilled R/C frame units a “pushover” type A analysis is performed and the horizontal load (H) versus horizontal displacement (δ) or shear strain (γ) response curve is obtained, as indicated by figure 11. The accumulation of damage to the masonry infills is also obtained linked to the increase of the shear strain levels as it results from this fully non-linear type A simulation (as indicated in figure 11). This is done for preselected shear strain values (e.g. 0.1%, 0.15%, 0.2%, 0.25%, 0.30% and >0.35%). For each one of these single-storey masonry infilled R/C frame units a number of type B simulations are next prepared. A “pushover” type B analysis is now performed. The properties of a multi-linear diagonal strut are found approximating for each single-storey infilled frame the stiffness and strength variation as obtained from its fully non-linear A type simulation. In figure 12, a comparison between push over curves obtained from simulation type A and simulation type B of a retrofitted single storey R/C masonry infilled frame unit can also be depicted. For the predicted shear strain value of 3,2‰ the expected performance (development and propagation of damage) can be deduced for each masonry infill (initial and retrofitted) of the multi-storey structure, as shown in the figures 13a and 13b.

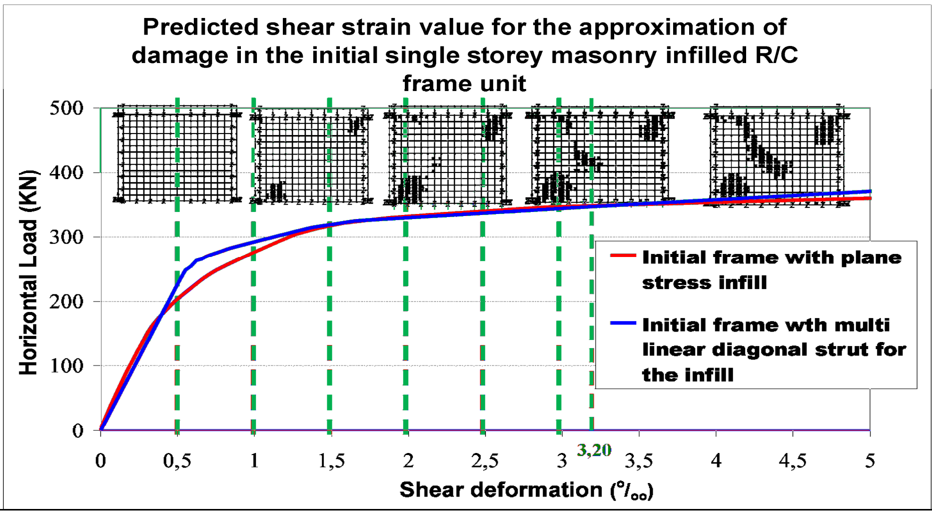


Figure 11: Comparison between push over curves obtained from simulation type A and simulation type B of a single storey R/C masonry infilled frame unit.

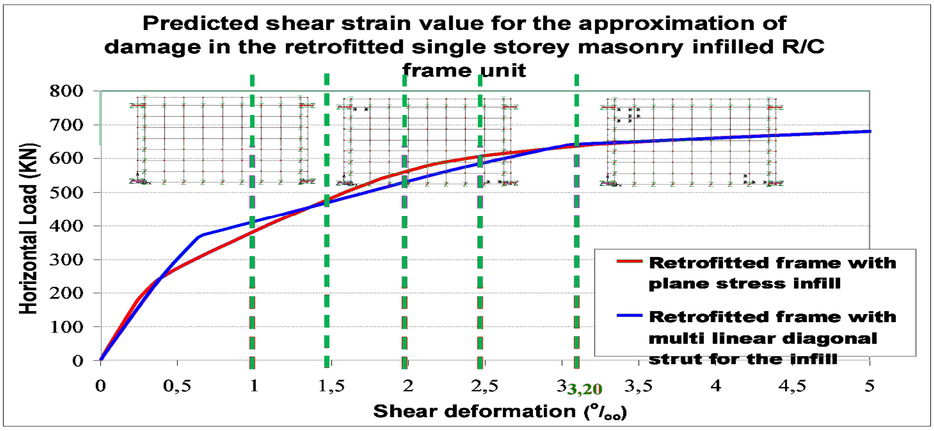


Figure 12: Comparison between push over curves obtained from simulation type A and simulation type B of a retrofitted single storey R/C masonry infilled frame unit.

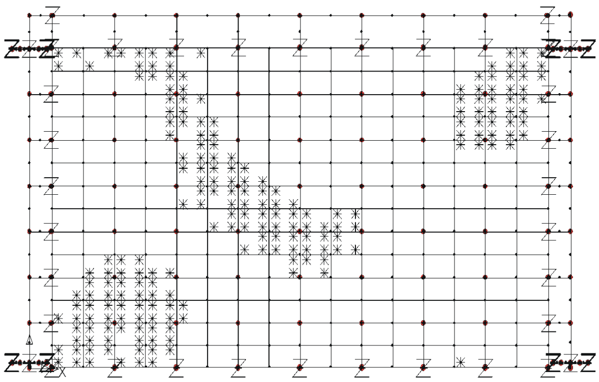


Figure 13a: Damage pattern of the infill, as predicted from the full non-linear analysis (type A) for the shear strain level $3{,}2^{o}/_{oo}$.

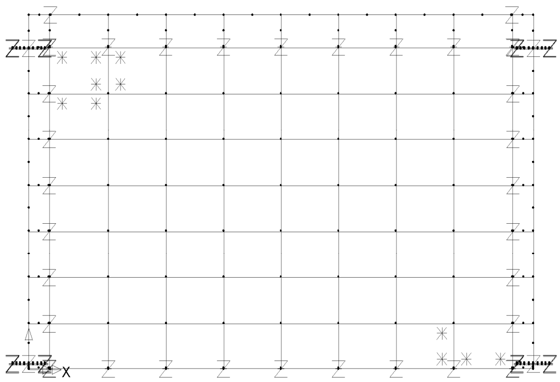


Figure 13b:Damage pattern of the strengthened infill, as predicted from the full non-linear analysis (type A) for the shear strain level $3{,}2^{o}/_{oo}$.

3.3 Numerical simulation of the Multi-storey frame and Predicted damage "Pushover" curves

Figure 14 depicts the base shear – top deformation curve obtained either by the fully non-linear "pushover" type A analysis for an initial masonry infilled 6-storey structure, when the top displacement reached the target value of 54mm, or the proposed equivalent type B analysis with the multi-linear diagonal struts. In the same figure the behaviour curve of a retrofitted 6-storey structure with strengthened masonry infills is also presented. The target displacement corresponds to approximately 0.3% shear strain level for the masonry infills. The employed type B simulation is also depicted in the top left of figure 14 together with the horizontal storey displacements at this maximum shear strain level (0.3%). As can be seen, the load-displacement response obtained by the equivalent post-elastic analysis is in good agreement with that predicted by the fully non-linear analysis. Using the procedure of step h of Table 1, the predicted masonry damage along the height of this structure was also obtained. Figure 15a,b depicts in more detail the predicted damage of the masonry infills of the 6-storey structural formation as it resulted from either the fully non-linear type A or the equivalent type B numerical simulations, respectively. As can be seen, good agreement is obtained between the masonry infill damage predictions of the equivalent type analysis with those resulting from the fully non-linear type A approach for the whole 6-storey structure. In figure 16a,b the predicted damage patterns are also presented for the retrofitted masonry infilled R/C frame that utilizes strengthened infills.

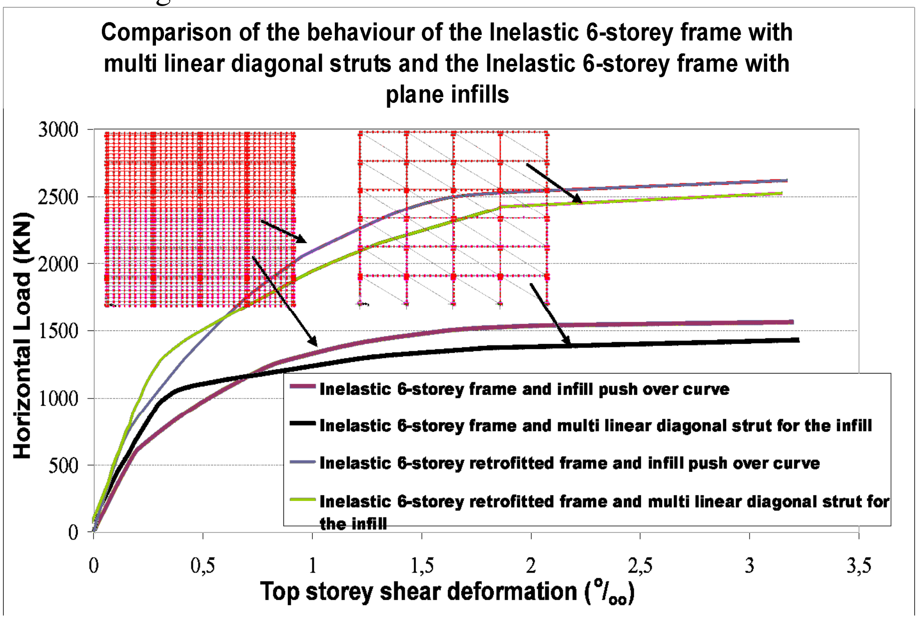
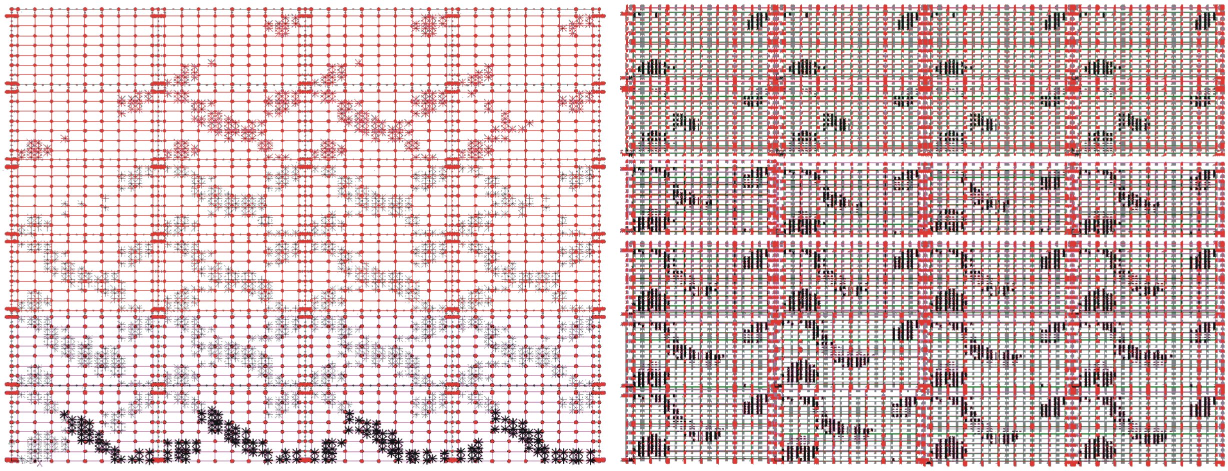


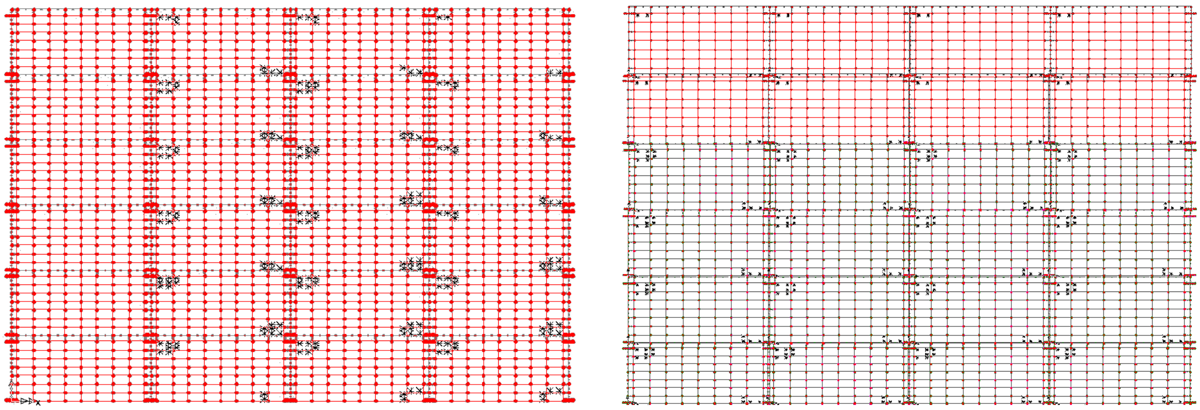
Figure 14: Base shear – top storey deformation "pushover" response as predicted by either type A or type B ($\gamma = 0.3\%$).



a) Masonry damage prediction type A

b)Masonry damage prediction type B

Figure 15: Detail of masonry infill damage patterns, as predicted for top storey target displacement equal to 0.3% of the building height by a) type A or b) type B simulations.



a)Masonry damage prediction type A

b)Masonry damage prediction type B

Figure 16: Detail of strengthened masonry infill damage patterns, as predicted for top storey target displacement equal to 0.3% of the building height by a) type A or b) type B simulations.

As can be seen from these figures there is reasonably good agreement in the pushover "top storey versus base shear" response of the 6-storey structural formation predicted by the equivalent type B analysis with that predicted with the considered more accurate fully non-linear type A analysis. Moreover, there is also reasonably good agreement between the damage patterns of the masonry infills predicted by the type B simulation as explained in step h) of the outlined methodology in Table 1 with the corresponding damage patterns of the masonry infills, as predicted by the more accurate fully non-linear type A analysis.

The corresponding "pushover" analysis for this strain level when employing the fully non-linear simulation of the masonry infilled frames lasted 50 minutes whereas the "pushover" analysis with diagonal struts lasted 2 minutes and 30 seconds. Thus, considerable gains 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.

4 CONCLUDING OBSERVATIONS

1. The strength and load-displacement hysteretic behaviour observed during the experiments of single-storey one-bay masonry-infilled R/C frames examined in this study is successfully predicted of by the proposed numerical simulation.
2. The development of plastic hinges at the predetermined positions of columns and beam of the surrounding R/C frame observed during the experiments as well as the damage patterns for the masonry infill, in terms of crack propagation is also successfully predicted.
3. Finally, the dissipated energy during the experimental "seismic-type" cyclic-loading sequence is in good agreement with that resulting from the proposed numerical simulation.
4. The employed numerical simulation of masonry-infilled R/C frames having their infill repaired with reinforced plaster, predicts successfully the observed during testing increase in stiffness, strength and energy dissipation due to this presence of the partially reinforced masonry infill.
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 behaviour of such structural assemblies in terms of stiffness, strength modes of failure, as demonstrated from the observed behaviour.
6. The proposed numerical simulation can accommodate the use of an interface provided that the mechanical properties of the constituents of such an interface are known.
7. The damage patterns of the masonry infill observed during testing were well approximated by the proposed numerical simulation. The well known damage patterns for relatively weak "Greek" type masonry in the form of either diagonal cracking or compression failure in the regions where the masonry infill corners meet the R/C column to beam joint, are reproduced quite well by the proposed simulation.
8. Based on the successful validation of the proposed numerical simulation of the non-linear response of single-storey one-bay masonry-infilled R/C frames an equivalent "pushover" analysis is proposed next for predicting the behaviour of masonry infills from their interaction with the surrounding R/C structural elements when these masonry infills are incorporated within multi-storey frame structural formations.
9. By comparing the response of a planar multi-storey R/C masonry-infilled frame, as predicted by the fully-nonlinear simulation type A validated in the first part of this paper and the proposed equivalent "pushover" type B analysis, it can be demonstrated that this proposed "equivalent pushover analysis" is quite successful in predicting reasonably well the *"top storey versus base shear"* response of the 6-storey structure used for validation purposes.
10. By comparing the response of a planar multi-storey R/C masonry-infilled frame, as predicted by the fully-nonlinear simulation type A validated in the first part of this paper and the proposed "equivalent pushover" type B analysis, it can be demonstrated that this proposed "equivalent pushover" analysis is quite successful in predicting reasonably well the *propagation of the masonry infills damage* along the height of the 6-storey structure used for validation purposes.

11. The computational time needed for this "equivalent pushover" analysis is considerably less than the computational time needed for the fully non-linear analysis of multi-storey masonry infilled R/C frames when all the non-linear mechanisms of structural members are included, presented in the first part of this paper. Thus, it can be used as a useful design tool in order to assess the state of masonry infills within complex multi-storey structural formations. The proposed approach can also be utilized in the seismic- design for assessing the state of masonry infills and their potential damage for either newly designed or for an existing structures as part of a potential damage screening process.
12. It must be stressed that the proposed "equivalent pushover" analysis is an approximation. It approximates part of the non-linear bahavior and the masonry-infill to surrounding frame interaction utilizing the stiffness and strength variation of masonry infilled single-storey one bay frame units that the multi-storey structure is decomposed to. In this framework, given the computer time and computer memory gains that can be achieved by the proposed approximations it can be utilized in practical applications following the procedures that are generally recommended for such "pushover" type of analyses in the relevant codes of practice for earthquake design .

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