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Earthquake Performance Analysis of a Masonry School Building's Retrofitted State by the Equivalent Frame Method

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ABSTRACT

Nonlinear analyses of masonry structures are frequently used in both engineering practice and academic studies. Due to the dominant nonlinear behaviour of masonry structures, complex and extensive finite element models are required to obtain accurate analysis results. While masonry walls are usually modelled using fine-meshed shells or solid elements in such structures, high computing power in modelling, analyzing, and post-processing results is necessary for the analyses of large structures. In recent years, the equivalent frame method, as a solution to this problem has been developed and presented in the literature. In this study, the equivalent frame method is used in a masonry structure modelling, and the axial force-bending relationship is represented by force-based fiber elements. The multi-linear load-deformation relationship reflects the shear behaviour of the walls. Within the scope of the study, an existing masonry school building is modelled using the equivalent frame elements with OpenSees software. Seismic performance analyses are done considering the existing and retrofitted states of the structure, and the results are discussed in a comparative manner.

Keywords: Equivalent frame model, masonry structures, OpenSees, seismic performance analysis, retrofit.

1. INTRODUCTION

There are many techniques in the field of structural engineering that facilitate the analysis and understanding of existing masonry structures. Modelling the masonry elements with shell (plate), solid or frame members are among the finite element modelling methods used in the analysis of masonry structures. Engineers can gain crucial insights into the behaviour of

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masonry buildings, aiding in the assessment of their structural integrity, retrofitting strategies, and overall safety by utilizing these methods. Equivalent Frame Modelling (EFM) and Solid Finite Element Modelling (SFEM) are two valuable methods that are frequently used in the current practice. These techniques enable engineers to simulate and evaluate the structural response of masonry buildings, providing precision in the assessment of their stability, strength, and overall performance.

EFM is a simplified approach that represents a masonry structure as an equivalent system of interconnected beams and columns which allows the approximation of the complex masonry system behaviour with a more manageable frame model, making it easier to analyze and understand the structural response. Bending moments, shear forces, and axial forces can be obtained from the interconnected beams and columns directly within the prescribed methodology. These internal forces and moments can further be used in identifying shear stresses, strains, and shear deformations. If fiber-based cross-sections are employed, stresses, strains and deformations can be obtained directly. EFM provides valuable insights into the load distribution, internal forces, and deformations of the structure and requires less computer power in terms of solution time by employing well-established principles of structural mechanics. It is particularly useful for preliminary assessments, predetermination of retrofitting strategies, and analyzing the global behaviour of masonry buildings under different loading conditions.

On the other hand, SFEM offers a more detailed and comprehensive approach to studying masonry structures. SFEM involves discretizing the structure into numerous solid finite elements, which are interconnected to simulate the behaviour of the entire system. Each element represents a small portion of the masonry, considering its material properties, geometry, and boundary conditions. SFEM allows for a more accurate analysis of stress distribution, strain concentrations, and failure mechanisms within the masonry elements by numerically solving the governing equations of structural mechanics. This method is particularly useful for investigating local phenomena, such as cracking, localized damage, and interaction between masonry units.

Both EFM and SFEM have their unique advantages and limitations when used in the analysis of existing masonry structures. EFM offers simplicity and efficiency in capturing the overall behaviour of the structure, making it suitable for preliminary assessments and initial design considerations with requiring considerably less computer power and solution time. Besides, SFEM provides a more detailed and realistic representation of the masonry behaviour, enabling the evaluation of the complex phenomena and assessment of the structural performance under various loading scenarios. However, it should be noted that SFEM requires more computational resources and expertise in numerical analysis.

There are many studies in the literature on the validation and application of these modelling techniques. Moreover, these methods are used on actual masonry buildings in some case studies with various analysis software. Some of these works are explained in this section for a better understanding of this study. Degli Abbati et al. [1] investigated the reliability of equivalent frame models (EFMs) by analyzing a 2-story masonry building, inspired by Pizzoli's town hall in Italy. EFMs were calibrated elastically using ambient vibration test results and then validated in the nonlinear range by simulating the dynamic response during the mainshocks of the 2016/2017 Central Italy earthquake. Camata et al. [2] presented a comparison between finite element models and EFMs for the analysis of seven two-story masonry walls with asymmetric arrangements of openings using the Scientific Toolkit for OpenSees (STKO) and the OpenSees framework. They found good agreement in the numerical comparisons between the EFMs and finite element models for irregular walls. However, discrepancies are raised for walls with mixed compression-shear damage mechanisms, as the simplified frame model tends to prioritize one behaviour over the other. Cattari et al. [3] conducted the seismic analysis of masonry structures by comparing two modelling techniques: Continuum Constitutive Laws Models (CCLM) belonging to Finite Element (FE) models and Equivalent Frame (EF) models. They discussed the calibration of constitutive laws for single panels and validated the simplifications made in EF models using a 2D regular Unreinforced Masonry (URM) wall. In their work, the use of CCLM provided accurate results but came with computational challenges and required extensive input data. Besides, EF models offered computational efficiency and required fewer mechanical parameters. Cattari et al. [4] also investigated the reliability of four existing rules for the a priori identification of pier geometry in the equivalent frame (EF) idealization of unreinforced masonry walls, focusing on irregular walls with different height openings at the same storey or small openings. The findings of their study provided practical recommendations for EF wall idealization, indicating that some existing rules work well, while others require precautions or modifications in specific cases. They suggested neglecting small openings in the EF idealization process. D'Altri et al. [5] provided a comprehensive review of existing modelling strategies for masonry structures and introduced a novel classification of these strategies. They categorized those into four main categories as block-based, continuum, geometry-based and macroelement models. Each category is thoroughly reviewed, and the future challenges in the computational analysis of masonry structures are discussed in their work. Gunes et al. [6] focused on the seismic assessment of a reconstructed historic ruined mosque located in a castle. Their study comprises four stages: on-site examinations, laboratory tests, reconstruction process, and seismic performance analyses. The presented methodology and findings in their study provide valuable information for the literature on reconstructing the structural integrity of deteriorated historic structures. Gunes et al. [7] also presented a seismic performance evaluation methodology and retrofitting proposal for masonry-infilled reinforced concrete (RC) buildings using nonlinear analyses. The methodology is illustrated using a case study of a university building constructed in the 1940s., which is significant for seismic analysis of masonry-infilled RC dual system buildings, both before and after retrofitting. Lagomarsino et al. [8] emphasized that the equivalent frame approach is an attractive modelling strategy as it enables the analysis of complete 3D buildings with reasonable computational effort, aligning with practical engineering needs and recommendations in national and international codes. They discussed the implementation of the equivalent frame model in the TREMURI program, which is used for nonlinear seismic analysis of masonry buildings. Liberatore and Addessi [9] discussed the equivalent frame model used for assessing in-plane mechanisms of masonry walls by employing a 2-node force-based finite element with a linear elastic element, two flexural hinges, and a shear link with elastic-perfectly plastic behaviour. For reflecting the lumped plasticity, a return algorithm based on the Haar-Kármán principle and the gradient projection method is used, which ensure good convergence properties and optimal characteristics of the solution. Marano et al. [10] conducted quasi-static nonlinear analyses on two masonry buildings by discretization of walls to an equivalent frame using a macro-element (force-based beam-column element with fiber-based cross-section discretization and a shear hinge at the mid-span) that combines the bending and in-plane shear responses. The analyzed buildings in their study represent examples of unreinforced and reinforced masonry from the Italian heritage, including a strategically monitored building damaged during the seismic events in Central Italy in 2016. Marino et al. [11] analyzed two unreinforced masonry buildings that were damaged during the Canterbury earthquake sequence in 2010/2011 using static and dynamic nonlinear analyses based on the equivalent frame approach. This approach's seismic response predictions are compared to observed building damage and time-history records from the earthquake sequence. They concluded that the equivalent frame method accurately predicts the seismic response of the clay brick URM buildings, providing valuable evidence for its use in the professional structural engineering community. Nicola et al. [12] provided a comprehensive review of nonlinear modelling techniques for analyzing the structural behaviour of masonry infills and their interaction with frame structures under in-plane loads. They discussed micro, meso, and macro approaches in detail where the macro approach combines frame elements with equivalent struts for the infill panel and is popular due to its simplicity and computational efficiency. Petracca et al. [13] proposed a continuous micro-model for analyzing masonry walls based on damage mechanics and compared this model with two existing discrete micro-models that use nonlinear interfaces for mortar joints and continuum elements for units. They analyzed critical aspects such as predicting failure load, collapse mechanism, computational efficiency, and the 2D plane-stress assumption in their work, which contributes to the understanding and comparison of different micro-modelling approaches for masonry analysis. Raka et al. [14] presented a model for seismic analysis of masonry structures based on the equivalent frame idealization, which builds upon previous research on force-based frame elements and considers axial, bending, and shear deformations using the Timoshenko beam theory. In their work, the shear panel response is set by incorporating a phenomenological cyclic section law, which is coupled with a fiber-section model that considers axial and bending responses. They concluded that the proposed panel model is computationally efficient, numerically stable, and suitable for analyzing multi-floor buildings with regular openings and box-like behaviour under seismic loads. Requena-Garcia-Cruz et al. [15] compared different equivalent frame (EF) modelling approaches for unreinforced masonry (URM) buildings with OpenSees software. They analyzed the Benchmark cases from the literature to test the reliability of the alternative approaches and compared results with a commonly used software in engineering practice. They emphasized that OpenSees can accurately analyze masonry structures with the EF approach, opening possibilities for further research on challenging phenomena like soil-foundation-structure interaction. Roca et al. [16] introduced an efficient method for assessing large historical masonry buildings which effectively models the complex geometries and nonlinear material behaviour by treating the load-bearing walls as equivalent frame systems composed of one-dimensional elements that incorporate biaxial constitutive equations to capture the nonlinear response of the material. The method they presented provides accurate predictions of the structural response and failure condition with computational efficiency which can be used to analyze real historical constructions and simulate repair and restoration operations. Shabani and Kioumarsi [17] developed a new macroelement, called the double modified MVLEM (DM-MVLEM) element, based on the multiple vertical line element method (MVLEM) in the OpenSees software platform for the computational analysis of unreinforced masonry (URM) buildings. The DM-MVLEM captures axial-flexural interaction with reduced computational effort compared to finite element models. They conducted experimental validation and comparisons with existing EFM methods (Unified Method and Composite Spring Method) to demonstrate the DM-MVLEM's ability in the prediction of damage patterns and simulation of nonlinear behaviour in URM walls, including spandrels. Siano et al. [18] examined the application of the Equivalent-Frame Method (EFM) in modelling existing unreinforced masonry (URM) buildings. They conducted a comparative study with the more accurate Finite Element Method (FEM) in the linear domain by analyzing regular and irregular geometrical configurations to measure the modelling accuracy of EFM. Siano et al. [19] also investigated the accuracy of the Equivalent Frame Method (EFM) in modelling the seismic nonlinear behaviour of unreinforced masonry (URM) buildings. They examined two variations of the EFM approach, including a fiber discretized beam element and a traditional beam element with lumped plasticity and tested the models using static nonlinear analyses under equivalent loading and boundary conditions with the evaluation based on a comparative simulation of a two-storey URM wall experiment. Vanin et al. [20] proposed a new three-dimensional macroelement for modelling the dynamic in-plane and out-of-plane behaviour of masonry panels in unreinforced masonry buildings which is implemented in the OpenSees software and validated with experimental results from shear-compression and free vibration tests of masonry panels. This macroelement extends a previously developed approach to incorporate both in-plane and out-of-plane behaviour, including second-order geometrical effects and a coupled shear/flexural response.

This study involves modelling an existing masonry structure using the equivalent frame elements within the OpenSees software. A comprehensive analysis is conducted to compare the effectiveness of strengthening using existing and retrofitted models of the building. The primary focus is on the application of the EFM and the results obtained for the specific case study. The study aims to demonstrate the practical use of EFM in analyzing and retrofitting masonry structures rather than providing a validation of the EFM method.

2. DESCRIPTION OF THE STRUCTURE

The structure analyzed within the scope of this study is the Gazi Mustafa Kemal Primary School building located in Karatay, Konya. The history, plan dimensions, geometric properties, materials, and structural system of this building are presented in the following sub-sections.

2.1. Historical Background

Gazi Mustafa Kemal Primary School is located in the Şems-i Tebrizi Neighborhood, the historical city center of Karatay district, Konya province. One side of the building is adjacent to Alaeddin Boulevard Street, and the building is situated in proximity to Dar-ül Muallimat School in the northern direction. The Cultural and Natural Heritage Preservation Board registered the building on November 13, 1982. The map and facet views of the building are given in Figure 1.

The Gazi Mustafa Kemal Primary School project is one of the standard designs drawn by Mukbil Kemal Taş, the architect of Gazi and Latife Schools in Ankara. Konya Governor İzzet Bey deemed the location of the Kazanli Medrese, situated in the vicinity of Alaeddin Hill, suitable for constructing the school. The construction was initiated by the German company Lenc (Leno) in 1926, and the structure was opened for education in 1927 (Figure 2).

Figure 1 - (a) Map, (b) Facet views of Gazi Mustafa Kemal Primary School Building [21]

Figure 2 - Archive photos of Gazi Mustafa Kemal Primary School [22]

The building has undergone several functional and name changes over the years. After Gazi Mustafa Kemal Primary School moved to a larger building, it was used as Gazi Mustafa Kemal Anatolian Hospitality and Tourism Vocational High School from 1998 to 2006. In 2006, the Hospitality and Tourism Vocational High School relocated to a new building, and the structure was used as the Karatay District National Education Directorate and Public Education Center until 2015 [22]. The structure was restored by Konya Metropolitan Municipality within the scope of the Mevlana Culture Valley Urban Regeneration and Transformation Project in 2018. The building is now in the service of the Konya Technical University Continuing Education Application and Research Centre Directorate.

2.2. Geometric and Material Properties

The structure follows a common type of story plans for educational buildings during the First National Architecture Period of Türkiye, as it is one of the standard designs prepared by Mukbil Kemal Taş for the Ministry of Education. It has a symmetrical rectangular plan (14.5 m x 36.3 m) and an I-shaped corridor scheme, positioned along the north-south axis. The corridor scheme connected to the external facade, has windows that provide natural lighting. The stairs providing vertical circulation are located on the symmetry axis, directly opposite the main entrance. The central part of the building consists of the entrance and core, with corridors and spaces arranged around them. The building has two floors above the basement floor as the ground and first floors. Floor heights are 2.9, 3.9 and 4.5 m from basement to first floors, respectively.

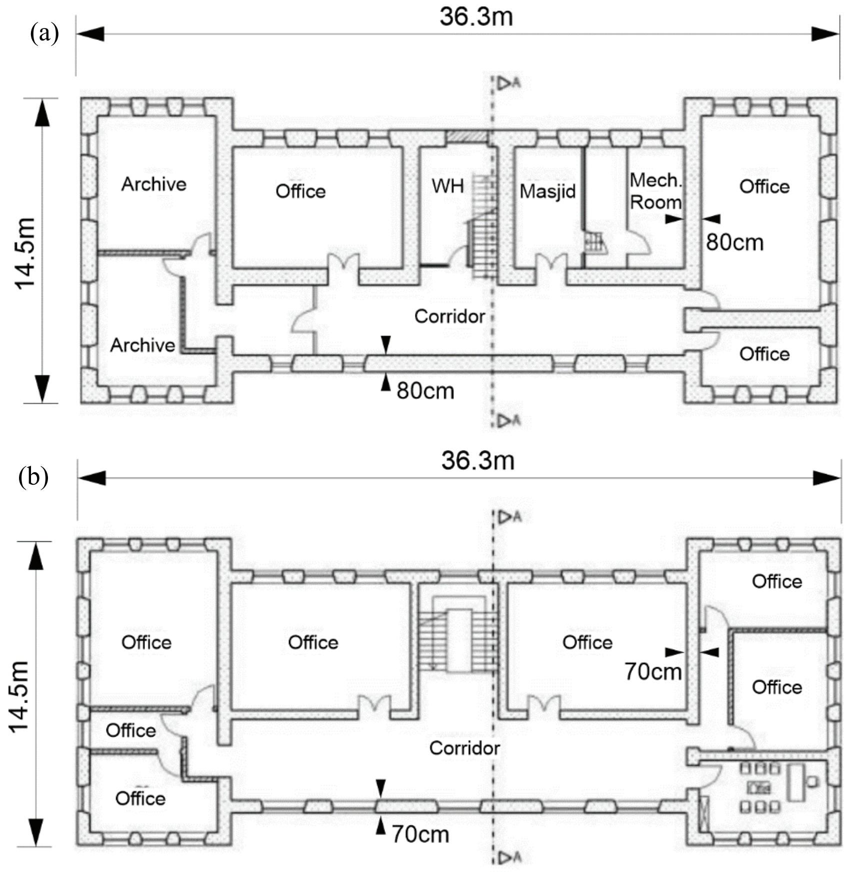

Figure 3 - (a) Basement and (b) first-floor plan drawings of the building [22]

Figure 4 - Elevation drawing of the building [22]

Gazi Mustafa Kemal Primary School is constructed using the masonry construction technique, with reinforced concrete slabs. Cut stones are used in the walls with varying thicknesses from 60 cm to 80 cm with approximately 70 cm wall thickness average. The stones of the arches used around the windows and doors on the facades are extended from the wall surface, preserving their original form and providing a dynamic appearance to the facade. Example floor plans and elevation drawings of the structure are presented in Figure 3 and Figure 4.

3. METHODOLOGY

The details of the equivalent frame method and the prepared finite element model are presented in the following sections.

3.1. Equivalent Frame Method and Software

The method specified by Lagomarsino et al. [8] is adopted for the formation of the equivalent frame model. In the relevant model, the structural elements of the masonry structure are idealized as wall (vertical) and spandrel beam (horizontal) elements, while the intermediate regions between them are modelled as rigid zones with linear-elastic rigid elements. Figure 5 presents the schematic representation of the relevant modelling technique. In our modelling approach, the assumptions and methodologies presented in the relevant literature, particularly Lagomarsino et al. [8], are thoroughly examined, providing a fundamental framework for our methodology. The objective of mitigating potential limitations related to our model assumptions is pursued by incorporating established principles and methodologies. However, the necessity of additional validation to bolster the credibility of our numerical model is acknowledged. Further validation methods will be explored in future research, including comparing our model predictions with experimental data and benchmarking against alternative modelling approaches to achieve this.

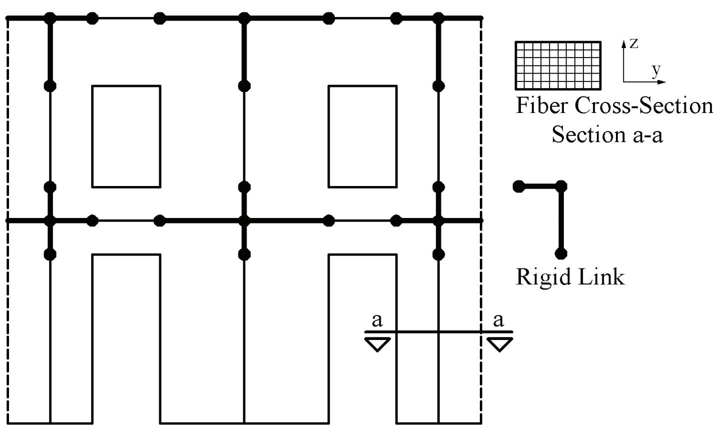

Figure 5 - Schematic representation of the equivalent frame modelling

An open-source structural analysis platform, OpenSees [23], is used in this study. The finite element model of the structure is prepared using Midas Gen [24] software and the prepared model is converted to the OpenSees' data type through object-oriented software developed by the authors. The analysis results are post-processed using the Scientific ToolKit for OpenSees, STKO [25].

In masonry structural elements, the axial force-bending behaviour is coupled and implemented through force-based elements and fiber sections. The *DamageTC1D* material model [13] is used, which considers strength degradation in compression and tension states based on fracture energy in fiber sections. The concept of "damage index" is defined within the range of 0 to 1, considering failure criteria for the relevant material. A value of 0 represents a material state with no strength loss, while a value of 1 represents a completely damaged material that has lost its strength.

In vertical elements, shear deformations are considered using a multi-linear shear deformation-shear force relationship. The total shear capacity, V_t, of the vertical elements is obtained as follows [26]:

$$V_t = B \cdot t \frac{f_{tu}}{1.5} \sqrt{1 + \frac{\sigma}{f_{tu}}} \tag{1}$$

In this equation, *B* represents the wall length, *t* is the wall thickness, f_{tu} is the tensile strength, and σ is the vertical stress. The axial force acting on the members may vary throughout the analysis. Within the current capabilities, it is not possible to account for the effect of this variability on shear behaviour. Thus, the axial force on members has been considered constant, which is used in calculating the shear capacity of members. The vertical stresses due to the resulting axial forces are obtained from the vertical load analysis. The shear behaviour is determined based on this stress and remains unchanged throughout the analysis, which is defined using the *ModIMKPinching* [27] material model.

The material properties of the Textile Reinforced Mortar (TRM) elements used for retrofitting are represented by elastoplastic materials. The retrofitting elements are modelled by including additional fiber elements on the inner and outer faces of the piers and spandrels. While the focus of our study was primarily on axial and shear behaviours at the cross-section level, a kinematic analysis incorporating well-known failure modes for masonry walls is not conducted. This aspect will be addressed in our future endeavors.

3.2. Finite Element Model

The 3D analysis model prepared in accordance with the previously described method is shown in Figure 6. The material and soil property values recommended in TBEC-2018 [28] are relied upon due to the lack of available material and soil test data for this specific structure.

Since there is no available data of any specific study determining the mechanical material properties of the structure, the material properties are determined using the data provided for cut stones in TBEC-2018 [28]. Some of the material properties are given in Table 1.

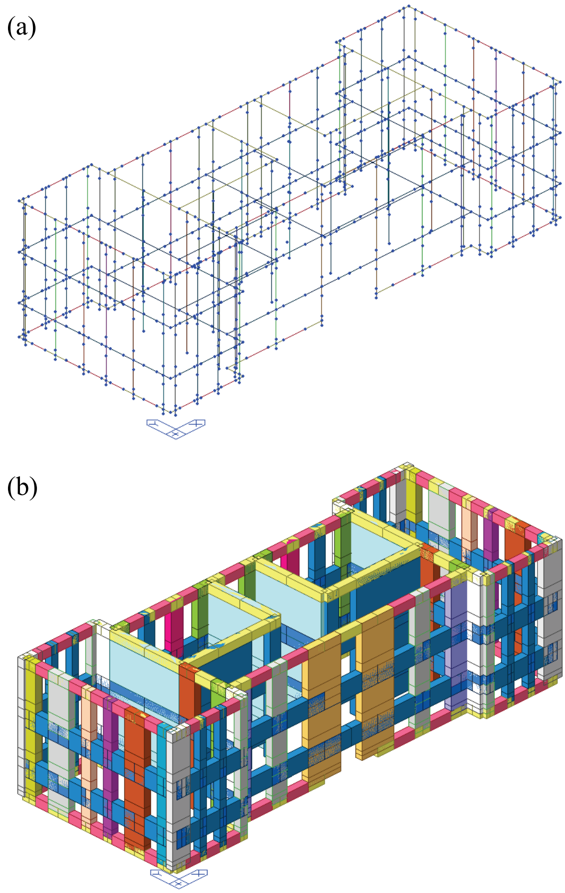

Figure 6 - (a) Frame, (b) extruded views of the 3D analysis model

Table 1 - Masonry material properties

Material Property	**Symbol**	**Value**
Block unit compressive strength	f_b	10.00 MPa
Mortar compressive strength	f_m	2.50 MPa
Characteristic compressive strength	f_k	3.00 MPa
Initial shear strength	f_{vko}	0.10 MPa
Tensile strength	f_t	0.15 MPa

The stress-strain relationships for the obtained *DamageTC1D* material model are shown in Figure 7.

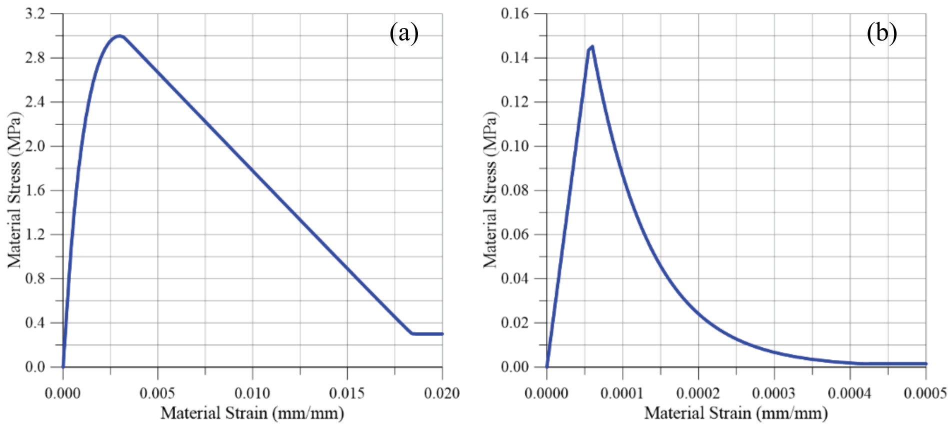

Figure 7 - (a) Compressive, (b) tensile behaviour of DamageTC1D material model

The force-deformation curves for shear behaviour vary for each element due to the geometry, material properties, and axial load affecting the element. In Figure 8, an example force-deformation curve is presented for a wall with 6.3 m length, 0.7 m thickness and 210 kN axial compression. The axial behaviour is defined using fiber sections, while shear behaviour is established based on the shear force-shear deformation relationships generated at the cross-section level. These two behaviours are combined for a single section using the "Section Aggregator" feature. However, it's important to note that the shear behaviour within OpenSees does not consider the influence of changes in axial load on shear strength. Therefore, the relationships pertaining to shear deformation are calculated based on the axial forces obtained from the initial gravity analysis (including self-weight, dead and live loads) and remain constant throughout the analysis.

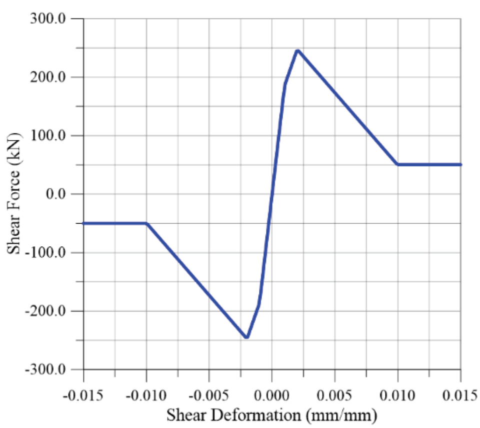

Figure 8 - An example force-deformation relationship for shear behaviour

Carbon fiber polymer grids with a cross-sectional area of 56 mm²/m are employed for the purpose of Textile Reinforced Mortar (TRM) retrofitting. The grids exhibit a tensile strength of 4900 MPa, an ultimate strain of 2%, and an elastic modulus of 245000 MPa. The mortar used for TRM retrofitting possesses a compressive strength of 15 MPa and a tensile strength of 2 MPa. A double-layered TRM application is implemented by applying TRM layers on both sides of all walls, with a layer thickness of 10 mm. The application of double-layered TRM on opposing sides of walls results in a total TRM thickness of 20 mm on each wall surface, thereby increasing the overall wall thickness by approximately 40 mm. In the finite element modelling of TRMs, additional two-layer fiber elements of 10 mm thickness have been added to both sides of each layer of the fiber sections. While the tensile strengths of these elements have been selected to be equivalent to the strength of the TRM grid element utilized, the compressive strengths are equalized to the compressive strength of the mortar used. Fiber elements of wall cross-sections in the finite element modelling of TRMs are presented in Figure 9.

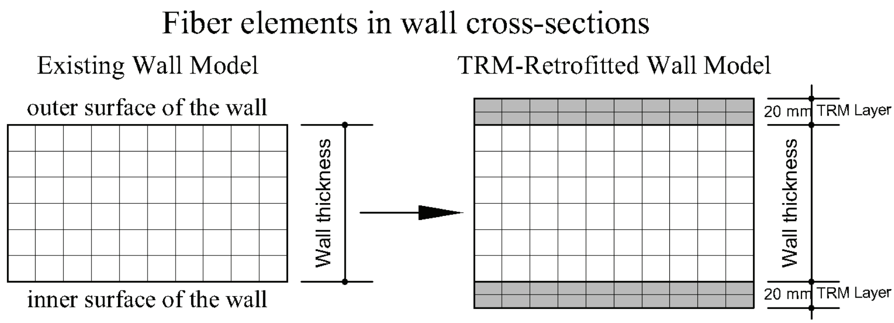

Figure 9 - Fiber elements of wall cross-sections in the finite element modelling of TRMs (not to scale)

Since the structure is a school building, the "Collapse Prevention" performance level according to GMERHB-2016 [29] is selected as the target performance level, specifically for the DD-1 seismic design level (earthquake with a 2% probability of being exceeded in 50 years). The soil class is assumed to be "ZC" because there is not any available specific study on the soil properties of the site. Table 2 summarizes the seismic parameters of the structure.

Table 2 - Seismic parameters of the structure

Parameter	**Symbol**	**Value**
Short period spectral acceleration coefficient	S_s	0.686
1.0 sec period spectral acceleration coefficient	S_1	0.148
Short period site coefficient	F_s	1.230
1.0 sec period site coefficient	F_1	1.500

Performance points are determined according to the criteria outlined in TBEC-2018 [28]. The relative lateral drift of the walls should not exceed 1% and the strains of the materials can exceed the strain limits by a maximum of 1.2 times for structures to satisfy the "Collapse Prevention" performance level as defined in GMERHB-2016 [29]. Since the structure has reinforced concrete slabs, a rigid diaphragm assumption is made for the floor slabs. Pinned boundary conditions are assumed at the base supports of unreinforced masonry walls due to the potential for significant stress imbalances resulting from uncertainty regarding whether the walls are fully embedded in the base. The mortar's low tensile strength compared to the masonry's compressive strength means that only very small strains are needed to induce "failure" in the mortar, particularly in the absence of reinforcement to help balance. This approach is accepted in the study of Aviram et al. [30]. Nonlinear static pushover analysis is performed in two stages: in the first stage, the structure is analyzed under gravity loads, and in the second stage, a horizontal pushover analysis is conducted in two orthogonal (x+ and y+) earthquake directions.

4. RESULTS AND DISCUSSION

The analysis results of the existing and retrofitted states of the structure are presented and discussed in detail in the following sections. Specific elements throughout the structure are selected, and their deformation and drift values are compared with the limit values specified in the regulation for historical structures GMERHB-2016 [29]. Furthermore, due to the utilization of the damage model in the study, damage indices for the selected elements are compared between the non-retrofitted and retrofitted states to observe changes in the damage incurred by the elements on a cross-sectional basis.

4.1. Existing State Results

Following the vertical (gravity) loading analysis, pushover analyses are performed for the application of horizontal seismic effects in both orthogonal directions. The displacement contours obtained from the horizontal pushover analyses are presented in Figure 10.

The damage indexes for fiber elements are provided for two different walls in Figure 11. Widespread tensile damage is observed in both vertical and horizontal elements throughout the structure with tensile damage indexes reaching a value of 1.0. Additionally, it is noted that damage indexes related to compressive stresses remain below the value of 0.24, indicating slight damage due to compressive stresses.

The seismic capacity diagrams for both directions are shown in Figure 12. Top displacement - base shear diagrams obtained from the pushover analyses for the existing state of the structure are presented in the next section (Figure 13).

The structural assessment is made at the performance point of the structure. It is observed that the behaviour of the masonry walls on the first floor is dominated by shear deformations. When the structural behaviour in the upper floors is examined, it is seen that the damages due to tensile stresses in the walls arise along with decreasing axial forces, and bending behaviour becomes more prominent, especially in walls with a low length-to-height ratio.

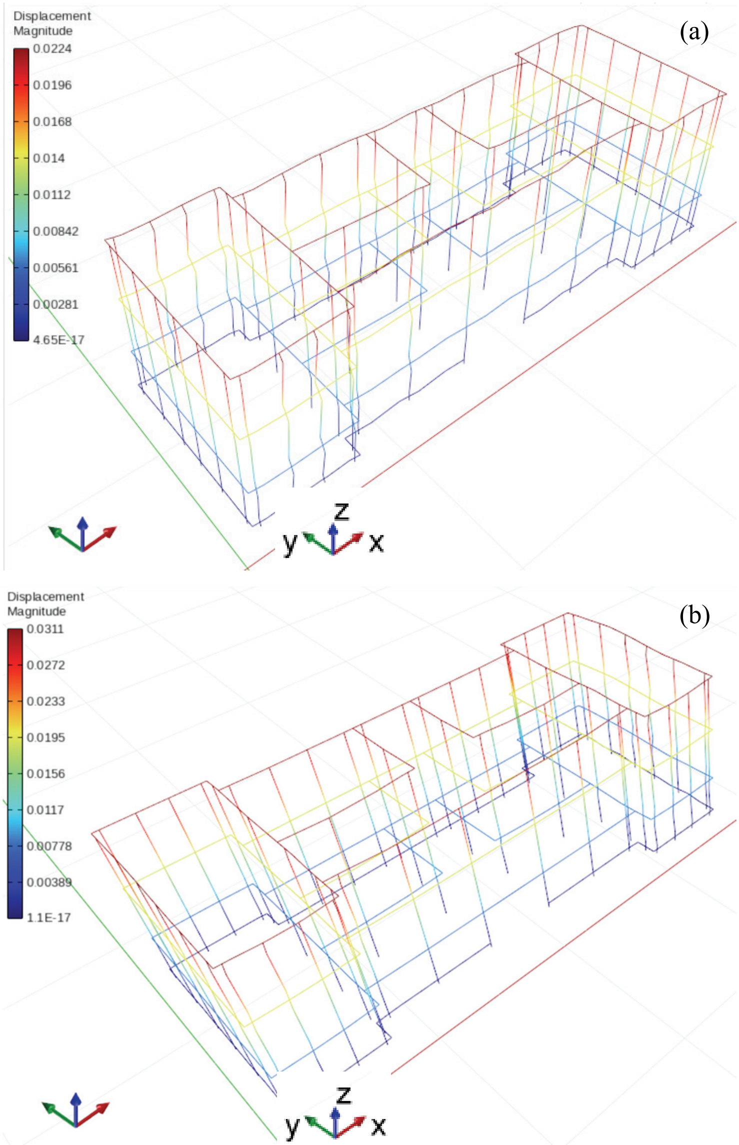

Figure 10 - Deformation magnitude contours of (a) x+ direction (b) y+ direction (units in m)

In Figure 15, the shear force-shear deformation relationship is given for an example wall. Although the wall has not reached its ultimate shear force capacity, the elastic limit is reached at the structural performance level. Although the relative drifts of walls meet the requirement of 1% relative drift criteria, many elements, especially spandrels, fail to satisfy the strain limit conditions at the performance point for the existing state of the structure.

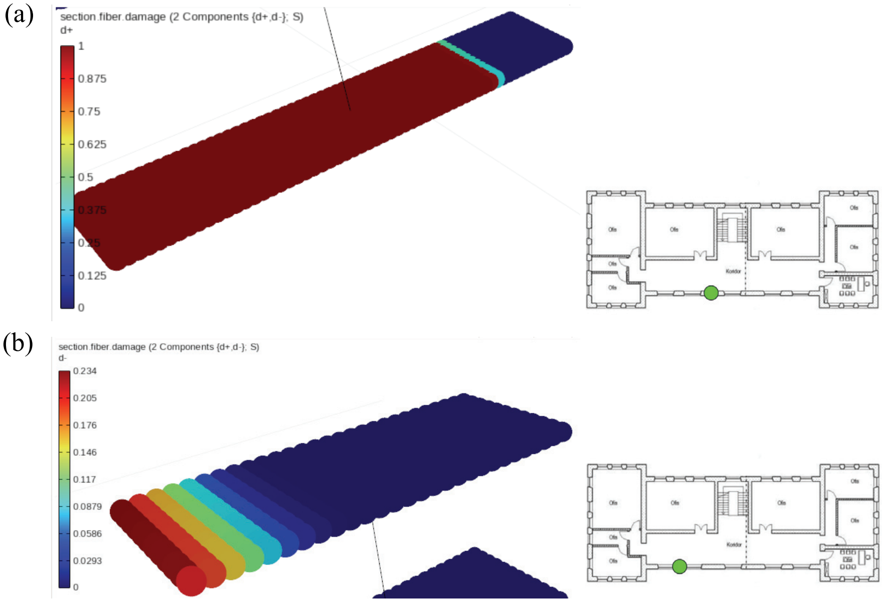

Figure 11 - Example damage indexes of two example walls for (a) tension, and (b) compression in the existing state

4.2. Retrofitted State Results

The seismic capacity diagrams for existing and retrofitted states for both directions are shown in Figure 12. The top displacement - base shear curves obtained from the pushover analyses for the retrofitted state of the structure are presented and compared with the curves of the existing state in Figure 13. In the x+ direction, the performance point of the structure is decreased from 22 mm to 13 mm. The base shear value corresponding to the performance point of the existing state is 4900 kN, which is increased to 6900 kN in the retrofitted state. In the y+ direction, the performance point of the structure is decreased from 24 mm in the existing state to 22 mm in the retrofitted state. The base shear value corresponding to the performance point in the existing state is 6050 kN, which is increased to 7250 kN in the retrofitted state. As seen from the top displacement - base shear diagrams, there has been a significant increase in the lateral load capacity of the structure. While the building's initial stiffness seems higher in the x direction compared to the y direction, the holes on the walls are more predominant on the structural behaviour in the x direction. Four main walls in y direction have no significant openings. Thus, retrofitting directly affects the initial stiffness and results in an increase in the x direction. This discrepancy in the distribution of openings leads to a lesser increase in stiffness in the y direction following the retrofitting process, resulting in the observed behaviour of the curves. The rapid onset of nonlinear behaviour is attributed to the relatively low strength of the masonry walls. It is believed that nonlinearity begins early in the analysis due to this factor.

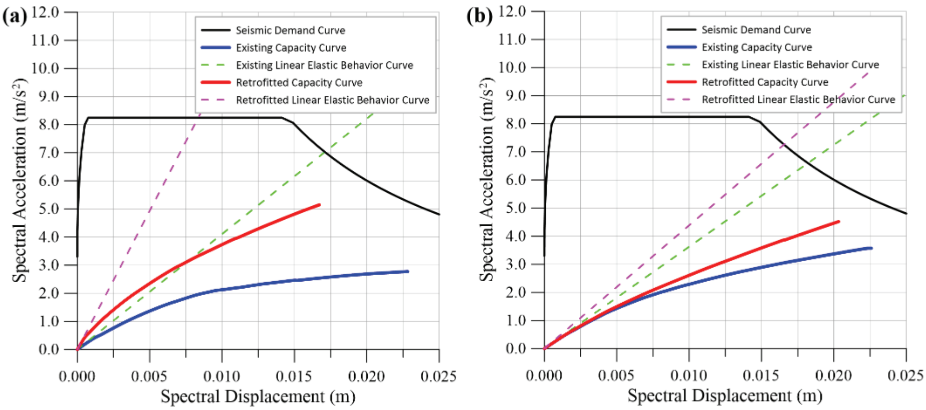

Figure 12 - Modal capacity diagrams for (a) x+, and (b) y+ directions for the existing and retrofitted states of the structure

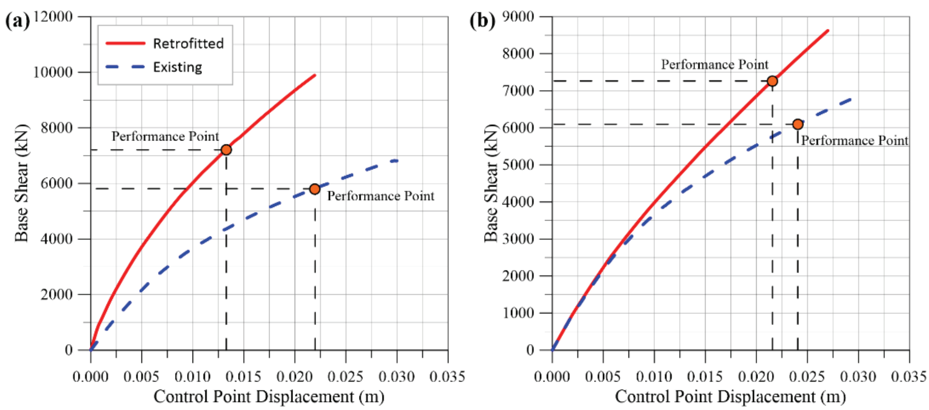

Figure 13 - Comparison of top displacement – base shear diagrams for (a) x+, and (b) y+ directions

In Figure 14, the fiber damage indexes in the retrofitted state for the two example walls previously provided in Figure 11 are presented. Due to the high tensile strength of the TRM elements, the tensile capacities of the walls subjected to bending are significantly increased in many cases, and in some walls, tensile damages are completely prevented. The compressive damage indexes are also reduced to much lower levels, such as 0.10, from the initial values of 0.24.

The shear force - shear deformation relationships for an example wall (with 6.3 m length and 0.7 m thickness) in the existing and retrofitted states are shown in Figure 15. The wall shear deformations exceeded the elastic limit significantly in the existing state, reaching a value of 0.002. In the retrofitted state, the shear deformations slightly exceeded the elastic limit, reducing to a value of 0.0011.

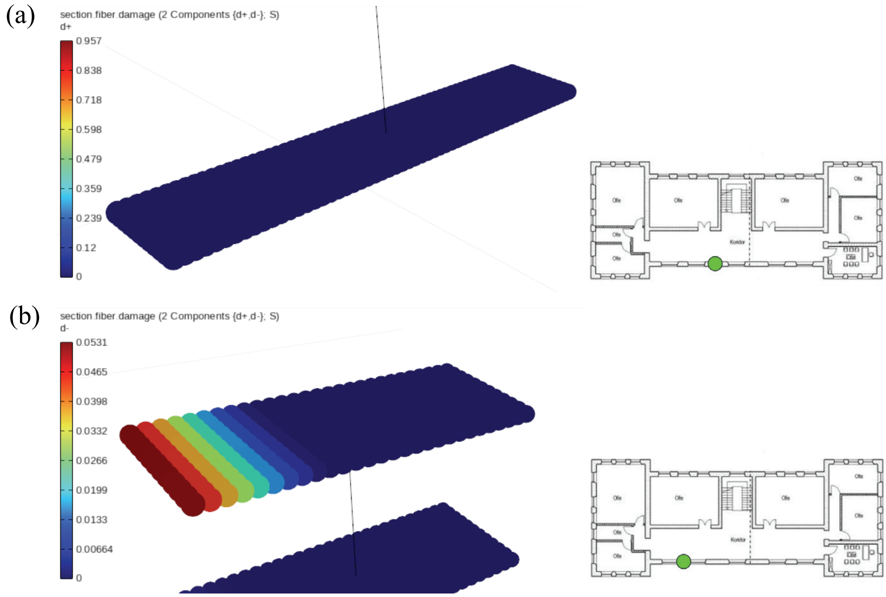

Figure 14 – Example damage indexes of two example walls for (a) tension, and (b) compression in the retrofitted state

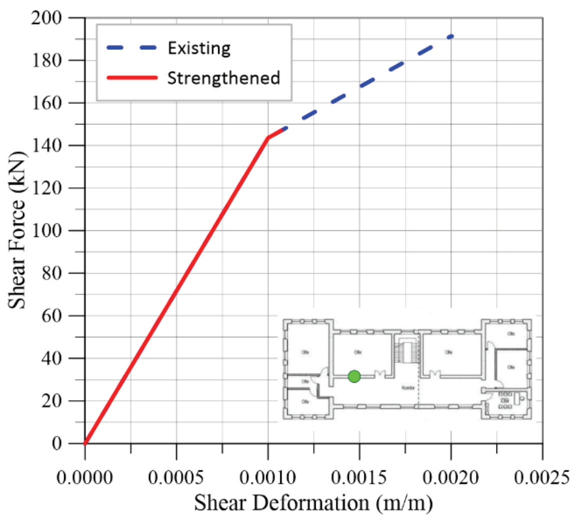

Figure 15 - Shear force – shear deformation diagrams comparison for an example wall

The retrofitted state of the structure satisfies both the drift and strain limit criteria for the target performance level. This indicates that the retrofitting measures are successful in improving the structural behaviour and meeting the required performance objectives.

5. CONCLUSION

The reliability of the equivalent frame method for masonry structures has been discussed in various studies, which requires less computing power in structural analysis with respect to solutions with solid and plane elements. In this study, the seismic performance analysis of an existing masonry structure and its retrofitted state is performed using the equivalent frame method. The primary focus of this study is on the application of the Equivalent Frame Method (EFM) and the results obtained from the specific case study, rather than on the validation of the EFM itself. The objective is to demonstrate the practical utility of EFM in the analysis and retrofitting of masonry structures.

Modelling, discretization, and the significant nonlinear behaviour of masonry structures make the determination of seismic performance quite challenging. In this context, the use of the equivalent frame model for masonry structures that can be modelled only through vertical and horizontal frame elements is presented as an alternative to plane and solid element models. A retrofitting study is conducted using this method, and the results are evaluated.

Textile-reinforced mortar retrofitting elements are applied on both the vertical (walls) and horizontal (spandrel beams) elements from their inner and outer faces. The seismic performance of the structure is significantly improved in the retrofitted model. It is observed that the tensile force capacities of elements with tensile damage are significantly increased. Similarly, the compressive damage indexes of masonry elements are significantly reduced. Moreover, the shear deformations in the existing state are reduced by almost half. It is concluded that the structure, which could not achieve the target performance level in the existing state, can achieve it in the case of retrofitting with the proposed method. Modelling masonry walls in such structures typically requires fine-meshed shells or solid elements, necessitating significant computing power for modelling, analysis, and post-processing of results and higher solution time, particularly in the analysis of large structures. Since the modelling was done only by frame elements in EFM, the analyses performed in this study indicate that the equivalent frame method has the potential to provide a streamlined modelling and analysis process and a faster solution for both existing and retrofitted states of these structures.

The application of the equivalent frame model in seismic analysis of masonry structures is addressed in our study by presenting a detailed analysis of a modelling and analysis approach for both existing and retrofitted states, thereby extending the understanding of the capabilities and limitations of this method. The challenges associated with modelling masonry structures, particularly regarding computational efficiency and accuracy, are addressed using the equivalent frame model. The use of this model in capturing the seismic behaviour of masonry structures is demonstrated, showcasing the method's potential as a viable alternative to traditional solid and plane element models. Additionally, the benefits of using the equivalent frame model for retrofitting studies, which include the modelling of fiber TRM layers are highlighted in our study, as it enables a streamlined approach to assess the seismic performance of retrofitted structures. Overall, the presented methodology in this study shows the alternative modelling and analysis steps that may be followed, paving the way for further advancements in applying the equivalent frame model in seismic analysis and retrofitting of masonry structures.

A parametric study considering various earthquake and retrofitting levels for the forthcoming research as a natural extension of the current work, as well as the comparison using a different finite element modelling method, is highly valued by the authors. Furthermore, comprehensive time-history analyses with the most up-to-date seismic records from recent Maraş earthquakes is recommended by the authors as future work.

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