NUMERICAL SIMULATION OF URM WALLS SUBJECTED TO OUT-OF-PLANE SOLICITATIONS USING A “UNIT AND INTERACTION” MICRO-MODELING APPROACH

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In most places in the world, unreinforced masonry buildings represent a large part of both patrimonial structures and contemporary buildings. Despite this wide usage, it has been clearly recognized that this kind of structure may be highly vulnerable to lateral solicitations such as the ones caused by wind loads or earthquakes. This paper presents the results of numerical investigations focusing on the mechanical behaviour of unreinforced brick masonry walls subjected to horizontal, vertical and diagonal bending induced by out-of-plane solicitations. The proposed study is carried out using a FE micro-modelling approach (SIMULIA – Dassault Systems) based on a “unit and interaction” concept. This concept, initially developed for an efficient computation of arch systems, is here transposed to wall systems: each masonry unit is modelled and the behaviour of head and bed joints is taken into account through specific contact laws managing both the normal and tangential effects.

Following a short introduction to the subject, the “unit and interaction” concept is detailed, insisting on strong and weak aspects and outlining the particular interest for studying the effects of out-of-plane solicitations. Then the paper illustrates how the developed FE models are likely to predict the response of masonry walls under out-of-plane loading: the paper proposes a comparison of obtained results with data reported in the literature. Finally, the paper outlines how the results of this preliminary study will be used in the analysis of walls subjected to two-way bending, where similar failure mechanisms contribute to the overall wall behaviour.

Keywords: URM, out-of-plane solicitation, FEM, micro-modelling, contact laws

INTRODUCTION

Masonry construction is widespread in all regions of the globe and Belgium is a country of masonry construction by excellence: this method of construction is still currently the most often used in the country. Despite this wide usage, some points of the masonry behaviour remain to be investigated; the response of unreinforced masonry (URM) walls under out-of-plane loading is part of these active research issues. Particularly, the behaviour under out-of-plane seismic loading is a “complex and ill-understood” aspect, as described by Paulay & Priestley (1992).

This research project aims to study the two-way out-of-plane behaviour of URM wall under dynamic loading. It intends to develop a simple analytical method for the out-of-plane behaviour verification of masonry walls. This analytical approach will rely on the results of a preliminary numerical study aiming to define failure mechanisms that are likely to occur. The
numerical analysis will allow verifying the influence of various parameters identified as controlling the failure occurrence. The validity of both the models will be established by comparison with experimental results. This paper presents the early steps of the research and preliminary results concerning the validation of the numerical modelling.

CONTEXT
The out-of-plane failure is a very common mode of collapse which can lead to the complete ruin of the structure and constitutes the most serious life-safety hazard for masonry construction (Yi et Al., 2002).

The vulnerability of masonry walls towards out-of-plane solicitations is related their mode of construction which consists of rows of bricks stacked the ones on the others and bound by mortar. The specific complexity is associated with the highly non-linear masonry behaviour, mainly governed by cracking and instability rather than usual material failure (Yi et Al., 2002).

The parameters that seem to have an influence on the failure mechanisms of an unreinforced masonry wall subjected to out-of-plane loads would be the dimensions of the wall, its slenderness, its boundary conditions, the relative resistance of the bricks and the mortar joints, the ratio applied loads/dead loads and the peak velocity demand (in the case of seismic loads) at the base and the top of the wall (Elmenshawi et Al., 2010; Griffith et Al., 2005).

Most of the masonry walls involved in real buildings are supported on 3 or 4 sides; these boundary conditions lead to consider that walls are submitted to bi-axial flexion when they are solicited by out-of-plane loads. Consequently the wall undergoes a combination of horizontal, vertical and diagonal flexion (Figure 1) (Vaculik et Al., 2010) that have to be taken into account.

![Figure 1: Various bending phenomena in a wall submitted to bi-axial flexion induced by out-of-plane loads (picture from Vaculik et Al., 2010)](image)

The illustration we will propose in this paper for our model dealing with horizontal bending, theoretical bases related to this particular type of flexion are recalled here. Under this kind of solicitations and depending on the relative strengths of brick units and mortar, walls can failed according to two failure modes: line failure and stepped failure. In case of “weak units - strong mortar” masonry, a line failure pattern tends to occur. This type of failure implies continuous cracks through brick units and head joints (Figure 2.a). The corresponding resisting mechanisms are the flexural tensile strength of head joint and the lateral rupture strength of brick units. In case of “strong units – weak mortar” masonry, which concerns ancient masonry with lime mortar but also most of the contemporary masonry, stepped failure takes place. This failure mode is characterized by a propagation of the crack following head
and bed joints (Figure 2.b). The two aspects involved when stepped failure occurs are the flexural tensile strength of head joint and the torsional and frictional capacity of bed joints (Willis et Al., 2004). Similar developments exist for diagonal and vertical bending (Griffith et Al., 2005, Doherty et Al., 2002, Derakshan et Al., 2009).

**Figure 2: Horizontal bending: a: line failure; b: stepped failure**
*(picture from Willis et Al., 2004)*

**INTEREST OF FINITE ELEMENT APPROACH**

Under bidirectional bending, the crack pattern that appears during the out-of-plane loading of an URM wall follows approximately the locations of the maximum tensile stresses. Furthermore, the crack patterns are similar to the ones predicted by the yield line theory for reinforced concrete slabs (Hamid, 2003, Martini, 1998). Based on results obtained by finite element simulations, Martini (1998) proposed a modified version of the yield line theory for interpreting the out-of-plane behaviour of URM walls. This research shows that reasonable correlation exists between both the methods. Analytical models, based on 3-dimensional collapse mechanism analysis, predicting the out-of-plane load capacity of URM walls have moreover been developed (Vaculik et Al., 2010; Sinha, 1978).

Depending on the required level of complexity and the objectives to achieve, various strategies of modelling of the masonry may be proposed.

- **Macro-model**: the macro-model approach considers the masonry as a homogeneous anisotropic material having equivalent properties. The mortar and the brick units are not distinguished which implies that zones of weakness of masonry, which are preferential crack localizations, can not be identified (Figure 3.a).

- **Micro-model**: the micro-models represent brick units and mortar joints with their appropriate mechanical and geometrical characteristics. In some cases, the zones of interface between the units and the mortar can also be modelled as potential planes of weakness (Figure 3.b).

- **Meso-model**: the meso-model approach constitutes an intermediate between macro- and micro-models. This method considers, as base element of the modelling, a virtual element compound of a set of brick units and mortar joints representing a portion of wall. These elements are connected between them by planes of cracking (Figure 3.c).
The works of Martini (1998) are based on a discrete-crack approach of micro-model type: brick units are elastic eight-node elements and joints are modelled using contact-interface elements. Results have shown that finite element modelling allows capturing the out-of-plane behaviour of masonry walls. Nevertheless, the modelling approach developed by Martini (1998) is computationally intensive and loads are only statically applied. Moreover the influence of parameters controlling the failure should be checked through a parametric study.

“UNIT AND INTERACTION” CONCEPT
When developing the numerical model, we decide to select the micro-model approach. This methodology offers the advantage to permit a precise representation of the material. Furthermore, as the method allows representing joint as zone of potential weakness, it is the adequate tool to understand the local behaviour. Finally, results obtained by Martini (1998) with his micro-model approach encourage us to continue in this way.

The “unit and interaction” concept developed for the numerical part of this research project is based on an alternative micro-model reported as “simplified micro-model”. This approach represents every brick unit separately as a classic micro-model but the effects of mortar are imposed by laws of contact between the units. The units are modelled with an extended volume so as to respect the geometry of the masonry element. This model constitutes a good alternative in the case of masonry with a regular pattern, for which the volume of mortar is low with regard to that of brick units. The approximation is acceptable, as far as the properties of the interface are correctly replicated. The choice of contact laws represents the biggest difficulty of the modelling; it can be achieved by the use of specific devices like Casagrande direct shear box allowing an experimental determination of joint behaviour.

The main advantage of the “unit and interaction” concept concerns their efficiency in terms of model construction and computation. Moreover, as bricks can be modelled as rigid body, it becomes possible to treat very large models. Finally this modelling method is intuitive: failure occurs in joints which is consistent with the “strong units – weak mortar” masonry type. Another significant advantage is the reasonable demand in computing resources of this modelling method.

ILLUSTRATION OF THE MODEL TO CAPTURE OUT-OF-PLANE BEHAVIOUR
In order to illustrate the applicability of the “unit-interaction” concept for capturing the behaviour of out-of-plane loaded masonry walls, experimental devices were reproduced in SIMULIA (Dassault systems) in accordance with the assumptions defined in the pre-mentioned concept. The three types of bending that can occur when two-way out-of-plane loading takes place should be inspected.
The first validation concerns the horizontal flexion. It is based on the experimental devices developed by Willis et Al. (2004) to validate their mathematical model predicting the resistant moments (fissuring, ultimate and residual).

The horizontal bending test specimens of Willis et Al. (2004) are 3.5 units long and six courses high (Figure 4.a). Bricks have nominal dimensions of 230 x 114 x 65 mm. Joints are made with normal Portland cement, hydrated lime and washed red bricklayers sand in proportion of 1:2:9. They are 10 mm thick. Span between supports is 800 mm and distance between loading lines is 250 mm. This loading configuration induces constant bending moment and zero shear force in the central region of the panel (Figure 4.b). Four springs attached at the reaction frame and placed at the top of the test specimens allow applying vertical compressive stress to the wall. During the test campaign, four levels of compressive stress have been applied (0; 0.075; 0.15 and 0.25 N/mm²). At the interface with floor and spring, sliding surfaces are realized with two Teflon sheet with grease between them. The corresponding coefficient of friction has been found to be approximately 0.053.

![Figure 4: a: Horizontal bending test device; b: loading configuration; c: front elevation view of horizontal bending test specimen and highlight of crack pattern (picture from Willis et Al., 2004)](image)

This horizontal bending test device is modelled on the assumptions of the “unit and interaction” model in the SIMULIA finite element program, respecting the specifications of the original system (geometry, property, boundary conditions …). Length and height of the bricks are adapted to the non-representation of joints and enlarged of one joint thickness in order to respect the geometry of the test specimens. In the “unit and interaction” model, bricks units are represented by solid rectangular volume with a high module of elasticity. Specific contact laws are used to model the interface between the brick units. From the point of view of the tangential behaviour, a method of penalty is applied in a classic model of Coulomb with a specific coefficient of friction. A condition of not penetration with separation authorized after the contact is chosen to represent the normal behaviour. These modelling choices were recently used in the study of masonry arches, healthy or affected by structural defects by Van Parys (2008): this work duly validates, analytically and experimentally, the numerical model. The simulation of different configurations, such has been done in this illustrative example, has permit to refine the model characteristics (characteristics of joints
(type of contact), mode of application of loads...) and the most convenient characteristics were retained for further simulations. A view of the horizontal bending model is shown in Figure 5.

![Figure 5: Horizontal bending test device modelled in SIMULIA](image)

The numerical simulations carried out with the proposed modelling approach give results comparable to those obtained by Willis et Al. (2004). Deformations and failure modes are consistent with those of experimental device: a single stepped crack develops along the entire height of the test specimen, between the loading lines (Figure 6). Note that in the experimental specimen, the crack passes through one of the bricks which can be explain by a local weakness of this last one. The possibility of occurrence of this phenomenon has not been reproduced in our numerical model.

![Figure 6: Results of the numerical simulation: a: Deformation of the wallet; b: Front elevation view of the whole model and highlight of cracking](image)

This illustrative example highlights the capacity of the “unit and interaction” concept to capture the URM behaviour under horizontal bending and the involved resistant mechanisms.

At time of writing this paper, the analysis of the influence of various parameters and researches concerning the diagonal and vertical bending are in progress and provide encouraging results.
APPLICATION TO URM WALLS SUBJECTED TO OUT-OF-PLANE LOADS
The aim of this research project is to define failure mechanisms susceptible to occur in out-of-plane masonry walls under seismic loads. The previous illustration has permit to show that the “unit and interaction” concept is convenient to capture the out-of-plane behaviour of unreinforced masonry and researches in progress about diagonal and vertical bending tend to confirm it. With a wealth of these results, the concept was applied to two cases study of two-way out-of-plane bending URM walls.

The first model is a wall of 8 by 8 masonry units of 300 x 200 x 140 mm, corresponding to a piece of wall of 2,4 x 1,6 m. Brick units are ordered according to a half-brick joint pattern. The wall is embedded on four sides. To represent the initial stress state, but also to activate contact between brick units, in-plane precompression is applied. An out-of-plane uniformly distributed pressure is then gradually applied to the all surface of the wall until failure.

As a result of out-of-plane pressure, the wall bulges. At ruin, the wall developed a failure mechanism. This mechanism can be highlight by observation of the maximal principal stresses on the front side of the wall and of the minimal principal stresses on the back side (where the out-of-plane pressure is applied) (Figure 7). Angles of the walls seem to impose a restraint; out-of-plane deformations are lower at these locations. Based on these observations, it is possible to rough out a representation of the mechanism (Figure 8.a). This last is close to the one classically predicted by the yield line theory of Johansen (Save, 1983) for 4-edge embedded wall (Figure 8.b).

Figure 7: a: Front elevation view of maximal principal stresses; b: Back elevation view of minimal principal stresses
A second model of 20 by 21 bricks units was developed in a similar way. In this model, the failure mechanism, similar to the preceding, is more obvious to discern. As previously, observation of the maximal principal stresses on the front side of the wall and of the minimal principal stresses on the back side permit to emphasize the mechanism (Figure 9). The restraint imposes by angles is more visible in this case. A representation of the failure mechanisms is given in Figure 10.

These two applications illustrate the applicability of the “unit and interaction” concept to represent the two-way out-of-plane behaviour of URM walls. This methodology will allow studying the influence of parameters such as the ratio expressing the dimensions of the bricks with regard to the dimensions of the wall and the various others parameters having been identified as controlling the failure (slenderness of the wall, boundary conditions...).
CONCLUSIONS AND OUTLOOK
The “unit and interaction” concept developed for this research has been applied to an illustrative example of horizontal bending and has shown its capacity to capture the out-of-plane behaviour of masonry walls. The concept was then applied to two cases study of two-way out-of-plane bending. In the two cases, observations of deformations of the wall and stresses permit to identify a failure mechanism similar to those predicted by the yield lines theory. This parallel with the yield line analysis had already been observed (Hamid, 2003, Martini, 1998, Vaculik et Al., 2010; Sinha, 1978) and will be discussed in the analytical part of this research project. Based on results of numerical analysis and yield line analysis, an analytical replication will be proposed in the following of the research project.

Until now the validation of the “unit and interaction” concept to capture the two-way out-of-plane behaviour of masonry has only concerned the horizontal flexion; diagonal and vertical flexion remain in progress. When the 3 flexion types will have been validated, the efficiency of the “unit and interaction” concept for representing the phenomena connected to the out-of-plane failure of masonry walls will be entirely established. Behaviour of two-way out-of-plane bending walls and influence of various parameters controlling the failure could then be numerically investigated. The mains parameters that will be consider are the ratio of dimensions of the wall / dimensions of the bricks units, the boundary conditions (with for example consideration of in-plane wall, floor and roof) and the mode of load’s application (statically, cyclically, dynamically...).

Based on results of the numerical study, the research aims to develop an analytical model to predict the out-of-plane strength of an URM wall. Experiments planned will allow verifying to accuracy of results of the numerical and analytical models.

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