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A Study of the Out-of-Plane Behaviour of Unreinforced Masonry Walls using a "Unit and Interaction" Micro-Modelling Approach

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Abstract

Unreinforced masonry (URM) buildings represent a significant part of historic structures but this type of construction is also widely used in contemporary buildings. This large usage is made despite their well-known vulnerability to lateral actions 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 out-of-plane solicitations. The proposed study is carried out using a finite element (FE) micro-modelling approach (SIMULIA – Dassault System) based on a "unit and interaction" concept. After the introduction, the "unit and interaction" concept is detailed, outlining strong and weak aspects and highlighting the particular interest for studying the effect of out-of-plane actions. This paper then proposes a validation of the accuracy of the model to capture the out-of-plane behaviour of masonry components. In this framework, the paper demonstrates the ability of the model to capture the horizontal, vertical and diagonal bending behaviour by numerically reproducing experimental features. Finally, the paper outlines how the results of these preliminary studies would thereafter be used in the analysis of walls subject to two-way bending, where similar failure mechanisms contribute to the overall wall behaviour.

Keywords: out-of-plane loads, unreinforced masonry, numerical simulation, unit and interaction, micro-modelling, contact laws

1 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 [1].

This research project aims to study the two-way out-of-plane behaviour of URM walls under dynamic loading. It targets 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 and the validity of both the calculation approaches will be established by comparison with experimental results.

This paper presents the early steps of the research as well as preliminary results concerning the validation of the numerical modelling.

2 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 [2]. The vulnerability of masonry walls towards out-of-plane actions is related to 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 [2].

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 applied loads on dead loads ratio and the peak velocity demand (in the case of seismic loads) at the base and the top of the wall [3,4].

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) [5] that have to be taken into account.

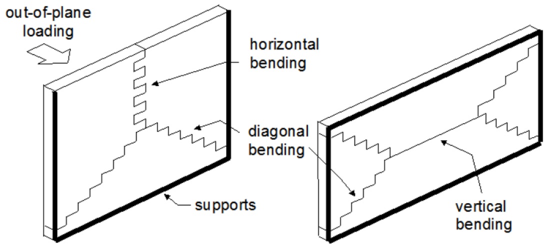
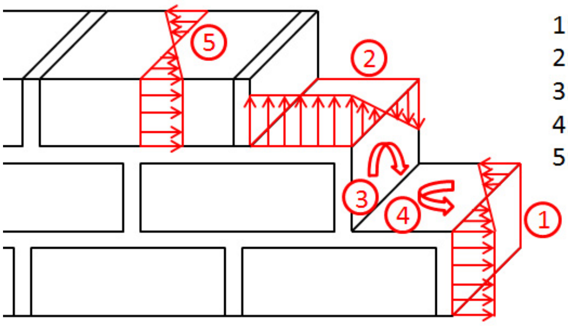


Figure 1: Various bending in a wall under out-of-plane loads (picture from [5])

Different strength aspects are involved in the development of a vertical, horizontal or diagonal crack line. These aspects are the flexural tensile strength of head joints, the flexural tensile strength of bed joints, the torsional and frictional capacity of head joints, the torsional and frictional capacity of bed joints and the lateral rupture strength of brick units (Figure 2) [6].



1: flexural tensile strength of head joints
2: flexural tensile strength of bed joints
3: torsional and frictional capacity of head joints
4: torsional and frictional capacity of bed joints
5: lateral rupture strength of brick units

Figure 2: Strength aspects involved in horizontal, vertical and diagonal bending

Under horizontal bending, 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 3.a1). 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 3.a2). 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 [6].

The failure mode associated with diagonal bending is characterized by the occurrence and the propagation of a diagonal crack in the wall, following head and bed joints (Figure 3.b). The strength aspects involved in the development of a diagonal crack line are the flexural tensile strength of head joints, the flexural tensile strength of bed joints, the torsional and frictional capacity of head joints and the torsional and frictional capacity of bed joints [6].

When vertical bending occurs, a horizontal crack develops. The sole strength aspect involved in the apparition of this type of crack is the flexural tensile strength of bed joints (Figure 3.c).

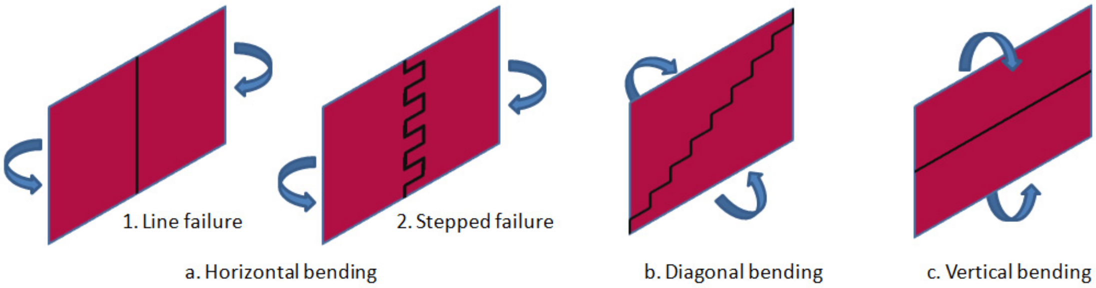


Figure 3: a: Horizontal bending (1: line failure; 2: stepped failure); b: Diagonal bending; c: Vertical bending

3 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 [7, 8]. Based on results obtained by finite element simulations, Martini [8] 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 [5, 6, 9].

Depending on the required level of complexity and the objectives to achieve, various strategies of modelling of the masonry may be proposed [10].

- **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 4.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 4.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 4.c).

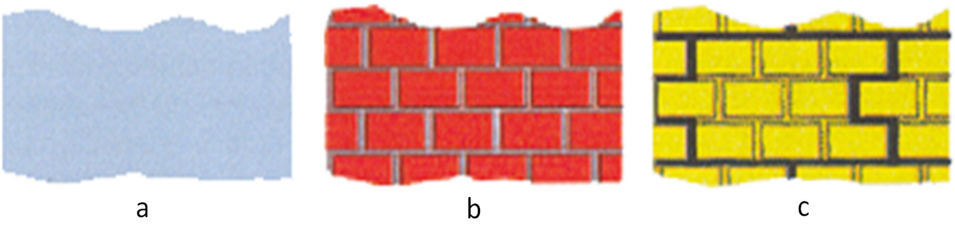


Figure 4: a: macro-model; b: detailed micro-model; c: meso-model (picture from [10])

The works of Martini [8] 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 [8] is computationally intensive and loads are only statically applied. Moreover the influence of parameters controlling the failure should be checked through a parametric study.

4 “Unit and Interaction” concept

When developing the numerical model, the authors decide to select the micro-model approach. The micro-modelling philosophy, impressed by a generalist character, appears to be closer to the reality. Indeed, the opportunity to take the effective unit-joint pattern into account prevents any handicap induced by morphological assumptions and the opportunity to define low level interactions between units avoids the usage of unique constitutive laws for replicating a complicated reality. Moreover, results obtained by Martini [8] with a micro-model approach are encouraging.

The authors transpose, for achieving an efficient prediction of the out-of-plane behaviour of masonry walls, a modelling philosophy initially developed for the yield calculation of masonry arch systems submitted to complicated actions [10]. The concerned “unit and interaction” (U&I) philosophy may be reported as a simplified micro-model approach. The micro-modelling approach has the interest, for replicating the behaviour of a masonry material, to effectively model each masonry unit with respect to the effective unit-joint pattern and to bring the highest care in managing the interactions between them. This approach is recognized to be a smart 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 innovative character of the numerical modelling approach which is proposed here concerns the recourse to specific contact laws for managing the manner whose adjacent units will interact together.

4.1 Modelling the units

In the proposed approach, each masonry unit has to be effectively modelled, according to its effective morphology. Depending on the objective, the units may be modelled either as rigid or deformable bodies. The use of **rigid bodies** constitutes a response to commonly encountered problems where the structural behaviour of the system is not handicapped by the characteristics of the constitutive material of the units (sufficient material stiffness to prevent deep influence of elastic deformations, sufficient material strength to prevent deep influence of crushing, ...). In such classical cases, the Ultimate Limit State response of the masonry wall may properly be obtained by assuming a rigid behaviour for the masonry units (limiting the number of degrees of freedom to be considered and allowing sensitive gains in computational efficiency). The recourse to **deformable bodies** for modelling the masonry units leads to the opportunity to propose a constitutive model for the material of the units. This material model could be elastic but also inelastic with, in this case, constitutive models which could be either simple (conventional Mises model, conventional Drucker-Plager model, ...) or quite more sophisticated (innovative Barcelona Model to model damage in compression or in tension, ...) with each time the possibility to consider either isotropic or anisotropic materials. Such possibilities allow to investigate less classical cases where the characteristics (stiffness, damage, ...) associated to the constitutive material of the masonry unit are likely to influence deeply the behaviour of the masonry wall. Besides, the recourse to deformable bodies may also provide practical Serviceability Limit State information's those are complementary to the Ultimate Limit State assessment data: the computation of strain and stress fields inside the system allows a comfortable visualization of the internal state of a structure or to compare results obtained by numerical simulations with on-site testing results. Nevertheless, the quality of such FE solutions being dependent on the mesh quality, the number of degree of freedom to manage (now dependent on the effective shape or size of the units) will significantly increase the computational costs.

4.2 Modelling interactions between units

The proposed approach will manage the interactions between adjacent units by relying on contact laws. These laws will govern the behaviour of interface based on the local normal and shear stress states. The basic normal and tangential behaviours for interfaces may be seen as the replication of a dry joint connection between units that represent the lowest level of complexity. Further than the fact that such a configuration is commonly encountered, it also constitutes a safe approximation for the structural assessment of any masonry system composed with mortar joint connection: neglecting any bond strength and any shear strength will lead to respectively underestimate the normal and the tangential capacities of a joint. In practice, the modelling of dry joint connections has mostly to fulfil three types of requirements: two for the normal component and one for the tangential component. The normal behaviour of the interface is, on one hand, governed by the character of non-penetration between adjacent units that will impose the value of the interfacial pressure in relationship with the overclosure between the concerned surfaces. The "hard contact model" establishes the relationship in such a way: adjacent surfaces transmit no contact pressure while the contact is not established (overclosure greater than zero) but, once the contact is established (overclossure less or equal to zero), no limit is imposed for the magnitude of the transmitted contact pressure (Figure 5). It is, on the other hand, governed by the character of separation that should be remained possible once contact has occurred (the units will not become stuck). The tangential behaviour of the interface is governed by a friction model that may be of several types. The "rough friction model" will prevent the occurrence of any sliding motion between the contacting surfaces while the "Coulomb's friction model" will enable the occurrence of sliding on the basis of a friction coefficient.

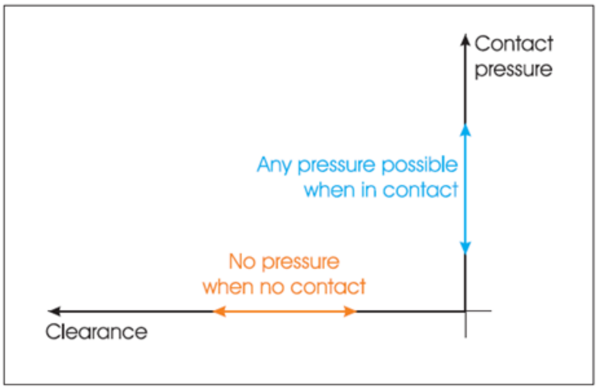


Figure 5: Hard contact model

Further than these basic possibilities of interaction modelling, it is possible to think about several opportunities of extension for both the normal and the tangential behaviour of the interfaces. Such extensions allow replicating advanced behaviour, making this way the model to appear as more realistic. The normal behaviour of the interface may be enriched by taking some bond strength into account: some possibilities of tensile stresses transmission normally to the joint may initially be foreseen until a given tensile strength bound is reached, allowing replicated the bond action of a mortar between adjacent units. Once the tensile strength bound has been reached, the model of the interface is assumed to follow a classical "hard contact model". The tangential behaviour of the interface may be enriched by taking some shear strength into account: the possibility of shear stresses transmission may initially be foreseen until a given shear strength bound is reached, allowing to replicate the bond action of a mortar between adjacent units. Once the shear strength bound has been reached, the model of the interface is assumed to follow the classical "Coulomb's friction model". Complementary possibilities are also available for more particular purposes: "contact stiffness characterization" if thick layers of soft mortar, "contact damping characterization" if dynamic actions, ...

Such a contact-based interface approach can be used either in bi- or tri- dimensional modelling spaces. It appears to be properly adapted for the problem treated in this study: for structural assessment operations, it could appear interesting to consider basic contact laws (neglected shear strength, neglected bond strength, ...) which will usually be sufficient for a proper replication of the behaviour and which are likely to become enriched if required (reduced bond strength, reduced shear strength, ...). In parallel, such a contact-based approach is associated to notions of great flexibility (pair contact or general contact, ...) and will typically be dedicated to take sliding occurrence into account. This is useful as the numerical modelling approach proposed here is aimed to be complementary to an analytical approach which will hardly take this phenomenon into account. Moreover, this modelling method is intuitive: failure occurs in joints which is consistent with the classical "strong units – weak mortar" masonry type. Considering these points, the method appears likely to identify the effective failure mode susceptible to occur (taking into account the morphology, the boundaries…). Besides, the "unit and interaction" concept offers the great advantage to be efficient in terms of model construction and computation. Furthermore, as bricks can be modelled as rigid body, it becomes possible to treat very large models.

5 Illustration of the model to capture out-of-plane behaviour

In order to illustrate the applicability of the "unit and interaction" concept for capturing the behaviour of out-of-plane loaded masonry walls, experimental devices were numerically reproduced 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 have to be inspected.

The practical realisation of numerical simulations with the proposed modelling approach requires opting for reliable FE software. In the context of the present research, it is proposed to rely on SIMULIA (Dassault systems) that is worldwide recognized for its robustness and the powerful facilities it embodies. In parallel, the coupling opportunities it offer at both the input and output levels with various programming environments also plead in its favour (such couplings could reveal of great interest in the context of externally piloted treatments).

5.1 Modelling criteria

Three bending test devices, one for each type of bending (horizontal, vertical and diagonal) were modelled on the assumptions of the "unit and interaction" concept in the SIMULIA finite element program, respecting the specifications of the original systems (geometry, property, boundary conditions …). Length and height of the bricks are adapted to the non-representation of joints and enlarged of one joint thickness so as to respect the geometry of the tests specimens.

In order to have the opportunity to analyse the stresses and strains evolution during the loading but also to compare results obtained by numerical simulations with experimental data, bricks are represents as deformable bodies with an elastic constitutive model. Interactions between units are managed in the safer approximation of dry joint connection: normal behaviour is represented by a condition of not penetration with separation authorized after the contact and tangential behaviour is handled by a method of penalty applied in a classic model of Coulomb with a specific coefficient of friction.

For the three cases, several types of loading should be taken into account along the loading history: three main steps have to be considered. The self weight is the component that will be applied on the system within a first step; it will activate the contact-based interfaces and then provide a structural character to the collection of bodies. Further than this modelling consideration, this loading reveals itself essential as it induce a vertical pre-compression in the wall. An eventual permanent loading constitutes a component to be applied on the system within a second step. It concerns loads whose effects are permanently applied on the system (supplementary vertical pre-compression due to the weight of upper floor for example). The live loads are applied on the system within the last step (out-of-plane loads in the case of this study). The structural assessment intends to estimate the effects of these loads towards the collapse of the wall.

5.2 Horizontal bending

The first validation concerns the horizontal flexion. It is based on an experimental device developed by Willis [6] (Figure 6) to validate his mathematical model predicting the resistant moments (fissuring, ultimate and residual).

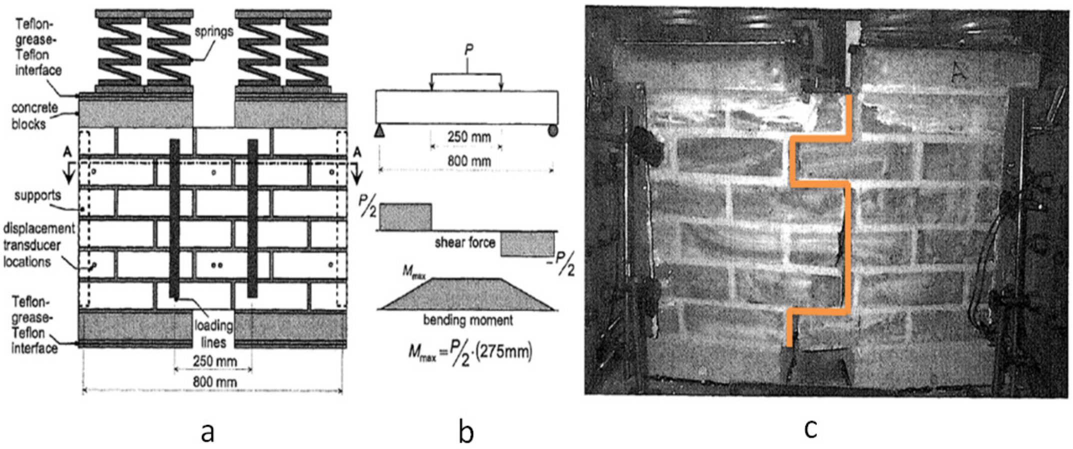


Figure 6: a: Horizontal bending test device; b: loading configuration; c: front elevation view of horizontal bending test specimen and highlight of crack pattern (picture from [6])

Numerical simulations carried out with the proposed modelling approach [14] give results comparable to those obtained by Willis [6]. 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 7).

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.

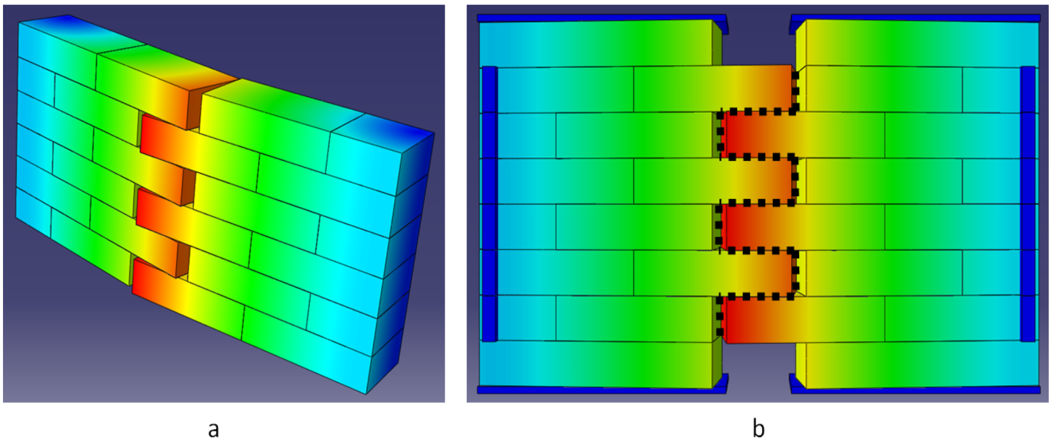


Figure 7: Results of the numerical simulation: a: Deformation of the wallet; b: Front elevation view of the whole model and highlight of cracking

5.3 Vertical bending

It is known that, whatsoever in 3- or 4-points bending or even in distributed bending, under vertical bending, a masonry wall ruin by the occurrence of a horizontal crack developing along a horizontal joint, about at mid-height of the wall [11, 12, 13] (Figure 8).

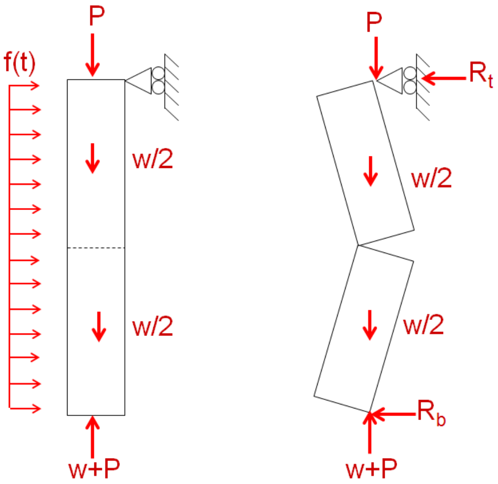


Figure 8: Failure mode under vertical bending

In order to validate the accuracy of the “unit and interaction” concept to correctly replicate this failure mode, a wallet of 4 units large and 8 units height was modelled in SIMULIA and loaded in 4-points bending (Figure 9a).

In this loading configuration, bending moment being constant between the loading lines, the three bed joints located at this place have the same probability to open. It is exactly what can be observed as result of the numerical simulation carried out in SIMULIA: three horizontal cracks develop, with similar aperture, in the three horizontal joints located between the loading lines (Figure 9b).

Note that in general, only one single crack is observed in experimental investigations or considered in analytical study. Concerning the experimental aspect, the occurrence of a single crack can be explained by the fact that the crack occurs and develops in the weakest joint (joint presenting a local weakness). If all joints were strictly identical (thickness, composition, adherence with units, implementation ...), multiple cracks could also occur. With regard to the analytical aspect, in an analysis of yield line type analysis, an infinite number of failure mechanisms are possible, but only one is retained which correspond to the opening of the crack which leads to the greater energy dissipation.

Taking these considerations into account, it can be considered that the "unit and interaction" model is well able to capture the behaviour of a masonry wall under vertical bending.

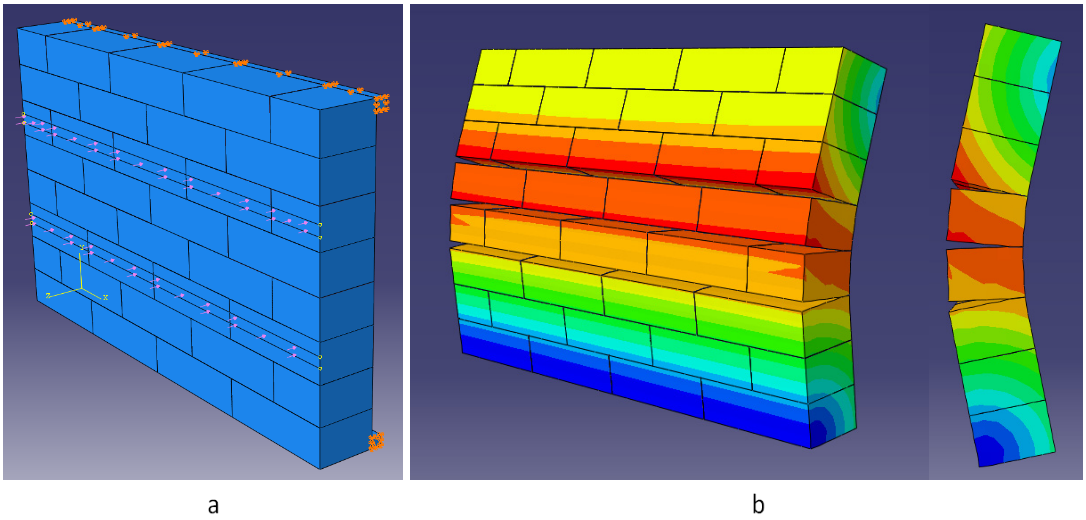


Figure 9: Vertical bending: a: Front view of the numerical model and the out-of-plane loads; b: Back and profile view of the failure mode obtained by numerical simulation

5.4 Diagonal bending

The third validation, based on an experimental device developed by Griffith et Al. [4], concerns the diagonal bending.

The diagonal bending test specimens of Griffith et Al. [4] are 3 units long and 5 courses high (Figure 10). 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. The orientation of supports and loading lines has been chosen parallel to the diagonal pattern of the wallet. Span between supports is 365 mm and distance between loading lines is 140 mm. This loading configuration induces constant bending moment and zero shear force in the central region of the panel. Tests were performed in a horizontal orientation. A view of the test specimen after testing is shown in Figure 11.

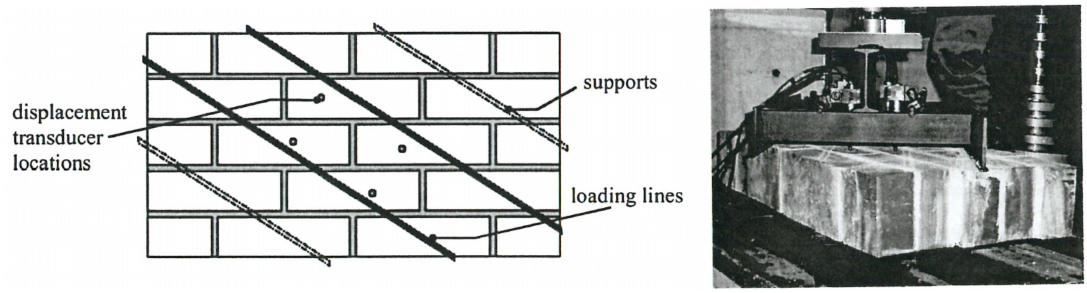


Figure 10: Diagonal bending test arrangement (picture from [4])

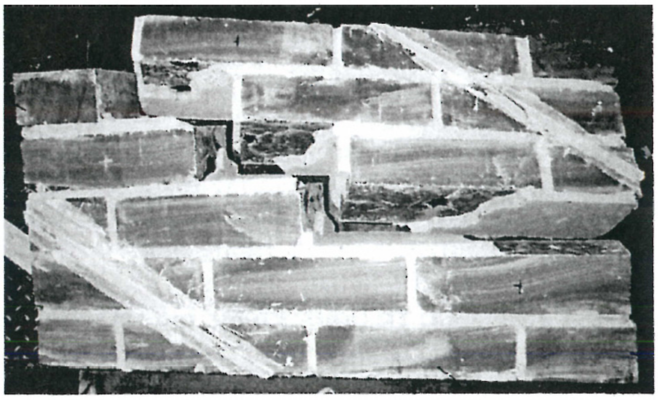


Figure 11: Diagonal bending specimen failed specimen (picture from [4])

This experimental device was modelled in SIMULIA, according to the modelling criteria detailed in paragraph 5.1 and respecting specifications of the original wallets. The only difference between the experimental device and the numerical model reside in the application of an in-plane pre-compression: any in-plane pre-compression was applied during the test while the application of this latter is necessary in the numerical model in order to activate contact between units. However, the low intensity of the in-plane pre-compression needed to activate these contacts does not lead consequences for the out-of-plane failure of the wall specimen.

As it can be observed by comparing Figure 11 and Figure 12b, results (deformations and failure modes) obtained by the numerical modelling are comparable to those obtained by the experimental approach: a single crack propagates along bed and head joints between the loading lines.

Note that in the experimental specimen, the crack does not propagate along bed and head joints in the lower right corner. This could be explained by a local variation in the mortar strength of the specimen [4].

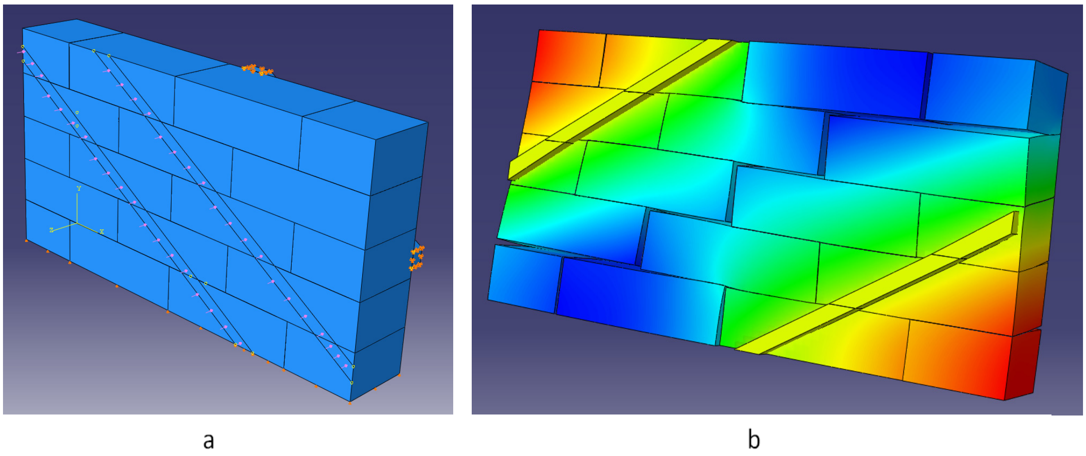


Figure 12: Diagonal bending: a: Front view of the numerical model and the out-of-plane loads; b: Back view of the failure mode obtained by numerical simulation

These three illustrative examples highlight the capacity of the "unit and interaction" concept to capture the URM behaviour under horizontal, vertical and diagonal bending and the involved resistant mechanisms.

Unfortunately, lacking of complete tests data, only a qualitative comparison on failure and deformation modes was possible. In order to palliate to this and to be able to perform a quantitative comparison, the authors are carrying out an experimental campaign on the three types of bending explained above.

Test specimens are 5.5 units long and 14 courses high. Bricks have nominal dimensions of 188 x 88 x 63 mm; of "Wanlin rouge plein" type. Joints are made with a dry mortar cement based (Portland cement) ready to prepare, strength class M5 (according to EN-998-2). They are 10 mm thick. Wallets are loaded on a 4-point bending configuration. Span between supports is one metre and distance between loading lines is 400 mm. This loading configuration induces constant bending moment and zero shear force in the central region of the panel. Supports and loading line can be turn vertically, horizontally or diagonally in order to test the three types of bending. A vertical pre-compression could be applied by 2 weights on lever arms system that press to the wall via a distribution beam in order to have a uniformly distributed pressure at the top of wall. This system allows applying the exact desired pre-compression in the wall. A photograph of the test device in vertical bending configuration is shown in Figure 13.

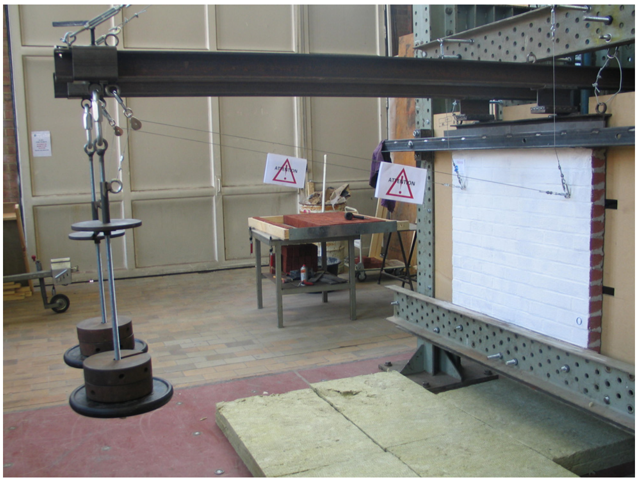


Figure 13: Experimental device in vertical bending configuration

6 Further investigations ... towards generalization

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 illustrations have permit to show that the "unit and interaction" concept is convenient to capture the out-of-plane behaviour of unreinforced masonry. 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 pre-compression 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 14). 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 15.a). This last is close to the one classically predicted by the yield line theory of Johansen [15] for 4-egde embedded wall (Figure 15.b).

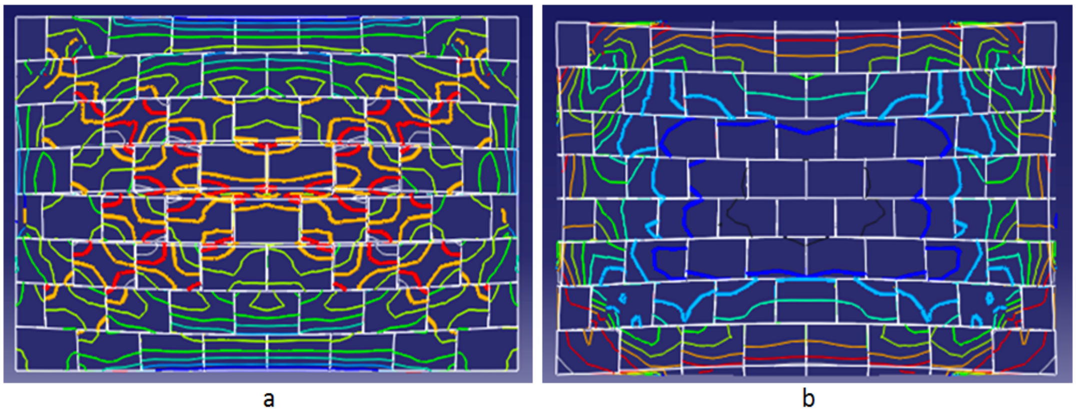


Figure 14: a: Front elevation view of maximal principal stresses; b: Back elevation view of minimal principal stresses

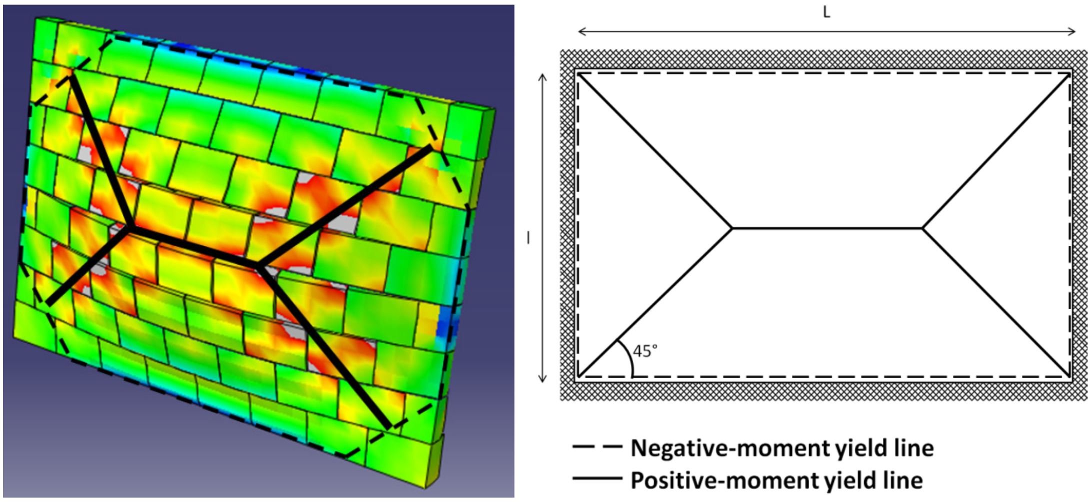


Figure 15: a: Failure mechanism obtained by numerical simulation for the 8x8 bricks wall; b: Failure mechanism according to the Johansen's theory for a 4-edge embedded wall

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 16). The restraint imposes by angles is more visible in this case. A representation of the failure mechanisms is given in Figure 17.

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...).

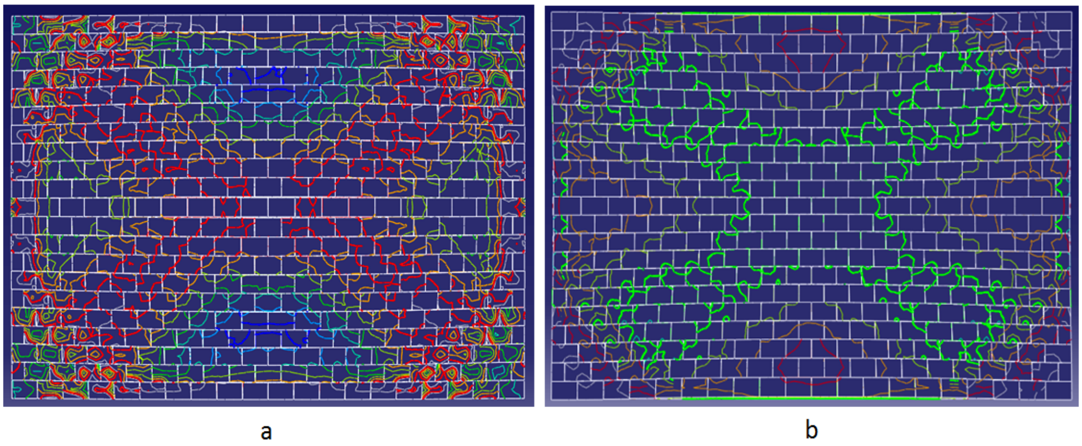


Figure 16: a: Front elevation view of maximal principal stresses; b: Back elevation view of minimal principal stresses

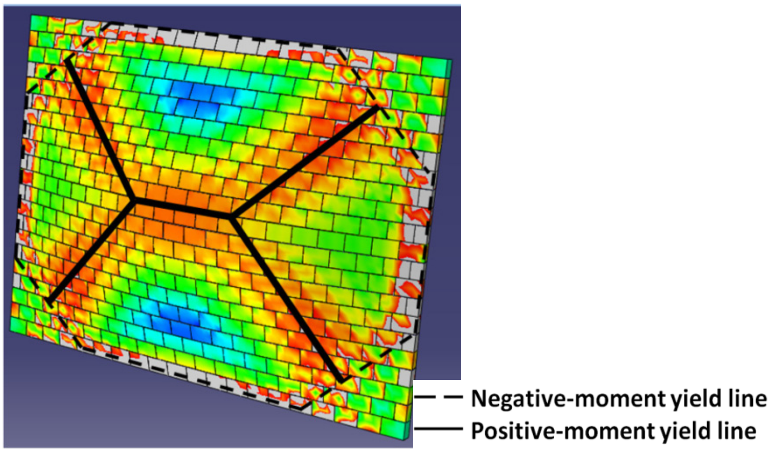


Figure 17: Failure mechanism obtained by numerical simulation for the 20x21 bricks wall

7 Conclusion and outlook

The “unit and interaction” concept developed for this research has been applied to illustrative examples of horizontal, vertical and diagonal bending and has shown his capacity to capture the three bending failure modes involved in the out-of-plane behaviour of masonry walls. The forthcoming comparison of numerical simulations with results of the experimental investigations currently carried out by authors will allow calibrating parameters of the model and definitively checking the accuracy of the “unit and interaction” concept to represent the phenomena connected to the out-of-plane failure of masonry walls.

The first results of numerical studies on the three phenomena involved in the out-of-plane failure being encouraging, the concept was 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 considered [5, 7, 8, 9] and will be addressed in the analytical part of this research project. The aim of the analytical studies is to develop an analytical model able to predict the out-of-plane strength of an URM wall.

Future phases of the numerical and analytical parts of this research project will study the influence of mains parameters that will be influence the resistance of wall towards out-of-plane loads. These main parameters are the ratio of dimensions of the wall on the 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, *etc.*).

References

[1] Paulay, T., Priestley, M.J.N., "Seismic design of reinforced concrete and masonry buildings", J. Wiley, 1992.

[2] Yi, T., Moon, F.L., Leon, R.T., Kahn, L.F., "Progress report: Large-scale tests of low-rise unreinforced masonry building system", Georgia Institute of Technology, Department of Civil and Environmental Engineering, Atlanta, 2002.

[3] Elmenshawi, A., Sorour, M., Parsekian, G., Duchesne, D., Paquette, J., Mufti, A., Jaeger, L., Shrive, N., "Out-of-plane dynamic behaviour of unreinforced Stone masonry", Proceedings of the 8th International Masonry Conference, pp. 1643-1652, Dresden, 2010.

[4] Griffith, M. C., Lawrence, S. J., Willis, C. R., "Diagonal bending of unreinforced clay brick masonry", Journal of the British Masonry Society Masonry International, Vol. 18, N°3, 2005.

[5] Vaculik, J., Griffith, M., Magenes, G., "Collapse load predictions for masonry walls in bending", Proceedings of the 8th International Masonry Conference, pp. 1243-1252, Dresden, 2010.

[6] Willis, C.R., "Design of unreinforced masonry walls for out-of-plane loading", Doctoral Ph.D. Thesis, University of Adelaide, 2004.

[7] Hamid, A., "Cyclic response of masonry elements, International short-course on architectural design of masonry", CEMA, Dresden, 2003.

[8] Martini, K., "Finite element studies in the two-way out-of-plane failure of unreinforced masonry", Proceedings of the 6th National Conference on Earthquake Engineering, Seattle, 1998.

[9] Sinha, B. P., "A simplified ultimate load analysis of laterally loaded model orthotropic brickwork panels of low tensile strength", The Structural Engineer, vol 56B, N°4, December 1978.

[10] Van Parys, L., "A contribution to the structural assessment of masonry arch systems with a focus on their behaviour towards springing displacements", Doctoral PhD Thesis, Polytechnic Faculty of Mons, 2008.

[11] Doherthy, K., Griffith, M.C., Lam, N., Wilson, J., "Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls", Earthquake engineering and structural dynamics, vol. 31, pp. 833-850, 2002.

[12] Abrams, D. P., Angel, R., Uzarski, J., "Out-of-plane strength of unreinforced masonry infill panels", Earthquake Spectra, vol. 12, n°4, pp. 825-844, 1996.

[13] Derakhshan, H., Ingham, J. M., Griffith, M. C., "Tri-linear force-displacement models representative of out-of-plane unreinforced masonry wall behaviour", 11th canadian masonry symposium, 2009.

[14] Bultot, E., Van Parys, L., "Numerical simulation of URM walls subjected to out-of-plane solicitations using a "unit and interaction" micro-modelling approach", provisionally in the Proceedings of the 15th International Brick and Block Masonry Conference, Florianopolis, Brazil, 2012.

[15] Save, M., "La théorie des charges limites et son application aux maçonneries", Restauration des ouvrages et des structures, pp 249-280, Presses de l'école nationale des ponts et chaussées, Paris, 1983.