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EQIVALENT FRAME MODELS FOR FRP-STRENGTHENED MASONRY BUILDINGS

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Abstract

Fibre-reinforced polymers (FRP) strengthening can be applied to decrease the seismic vulnerability of existing masonry buildings, both with regard to in-plane and out-of-plane failure mechanisms. Experimentally, the impact of strengthening solutions has been thoroughly studied. There are, however, few efficient and reliable numerical modeling approaches that can accurately capture the effect of such strengthening on the seismic response of the masonry building. Therefore, we herein develop and validate a modeling approach to capture the effect of FRP strengthening on the behaviour of masonry walls. To model this effect, we use a recently developed macro-element, which can capture both in-plane and out-of-plane failure modes. In the macro-element, the intervention is modelled by adding fibres representing the longitudinal FRP strips to the section model. These fibres were modelled as linear elastic in tension up to the failure with a zero compressive strength. Transversal FRP strips effect the shear strength, and in the macro-element, this is accounted for by increasing the cohesion in the equation for the shear strength. To validate the model, we also compare the numerical simulations with existing experimental results obtained from the literature. Overall, the proposed modeling approach accurately predicts the in-plane and out-of-plane response, implying that equivalent frame models can predict the response of masonry buildings with FRP-strengthened walls. To conclude, the models described in this paper can be used for a time-efficient assessment. Moreover, it can help in selecting the optimal strengthening approach for future retrofitting. This aspect is especially important for the cultural heritage structures, where excessive retrofitting should be avoided.

Keywords: fibre-reinforced polymer, equivalent frame models, in-plane capacity, shear reinforcement, masonry, building strengthening

1. Introduction

Equivalent frame models (EFMs) are extensively used for modeling the nonlinear seismic response of entire unreinforced masonry buildings (URM) because they provide a good balance of accuracy and computational cost [1, 2, 3, 4]. Various strengthening techniques of URM buildings have been tested experimentally; a recent review can be found in [5]. Since strengthening one element can induce the failure of another, it is important to assess the entire system response through a numerical model of the entire building.

The goal of this article is to develop and validate a method for modeling FRP-strengthened URM buildings using EFMs. We illustrate how a novel macro-element developed by [4] may be used to investigate the impacts of FRP strengthening on the in-plane and out-of-plane capacity of masonry walls, as well as on the overall behavior of a building.

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2. Numerical approach

The three-dimensional macro-element by [4], which has been implemented in OpenSees [6] is the basis for our EFM approach for retrofitted masonry walls. This macro-element has been built on the in-plane response developed by [2] and enhanced to capture the out-of-plane response of the masonry panel. When modelling the FRP strengthening, we separately address the increase in shear and flexural capacity.

2.1. Increase in shear capacity

The increase in shear capacity, obtained from applied FRPs, is calculated using engineering models that anticipate the shear resistance of FRP retrofitted masonry walls. Several guidelines and design standards are available in the literature, [7] and [8] provide a review of existing models. Shear strength of FRP-strengthened masonry panel is calculated as the sum of the shear strength of the uncracked masonry wall and the shear strength provided by the FRP reinforcement. We differ the increase due to grid and diagonal FRP layout. Following the macro-element formulation, this increase in shear capacity is taken into account through the value of cohesion.

2.2. Increase in flexural capacity

The flexural behaviour of the macro-element can be characterized by using fibre sections, where the cross-section of a wall is discretized in fibres and a specific material law can be assigned to it. We used the approach by [9] to model the increase in flexural strength due to FRP reinforcement by adding FRP fibres to the section. The macro-element developed by [4] comprises three fibre sections that can contain three nonlinear sections at the element ends and at midlength. This option can be useful for representing the difference between FRPs that are anchored or not to the slabs. The material model that is assigned to masonry fibres has zero tensile strength, limited compressive strength, a damage behaviour in compression and no strength degradation [4]. The FRP reinforcement was formulated as linear elastic in tension up to failure and with a zero compressive strength.

3. Validation of numerical approach

3.1. Masonry walls

Monotonic, quasi-static cyclic, dynamic, and four-point bending (out-of-plane) experimental campaigns were chosen to validate our approach [10].

For the in-plane response validation, we choose the experimental campaign done by [11] on brick half-scale hollow clay block masonry walls retrofitted on only one side with quasi-static shear compression test setup. Figure 1 presents the force-displacement response of a masonry wall retrofitted with glass fibres. Experimental data is presented in black, while red shows the response we obtained numerically using herein proposed approach. It can provide accurate estimates of the initial stiffness and maximum force capacity.

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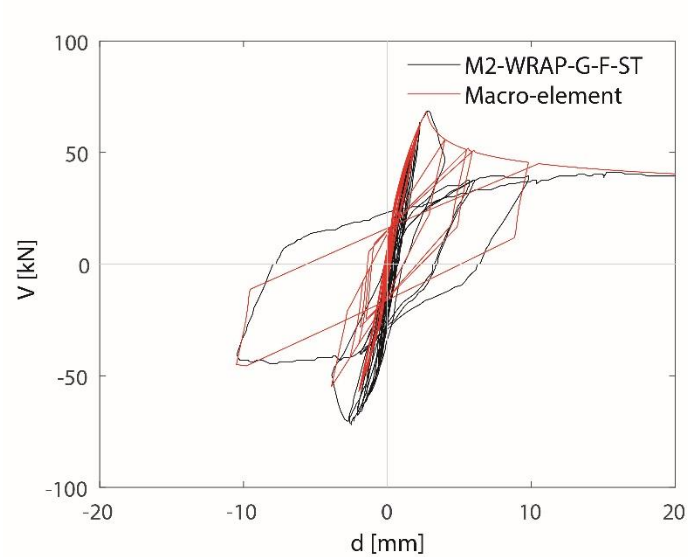

Figure 1 - Resulting output from our model for the simulation of the quasi static cyclic tests carried out by [11] specimen retrofitted with GFRP M2-WRAP1-G-F-ST

3.1. Masonry building

We examine hypothetical retrofit solutions of a structure that was dynamically tested in its unretrofitted configuration [12] to demonstrate how our approach for FRP-strengthened masonry walls may be used to evaluate potential retrofit solutions at the building level. The CoMa-WallS building, which is a modern mixed reinforced concrete - unreinforced masonry structure, tested by [12] was chosen for this purpose. In [13] the building was modelled in its unretrofitted state. When tested on uni-axial shake table, it experienced out-of-plane failure in the top storey and in-plane failures in the first and second storey.

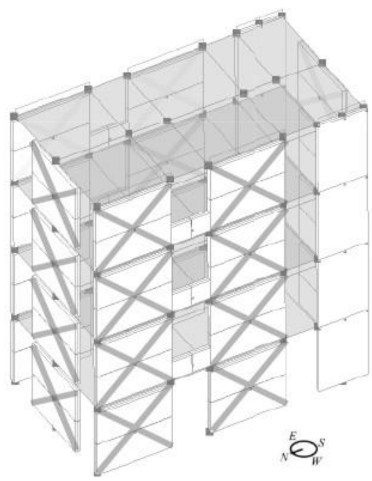

Figure 2 - Equivalent frame model of the building tested by [12] modelled in unstrengthened configuration in [13] with applied CFRPs

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The numerical models included a hypothetical configuration with carbon fibres applied in a diagonal arrangement on both sides of the wall; it was assumed that the fibres were not anchored in the slab (Figure 2).

When the out-of-plane displacement of the middle section of the top storey wall of the unretrofitted configuration (i.e. the configuration that was tested experimentally) is compared to that of the proposed strengthened configuration, we can see that the FRP-strengthened model demonstrates the efficiency of FRPs in preventing excessive out-of-plane displacements (Figure 3). As a result, local failures might be avoided by using composites, assuring the global response of a building.

The effect of the retrofitting solutions was also visible when the deformation demands in terms of shear and flexural deformation at failure were examined. Furthermore, the failure mode changed, the shear failure was developed instead of flexural. The maximum displacement is significantly reduced after applying CFRP, even if the CFRP is not anchored in the slabs. The PGA that the retrofitted structure can resist is therefore greater than when no strengthening is applied.

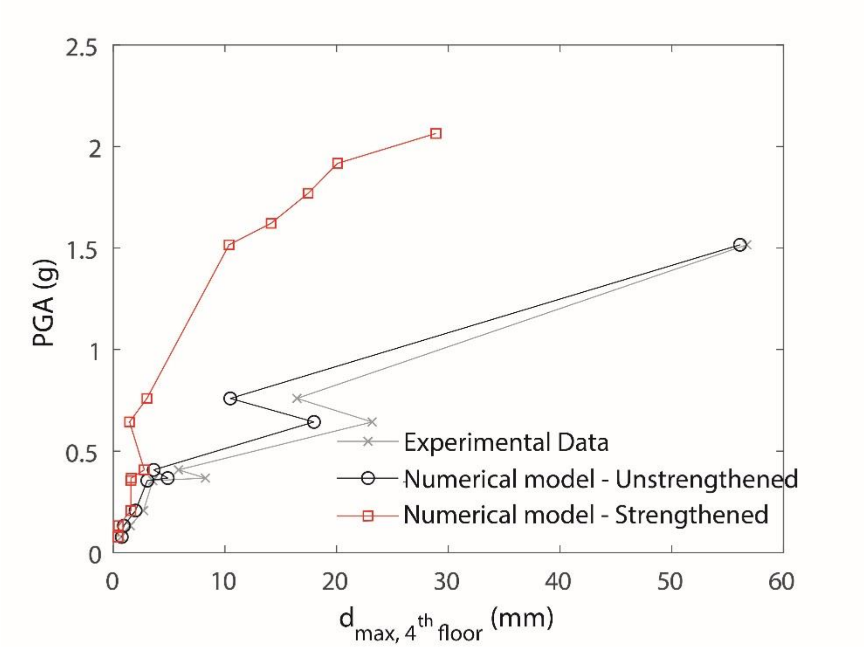

Figure 3 - Resulting output from our numerical model (strengthened configuration) for the simulation of the shake table tests by [12] modelled in unstrengthened configuration in [13]. Comparison of the global response in terms of maximum displacements.

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4. Conclusions

In this paper, we propose a numerical approach for modelling FRP-strengthening applied on masonry structural elements. Our main objective is to develop and validate a tool that can be used for reliable and time-efficient assessment of FRP-retrofitted masonry buildings. We can obtain a simulation of probable failure mechanisms and damage patterns for different types of FRP materials and retrofitting configurations in this way. Finally, the models presented here can assist in determining the optimal strengthening strategy for future retrofitting. This is especially relevant when it comes to cultural heritage structures, where excessive retrofitting should be avoided. Future work based on this paper could include the application of textile-reinforced mortars (TRM) instead of FRPs.

Acknowledgements

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