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# Experimental Evaluation of the Cyclic Behaviour of Scaled (1:3) Reinforced Concrete Frames

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**Abstract** This paper presents laboratory test results for two-column one-bay reinforced concrete (R/C) bare frames with or without masonry infills for 1:3 scale prototypes when the top beam is subjected to horizontal cyclic loading using 50kN axial load per column. It is well documented that infills affect the dynamic characteristics of building structures. At the same time, their uncertain behaviors have also been recorded. Many parameters, such as the infill materials, reinforcing of infills, connection to the surrounding frame by means of surrounded joint contact, local techniques, and others affect structural system behavior. The masonry infills increase the overall horizontal lateral strength and stiffness and partially structural strength; hence, proper use can positively affect the general seismic behavior. Masonry infill benefits were tested using several specimens: one virgin bare frame, one virgin bare frame with masonry infills, and one virgin frame with masonry infills and reinforced cement plaster. In this experimental series, the aim was to investigate and study the following parameters concerning the general problem of the frames and masonry infills under the influence of cyclic horizontal loading: the frame type, the masonry infill type and, the strength of mortars and coating used to construct the brick walls. The obtained results align with the results of similar studies in Greece. All results address the influence of the infills concerning stiffness, strength, and energy dissipation of the infilled R/C frames, which are significant parameters that should not be neglected.

**Keywords** R/C Frame, Masonry Infill, Lateral Strength, Stiffness

## 1. Introduction

Recent earthquakes experiences have shown that masonry infills have been seriously damaged many times. It could be said that the infill wall absorbed a part of the seismic energy. However, the problem is more complex as it is a dynamic structural system, and the stress-causing seismic loads are affected by the change in the stiffness of the walls [1] [2] [3]. Many multi-story R/C structures built-in seismic areas have the ground floor designed as a parking space. Therefore, the openings of the R/C frames at this level remain without masonry infills, whereas all other floors have masonry infills for the corresponding openings of the R/C frames.

As this behavior was not well understood in the past, many structures have soft floors designed and constructed with structural elements that must be upgraded to increase their ability to respond to such increased loads by future seismic activity. It causes structural damage (change of rigidity through uncontrolled damage) unless the R/C building elements on the ground floor are appropriately designed.

Conversely, the presence of masonry infills can drastically change the intended dynamic response of the structure, creating forces in improperly designed structural parts, adversely affecting response to horizontal seismic loads. Modern codes and regulations in various countries are still wary of considering masonry infills when calculating the intensity of seismic behavior for multi-story structures. It is because the extent of the effect of different masonry infill parameters in different frames has not been thoroughly investigated, and a generally accepted and relatively simple modelling simulation has not been formulated [4]. Several research studies and documented works have highlighted seismic vulnerabilities R/C structures with masonry infills in recent decades. In these structures, the seismic response is particularly affected by the existence of rigid masonry infill, which significantly modifies the response of the bare R/C frame, causing, in many cases, a fragile and unexpected collapse. Due to the heterogeneity of masonry infills and the properties of scattered materials, interaction design modelling between frames and masonry infills is a difficult task for engineers; so in most cases of the seismic design of structures, the structural effect of masonry infills is ignored [5].

This research investigated the influence of strengthening the brick walls in the infilled frame under cyclic lateral loading. The method of strengthening and the ways of loading have been investigated by other researchers [6] [7]. This research studies the influence of strengthening brick mortars and cement coating the walls. This paper tries to address the above issues and explore masonry infill interactions. R/C frames subjected to seismic loads are evaluated using the study of physical frame models with masonry infills using a 1:3 scale, under the influence of horizontal cyclic loads, using a reaction frame system, as part of an extensive research program that began in 1994. This research effort was based on an original experimental investigation carried out at the Laboratory of Strength of Materials and Structures in the Department of Civil Engineering at the Aristotle University, Thessaloniki. The experimental investigation includes single-story one-bay 1/3-scale infilled R/C frames built from original material, such as steel, concrete, and masonry infill (hollow masonry units and mortar). This study is valuable for further research to understand the behavior of virgin frames that include infill bricks. The study helps control assumptions so that analytical models can assess the influence of masonry infills in actual constructions when undergoing seismic simulation.

## 2. Research Significance

In this experimental series, the aim was to investigate and study the following parameters concerning the general problem of the frames and masonry infills under the influence of cyclic horizontal loading. The following parameters were considered specifically for our frames:

- Three categories of two-column frames, bare frame without masonry infills (F1BN), one bare frame with ordinary masonry infills (F2N), and one bare frame with strengthened masonry infills (F3NP)
- Frame type
- Masonry infill type
- The strength of mortars and coating used to construct the brick walls.

## 3. Construction Method

The tested laboratory models include 1/3-scale infilled R/C frames with a similar scale, geometry, and construction materials used for the 5-story three-dimensional building constructed at the European test site in Volvi district, Greece.

This research is part of the European Program (Euroseistest)» [8], which aimed to operate in a seismically active European region and conduct extrusion and other field experiments for the studies concerning Engineering Seismology knowledge and Earthquake Engineering. The elastic modulus scale factor Er between the modelling and prototype materials is identical to Er =Fr (stress scale factor). So, for the construction of the 1:3-scale physical models, the elastic modulus scale factor Er was chosen to be 1.0 based on a parametric study of prototype materials tested for this purpose [9]. The description of the single-story infilled R/C frame specimens ("bare" or masonry infilled) is given together with the instrumentation used to measure specimen behavior.

Several displacement sensors were placed to measure the relative displacement of the deformed specimens relative to the initial values. The relative displacements between the frame and the masonry infill were also measured during the loading sequence. **Figure 1** shows a typical 1:3-scale bare model frame, and **Figure 2** shows the layout of a model frame placed into the reaction frame with the instruments used to measure displacements.

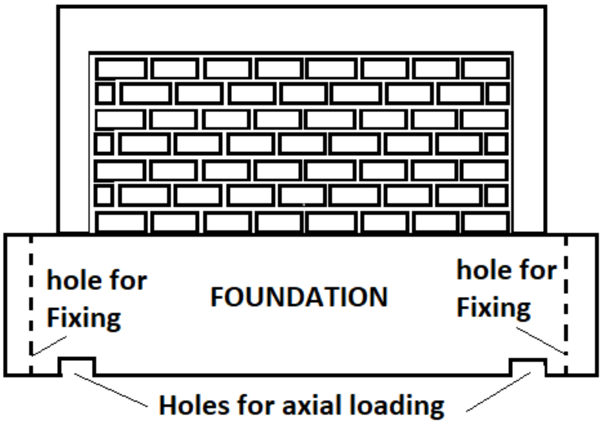

**Figure 1.** Typical 1:3 scale bare frame

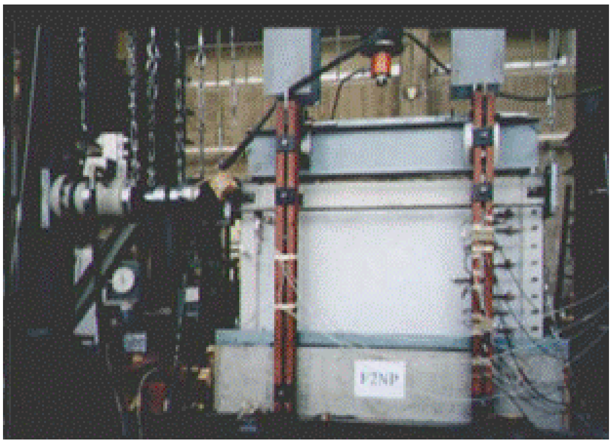

**Figure 2.** The layout of concrete model frames into the reaction frame

# 4. Experimental Procedure

## 4.1. Design and Construction of One-Bay One-Story Model Frames

Individual two-column bare frames with a single bay and story were constructed with and without masonry infills. The 1:3 scale models were tested at the Laboratory of Strength of Materials at Aristotle University of Thessaloniki (AUTH). The frames were tested under horizontal cyclic loading as a simplified representation of the seismic inertial forces. The two columns were simultaneously loaded with stable vertical loads. These vertical actions simulate the influence of the axial column loads related to the multi-story building in Volvi district, Greece.

## 4.2. Technical Properties of Materials Used for Frame Construction

All 1:3 scale physical models presented in this work are two-columns one-story R/C frames with or without masonry infills, having the same geometry. The design requirements for the prototype (ideal 1:1 scale frame) and model frame (1:3 scale) are shown in Table 1.

**Table 1.** Design requirements for the prototype (Ideal frame in scale 1:1) and model frame (scale 1:3) Prototype (ideal) Prototype (ideal)

| Frame Properties | Prototype (ideal) | Model (1:3) |
|---|---|---|
| Span (axis to axis) (mm) | 5160 | 1720 |
| Height (mm) | 3000 | 1000 |
| Column cross section (mm) | 350x350 | 110x110 |
| Beam cross section (mm) | 300x450 | 100x155 |
| Columns Reinforcement | 4Φ16 | 4Φ5.5 |
| Beam Reinforcement | 4Φ17 | 4Φ5.5 |
| Ties diameter | Φ16 | Φ5.5 |
| Ties span for column (mm) | 15 | 5 |
| Ties span for beams (mm) | 22 | 7.5 |

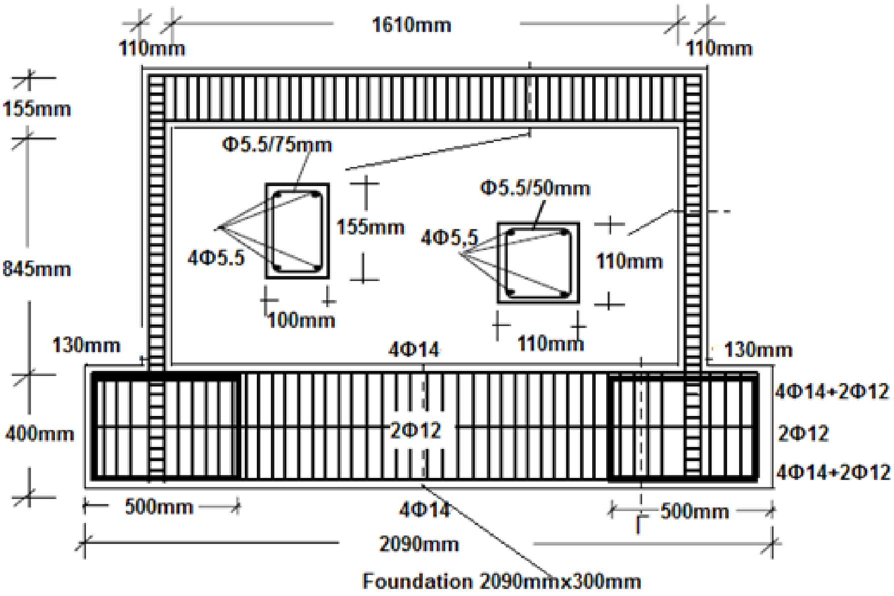

**Figure 3**a. Details of 1:3 scale tested frames

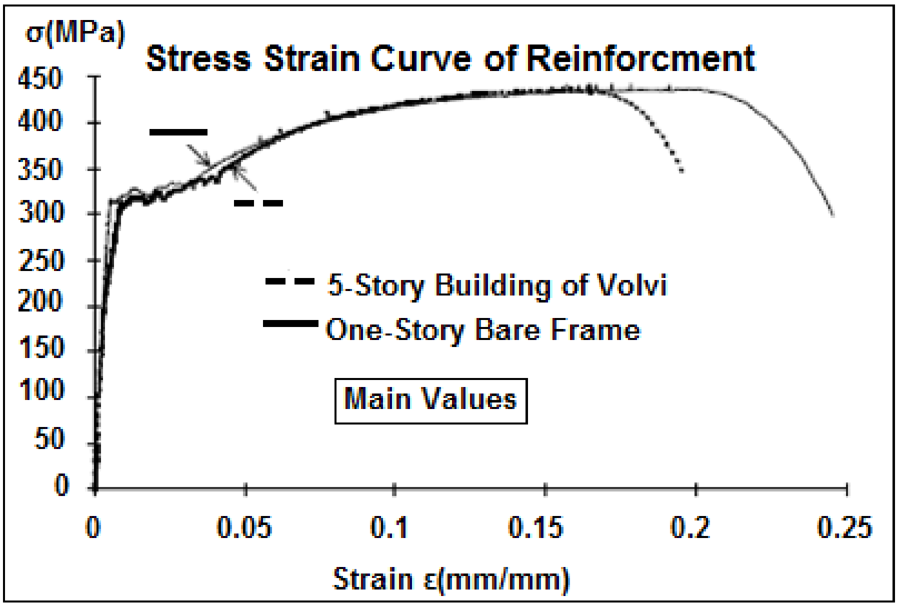

**Figure 3b.** Steel bar (1:3 scale) stress-strain curves compared to steel bars for target frames of the 5-story (1:3 scale) building

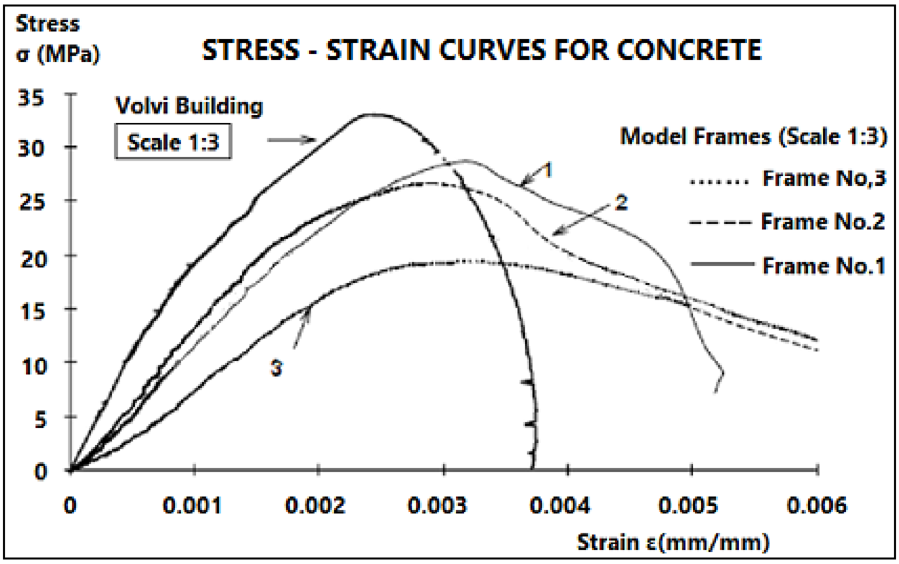

**Figure 4.** Concrete stress-strain curves for all frame models (1:3 scale) compared to the concrete of target frames of the 5-story building (1:3 scale)

The technical properties of the material used to construct the frames (with or without masonry infills) are specified below:

Reinforcement: reinforcement details are shown in **Figure 3a** and **Figure 3b**, indicating the excellent agreement of the stress-strain curve concerning the reinforcement steel for model frames compared to the 5-story 1:3 scale target model.

Concrete: Concrete is a tripartite mixture consisting of cement as a binder, aggregate materials of suitable size, and water as the process fluid. Concrete design for scale models is usually done based on the component weighing method and is generally governed by the same composition rules as the concrete construction. The mechanical properties of a mixture of concrete mixers directly depend on the proportion of individual components, mixing and maintenance process, and age. Aggregate type and size selection are based on two criteria: (a) The smallest dimension of the building element to achieve a good mixture and the R/C cover and (b) the use of aggregate curve lines given by regulation concerning R/C, displaced according to geometrical size scale 1r to smaller granule sizes. **Figure 4** shows the stress-strain curve model frame concrete and 1:3 scale target frames.

Bricks: Perforated commercial bricks of 5.85 cm x 8.5 cm x 19 cm size were used to construct the infill walls for filling the bare frames were and have. Their compression strength at 5.85 cm thickness was 4.8 MPa.

Mortar: The mortar is designed to fill the intermediate spaces (joints) between the bricks to bond solid masonry walls to transfer shear, tensile, and flexural stresses to the wall. All masonry mortars must be adequately workable to fill all brick irregularities and create joints without gaps.

Therefore, the mortars were prepared with a slightly plastic consistency. Mortars with different proportions of materials were also tested to study the influence of proportions on increasing or decreasing the shear strength of masonry infills walls (mortar V1 and mortar H). These mortars are tested in compression as shown in **Figure 5** and the stress – strain curves for these materials are given in **Figure 6**.

Cement Plaster: Coating was constructed using cement mortar having 350 kg /m3 cement. Three cubes were kept from each coating surface cement mortar to control its strength. Two categories of coatings were used: Fibre-based (soft wire with 0.75mm diameter and 5 cm average length) and fibre-free coating-2. **Figure 7** depicts the stress-strain curve of coating materials for the infill walls.

**Figure 5.** Compression test layout of mortar

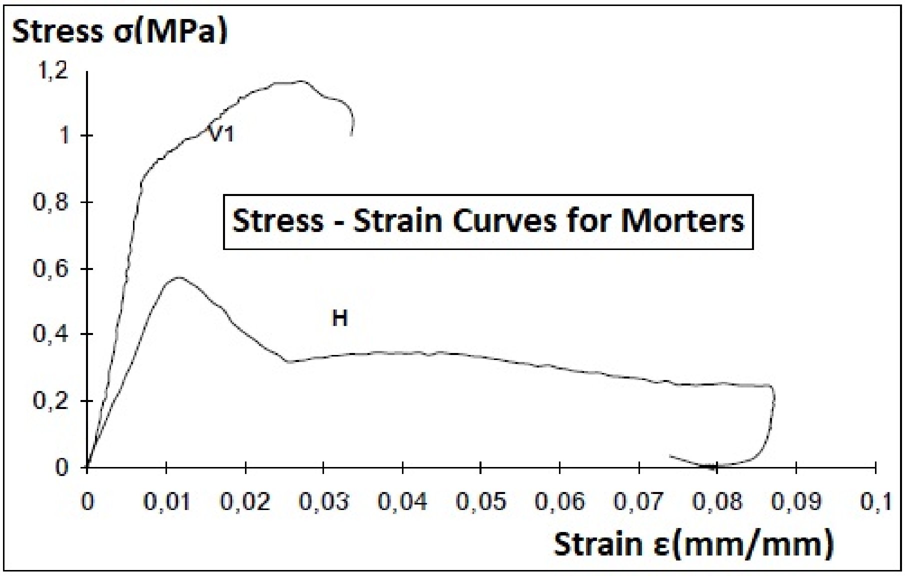

**Figure 6.** Stress-strain curve for mortars

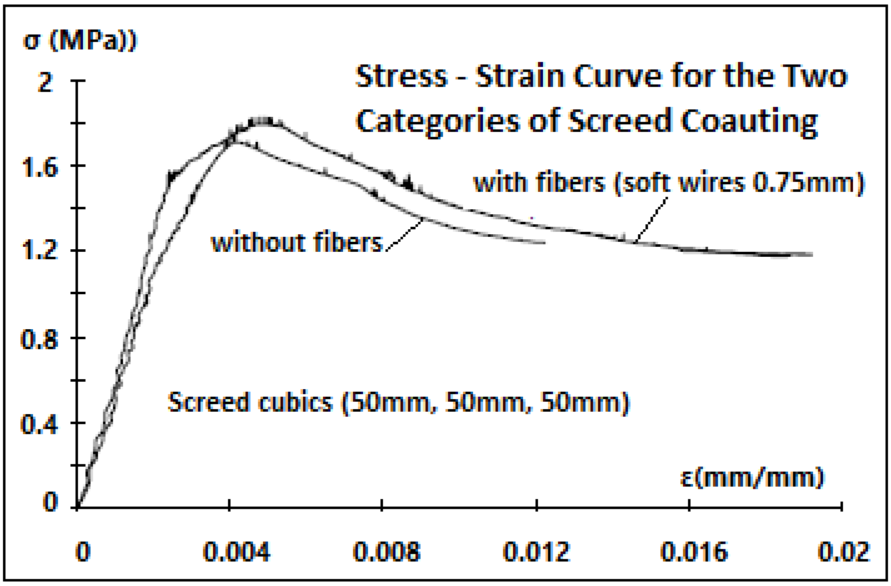

**Figure 7.** Compressive stress-strain curves of the two coating categories

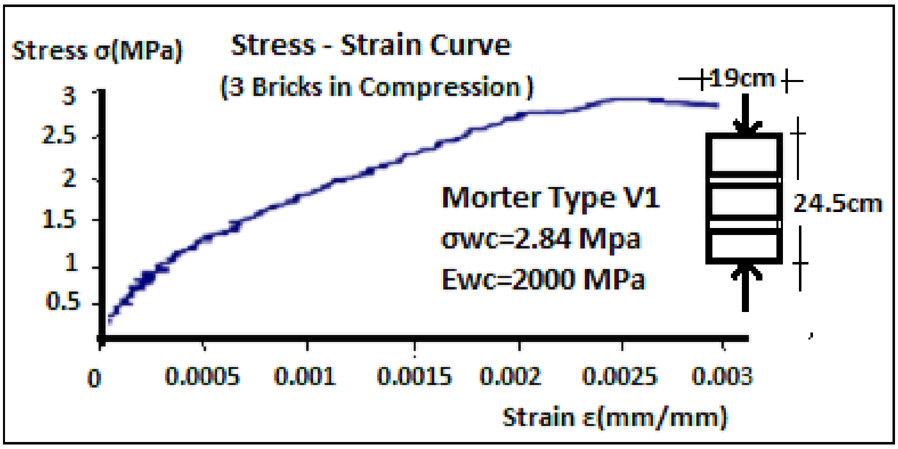

**Figure 8.** Stress-strain curve of the three brick walls with mortar type V1 during compression

Compressive strength of the masonry infills: In the present study, the net compression test was done in simple specimens with three bricks and wall specimens with dimensions of 68.2x37cm (**Figure 8**). A series of such tests found an average compressive strength of σwc=2,84MPa for the three bricks built with mortar V1; wall specimens had an average compressive strength of σwc=2,765MPa and σwc=1,91MPa for mortars V1 and H, respectively. Also, the corresponding mortar V1 and H walls were repaired using reinforced coating, giving average crush strength values of σwc= 3,72MPa and σwc= 2,33MPa, respectively.

Indirect Shear strength of masonry infills: The factors mentioned above influence individual mortar and brick material compressive strength and shear resistance to some extent. A pure shear experiment could determine the shear behavior and strength of the walls if the masonry was not turned during the experiment. For this reason, a shear resistance test is prescribed using an experimental arrangement: diagonal tensile square test subjected to diagonal compression load (**Figure 9**), where the shear stress $\tau_0$= P*0.707/(t x l), t is the thickness of the wall, and l the length of the wall.

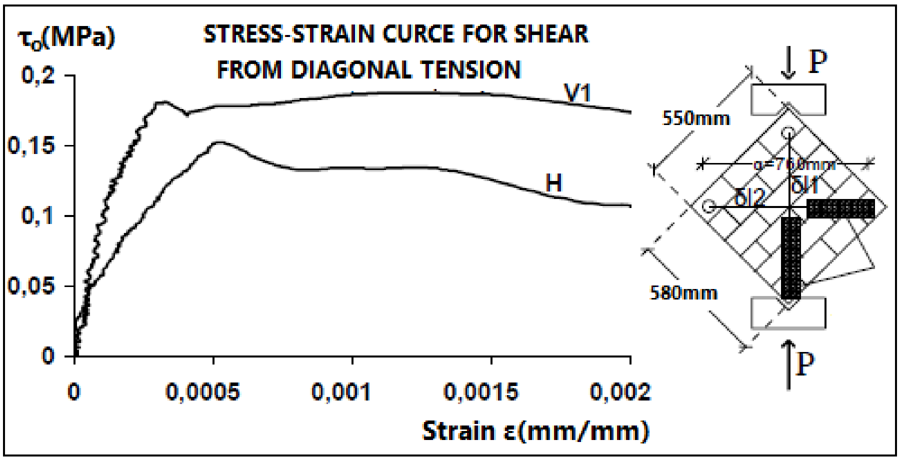

**Figure 9.** Stress-strain curve for the shear test at masonry infill walls

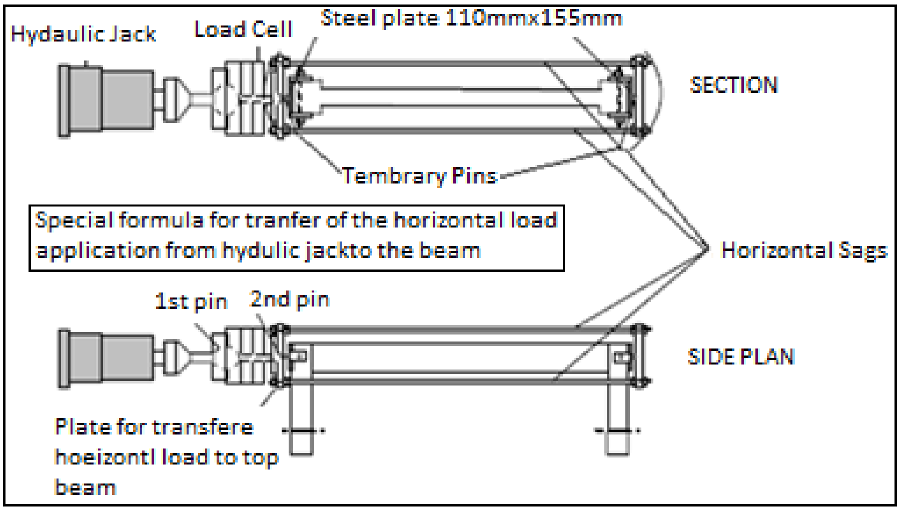

**Figure 10.** Horizontal load-carrying arrangement

### 4.3. Test- Up and Procedure

Lateral loading was applied using one double-acting horizontal hydraulic jack at the axis of the R/C beam, which is connected via the hinge (first hinge) to the Load Cell and again connected to the beam via a hinge connection (second hinge) (**Figure 10**).

Two steel plates on each side of the frame were used on the outer sides of the R/C frame (at beam depth). These plates had a small central groove on their outer side where a small steel sphere (temporary hinge) was precisely fitted. The whole system was secured through a small pre-tensioning system of two metal plates and four horizontal threaded steel rods. The above arrangement is used to avoid spacing during a change in displacement direction and eliminate compulsions at the points of application of displacement (at the hinge). Also, the existing hinges prevent the development of accidental bending moments and intersecting forces on the Load Cell and the horizontal hydraulic jack. Such forces are undesirable as they alter the actual values of the imposed axial loads. An IPB300 metal beam was mounted on top of the beam supported by hinges at the central point of each column to impose vertical axial loads on the center of R/C columns. The vertical load was applied at the center of the IPB300 beam using a vertical hydraulic jack that could be rolled to apply forces to the axis of symmetry in the middle of the specimen opening (see **Figure 10** and **Figure 11**)

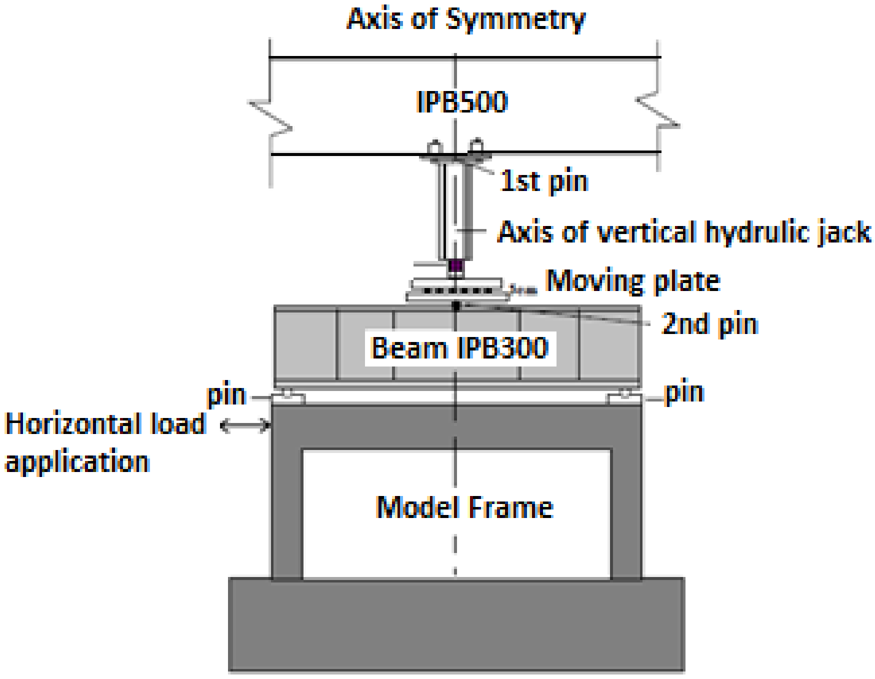

**Figure 11.** The layout of application of vertical load

The specimen weighing axis has a special connection (scroll) that allows unobstructed horizontal movement of the weighing only in the direction of the horizontal reversible loading. At the same time, the vertical load on the axes of the posts is applied parallelly. These arrangements support the specimens, perpendicular to the horizontal loading level and avoid accidental out-of-plane displacements. The loading history program includes complete reversals of gradually increasing horizontal displacements (pseudo-static loading). Three reversals were applied for each displacement level corresponding to three imposed displacements per level cycle and three respective response loops. The maximum required displacement remains constant. The change in displacements in each circle follows a sine-like change law. Successive stages have discrete charge history, interfering with interruptions between the stages. The rate of change of the forced displacement was 0.01Hz.

## 5. Experimental Results and Discussion

Three frames, F1BN, F2N, and F3NP, were tested. The behavior of the specimens (bare and infilled frames) is presented. Each specimen was tested under the combination of a 50 kN axial compressive load on each column and a horizontal cyclic load of gradually increasing displacements on the top beam of each R/C frame model. The structural behavior of each model was measured and recorded throughout the experimental series. These measurements were assessed, combined, and presented using diagrams that record the variation in dominant behavior parameters, such as:

- Change in stiffness
- Change in lateral strength
- Change in energy dissipation

Frame specimen behavior was studied extensively using force-displacement hysteretic curves and force-displacement envelope curves that record the variations in initial stiffness, strength, and energy dissipation along with the failure response for these masonry wall specimens. Valuable conclusions are drawn from assessing the influence of specific parameters on the cyclic behavior of these frames concerning the mechanical properties. The following hysteretic curves represent the three experimental series (**Figures 12 to 14**).

### 5.1. Failure Modes and Deformations

The progressive increase in displacement in the bare frames F1BN under the cyclic horizontal loading process, creates the following stages concerning deformation development:

Stage 1 Elastic behavior - non-cracked building elements: It lasted until the first occurrence of visible cracks. The diagonal deformations at the end of this stage for the bare frame were of the order of $\gamma$=0.54‰ ($\delta$=0.5 mm) and $\gamma$=1.08‰ ($\delta$=1.0 mm).

Stage 2 Slightly inelastic behavior - cracked building elements: The structural elements had reduced stiffness. Diagonal displacements at the end of this stage at the order of $\gamma$=8,7 ‰ ($\delta$=8,0 mm).

Stage 3 Inelastic behavior - large deformations: The first pair of plastic joints were formed at the base of columns for the bare frame. Higher displacement caused the formation of a pair of plastic joints; the bare frame had such a pair at the top of the column.

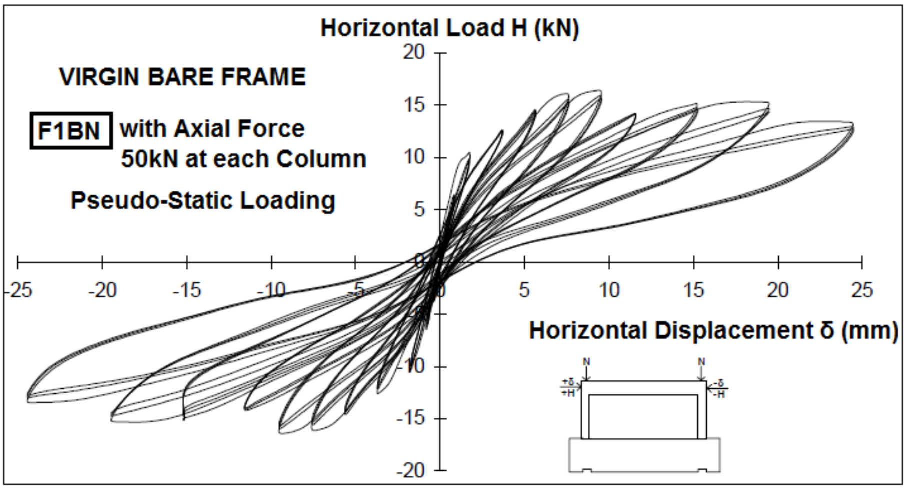

**Figure 12a.** Lateral load-displacement loops of bare frame F1BN

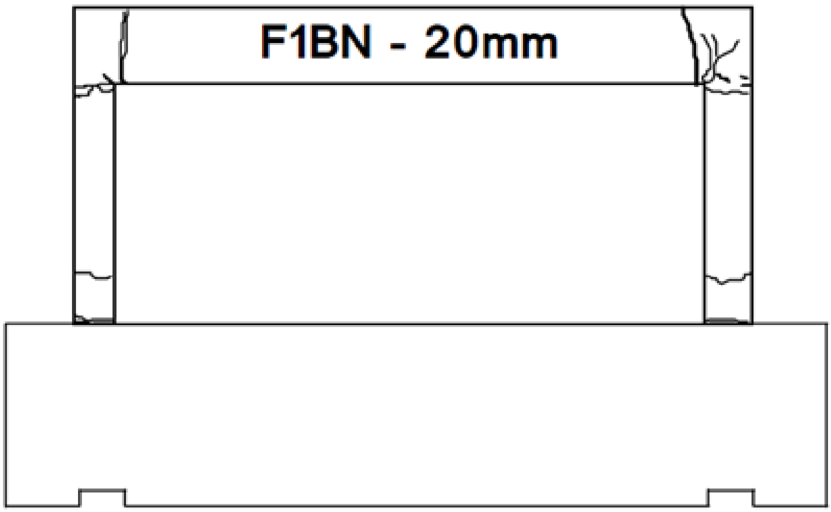

**Figure 12b.** Failure mode fo bare frame F1BN

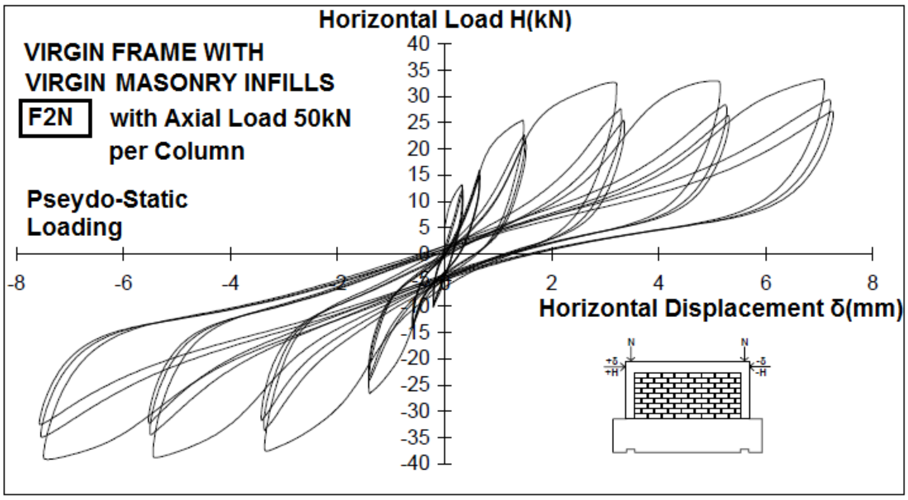

**Figure 13a.** Lateral load-displacement loops of frame F2N with ordinary Masonry Infills

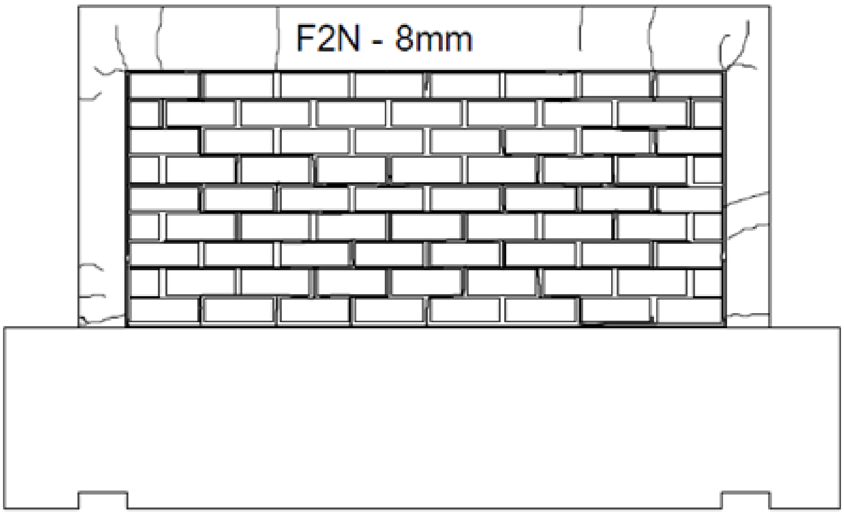

**Figure 13b.** Failure mode of frame F2N

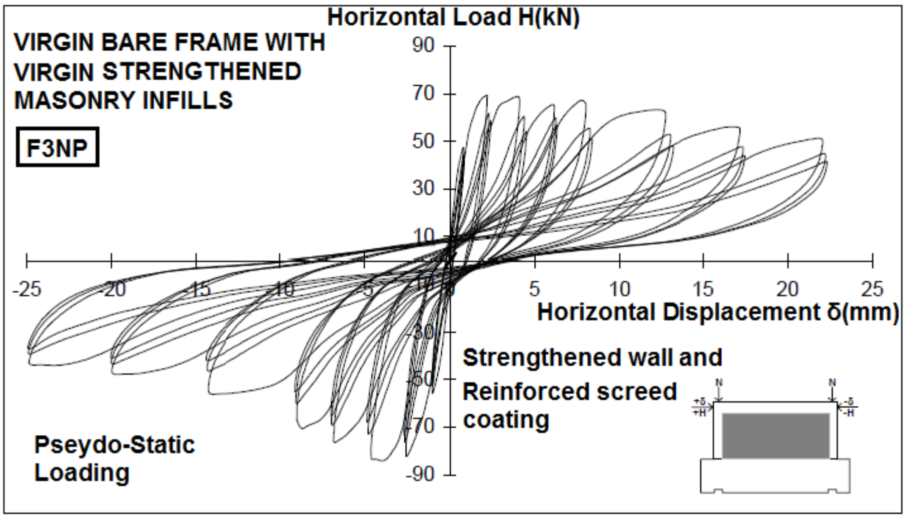

**Figure 14a.** Lateral load-displacement loops of frame F3NP with strengthened masonry infills using type V1 mortar and Caot-1 type fiber plaster

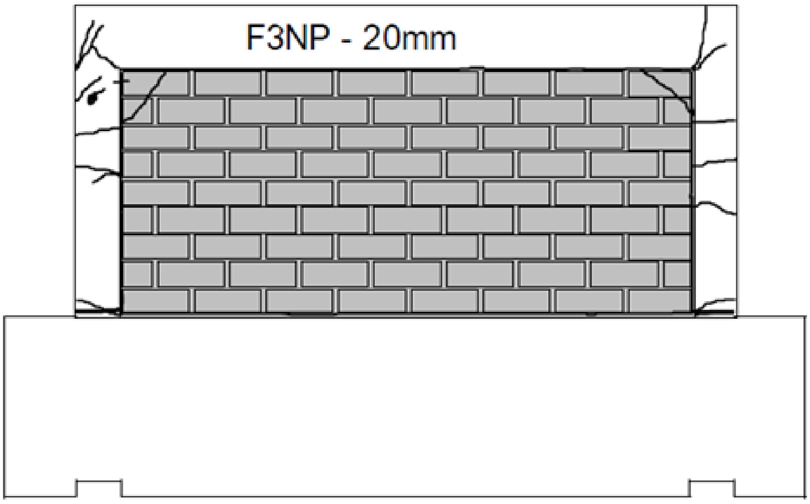

**Figure 14b.** Failure mode of frame F3NP

### 5.2. Failure Modes and Deformations of Frames with Masonry Infills (F2N & F3NP)

The failure modes of frames F2N and F3NP are shown in **Figure 13b** and **Figure 14b**, respectively. The progressive increase in frame displacement with masonry under the cyclic horizontal loading has created the following deformation development stages.

Stage 1 Elastic behavior - full-rigid body behavior: The diagonal deformation at the end of this stage was γ=2.2‰ (at δ=2 mm) for the frame F2N and was γ=4,3‰ (δ=4 mm) for the frame F3NP.

Stage 2 Slightly inelastic behavior – cracked R/C elements - wall cracking: At the end of this stage, which was the end of the experimental series, the diagonal deformations were γ=8,7‰ (δ=8 mm) for the frame F2N and γ=6,5‰ (δ=6 mm) for the frame F3NP. For frame F3NP, two more stages were observed:

Stage 3 Slightly inelastic behavior - cracked R/C elements - local masonry wall failure: At the end of this stage, the diagonal deformation was γ=8.7‰ (δ=8 mm), the first pair of plastic joints was formed at the two ends of the beam. For a given displacement during the 7.09 mm loading sequence, the corresponding diagonal deformation was γ=7.7‰.

Stage 4 Elastic behavior of R/C - element collapse of the infills at the corners: At this stage, plastic joints formed at the beams' ends and the base of columns, while the bricks at the corners of the wall were crushed.

Initially, the presence of masonry infills in frames increases the frames' lateral strength, initial stiffness, and energy dissipation capacity, as shown in **Figure 15**, **Figure 16**, and **Figure 17**, respectively.

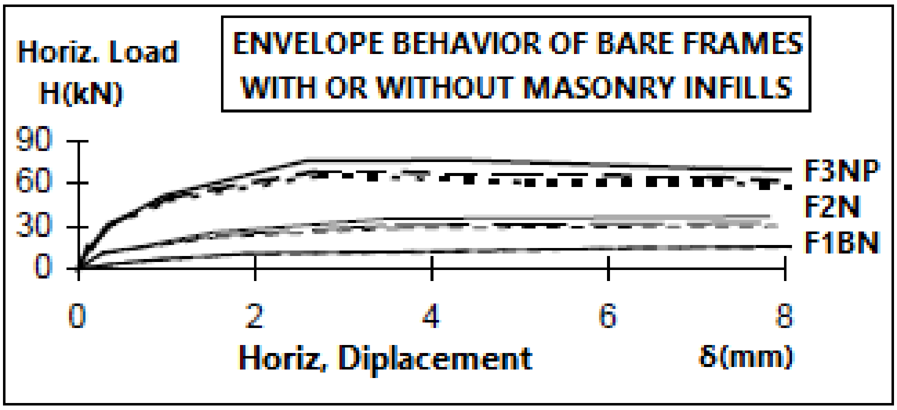

**Figure 15.** The envelope behaviour of bare frame F1BN compared to F2N and F3NP with masonry and strengthened masonry infills

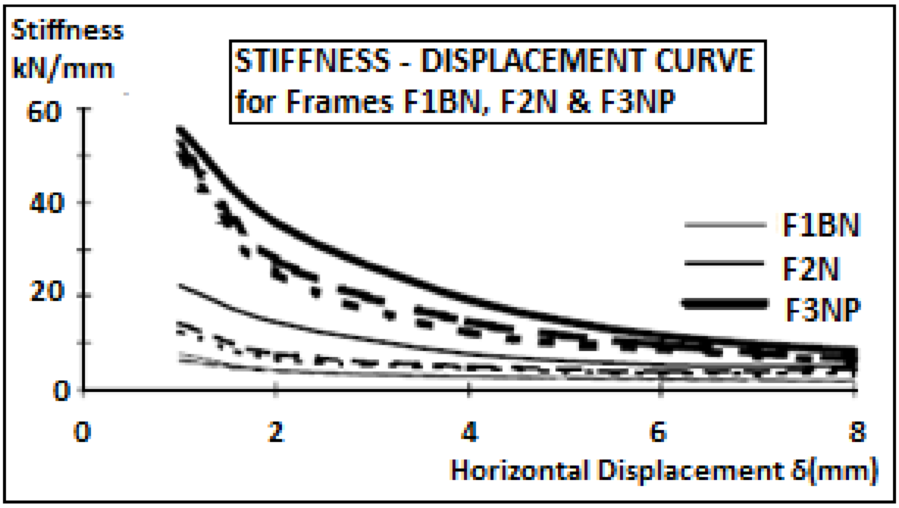

**Figure 16.** The envelope behaviour of stiffness of bare frame F1BN compared to F2N and F3NP with masonry and strengthened masonry infills

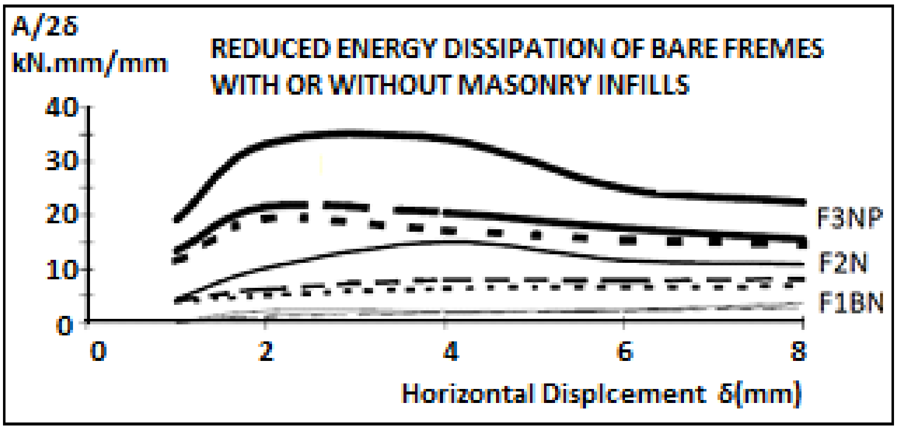

**Figure 17.** The energy dissipation of behavior of bare frame F1BN compared F2N and F3NP with masonry and strengthened masonry infills

**Table 2.** Plasticity and energy dissipation of frames with masonry infills

| a/a | Researchers | Masonry Type | link with Frame | Strength Ratio | Stiffness Ratio | Energy Dissipation Ratio |
|---|---|---|---|---|---|---|
| 1 | K. Stylianidis [10] | Plain | No | 1.50 ~2.40 | 3.50~7.60 | 5.70~14.40 |
| 2 | Th. Valiasis [11] | Plain | No | 1.53~2.68 | 2.66~4.70 | 4.70~6.20 |
| 3 | Bilal Yasin [12] | Plain | No | 1.52~1.88 | 1.26~2.03 | 4.25~6.70 |
| 4 | This Paper | Plain<br>Strengthen | No<br>No | 1.62 ~2.22<br>2.41 ~3.95 | 2.29~4.12<br>2.25~ 5.2 | 4.49-9.75<br>8.64~12.66 |

In the case of relatively weak infills, based on the examined infilled frames, the failure modes of the infilled frames are almost the same as the corresponding bare frames. In the case of relatively strong infills, the frame's load capacity, stiffness, and energy dissipation capacity increase more. Masonry infill behavior can be simulated using disc failure mode.

## 6. Conclusions

As shown in Table 2, the obtained results align with the results of similar studies in Greece. All results address the influence of the infills concerning stiffness, strength, and energy dissipation of the infilled R/C frames, which are significant parameters that should not be neglected. This influence is determined by the details and building practices used to construct the infill panels within the R/C frames. The original experimental material and quantitative and qualitative conclusions drawn from the study are significant and provide a comprehensive understanding of a complicated problem.

The study of the cyclic behavior of single-story infilled R/C frames and masonry walls has produced an original experiment. The behavior of infilled R/C frames was evaluated to represent original conclusive observations.

The hysteretic loops of the bare frames are rich, typical of the inelastic rotation of the plastic hinges (see **Figure 12** to **14**). On the contrary, pinching effects occur at the infilled frames, typical of brittle behavior due to infill cracking.

The investigation is significant because it attempts to quantify the behavior of all constituents of an infilled R/C frame. The mechanical properties of the constituents of an infilled R/C frame can be used to create a numerical simulation for the infilled frames. Individual or combined accuracy can be calculated for the constituents. The research effort produced experimental data for use in similar numerical simulations. Moreover, it produced qualitative conclusions about the significance of the infilled R/C frame constituents (frame, infill-frame surrounded joint contact, and infill panel) that can provide vital guidance to form and validate such numerical simulation

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