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MICRO MODELLING FOR OUT-OF-PLANE BENDING OF MASONRY

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Abstract

The application of the finite element methods (FEM) is common in practice, both for modern structural research and design of the linear behaviour of structural elements. However, such investigations are not as well established for the non-linear structural analysis of masonry structures. The multitude of unit-mortar combinations with very different properties makes a close-to-reality description of masonry structures very difficult.
In order to localize the initiation of cracks in a structure and to investigate the crack development, it is necessary to use finite element models, in which such physical phenomena can be simulated. A complex micro-model, in which all components are individually modelled, lends itself to a comprehensive representation of the realistic structural behaviour of masonry.

Key Words

Numerical simulation, Out-of-plane bending

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1 Introduction

In the current version of the EuroCode 6 (EC 6), two models for the calculation of out-of-plane bending of masonry are included; the arch-model and the panel-model.
The former is used for specific support conditions, which can absorb the thrust forces of the arch to interpolate the panel-shear-stresses. This is the traditional calculation model for load-bearing structures consisting of anisotropic materials. For this type of model it is not important whether the crack initiation is concentrated in a particular part of the structure, such as at the joints in masonry structures, or in the whole structure, as is the case in reinforced concrete structures.
For the panel-model, the longitudinal geometric instability of the support condition is insignificant. The resistance depends only on the flexural and lateral strength of the structure as well as on the support conditions. The panel-model is commonly applied for reinforced concrete and with the introduction of the EC 6, is to be used for masonry. For example, an appropriate application of this model is the calculation of the wind load effects on masonry infill walls.
In the EC 6, bending moment coefficients ‘α’ have been established. These are based on three factors: a) the ratio of the ultimate flexural strength parallel and perpendicular to the bed joints ‘μ’, b) the support conditions at the edges of the walls and c) the height to length ratio of the panel, such as the values of Czerny, Pieper/Martens, Stiglat/Wippel or Herzog. The theoretical basis is, among other things, the yield-line theory from the field of reinforced concrete.
How this principle is applied to masonry structures is critical. Reinforced concrete, as a construction material has a distinct yield behaviour. When the reinforcing begins to yield, plastic moments develop, which remain constant despite the section rotation increasing. These rotations continue until a mechanism develops and the whole structure collapses. The yield-line theory is only valid for sufficiently ductile materials. Masonry, however, has a brittle failure behaviour and softening effect instead of a yield behaviour.
Therefore, the yield-line theory for calculating the structural behaviour of masonry should be reviewed.

2 Numerical models for masonry

The non-linear behaviour of masonry is characterized by the individual components: the masonry units, the mortar and the contact surfaces between them. As a result of the various elements masonry has material properties, which are non-homogeneous and due to the regular bond patterns, highly orthotropic.
The inhomogeneity should be considered during the numerical simulation of the masonry bearing capacity. This can be achieved either with a discrete description of the masonry units, the mortar and the bonding-conditions, i.e. contact surfaces, or with a smeared continuum.

2.1 Macro-model (Smeared continuum)

In a macro-model with a smeared continuum, the masonry is described as an isotropic material and the characteristic properties are ‘smeared’ over the entire masonry structure.

The failure surface, based on Ganz, for such a smeared model is clearly illustrated in Figure 1.

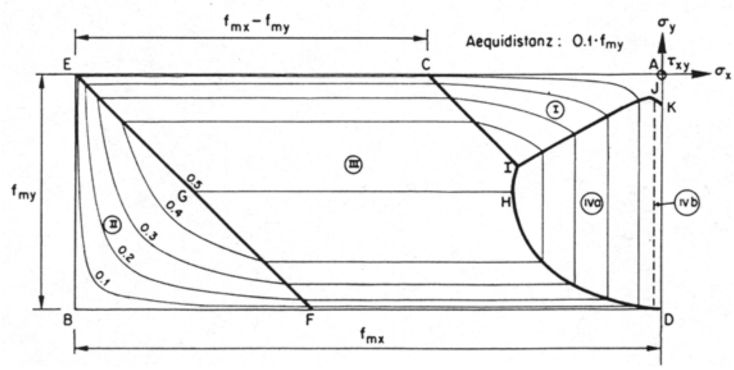

Figure 1. Failure surface for various models based on Ganz

Localized conditions of the characteristic phenomena, such as cracks along the interface, cannot be represented sufficiently nor realistically enough through a homogenisation of the entire surface.

2.2 Micro-model (Discontinuum)

A complex micro-model, in which all components are individually modelled (Figure 2), lends itself to be used for a comprehensive and realistic representation of masonry's structural behaviour. This can be achieved by representing the masonry units and the mortar by means of 3-D finite elements for the numerical simulation. Further, the interface between the masonry units and the mortar is approximated with non-linear interface elements.

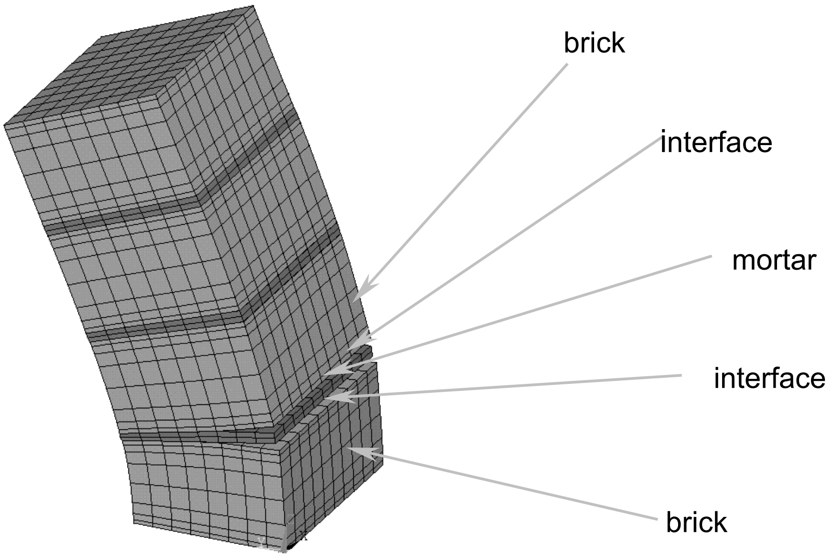

Figure 2. Micro-modelling of masonry

As a result of the various discrete elements, one is not limited to representing only the overall structural behaviour, as is the case with the macro-model. The documentation of the overall crack development as well as of localized cracks can be modelled more realistically through the use of a micro-model.

2.3 Field of application - Macro-model vs. Micro-model

Whether one makes use of a macro- or micro-model, depends on the geometry of the structure, the potential numerical effort and the needed results, i.e. degree of precision required.
For a numerical analysis of a complex masonry structure, the effort for a discrete simulation of the masonry units, the mortar joints and the interface, is not warranted. Particularly, if one's focus is the overall behaviour of the entire structure, such as of a residential house or a natural stone arch bridge.
However for historic masonry structures (Figure 3), for which the material properties usually cannot be clearly determined, the most efficient approach is to use a smeared micro-model for the numerical simulation.

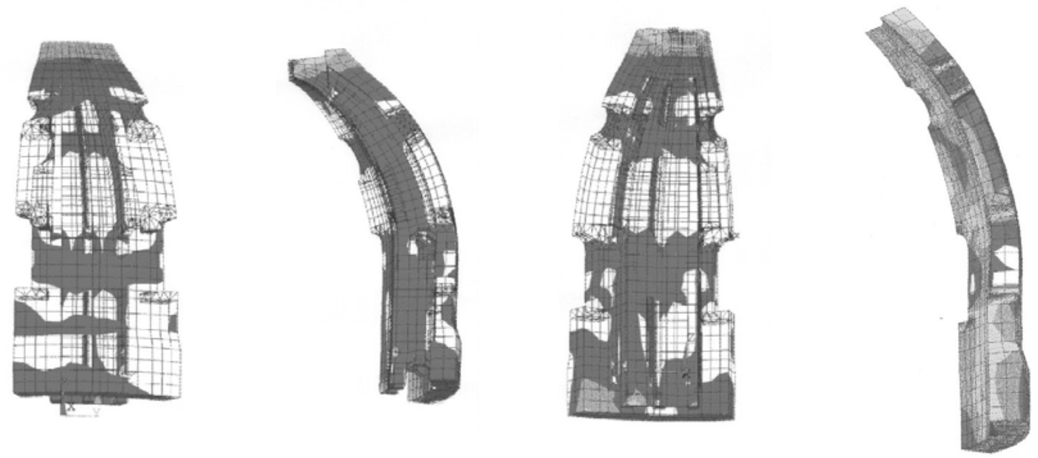

Figure 3. Smeared FEM-macro-model of the Frauenkirche cupola in Dresden, Germany

On the other hand, for research purposes, where one is looking to establish new evaluation methods of modern masonry constructions (Figure 4), the application of a discrete micro-model for the masonry units, the mortar joints and the interface is necessary. In this case the overall behaviour of the masonry construction is not the primary goal. Rather the exact localization of maximum tension zones, cracks along the joints or through the cross-section of the masonry unit and the failure of the interface bond between the unit and the joint is of interest. By focusing on a relatively small portion of a wall and by making use of the inherent structural symmetry, one is able to minimize the numerical effort through the implementation of a discontinuum/discrete model.

Figure 4. Micro-modelling for modern masonry structures

3 Numerical investigation for out-of-plane bending of masonry

3.1 Numerical model – case study

A numerical analysis was conducted for a calcium-silicate masonry panel, which is simply supported on all edges. The support conditions approximate the definition of position E in Annex E of the ENV 1996-1-3.
Figure 5 shows the panel with a uniformly distributed load.

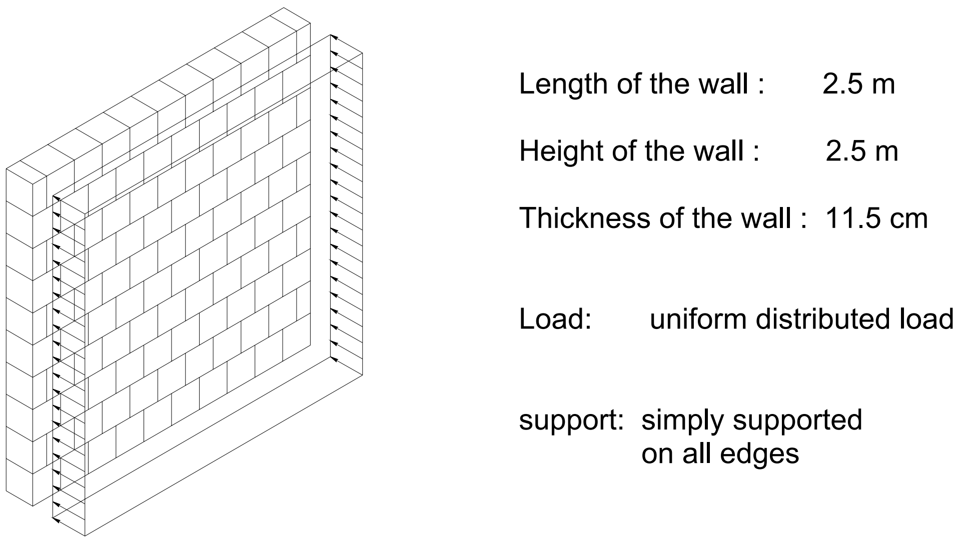

Figure 5. Geometry and loading of the masonry structure

Zur Erfassung aller Einflussgrößen wurden die einzelnen Materialparameter durch ein numerisches Mikro-Model abgebildet.
The fundamental principle for the representation of the material non-linear properties of masonry and mortar joints is based the concrete failure criterion of William and Warnke. The three dimensional failure limit curve is illustrated in Figure 6.

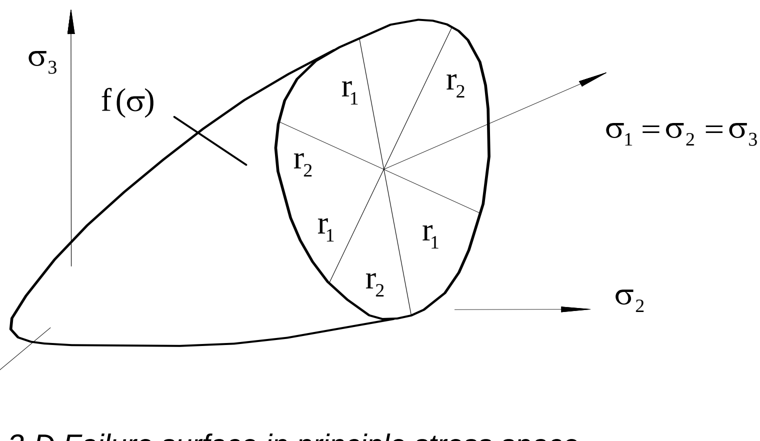

Figure 6. 3-D Failure surface in principle stress space

The accuracy of the non-linear crack-criterion depends on the number of definable parameters for the description of the failure-surface. The brittle failure criterion of William and Warnke is based on a five parameter model in the three-dimensional stress space.

Surface-to-surface contact elements are used for the representation of the contact condition (Figure 7).

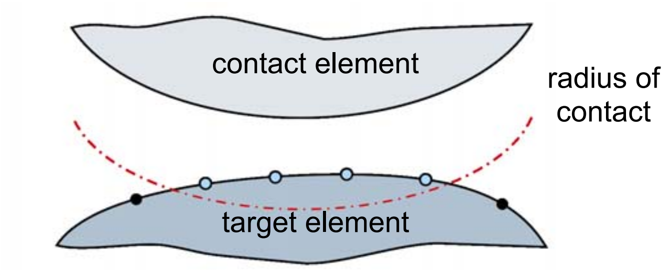

Figure 7. Schematic representation of the surface-to-surface contact elements

A snapshot of the actual contact condition (open/closed), the size and position of the crack opening as well as the current adhesive stresses and adhesive shear stresses, which are transferred across the contact surface, can be visualized for the entire process of the load applications.

The material properties, as shown below, of the masonry units, the thin layer mortar and the bond between the two, were used for the numerical simulation with this micro-model.

Calcium-silicate masonry unit	
Uniaxial compression strength:	26.0 N/mm²
Uniaxial tension strength	1.43 N/mm²
Poisson's ratio	0.18

Thin layer mortar	
Uniaxial compression strength:	15.3 N/mm²
Uniaxial tension strength	1.84 N/mm²
Poisson's ratio	0.28

Bond behaviour between units and mortar	
Adhesive tension strength	0.41 N/mm²
Adhesive shear strength	1.02 N/mm²
Friction coefficient	0.32

3.2 Results

The bearing capacity of masonry panels under lateral loading was investigated for numerous height to length ratios. The analysis was verified with selected experimental tests, i.e. for selected aspect ratios and materials.

Figure 8 shows the maximum principle tension stresses in the masonry panels for an aspect ratio of h/l = 0.67 and h/l = 1.67.

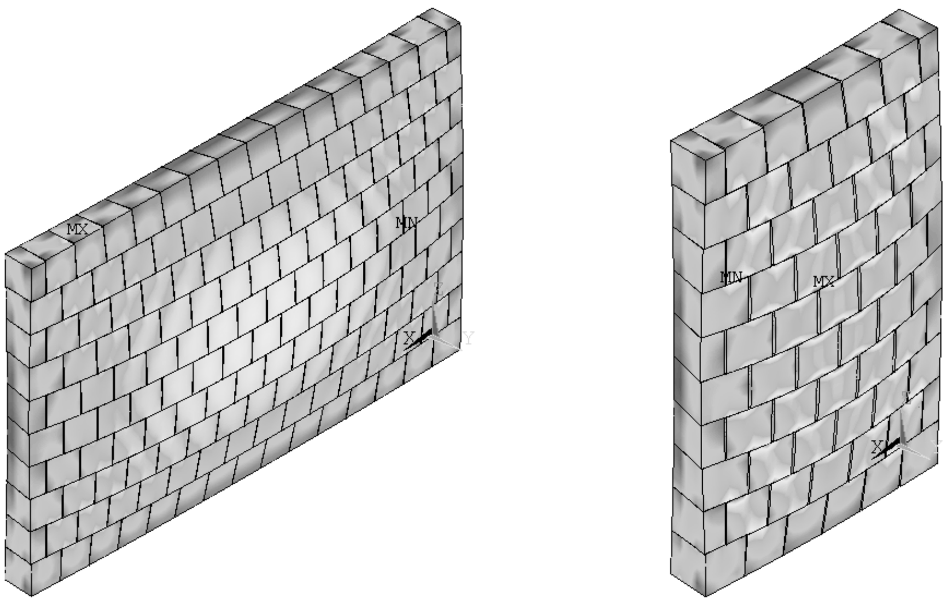

Figure 8. Maximum principle stresses in the masonry panels

A review of the numerical results of other analysed aspect ratios for a simply supported masonry panel is shown in Figure 9.

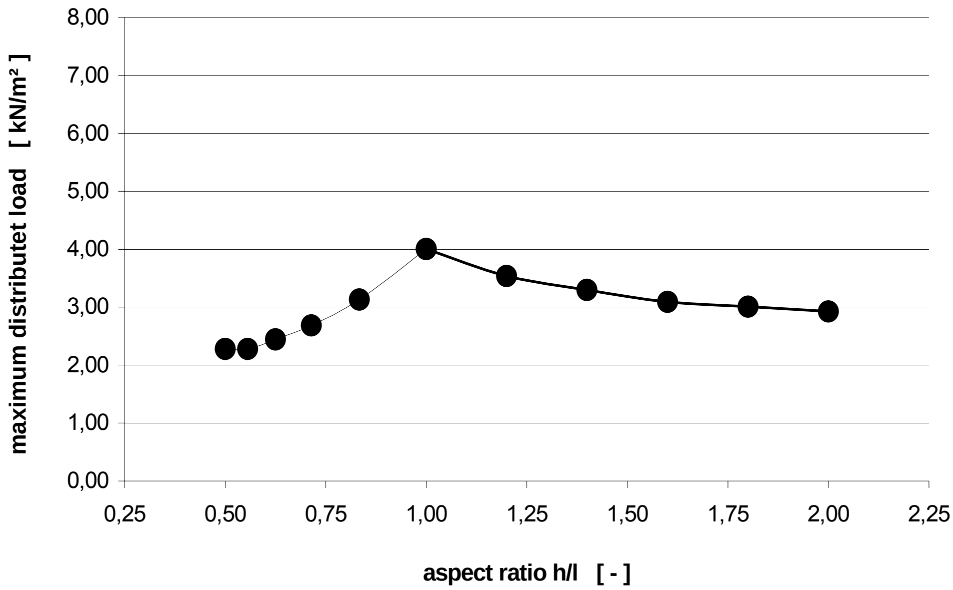

Figure 9. maximum distributed load on the masonry panel

4 Conclusions

The comparison of the results from the numerical investigation for various height to length ratios with the calculation in the ENV 1996-1-3 is illustrated in Figure 10. It points up, that the real masonry structures would already collapse under a smaller load, than those allowable based on the calculations. The bending moment coefficients as currently defined in the EC 6 therefore result in a safety risk based on the out-of-plane structural calculations of masonry walls.

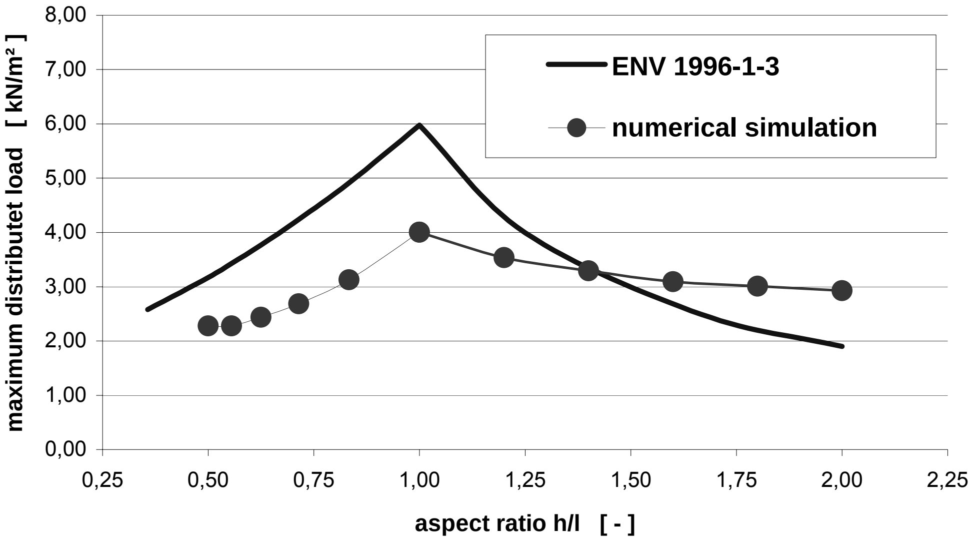

Figure 10. Comparison of the numerical results with the calculation in the EC 6

The adjustment of the bending moment coefficients to the real behaviour of the masonry panel based on the numerical investigation, as shown in Figure 11, can circumvent the existing safety risk.

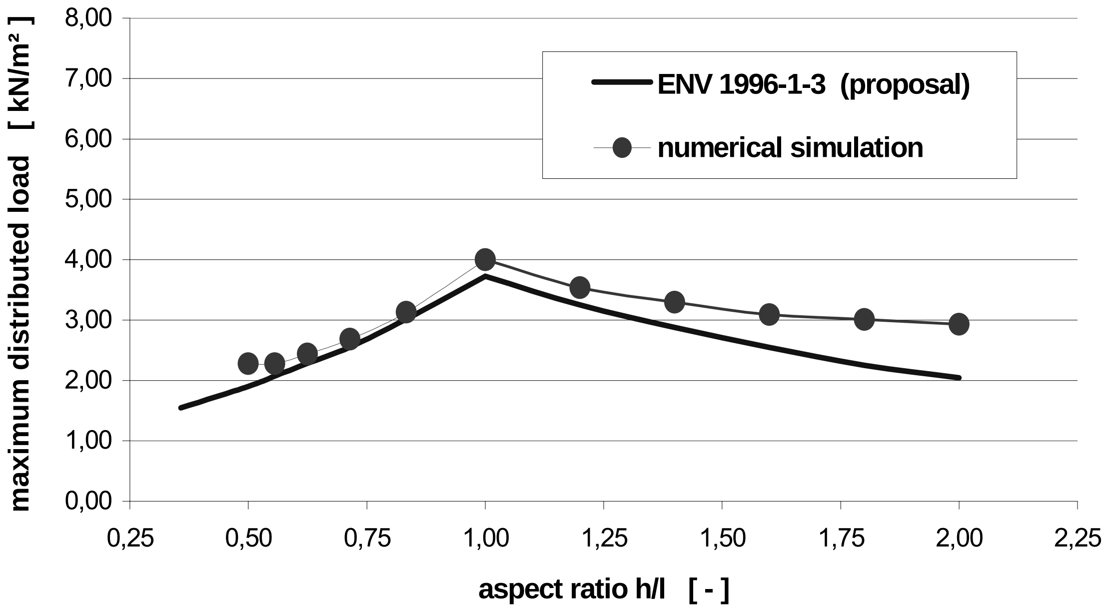

Figure 11. Adjustment of the bending moment coefficients

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