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STRUCTURAL STRENGTHENING OF HISTORIC MASONRY BUILDINGS USING MESH REINFORCED COMPOSITE MATERIALS

PhD thesis – Summary

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The seismic retrofit of historic masonry structures is a complex research topic, offering various research opportunities since a diversity of strengthening strategies can be currently employed, ranging from traditional to contemporary materials and techniques.

However, existing/heritage masonry structures bring forward a series of challenges. The complexity of this topic arises from the fact that historic buildings are most of the time highly decorated on the outside or sometimes on the inside. Preserving the interior/exterior aesthetics and original features is therefore crucial. Internal interventions could disrupt these elements, leading to a loss of cultural and historical value. Similarly, the preference for public buildings with outside decorations might be to conduct the intervention on the inside, especially where the external façade's appearance is critical to the adjacent urban context. Therefore, solutions that could be used in this context had to be analysed.

Considering this, a research was performed on historic masonry structures characteristic for Timisoara, a city in the western part of Romania. It highlights the importance of improving the structural behaviour of this type of structure while maintaining the authenticity and aesthetics of the building. The main aim of the study was to test and understand the behaviour of strengthening solutions, which can also ensure the authenticity of historic buildings and limit the strengthening intervention to the more adapted surfaces while preserving the original decorations and building aspect.

Therefore, the thesis was organised into five chapters, considering its main objectives and approaching the strengthening of historic masonry structures from two points of view. The study can be divided into three main parts:

1. The first part is connected to the analysis of the currently built environment and available literature on this topic. It is meant to highlight the main characteristics of historic masonry structures, geometric features and building techniques. Ultimately, commonly used strengthening solutions are presented, and their main differences are brought forward.
2. In the second, the emphasis was placed on the analysis of the structural behaviour of historic masonry brick specimens built using recovered bricks and reconstructed with lime-based mortar under in-plane shear loads. Since the main purpose was to discover aestetically and socially acceptable strengthening options that would lead to structural retrofit of historic masonry buildings while preserving their architectural value, steel mesh reinforcements with a lime-based matrix applied on one or both sides were considered. The specimens were tested for shear strength in laboratory conditions according to the ASTM E519/E519M – 15, and the recorded results were analysed to observe the performance of the proposed solutionDa s

in terms of resistance, stiffness, and ductility.

3. Ultimately, in the last part, numerical simulations were made on masonry wallets and, subsequently, on a sample structure to understand the effect of the strengthening solutions in a global analysis. The recorded results were also analysed in order to observe the performances of the proposed solutions in terms of resistance and stiffness and understand how the observations made during the laboratory tests could be further used in historic masonry structure strengthening projects.

The first chapter presents a general overview of the thesis and highlights its context, main scope, and the need for intervention.

The necessity for intervention was brought forward by a multitude of factors:

1. Seismic activity degradation
2. Climate degradation that is gradual in its nature, but can lead to sudden failure events, like roof or cornice collapses due to roof structure water actions, or even sudden detaching of plaster surfaces and decorations that are loose to a point where a storm or frost make them fall off
3. Foundation settlement, often combined with damaged rainwater collection systems
4. Human intervention, like incompetent removal of structural elements, use of incompatible materials.

The chapter emphasises the region on which the study was performed, namely Timisoara and the Banat Region, found in Eastern Europe, in the western part of Romania [1].

The seismic action is significant as its hazardous moment is unforeseeable. It can lead to considerable damage to unreinforced masonry buildings and loss of life and, consequently, to the culturally valuable elements of historic buildings or urban areas. In Romania, the Banat region is known as a seismic zone with its own geo-seismic characteristics, with earthquakes with short periods of vibration (ranging from below 0.2 seconds to up to 0.3 seconds) that impact large masonry structures, pulse actions with a strong initial cycle followed by cycles of reduced intensity and horizontal and vertical components of similar acceleration.

This aspect should be considered in the context in which the entire Timișoara city centre is a listed protected area subjected to preservation. The same situation is met in the surrounding important cities. This underscores the pressing need for interventions to strengthen masonry walls in seismic-prone regions while preserving the architectural expression and cultural value of historic brick structures. Contemporary conservation philosophy emphasises minimal alteration to the original behaviour of monuments, thus discouraging the use of very high-strength materials and rigid additions, which are deemed inappropriate for such applications [2].

The research presented in the thesis tried to align the need for structural strengthening and align it with the ICOMOS principles [3], [4], [5], [6], [7], [8]. The "International Charter for the Conservation And Restoration Of Monuments And Sites (The Venice Charter 1964)" [3], The Declaration of Amsterdam" [4], the "The Nara document on authenticity" [5] and the "Burra Charter" [7] which highlight that importance of the cultural value of heritage structures, the social and physical context of the building and, ultimately, the social consequences of the interventions, mainly in the case of owners and tenants while emphasising the importance of preserving the authenticity of the built heritage.

Therefore, the chapter brings forward the main research goals relevant in this context:

1. Ensuring the authenticity of the materials and design
2. Limiting the strengthening intervention to the more adapted surfaces to receiving it, while preserving the original decoration
3. Using compatible materials with the original structure from a historical but also from a physic-chemical point of view

4. Considering the environmental impact of the materials and techniques used.
5. Adapting the intervention to the human and social factors, as in Romania, the context of apartment ownership presents unique challenges for masonry wall strengthening, particularly in seismic-prone areas. Many apartments are owner-occupied, making it impractical to relocate residents during structural interventions due to financial, logistical, and social reasons. Many residents may also be reluctant to leave their homes, even temporarily, due to personal attachments and security concerns. Consequently, there is a strong preference for carrying out necessary strengthening work exclusively from the exterior.
6. In the case of historic buildings, preserving the interior aesthetics and original features is crucial. Internal interventions could disrupt these elements, leading to a loss of cultural and historical value. Similarly, for public buildings with decorations outside, the preference might be to conduct the intervention on the inside, especially where the external façade's appearance is critical to the adjacent urban context.

The second chapter focuses on a detailed evaluation of the development and current condition of masonry structure strengthening solutions. The primary areas of attention were the analysis of traditional and contemporary reinforcement materials and techniques, the understanding of suitable numerical analysis strategies, and the integration of seismic and thermal retrofitting solutions. The purpose of this chapter is to bring attention to the recent developments in reinforcement techniques and how these techniques can be used to improve the structural performance of masonry buildings while considering their cultural value.

The chapter starts with the fact that masonry has been an important material used throughout history because of its durability, aesthetics, and load-bearing capacity. More than this, it was used in various regions, with or without seismic activity, proving its versatility but also leading to high vulnerabilities over time. Therefore, in order to maintain their structural integrity and ensure the safety of the inhabitants, suitable strengthening solutions have to be found, which could also ensure the protection of valuable features [9] .

Over several centuries, masonry structures have evolved significantly and have been influenced by technological advances, architectural styles, engineering knowledge, and available materials. A thorough understanding of these construction techniques is required for developing successful reinforcement methods that preserve the original design while improving their structural performance [10]. From a diverse variety of masonry blocks, including stone blocks, clay bricks, and concrete blocks, which have been used for a variety of purposes throughout history, to the analysis of various bonding patterns, including English, Flemish, and running bonds – stretcher bond and header bond the chapter highlights that each decision regarding materials and building techniques can lead to a better load transfer and ultimately influence the structural behaviour. [11].

Another important aspect approached in this chapter is the understanding of the geometry of historically important masonry buildings. Studies show that masonry walls, in the case of historic buildings, have a thickness that could reach between one and two meters. Contemporary masonry structures, on the other hand, are often thinner than the historical ones due to the presence of reinforced concrete elements included in order to ensure better structural behaviour [12] reaching down to 95 mm in the case of load-bearing cavity walls in areas with low seismicity [13]. However, thicker walls might be more vulnerable to earthquake stresses due to their increased mass. Reinforcement methods must, therefore, achieve a balance between these parameters in order to improve the general performance of the exterior load-bearing walls. Thinner and more flexible reinforced walls decrease total weight and enhance flexibility to enhance seismic performance [14].

Ultimately, the focus of the chapter shifts towards the understanding of contemporary strengthening materials compatible with historic masonry structures. Eight different solutions were considered, some respecting the ICOMOS heritage strengthening guidelines but others not. The following materials were taken into consideration:

1. Concrete jackets with embedded steel mesh – a solution that has been used since the 20th century to strengthen and stabilise masonry structures, particularly in seismic zones [15]. This method provides a robust external shell that improves load distribution and resistance to lateral forces and effectively improves the compressive and shear strength of masonry walls, which makes them widely used in retrofitting historical buildings to enhance their seismic resilience.
2. Fibre-reinforced polymers (FRP) are a solution that comprises composites such as carbon, glass, and aramid fibres meant to provide high tensile strength combined with low weight and corrosion resistance. They are flexible and can be applied in various forms, such as sheets, strips, or rods [16], being therefore commonly used for external reinforcement, meant to improve the tensile and flexural strength of existing masonry structures [17].
3. Fibre-reinforced cementitious matrix (FRCM) combines fibre reinforcements, such as carbon or glass, with a cementitious matrix, offering improved bonding with masonry substrates. This composite material provides enhanced durability and resistance to environmental degradation while also offering a balanced combination of strength and compatibility [18].
4. Textile-reinforced mortar (TRM) solutions incorporate high-strength textiles, such as glass, basalt, or even steel fibres, within a mortar matrix, enhancing the ductility and strength of masonry walls. This method is particularly suitable for reinforcing complex geometries and curved surfaces, making it suitable for both historical and modern structures. Its flexibility and adaptability make it an ideal choice for preserving the aesthetic integrity of historic buildings while providing structural reinforcement [19].
5. Composite reinforced mortar (CRM) integrates fibres and additives within the mortar, improving its mechanical properties and durability. This composite material is used to strengthen masonry walls, providing enhanced resistance to cracking and environmental degradation, presenting a significant enhancement of the load-bearing capacity of masonry walls [20]
6. Steel fibre reinforced polymers (SFRP) combine steel fibres with a polymer matrix, providing enhanced toughness and load distribution capabilities. SFRP offers high tensile strength and durability, making it suitable for reinforcing critical structural elements being generally used to reinforce masonry structures against seismic and dynamic loads. More than this, it can also be used in the case of historic buildings, leading to significant improvements in structural performance without compromising the value of the architectural heritage [21].
7. Cross-laminated timber (CLT) strengthening solutions offer high strength-to-weight ratios and are used for internal reinforcement, improving seismic performance, preserving exterior aesthetics, and being a sustainable and reversible reinforcement solution [22].

Subsequently, the focus of the chapter shifts towards historic masonry assessment procedures for structures located in seismic areas, which include shear testing, diagonal compression testing and numerical simulations. All these assessment methods are used to understand the influence of different strengthening solutions [23]. During laboratory tests, an important component in understanding the seismic behaviour of a structure is the analysis of the diagonal tensile strength of a wall specimen, which can be achieved using the guidelines defined in different standards, like EN 1052-3 [24] or ASTM E519/E519M-15 [25]. Additionally, in order to understand the effect of seismic strengthening solutions on a whole structure, various computer software can be considered, such as discrete element modelling (DEM) or finite element analysis (FEA) [26]. ANSYS, ABAQUS, DIANA, and other well-known platforms offer tools for simulating complex structures [27] and case studies demonstrate that they can successfully be applied to understand the behaviour of both contemporary and historic masonry structures [21], [28], [29].

The chapter provides important insights into the development and effectiveness of a wide range of reinforcing materials and techniques, emphasising the need to provide solutions suitable for historic masonry buildings. To provide holistic retrofitting solutions, future research should focus on the development of innovative materials, the optimisation of reinforcing solutions, and the development of interdisciplinary solutions. It highlights that among the particular areas that demand more research are the long-term performance and durability of contemporary reinforcement materials, the optimisation of single-side strengthening methods, the creation of affordable and scalable solutions for combined seismic and thermal retrofitting, and the improvement of numerical modelling tools for more realistic simulation of reinforced masonry behaviour [30].

The third chapter investigates the diagonal tension cracking of historic masonry walls subjected to shear forces, as this failure mechanism presents a real danger leading to sudden brittle collapse. In the context mentioned in the first chapter, the study focuses on the heritage buildings of Timișoara and its surroundings within the historical context. This zone is scattered with many buildings that use similar construction techniques dating from the 19th century to the beginning of the 20th century. The study starts with characteristic brick masonry structures from the western part of Romania built until the beginning of the 20th century; their structural characteristics are highlighted after extensive studies performed between 2015 and 2021 [31]. Additionally, based on the analysis of the brick pattern visible in the case of buildings with damaged exterior plaster or structures which are currently being restored, a clear use of English bond was also observed with one line of stretchers and one subsequent line of headers.

In order to understand the shear behaviour of the considered masonry wallets as a basis for the testing layout, the ASTM International standard E519/519M-15 was selected as the results can be compared to a large pool of similar work. The experimental tests were performed in a dedicated laboratory of the INCD URBAN-INCERC (National Institute of Research and Development in Construction, Urbanism and Sustainable Development) facility.

For the laboratory tests, fifteen masonry specimens were built according to the standard dimension of 1200x1200 mm in-plane dimension. The thickness of the specimens was selected to be similar to the historic masonry walls present on the first floors of many existing buildings from the studied era, thus a 1½ brick thickness was used, built in an English bond pattern, resulting in a total thickness of 450 mm, which is generally thicker than the majority of the reported tests in the literature.

To get more accurate results, attention was also paid to the historic accuracy of the specimens regarding to materials used and to the workmanship. Therefore, the used brick was recovered from a demolition site of a utilitarian 1910 construction (animals stable), near Timisoara and all joints including vertical ones were filled with mortar mixed according to one of the building manuals of the time, the Lothar Abel's "Allgemeiner Bauratgeber - Ein Hand- und Hilfsbuch für Bauherren, Architekten, Baunternehmer, Baumeister, Bautechniker, Bauhanweker, Landwirte und Rechnungsbeamte" [32] was consulted considering a 1:3:1.25 (hydrated lime, sand, water) proportion by volume.

Four sets of specimens were prepared:

1. The first group composed of three specimens represented the original unreinforced masonry which was used as reference for the future tests being only covered in a simple lime sand plaster considering the historic information.
2. The second set of three specimens were strengthened on both sides. For these specimens the strengthening layer was composed of Geocalce F Antisismico [35] mortar, a NHL M15 class lime mortar, with a thickness of 10–15 mm. On both sides, two perpendicular reinforcement layers of 300 mm-wide Geosteel G600 [36] were applied to a layer of fresh mortar and were immediately covered by another layer of the same mortar.

3. The third set of three specimens were strengthened on only one side to simulate the intervention on one side without disturbing the apartment owners or destroying decoration. In this case the strengthening consisted of two perpendicular layers of Geosteel G1200 [33], applied as three 300 mm-wide strips in each direction along the 1200 mm width of the specimen. The same Geocalce F Antisismico mortar was used as the matrix for the reinforcement. The un-reinforced side was finished with a sand-lime plaster.
4. A fourth set of specimens was kept for future alternative strengthening solutions

The masonry wall specimens were tested under uniaxial diagonal compression loads in order to determine the in-plane shear behaviour of the original un-strengthened and subsequently strengthened specimens. On both sides, each diagonal was monitored using LVDT transducers (Linear Variable Differential Transformer) that could measure both expansion and contraction.

After the laboratory test were concluded, the obtained results were analysed and subsequently compared to fully understand the effectiveness of the considered strengthening solutions. The results were analysed in terms of force-deformation curves, force-drift characteristic curve, shear stress-strain curves and ultimately ductility and energy dissipation. Finally, the failure mechanisms of each specimen were analysed.

First the unreinforced sample was tested and analysed. The deformations recorded during the laboratory tests were quite similar in both directions, reaching a displacement of up to 0.7 mm horizontally and 0.85 mm vertically which highlights the rigidity of the considered wallets. At around 80 kN, the sample experienced a brittle failure despite the low displacements. The behaviour of the unreinforced specimen confirmed the brittle nature of the diagonal tension cracking type of failure.

Two of the double-sided strengthening specimens were tested. The main difference from the unreinforced masonry specimen was that after the plastic deformation began the force continued to gradually rise in a strain-hardening phenomenon. Compared to the unreinforced masonry specimen, the maximum load applied to the masonry wallets reached up to 280 kN, presenting a 3.5 increase. The same was also observed in the case of the recorded deformations in horizontal and vertical direction, both specimens presenting a certain level of ductility. The stress-strain characteristic response curve also shows a ductile behaviour of the specimen and the fact that the reinforced masonry can take further stress after cracking.

When comparing the shear behaviour of the unreinforced masonry specimen with the double-sided strengthened specimens it could be observed that there is a significant increase of the ductility of the wallets, the drift increasing from 0.155% in the case of unreinforced masonry specimen up to 0.493%. The same can be observed in the case of the position of the cracking point where the shear stress is presenting a 176% increase in the case of the strengthened specimens.

The chapter focuses subsequently on the testing results obtained from the single-sided strengthened specimens. During the laboratory tests, none of the tested specimens suffered complete collapse. The damage was visible on the unreinforced side, while the reinforced one had no distinguishable cracks. The cracks were more distributed probably due to traction exerted on the masonry units by the steel mesh resisting elongation horizontally on the reinforced side.

When comparing the shear behaviour of the unreinforced masonry specimen with the single-sided strengthened specimens it could be observed that there is a significant increase of the ductility of the wallets due to the presence of the steel reinforcements, the drift increasing from 0.155% in the case of the unreinforced masonry specimen up to 1.093% in the case of single-sided strengthened specimens. The same can be observed in the case of the position of the cracking point where the shear stress is presenting a 52% increase in the case of the strengthened specimens. Similarly to the specimens reinforced on two sides, the single-sided strengthened specimens exhibited ductility and damage localised in the masonry mass. The presence of the steel reinforcement led to strain-hardening in the post-elastic range and also to an important ductility of the system. The shear-input energy was absorbed in this process by the steel cords leading to a late-failure situation.

A thorough analysis was subsequently done on the drift – shear stress results plots, where the maximum shear stress and their drift were identified and analysed for further comparison. Also, the maximum drifts corresponding to the collapse for the unreinforced specimen and extensive deformation for the singe- and double-sided strengthened specimens were identified. It was observed that the pseudo-ductility increases to 277% for the double-sided strengthened specimens and 240-323% for the single-sided strengthened specimens.

Considering the principal concept expounded in this study, this chapter highlights the impact of the considered strengthening solutions on the shear behaviour of the tested masonry wallets. From the three sets of tests, the solution that uses one-sided strengthening shows the following improvements with regard to the unreinforced masonry wallet:

1. Drastically changes the behaviour of the masonry from brittle to a pseudo-ductile masonry-reinforcement assembly
2. Extends the elastic behaviour of the masonry by 39-52% (176-200% for the two-sided strengthening)
3. Increases the pseudo-ductility by at least 140%. The specimens strengthened on two sides had shown similar increase in drift capacity.

It is emphasised that in the context where due to certain limitations and goals it is not possible to strengthen both sides of a masonry, the strengthening on one side can yield tangible results in getting the buildings safe and limiting the damage due to expected seismic activity. Therefore, it becomes apparent that depending on the scale of the structural retrofit and the state of conservation of the historic masonry structure, single-sided or double-sided strengthening solutions can be employed.

In the fourth chapter, based on the experimental results obtained from the diagonal compression tests, from separate tests performed on the constitutive materials (bricks and lime mortar) and from information provided by material suppliers, numerical computer simulations were performed in order to better understand the behaviour of the considered strengthening solutions. Three approaches and two different numerical simulation software were used:

1. the DIANA software used to perform a macro-model analysis of the tested masonry wallets and identify if the crack pattern observed during the laboratory test can also be obtained using a calibrated numerical simulation software
2. the 3Muri software, used to first calibrate the considered materials based on the behaviour observed during the laboratory tests and subsequent use of the calibrated value to perform additional numeric simulations on a sample structure which comprises all the characteristic features of masonry structures in this region.

For the macro-modelling in the DIANA software a homogeneous model with anisotropy was considered, adopting different constitutive laws in direction parallel to the bed joints versus the direction of the head joints. An extension of the smeared crack model was used as the description of the material constitutive laws were shifted from an isotropic stress-strain relation to an orthotropic one upon crack occurrence [34] .Tensile cracking and compressive crushing were designated to occur along the bed and head joints, while shear failure was considered only along the bed joints. The tensile behaviour was assumed to be identical in both the bed and head joint directions. The stress-strain response was characterised by linear softening with secant unloading and for shear, failure was modelled using the Coulomb friction model along the bed joints, with the stress-strain curve exhibiting linear softening until cohesion was reduced to zero. The mechanical properties of the unreinforced model were based on material laboratory tests performed on masonry elements, while the one- and double-sided reinforcement material characteristics were selected according to the manufacturer's specifications [35][36]. In the case of the one-sided reinforced model, the parameters were averaged between the URM and double-sided models, except for cohesion, which was higher in the one-sided model. This adjustment was made to account for the out-of-plane deformation observed in the one-side strengthened wall after testing, suggesting that the load was primarily resisted by the strengthened side, thus necessitating an increase in cohesion.

The three models led to shear stress – shear strain responses that closely matched the experimental results. When analysing the differences between the laboratory tests results and the numerical results, it could be observed that in the case of the unreinforced masonry wallet the differences are under 5%. The same (under 5% differences) can be observed in the case of the double-sided reinforced samples, in the elastic and plastic area, with difference reaching up to 15% in the pre-peak softening area. In the case of the single sided reinforced samples a very good match can also be observed for the cracking shear force, but an acceptable match, with a difference of maximum 15% was obtained in the elastic and plastic portion.

However, the double-side strengthened model did not exhibit pre-peak softening and rather showed an elastic-plastic behaviour, likely because the macro-scale models treated masonry as a homogeneous material [34][29]. The crack patterns and their progression were like those observed in the experiment. Initially, damage appeared at the corners of the wall and extended as deformation increased. At the ultimate state, shear damage was distributed across the wall in locations similar to the experiment.

In order to evaluate the strengthening effects at a building scale, a complementary FE analysis was performed using the 3Muri software from S.T.A. DATA, a software is able to simulate the seismic loading and for this reason is used generally in seismic areas where masonry structures are being retrofitted.

Before proceeding with a larger structure analysis, the parameters used for the materials were calibrated. To this end, a small assembly was modelled which included 1200x1200x450 mm wallet specimens, as analysed during the laboratory tests. Using the calibrated unreinforced masonry data and known library values for the bidirectional used reinforcement, pushover simulations were performed for all the three models. The unreinforced model showed good consistence between the real and the simulated specimen while the one- and double-sided reinforced models presented differences between 7 and 8% in the case of the maximum shear forces. For the single-sided reinforced models the pre-peak softening was not present in the simulation, similarly to the DIANA environment.

Subsequently, a simplified structural model was proposed in order to study the wall panel behaviour in a panel matrix with different geometrical shapes. The 3d model consisted of a tower structure with 3 levels and wall thicknesses as identified in case of the historical buildings in Timisoara.

For the simulation the EN 1998-1 was used for the estimation of the seismic load. The seismic action type and soil parameters were selected closely to those of the Banat region of Timisoara, and the soil type D, according to Eurocode 8, was considered to be the most suitable, being predominantly a cohesive soil.

After performing the pushover numerical simulation the state of the walls at the end of loading and the response curves of the lateral shear wall – top displacement of each model was analysed.

It was brought forward that in the case of the analysed un-reinforced masonry wall, after its shear failure, the entire wall behaviour was constant but showing low ductility. The failure was recorded at a top displacement of 5.84cm. For the un-reinforced masonry wall model most of the damage occurred at ground level where the piers fail. The upper floor elements receive only a limited part of the lateral shear forces.

The response of the model strengthened on both sides was also identified as elastic-plastic showing a very good ductility. The failure was recorded at a top displacement of 11.55cm, presenting a significant, almost double increase of the top displacement compared the unreinforced masonry model. The strengthening on both sides proves to be efficient in increasing and distributing the damage to all levels in a first step. However, in final states the spandrels, not the piers, are more loaded and are subjected to failure. Probably a better connection between piers at each floor level could be thought.

The response of the single-sided strengthened model can also be considered elastic-plastic showing also a very good ductility. The failure was recorded at a top displacement of 10.76cm, presenting also a double increase of the top displacement compared the unreinforced masonry model. According to the response curve a slight decrease of the shear strength was observed after the elastic area. The wall strengthened on one side received similar damage to the double-sided one with some difference in damage identified at the lower level, where the damaged pier exhibits cracks due to shear, not bending. The final displacement reached is similar, but at a lower force than in the case of the double-sided reinforced model.

For the three scenarios, the pushover curves were the most compelling and offer the most conclusive information about the behaviour of the wall panel. The maximum reached drift for the un-reinforced masonry simulation was used as a reference point, at 5.84cm. A comparison was made at this drift to evaluate the force for each scenario. The comparative analysis showed that the double-sided strengthening is improving the initial rigidity of the masonry walls with 4% compared to the unreinforced masonry wall while the one-sided strengthening solution is slightly decreasing its initial rigidity with 0.33%. Yet, a significant improvement of 25% was observed in both maximum shear force and shear force at the 5.84 cm drift in the case of the double-sided reinforced solution. On the other hand, the one-sided strengthening solution was offering a 17% increase of the maximum shear force compared to the unreinforced masonry model, and an approximately 8% increase of the shear force at the 5.84cm drift.

The conclusions of the chapter highlight the reinforcement materials applied on the surfaces of masonry walls can significantly improve the behaviour of a building and that even a one-sided approach can be used, despite the lower benefits in comparison to the consecrated double-sided one. Besides this, the numerical simulations show that the global system might be affected by changes of the element stiffness and alternate failure mechanisms and load redistribution might appear, weaker elements being most likely the cause. This calls for a more complex investigation in case of intervention at building level to explore better connection between the masonry elements and to expose and propose adequate consolidation measures for the most vulnerable components.

The last chapter represents the conclusions of the thesis and highlights once again that the conservation and restoration of historic buildings should be addressed in a interdisciplinary way in order to increase the load-bearing capacity of the structure while preserving the authenticity and aesthetics of the building.

It brings forward the main outcomes of the study and the significant difference in the behaviour of the wall specimens based on the considered strengthening solution. While the unreinforced masonry wallet failure was sudden and brittle, the reinforced specimens showed an increased level of ductility, offering a significant opening of the cracks. The shear forces that the reinforced specimens took compared to the unreinforced masonry wallet showed an increase by 85% for the one-sided strengthening respectively by 350% for the two-sided strengthening. The stress-strain graphs show very little post-peak decrease compared to similar tests. This could be due to the use of steel fibre reinforcement, that stays elastic at the test strain values, the damage being localised in the masonry and binding mortar.

The considered finite-element models, in both DIANA and 3MURI, which were calibrated based on the performed laboratory tests, also offered conclusive results in terms of resistance, initial stiffness and ductility. These could serve in further parametric analyses to obtain improved results, adapted for given structural interventions.

Although the double-sided strengthening solution was showing a significant influence on the shear strength of the masonry walls specimens according to the laboratory test, the numerical simulations highlighted that this might not be entirely applicable in real situations. The real effect of the strengthening can prove out to be inefficient if the corresponding strengthening solutions are not applied to all the load-bearing elements and proper connection between them can be ensured. At the same time, the analysis showed that in most situations the application of strengthening solutions on one side of the exterior load-bearing elements might be enough to ensure a sufficient improvement of their shear strength. Thus, the structural refurbishment with seismic and static upgrades is possible without moving the building inhabitants out and can be considered for future projects. This kind of intervention has least impact on the image of the strengthened building which is crucial for the listed heritage buildings and historic zones within the cities.

The main achievements and personal contributions are:

1. A thorough analysis of similar studies performed on historic masonry structures, with emphasis on the single- and double-sided strengthening of these structures and reduction of seismic vulnerabilities
2. An extensive desk and on-site survey of characteristic masonry structures in the western part of Romania
3. Laboratory testing performed to determine the characteristic mechanical properties of the retrieved brick masonry and mortar specimens
4. Reconstruction of masonry specimens using historic bricks retrieved from a demolished building and a traditional mortar recipe using just lime, sand and water (1:3:1,25 ratio)
5. Laboratory shear testing on unreinforced masonry specimens and understanding of their shear behaviour considering the 45cm thickness. This thickness is seldom used in practical studies.
6. Laboratory analysis of the effect of single-sided and double-sided strengthening on the shear behaviour of the considered masonry specimens; analysis and comparison of the in-plane vertical and horizontal deformation measured on the masonry specimens
7. FE modelling of the tested unreinforced and reinforced masonry wallets and calibration of the models against the laboratory test results
8. Non-linear finite element modelling of a structure using the masonry material properties resulted from experimental testing
9. Analysis of the results obtained from the non-linear finite element model

The thesis is opening a series of research topics which have to be further approached in order to ensure the preservation of heritage structures for future generations:

1. Future research is still necessary in order to fully understand the effect of contemporary reinforcement solutions, like vertical strips, rods or oblique helical bars, on the seismic behaviour of historic brick masonry structures
2. Laboratory tests have been performed until now on the 45cm thick wallets under in-plane diagonal compression. It is also important to explore the effect of the considered strengthening solutions on the out of plane behaviour
3. Cyclic load testing simulating the seismic reversals can be conducted to understand the efficacy of strengthening solutions on buildings
4. Numerical simulations have been calibrated considering the behaviour of the wallets and the calibrated values have been used until now in order to understand the behaviour of a small tower-like structure. It is important to perform non-linear dynamic simulations on characteristic existing buildings and understand the effect of the strengthening solution on its global seismic behaviour
5. Integrated thermal and seismic retrofit solutions are rather few but the study shows that by using suitable materials improvement from both points of views can be achieved, especially

for the out of plane loads. Further studies are still necessary in order to fully develop and understand the effect of the integrated solution on historic buildings

The research outcomes presented in this thesis have been published journals and conference proceedings:

- 1 paper in Web of Science indexed journals;
- 4 papers in Web of Science indexed proceedings;
- 3 papers in international database proceedings (SCOPUS)

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