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Out-of-plane behaviour of masonry specimens strengthened with ECC under impact loading

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ABSTRACT

The work described herein sets out to investigate experimentally (via drop-weight testing) the out-of-plane behaviour of beam-like masonry specimens under impact loading when strengthened with a thin layer of engineered cementitious composite (ECC). The subject prismatic specimens essentially consist of a stack of ten bricks connected with mortar joints which are subjected to four-point bending tests. The impact load is applied via a steel mass allowed to fall from a certain height (drop-weight test). Specimens are subjected to consecutive impact tests until their collapse. Each specimen is strengthened by applying a thin ECC layer to the lower face of the prism (acting in tension) or to both, upper and lower, faces (acting in compression and tension respectively). These specimens are considered to provide a simplistic representation of a vertical strip of a masonry infill wall subjected to out-of-plane actions characterised by high loading rates and intensities (associated with impact and blast problems). The drop-weight tests reveal that the proposed strengthening method successfully increases the load-carrying capacity of the subject specimens compared to that observed under equivalent static testing, allowing them to absorb more effectively the energy introduced during impact without the production of debris. Nevertheless, it is important to mention that the behaviour exhibited by the ECC layer during impact testing is characterised by the formation of more localised and wider cracks compared to the fine distribution cracks observed when the same specimens are subjected to equivalent static testing.

1. Introduction

The available experimental and numerical information shows that masonry infill walls can affect the behaviour of frame structures as they cause redistribution of the internal actions developing along the structural elements [1–3]. Infill walls can be subjected to a range of out-of-plane actions associated with extreme weather conditions earthquakes, accidental (progressive) collisions, explosions. The time history of the loads generated is characterised by different forms, loading rates and intensities. The out-of-plane behaviour of masonry infill walls is generally characterized by a limited load carrying capacity and ductility(deformation) [4–8]. The damage sustained by the infill walls due to the application of out-of-plane loads can have a detrimental effect on the overall behaviour of framed structures leading to partial or total failure [4,5]. Furthermore, field observations recorded after major seismic events (i.e. Italy [9–11], Spain [12] and USA [13]) report that the extensive damages sustained by infill walls due to their out-of-plane response usually result in the production of debris which can cause injuries and fatalities [14]. When infill masonry walls are subjected to more extreme loading conditions, characterised by high loading rates and intensities (associated mainly with impact and blast problems) fragments (of different shapes and sizes) are generated which move at high speeds and can also cause injuries, fatalities and further damage to the structure [15,16,42,44]. The latter is confirmed by field observation recorded after explosions [17].

In order to safeguard the structural integrity and public safety, it is often necessary to appropriately strengthen masonry infill walls allowing them to undertake loads applied in the out-of-plane direction even when characterised by high loading rates and intensities while prohibiting the generation of debris. The limitations [26–28] characterising existing methods employed for strengthening infill masonry walls associated with application of external layers of reinforced concrete/mortar or strips of fibre reinforced polymers (FRP) or metals onto the surface of the masonry wall [18–25] to form a composite member has led to the use of engineered cementitious composites. The application of a thin ECC layer onto the surface of the masonry specimens

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Nomenclature

ε	strain
$\dot{\varepsilon}$	strain rate
δ	displacement
$maxP_d$	peak value of impact load generated during drop-weight testing
$maxP_s$	load carrying capacity of individual specimens established under static loading
$max\ \overline{P}_s$	average value of $maxP_s$ established for different specimens
$maxd_s$	peak mid-span deflection exhibited by individual specimen under static testing
$max\ \overline{d}_s$	average value of $maxd_s$ established for different specimens
$maxR_d$	peak reaction force generated when conducting impact tests on individual specimen
$maxd_d$	peak value of mid-span deflection measured when conducting impact tests on individual specimen
$\dot{P}$	the loading rate measured under drop weight tests
P_d	intensity of contact (impact) load under drop weight testing
$P_{s,cr}$	load at which cracks start to develop on individual specimen when subjected to static testing
$\overline{P}_{s,cr}$	average value of $P_{s,cr}$ established for different specimens
R_d	reaction force generated under drop weight testing
$resd_d$	residual value of deflection measured after each drop weight test
t_R	time at which the peak reaction load attended under drop weight testing
t_P	time at which the peak impact load attended under drop weight testing
t_d	total time duration of impact loads under drop weight testing
$\Delta t_{P\text{-}R}$	delay which measured between the peak impact load and peak reaction load under drop weight testing
E	elastic modulus
f_c	compressive strength
f_t	tensile strength
$\sigma_{First\ crack}$	first crack stress
$E_{first\ crakc}$	first crack strain
σ_{max}	Maximum stress
ε_{max}	Maximum strain
$\varepsilon_{failure}$	Failure strain
V	Shear strength
G	Shear modulus

has been found to enhance their out-of-plane behaviour in terms of load-carrying capacity, stiffness and ductility under static loading [29–32]. This enhancement is associated with the ability of the engineered cementitious composites (ECC) to exhibit a ductile, strain-hardening behaviour under uniaxial tension, typically characterised by a high strain capacity and toughness [33]. This is mainly attributed to the ability of the subject material to form multiple fine cracks, with an average crack width of less than 100 µm [34]. The tensile behaviour of ECC is strain-rate dependent [35,36] because under increasing loading rates it exhibits: (a) an increase in tensile strength, (b) a reduction in strain capacity accompanied by (c) the development of less cracks which are more localised and wider compared to those observed under static loading [35,36]. Overall the behaviour of ECC specimens subjected to impact tests is characterised by higher integrity and energy absorption, better distribution of the micro-cracks forming in damaged zone, reduction of fragmentation, less spalling and lower damages due to debris compared to that exhibited by the same specimens constructed using regular reinforced concrete [37,38].

Present work investigates experimentally the behaviour of beam-like masonry specimens, essentially consisting of a stack of bricks connected with mortar joints, when subjected to four-point bending tests in which the load is applied via a drop-mass allowed to fall from a certain height (drop-weight testing). The subject specimens provide a simplistic representation of a vertical strip of a masonry infill wall which can be subjected to loads with different characteristics (associated with their distribution, time-history, loading-rate and intensity). The experimental investigation aims at assessing the level of enhancement achieved in the out-of-plane behaviour when the prismatic masonry specimens considered are strengthened with: (i) a single ECC layer added to their lower face (acting in tension); (ii) two ECC layers, one applied to their top (acting in compression) and one to their lower (acting in tension) face. During testing measurements are recorded describing certain important aspects of the dynamic response exhibited by the specimens throughout the loading process. These measurements include the time-history of the contact (impact) and reaction forces generated as well as the displacement, strain and associated strain-rate exhibited at certain points along the element span throughout the test. Emphasis is also focused on recording the deformation and cracking profiles exhibited throughout the loading process up to failure as these provide an indication of the internal stress-state developing within the specimens. To achieve this, both, conventional instrumentation (i.e. load cells and LVDT) as well as high speed photography are employed. Present work forms an extension of previous experimental studies [45] that demonstrated the ability of the proposed method to enhance the out-of-plane behaviour of the same specimens (compared to that exhibited by the un-strengthened specimens) under equivalent static loading. The results obtained from the latter study form a benchmark against which the results obtained from the drop-weight tests are compared to.

2. Specimen fabrication

A total of eleven prismatic specimens were fabricated and subjected to drop-weight testing. Each specimen consisted of a stack of 10 bricks with 9 mortar joints in between. Six specimens (see Table 1) were retrofitted with a 15 mm thick layer of ECC fully-bonded to the bottom face of the beam-like specimens (see Fig. 1). Four of these specimens were subjected to high intensity impact testing (HO-series) and the other two to lower intensity impact testing (LO-series). The five remaining specimens were retrofitted with two 15 mm thick ECC layers which were fully-bonded to the top and bottom faces of the prisms. The dimensions of the masonry prismatic specimen are: 720 (± 20) mm in length, 210 mm in width and 117 mm in thickness for the case of the specimens with one ECC layer (see Fig. 1) and 132 mm thick for specimens retrofitted with two layers of ECC. Two of these specimens were subjected to high intensity impact loading (HT-series) whereas the remaining three were subjected to lower intensity impact loads (LT-series).

Material: class B Engineering solid clay bricks were used in accordance to BS EN 771-1 [39] with dimensions of 210 × 102 × 65 mm. The mortar used to form the joints comprised of one part of CEM I

Table 1
Summary of the experimental schedule.

Number of ECC layer(s)	Impact load	ID	Test number
One layer	H-series	HO	4
	L-series	LO	2
Two layers	H-series	HT	2
	L-series	LT	3