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Out-of-plane flexure behaviour of fly ash-lime-gypsum brick masonry walls

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ABSTRACT

Industrial by-products such as fly ash is being used for the manufacture of building products such as fly ash bricks. This paper is focused on understanding the out of plane flexural behaviour of fly ash-lime-gypsum (FaL-G) brick masonry, through experimental investigations. Results of the flexure strength of FaL-G brick masonry walls (under different pre-compression) in the two orthogonal directions, are discussed. Load displacement and moment-curvature relationships for the two cases presented. The cracking flexural stress using linear elastic analysis was predicted and compared with the experimental value. The results reveal that (a) the flexure strength of FaL-G brick masonry walls increases linearly with the increase in pre-compression, (b) the flexure strength parallel to bed joints is two times more than that of the flexure strength perpendicular to bed joints under zero pre-compression, (c) lateral displacements for the FaL-G brick masonry walls are larger for the case of bending perpendicular to bed joints when compared with those for bending parallel to bed joints and (d) The cracking flexural stress for the FaL-G brick masonry can be predicted closely with those of experimental values using linear elastic analysis.

1. Introduction

The masonry consists of the masonry units and the mortar joints. Varieties of concrete-based products and fired clay units are used as masonry units for the structural masonry. Even though these materials are durable, they have been questioned as unsustainable options because of the issues concerning energy, environment and conservation of natural resources. Also, the walling materials are consumed in bulk quantities and hence consume large quantities of natural resources in an unsustainable fashion. There is a need for energy efficient and environment friendly alternative materials for the masonry. The fly ash blocks/bricks represent one such alternative for the conventional masonry units. The fly ash is a by-product from the coal based thermal power plants. In India, coal based thermal power stations contribute to about 70% [1] of the power generation producing about 164 million tonnes of fly ash annually [2]. Though part of the fly ash (40%) is being consumed by the cement industry in India [2], there is a need for bulk utilisation of the fly ash to circumvent the environmental problems related with the storage and the disposal of fly ash.

The class F or equivalent grade fly ash is pozzolanic in nature and has low calcium content. The fly ashes with lower lime fractions (Class F) are used for the manufacture of the fly ash bricks or blocks [3]. The pozzolanic nature of the fly ash is exploited in the manufacture of the fly ash bricks. The reactive silica and alumina present in the fly ash are the main sources of pozzolana. Therefore, lime (calcium hydroxide) becomes an essential additive to fly ash for deriving strength from the lime-fly ash mixtures. The lime pozzolana or the lime-fly ash reactions are slow at ambient temperatures and environmental conditions. It becomes essential to accelerate these reactions and enhance the rate of strength gain, in order to derive meaningful strengths for the lime-fly ash products in a reasonable duration of curing time (28 days). The lime-fly ash reactions can be accelerated either by using the accelerating additives such as gypsum [4–16] or by curing at elevated temperatures [16–20].

Fly ash – lime – gypsum (FaL-G) compacted at optimum moisture into a brick is termed as FaL-G brick. FaL-G brick technology is quite popular in India as there are more than 700 small scale FaL-G brick manufacturing units using high volume fly ash with gypsum as an additive to accelerate the rate of strength gain [6]. The FaL-G bricks manufactured from these units are being used for the load bearing masonry walls and infill walls in framed structures (Fig. 1).

There are several investigations on the FaL-G material and the FaL-G brick technologies in the recent past [4–16]. There are limited studies on the behaviour of FaL-G brick masonry.

Chitharanjan [4] investigated on the compressive strength of the masonry wallettes built using low density FaL-G blocks having a compressive strength of 4.12 MPa. The masonry compressive strength was in the range of 1.5–2.0 MPa for different aspect ratio of the masonry

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Fig. 1. FaL-G brick masonry building (confined masonry walls).

wallettes. Gourav and Reddy [16] carried out experimental investigations on the characteristics of the compacted FaL-G bricks, compressive strength and flexure bond strength of FaL-G brick masonry. This investigation revealed that the FaL-G brick masonry with cement lime mortar resulted in very high flexural bond strength when compared with the flexure bond strength of burnt clay brick masonry. Higher bond strength in FaL-G brick masonry was attributed to the development of the chemical bond at the interface between the mortar and the FaL-G brick in the FaL-G brick masonry, in addition to mechanical interlocking of cement hydration products. There are hardly any studies on the behaviour of FaL-G brick masonry walls under flexure and shear.

The masonry walls can experience lateral loads due to seismic, wind, eccentric loads etc., causing out-of-plane bending or in-plane shear. The flexural strength of unreinforced masonry (URM) is influenced by the bond between the masonry unit and the mortar, the masonry unit strength (particularly for flexural strength parallel to bed-joints) and the pre-compression.

Knowledge on the flexural behaviour of the FaL-G brick masonry walls is essential for assessing flexure strength of masonry walls and structural design of masonry. Hence, the present study is focused on the out-of-plane flexural behaviour of FaL-G brick masonry through experimental investigations. The out-of-plane flexural behaviour of FaL-G brick masonry wallettes were evaluated considering lateral bending parallel to and perpendicular to bed-joints.

2. Earlier work on the flexure strength of masonry

A number of investigations addressing various aspects of the flexural behaviour of masonry walls can be found in the literature. Majority of these investigations pertain to the burnt clay brick masonry and the concrete block masonry.

Hendry [21] reviewed the research work on the flexural strength of brickwork, with and without pre-compression, and suggested that it was possible to estimate the flexural strength of various types of walls by introducing global safety factors depending wholly on resistance of brickwork to tensile bond strength or arching effects. Lawrence et al. [22] performed a series of lateral loading tests on brickwork to determine the flexural strength and the modulus of elasticity in the two orthogonal directions. Hamid and Drysdale [23] reported the flexural tensile strength of concrete block masonry, for both the cases of normal and parallel to the bed-joints. Drysdale and Essawy [24] tested concrete block walls for out-of-plane bending and showed that the pre-compression, delays the development of cracking stress, and the first cracking and the failure pressures were highest with pre-compression.

Sinha et al. [25] described the failure criterion and the behaviour of brickwork in biaxial bending. The experiments showed that the modulus of elasticity in the two orthogonal directions (stiffness orthotropy of the brickwork) exerted great influence on the behaviour and the failure of brickwork panels. The experimental results were compared with the predicted results based on the yield line method, the FE analysis in conjunction with the Rankine maximum stress theory and fracture line analysis.

Griffith et al. [26] tested unreinforced wall panels under out-of-plane static and dynamic loading and proposed an empirical force-displacement relationship for displacement-based method of analysis. The static push tests were conducted and the nonlinear force-displacement behaviour was compared with the linear elastic theory and the rigid body theory. The linear elastic theory results agreed well with the experimental values rather than the rigid body theory results. Lu et al. [27] developed a comprehensive finite element model for unreinforced masonry considering the material and the geometric nonlinearity, with the capability of capturing post-cracking and the post-buckling behaviour.

Griffith and Vaculik [28] subjected the unreinforced clay brick masonry walls to out-of-plane loading, to investigate the load-deflection behaviour of unreinforced masonry (URM) walls beyond their peak points. The experimental results showed that the laterally loaded masonry walls have some ductility and a substantial displacement capacity beyond the point of cracking and displacement.

Popehn et al. [29] experimentally studied the behaviour of slender URM walls subjected to axial compression and out-of-plane lateral loads. The experimental force-displacement responses were validated, in turn, verified using two mathematical models, a finite element model and a linear elastic buckling solution.

Najafgholipour et al. [30] proposed an analytical method for in-plane /out-of-plane capacity interaction in brick walls. The method was based on numerical investigations considering wall aspect ratio and the material properties, which had the most influence on the level of the interaction. The results showed that the analytical method produced the accurate results.

Vaculik and Griffith [31] described a methodology for modelling the nonlinear, inelastic load-displacement behaviour of two-way spanning unreinforced masonry walls subjected to out-of-plane loading. The out-of-plane load-displacement model provided an acceptable lower bound estimate verifying the experimentally measure data.

Bui and Liman [32] experimentally studied the out-of-plane behaviour of hollow concrete block masonry walls unstrengthened and strengthened with Carbon Fibre Reinforced Polymer (CFRP) composite. The study concluded that under the real boundary condition, the effectiveness of the strengthening system is smaller than the simply supported walls.

Navarrete-Macias et al. [33] experimentally determined the out-of-plane behaviour of confined masonry walls subjected to concentrated loads. The results showed that for walls with the same aspect ratio, as the axial stress increases, the out-of-plane strength increases and for walls with the same axial stress, as the aspect ratio increases, the strength decreases.

Jayasinghe and Mallawaarachchi [34] reported flexural strength of compressed stabilized earth block masonry. Both flexural strength parallel to and perpendicular to bed-joints were determined. Tennant et al. [35] studied the flexural behaviour of cement stabilized soil blocks (CSSB) masonry and verified the same using the masonry building code. Graziotti et al. [36] studied the out-of-plane behaviour of unreinforced calcium silicate masonry, single leaf and cavity walls using shake table tests. Messali et al. [37] tested unreinforced calcium silicate masonry both for in-plane and out-of-plane using shake table. Out-of-plane testing's were done with one-way, two-way and two-way with opening conditions.

The literature on the flexural behaviour of masonry reveals the following.

1. Masonry resists flexural stresses due to good bond between the masonry unit and the mortar. Masonry is orthotropic in nature, the flexural strength of masonry when tension developed is parallel to