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Simulation of the fire resistance of calcium silicate masonry walls

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ABSTRACT:

The contribution presents finite element simulations, sensitivity analysis and parameter identifications of fire tests on calcium silicate masonry walls. Temperature gradient, mechanical load and the failure resp. the fire resistance time of the wall can be reconstructed close to reality (i.e. the tested specimen) using the developed finite element model. The finite element simulations were computed using the program system ANSYS with a special material model developed for calcium silicate masonry.

The sensitivity analysis, accomplished by the optimization platform optiSLang, distinguishes parameters of substantial influence on the fire resistance of calcium silicate masonry walls. By means of evolutionary optimization algorithms relevant material and system parameters were identified.

With the developed model it was possible to predict the fire resistance time as well as the damages caused by fire load. In addition the presented approach shows high potential for optimizing building materials with regards to their structural fire resistance.

Keywords: *Calcium silicate masonry, fire resistance, finite element simulation, ANSYS, optiSLang, multiPlas*

NOTATION

F_i	yield condition;
Ω	*hardening / softening function*
σ_S	*load;*
σ_m	*hydrostatic stress;*
σ_y	*strength;*
f_{c1}	*uniaxial compression strength;*
f_{c2}	*biaxial compression strength;*
f_t	*uniaxial tensile strength*

1 INTRODUCTION

The aim of a joint research project of the European Calcium Silicate Producers Association (ECSPA) was the fundamental investigation of the behaviour of calcium silicate masonry walls subjected to fire load as well as the relevant influences on the fire resistance. These investigations were accomplished

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both by simulations and an accompanying test programme. The test programme at the fire test stand of the Technical University of Brunswick (Germany) comprised 6 one-sided fire loaded masonry walls with thickness of 0.15 m, 0.175 m and 0.214 m. All walls were 3 m long and 3.25 m high. The tests served to demonstrate the fire resistance but also to develop a realistic simulation model as basis for the prognosis of the behaviour and the fire resistance of calcium silicate masonry walls.

2 SIMULATION PROCESS

Figure 1 shows the simulation process. It consisted of three parts:

- the transient thermal finite element analysis of the fire load and the calculation of time-dependent temperature distribution in the masonry wall with ANSYS,
- the coupled nonlinear mechanical finite element analysis of the deformation behaviour, stresses, cracking, damages as well as the structural failure when reaching the fire resistance time with ANSYS-multiPlas [3], [1]
- the sensitivity analysis using stochastic Latin Hypercube Sampling and the parameter identification with efficient genetic and evolutionary optimization algorithms in optiSLang [2]

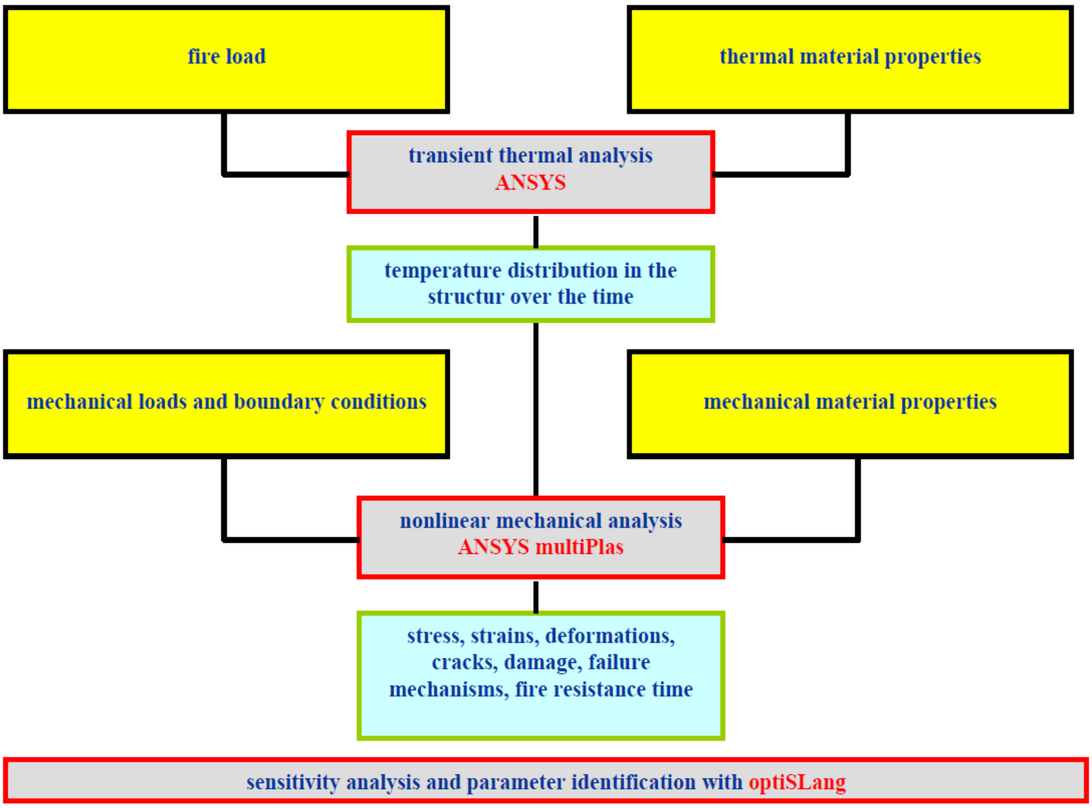


Figure 1. Simulation process

For entire process of the coupled thermal-mechanical FE-analysis a parameterized approach (variable model parameters instead of distinct values) was chosen. The input parameters describe the loads, boundary conditions and material properties (yellow boxes in Figure 1). The response values are the computation results such as temperatures, deformations, fire resistance (blue boxes in Figure 1). The results of the sensitivity analysis showed important correlations between input parameters and response values. Furthermore did the sensitivity analysis reveal the potential parameters which allow an alignment between measurement (test) and simulation by means of inverse computing (parameter identification).

3 MODELING MASONRY

The calcium silicate masonry walls were computed with a discrete simulation model. For the simulation of the strength of the calcium silicate units a modified elasto-plastic Drucker-Prager material model [3] was used. The yield condition consists of two yield criteria (eq. (1) to (4)), whereby the masonry unit strength can be described close-to-reality under compression, tension and shear loading. The yield condition is shown in Figure 2.

$$F_1 = \sigma_S + \beta_t \sigma_m - \tilde{\sigma}_{yt}\,\Omega_1 \tag{1}$$

$$\beta_t = \frac{\sqrt{3}\,(f_c - f_t)}{f_c + f_t} \qquad \tilde{\sigma}_{yt} = \frac{2\,f_c\,f_t}{\sqrt{3}\,(f_c + f_t)} \tag{2}$$

$$F_2 = \sigma_S + \beta_c \sigma_m - \tilde{\sigma}_{yc}\,\Omega_2 \tag{3}$$

$$\beta_c = \frac{\sqrt{3}\,(f_{c2} - f_c)}{2\,f_{c2} - f_c} \qquad \tilde{\sigma}_{yc} = \frac{f_{c2}\,f_c}{\sqrt{3}\,(2\,f_{c2} - f_c)} \tag{4}$$

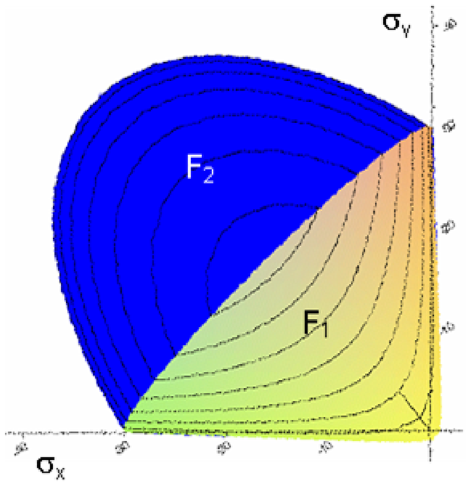


Figure 2. Modified Drucker-Prager Model for calcium silicate masonry units

Figure 3 shows the nonlinear stress-strain relations of the simulation model for calcium silicate masonry units. Under tension loading calcium silicate masonry units show a relatively brittle softening behaviour with local cracking. For this a smeared crack model was used. The softening process was formulated as a function of the energy dissipation during the cracking process. In the developed material model both the yield condition and the hardening/softening functions were formulated temperature-dependent.
The masonry joints were modelled as friction joints (contact elements with a combined Mohr Coulomb and tension cut off material model).

The used elasto-plastic simulation model for calcium silicate masonry was verified by different single and mixed mode tests (without fire loading) in [1]. This material model is available in the material library multiPlas [3] for ANSYS.

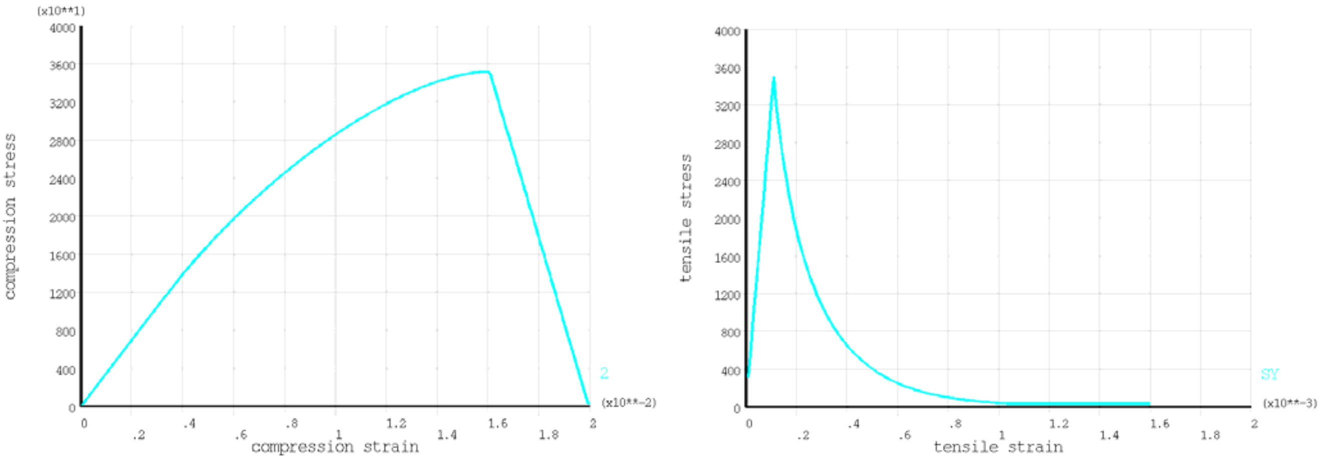


Figure 3. Stress-strain-relation: left – compression, right – tension

4 VERIFIKATION AND PARAMETER IDENTIFICATION

For the parameter identification an optimization task was formulated, which contained the minimization of the difference between measurement and simulation as target function. The optimization was carried out with the software platform optiSLang [2] using powerful evolutionary and genetic algorithms.

The inverse computed (hereafter referred to as "identified") temperature-dependent curves of the density in Figure 4a show similar characteristics as the one give in Eurocode 6 [5]. Figure 4b shows the identified temperature-dependent curves of the heat conductivity. For the wall thicknesses of 0.175 and 0.214 m in particular the singularity of the heat conductivity indicated in Eurocode 6 [5] at 100°C and the decrea of the heat conductivity down to zero at 1200 °C could not be confirmed. Figure 4c shows the identified curves of the temperature-dependent specific thermal capacity as well as the curve given in Eurocode 6 [5]. In principal the curves correlate quite well, however the identified reduction of the specific thermal capacity at approx. 150°C is lower than in [5].

Figure 5a shows the identified temperature-dependent thermal strain curves . They match well for all the examined wall thickness and correspond very plausibly with the measured temperature and deformation processes, but differ substantially from the curve given in Eurocode 6 [5]. . Contrary to the thermal strain the identified the temperature-dependent curves of the elastic modulus in Figure 5b match well with the curve in [5].

Figure 6 shows as an example the calculated and measured temperature gradients for wall 2. After the parameter identification the correspondence between simulated and measured temperature was very good. The temperatures simulated with the prognosis model were within the scattering range of the measured values.
Figure 7 and Figure 8 show exemplarily the simulated and measured deformation curves for two walls (wall 3, 4) with different wall thicknesses (0,214 m and 0,15 m). For all tested walls a very good compliance between simulated and measured deformation curves was found. The simulation model is also able of reproducing the relaxation of the deformation processes, which are due to chemical conversion respectively material deterioration of the masonry units at the fire loaded side. From the

simulation the fire resistance of the specimen could be determined with maximum deviation from the test results of 6% (5 min).

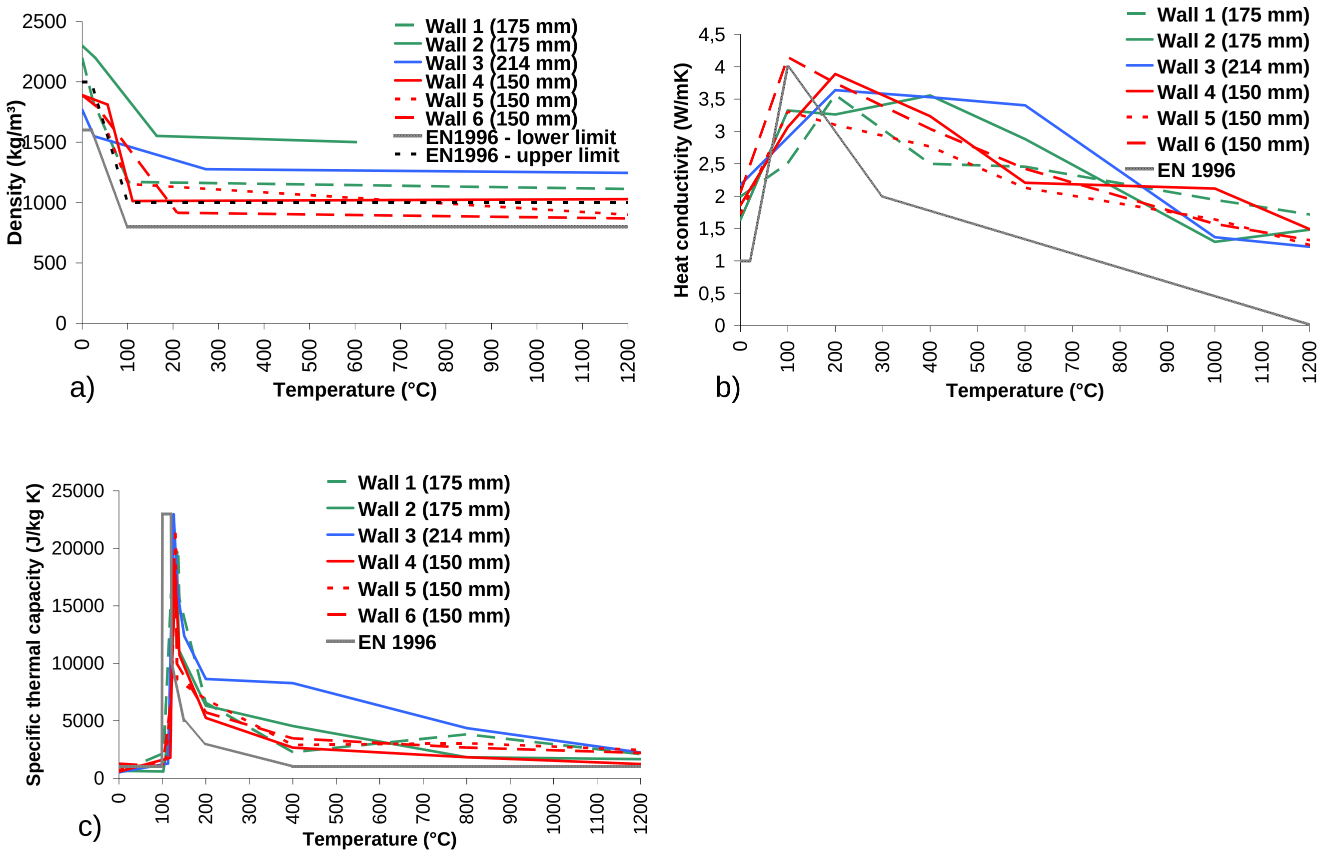


Figure 4. a) Identified curve of the density over the temperature; b) Identified curve of the heat conductivity over the temperature; c) Identified curve of the specific thermal capacity over the temperature

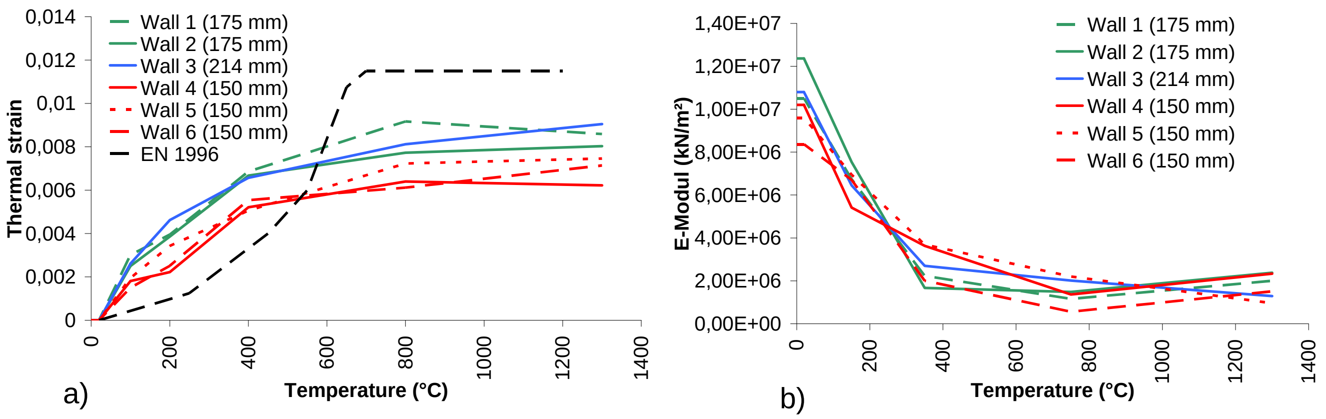


Figure 5. a) Identified curve of the thermal strain over the temperature; b) Identified curve of the young's modulus over the temperature

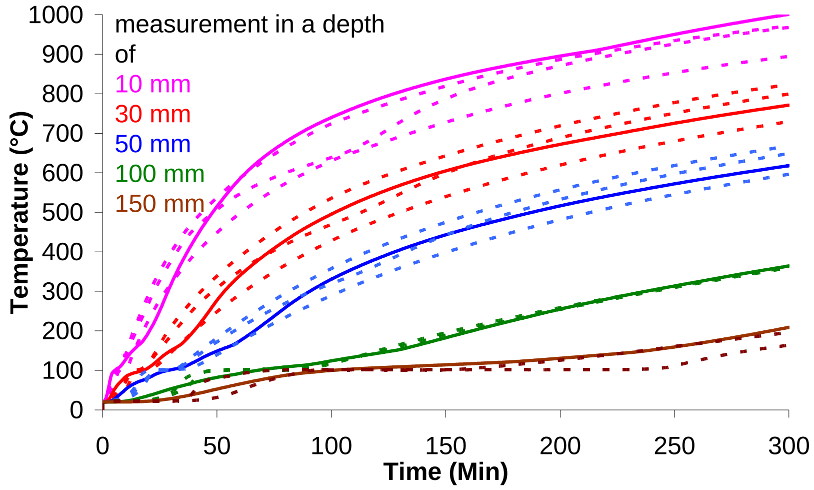


Figure 6. Temperature signal – measurement versus simulation (example wall 2)

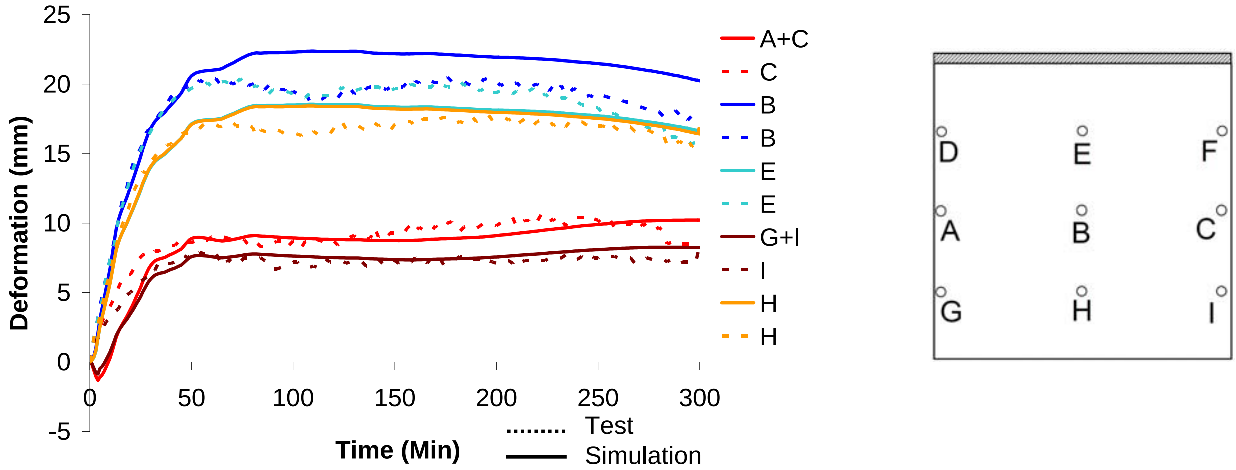


Figure 7. Wall 3 (d = 0,214 m) deformation signal – measurement versus simulation

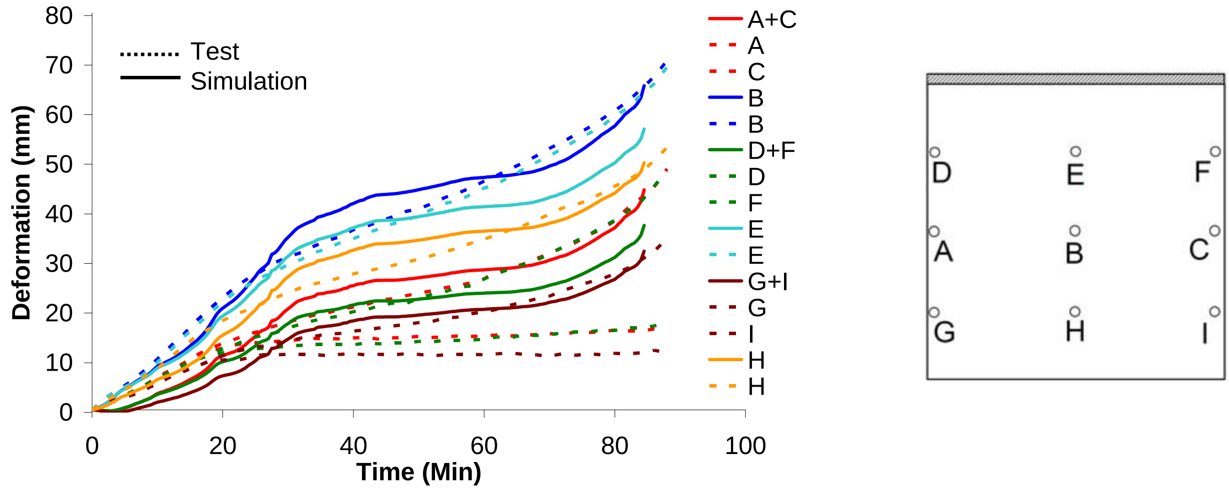


Figure 8. Wall 4 (d = 0,15 m) deformation signal – measurement versus simulation

In Figure 9 and Figure 10 the computation results for wall 2 are presented as an example. The horizontal deformations perpendicular to the wall surface (u_y) shown in Figure 10a demonstrate that an accurate simulation requires a 3D-modeling, due to the vertical and horizontal expansion of the fire loaded wall side.
The distribution of the vertical stresses shown in Figure 9a are typical for fire loaded masonry walls. The fire loading develops a high temperature gradient, which leads to vertical compression stresses on the fire exposed side and tension stresses in the centre of the masonry wall cross section. From the bending of the wall, vertical compression stresses result also on the "cold" (not fire exposed) wall surface. Figure 9b shows the distribution of the horizontal stress. On the fire exposed side compression stresses develop. On the "cold" wall side horizontal tension stresses develop near the head joints. These tension stresses lead to vertical cracks (s. Figure 11) respectively to plastic strains in the simulation (s. Figure 10b). The comparison of the Figure 10b and Figure 11 shows a good correlation between computed plastic strains and the observed cracks.

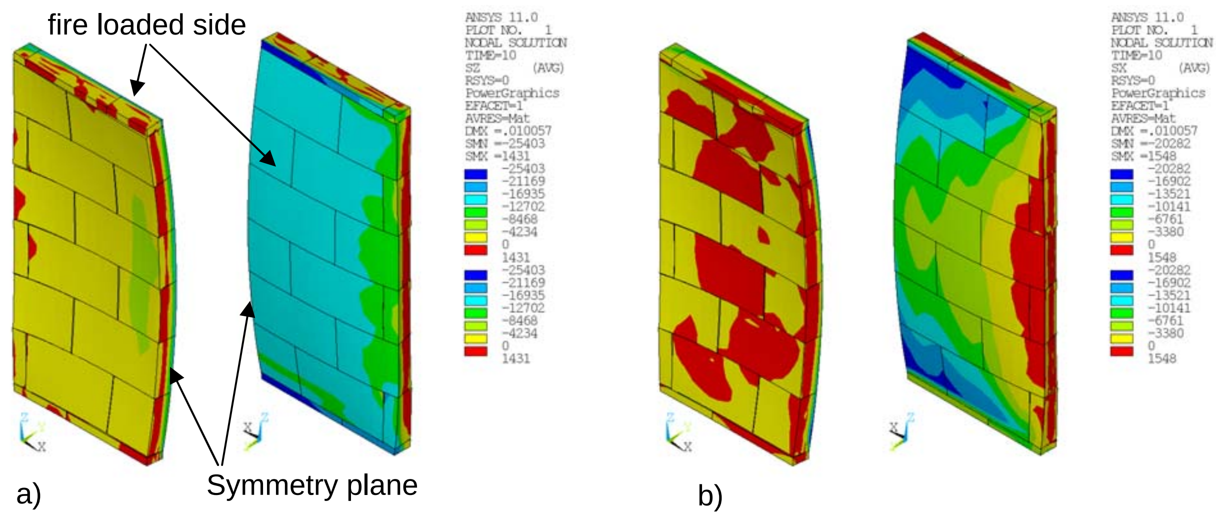


Figure 9. a) Typical distribution of the vertical stress in z-direction σ_z (kN/m²), example wall 2 b) typical distribution of the horizontal stress in x-direction σ_x (kN/m²), example wall 2

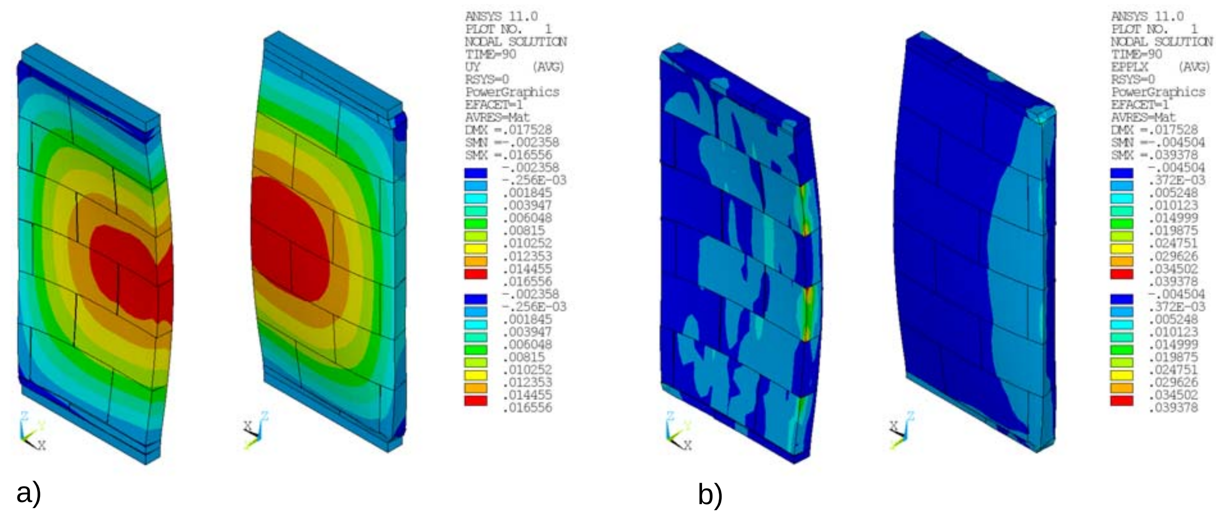


Figure 10. a) Horizontal deformations u_y (m), wall 2 after 90 min, Plastic strain after 90 min, wall 2

Figure 11. Observed cracking on the "cold" side, example wall 2

5 IMPORTANT PHENOMENA AND SENSITIVITIES OF FIRE LOADED CALCIUM SILICATE MASONRY WALLS

Fire loaded calcium silicate masonry walls show particularly three phenomena:

i) desiccation and consequently a progressing dampness front,
ii) chemical conversion respectively material deterioration at approx. 550 to 600 °C,
iii) three-dimensional deformation behaviour because of the one-sided fire load.

The two first phenomena were considered during the simulation process through parameter identifications in particular the specific thermal capacity and the thermal strain. A realistic prognosis of the deformation behaviour and the cracking is only possible with a three-dimensional finite element model.

By means of the sensitivity analyses with optiSLang [2] the relevant influence parameters on the fire resistance of calcium silicate masonry walls could be identified. As input variables for the global sensitivity analysis the load, boundary conditions, geometry parameter and material parameter were varied and 150 Designs were computed. Even though only one of the walls was tested with plaster on both side , the analyses showed (and confirmed) that a layer of plaster on the fire exposed side has a strong and positive impact on the temperatures in the wall and hence also on the fire resistance of the wall (s. Figure 12). Figure 13 shows the results of the global sensitivity analysis for walls without plaster. The fire resistance for these walls is influenced by:

- the wall thickness,
- the level of vertical load,
- the thermal strain and
- the boundary conditions at the top of the wall.

Other parameters like e.g. the stone length and stone height, the type of mortar, filled or unfilled head joints or the absolute size of the elastic module have no considerable influence on the fire resistance of calcium silicate masonry.

From the local sensitivity analysis (fixed geometric and loading condition, variable material properties) at one wall (s. Figure 14) it results, that the deformation behaviour, the cracking and the fire resistance are dependent of the thermal strain (pmThEps), the dilatancy (pmDelc) and the masonry strength (pmFm).

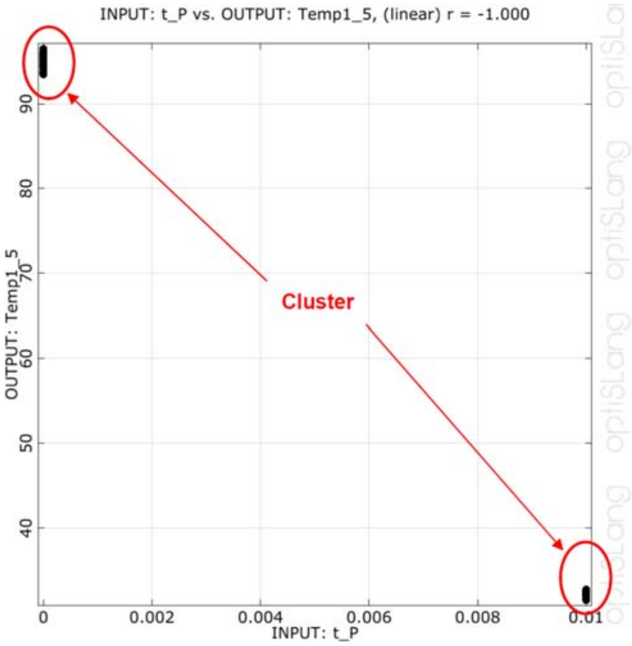
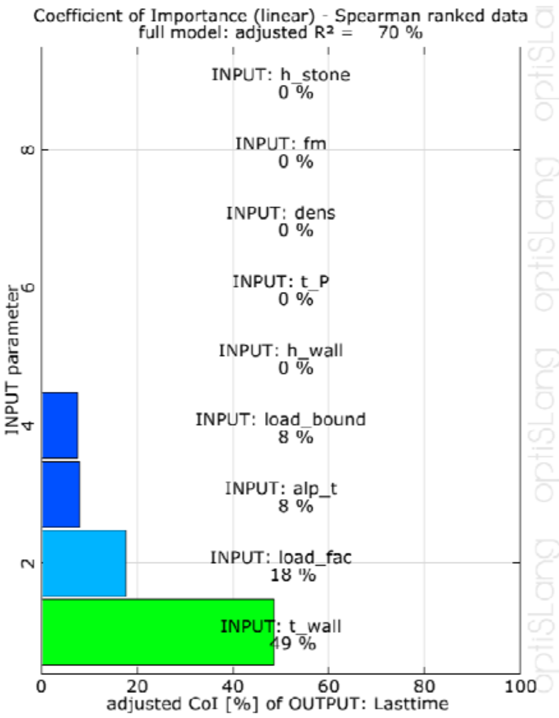


Figure 12. Anthill plot temperature in 10 mm of depth after 5 min fire loading versus thickness of plaster t_P



<u>relevant parameters:</u>

boundary conditions at the wall head

thermal strain

level of vertical load

wall thickness

Figure 13. Coefficient of importance of all input parameter versus fire resistance time (walls without plaster)

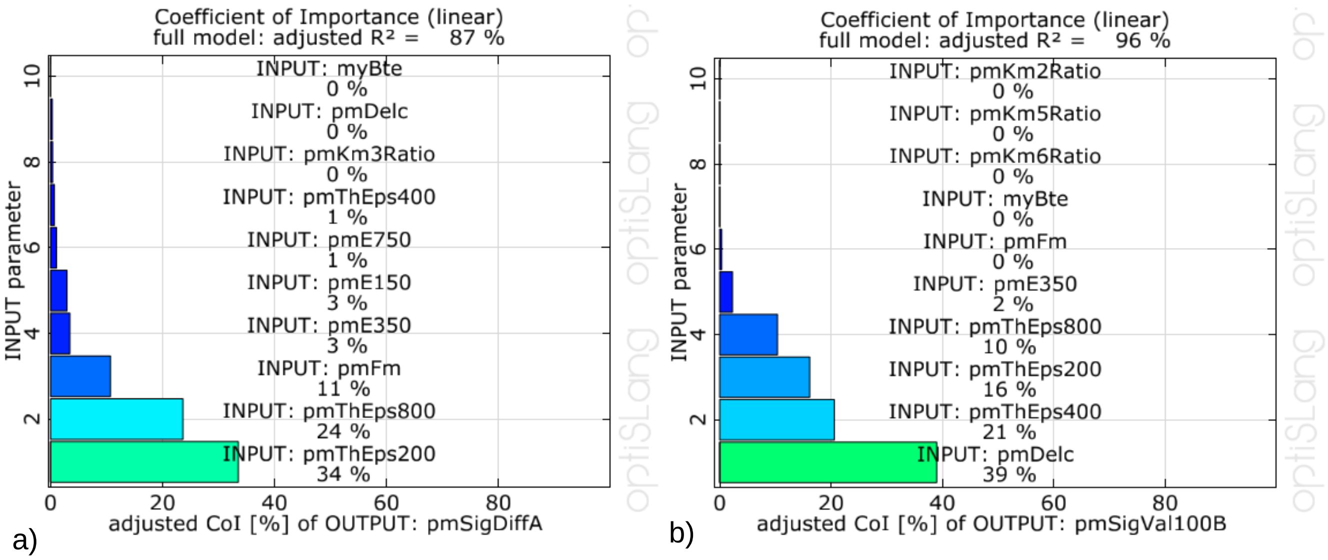


Figure 14. Coefficient of importance (CoI) of all input parameter versus deformations. a) measuring point A; b) measuring point B (measuring points A and B s. Figure 7)

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