Engineering Structures 32 (2010) 1244–1251

Contents lists available at ScienceDirect

Engineering Structures

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

Micromodelling of eccentrically loaded brickwork: Study of masonry wallettes

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ARTICLE INFO

Article history:
Received 29 October 2009
Received in revised form
27 November 2009
Accepted 22 December 2009
Available online 8 January 2010

Keywords:
Brick masonry
Eccentric loading
Compressive strength
Finite element
Collapse mechanisms
Micromodelling

ABSTRACT

Arches, vaults and pillars are subjected to significant eccentric loading; for this reason, their assessment needs the effect of strong stress gradients to be taken into account. Based on a series of tests, this paper discusses the outcomes of nonlinear finite element modelling of the tests looking for a deeper insight into the micromechanics of brickwork collapse; i.e. into the phenomena activated inside the bricks, the mortar joint and at the brick/mortar interface at collapse. The Craft model is used as a constitutive model for mortar and bricks, while the brick–mortar interface is represented by interface elements. The results of the FEM analysis, were found to be comparable with the load–displacement and moment–curvature experimental response, and support some conjectures formulated, but not demonstrated, during the testing campaign.

1. Introduction

Concentric loading of masonry structures is a standard loading condition useful for laboratory tests and for assessment purposes, but represents only an average description of the actual stress state and is rarely, if ever, met in masonry. For several structural elements, the stress distribution is characterized by strong stress gradients, such as in the case of pillars, vaults and arches. In the latter case, the activation of plastic hinges (i.e. sections where the relative rotations between adjacent sections are localised) requires that the compressed part be reduced to a small fraction of the full section and is an example of such a situation where strong stress gradient makes the uniform stress distribution inappropriate. In some other cases, the stress gradient may be relatively smooth, such as for masonry walls, but also in these cases the uniform distribution of stresses, that is frequently referred to by engineers, is a doubtful reference case.

The effect of eccentric loading has been investigated by means of both experimental and theoretical approaches. Assuming a priori a linear elastic compressive constitutive model for brickwork, and a tensile vanishing strength, several authors found that the compressive strength of masonry, under eccentric loading, seems to be significantly higher than that measured for concentric loads [1–5]. This outcome is troublesome because it relates a material property (i.e. the compressive strength) to the loading condition, that is independent from the mechanical properties of the material [6–9]. Due to this uncertainty, the only code allowing a strength increase in the case of eccentric loading is the past UIC code [10], while its last revision [11] was changed to be coherent with Eurocode 6 [12], which does not allow such an increase.

More recent theoretical and experimental research investigated the mechanical response and the collapse mechanisms of eccentrically loaded masonry and has attempted to evaluate the behavior of masonry subjected to eccentric loads [7–9]. The effect of fatigue and of the brick water content on the compressive strength however remains substantially an open issue but has been recently considered in Roberts et al. [4]. These latest results clarified some of the aspects of the mechanics of eccentrically loaded masonry. Concentric loading is a determinate problem where the compressive strength can be estimated by just dividing the peak load by the resistant section. Eccentric loading is however an indeterminate problem since the strain distribution over the section has to be postulated, usually assuming the Navier hypothesis of a plane section, with the resulting stress distribution being derived from a constitutive model determined a priori. The increase of compressive strength for eccentric loading, therefore, may be partly explained as the apparent effect of a linearly elastic compressive constitutive model for a material that, close to the peak load, exhibits nonlinear permanent strains and does not fit a linearly elastic model [7–9]. In addition there are also significant difficulties in undertaking consistent experiments; for example external constraints in the test

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doi:10.1016/j.engstruct.2009.12.050

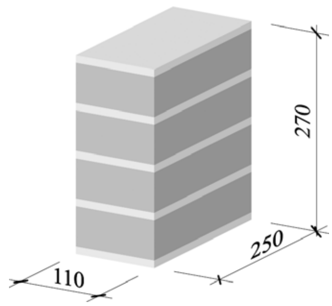

Fig. 1. Geometry of the tested specimens (dimensions in mm).

setup in some of the experimental programmes affected the test results, generating an undesirable non-constant eccentricity of the loading and as a result creating test data with an uncontrolled bias.

The collapse micromechanics of solid clay brickwork subjected to eccentric loading is still largely unknown. Tests have shown some features common to the collapse mechanism of eccentrically loaded brickwork prisms [7] but have to date given no clear explanation for them. Limit Analysis procedures [8] allowed some further insight into the phenomenon close to the peak load but the effect of the elastic mismatch between mortar joints and clay bricks is still largely unknown since Limit Analysis does not provide any information before and after the peak load. FE nonlinear models [6,13,14] can provide some information on the micromechanics of the collapse mechanism of eccentrically loaded brickwork. In Brencich and Gambarotta [7] FE models have been used to analyze the crack pattern at the onset of the non-linear response of brickwork referring to brickwork prisms with horizontal mortar joints.

In this paper, nonlinear FE models of brickwork wallettes are used to help gain a deeper insight into the micromechanics of brickwork collapse. The nonlinear behavior of the materials is considered by using the Craft constitutive model [15,16], as well as modelling the brick–mortar interface. The methodology is verified by comparison with the results from previous laboratory tests [7,8]. The FE models are then used to investigate the behavior of eccentrically loaded brickwork prisms, taking into account all the nonlinear phenomena both in the clay brick and in the mortar joint. This suggests that the collapse mechanism of eccentrically loaded brickwork prisms is due to a concentration of tensile transversal stresses in the brick close to the external surface on the compressed side of the specimen, which activates the collapse of the prisms.

2. Experimental data

Fig. 1 shows the wallettes tested under concentric and eccentric loading according to the test program shown in Fig. 2. The main geometric dimensions are:

(a) 110 × 250 × 270 mm, four brick layers and five mortar joints for the specimens.
(b) 110 × 250 × 55 mm for the bricks.
(c) Thickness of the mortar layer: 10 mm.

Table 1 shows the mechanical parameters of the bricks and of the two types of mortar used in the tests.

Load eccentricity ranged from the concentric case ($e = 0$ mm), to moderate (40 mm and 60 mm), to severe eccentricity (80 mm); i.e. from 0, 1/6th, 1/4th, 1/3rd of the specimen section was undertaken in order to compare the results for concentric loading to the data for moderate stress gradients (40 mm, whole section still in compression), strong gradients (60 mm, approximately 1/3rd of the section in traction) and severe gradients (80 mm, approx. 1/6th of the section in compression). All the experiments tests had been repeated two or three times and the collapse mechanisms have also been recorded.

The tests were displacement controlled, the load being measured by means of a load cell and the displacement being measured by LVDTs, as can be seen in Fig. 3. The friction between the loading plates (60 mm thick) and the specimens could not be removed because this could result in unstable tests for eccentric loading. Further details can be found in Brencich et al. [8] and Corradi [18]. Similar specimens had been previously tested by Brencich and Gambarotta [7], Roberts et al. [4] and Kaushik [17].

3. Finite element modelling

3.1. General

The specimens were modelled by three-dimensional FE models using LUSAS 14.1 [18]. Bricks, mortar and brick–mortar interface have been modelled assuming nonlinear constitutive equations with material parameter values based, in the first instance, on the tests performed on the materials and for those cases where test data is unavailable on an optimization procedure fitting the test data. In order to properly investigate the micromechanics of the collapse mechanisms (i.e. the nonlinear, the cracking and crushing phenomena inside the brickwork) the FE models were three-dimensional. Due to the complexity and three-dimensional intrinsic nature of the phenomenon investigated, two dimensional models would have provided unreliable results [14,19]. Some simpler FE models had already been used on these geometries aimed at gaining an initial insight into some local effects, in Brencich and Gambarotta [7].

3.2. Finite elements, boundary conditions and loads applied

Given the symmetry of the specimens, only 1/4th of them needed to be modelled. In this way the cost of computation required by each model was reduced. The corresponding boundary conditions were applied to the planes of symmetry.

The models take into account the presence of the steel bearing plate used in the tests to distribute the applied load on the

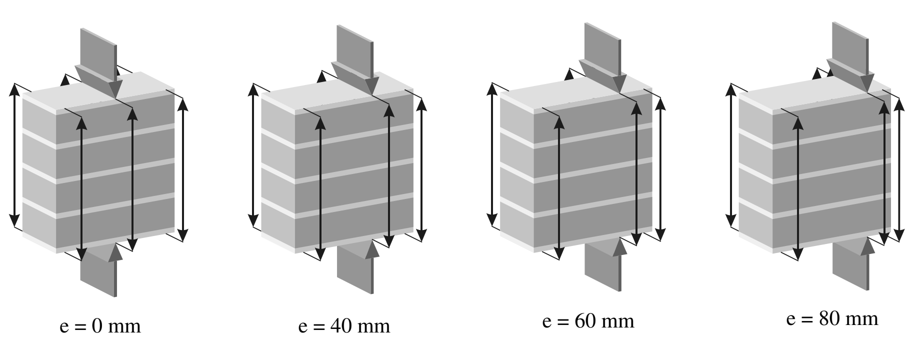

Fig. 2. Testing program and LVDTs position.