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Modelling of the behaviour of seismically strengthened masonry walls subjected to cyclic in-plane shear

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ABSTRACT

A research project on the structural behaviour of seismically strengthened unreinforced masonry (URM) walls is underway at ETH Zurich. The main goal of the research project is to investigate the influence of the prefabricated, pre-stressed strengthening elements on the structural behaviour of masonry walls under cyclic shear loading. Load tests on a series of full scale clay block masonry specimens, which consisted of an URM wall strengthened with two pre-stressed elements have been completed. Test results are analysed and discussed in the present paper. Analytical modelling of the behaviour is accomplished by applying the methods of the theory of plasticity, namely the lower bound theorem, i.e. ideal-plastic material behaviour whereas numerical modelling assumes an elastic–plastic material behaviour. The procedure based on the advanced finite element model and continuous stress fields, and the analytical model based on discontinuous stress fields, which are able to predict the behaviour of the above-mentioned wall system, are proposed and verified by the comparison with experiments. In addition, a simplified model, adopted for practical application is introduced and two examples are calculated. A satisfactory agreement between the proposed models and test data has been found. The paper closes with a set of conclusions and recommendations for practical application and for future research.

1. Introduction

In general, the earthquake performance of unreinforced masonry (URM) shear walls is often unsatisfactory. Under strong motions a brittle (shear) failure could be expected. The failure mode is also strongly influenced by the wall's geometry and the existing normal (compression) force in the wall. Within the framework of a research project at ETH Zurich, the possibility of improving such relatively poor performance by strengthening URM walls with laterally placed prefabricated elements was investigated. These elements act mostly as the tension ties allowing a larger stress field to be formed inside the URM walls. Thus, the wall system, i.e. a URM wall with two strengthening elements, could lead to better shear performance of URM, excluding the need for the reinforcement in URM and/or reinforced concrete walls in the buildings. Moreover, the advantage of the presented system lies in the fact that the combination of masonry and concrete walls in building could be avoided, thus eliminating incompatibility in deformation capacity between masonry and concrete. Finally, the execution of strengthened masonry walls is more cost-effective than is the case with plane reinforced concrete walls.

The main goal of the research project is, based on the series of full scale load tests, to investigate the influence of these strengthening elements on the structural behaviour of masonry walls under static–cyclic shear loading and to develop a model able to predict the walls behaviour. Load tests on a series of four full-scale clay block masonry walls have been completed, see Becker et al. [1], and the test results are analysed and discussed in the present paper. The procedure based on advanced finite element model and continuous stress fields, and the analytical model based on discontinuous stress fields, which are able to predict the behaviour of the above-mentioned wall system, are proposed and verified by the comparison with experiments. In addition, a simplified model, adopted for practical application is introduced and two examples are calculated. Note that the presented models are based on the push cycle, but are, of course, valid for the pull cycle, too. The paper closes with a set of conclusions and recommendations for practical application.

2. Previous investigation

A substantial amount of theoretical work has been invested in modelling structural masonry. Simple models are based on the linear theory of elasticity and its application to structural masonry. Regarding the serviceability limit state, i.e. when investigating

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the behaviour of masonry subjected to load levels up to 40–50% of the ultimate load, the applicability of the linear theory of elasticity is beyond dispute. However, when approaching higher load levels nonlinear modelling is generally required. Hereby, both geometrical and material nonlinearities (e.g. cracking) must be taken into account. Since only very few closed form solutions for nonlinear problems are available, numerical solution methods must be applied. Such solutions are usually obtained by means of Finite Element Method (FEM) procedures. However, the main problem when applying FEM is related to the modelling of the material. Since masonry is composed of two components, i.e. masonry units and mortar, and is highly heterogeneous, modelling the physical reality is very demanding. In general, three different approaches, i.e. types of models, are found in the literature: micro, simplified micro (meso) and macro models. In micro modelling, masonry units and mortar joints are represented by continuum elements, whereas the masonry unit-mortar interface is represented by discontinuous elements. In the meso modelling masonry units are represented by continuum elements whilst the mortar joints and masonry unit-mortar interface are lumped into discontinuous elements. The meso-modelling is particularly effective when seeking to match the experimental findings in respect to local and not only global results, see Colliat et al. [2] and Ibrahimbegovic et al. [3]. Finally, in macro-modelling masonry is treated as a continuum, i.e. represented as one material with smeared material properties. Several methods based on macro-element discretization have been developed, see Magenes [4], Chen et al. [5], Yi et al. [6]. In this approach, each panel in the structure, i.e. piers and spandrels, is modelled by using a single element. Such elements are based on the simplification of both the material behaviour and the stress field within the panel. These elements seem the most appropriate for the design and assessment of masonry buildings because of the simplicity of modelling, the straightforward interpretation of the results, particularly in terms of collapse mechanisms, and the accuracy demonstrated in different validations (e.g. Lourenco et al. [7]) as well as the possibility of implementation in the software packages. A recent comprehensive review of the micro- and macro-modelling approaches for masonry structures can be found in Roca et al. [8].

Although significant progress has been made in the field of the above-mentioned modelling strategies, e.g. development of the so-called homogenised modelling, see e.g. Lourenço et al. [9], these approaches are still not suitable for the analysis of structural masonry in everyday engineering practice. This is because a considerable number of material parameters are needed as input for a meaningful analysis using these approaches, and these parameters are not always available. Furthermore, the current micro and macro models have a limited range of validity and also require significant computational resources and high expertise. In addition, due to the great difficulty in formulating robust numerical algorithms representing satisfactorily the inelastic behaviour of masonry, micro and macro analyses of masonry structures are often limited to the structural pre-peak regime, see Maruccio [10] and Xu et al. [11]. However, the importance of the post-peak response is clear in order to evaluate the deformation capacity and to assess the structural safety.

An elegant way of modelling structural masonry is the application of the theory of plasticity. In spite of the limited ductility of masonry, good results can be achieved by applying the limit theorems of the theory of plasticity. Especially discontinuous stress fields, a tool based on the lower bound theorem, have proven to be very efficient and reliable. Moreover, their simplification to strut-and-tie models has been successfully applied to describe the structural masonry's response to various loadings, see Mojsilović and Marti [12]. An obvious drawback of these models, since they are based on perfectly plastic masonry behaviour, i.e. null elastic deformation prior to yielding, is that the deformation state cannot be determined. A new model based on continuous stress fields, which allows the determination of the deformation state, has recently been introduced, see Fernandez Ruiz and Muttoni [13]. Although this model was developed for reinforced concrete, it could be satisfactory applied to structural masonry, as shown later in the paper.

The previous research activities related to masonry's behaviour under cyclic shear loading focused both on theoretical and experimental aspects. A substantial amount of theoretical work has been invested in modelling structural masonry under cyclic shear. Both analytical and numerical solutions are reported in the literature, e.g. Magenes and Calvi [14], Tomaževič [15], Tomaževič and Weiss [16], Calderini et al. [17], ElGawady et al. [18]. In general, the response of masonry walls subjected to cyclic shear is nonlinear and depends on the vertical pre-compression of the wall. Additionally, a reduction in both strength and stiffness of masonry can be observed during cyclic loading and has to be accounted for. Usually, the hysteresis curve, i.e. the relationship between the horizontal load and horizontal displacement, is chosen as the representative load-deformation characteristic for evaluating the deformation capacity of masonry. This relationship is often modelled by a (bilinear) linear-elastic, ideal-plastic curve. In order to determine the curve's parameters, the ultimate value of the shear force and two characteristic horizontal displacements, namely at the transition from the elastic to plastic range and the ultimate plastic deformation are needed. After setting the value of ultimate shear force and estimating the elastic stiffness, the former displacement can be readily calculated. In general, elastic stiffness is difficult to determine and for practical applications it is usually calculated on the basis of elastic beam theory incorporating shear deformation, see e.g. Tomaževič [15]. It should be noted here that, in general, the determination of the elastic stiffness is subject to variation and the data obtained from tests exhibits a large scatter.

Regardless of the mechanical model applied, in order to gain a deeper insight into the behaviour of structural masonry and due to its very complex modelling a verification of structural masonry behaviour, whether obtained theoretically or numerically, is usually based on experiments. Furthermore, keeping in mind the composite structure of masonry and its anisotropic behaviour it is important to perform full-scale tests. A large number of static, static–cyclic, dynamic and pseudo-dynamic tests on different set-ups and with different test programs are reported in the literature. Some of the work relevant to the contents of the paper can be exemplarily found in, e.g., ElGawady et al. [18], Modena [19], Frumento et al. [20], Tomaževič et al. [21], Mehrabi et al. [22], Russell et al. [23].

In conclusion, despite the rigorous attention that the modelling has received from the research community for a long time there are still some open questions that have to be solved. The modelling of structural masonry is rather complex and challenging but is of the utmost importance for developing reliable and practical models that support the engineering community in their effort to provide the safe and economical design of structural masonry.

3. Experimental investigation

3.1. Test program and masonry materials

Load tests were carried out on a series of four clay block masonry specimens. Each masonry wall had a height h_w = 2.6 m and a thickness t_w = 0.175 m and was placed between two prefabricated and pre-stressed in-filled clay block elements of length l_s = 0.5 m which were friction-locked connected to the wall, see Fig. 1. Dry, factory-made standard cement mortar was mixed with