Construction and Building Materials 103 (2016) 47–66

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Assessment of the properties to characterise the interface between clay brick substrate and strengthening mortar

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HIGHLIGHTS

- The interface properties between a PFRM strengthening overlay and substrate were analysed.
- The mechanical characterisation of the interface based on direct shear tests was discussed.
- The obtained failure modes were used to assess the orthotropic properties of the interface.
- The constitutive laws of the interface were assessed based on the test results.

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form 7 November 2015
Accepted 18 November 2015
Available online 28 November 2015

Keywords:
Interface behaviour
Shear response
Direct shear test
Failure criteria
Masonry strengthening overlay

ABSTRACT

The behaviour of masonry elements under in-plane and out-of-plane loads can be improved through the application of strengthening systems based on reinforcing overlays. After strengthening, the transition region between the original substrate and the strengthening layer is especially stressed, and premature failure of the strengthened masonry is reached if insufficient interfacial capacity is assured. Therefore, the assessment of the mechanical behaviour of the interface is critical to the development of the masonry strengthening system based on the application of strengthening overlays.

In this research a method for the characterisation of the interface behaviour between two different materials, a polypropylene fibre reinforced mortar (PFRM) and a ceramic brick used for masonry construction is presented. Direct shear tests were carried out in couplet specimens. Due to the orthotropic nature of the bricks surface, the shear load was applied along three different directions in order to perform an overall estimation of the interface behaviour. The peak and residual shear stresses, as well as the failure modes, were obtained at different levels of the normal stress. Based on these experimental results constitutive laws were assessed for the simulation of the interface mechanical behaviour based on the Mohr and Mohr–Coulomb failure criteria.

1. Introduction

Masonry was one of the main techniques used in the construction of old structures and still is widely used in new buildings. Nevertheless, it is in the case of already existing buildings that masonry often plays a key role as a structural component. The evolution of the design codes has tended to impose more demanding requirements, especially in the case of the action in seismic regions. Consequently, due to this and other durability driven performance insufficiencies, techniques to retrofit existing masonry constructions have recently been developed, and their performance evaluated. These techniques aim to fulfil higher demands in terms of load bearing capacity and increase the ductility response of masonry elements.

A considerable number of strengthening techniques are nowadays based on the application of reinforcing overlays. These systems often show vulnerability at the level of the interface due to the sharp gradient of mechanical properties between the substrate and the reinforcing material [1]. This work presents an experimental program developed with the aim of characterising the mechanical properties of the interface between a polypropylene fibre reinforced mortar (PFRM) strengthening overlay, which is part of a FRCM based masonry strengthening system, and a masonry substrate. The results obtained were used to derive the orthotropic constitutive laws of the interface based on both the hyperbolic Mohr and the Mohr–Coulomb failure criteria.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.11.036
0950-0618/

Nomenclature

FRCM	fabric reinforced cementitious matrix	τ	shear stress
PFRM	polypropylene fibre reinforced mortar used in the FRCM system	τ_p	peak tangential stress
A_{eff}	effective interface area between the two units	τ_r	residual tangential stress
c	cohesion	$\tau_{crit,i}$	tangential values estimated by the criterion
$c^*_{0,p}$	initial apparent cohesion	$\tau_{exp,i}$	tangential experimental values
c^*_p	peak apparent cohesion	$\bar{\tau}_{exp}$	tangential mean value of the experimental results
$\varnothing_{0,p}$	initial friction angle	T_p	peak horizontal load
$\varnothing_p$	friction angle	T_r	residual horizontal load
μ	tangent of friction angle	σ	normal stress
N	vertical load	χ	tensile strength
		χ'	residual tensile strength

1.1. Overlay strengthening techniques

Additional strengthening overlays can be applied to existing masonry with the aim of improving its structural behaviour. This technique is of special importance in areas of high seismic activity, as a means to comply with the current code requirements in terms of resistance to horizontal loading, in particular the seismic action. Typically, the strengthening overlay can be applied manually or mechanically, and is composed by a cement mortar matrix and a reinforcing mesh. The tensile and ductility behaviour of the strengthening overlay is improved by using fibres and meshes made of steel, polymers, carbon or glass [2–8]. The application of these reinforced strengthening overlays improves both the in-plane and the out-of-plane load carrying capacity of the masonry [9]. Alternatively, the overlay strengthening system can be composed of materials showing tensile strain-hardening behaviour in the hardened state, avoiding the use of reinforcement meshes. These materials, typically designated as strain hardening cementitious composites (SHCC), reach tensile strengths higher than the stress at crack initiation, and ultimate tensile strains clearly exceeding 1%. These materials typically develop diffuse crack patterns while loaded in tension, and the maximum crack width remains controlled typically below a maximum of 0.1 mm in the hardening phase. SHCC materials can be applied using the shotcreting technique or manually [10,11]. SHCC based strengthening systems can lead to the increase of the shear capacity of the masonry, to the improvement of its deformability and to the enhancement of its energy dissipation capacity during cyclic loading [12].

Some of the advantages and disadvantages of the masonry strengthening techniques that are based on the addition of strengthening overlays to the original masonry element are presented by Elgaway et al. [2,13]. The advantages identified include the low cost, the durability, the uniform behaviour, the increase of in-plane strength up to 3.6 times, the improvement of the out-of-plane stability, and the increase of the energy dissipation ability before failure. The increase of the dead weight of the strengthened elements, the requirement of surface treatments, the architectural changes of the structure, and the high disturbance during works are the main disadvantages identified [2,13].

1.2. Experimental characterisation of the interface behaviour

1.2.1. Test setups

The mechanical response of the interface between different materials subjected to shear loads is an important topic both in the design of new construction and in the rehabilitation of existing structures [14–16]. In particular, regarding the interface properties of masonry substrates, several authors have conducted research on the assessment of the shear force-slip response of the interface between units [17–21]. The testing schemes used to perform the experiments are diverse, mainly regarding the specimen's geometry, boundary conditions and loading configurations adopted during testing. Some of the most popular loading arrangements and specimen geometries are presented by Van Der Pluijm [22] and Montazerolghaem et al. [23]. Although distinct loading arrangements have been tried, introducing a pure shear stress distribution in a joint is nearly impossible, as well as to achieve a totally uniform shear and normal stress distribution along the interface [22].

The characterisation of the shear behaviour of mortar joints according to the standard EN1052-3 [24] is carried out by performing the triplet tests. However, according to Hofmann et al. [25] and Montazerolghaem et al. [23], this test setup induces local stress concentrations, as shown in Fig. 1. The approximated normal and the shear stresses were obtained using linear finite element analysis. These stress concentrations directly disturb the evenness of stress distribution in both ends of the mortar joint. The failure modes show a clear trend for the occurrence of stepped crack, which can introduce unwelcomed rotations, as reported by Lourenço et al. [26].

The numerical evaluation performed by Hofmann et al. [25] shows that the couplet setup of Hofmann, presented in Fig. 2, leads to a better approximation of a uniform shear stress distribution along the joint than other test setups. Nevertheless, the test setup is too complex to adopt as standard method. A simplified version of this test setup is presented by DIN, see Fig. 3, leading to an almost uniform shear stress, even if an appreciable uneven normal stress distribution occurs at the joint.

An alternative shear test setup proposed by Vasconcelos and Lourenço [18] also uses a specimen with two units, see Fig. 4. In this case the specimen is placed between two thick steel plates and attached to the steel plates by steel bolts, so that the shear force can be transmitted to the specimen. Thin steel sheets are attached to the steel plates to concentrate the shear load as close as possible to the bed joint, aiming to prevent bending moments and to provide a more uniform shear stress distribution. In addition, two thin sheets of Teflon are placed between the steel plates and the specimens to minimise bending effects due to friction.

1.2.2. Data derived from the tests

The values of the two strength parameters, cohesion c or f_{v0} as described by EN1052-3 [24], and the tangent of the friction angle $\mu = \tan\varphi$, for different types of interfaces obtained by triplet and couplet tests are presented in Table 1.

1.3. Mohr and Mohr Coulomb failure criteria

The shear strength and shear force-slip response at the interface between the masonry substrate and the strengthening overlay is not unique, but dependent on the level of normal stress applied. In general, the material strength under a multiaxial stress state