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Mechanics of hollow concrete block masonry prisms under compression: Review and prospects

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Abstract

The aim of this work is to critically assess the mechanical properties of hollow concrete masonry using experimental results from prisms constructed with blocks of two different strengths and four types of mortar. A key conclusion is that mortar is mostly responsible for the non-linear behavior of masonry. Moreover, a strongly non-linear relationship between masonry elasticity modulus and compressive strength is found, which contradicts the simple linear relation proposed by Eurocode 6 [CEN. Eurocode 6: Design of masonry structures – Part 1 – Common rules for reinforced and unreinforced masonry structures. EN-1996-1-1; 2005.]. The porosity of mortar and the state of stress that mortar undergoes in the process of compressive loading can be responsible for changes in the mechanical properties, such as elasticity modulus and Poisson's ratio. Finally, different types of mortars induce different failure modes in the masonry prisms and there is clear evidence that the failure of hollow concrete masonry starts after onset of mortar crushing. In order to better reproduce the observed experimental behavior, a tentative model for the mortar Poisson's ratio variation upon loading is also presented.

Keywords: Stress–strain diagram; Elasticity modulus; Non-linear behavior; Lateral deformation; Failure modes; Poisson's ratio model

1. Introduction

The compressive behavior of masonry is of crucial importance for design and safety assessment purposes, since masonry structures are primarily stressed in compression. These values can be obtained from tests on small assemblages or tests on the components. The testing methods vary considerably and depend of the compressive strength of block and mortar. The present approach from codes, e.g. Eurocode 6 [1], is to make the compressive strength of the masonry composite to depend from the compressive strength of the masonry components (unit and mortar). This empirical approach is obviously conservative and results from a lower envelope of a large set of experimental data, meaning that the compressive strength of masonry can be severely underestimated. The alternative solution today is to carry out a series of tests in expensive wallets, which is hardly feasible for all possible masonry materials.

Atkinson et al. [2] state that the prediction of compressive strength and deformation characteristics of full scale masonry based on compressive tests of stack-bond masonry prism and the interpretation of the results of prism tests have a significant influence on the allowable stress and stiffness used in masonry design. Obviously, besides the strength another relevant parameter for design is the stress–strain relationship. In particular, the elasticity modulus is a mechanical property influenced by different factors. Here, it is noted that the elasticity modulus of masonry as a composite system includes the effect of the components, namely mortar and unit. Due to the periodic nature of masonry and the fact that most of the deformation is usually concentrated in the units, measurements are often made between plates, even if the measurements

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should be made at mid-height of the units. Relevant factors affecting the effective elasticity modulus of masonry are the large scatter of experimental tests, the compressive strength of the unit, the type of the unit (hollow or solid), the compressive strength of mortar, the state of stress developed during loading, testing technique and construction details. Eurocode 6 [1] states that, in the absence of experimental results, the secant elasticity modulus can be obtained from $E_{mas} = k \cdot f_{k\,mas}$. The recommended value of k is equal to 1000, independently of the unit geometry, the mortar type or the joint thickness. This kind of relationship would give only an approximate estimate of the elastic modulus. To compare this rule with experimental results, the model of Knutson [3] is adopted to predict the stress–strain relationship.

Cheema and Klingner [4] described the failure criterion curve for hollow prisms using the modular ratio between mortar/block and the failure type (by mortar crushing and transverse block splitting). Material non-linearity was accounted for by using secant modulus, and the strength of constituent materials was computed considering the effects of multiaxial stresses.

An experimental investigation on blockwork masonry prisms was conducted by Khalaf et al. [5,6] to study the effect of different materials on the compressive strength. The conclusion of this work is that an increase of mortar strength of ungrouted prisms by 188% and 72% produced only an increase in the prism strength of about 20%.

An experimental investigation was conducted by Vermeltfoort [7] to study the brick–mortar interactions for more accurate explanation of the behavior of masonry when submitted to compressive loading. Vermeltfoort [7] concluded that further research is required for Poisson's ratio of masonry controlling the lateral deformation of specimens. Poisson's ratios are also essential in numerical simulations.

It is noted that most experimental results available in the international literature address hollow concrete grouted masonry, whereas the focus here is ungrouted masonry. The main objective of this investigation is to understand the axial and lateral displacement capacity of concrete hollow block-masonry prisms, considering the influences of varying block–mortar strength combinations. At present, a complete understanding of the mechanisms involved in the deformation and failure of compressed masonry is not possible and it is believed that the development of a theoretical model of universal application is a rather hard task, because of the multiples factors that influence the behavior of brittle materials loaded in compression.

The paper addresses different relevant issues for the discussion of the mechanics of hollow concrete block masonry under compression, namely the shape of the stress–strain diagram, the deformation properties, the lateral deformations of the block, the failure modes and the need of an adequate effective Poisson's ratio model for the mortar. In particular, it is advocated that the failure mechanism of masonry depends on the difference of Poisson's ratio between unit and mortar and their mutual interaction on the interface of both materials.

2. Shape of the stress–strain diagram for the masonry composite

Knutson [3] proposed a non-linear shape for stress–strain diagram σ–ε of masonry, whereas Atkinson et al. [2] concluded that there are three typical types of behavior in stress–strain diagrams, namely brittle, ductile and bilinear, depending on the type of mortar and confining stresses.

The elasticity modulus, usually adopted as the measure of stiffness, represents either a secant or tangent modulus, being the latter given by

$$E_t = d\sigma/d\varepsilon \qquad (1)$$

The tangent elasticity modulus E_t can be used as an approximation of the relation between stress and strain in the neighborhood of a given point. Knutson [3] reports that Ritter suggests adopting the following formula for the tangent modulus of elasticity E_t

$$E_t = E_0(1 - \sigma/f_c) \qquad (2)$$

as a function of the initial tangent elasticity modulus E_0 and the ratio between the normal stress σ and the masonry compressive strength f_c. Introducing Eq. (2) in Eq. (1), integrating and rearranging, it is possible to obtain:

$$\varepsilon = \int \frac{1}{E_0 \cdot \left(1 - \frac{\sigma}{f_c}\right)} \cdot d\sigma \qquad (3)$$

The solution of Eq. (3), hereby denoted as Ritter curve, is a logarithmic relation between two non-dimensional values, namely the normalized strain $Kr \cdot \varepsilon$ and the normalized stress σ/f_c, given by

$$Kr \cdot \varepsilon = -\ln\left(1 - \frac{\sigma}{f_c}\right) \qquad (4)$$

where $Kr = E_0/f_c$ is the so-called Ritter constant, which for concrete assumes a value of 1000.

Knutson [3] evaluated the stress–strain diagrams for various masonry materials and showed that they can be cast into a mathematical form. The model aims at representing the complexity of material assembly and requires shape and materials parameters. The experimental masonry strain–stress diagram for different combinations of mortar and brick (three solid and one hollow) are shown in Fig. 1. This author concluded that the stress–strain relationship could be approximated through:

$$\varepsilon = -\frac{f_c}{E_0}\ln\left(1 - \frac{\sigma}{f_c}\right), \quad \text{if } \sigma/f_c \leqslant 0.75, \text{ Ritter curve} \qquad (5)$$

$$\varepsilon = -4\frac{f_c}{E_0}\left(0.403 - \frac{\sigma}{f_c}\right), \quad \text{if } \sigma/f_c > 0.75, \text{ Ritter curve correction} \qquad (6)$$