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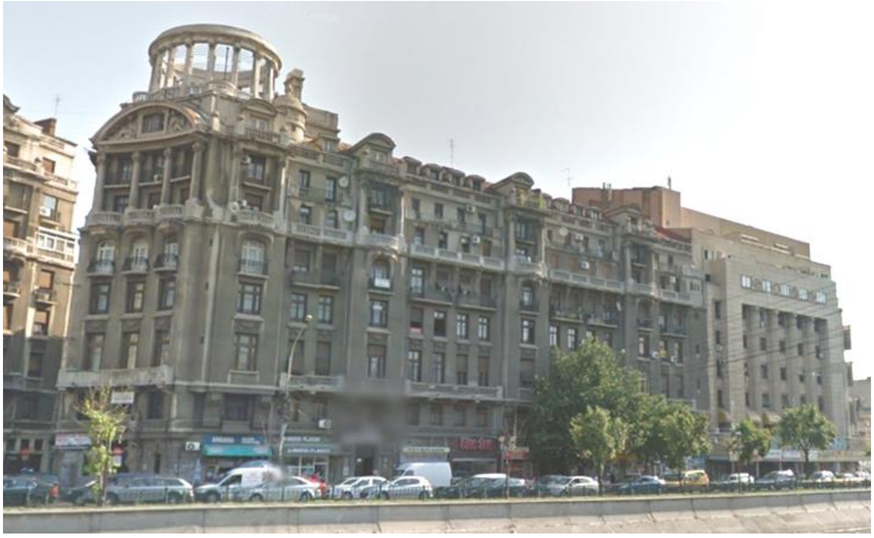
PHD THESIS

THE SEISMIC RESILIENCE OF INTERWAR STRUCTURES

SUMMARY



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Bucharest, 2022

Acknowledgment

I thank to the scientific coordinator prof. Ramiro Sofronie for his guidance and for the determination of supporting me in the process of finalizing the doctoral thesis. I also thank him for constantly motivating me in difficult times and for sharing his rich professional and life experience with me.

I thank to the official commission, formed by prof. Valentin Feodorov, prof. Marius Moșoarcă and conf. Daniel Stoica.

I thank to my former colleagues for sharing their experience with me and for giving me the opportunity to be involved with them in extraordinary projects.

With gratitude and love, I dedicate this thesis to my wife and family, who have constantly supported and encouraged me throughout my doctoral studies.

Bucharest, april 2022

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CHAPTER 1. Introduction

1.1. Explaining the title, the importance of subject

The thesis refers to solid brick masonry made of burnt clay with clean lime mortar. This masonry, the oldest and also the original masonry, is non-composite. Saint Venant's principle of geometric continuity is not valid.

The original masonry differs from all other types of masonry, even simple or reinforced. Lime mortar masonry is the only one capable, of all masonry types, of the phenomenon of adaptation. Under these conditions, it satisfies Aesop's philosophy.

Fig. 1.1.1. Aesop

Interwar Romania was an exporter of grain and oil. Economic development has led to an increase in the number of heritage, monumental, collective, administrative and industrial buildings.

Fig. 1.1.2. Royal Palace in Bucharest

The goal of the thesis is to evaluate, protect and enhance them in the context of seismicity of the national territory, especially for sites with high seismicity.

However, Romania is a country having a unique seismicity in Europe, which is different to Greece, Italy, Turkey. Its unique elements are the subcrustal depth, duration and large magnitude.

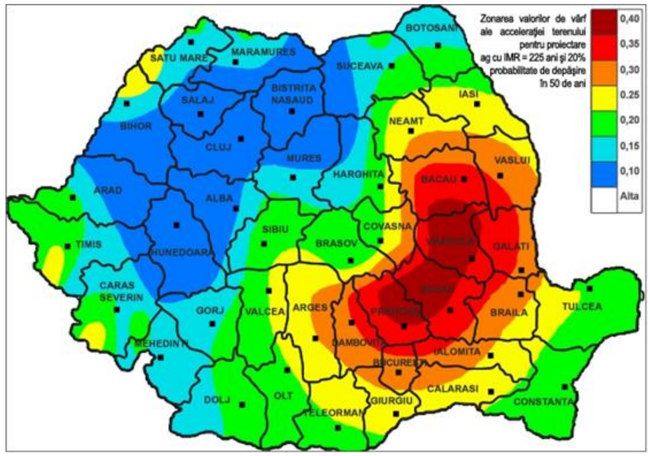


Fig. 1.2.1. Seismic map of Romania in 2022

Currently, there are both nationally and internationally debates on the construction of resilient cities, buildings, systems, companies or procedures in the case of unforeseen events. This is also the case of This is also the case of the seismic resilience of the patrimonial fund built from the interwar period.

CHAPTER 2. The objectives of the thesis

This doctoral thesis has the following objectives:

1. Exposing the state of knowledge, regarding both the general concept of resilience, as well as seismic resilience in particular;
2. Showcasing the state of knowledge when it comes to calculation concepts and the structure of interwar buildings in Romania;
3. Criticism of the state of knowledge, referring to the concept of resilience, and the clarification of this very concept;
4. Establishing the influence of seismic resilience over lime mortar masonry, specific to interwar structures;
5. Clarifying the differences between masonry which uses solid bricks and lime mortar, and masonry which uses ceramic bricks, having vertical gaps and cement mortar;
6. Numerical interpretation of experimental models involving masonry with lime mortar;
7. Identifying the main types of interwar structures in Romania and philosophical concepts that are the basis for them;
8. The experimental determination of the performances of the lime masonry, reinforced with polymeric grids and confirmation through comparative numerical models;

9. Determining the seismic resilience of interwar buildings that are made of lime masonry by using case studies, as well as proposing solutions for its enhancement;
10. Realizing a comparative economical evaluation from the perspective of the year 2021.

CHAPTER 3. The state of knowledge in the field considered by the thesis

3.1. The concept of resilience in the specialised literature

The notion of resilience was formulated by Robert Hooke, in 1678, at London. Later, in 1930, Timosenko defined it and gave it a mathematical formula.

Resilience is the largest amount of energy per unit volume that can be stored in a bar without permanent deformation.

I studied over 25 definitions from the technical literature. There is no general consensus on the meaning of this notion.

3.2. Calculation and composition concepts of interwar buildings in Romania

The structural design of interwar buildings was made only to gravitational actions, and the main types are buildings with structural walls of load-bearing masonry and buildings with reinforced concrete frames and inframed masonry.

Fig. 3.2.1. Buildings with structural masonry walls

Fig. 3.2.2. Buildings with reinforced concrete frames and inframed masonry

Masonry is a very old material, symbolically of over 10,000 years, while reinforced concrete is less than 150 years old.

CHAPTER 4. Criticism of the state of knowledge

4.1.The concept of resilience

Romanian design codes do provide for seismic protection requirements, but they do not mention the notion of resilience. I adopted the definition which was published in the Journal of Geological Resource and Engineering 7 (2019) 132-139, New York, entitled “On the seismic resilience”. The basic idea of the article is to assimilate resilience with reliability.

$$R_{res} = R_{rel}$$

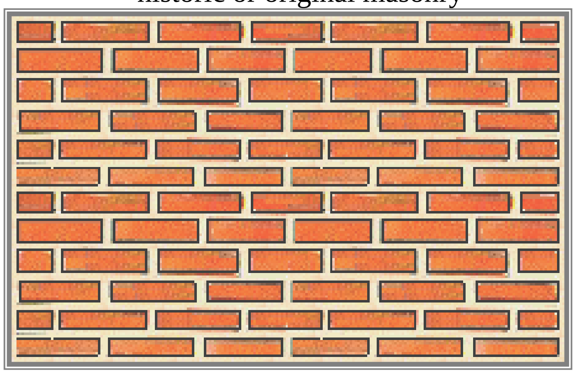
Seismic resilience is the probable capacity of buildings of self-defense against earthquakes.

The concept of resilience has been taken over and used in many fields of activity. Criteria for evaluating its definitions have been established in this chapter. There is no unitary idea.

CHAPTER 5. The approach of the subject in the doctoral thesis

5.1.Types of masonry

Solid brick masonry and lime mortar also called historic or original masonry



- Over 10,000 years old;
- Adaptable, ductile, with free vertical joints, non-composite,

Hollowed brick masonry and cement mortar, or "Mascrete", as an acronym for concrete

- Appeared in the USA in 1871 and 1906;
- Monolithic, brittle, no vertical joints, composite

5.2.The three known types of reinforcement

Although the used term is "reinforcement", a clear distinction must be made between the well-known way in which the concrete is reinforced with steel reinforcement and the way in which the polymer grids with the substrate of lime mortar work. [53] Thus, there are 3 distinct types of reinforcement:

I. 1867, Paris - Joseph Monier, reinforced concrete in which the cooperation between concrete and reinforcement is explained by the vise effect. It is based on friction and / or shear with unit stresses of type τ (MPa);

II. 1962, London - Henry Vidal, granular and non-cohesive ground reinforcement, which is made on the basis of anchoring the reinforcement to normal σ (MPa), tensile stresses;

III. 1995, Bucharest - Romanian patent for reinforcing brick masonry filled with lime mortar with polymer grids, with uniformity of efforts around geometric imperfections.

5.3.Landau's concept of dislocation, Landau being the winner of Nobel prize in 1962

Polymer grid reinforcement is based on the observation that the vertical joints of polymer grid masonry act as geometric imperfections that cause local concentrations of unitary stress, according to Landau's theory. Concentrations of stress resulting from geometric imperfections such as vertical joints can be redistributed in the mass of masonry, to areas with lower stress, using polymer grids. The grid takes over the efforts in the masonry and redistributes them uniformly, in the masonry mass, with the help of mortar. Polymer grids and masonry work independently of each other.

The principle of "full on joint" applies to masonry. Also, the vertical joints are generally equidistant and the coverage of the vertical joints is symmetrical.

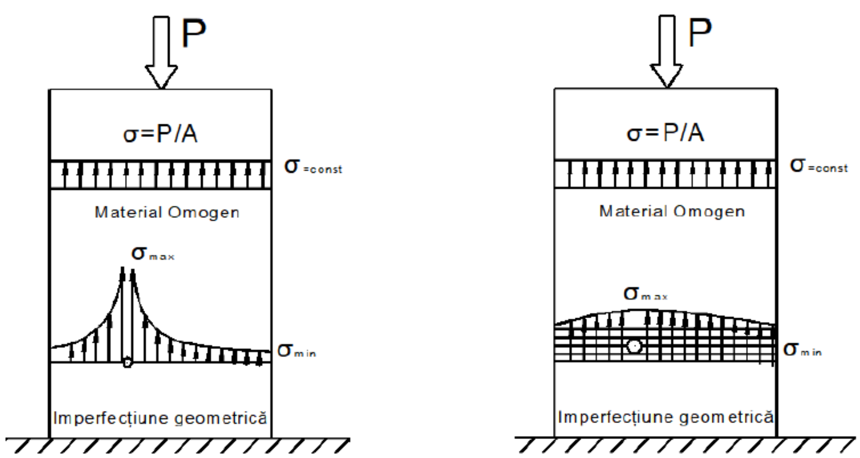


Fig. 5.3.1. The alleviation of the stress with the help of grids [47]

5.4.Experimental research on the seismic behaviour of historical masonry in Italy

5.4.1.General data

An 3D model of reinforced masonry building with real-size RG20 polymeric grids was constructed. It has only one axis of symmetry. The flooring above is made of wooden material. The model was made by hand, with M2 mortar according to EC6 standards, which corresponds to the Romanian M10 lime-cement mortar. [47]

In the first phase, the model was not plastered nor on the inside or the outside. Reinforcement at the level of the horizontal joints with polymeric grids was used. In the second phase, the same model was repaired and coated with polymeric grids, then plastered with the same M10 mortar. The tests they were subjected to were modelled on the 1977 Vrancea earthquake. The accelerogram was amplified by 1, 2, 3….8 times, so the tests lasted 3 hours for each try. [47]

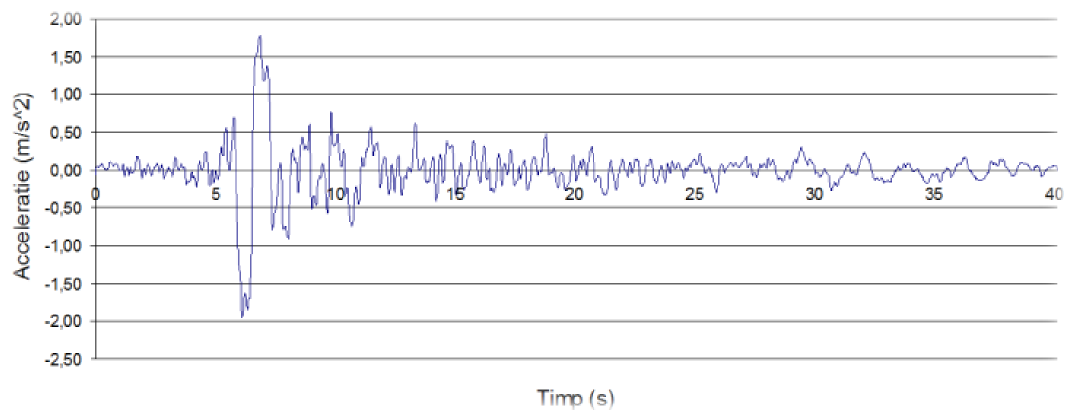


Fig. 5.4.1. Vrancea 77 accelerogram with N-S component [47]

5.4.2. 3D model of a heritage building made of solid brick masonry with lime mortar in an unconfined version – July 2001

The 3D model of the heritage building was made of solid brick masonry with lime mortar. The top view dimensions of the model were 2.78x2.17 m, while its height was 2.9 m. The thickness of the walls was 23 cm, and the dimensions of the bricks were 230x105x60 mm. On two opposite walls, two semicircular arched window openings were made. The weight of the model was 7.2t, and the metal framework also weighed 2 t. [47]

Fig. 5.4.2. Before the test [47]

Fig. 5.4.3. After the test [47]

5.4.3. **3D model of a heritage building made of solid brick masonry with lime motar in a variant that is confined with polymeric grids – November 2001**

The model of the heritage building, which was made of solid brick masonry with lime mortar was, after testing, repaired and consolidated through coating with polymeric grids and plastering with the same type of mortar.

Fig. 5.4.4. Before the test [47]

Fig. 5.4.5. After the test [47]

From the point of view of degradations, 45 degrees cracks were developed at the corners of the gaps, as well as local effects caused by support. However, the model kept its integrity. It was later found that the reinforcement had failed, but the bricks remained intact. This mechanism has positive effects, demonstrating that in the case of solid brick masonry, the coating with polymer grids is a reversible process. [47]

Fig. 5.4.6. The solid brick model – the bricks are still intact, while the reinforcement broke down [47]

Fig. 5.4.7. The hollowed brick model – the bricks broke down, while the grids are still intact [47]

5.5.Design code requirements from 2021

In 2021, the seismic codes underlying the investigation and consolidation of existing buildings, including heritage ones, are P100-3/2019, P100-1/2013 and CR-6/2012. Unfortunately, the notion of seismic resilience is not even mentioned in the aforementioned codes. This is an additional argument for this notion to be clearly and concisely defined.

The essential principles in the preservation of historical monuments are set out in the documents issued by the Venice Convention of 1964 and the ISCARSAH Recommendations of Paris in 2001. The main principles are the reversibility of the adopted consolidation solutions and the avoidance of the association between masonry with lime mortar and reinforced concrete. **The reinforcement of brick masonry with polymer grids fulfills both the requirements of the 1964 Venice Charter and the 2001 ICOMOS Recommendations in Paris.**

CHAPTER 6. The numerical interpretation of the experimental results

6.1. Numerical interpretation of experimental research, using the SAP2000 program

A numerical interpretation of the results obtained within the ISMES experiment, was carried out. In order to highlight the efficiency of the coating solution that involves polymeric grids, two calculation programs were used: SAP2000 and DIANA FEA.

6.1.1. Numerical modelling using the SAP2000 program

The numerical model was made using solid FEM elements, with eight nodes and six faces.

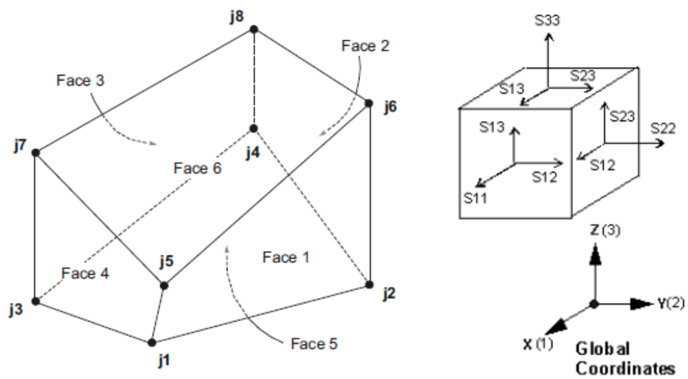


Fig. 6.1.1. Solid element, highlighting the local axes [55]

In the first variant, the reinforcement with polymeric grids was only made at the level of the horizontal joints, while in the second one, the confinement was made by coating with polymeric grids and lime mortar.

6.1.2. Determining the dynamic characteristics and the drift

In order to determine the dynamic characteristics, an additional model was developed for serving as a standard, without the contribution of any type of reinforcement. The second numerical model was reinforced with polymeric grids inserted at the level of the horizontal joints. The third one, in addition to the reinforcement with polymeric grids at the level of the horizontal joints, was coated with RG20 biaxial polymeric grids and lime-cement mortar, in a layer with a thickness of approxiamtely 2.5 cm.

6.1.3. Considerations regarding the dynamic characteristics and the drift

The influence of the polymeric grid reinforcement solution on the overall rigidity of the structural system is minor. Because the dynamic properties are insignificantly altered, the adaptability characteristic of the solid brick masonry and lime mortar is not affected.

6.1.4. Determining the stress diagrams for the joint reinforced model and the confined model

The stress diagrams for the joint reinforced model and the confined model were determined. The diagrams were presented comparatively to highlight the effect of confinement with polymeric grids. The main trend was for the confinement with polymeric grids and lime mortar to take over the peak efforts and redistribute them to areas with lower loads.

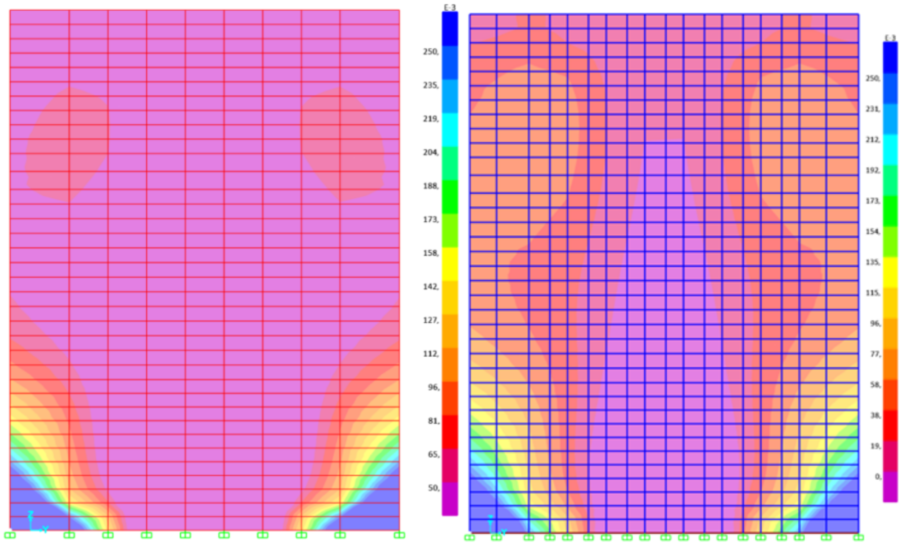


Fig. 6.1.4.1. The normal tension for the S11 solid wall (kPa) model 2 – reinforced at the joints (left) and model 3 – confined (right)

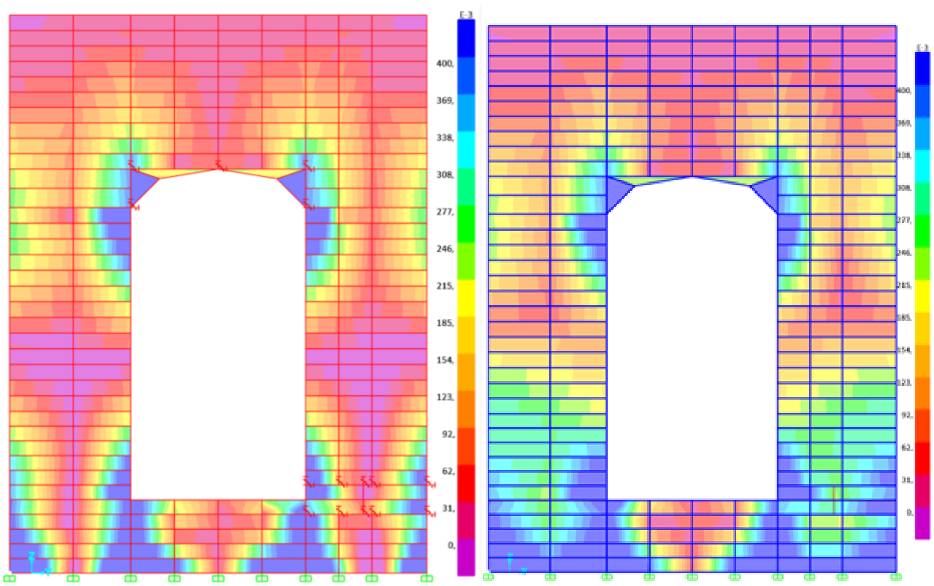


Fig. 6.1.4.2. The normal tension for the S11 wall featuring window gaping (kPa) model 2 – reinforced at the joints (left) and model 3 – confined (right)

6.1.5. Considerations regarding the comparatively presented stress diagrams

Considering the stress diagrams, it can be noticed that the polymeric grids contribute to a spread of the concentrated efforts, where they are present. Therefore, the peak efforts are transmitted with the help of this system to a larger area of the wall, leading to their uniformization.

6.1.6. Determination of the potential energy diagrams

Three numerical models were made. The first one, used as a standard, was not reinforced. The second numerical model (model 2) was reinforced with polymeric grids inserted at the level of the horizontal joints. The third one (model 3), in addition to the reinforcement with polymeric grids at the level of the horizontal joints, was coated with RG20 biaxial polymeric grids and lime-cement mortar, in a layer with a thickness of approximately 2.5 cm.

For each of the three models, a diagram of the virtual mechanical work determined by the horizontal seismic force was made.

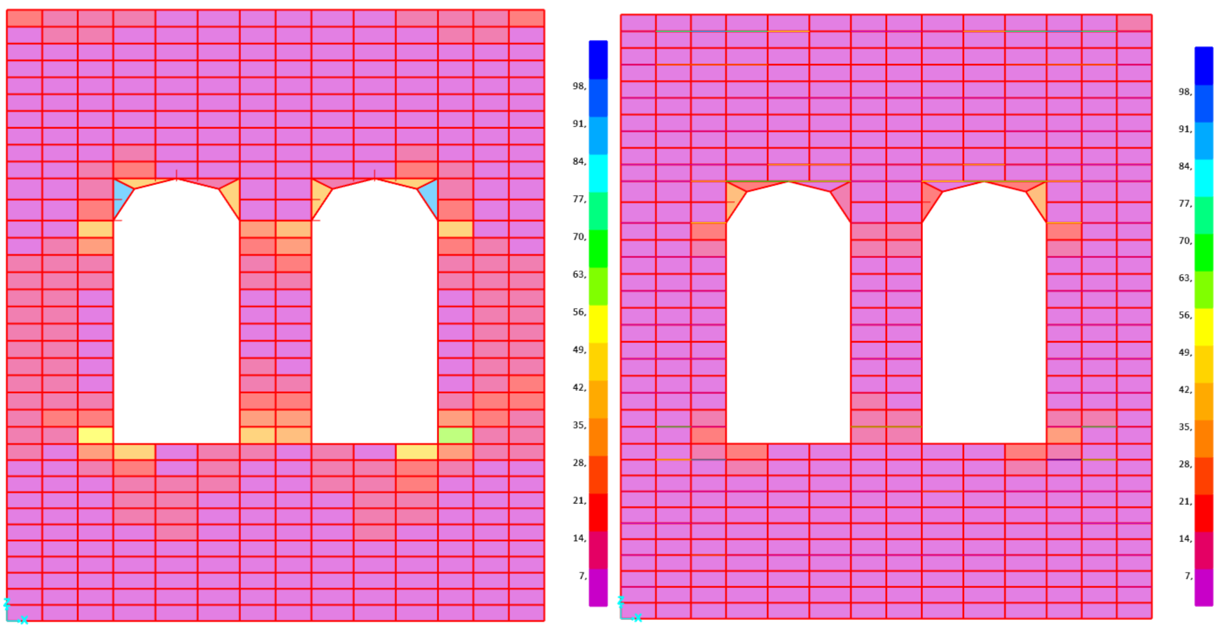


Fig. 6.1.6.1. Comparative diagrams of the potential deformation energy for model 1, (left photo) and model 2 (right photo), for the wall featuring window gaping

6.1.7. Considerations regarding the comparatively presented potential deformation energy diagrams

It can be easily seen that in the case of the unreinforced model (model 1), the virtual mechanical work done by the seismic force is taken over by the solid masonry elements. For the two reinforced models (model 2, model 3) it can be noticed that the mechanical work done by the seismic force is taken over either by the polymeric grids inserted at the level of the horizontal joints, or by the polymeric grids along with the jacketing. Therefore, the deformations are taken over by the coating with the polymeric grids.

6.1.8. Final considerations

For the initially developed models, stiffness assessments, stress diagrams and virtual mechanical work diagrams were made. The two models that made use of grid reinforcement, whether it was joint reinforcement or the confined model, were compared to the simple, unreinforced masonry model.

Coating with polymeric grids is a very efficient tool for consolidating structures. The system is perfectly compatible with the nature and the way of working of the lime mortar masonry, enhancing its qualities and alleviating its weaknesses. Given the previous argument, it can be said that reinforcement with polymeric grids is a very good solution to increase the seismic resilience of interwar structures made of lime masonry.

6.2. Numerical interpretation of experimental research, using the DIANA FEA program

Numerical modelling was performed in the DIANA FEA finite element, which is specialised among others in calculations related to masonry structures. The calculations were made for the two variants, one in which the model is reinforced with polymeric grids at the joints, and the other one, in which the model is coated with polymeric grids.

6.2.1. Nonlinear calculations performed in DIANA FEA for the two models

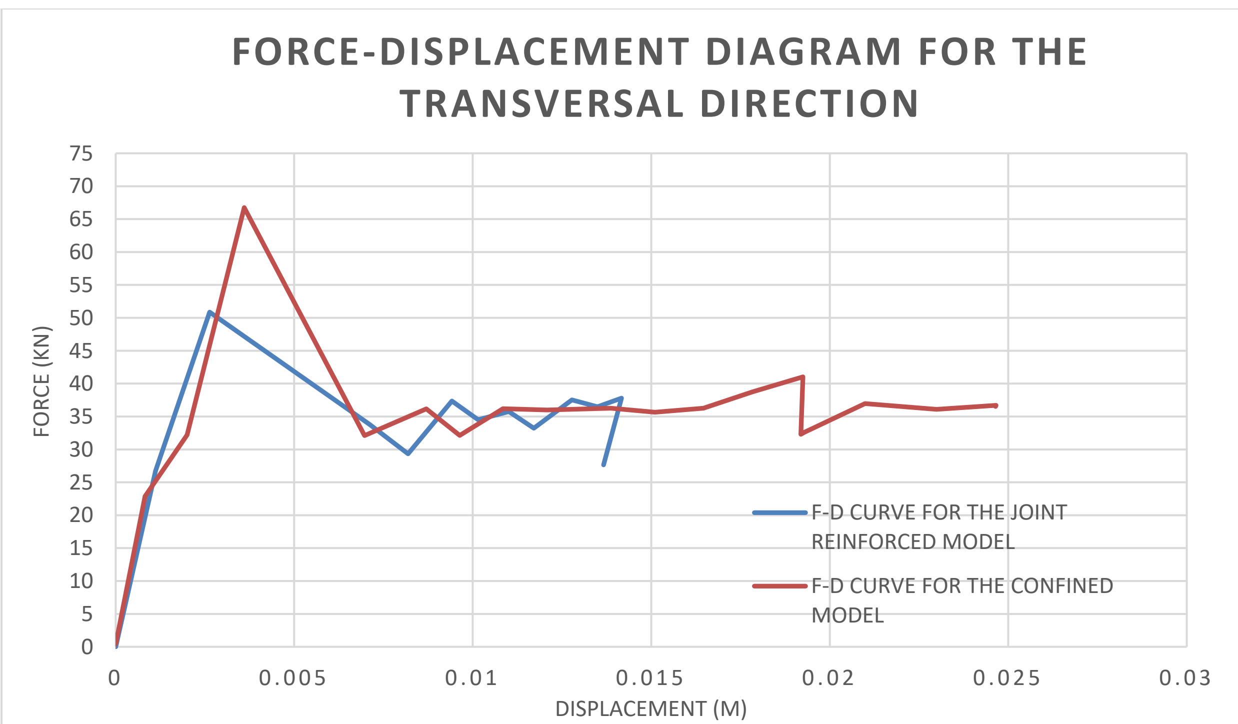


Fig. 6.2.1.1. Comparative graph of the force-displacement diagrams for the transversal direction

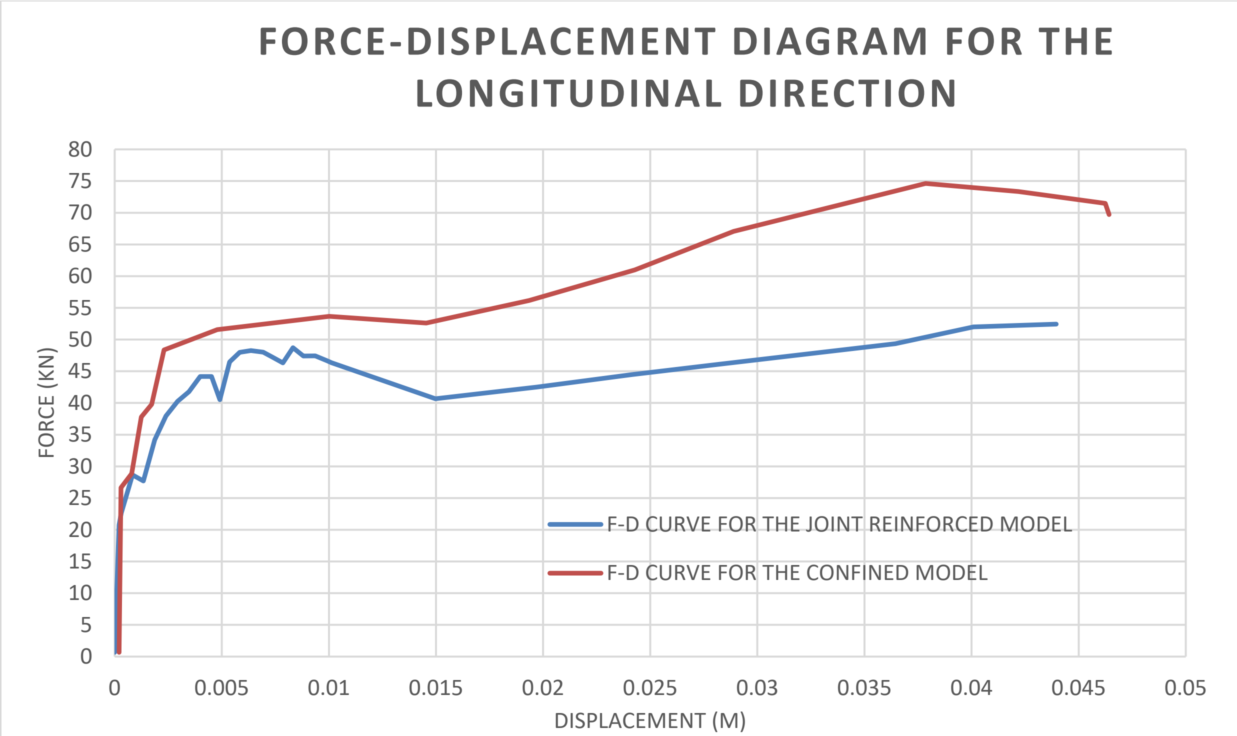


Fig. 6.2.1.2. Comparative graph of the force-displacement diagrams for the longitudinal direction

6.2.2. Comments based on the biographical curves

The analysis of the comparative graphs of the force-displacement curves for both main directions of the structure leads to the following results:

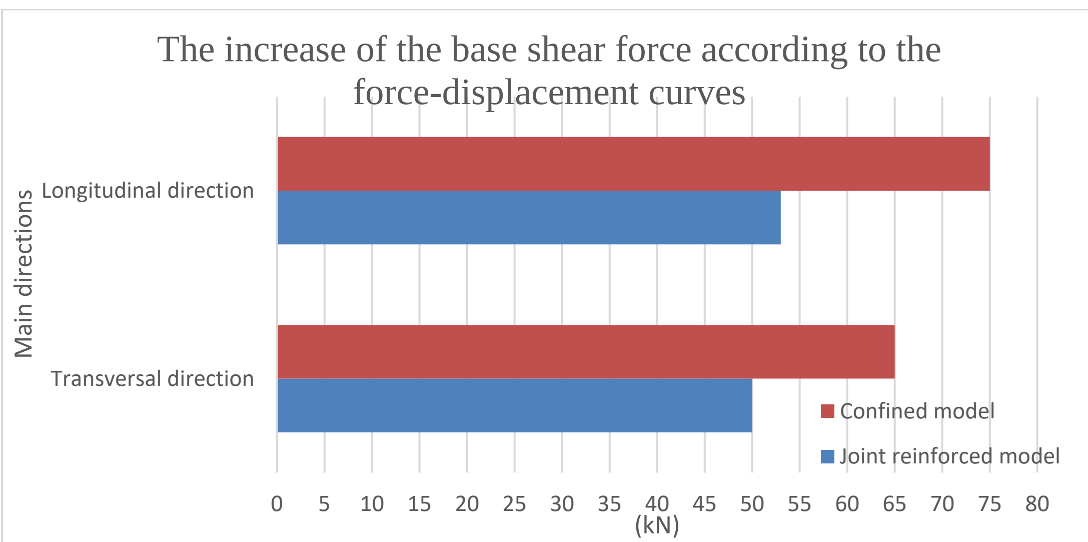


Fig. 6.2.2.1. Comparative graph for the base shear force in both directions

The maximum base shear force is increased by the reinforcement with polymeric grids from 50 kN to 65 kN in the transversal direction and from 53 kN to 75 kN in the longitudinal direction.

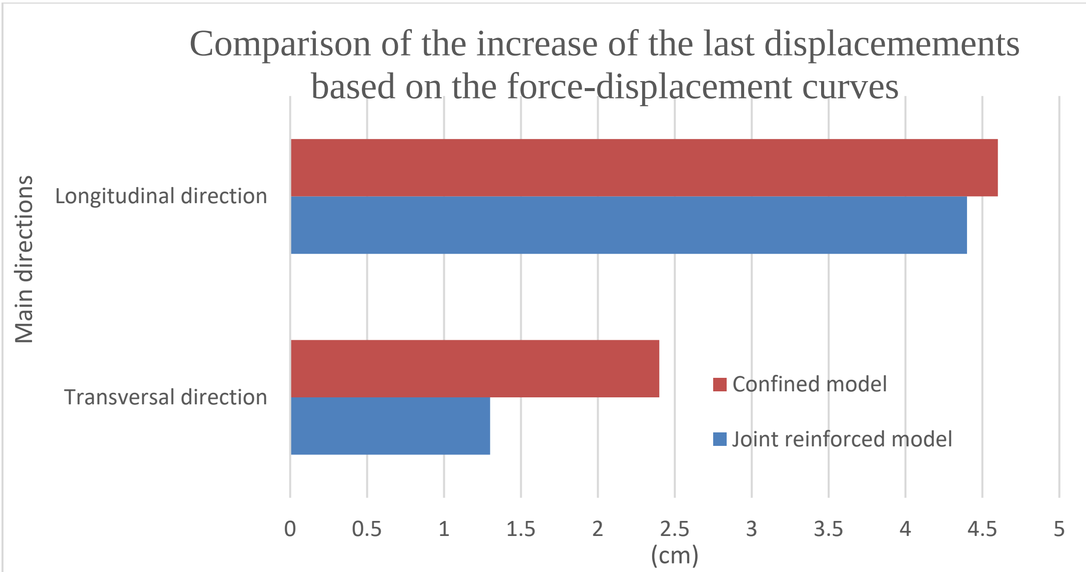


Fig. 6.2.2.2. Comparative graph of the last displacements for both directions

Based on the force-displacement curves, the calculation of the deformation energy related to the plasticization mechanism of the structure was performed.

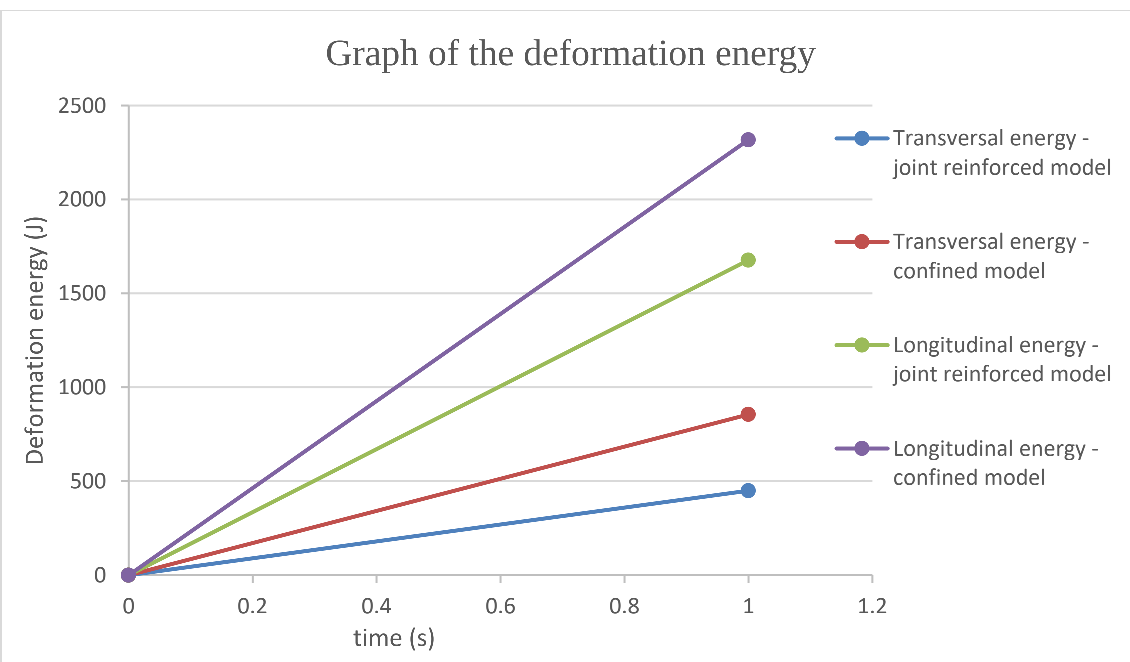


Fig. 6.2.2.3. Comparative graph for the deformation energy

According to graph 6.2.2.3., the confined masonry with polymeric grids leads to an increase of 90.24% for the transversal direction and of 38.18% for the longitudinal direction of the deformation energy related to the plasticization mechanism of the structure.

6.3. Parametric study related to the enhancement of the seismic resilience by using the polymeric grid coating solution

6.3.1. General data and determination of the modes

The numerical interpretation of the ISMES experiment admits the model to be valid. In order to study the increase of seismic resilience with the help of polymeric grids, 6 numerical models were considered for parametric study. They closely follow the geometry of the ISMES model, but the difference comes from the material characteristics. Each model has different characteristics when it comes to compressive strength. The values are representative for the old solid pressed bricks and for the mortar. Models 1, 2 and 3 can be assimilated with masonry, predominantly associated with lime mortar and solid pressed bricks with low strength, while models 4, 5 and 6 can be assimilated with modern masonry, predominantly associated with cement mortar and solid pressed bricks with higher strength.

The comparison of the oscillation modes of 6 models shows a contribution of the confinement with polymeric grids to the overall rigidity of the structure. This is more important for models with lower strength and rigidity characteristics of the masonry, such as models 1 and 2. The contribution of grid confinement decreases as masonry characteristics improve, such as in models 5 and 6, so it ends up becoming minor.

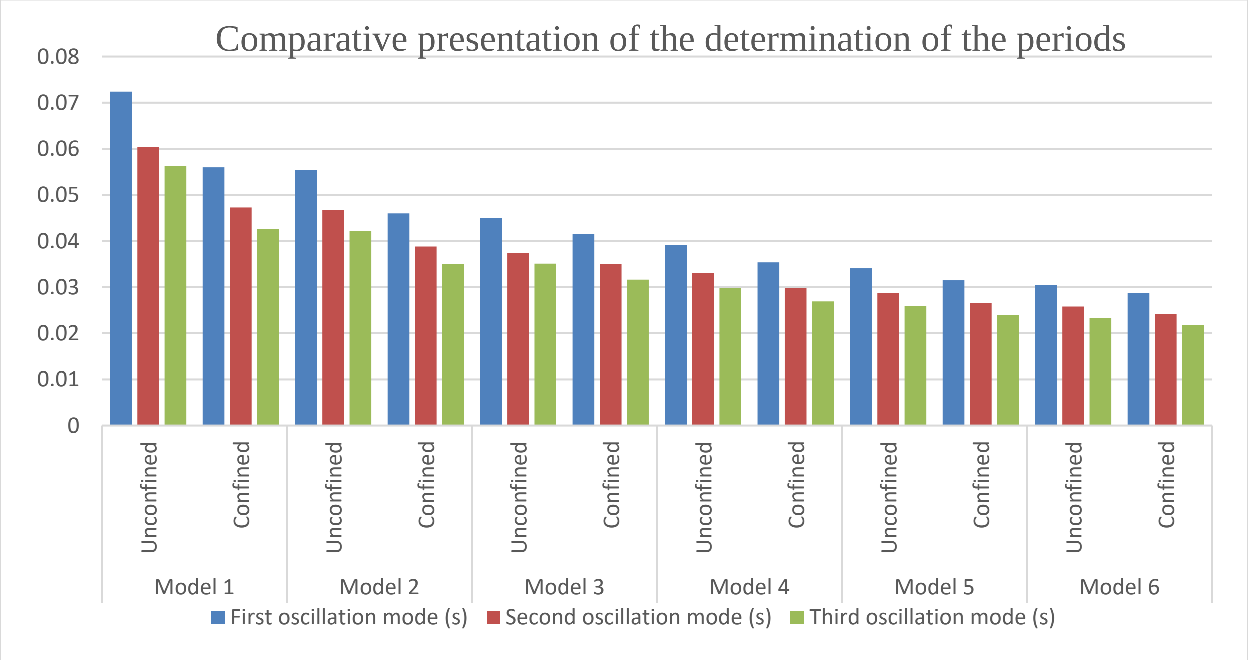


Fig. 6.3.1. The periods presented comparatively, for models 1-6

6.3.2. Determination of the biographical curves

Nonlinear calculations were made for the 6 considered models, for each model there are 2 versions, so in total, there would be 12 models. The purpose is to study the contribution of the polymeric grid confinement to the overall rigidity and resistance of the structure.

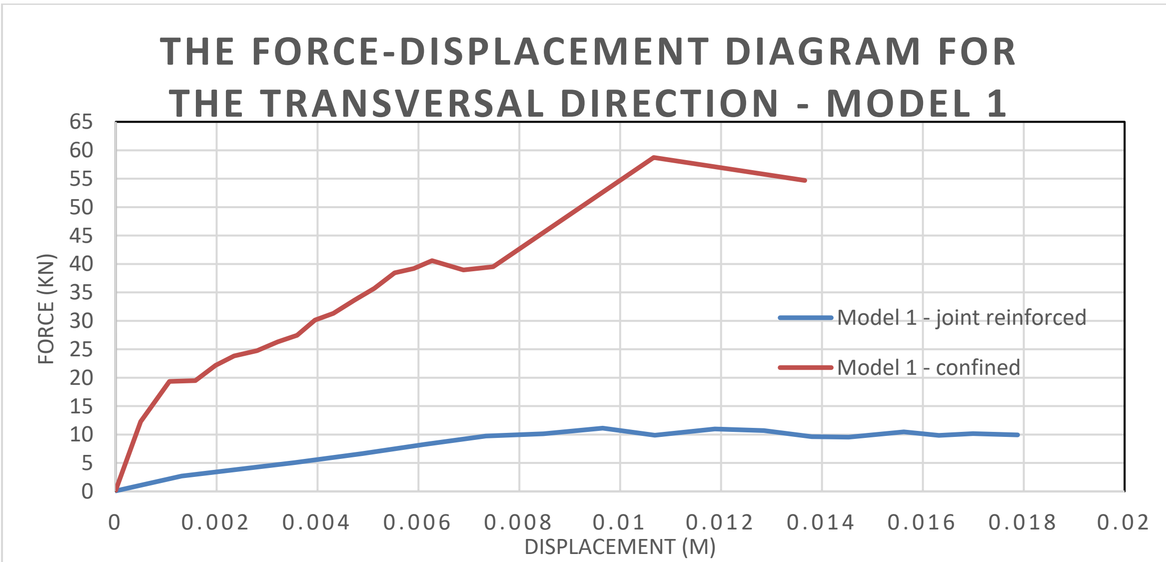


Fig. 6.3.2.1. The force-displacement diagram for the transversal direction – model 1

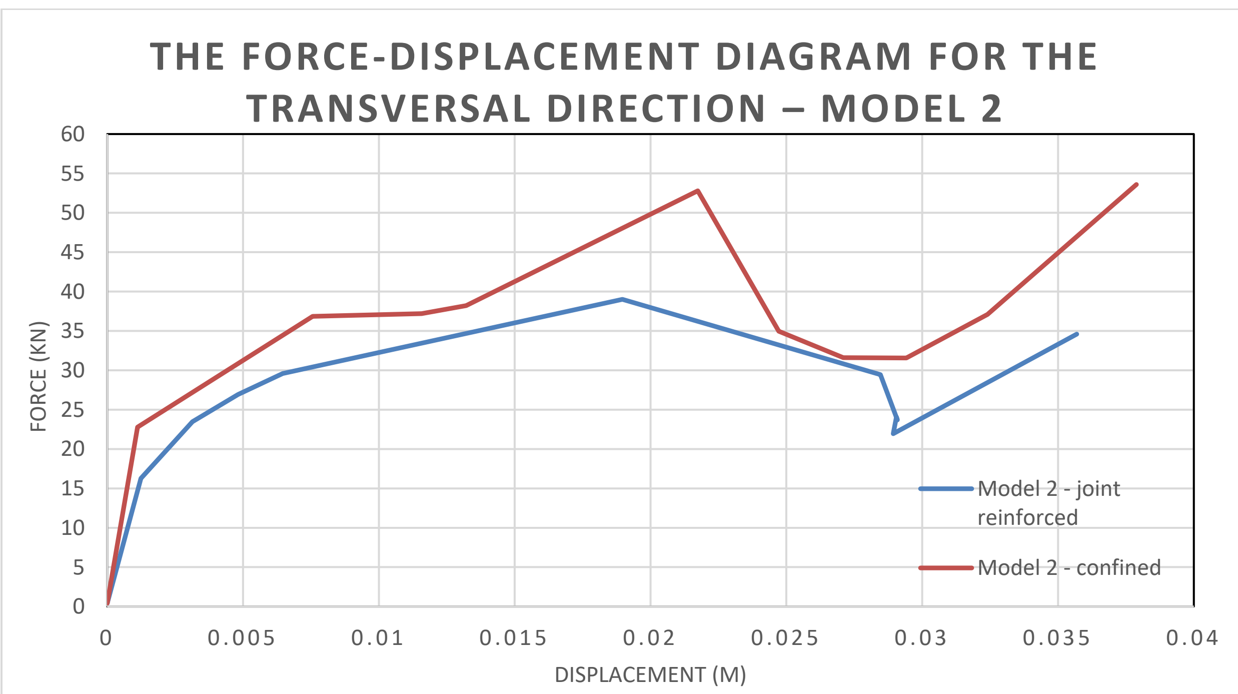


Fig. 6.3.2.2. The force-displacement diagram for the transversal direction – model 2

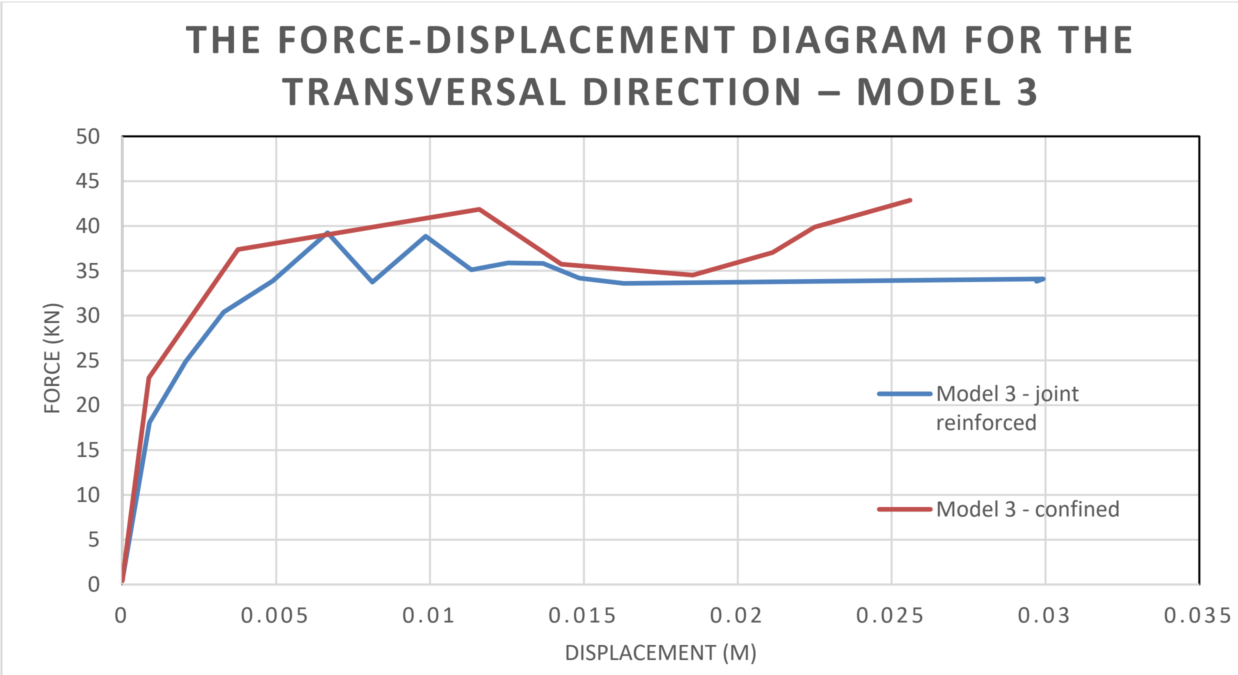


Fig. 6.3.2.3. The force-displacement diagram for the transversal direction – model 3

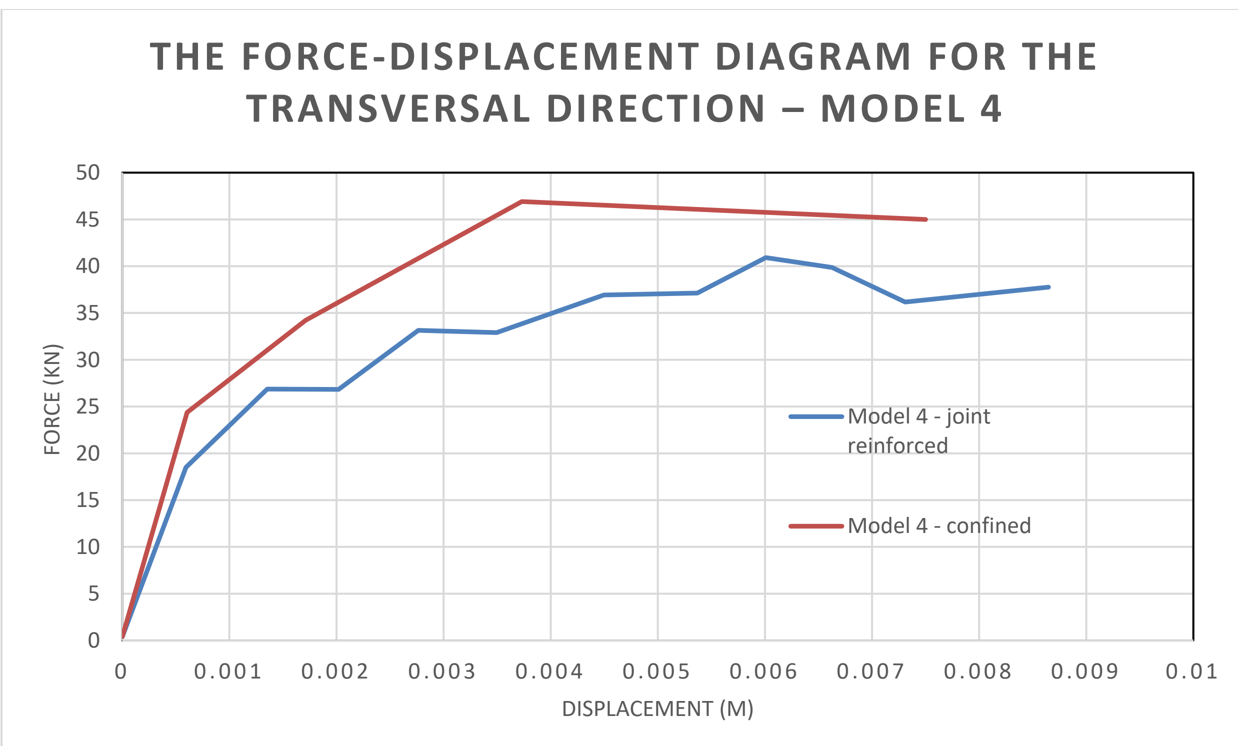


Fig 6.3.2.4. The force-displacement diagram for the transversal direction – model 4

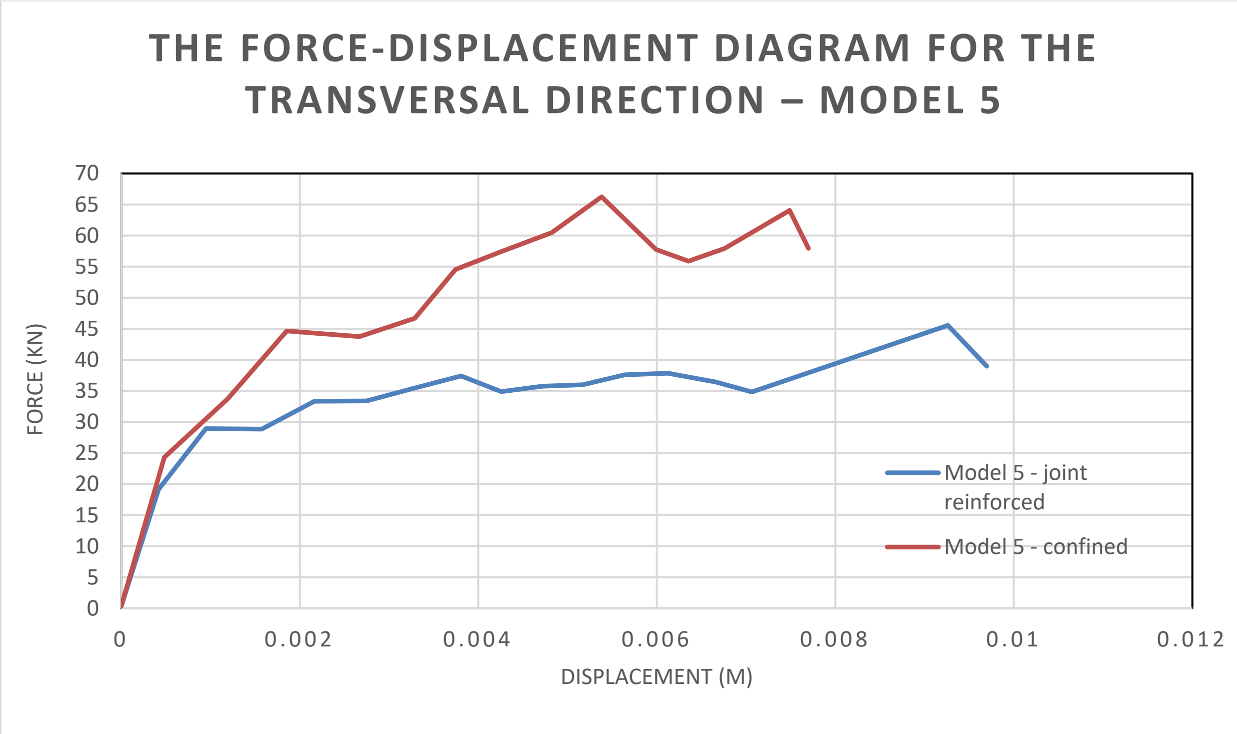


Fig. 6.3.2.5. The force-displacement diagram for the transversal direction – model 5

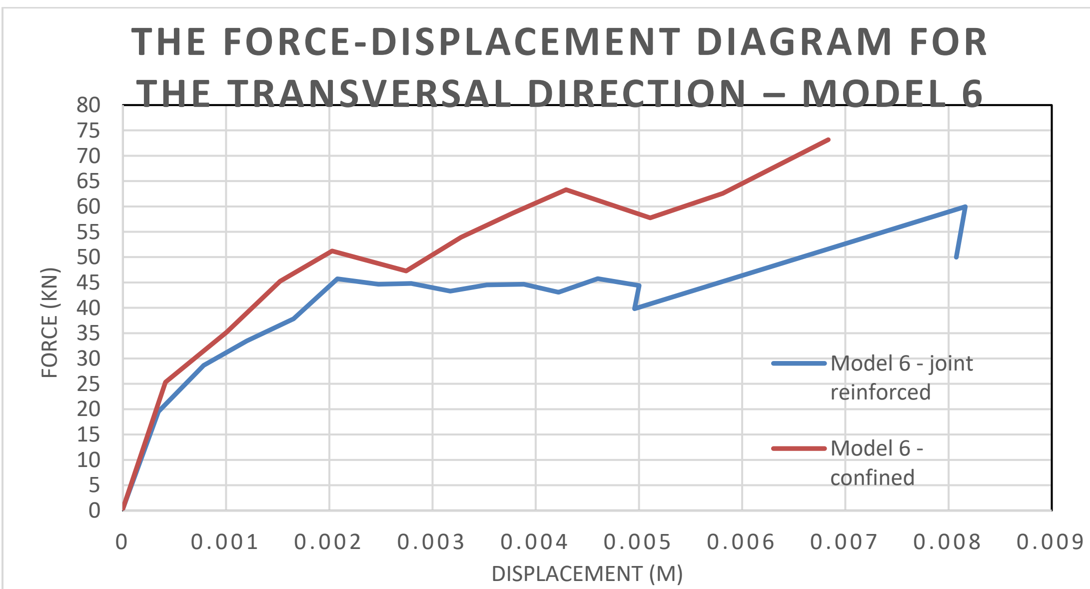


Fig. 6.3.2.6. The force-displacement diagram for the transversal direction – model 6

The parameters that are studied for each model are the following:

- Fe – the base shear force at which the limit of the elastic behaviour of the structure is reached;

- Fu – the base shear force corresponding to the plasticization mechanism of the structure;
- De – the movement for which the limit of the elastic behaviour of the structure is reached;
- Du – the movement corresponding to the plasticization mechanism of the structure.

6.3.3. Considerations based on the biographical calculations of the 12 numerical models

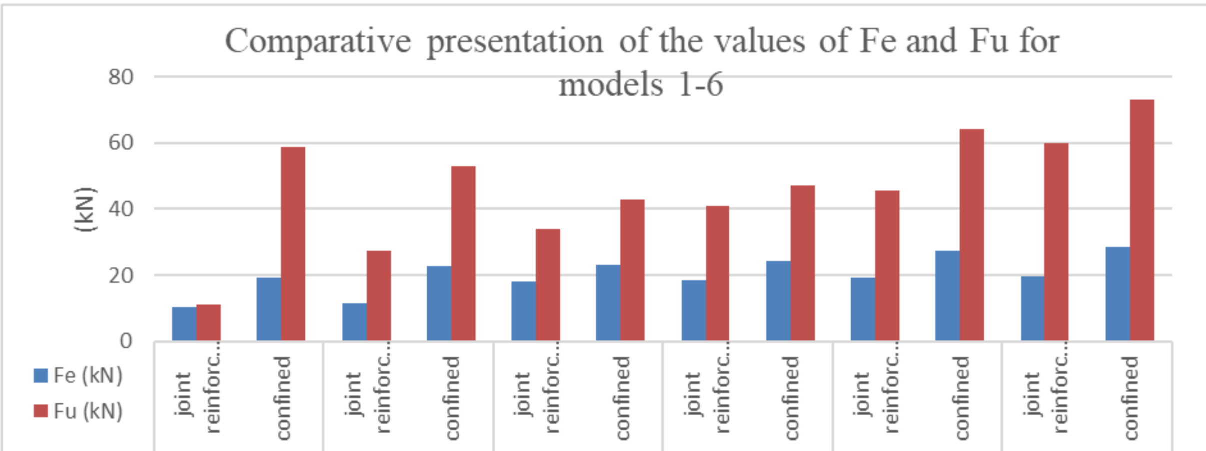


Fig. 6.3.3.1. Comparative presentation of the Fe and Fu parameters for models 1-6 in the reinforced at the joints and confined variants

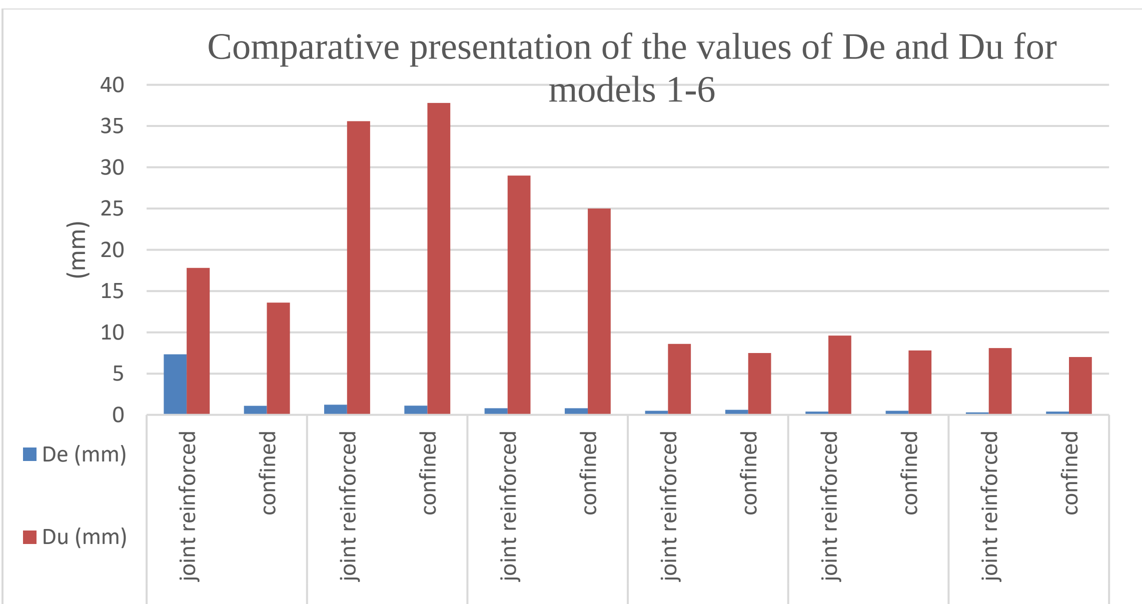


Fig. 6.3.3.2. Comparative presentation of the De and Du parameters for models 1-6 in the reinforced at the joints and confined variants

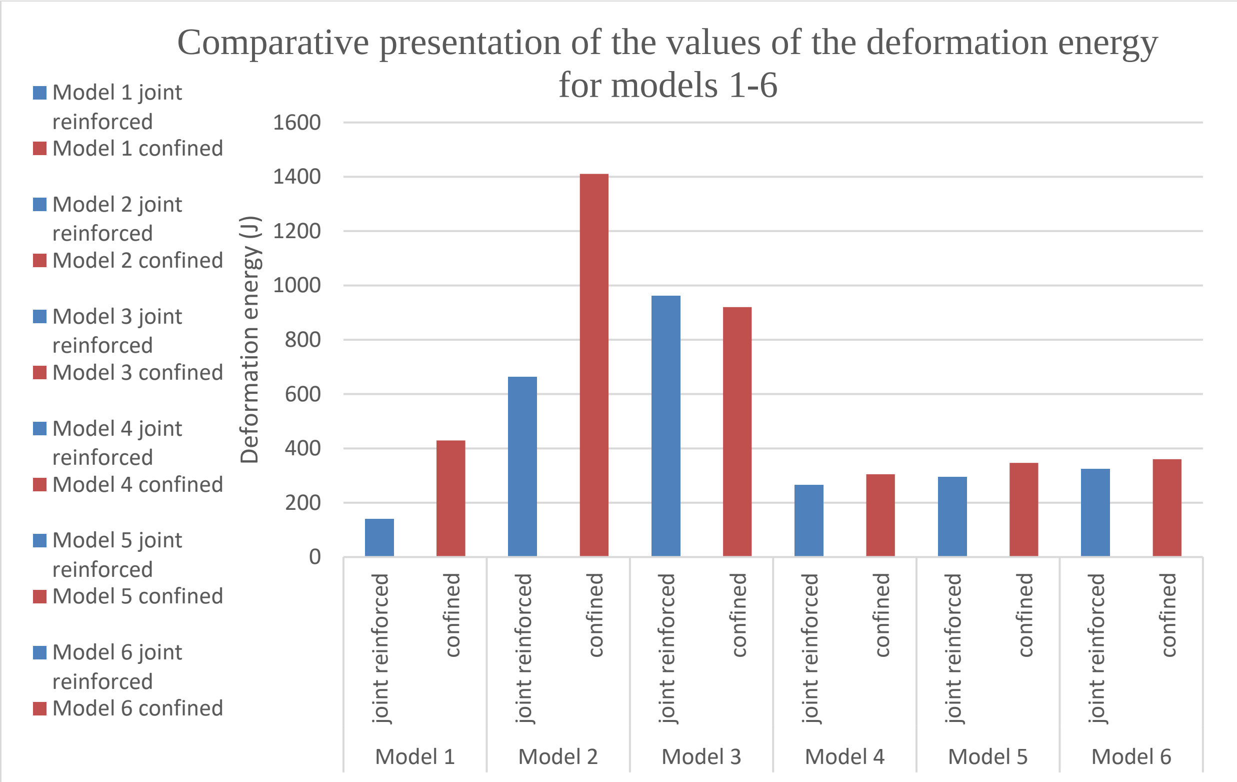


Fig. 6.3.3.3. Comparative presentation of the values of the deformation energy for models 1-6 in the reinforced at the joints and confined variants

6.3.5. Final considerations

Polymeric grid confinement of the representative numerical models leads to the increase of their resistance and rigidity characteristics, so this is an efficient measure. However, the increase is uniform for all models. As it can be seen, the models associated with lime masonry show a more pronounced increase in the aforementioned characteristics. This highlights polymeric grid reinforcement as an efficient, supple and reversible measure used to increase the seismic resilience of interwar structures.

6.4. Numerical interpretation of the grid reinforcement solutions by making use of experimental models

6.4.1. General data

In order to numerically analyse the grid reinforcement solution, 5 numerical models with different degrees of complexity were taken into account, for each of which comparative analyses were performed. The considered models are relatively simple, but they feature different geometric shapes and different gaping layouts. Each model is to be assessed both for the simple version, and the version that involves confinement with polymeric grids.

The purpose of the analysis is to identify the influence of the coating solution with polymeric grids and lime mortar and to observe the differences between it and other types of coating.

No. Model	Description of the considered numerical model	Length (m)	Width (m)	Height (m)	Dimensions of the gap (m)
1	**Column with the cross-section plane ratio of the sides being equal to 2**	0.5	0.25	2.9	Without
2	**Column with the cross-section plane ratio of the sides being equal to 4**	1	0.25	2.9	Without
3	**Solid wall**	5	0.25	2.9	Without
4	**Solid wall with a central gap for a door**	5	0.25	2.9	0.9 x 2.1
5	**Solid wall with a side gap for a window**	5	0.25	2.9	0.9 x 0.9

Tabel 6.4.1. Identification of the geometric characteristics of the 5 models

The material characteristics of the models are similar to those of the model used in the ISMES experiments. Thus, the material from which they are made is simple unreinforced masonry, made of solid bricks and lime mortar.

6.4.2. Determination of the dynamic characteristics and the drift

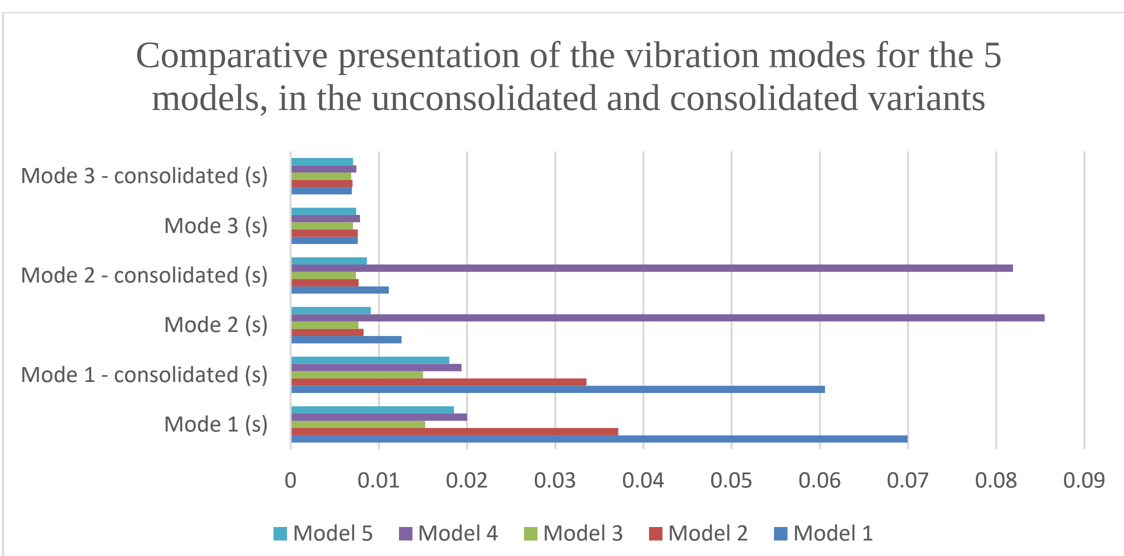


Fig. 6.4.2.1. Comparative presentation of the vibration modes for the 5 models

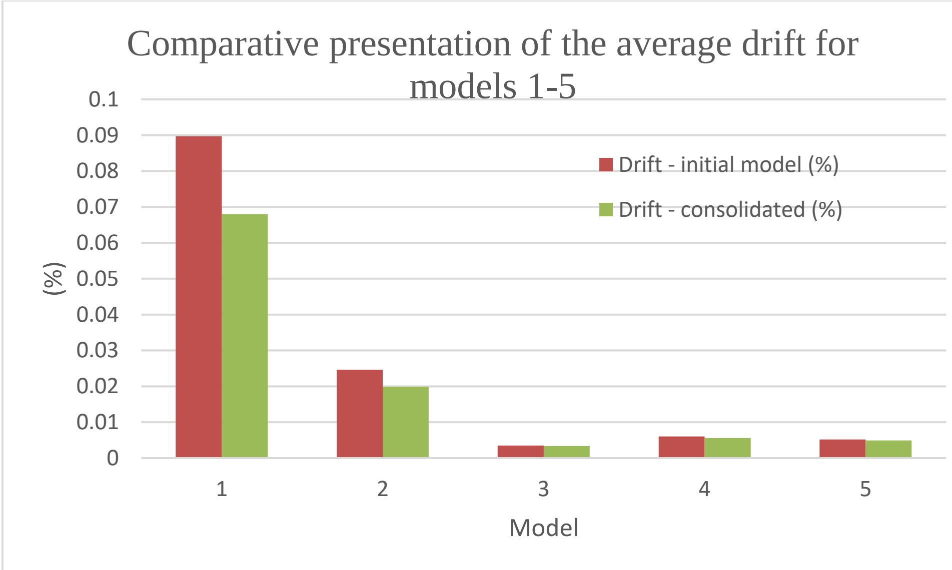


Fig. 6.4.2. Comparative presentation of the average drift for models 1, 2, 3, 4, 5

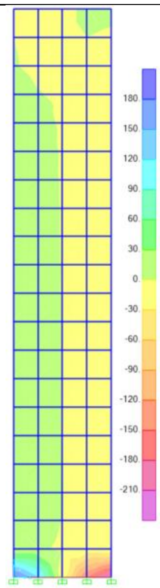
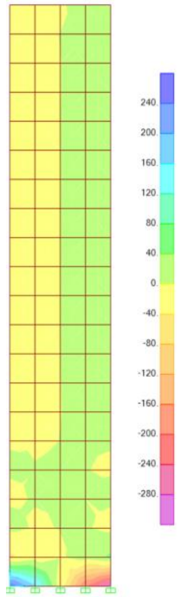
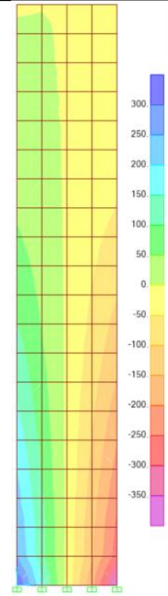
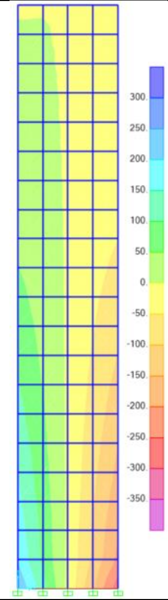
The variation of the oscillation modes reveals that there is a contribution of the grid coating, but it differs depending on the geometry of the coated element. Thus, for models 1 and 2, of the column type, the contribution of the coating is major, the decrease of the periods being between 6.66% and 13.38%. For models 4 and 5, of the gapped wall type, the decrease of the modes is less important, varying between 5.22% and 2.86%. The solid wall model, model 3, has the smallest contribution to the overall rigidity, being relatively insignificant. Its variation is between 3.65% and 1.51%.

The observations made regarding the vibration modes are also valid in the case of the drift check. The greatest contribution of the grid reinforcement is given by models using a geometry of the column type, namely types 1 and 2, as the values are between 18.96% and 24.15%. Models 4 and 5 benefit from a moderate contribution, which is between 5.3% - 7.43%, and model 3, the solid wall one, has an insignificant contribution, of only 2.97%.

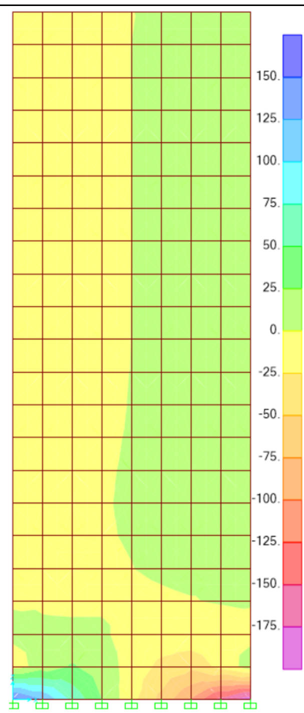
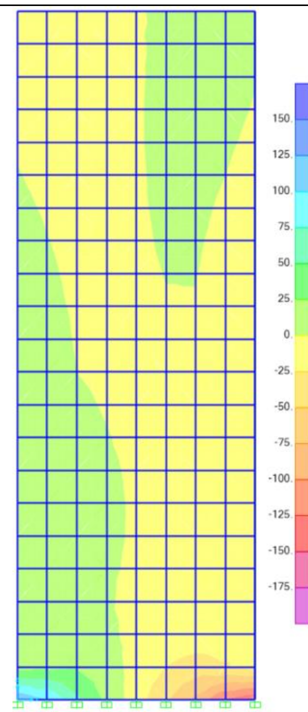
Polymeric grid coating can create a confinement effect, the contribution of which is significantly more important for the structural elements with a ratio of the sides closer to the value of the ratio of the sides of the columns. For structural elements with wall behaviour, the confinement effect given by the coating with polymeric grids is almost zero.

6.4.3. Determination of the stress diagrams for model 1

S11 normal tension (kPa) model 1 – simple masonry	**S11 normal tension (kPa) model 1 – confined**	**S22 normal tension (kPa) model 1 – simple masonry**	**S22 normal tension (kPa) model 1 – confined**

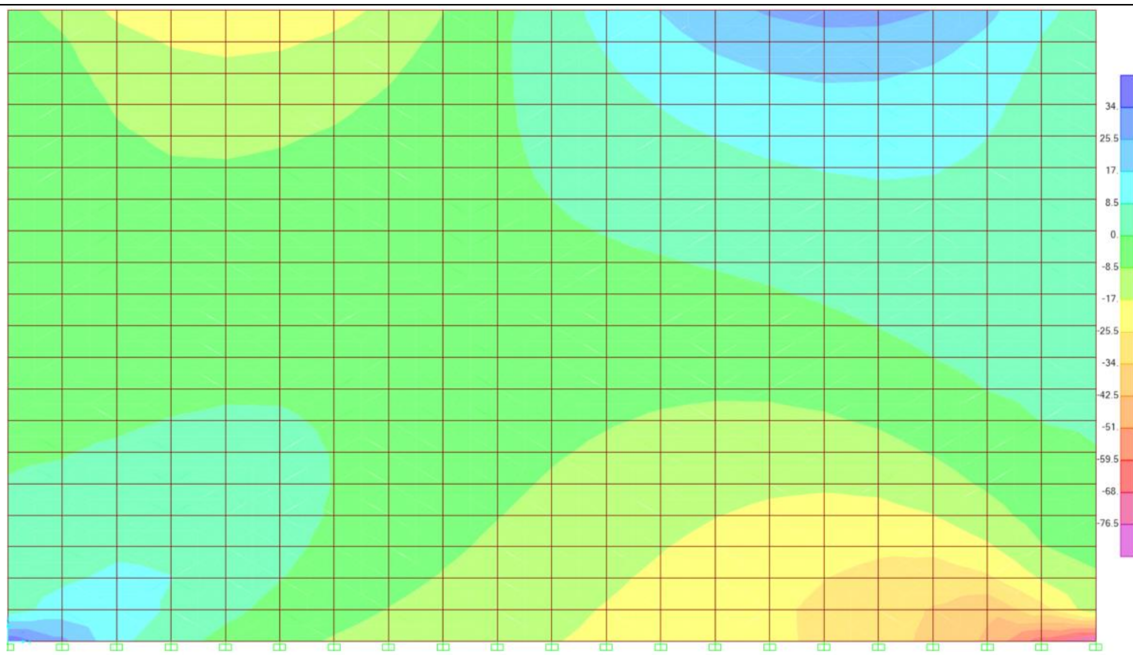
			
Values between -280 kPa and 240 kPa	Values between -210 kPa and 180 kPa	Values between -350 kPa and 300 kPa	Values between -280 kPa and 240 kPa

6.4.4. Determination of the stress diagrams for model 2

S11 normal tension (kPa) **model 2 – simple masonry**	**S11 normal tension (kPa)** **model 2 – confined**
	
Values between -175 kPa and 150 kPa	Values between -140 and 120 kPa

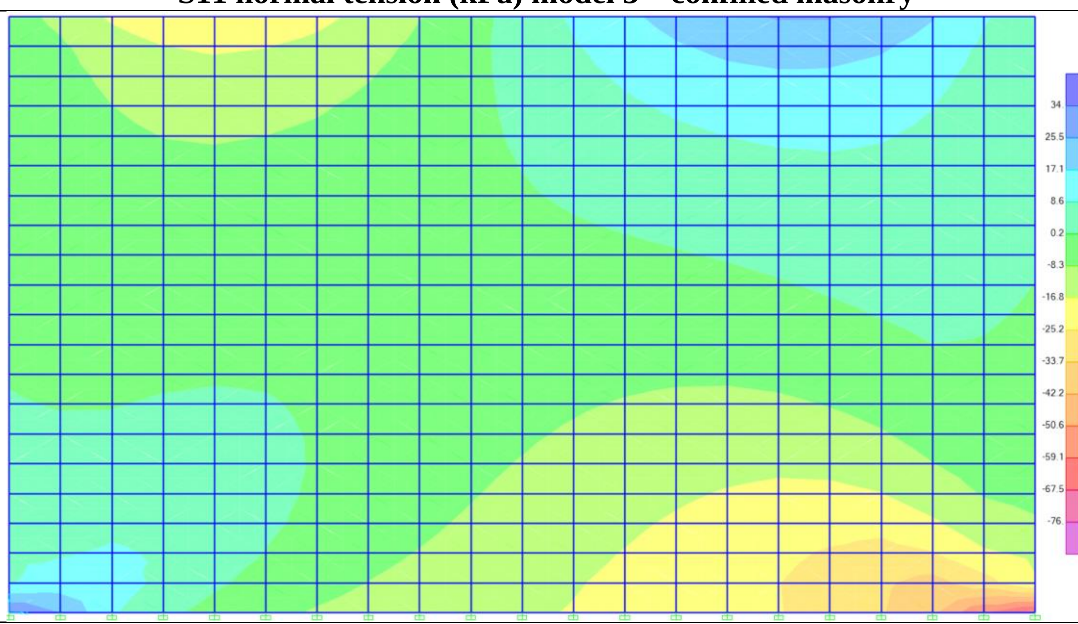
6.4.5. Determination of the stress diagrams for model 3

S11 normal tension (kPa) model 3 – simple masonry



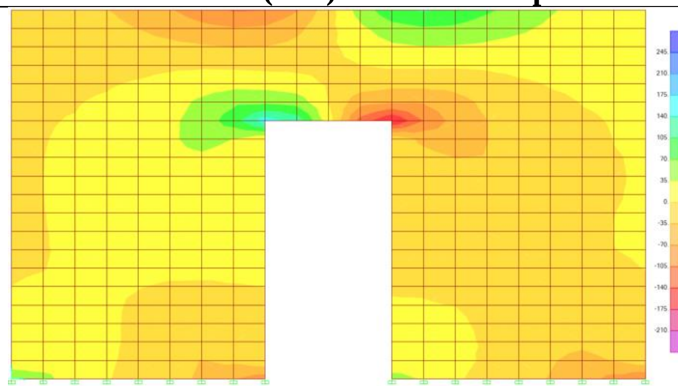
Values between -76,5 kPa and 34 kPa

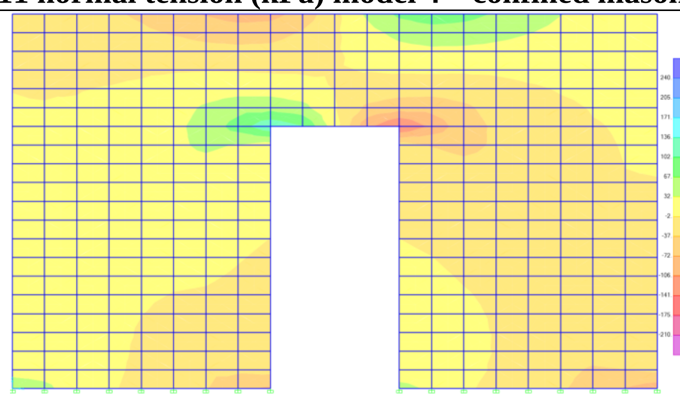
S11 normal tension (kPa) model 3 – confined masonry



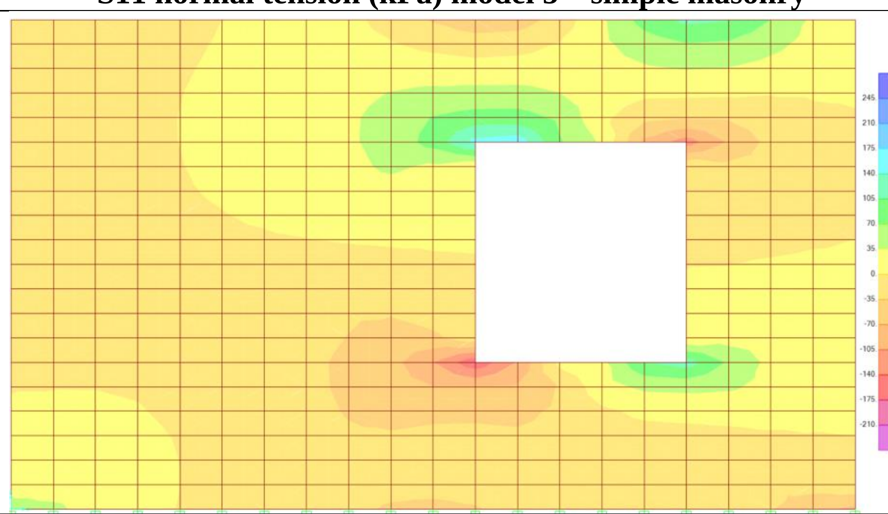
Values between -67 kPa and 30 kPa

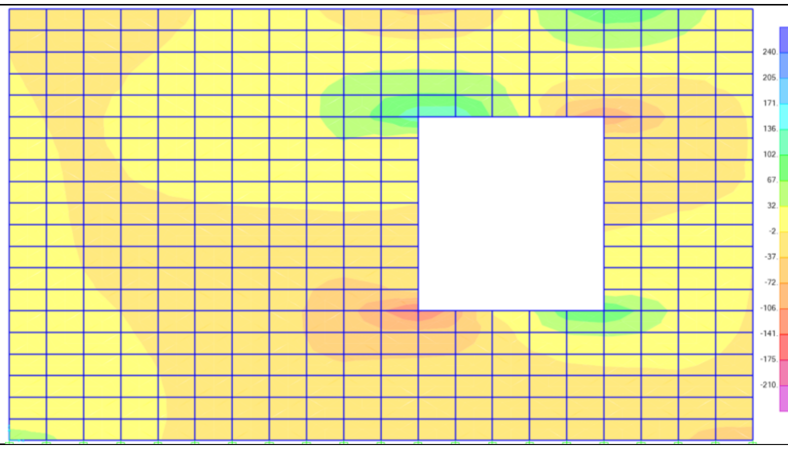
6.4.6. Determination of the stress diagrams for model 4

S11 normal tension (kPa) model 4 – simple masonry

Values between -210 kPa and 240 kPa

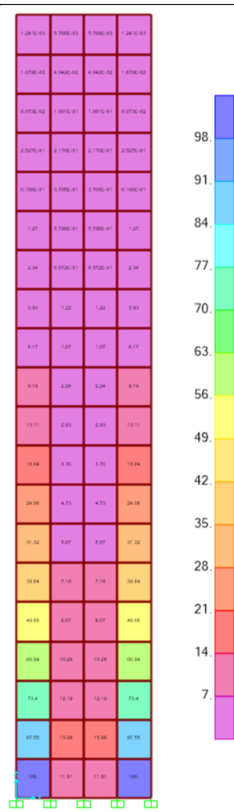
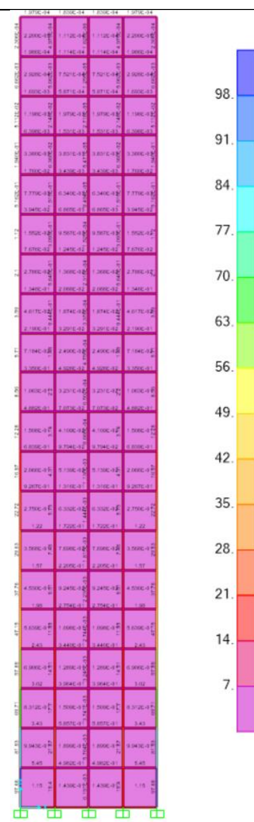
S11 normal tension (kPa) model 4 – confined masonry

Values between -175 kPa and 150 kPa

6.4.7. Determination of the stress diagrams for model 5

S11 normal tension (kPa) model 5 – simple masonry

Values between -210 kPa and 240 kPa

S11 normal tension (kPa) model 5 – confined masonry

Values between -156 kPa and 182 kPa

6.4.8. Determination of the potential energy diagrams for the 5 models

The potential deformation energy diagram for model 1 – simple masonry	**The potential deformation energy diagram for model 1 – confined masonry**
	

It can be observed that the polymeric grids contribute to the spread of the concentrated efforts, where they occur. Thus, the peak efforts that appear are transmitted with the help of this system to a much larger area of the wall, contributing to their uniformization.

6.5. Biographical calculations for the considered models

For the 5 considered models, non-linear static calculations were performed, both in the modelling version involving simple masonry, as well as the version involving masonry reinforced with polymeric grids. The purpose is to determine the parameters of the force-displacement curve for each model and to compare, by analysing the parameters, the differences between the non-linear models made in simple masonry and the confined models.

The program that was used is Diana FEA and the used hysteretic models are integrated into it.

Model 1, the simple masonry variant and the grid coating variant

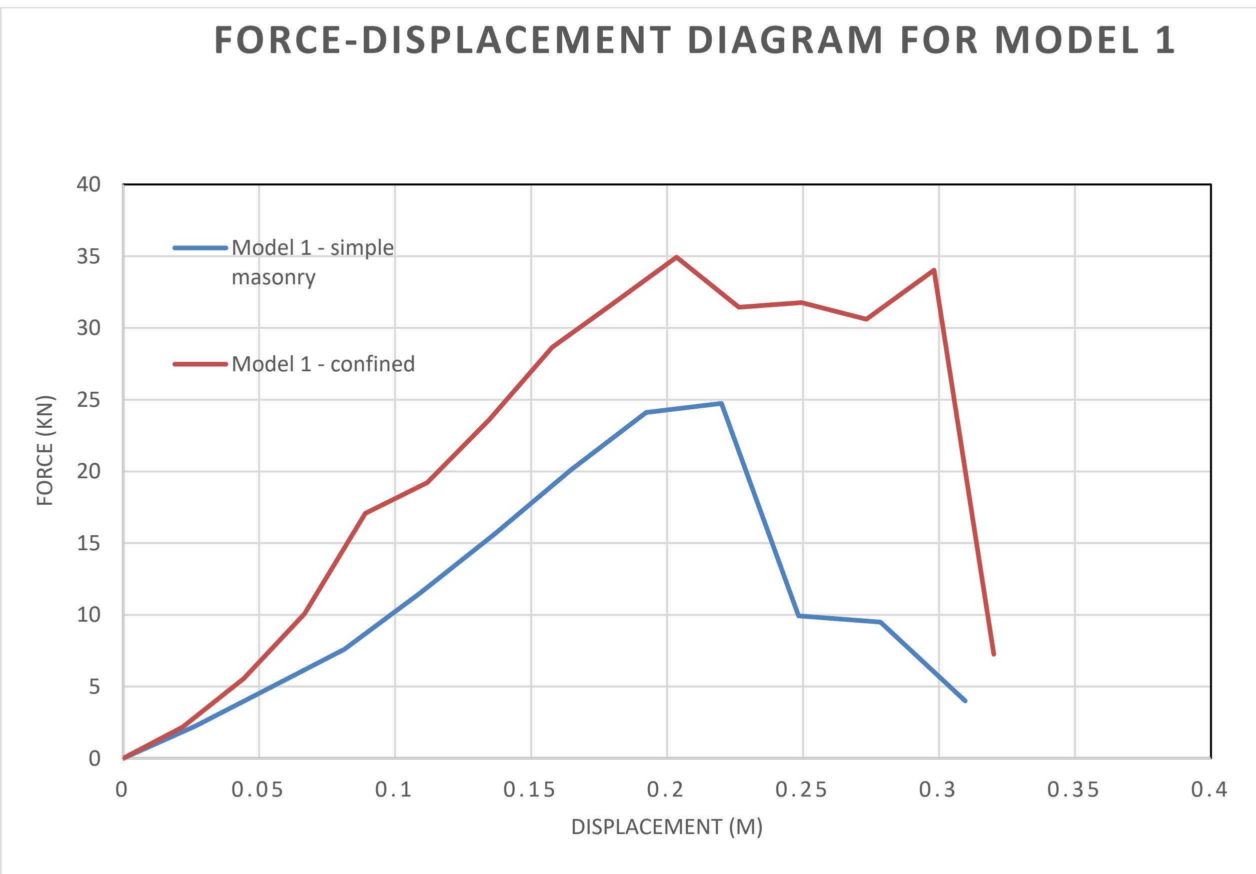


Fig. 6.5.1 Comparative force-displacement diagram for model 1 – simple/confined masonry

Model 2, the simple masonry variant and the grid coating variant

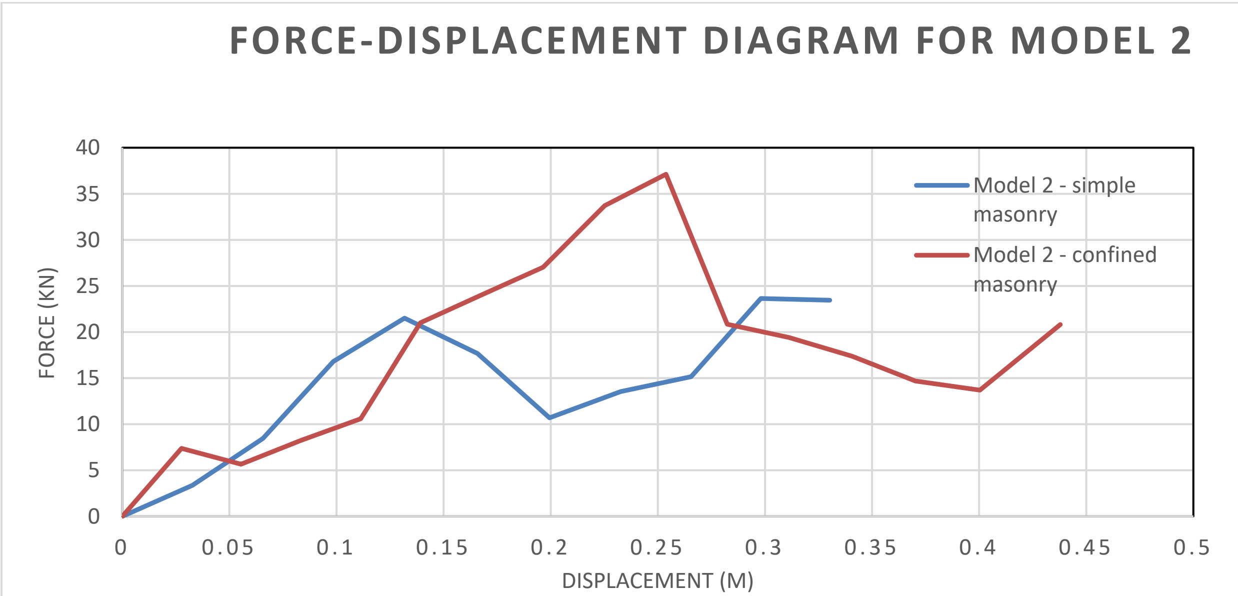


Fig. 6.5.2 Comparative force-displacement diagram for model 2 – simple/confined masonry

Model 3, the simple masonry variant and the grid coating variant

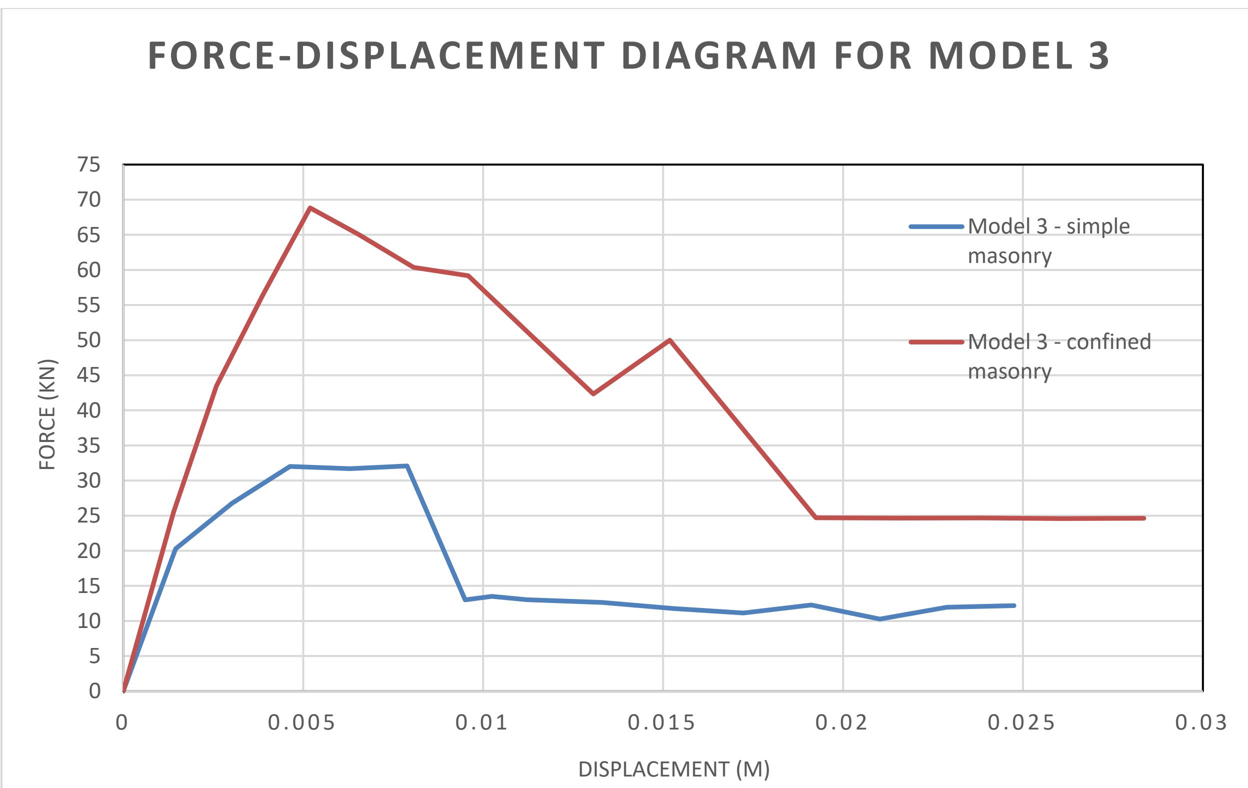


Fig. 6.5.3 Comparative force-displacement diagram for model 3 – simple/confined masonry

Model 4, the simple masonry variant and the grid coating variant

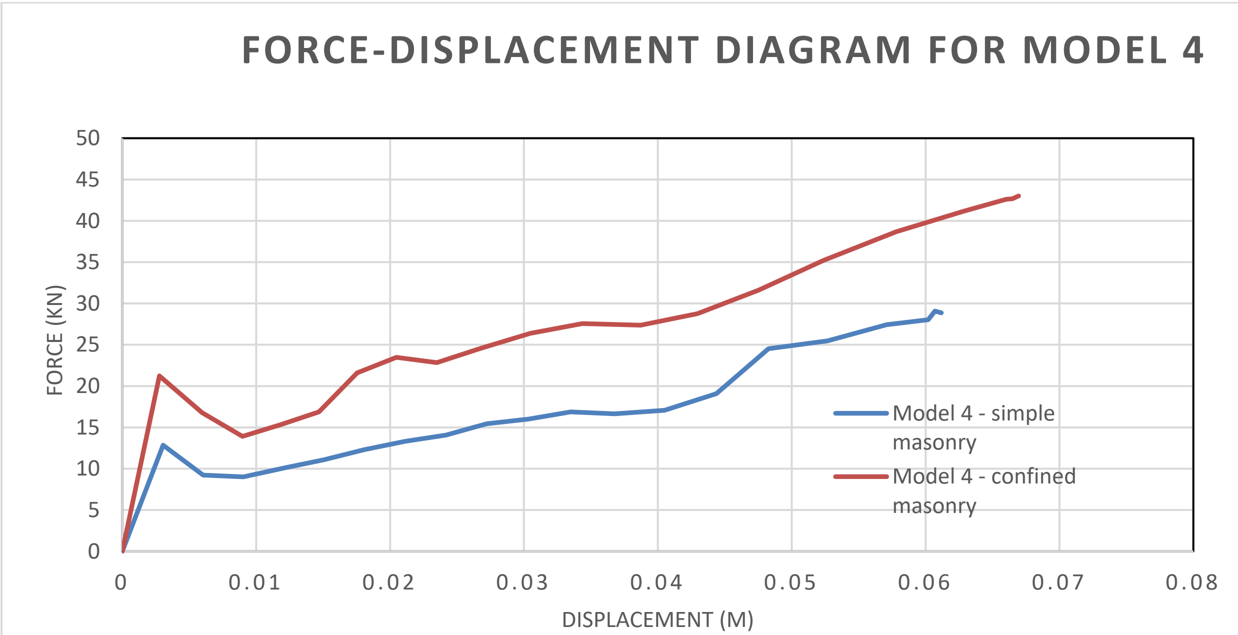


Fig. 6.5.4 Comparative force-displacement diagram for model 4 – simple/confined masonry

Model 5, the simple masonry variant and the grid coating variant

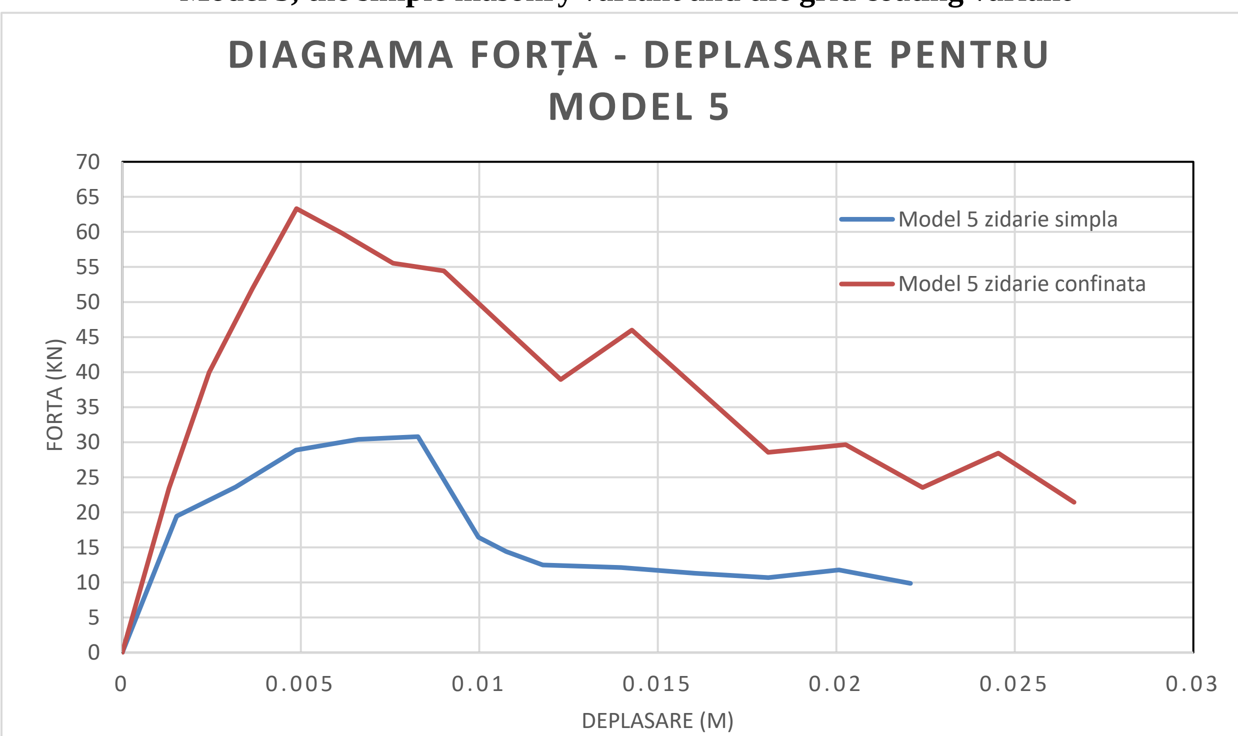


Fig. 6.5.5. Comparative force-displacement diagram for model 5 – simple/confined masonry

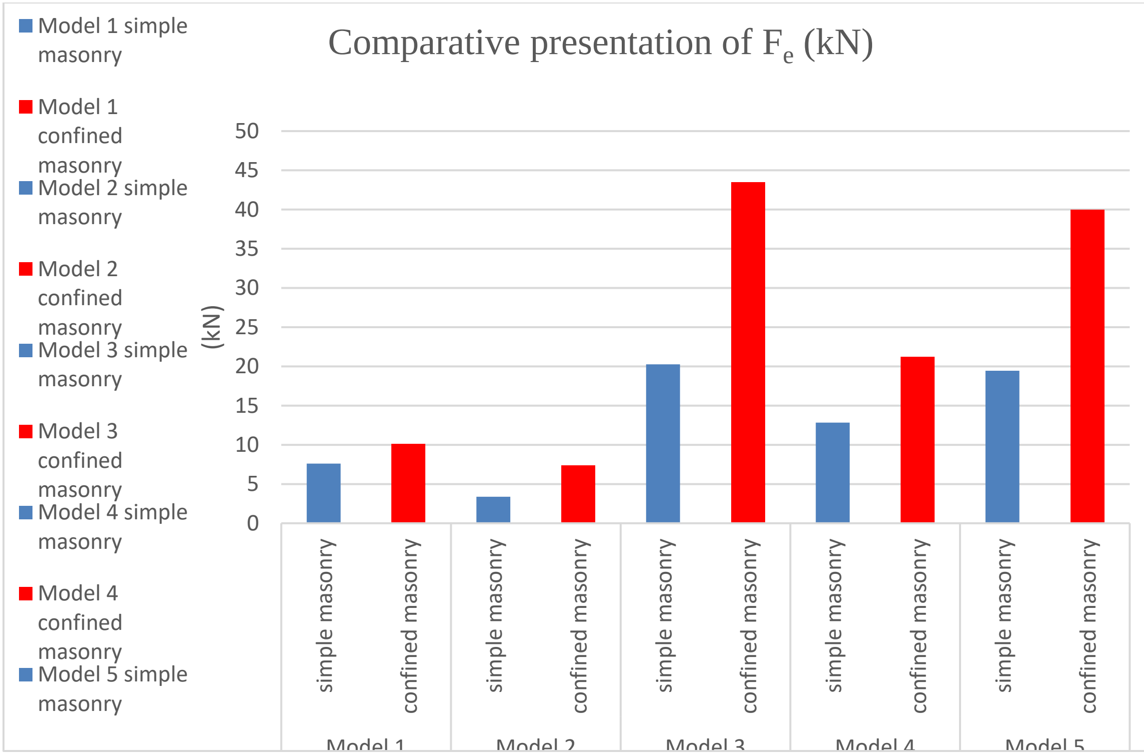


Fig. 6.5.6. Comparative presentation of Fe for the 5 models

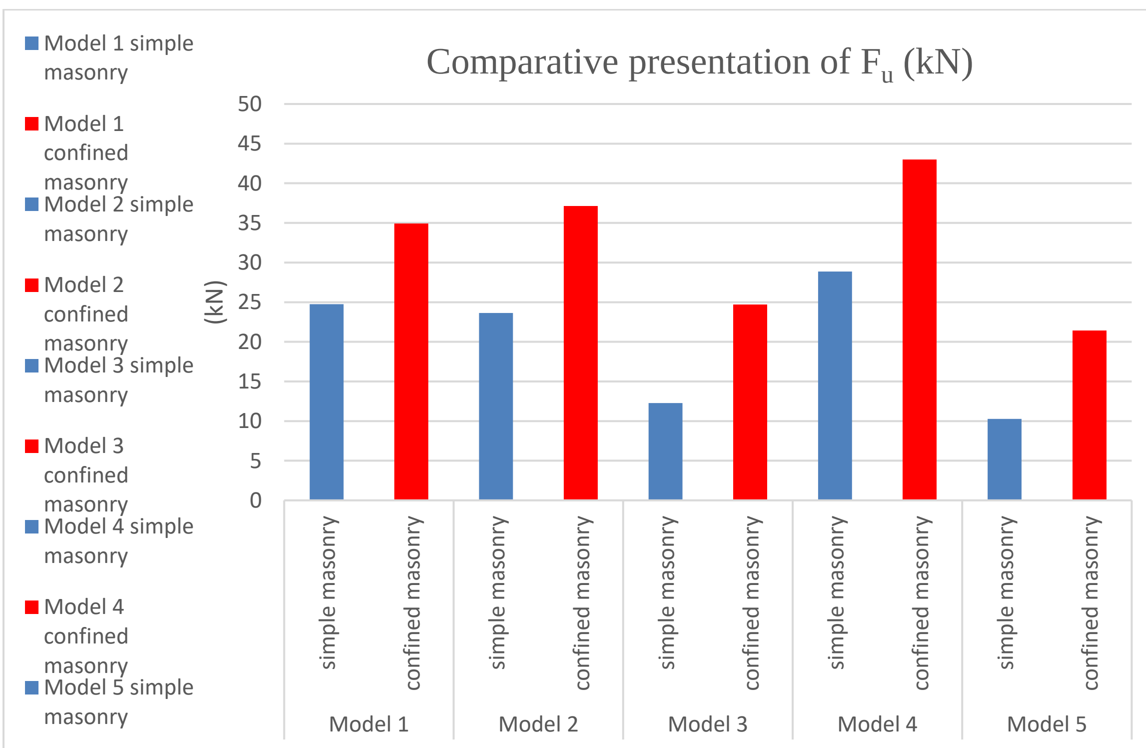


Fig. 6.5.7. Comparative presentation of Fu for the 5 models

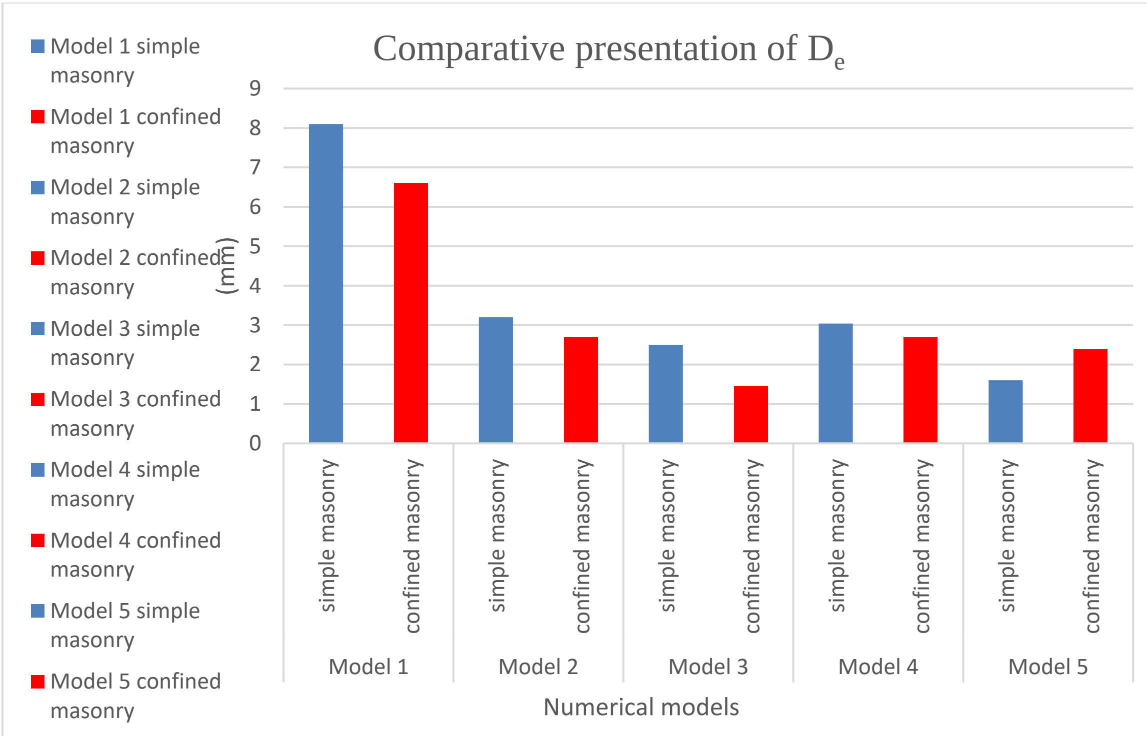


Fig. 6.5.8. Comparative presentation of De for the 5 models

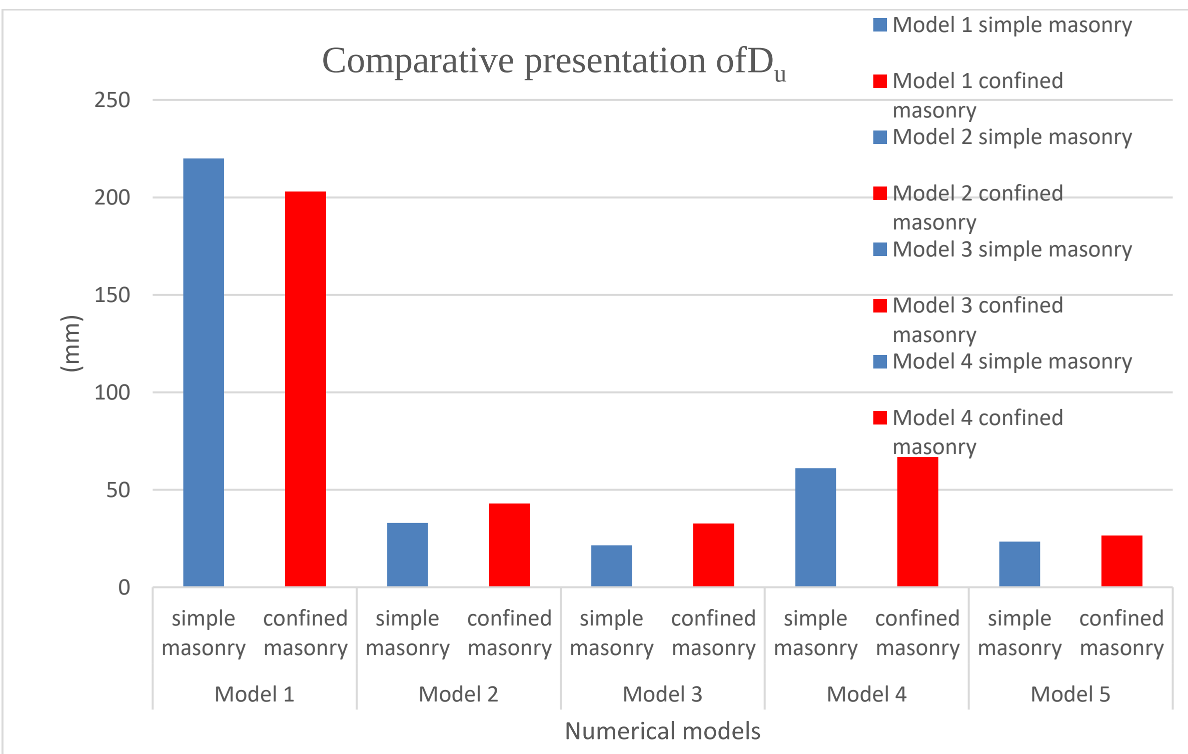


Fig. 6.5.9. Comparative presentation of Du for the 5 models

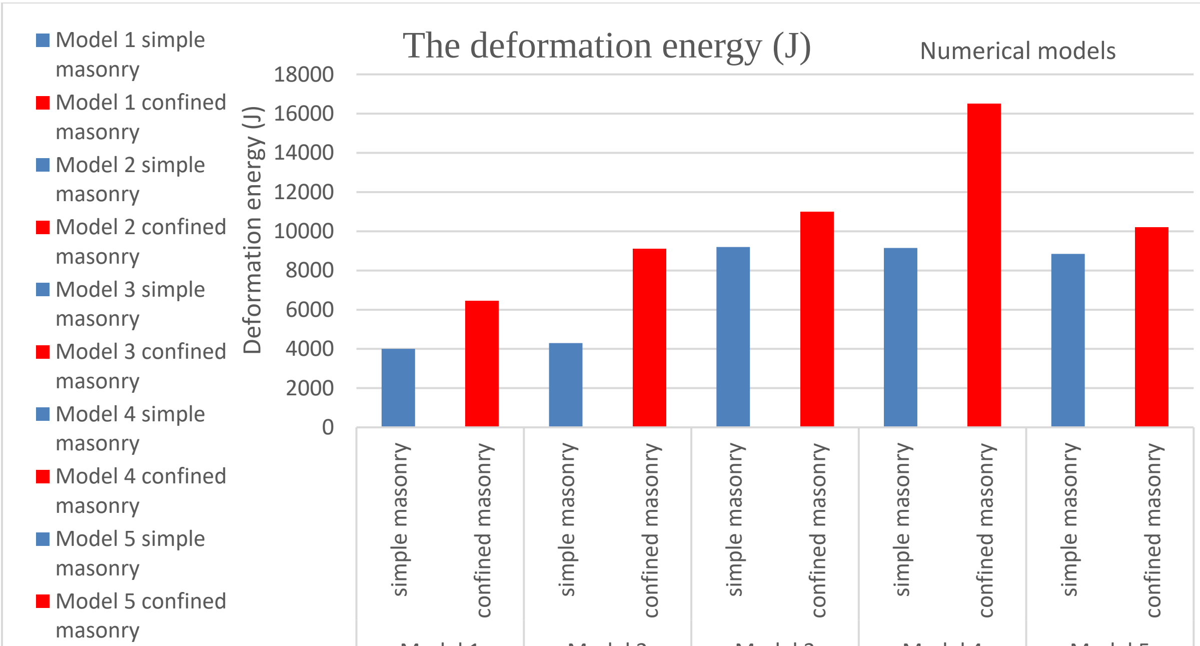


Fig. 6.5.10. Comparative presentation of the deformation energy for the 5 models

6.5.1. Final considerations

Polymeric grid confinement of the representative numerical models leads to the increase of their resistance and rigidity characteristics, so this is an efficient measure. The analysis of the stress values reveals the fact that the polymeric grid consolidation solution tends to reduce the peak values of the stress diagrams, and at the same time to increase the efforts in the areas with lower loads. Their role is to lead to an uniformization of the efforts.

CAPITOLUL 7. CULTURAL HERITAGE BUILDINGS

Churches are the most important constructions belonging to the cultural heritage that were built before the 19th century. They are a proof of the religiousness and the Christian Orthodox culture of the Romanian people. They are built according to a gravitational conception, being generally characterised by pronounced monumentality, and empty vicinities. The Cașin Monastery church is a relevant example in this case.

Chapter 8. ARCHITECTONIC HERITAGE BUILDINGS

Just like the cultural heritage buildings, these buildings are characterised by monumentality, important dimensions, and generally, empty vicinities. They are located in large spaces and on the grand boulevards, in order to impress passers-by. Also, they are built according to a purely gravitational conception, without taking into consideration seismic calculations. This chapter describes architectonic heritage buildings such as the Bragadiru Palace or the Adriatica Trieste Palace.

Chapter 9. OFFICE AND RESIDENCIAL BUILDINGS

Current office and residential buildings are starting to develop vertically, in contradiction to their horizontal development which was typical until the interwar period. Therefore, each parcel of land is fully used, leading to buildings developing chaotically in the place, according to the form of the parcel, and vicinity problems are current. Given their role, they were designed mostly in order to be useful to the occupants, and less in order to impress.

Chapter 10. Case study 1: CAȘIN MONASTERY CHURCH, BUCHAREST

10.1.Technical description

The Cașin Monastery in Bucharest is a mixed construction, having as a resistance structure a spatial and elastic skeleton made of straight and curved bars, with rigid nodes, made of monolithic reinforced concrete covered in massive brick masonry. [63] The construction conception of the monastery is essentially gravitational.

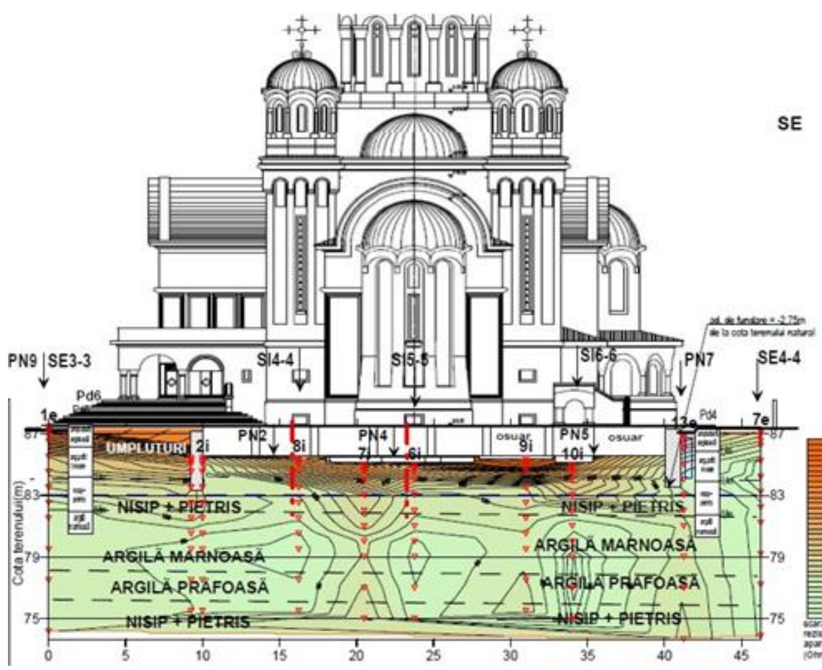


Fig. 10.1.1. Central, vertical, longitudinal geoelectic section [63]

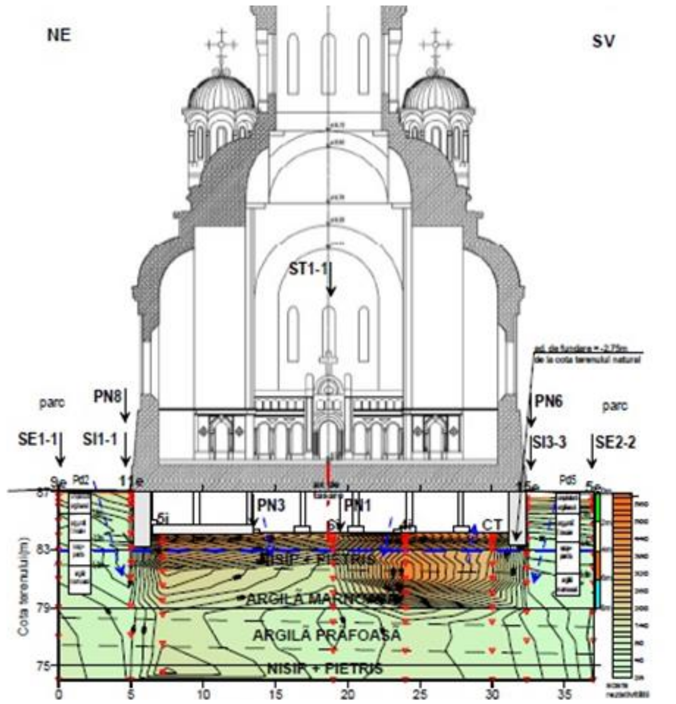


Fig. 10.1.2. Central, vertical, transversal geoelectric section [63]

The geoelectric sections identify the problem that led to the existing degradation of the church. The land has an inhomogeneous structure and the foundation system consisting of insulated foundations is inadequate, leading to differentiated settlements.

The consolidation solution consists in increasing the strength of the reinforced concrete elements and restoring the continuity of the masonry walls, in case they are fissured. It is considered that the differentiated compactions have already been consumed, and an intervention on the foundation system is not going to have a significant impact. In order to bring the construction to its original state, the elements of reinforced concrete and masonry that are cracked as a result of differentiated compactions are to be consolidated. For the columns, a 10 cm reinforced concrete jacket, using C25/30 concrete, is to be used. The walls are to be consolidated by using an 8 cm thick reinforced concrete jacket. The same procedure is to be done for the beams. The reinforced concrete slab from the level 0 is to be concreted over, given the major fissures in it. The thickness of this layer is to be of 10 cm. After going through the procedures, an assessment of the seismic resilience for the initial structure is to be carried out.

The second solution is to build a reinforced concrete raft with the role of connecting the existing isolated foundations and of preventing any differentiated compactions. Its role is to reduce the pressure on the base of the foundation. Also, a perimetre reinforced concrete wall is to be made, with a width equal to the thickness of the wall and a height of 3 m. The goal of the wall is to stabilize the building and to prevent differential compactions, as well as to stop water infiltration below the foundation level.

The changes which are proposed according to the second solution do not directly improve the seimic resilience of the superstructure, but they do secure the infrastructure part of the building, reducing the chances of previous problems arising from the poor foundation system to recur.

The obtained results are summarized in the table 10.2.1.

10.2.Comparative summary of the two consolidation solutions

Comparing the consolidation solutions				
		Existing structure	**The first consolidation solution**	**The second consolidation solution**
The weight of the structure (kN)		64212	67028	83255
The base shear force (kN)	Longitudinal	8717	8775	8919
	Transversal	10113	10053	10953
The fundamental oscillation period (s)		0.51	0.49	0.51
The second oscillation period (s)		0.46	0.45	0.46
The third oscillation period (s)		0.34	0.34	0.35
Maximum resilience		**40%**	**79%**	**79%**
Minimum resilience		**40%**	**68%**	**68%**

Tabel 10.2.1. Summary table which compares the consolidation solutions

Chapter 11. Case study 2: A MONUMENTAL BUILDING IN BUCHAREST

11.1.Technical description

The building was made in 1926, and the height regime of the building is partially 2B+Gf+Mz+5+Attic, and on the main façade it is 2B+Gf+Mz+6. [48].

The construction system consists of a redundant spatial structure, made up of columns, floor beams with slabs and stairs, all made of monolithic reinforced concrete, poured in situ. The exterior enclosing walls, as well as the interior partition walls are made out of brick masonry, which in turn is made of solid porous bricks and clean, cement-free fat lime mortar. The construction system is entirely based on a gravitational design.

11.2.Mathematical modelling and the analysis of the dynamic characteristics

In order to identify the degree of influence of the conctact between the reinforced concrete skeleton and the framed masonry, several numerical models have been made.

The first numerical model, with pure frames, is the one corresponding to a non-existent influence of the infills on the overall rigidity of the structure. Walls are considered only as a dead weight The second model involves considering the infills as diagonals. The third numerical model involves considering the infills as shell elements.

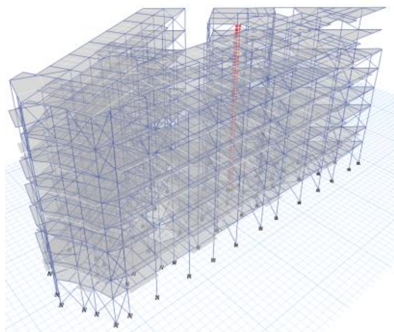


Fig. 11.2.2. 3D numerical model for the "diagonals" modelling variant

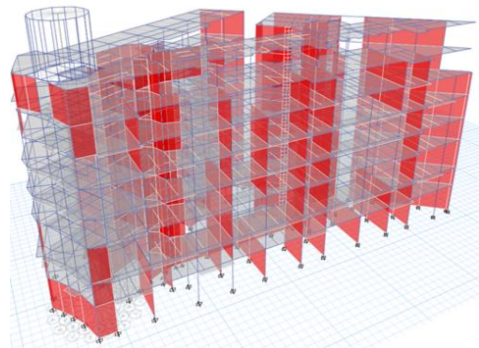


Fig. 11.2.3. 3D numerical model for the "shell" walls modelling variant

Subsequently, measurements were made to determine the dynamic parameters of the building.

Vibration modes	"Pure frames" model	Equivalent diagonals masonry model according to P100-3/2008	"Shell"masonry model	Results of the "in situ" dynamic measurements
T1 (s)	**1.663**	**1.079**	**0.714**	**0.69**
T2 (s)	**1.438**	**0.951**	**0.616**	**0.53**
T3 (s)	**1.402**	**0.601**	**0.381**	**0.32**

Table. 11.3.1. Comparative table showing the different dynamic features of the building [31]

The comparative table shows very different values for the dynamic characteristics, which may differ by up to 438% (T3 for the pure frames = 1.402 s, T3 during the in-situ measurements = 0.32 s). Moreover, it turns out that the numerical model that is the closest to the in-situ measurements is the one in which the masonry is modelled with "shell" elements. This model corresponds either to an important collaboration between the reinforced concrete frames and the framed masonry walls, or to the model of confined masonry.

11.3.Enhancing the seismic resilience – solution 1

The first consolidation measure that is proposed is a minimum solution, compatible with ISCARSAH recommendations. This measure consists in going from a simple connected outer contour, according to Vlasov's theory, to a double connected outer contour, according to Bredt's theory. There are two variants of the solution, which as a concept are identical, but differ when it comes to the used materials. Thus, a structural reconformation without consolidation is proposed. The first variant involves connecting the wings with walls and reinforced concrete slabs. The second solution involves binding the wings with metallic elements.

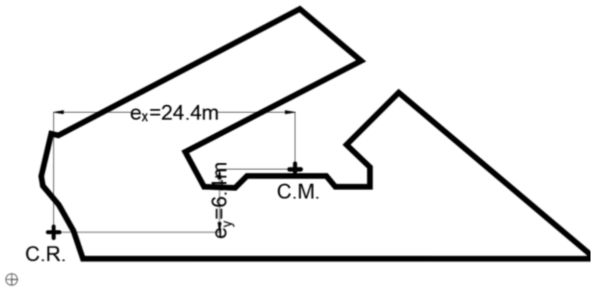


Fig. 11.3.1. Comparative presentation – The centre of mass and the centre of rigidity for the current level, unconsolidated version

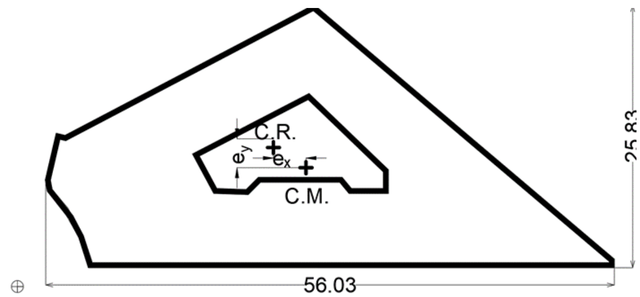


Fig. 11.3.2. Comparative presentation – The centre of mass and the centre of rigidity for the current level, consolidated version

11.4.Enhancing the seismic resilience – solution 2

The second solution which is proposed in order to increase the seismic resilience is in addition to the first one. It consists of changing the structural system: from a structure made up of reinforced concrete frames and framed masonry to a structure with isolated reinforced concrete walls and mostly gravitational frames with framed masonry.

The obtained results are summarized in the table 11.5.1.

11.5.Comparative summary of the two consolidation measures

Comparing the consolidation solutions				
		Existing structure	**The first consolidation solution**	**The second consolidation solution**
The weight of the structure (kN)		87672	90421	93368
The base shear force (kN)	Longitudinal	22296	23746	18157
	Transversal	20454	21413	16557
The fundamental oscillation period (s)		0.714	0.71	0.66
The second oscillation period (s)		0.616	0.6	0.52
The third oscillation period (s)		0.381	0.28	0.28
Maximum resilience		**45%**	**49%**	**82%**
Minimum resilience		**37%**	**43%**	**76%**

Tabel 11.5.1. Summary table which compares the consolidation solutions

Chapter 12. Case study 3: THE BRAGADIRU PALACE

12.1.Technical description

The palace building has an irregular shape in plan, with maximum dimensions of 120.32 m x 38.26 m. The height regime of the building is Ug + Gf + F + M, for buildings A and B, and Ug + Gf + 2F for C section. The building consists of three sections and is free on all sides. [78]

The seismic resilience of the existing structure was assessed. Two consolidation solutions have also been proposed. The first solution is to make a 6 cm thick coating, reinforced with welded steel nets, as well as adding reinforced concrete floors. The second solution is coating with polymer grids and 2 cm thick lime plaster and keeping the wooden floors. The results obtained were summarized in Table 12.2.1.

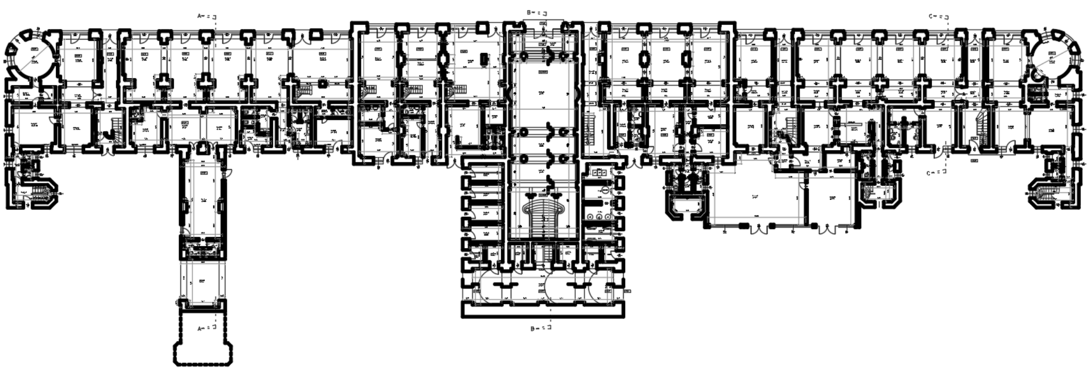


Fig. 12.1.1. Layout of the ground floor

12.2.Sinteza summary of the two consolidation solutions

Comparing the consolidation solutions				
		Existing structure	**The current consolidation solution**	**Consolidation with grids**
The weight of the structure (kN)		286552	329635	292183
The base shear force (kN)	Longitudinal	107070	122993	109221
	Transversal	74372	85393	75786
The fundamental oscillation period (s)		0.408	0.198	0.39
The second oscillation period (s)		0.360	0.148	0.34
The third oscillation period (s)		0.347	0.144	0.32
Maximum resilience		**62%**	**89%**	**82%**
Minimum resilience		**57%**	**82%**	**76%**

Tabel 12.2.1.Summary table that compares the consolidation solutions

Chapter 13. Case study 4: A RESIDENTIAL PATRIMONIAL BUILDING IN BUCHAREST

13.1.Technical description

The footprint of the building has the configuration of an enclosed, irregular and convex polygon, with all the sides being of different sizes. The block was built in 1934 and it is located downtown Bucharest.

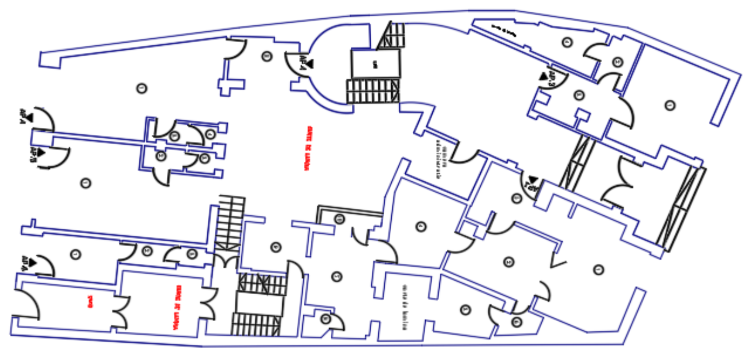


Fig. 13.1.1. Original layout of the ground floor [69]

It can be stated that in the northern, anterior half, the height regime of the building is B+Gf+5+Rf+Attic, while in the southern, posterior half, it is B+Gf+5. The construction system consists of a spatial structure made up of foundation beams, columns, floor beams with slabs and stairs, all made of monolithic reinforced concrete, poured in situ. The infills are made from solid bricks and lime mortar.

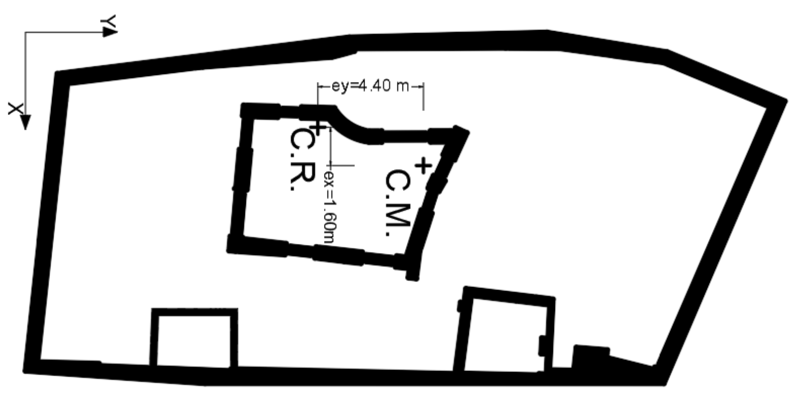


Fig. 13.1.2. The centre of mass and the centre of rigidity for the current level

13.2.Mathematical modelling and the analysis of the dynamic characteristics

Several calculation models have been developed in order to estimate the contribution of the framed masonry to the overall rigidity of the structure. Initially, it was assumed that there was no cooperation, as a model with pure frames was regarded, in which the masonry was considered only as a load distributed on the beams, without having any contribution to the overall rigidty of the structural system.

The intermediate situation is that in which there is a certain degree of cooperation but it is not complete. In the last modelling variant, it was assumed that there was a high degree of cooperation. Thus, an equivalent model was created, with the walls modelled as ‘’shell’’ type surface elements. The three models were compared.

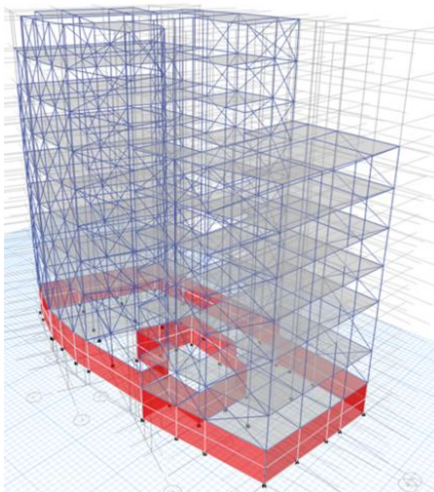


Fig. 13.2.2. 3D numerical model for the modelling variant that involves diagonals

Fig. 13.2.3. 3D numerical model for the modelling variant that involves ‘’shell’’ walls

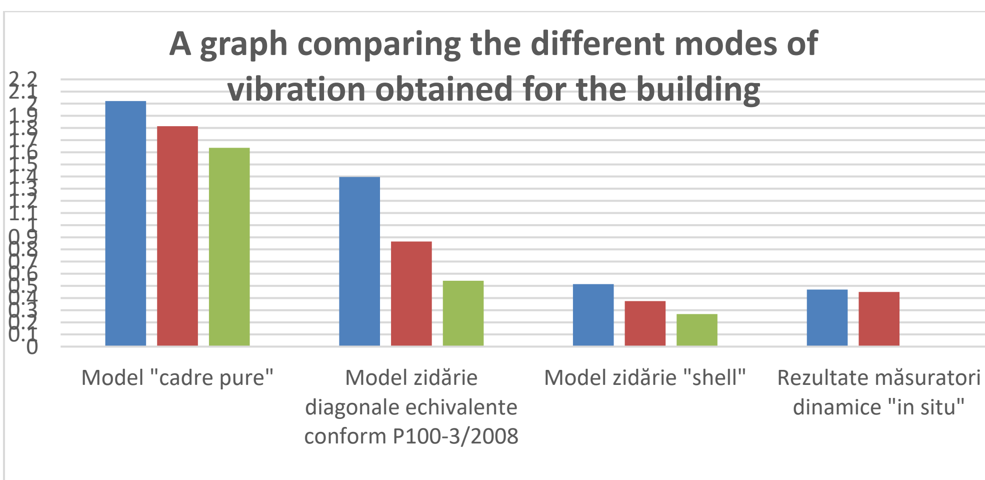


Fig. 13.2.4. A comparative graph featuring the different dynamic characteristics obtained for the building

Given the obtained results, it is considered that the model made with ”shell” type elements, which was calibrated according to in-situ tests, is the closest to reality. Therefore, it was used in the seismic risk assessment and the proposed solutions for consolidation.

13.3.Enhancing the seismic resilience – solution 1

The first consolidation measure which is proposed involves a minimum solution, compatible with ISCARSAH recommendations. Through this method, the increase of seismic resilience is done by reconforming the structure, without direct consolidation measures. The inner courtyards are to be enclosed with a reinforced concrete slab.

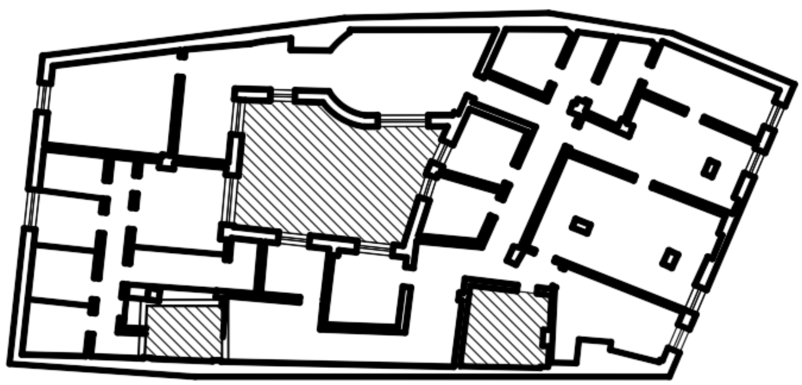


Fig. 13.3.1. Current level layout using hatching in order to identify the light meshes that are enclosed with plates

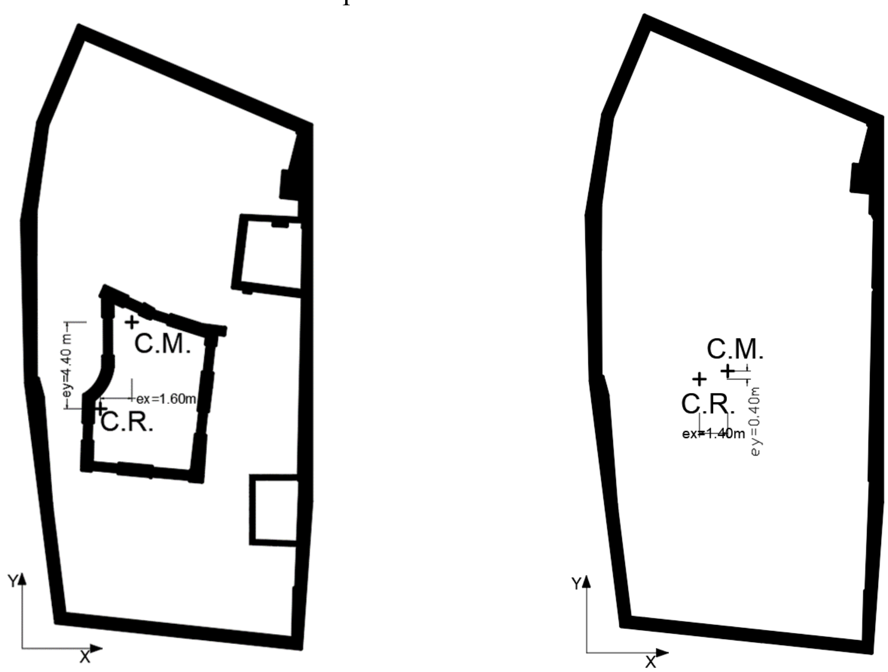


Fig. 13.3.2. The centre of mass and the centre of rigidity for the current level, the initial version being on the left, the first solution of enhancing the seismic resilience being on the right

This intervention measure leads to an improvement of the dynamic characteristics by decreasing the distance between the centre of mass (C.M.) and the centre of rigidity (C.R.). At the same time, they get closer to the geometric centre of the plane.

13.4.Enhancing the seismic resilience – solution 2

The second solution which is proposed in order to increase the seismic resilience is in addition to the first one. It consists of changing the structural system: from a structure made up of reinforced concrete frames and framed masonry to a structure with isolated reinforced concrete walls and mostly gravitational frames with framed masonry.

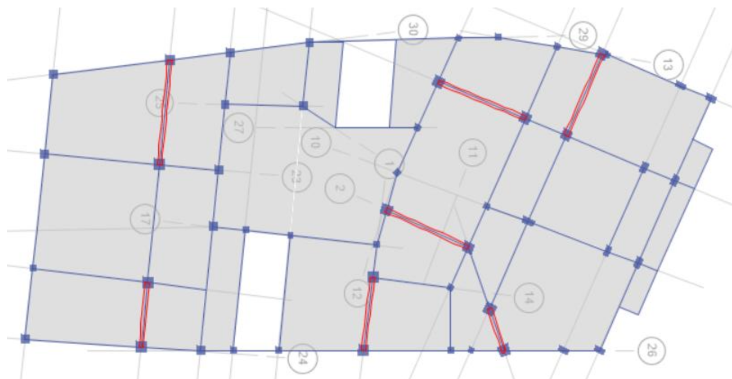


Fig. 13.4.1. The current floor layout, showing the structural walls that were inserted

The results obtained were summarized in Table 12.2.1.

13.5.Comparative summary of the two consolidation solutions

Comparing the consolidation solutions				
		Existing structure	**First consolidation solution**	**Second consolidation solution**
The weight of the structure (kN)		42767	46722	48943
The base shear force (kN)	Longitudinal	7575	8223	9141
	Transversal	9597	10411	10222
The fundamental oscillation period (s)		0.47	0.47	0.40
The second oscillation period (s)		0.36	0.32	0.29
The third oscillation period (s)		0.26	0.22	0.21
The drift on the first level (%)		0.81	0.82	0.19
Maximum resilience		**62%**	**66%**	**78%**
Minimum resilience		**54%**	**58%**	**75%**

Tabel 13.5.1.Summary table that compares the consolidation solutions

Chapter 14. Case study 5: MULTISTORY RESIDENCIAL BUILDING FROM BUCHAREST

14.1.Technical data

The building was erected in 1925. The height regime of the building is Sp + P + 3E, and the level are high, as usually for an interwar structure. The building was designed considerring only gravitation, with no earthquake consideration.

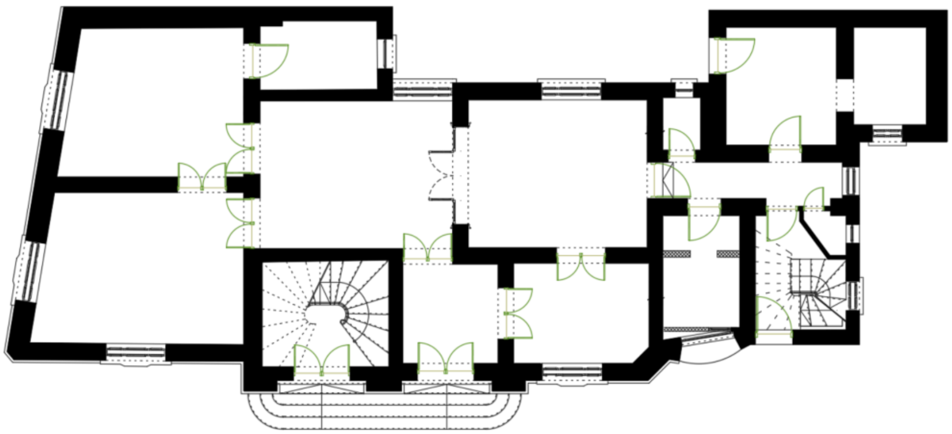


Fig. 14.2.1. Layout of the ground floor [71]

From a construction point of view, the building consists of the following structural subassemblies: slightly crumbly brick foundations, hydraulic lime and a simple concrete base, as well as walls made out of solid ceramic bricks with lime mortar, reinforced concrete floors above the basement, as well as wood and reinforced concrete floors above the other levels and wooden framing. [71]

14.2.Mathematical modelling and analysis of dynamic characteristics

Vibration modes	"Shell" masonry model	"In situ" dynamic measurements results
T1 (s)	0.377	0.45
T2 (s)	0.28	0.32
T3 (s)	0.252	-

Tabel. 14.2.1. Comparative table showing the different dynamic characteristics [82]

The numerical model was calibrated using dynamic measurements, which provide some clues about the actual state of degradation of the structure. The first solution taken into account in order to enhance the seismic resilience is a structural reconformation without consolidation. In the second solution, The structural walls are to be strenghtened by making a reinforced plaster with a thickness of 6 cm and reinforced with welded mesh with a diameter of φ8/100/100. The consolidation is to be done only on the inside of the structure, in order to keep the façades of the structure intact. Also, reinforced concrete floors are to be made, along with belts around the perimeter on every slab area outlined by 4 grids. 15 cm thick slabs are to be used. The third consolidation solution is a modern one, and it is compatible with the lime masonry. It is that of coating both sides of the wall with polymeric grids. The syntesis of the results is presented in table 14.3.1.

14.3.Comparative synthesis of the three consolidation solutions

Comparison of the results					
		Existing masonry	**Reconformation without consolidation**	**Current consolidation**	**Polymeric grids**
The weight of the structure (kN)		15128	19997	19403	15550
The base shear force (kN)	Longitudinal	3994	5291	4844	3994
	Transversal	4709	6257	5219	4709
The period of the fundamental mode (s)		0,45	0,42	0,218	0,43
The period of the second mode (s)		0,32	0,317	0,151	0,31
The period of the third mode (s)		0,303	0,247	0,142	0,301
Maximum resilience		**55%**	**58%**	**90%**	**83%**
Minimum resilience		**43%**	**52%**	**77%**	**74%**

Table 14.3.1. Summary table comparing the consolidation solutions [88]

Final conclusions regarding the case studies

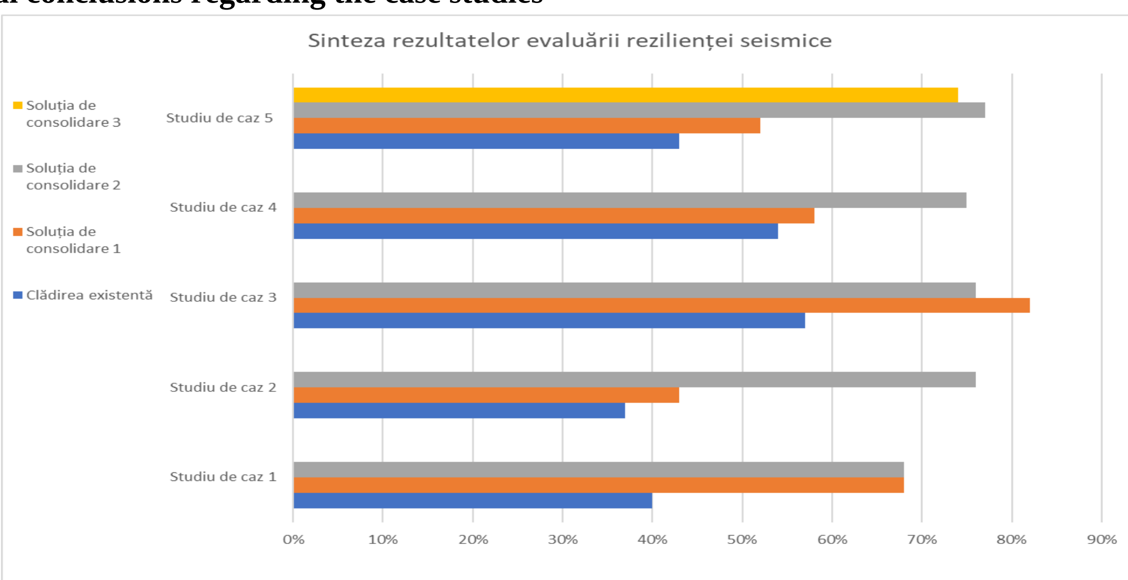


Fig. 14.3. A synopsis of the evaluation of the seismic resiliences for the 5 case studies

Chapter 15. The economical performances

15.1.Technical data

In order to realise an economical assessment, a flat masonry wall with a length (L) of 3.00 m and a height (H) of 2.00 m was chosen. The calculation was made for solid pressed bricks and ceramic bricks with vertical hollows. The chosen size of the brick slabs, l x b x h, is 12x26x6.5 cm. These dimensions allow the walls to be built with all three proposed thicknesses. The slabs of ceramic bricks with vertical hollows have 3 dimensions (l x b x h), depending on the thickness of the walls: 0.25x0.12x0.25 cm, 0.25x0.25x0.25 cm, 0.25x0.38x0.25 cm.

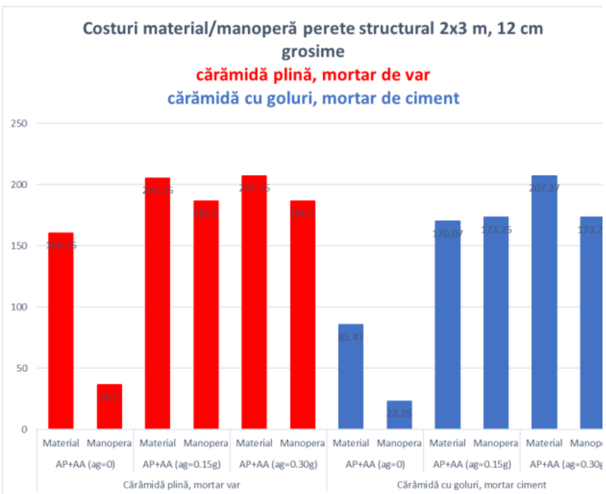


Fig. 15.4.1. Material and labour prices for a 12 cm thick wall

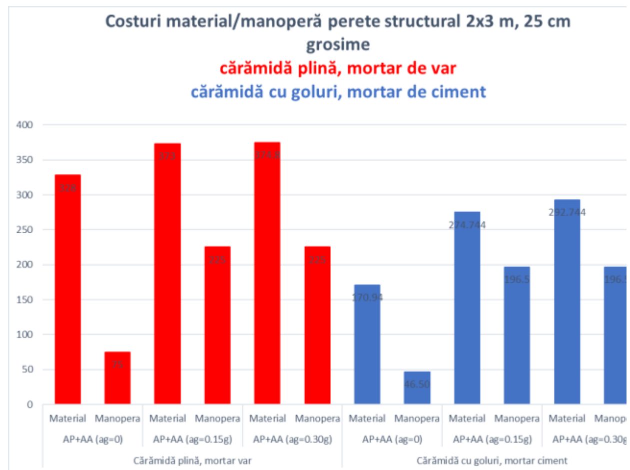


Fig. 15.4.2. Material and labour prices for a 25 cm thick wall

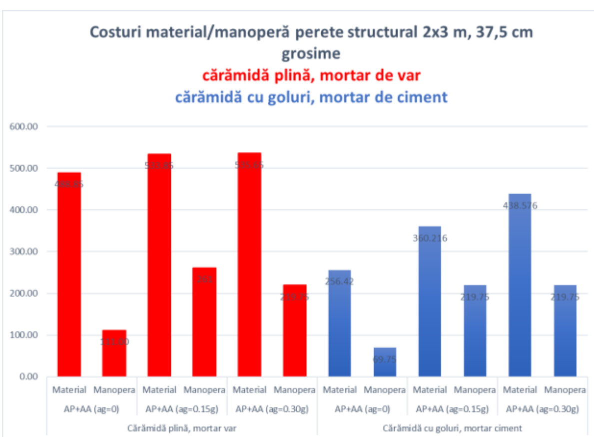


Fig. 15.4.3. Material and labour prices for a 37.5 cm thick wall

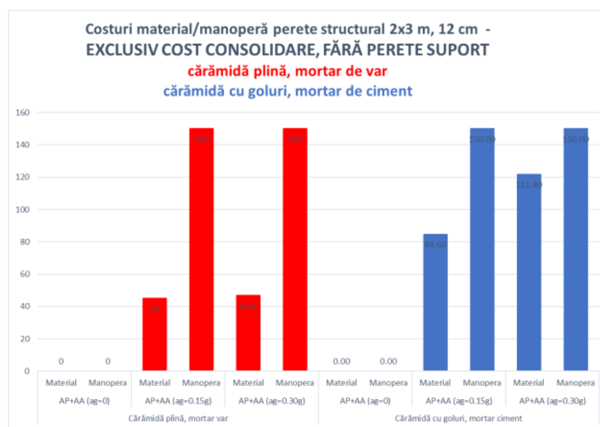


Fig. 15.4.4. Material and labour prices only for the consolidation of a 12 cm thick wall

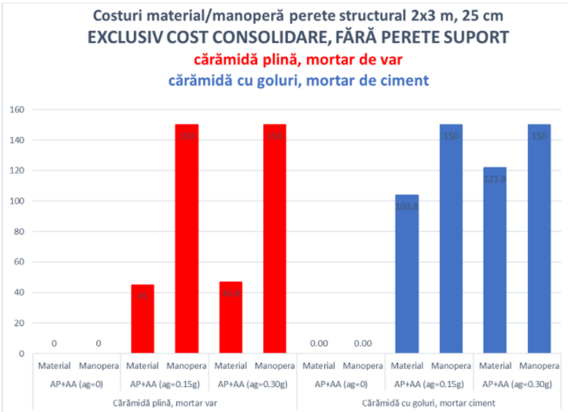


Fig. 15.4.5. Material and labour prices only for the consolidation of a 25 cm thick wall

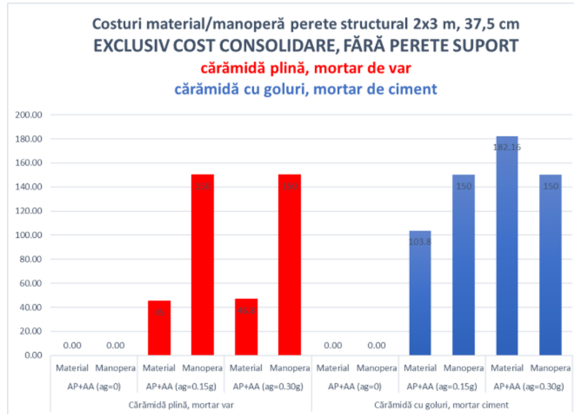


Fig. 15.4.6. Material and labour prices only for the consolidation of a 37.5 cm thick wall

15.2.Conclusion

The cost of consolidating a solid masonry wall with lime mortar is lower than that of consolidating a hollow brick wall with cement mortar.

The cost of building a solid masonry wall with lime mortar with polymeric grid plastering is higher than the cost of building a hollow masonry wall with cement mortar.

Chapter 16. Conclusion

The objectives that were considered within this doctoral thesis have been achieved.

Chapter 17. Personal contributions

The personal contributions are the following: defining seismic resilience in the context of interwar buildings, the validation of experimental models by making use of numerical interpretation, the evaluation of seismic resilience for interwar buildings, as well as solutions for its enhancement.

Bibliography

The bibliography includes 87 sources.