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Modelling the out-of-plane behaviour of masonry walls retrofitted with engineered cementitious composites

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ABSTRACT

The out-of-plane behaviour of masonry infill walls retrofitted using engineered cementitious composites (ECC) is investigated numerically in this paper. The behaviour of beam-like masonry specimens, considered to provide a simplistic representation of masonry infill walls, subjected to static four-point bending testing is investigated numerically through the use of nonlinear finite element analysis. The specimens are strengthened using a thin layer of ECC which is fully or partially bonded to their lower face (acting in tension). The numerical predictions obtained are validated against relevant test data and are used to provide insight into the mechanics through which the ECC layer enhances the out-of-plane behaviour of the subject specimens in terms of strength, stiffness and deflection. It was found that the specimens retrofitted with a partially bonded ECC layer exhibit more ductile behaviour (deflection) compared to those retrofitted with a fully-bonded ECC layer (the latter exhibiting higher load-carrying capacities). Finally, the validated models are employed to carry out a parametric study to investigate the effect of different design parameters, associated mainly with the properties of the materials used, on the behaviour of the specimens considered.

1. Introduction

The available experimental and numerical studies clearly show that infill masonry walls contribute to the redistribution of the internal actions developing within the structural elements of a frame, resulting in the redirection of the loads towards other regions of the structures [1–4]. These studies reveal that the out-of-plane behaviour exhibited by infill masonry walls is essentially brittle, characterised by low load-carrying capacity and deformability [5]. This suggests that such walls are vulnerable to the application of loads in the out-of-plane direction (e.g. wind, earthquakes, impact explosions and blast loads) which can result in them sustaining a significant level of damage (in the form of cracking) that can potentially lead to their partial or even complete collapse [6,7]. After sustaining a certain level of damage, an infill wall can no longer contribute to the response of the frame structure with its in-plane stiffness. This can potentially have a detrimental effect on the overall response of frame structures resulting in often unpredictable (and often brittle) forms of failure [5]. Current codes of practice [8,9] recommend the calculation of the load-carrying capacity of masonry infill walls associated with out-of-plane behaviour under seismic excitation [8] and even suggest that appropriate measures are taken in order to prohibit partial or total out-of-plane collapse of slender masonry infill walls [9]. Furthermore, it is interesting to note that the damages sustained by masonry infill walls during earthquakes have been identified as the primary cause of injuries and fatalities [10] whereas the associated repair costs represent a large portion of the total costs associated with the overall rehabilitation of the frame structures.

Aiming to improve the out-of-plane performance of masonry walls, several retrofitting methods have been developed to date. This often entails the formation of an additional layer that is attached to the surface of the masonry wall aiming to form a composite member with enhanced structural properties. This is usually achieved by employing an external reinforcement mesh embedded within a new layer of concrete [11–15], using strips of steel or fibre reinforced polymer (FRP) which are attached onto the wall surface through the use of dowels or epoxy resins [16–18]. These methods can address the certain weakness of the out-of-plane behaviour of the masonry infill walls. However, their application is often intrusive and characterised by a series of problems associated with the increase of the mass of the building, high cost, poor performance at high temperatures, problems associated with their bond to the surface of the masonry wall and finally the production of fragments or debris when overloaded [18–20].

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The experimental study conducted hereby focusing on enhancing the behaviour of the infill masonry walls and addressing many of the shortcomings of the existing retrofitting methods. This study considers the use of a thin layer of engineered cementitious composite (ECC) which is fully or partially bonded onto the face of the wall acting in tension (opposite to the face on which the out-of-plane action is applied) [27,45,47–49]. The present investigation focuses on studying numerically, via nonlinear finite element analysis, the potential benefits stemming from the use of ECC for enhancing the out-of-plane behaviour of simply-supported masonry beam-like specimens. These specimens essentially consist of a stack of 10 bricks connected through 9 mortar joints the behaviour of which was established experimentally in the past when subjected to static 4-point bending tests [21,22]. The subject specimens are considered to provide a simplistic representation of the masonry infill walls. The proposed method attempts to take advantage of the ductile, strain-hardening behaviour exhibited by ECC under uniaxial tension which is also characterised by a high tensile strain capacity (up to 5%) [23]. This behaviour is mainly attributed to the ability of ECC to form multiple fine cracks, characterised by widths of less than 100 μm [23,40,46].

Existing studies confirm that the use of ECC layers can improve the out-of-plane behaviour of masonry beam-like specimens subjected to static four-point bending tests [24–27] in terms of load carrying capacity, stiffness and ductility (compared to that established by the un-strengthened specimen) [25–27]. However, it is important to note that all relevant studies carried out to date on masonry beam-like specimens (similar to those mentioned above) strengthened with fully bonded layers of ECC reveal that failure is associated with the development of localised (instead of distributed) cracking concentrated close to brick/mortar interfaces. This cracking develops as an extension of the cracking exhibited due to the failure of the brick-mortar interface in the mortar joints (forming between consecutive bricks) at the mid-span region of the specimens (area where the bending moments and associated tensile stresses obtain their maximum values) which suggests that the full potential of ECC is not utilized [24–27]. Recent experiments [27,45,47–49] reveal that the use of partially bonded ECC layers can effectively promote the development of distributed (instead of localised) cracking along the un-bonded region of the ECC layer (between the two loading points) thus improving the ductility characterising the out-of-plane behaviour of the ECC-retrofitted masonry specimens while making more effective use of certain aspects of the ECC material behaviour exhibited under uniaxial tension (i.e. high tensile strain capacity and ductility).

It is interesting to note that the available test data often cannot provide a detailed description of the mechanics underlying specimen behaviour (e.g. stress-strain distribution, effect of interaction of the specimen and apparatus, etc.) nor can it accurately quantify the effect of certain parameters (due to the limited amount of available data). Due to these limitations, the finite element models are employed for the detailed studying the behaviour of masonry specimens retrofitted with different techniques including (i) external reinforcement concrete/mortar layer [41], (ii) strips of steel or reinforced polymer (FRP) [42,43] and (iii) the fibre reinforced cementitious matrix [44]. A non-linear finite element analysis (NLFEA) is presently employed through the use of ADINA [35] which is capable of conducting static and dynamic nonlinear analysis. The subject package also incorporates a range of constitutive models that can be calibrated in order to realistically describe the behaviour of the materials used for the construction of the subject specimens (e.g. brick, mortar, ECC) as well as their interaction (at the brick-mortar or brick-ECC interfaces). The calibration of the subject models is achieved by comparing its predictions to available test data obtained from a series of experiments carried out in the past [27]. After calibration the latter models are used in order to develop more intricate FE models representing the masonry beam-like specimens mentioned above and their predictions are validated against available test data [27]. The validated models are then employed to carry out a parametric study in order to assess the effect of different parameters on the performance of the retrofitted beam-like specimens when subjected to 4-point bending tests. These parameters are associated with the variation of the properties of the various materials considered herein as well as the level of bond developing between the masonry and the ECC layer.

2. Experimental background

The numerical study discussed in the present article forms an extension to previously published experimental work investigating the out-of-plane behaviour of masonry beams-like specimens retrofitted with ECC and subjected to 4-point bending tests [27]. Initially, the main properties of the materials (brick, mortar, ECC) used for the construction of the specimens and their interaction (at brick/mortar and brick/ECC interfaces) were established and used to calibrate the individual parameters of the relevant material and interface models available in ADINA. A series of four-point bending tests were subsequently carried out on masonry beam-like specimens which are either un-strengthened or retrofitted through the use of fully or partially bonded ECC layers [27]. The measurements obtained from these tests are used to validate the predictions of the FE models concerning certain aspects of the behaviour of the subject masonry specimens.

2.1. Summary of experiments carried out in the past

A concise description of results is presently provided concerning the experiments carried out in the past [45] that form the basis of the numerical investigation described herein. Emphasis is mainly focussed on describing the type of specimens considered, as well as the experimental setups employed for conducting the tests. A more detailed description of these experimental studies is provided elsewhere [45]. The test data obtained is presented together with their numerically established counterparts later on.

Individual brick units were initially tested under uniaxial compression in accordance with ASTM C67-14 [28] to determine their average compressive strength ($f_{c,brick}$) and modulus of elasticity (E_{brick}). The bricks used are Class B solid clay Engineering bricks (BS EN 771-1) [29] with dimensions of 210 mm × 102 mm × 65 mm. Similarly, plain mortar cylinders where also subjected to uniaxial compression tests in order to determine their mean compressive strength ($f_{c,mortar}$) and modulus of elasticity (E_{mortar}). M12 mortar was used in accordance to BS EN 998-2:2010 [30] comprising one part of CEM I 52.5 N Portland cement (BS EN197-1 [31]) and three parts (by mass) of fine dry silica sand (with an average particle size of 120 μm). The water-to-cement ratio was 0.85 (by mass).

The behaviour of ECC was established under uniaxial tension [40]. For this purpose ECC dog-bone specimens were prepared in accordance to JSCE [32] and subjected to uniaxial tensile testing (see Fig. 1e). The behaviour of ECC under uniaxial compression was established using 50 mm × 50 mm × 50 mm cube specimens (see Fig. 1f). The ECC binder comprised of CEM I 52.5 N Portland cement in accordance with BS EN197-1 [31] and fine fly-ash (Superpozz SV80, Scotash) which were mixed together as specified in Table 1 (for more detail see [27]). Polyvinyl alcohol (PVA) fibres with an average diameter of 39 μm and a tensile strength of 1600 MPa were introduced into the mix at a dosage of 2% by volume.

Crossed-brick couplets were tested to establish the bond strength of the brick/mortar interface in tension in accordance to