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A semi-random field finite element method to predict the maximum eccentric compressive load for masonry prisms

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HIGHLIGHTS

- A probabilistic approach to predict behaviour of eccentrically loaded masonry.
- Variance values needed for semi-random finite element (FE).
- Coupled analysis of FE and Latin Hypercube method for parametric models.
- Outcomes in the range of Class A distribution functions.
- RMSD of method for mean was 2.2 KN – demonstrating robustness.

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ABSTRACT

An accurate prediction of the compressive strength of masonry is essential both for the analysis of existing structures and the construction of new masonry buildings. Since experimental material testing of individual masonry components (e.g., masonry unit and mortar joints) often produces highly variable results, this paper presents a numerical modelling based approach to address the associated uncertainty for the prediction of the maximum compressive load of masonry prisms. The method considers a numerical model to be semi-random for a masonry prism by adopting a Latin Hypercube simulation method used in conjunction with a parametric finite element model of the individual masonry prism. The proposed method is applied to two types of masonry prisms (hollow blocks and solid clay bricks), for which experimental testing was conducted as part of the 9th International Masonry Conference held at Guimarães in July 2014. A Class A prediction (presented before the tests were conducted) was generated for the two masonry prisms according to the proposed methodology, and the results were compared to the final experimental testing results. The root mean square deviation of the method for prediction of eccentric compressive strength of both types of prisms differed by only 2.2 KN, thereby demonstrating the potential for this probabilistic approach.

1. Introduction

Determination of the mechanical behaviour of masonry material is important in order to determine the safety of historical masonry structures and to design new masonry buildings. For many types of masonry structures (e.g., load-bearing walls, vaults, and pillars) the predominant load-carrying ability of masonry is through axial loading in compression. As such, determination of the compressive strength of masonry is crucial to ensure the overall performance for many masonry structures. However, there generally exists some degree of uncertainty in the determination of properties for individual masonry constituents obtained from experimental testing, which is rather high when the properties of the composite are estimated from the properties of the components.

To overcome these limitations, this paper presents a novel methodology for the prediction of the maximum compressive load for masonry prisms. The methodology adopts a probabilistic approach to consider the variation in experimental data for the individual masonry components [1,2]. This methodology was recently presented at the 9th International Masonry Conference, for which experimental data provided validation. The methodology was applied to produce a Class A prediction [3] for two different

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prisms: (1) a hollow block masonry prism and (2) a clay brick masonry prism. The two prism types were subsequently tested experimentally to determine the maximum compressive load, thereby allowing for the accuracy of the predicted results to be assessed [1,2]. This paper presents the proposed method and the detailed outcomes.

2. Background

Despite the large quantities of masonry experimental data and the number of theoretical approaches currently available for the estimation of masonry strength under compression, masonry material behaviour is not yet fully understood [4]. The need for further research is confirmed by the fact the modern design codes [i.e., EuroCode6 [5] and ACI [6]] employ semi-empirical relations for compressive strength prediction, instead of simplified theoretical approaches [7]. Traditionally masonry compressive strength has been determined by two approaches [8]. The first involves the use of prescribed tables (or analytical expressions) that predict masonry strength based on the individual block strength and mortar type according to empirical formulae [using standards, e.g., EuroCode6]. The second consists of the testing small masonry assemblages either stacked bond prisms with height-to-thickness ratio (h/t) of at least 2 but no greater than 5 or wallettes [5].

The results from experimental testing of masonry assemblages tend to be quite variable due to testing conditions, material variability (both unit and mortar), and workmanship. Furthermore, multiple prism samples are required to produce a reliable estimation of the masonry stress and stiffness data for use in large-scale structures. Previous experimental tests have demonstrated a high level of uncertainty in the prediction of masonry compressive strength. For example, [9] in the testing of 84 sets of masonry prisms reported a coefficient of variation (COV) of 0.23 for compression strength and 0.34 for the elastic modulus. In a similar study [4], COV values of 0.30 and 0.40 for the compressive strength and elastic modulus, respectively, were reported. Kaushik et al. [9] also reported discrepancies of up to 480% when various analytical prediction methods [5,6,10,11] were compared to a wide variety of experimental results for brick masonry prisms [9,12–19]. This same study demonstrated that when mortar strengths were less than 20 MPa unconservative errors in excess of 100% were predicted when analytical equations from current codes were applied [117% for EuroCode6 [5], and 110% for ACI [20]].

In an attempt to provide more accurate predictions of the compressive strength of masonry, sophisticated non-linear numerical models have been adopted. Ahmad and Ambrose [8] pioneered the use of a three-dimensional (3D) finite element model to study the complex behaviour of hollow block prisms under axial compression. The most significant parameters were found to be mortar type, prism geometry, and bearing plate stiffness; results for concrete masonry prisms were also presented but without experimental validation. A homogenised finite element (FE) model [7] predicted closer experimental outcomes than current codes when considering a wide range of previously reported experimental results [12,15,21]. The average absolute error was 32% for the of the homogenised FE model, 36% for EuroCode6 [5] and 43% for ACI [20] and both showed non-conservative estimations for clay bricks [21]. Blackard et al. [22] generated only a 12% discrepancy with a 3D FE model for a masonry prism consisting of clay bricks and cement mortar under non-eccentric loading, for experimental data with a COV equal to 0.10. However, the estimated peak reached in the adopted plane strain method was 41% higher than the corresponding experimental results. Even when the generalised plane strain was adopted, the peak was 25% higher than the experimental results. Notably, when tensile cracking was of interest, Pina-Henriques and Lourenço [23] advocated adopting meso-scale approaches to incorporate heterogeneity at a lower level and to induce tensile cracking under uniaxial compression.

Overall, the literature review shows that the better estimation is needed to increase the accuracy of material strength of masonry, which could influence the safety and cost issues in assessing relevant structures.

3. Methodology

In this study, a probabilistic methodology was adopted for the determination of the maximum compressive load for two types of masonry prisms. To do so, a Semi-Random Finite Element Method (SRFEM) was adopted. This method make uses of random field theory [24] to consider the variance in the determination of the individual masonry material components (e.g., blocks and mortar joints). Generally, the Random Finite Element Method (RFEM), not available commercially, is an extension of the Finite Element Method that is able to add randomness to all the integration points of the FE model by applying random field theory (i.e. each integration point has randomly assigned a different characteristic in term of material properties) [25]. To simplify the model, a semi-random field concept was applied, and each block or mortar layer was characterised by different material properties.

The methodology used to conduct the semi-random field finite element analysis is illustrated in Fig. 1. A parametric finite element model of each prism was initially generated using ABAQUS commercial finite element software [26]. Loading was applied in a quasi-static manner, so as to simulate the loading process that will be adopted in the testing phase. The models were subsequently coupled with a Latin Hypercube Sampling (LHS) algorithm generated in MATLAB [27]. The statistical distribution of each material property was determined according to the experimental results, provided before masonry prism testing [1,2]. The parametric models were subsequently conducted, which simulated the arbitrary sets of material properties. Plasticity parameters for the applied constitutive law were calibrated with experimental test results, again provided before masonry prism testing. A stochastic analysis was then conducted, and the maximum compressive load for each prism was determined according to the results of the probabilistic analysis.

Two sets of eccentric loading tests (three tests for each type) were carried out 240 days after construction of the masonry specimens, allowing for an assessment of the accuracy of the numerical prediction. Fig. 2 shows the geometry of the specimens and the location of the applied loading where additional information regarding the experimental testing may be found in [1,2].

3.1. Material constitutive law

A continuum plasticity-based damage model [28] was adopted for defining the failure behaviour of each component of the masonry prisms (i.e., bricks, mortar layers, and concrete hollow blocks). This material model assumes that the main two failure mechanisms of the brittle material are tensile cracking and compressive crushing. The evolution of the yield (or failure) surface is controlled by two hardening variables, the tensile equivalent plastic strain, $\tilde{\varepsilon}_t^{pl}$, and the compressive equivalent plastic strain, $\tilde{\varepsilon}_c^{pl}$, which are linked to the failure mechanisms under loading. The model assumes that the uniaxial tensile and compressive response of the material is characterized according to a softening law, as illustrated in Fig. 3.

Under uniaxial tension, the stress–strain response follows a linear elastic relationship until the value of the failure stress, σ_{t0}, is reached. The failure stress corresponds to the onset of micro-crack-