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Retrofitting of masonry walls by using a mortar joint technique; experiments and numerical validation

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ABSTRACT

This paper presents research on a conventional but practical retrofitting method for masonry walls along with the numerical modelling of it under in-plane lateral shear–compression loading. The latter is capable of predicting the experimental collapse load and overall behaviour quite accurately. The retrofitting approach is based on building a wall parallel to an existing single-leaf wall and bonding the two leaves together using a mortar (collar) joint, merging the two individual panels into a unified double-leaf wall. Experiments on this retrofitting approach for both undamaged and damaged masonry walls have been introduced in the present paper. The tests revealed that the pre-damage application can increase the strength by 50% while the post-damage one can restore the initial strength. A micro-scale numerical model has been devised by considering the bricks as rigid elements and the mortar joint as a nonlinear failure surface. The model was implemented in the commercial Finite Element (FE) software MIDAS FEA and the numerical results were verified against the available experimental data.

1. Introduction

Masonry is a composite material made of brick units and mortar that has been used for centuries in building construction. It is in wide usage in seismic-prone areas, especially in the form of infill panels within reinforced concrete (RC) or steel frames. Therein, infills are customarily considered as secondary elements (also referred to as non-structural elements) to the structure and are for simplification not considered in the calculations of seismic capacity. Yet they sustain a large portion of the energy dissipation [1]. As such, their performance can be a decisive factor leading which may lead to a catastrophic structural failure. With this in mind, masonry structures often need to be repaired following earthquake events or enhanced prior to seismic actions in order to ensure that they can perform their highly sought energy absorption and force relieving roles [2]. In the past decades, researchers have implemented different methods to enhance the seismic behaviour of unreinforced masonry walls. These range from the so-called conventional techniques [3] to the latest modern retrofitting techniques [4].

Conventionally, the surface treatment is an approach to improve the masonry wall behaviour. Typical surface treatment includes ferrocement, reinforced plaster and shotcrete, with shotcrete being the most often used method [4]. According to the method, shotcrete overlays are sprayed onto the surface of a masonry wall over a mesh of reinforcing bars. ElGawady et al. [5] carried out tests on retrofitted masonry walls by applying shotcrete. The retrofitting was carried out on either one or both sides, using consistently the same thickness and reinforcement. The test results showed that the ultimate lateral load resistance of the wall can be increased by a factor of approximately 3. However, disadvantages of this method include the considerable time required for the implementation and the adverse impact on the aesthetics of the retrofitted structure.

Grout and epoxy injections are also a broadly used retrofitting approach. The main purpose of the injections is to restore the original integrity of the retrofitted wall and to fill possible behaviour-damaging voids and cracks, which are present in the masonry due to physical and chemical deterioration and/or mechanical actions [3]. The technique was found effective in restoring the initial stiffness and strength of masonry, while its practicality, relatively minimal cost and easiness of implementation have rendered it rather popular among engineers. However, any such approach trivially will be successful only if the mechanical properties together with the physical and chemical attributes of the employed mix end up being compatible with the masonry to be retrofitted [6].

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Some of the drawbacks of the quoted conventional methods can be overcome by the Fibre Reinforced Polymer (FRP) reinforcement. Retrofitting of unreinforced masonry walls using FRP can increase the lateral resistance by a factor ranging from 1.1 to over 3 [4]. Alcaino and Santa-Maria [7] presented experimental results from clay brick masonry walls retrofitted with carbon fibre. From the results analysis, it was found that the strength of the walls could increase between 13% and 84%. Also, Mohmood and Ingham [8] conducted a research program in order to investigate the effectiveness of FRP additions as seismic retrofit interventions for in-plane loaded unreinforced masonry walls. The experimental results showed that the shear strength increased up to a factor of 3.25. In general, the retrofitting of masonry walls using FRP material addition has the common advantage of little added mass while mostly producing low disturbance for achieving a relatively high improvement in strength. However, the main drawbacks are the high cost, the high technical skill required for their installation, the affecting of architectural aesthetics and the not so broad experience with these materials particularly relevant to their aging.

To the authors' knowledge, most of the research on the mechanical behaviour of masonry and the retrofitting measures were focused on single-leaf walls, with only very few exemptions expanding on double-leaf or multi-leaf masonry walls. Predicting the behaviour of multiple-leaf masonry walls is a challenging issue, given the influence of a wide range of factors as the mechanical properties of the leaves, their dimensions and the way they are connected to each other. Still, double-leaf walls can be found in many historic structures as well as in modern structures and they have regularly been exposed to considerable earthquakes obviously affecting the holistic structural dynamic performance. Therefore, it feels necessary to also conduct research on such a construction system shedding light to previous gaps in knowledge. Anand and Yalamanchili [9] analysed a composite masonry wall made of block and brick units and tied together by two different in thickness collar joints, 9.5 mm and 51 mm. The composite masonry walls were subjected to both vertical and horizontal loads in a 3D arrangement. From the results analysis, it was found that the collar joint failure is brittle in nature. Pina-Henriques et al. [10] conducted a series of experimental tests on multi-leaf masonry wall panels under a combined shear and compression load with the aim to predict their load carrying capacity and failure mode. The specimens consisted of two external leaves made of stone blocks bonded together with mortar joints while the internal leaf consisted of a mixture of mortar with stone aggregates. A simplified calculation for predicting the compressive strength of composite walls has been presented and good agreement with experimental results obtained. Ramalho et al. [11] modelled the experimental specimens of Pina-Henriques et al. [10] by applying a damage model which was developed to interpret the time evolution of mechanical damage in brittle materials. The models were implemented using the finite element codes ABAQUS and FEAP and comparisons made on the results obtained. The proposed numerical codes were able to capture the different features of the nonlinear mechanical behaviour of multi-leaf walls. However, as perfect bonding was assumed between the adjacent layers during the modelling, some of the numerical results were overestimated. Also, Binda et al. [12] conducted research on multi-leaf masonry walls in order to understand the load-transfer mechanisms between the individual walls although the collar joint which was used for the construction of the walls were much thicker than what is suggested in British Standard 5628-1:2005 [13] (i.e. the space between two parallel single-leaf walls is to not exceed 25 mm).

In this paper, a conventional though practical, novel retrofitting approach is introduced. Namely, the traditional method of building a wall parallel to an existing single-leaf wall and bonding the two together using a mortar collar joint is being considered as a possible strengthening and retrofitting technique. The method does not require sophisticated workmanship because of its easy implementation, which further renders it cost-effective.

In general, the application can be divided into two categories: (a) the pre-damage enhancement; and (b) the post-damage repairing. Earthquake being a specific very interesting catastrophic damage case with great relevance to masonry wall failures is what will be particularly discussed hereafter. For the purpose of the specific project in pre-earthquake enhancement tested walls, the second wall was built parallel to the existing one and bonded with a relatively thin collar joint before the test. For the case of post-earthquake repaired walls, the second wall was attached to the existing one after it had been tested (and as such partially damaged). The collar joint dimensions were kept constant while the damage progressed only to the very early plastic range (i.e. cracking far from collapse). A preliminary parametric study has been conducted to evaluate the performance of the enhancement method using a monotonically increasing quasi-static loading scheme. Notably, the whole study is not only relevant to earthquake engineering, which is a rarity in UK; double-leaf (collar jointed) walls can also be used to improve a structure's lateral stability (e.g. against wind or blast loading) through adding stiffness [14]. Thus, this research broadly aims to generate knowledge and understanding which can be directly applied in a number of structural applications.

On the numerical modelling side, in the past decades, research relevant to masonry walls has been advanced considerably. However, the modelling of a load bearing masonry wall or masonry infill under in-plane combined loading remains difficult primarily due to the complex mechanics developed within the different materials of the wall. A number of different approaches have been implemented to simulate the mechanical behaviour of masonry walls subjected to static or dynamic loading that can act in-plane, out-of-plane or even simultaneously in both planes. The selection of the most appropriate method to use depends on, among other factors, on the structure under analysis; the level of accuracy and simplicity desired; the knowledge of the input properties in the model and the experimental data available; the amount of financial resources; time requirements and the experience of the modeller (Lourenco [15]). Preferably, the approach selected to model masonry should provide the desired information in a reliable manner within an acceptable degree of accuracy and with least cost. According to Lourenco [15], the available strategies for the numerical modelling of masonry structures would fall within one of two categories: (a) micro-scale; and (b) macro-scale modelling.

In macro-scale modelling, the masonry units and mortar joints are smeared into an averaged continuum. There are no distinctions between the units, the mortar and their interfaces. This model can be applicable when the dimensions of a structure are large enough, compared to the constituent parts, so that a description involving average stresses and strains becomes acceptable [16]. Considerable computational time can be saved by applying this method. However, unconditionally accurate results and fine-detail of the behaviour cannot be captured by the nature of this approach. On the other hand, the micro-scale modelling can be split into the following two approaches: (a) simplified micro-modelling; (b) and detailed micro-modelling. In the simplified micro-modelling approach expanded units are modelled as continuous elements while the behaviour of the mortar joints and unit-mortar interface is lumped in discontinuous elements. In the detailed micro-modelling approach both the masonry units and the mortar are discretised and modelled with continuum elements while the unit/mortar interface is represented by discontinuous elements accounting for potential crack or slip planes. Detailed micro-