Comparison of Masonry Homogenization Methods –
Macromodelling and Micromodeling of Walls Behaviour
Made of Autoclaved Aerated Concrete Masonry Units

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Abstract. The adopted method of empirical homogenization strictly determines the degree of faithful reproduction of the masonry structure's work in terms of the analysis of cracking forces, destructive forces, and the mechanism of structure destruction. The high level of detail of the numerical model may make it impossible to perform calculations and predict internal forces for larger structures or entire buildings. The study aims to compare two different masonry homogenization techniques and determine the advantages and disadvantages of the adopted methods. The concept of a micromodel, in which the contact of two materials - a masonry unit and a mortar, was simulated using contact elements in the interface planes and a macromodel in which the wall was modelled as a homogeneous, isotropic material, omitting contact surfaces. The analysis subjects were standard wall models made of autoclaved aerated concrete (AAC) masonry units in axial and diagonal compression tests. In the numerical calculations, the elasto-plastic model with degradation implemented. The Menetrey William boundary surface describes the compression phase, and the Rankine criterion determines the tensile phase. In the axially compressed walls, the relations of forces and vertical and horizontal deformations compared, and in the shear walls, the forces and values of strain angles analyzed. In both models, the mechanisms of wall destruction and scratching were considered. The initial parameters of the elasto-plastic model derived from the results of wall tests using various model validation techniques. The calibration coefficient was used in the micromodel, determined as the quotient of the wall's compressive strength and masonry unit's compressive strength. The fracture energy value was also corrected. In the macromodel, the masonry's modulus of elasticity and the tensile strength value calibrated. Calculations based on the micromodel were consistent with the test results at the relative error level of 2%. The observed damage and scratches to the walls after the tests were consistent with the numerical projection. The macromodel calculations showed the convergence of the results in scratch morphology, scratching and destructive forces. The most significant differences occurred in shear deformations. The macromodelling approach allowed for capturing the wall's global tendency to deteriorate without opening the contact surfaces locally (cohesive cracks), as is the case during the tests.
1. Introduction
Numerical calculations of masonry structures based on the finite element method (FEM) are used at various construction stages - starting from the design of modern brick buildings to the diagnostics of existing structures - including assessing the technical condition of historic buildings [1]. Despite the commonly used FEM method [2,3,4], there is a need to create more accurate masonry homogenization techniques, which will enable faithful reproduction of the structure's behaviour. Some of the currently used modelling methods are burdened with a high degree of labour and time consumption.

The anisotropic masonry structure consisting of at least two different materials - a masonry unit and a mortar - significantly complicates the numerical calculations and selecting the appropriate homogenization method. To accurately reproduce the masonry's behaviour, it is necessary to find the relationships between the homogenized masonry's mechanical parameters and its components' mechanical properties. The strength criterion of the material should also be adequately defined. In numerical analyses, mainly nonlinear material models based on experimental observations, differing in the adopted constitutive relationships, are used. Strength criteria can be adopted either for the wall components or for a substitute material with average properties of mechanical parameters. The famous masonry modelling methods classification is based on two concepts - a micromodel and a macromodel [5]. They differ in the degree of computation complexity, the detail of the structure mapping and the number of necessary mechanical parameters.

Micromodeling [6] bases on a detailed mapping of the structure [7,8,9], treating the wall as a heterogeneous material. Typically, the finite element mesh size is so tiny that the structure's discretization occurs within each component material - both the masonry element and the mortar. An interface element may represent the interface between elements or modelled as continual elements representing masonry and mortar elements. The time-consuming and complexity of calculations in this homogenization method make the micromodel unsuitable for analyzing large fragments of structures or entire brick structures. This approach is appropriate for more detailed analysis [10, 11] of the scratch or damage morphology of the wall and the connections between the component materials. Micromodeling is dedicated to the analysis of small fragments of the entire structure.

Macromodelling is a computational concept base on a significant simplification of the actual masonry structure. As part of such analysis, the wall is described as a material with the same mechanical parameters [12, 13]. The wall is most often treated as a homogeneous composite with anisotropic properties, described by the relationship between averaged stresses and averaged strains. Although such an assumption leads to a significant simplification of the structure, it causes many difficulties in selecting the modelling's mechanical parameters. Although the macromodel does not allow for the analysis of local effects, including the accurate mapping of crack damage, it enables the analysis of larger brick structures and even entire buildings [14, 15, 16]. In such an analysis, the finite element mesh may include larger wall fragments, i.e. it may reach several wall elements.

The paper presents two standard techniques of masonry homogenization - micromodeling and macromodeling. The analyzed numerical models were calibrated based on standard tests of compression and shear walls made of autoclaved aerated concrete (AAC). The stress-strain relationships were considered, and the morphology of scratches and damages was compared. The study demonstrates the possibilities and limitation of proposed homogenization methods, emphasizing the masonry structure's specificity.

2. Materials and methods
2.1. Compressed walls
The numerical validation of FEM micromodels and macromodels was based on standardized models of masonry walls. Compressive strength tests were carried out following PN-EN 1052-1: 2001 [17] in a series of six test elements. The walls were 1.20 m high, 1.18 m wide and 0.18 m thick. The tested compression walls are shown in Fig. 1a. Models tested after a 28-day maturation period in a machine with a range of 2000 kN and an indication accuracy of 0.001 kN [18]. Samples are equipped with
double-sided frame systems with base lengths adapted to the test elements' dimensions and the joints' position. Along each side of the frame, displacement measurements were made using PJX-10 inductive displacement transducers with an indication accuracy of 0.002 mm. A relationship between vertical stress \( y \) - vertical strain \( \gamma \) and horizontal strain \( \alpha \) were drawn up based on the measured horizontal and vertical displacements.

### 2.2. Shear walls

Apart from compression tests, shear tests were performed [18, 19] in six test elements. Masonry models of the exact dimensions were used, but this time walls were compressed along a diagonal. The shear stresses were generated indirectly by the compressive forces oriented obliquely to the bed joint's plane. The tests were carried out per ASTM E519-81 [20], according to which concentrated forces are loaded on a square model with a side length longer than 1.0 m. In the wall's central area, the values of normal stresses correspond to the principal stresses \( \sigma_1 \) and \( \sigma_2 \) inclined at an angle of 45° relative to the bed joints surfaces. The geometry of the shear walls was the same as that of the compression walls. During the tests, the loading force was measured through two electrofusion coupled dynamosimeters with a range of 100 kN each, and horizontal and vertical displacements were measured using inductive displacement transducers of the PJX-20 type. The sensors are placed along two diagonals on both sides of the wall. Measurements were made on the length of the bases of the same length, equal to 932 mm. The length of the bases was selected by the guidelines of ASTM E519-81 [20] so that they cover the most extensive diagonal length. The results are presented in the charts tangential stress - shear angle. The tested shear walls are shown in Fig. 1b.

![Figure 1](image)

**Figure 1.** Wall models used to validate numerical calculations a) compressed walls testes according to PN-EN 1052-1:2001 [17] b) shear (diagonally compressed) walls testes according to ASTM E519-81 [20]

### 3. Numerical modelling - empirical homogenization

#### 3.1. Material model

Numerical calculations of compression and shear walls based on two empirical homogenization concepts: micromodel and macromodel. An advanced material model dedicated to assessing concrete structures and masonry structures was used [18]. The nonlinear *Cementitious 2* model is a combination of an elasto-plastic and elasto-brittle model. The Rankine criterion describes the material in the tensile state with a model of smeared band of cracks or cracks with constant directions with an exponential weakening function. In the compression phase, a material is determined by the Menétrey-Willam interface (M-W-3) [21,22,23]. Calibration of the model's mechanical parameters was carried out by empirical homogenization based on averaged test results for compressed and shear walls.
### 3.2. Micromodelling

Walls compressed in the perpendicular direction to the bed joints surfaces were calculated using 2D plane models. Mortar was omitted and substituted by contact elements. Such a numerical approach enables analyzing the morphology of scratches and the walls' load-bearing capacity [18]. The finite elements, which are representing the masonry units assigned the initial parameters - Table 1. Interface elements also replaced contact between the wall and the steel elements of the testing machine. The coefficient of friction was assumed to be $\tan \alpha = 0.1$ and the cohesion $f_{c,0} = 0$. The load was treated as vertical displacement of the testing machine's upper edge and was equal to 10mm - plane 2D models of compressed wall and shear depicted in Fig. 2a and Fig. 2b.

![Figure 2](image_url)

**Figure 2.** Numerical micromodels of masonry a) compressed walls b) diagonally compressed walls

1 – homogenized masonry's structure made of AAC, 2 – contact planes representing the bed joint surfaces, 3 – contact planes representing the joint head surfaces, 4 – contact planes representing the connection between masonry and steel elements, 5- steel elements of the testing machine

### Table 1. Initial and calibrated calculation parameters for the elasto-plastic model with degradation

| no. | parameter                                      | initial value | calibrated value |
|-----|------------------------------------------------|---------------|------------------|
| 0   | calibration coefficient                        | 0.70          |                  |
| 1   | initial modulus of elasticity $E_i$ [N/mm²]    | 2204          | 2204             |
| 2   | Poisson’s ratio [-]                           | 0.180         | 0.130            |
| 3   | tensile strength $f_t$ [N/mm²]                | 0.610         | 0.430            |
| 4   | fracture energy $G_f$ [MN/m]                  | $5.21 \times 10^{-5}$ | $3.62 \times 10^{-5}$ |
| 5   | compression strength $f_c$ [N/mm²]            | -4.25         | -2.970           |
| 6   | plastic deformation under compression $\delta_p$ [-] | $-3.33 \times 10^{-4}$ | $-2.33 \times 10^{-4}$ |
| 7   | ultimate displacement under compression [m]   | $-5.00 \times 10^{-4}$ | $-5.00 \times 10^{-4}$ |
| 8   | reduction of compressive strength [-]         | 0.80          | 0.80             |
| 9   | shear stiffness reduction factor [-]           | 20            | 20               |
| 10  | average aggregate size [mm]                   | 20            | 20               |
| 11  | plastic flow direction [-]                    | 0             | 0                |

The initial parameters (listed in Table 1) caused that modulus of elasticity in the calculation was consistent with test results, but the maximum compressive stresses' values were 45% higher than in research. The apparent differences in the maximum compressive stresses' values were due to the
evident influence of omitting bed joints presence and replacing them with contact elements. It was also essential to adopt the failure surface and weakening parameters corresponding to the wall masonry unit instead of the wall's adequate failure surface.

Model's parameters were calibrated to obtain numerical calculations consistent with the test results. For this purpose, the compressive and tensile strengths of the masonry units and plastic deformations were corrected using a reduction factor defined as the quotient of the masonry's compressive strength to the compressive strength of the masonry unit \( \left( \frac{f_{cm}}{f_b} \right) \). The value of the calibration coefficient for the autoclaved aerated concrete masonry was equal to \( \frac{f_{cm}}{f_b} = 2.97 / 4.25 = 0.70 \). Such corrected boundary conditions were summarized in Table 1 (right column). Furthermore, the fracture energy was also corrected using the empirical formula (1) developed in the study [18].

\[
G_f = 0.000085f_t 
\]

in which: \( f_t \) – tensile strength of the masonry unit [N/mm²].

The model with calibrated parameters showed good agreement of the numerical results compared to test results – differences between values of maximum stresses did not exceed 2% - Fig 4a. The values of vertical and horizontal deformations were also similar to the test results. After reaching the maximum compressive stresses, the material weakened, and plastic deformation took place. In the compressed walls' micromodels - the scratches were evenly distributed in the central area of the wall and developed towards the corners of the model, covering the entire masonry units - Fig. 3b.

In a diagonally compressed micromodel, the tangential stress-deformation angle coincided with the test results until the value of maximum tangential stresses were reached- Fig. 4b. The increase in deformation angle resulted in a noticeable reduction in the value of stresses. No such phenomenon was observed in the test because masonry walls showed a brittle (rapid) destruction mechanism. Calculated tangential stress values and experimental values differed by up to 7%. A similar situation concerned deformation angles at cracking stresses and maximum stresses - the differences between the calculated and measured values did not exceed 8%.

![Figure 3](image1.png)

**Figure 3.** Cracking patterns and damages of compressed masonry a) cracks in the test, b) cracks in the numerical micromodel
The crack patterns at maximum stresses were also analyzed. Cracks ran vertically through the layers of bed joints - Fig. 5a, and close to the supports also through the masonry units. A similar result was obtained in the numerical micromodel, but there were also cracks running vertically through the masonry units in the wall's central part - Fig. 5b.

### 3.3. Macromodelling

Similarly to the previous considerations, macromodels of compressed and shear walls were built. The numerical models' details with the marked finite element mesh are presented in Fig. 6a and Fig. 6b. The models omit the contact planes between each masonry unit, and the entire wall is mapped with an isotropic shell model with the failure surface depending on the value of hydrostatic stress.

The applied macromodel simplifications compared to the micromodel, with the initial model parameters (presented in Table 1), resulted in unacceptable discrepancies with standard test results. An empirical calibration of material parameters was performed to obtain the closest numerical representation of the masonry's actual behaviour. The best compliance of the calculations with the test results was obtained by modifying the modulus of elasticity and reducing tensile strength. The values of the correction factors are shown in Table 2.
Figure 6. Numerical macromodels of masonry a) compressed walls b) diagonally compressed walls

1 – homogenized masonry's structure made of AAC, 2 - steel elements of the testing machine, 3 - contact planes representing the connection between masonry and steel elements

Table 2. Initial and calibrated calculation parameters for the elasto-plastic model with degradation

| No. | parameter                      | initial value [N/mm²] | corrected value [N/mm²] | correction coefficient |
|-----|-------------------------------|-----------------------|-------------------------|------------------------|
| 1   | initial modulus of elasticity $E_i$ | 2204                  | 2069                    | 0,94                   |
| 2   | tensile strength $f_{ti}$      | 0,610                 | 0,076                   | 0,12                   |

In the compressed walls, full compliance of the vertical deformations with the test results was obtained at cracking stress $0,33\max$ with a 16% divergence at the same stress level for horizontal deformations. The maximum stresses were 6% lower than those obtained in the standard tests - Fig. 7a. In the shear wall's numerical macromodel, the deformation angle was consistent with the test results at the maximum stresses $\max$. The divergence of the wall's deformations angle at the cracking stress level $0,33\max$ was 19% - Fig. 7b.

Figure 7. Results of numerical calculations based on the macromodel a) compressed wall – the relationship between normal stress and vertical and horizontal strain b) diagonally compressed walls – the relationship between tangential stress and strain angle
The morphology of wall scratches is analyzed in a similar way as in the case of micromodels. Better compliance of the numerical results with the test results was obtained in macromodel of compressed walls. The scratches appeared mainly along the diagonals of models, creating a cone-shaped shape – Fig. 8a. More significant discrepancies became apparent in the diagonally compressed walls. The calculations failed to capture the wall destruction's cohesive nature, but only the model's area subject to material weakening was determined – Fig. 8b. Test models were damaged in the bed joints surfaces between the masonry units – Fig.5b.

![Figure 8](image)

**Figure 8.** Cracking patterns and damages of numerical masonry models a) cracks morphology for compressed wall b) cracks morphology for shear wall

### 4. Results and discussions

Both in micromodels and macromodels, a faithful representation of the compressed wall's work was obtained, particularly the relationship between stress and vertical deformation (deformation in the load direction). In such cases, the destruction concerned crushing the masonry units, and the contact surfaces between the elements did not play a crucial role. A compressed wall works mainly in the elastic phase up to 2/3 of the maximum stress. Thus, the description of such a wall's behaviour can be successfully realized using a micromodel or macromodel.

In diagonally compressed walls, the nonlinear nature was noted at a low level of tangential stresses. This phenomenon was related to the gradual progression of damage in bed joints surfaces. The cohesive nature of the destruction mechanism determined the nonlinearity of the masonry structure. Micromodeling, which consisted of replacing the bed joints surfaces with interface parameters, enabled capturing such occurrence. Despite using an advanced model with degradation, the cohesive cracks and damage wall in the macromodels was not achieved. In walls where the dominant factor is shear, macromodeling may cause significant discrepancies in the numerical results compared to the actual work of the masonry structure, even at a low level of stresses.

### 5. Conclusions

The numerical verification of FEM micromodels and macromodels was made by comparing the calculation results with the test results by analyzing scratch morphology and the crack's patterns at the maximum stress and stress-strain relationship. The analyzes show that both micromodels and macromodels can be successfully used in the analysis of compression walls. Shear walls require a more detailed computational approach due to the cohesive contact phenomena in the bed joints surfaces between masonry units. Macromodels that treats wall as an isotropic structure not represent genuine connection in walls.
The presented calculation results concerned only walls made of autoclaved aerated concrete (AAC). Further work should include analyzes of models made of other types of masonry materials. It is also worth calculating the masonry for thicker bed and head joints. It is also recommended to extend the calculations to larger wall analyzes or calculations using 3D micromodels and macromodels.

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