EXPERIMENTAL AND NUMERICAL STUDIES ON MASONRY AFTER EXPOSURE TO ELEVATED TEMPERATURES

EXPERIMENTELLE UND NUMERISCHE UNTERSUCHUNGEN ZUM VERHALTEN DES MAUERWERKS NACH THERMISCHER EINWIRKUNG

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SUMMARY

In this work, experimental and numerical studies are performed to investigate the influence of elevated temperature on the residual (post-heating) behaviour of masonry. Two different types of solid brick units namely, clay bricks and calcium silicate bricks, were used in the study. The tests were performed on the individual brick units, the cement mortar as well as the masonry prisms (brickwork bricks and cement mortar). The residual performance of the specimens was tested to verify the influence of temperature on the behaviour of masonry. The numerical (3D finite element) modelling of the specimens was performed and temperature dependent microplane model was used as the constitutive law for the brick and mortar. The numerical modelling approach has been validated and shown to be able to realistically simulate the residual behaviour of masonry after exposure to elevated temperature. The results of experimental and numerical study show a relatively moderate influence of temperature on the strength but a strong influence on the stiffness of the masonry system.

ZUSAMMENFASSUNG

Im vorliegenden Beitrag werden die Ergebnisse der experimentellen und numerischen Untersuchungen zum Verhalten des Mauerwerks nach thermischer Einwirkung berichtet. Die Untersuchungen wurden an Mauerziegeln und an Kalksandsteinen durchgeführt. Es wurde das Verhalten der Einzelsteine, des Zementmörtels und des Mauerwerks (Pfeiler) nach einer thermischen Beanspruchung untersucht, um den Einfluss der Temperatur auf das Druckverhalten des Mauerwerks im residualen Zustand zu beschreiben. Numerische Berechnungen

(3D-Finite-Elemente) wurden unter Anwendung des temperaturabhängigen Microplane-Modells für Mauersteine und Mörtel vorgenommen. Der numerische Ansatz wurde anhand der Versuchsergebnisse validiert. Die Ergebnisse der Studie zeigen einen moderaten Einfluss der Temperatur auf die Druckfestigkeit und einen wesentlichen Einfluss auf die Steifigkeit des Mauerwerks.

KEYWORDS: Masonry, elevated temperature, residual performance, calcium silicate bricks, clay bricks, numerical modeling, microplane model.

1. INTRODUCTION

Masonry structures represent one of the oldest construction concepts. Due to their historical value, significant research has been performed in the past on the effect of fire on masonry structures [1-6]. Real fire events [3], as well as fire testing [5, 6] have shown an excellent performance of masonry walls and structures under fire and high temperature conditions.

Nevertheless, the abundant information obtained from fire resistance tests is not sufficient to assess the residual structural reliability of the tested members. The modern engineering approach to fire design requires a better understanding of the fire and post-fire behaviour of masonry structures and specific guidelines are needed in codes [7] for estimating the residual strength of the masonry walls after fire accidents.

The post-fire safety of masonry structures is a rising branch of research [8, 9]; however, some limits of applicability are related to expensiveness of masonry testing and to the complexity of numerical modelling of a composite material. Masonry is a heterogeneous system consisting of brick units (blocks) and mortar (joints). The overall behaviour of the masonry system at material level is dependent on the combination of brick units and mortar. When exposed to elevated temperature (e.g. fire accident), the complexity of masonry behaviour further increases. The material behaviour changes due to the change of its mechanical properties and due to the thermal strains.

As mentioned above, the experimental work performed on masonry walls has shown an excellent fire resistance, especially for the masonry made using clay bricks [5, 6]. Based on these works, guidelines on the fire design using tabulated data have been incorporated in the codes [7]. In annex D of EN 1996-1-2, temperature-dependent thermal and mechanical properties are provided for different masonry units in comparison to normal concrete. Fig. 1 shows the normalized stress-strain curves recommended by Eurocode 6 [7] for: (a) clay brick units and (b) calcium silicate brick units.

It is interesting to observe that according to [7], the clay bricks display a gradual reduction in strength with increasing temperature, while the calcium silicate bricks are first characterized by an increase in strength for moderate temperatures and the strength reduces only at higher values of temperatures. In general, due to the materials used and process of manufacturing, the brick units might show a decrease or increase in the strength due to the exposure to elevated temperature. Nevertheless, the overall strength of the composite masonry system is governed by the properties of brick units and the mortar, which always show reduction in strength due to elevated temperature. Furthermore, these data are valid only at elevated temperatures and not in residual state (cooled down to room temperature after exposure to elevated temperatures).

a) b)

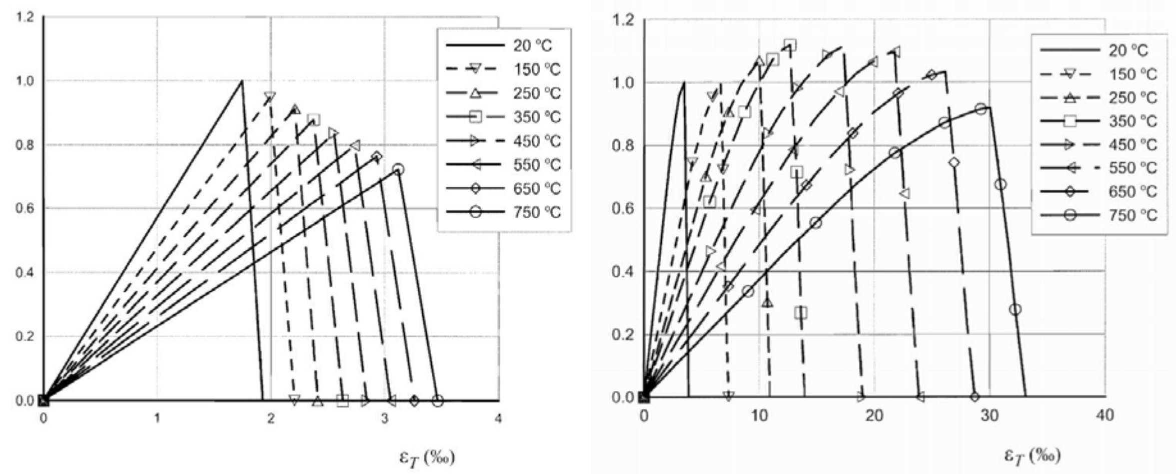


Fig. 1: Normalized stress-strain curves for (a) clay brick units and (b) calcium silicate brick units at elevated temperatures according to [7]

This work aims at experimentally and numerically investigating the performance of masonry in residual state, after exposure to elevated temperature. The investigations have been carried out to determine the mechanical properties of the brick units, the mortar as well as the masonry prisms after exposure to elevated temperature achieved through slow heating, retention at elevated temperature and cooling down to room temperature. Static compression tests were performed to obtain the load-displacement behaviour in order to determine the strength and stiffness variation. Two different types of solid brick units namely, clay bricks and calcium silicate bricks, were used in the test specimens. The details of the experimental work, the numerical modelling approach as well as the results are discussed in this paper.

2. EXPERIMENTAL PROGRAM

As a first step of the study, the behaviour of masonry after exposure to elevated temperatures was experimentally investigated [10]. To better understand the interaction of the two components, namely brick units and mortar, the tests were performed on (i) individual masonry units (clay bricks and calcium silicate bricks), (ii) masonry mortar, and (iii) masonry prisms (brickwork with clay bricks and calcium silicate bricks).

Post-heating material behaviour of the three specimen types was investigated for the temperature range between 20°C and 1100°C. Thermal exposure consisted of heating up to target temperature at a heating rate of 2°C/min, 2 hours retention at target temperature and cooling. Following the thermal exposure, mechanical properties of the materials were measured in residual state. Masonry units and masonry prisms were tested under compression and mortar prisms were used to measure the bending and compressive strength of the mortar. For statistical purposes, the tests were performed on three specimens each for every case.

a) b)

Fig. 2: Compression test on masonry prisms – test setup – a) Calcium silicate brick prism; b) Clay brick prism

The compression tests on masonry brick units were performed acc. to DIN EN 772-1 [11]. Tests were performed on single units under load control, whereby the loading velocity was chosen such to reach the peak load within 2-3 minutes. Mortar prisms were tested under compression acc. to DIN EN 1015-11 [12]. The tests were performed under load control, whereby the loading velocity was chosen such to reach the peak load within 1-3 minutes. Masonry prisms were tested under compression following DIN EN 1052-1 [13]. In order to measure the stiffness of the specimens, one LVDT each was applied on two shorter sides of the specimen. Tests were performed in displacement control, whereby the cylinder (machine) displacement was controlled.

2.1 TEST RESULTS

2.1.1 Residual compressive behavior of mortar and brick units

After the heat treatment, the residual compression tests were performed on the masonry units (CS - calcium silicate bricks, CL - clay bricks) and the mortar, the results of which are summarized in Fig. 3. The mean compressive strength of the mortar prisms was obtained as approx. 25 MPa at room temperature and for the specimens exposed to 100°C. Beyond this, the compressive strength of mortar (Fig. 3a) reduces almost linearly with the increasing exposure temperature, as can be expected for low strength cementitious materials. The degradation occurs as a combination of physical and chemical changes, which take place within the cement paste, sand and the interface between the two. The residual compressive strength of the brick units displays a different type of trend (Fig. 3b), with the compressive strength of the bricks initially increasing with temperature. For calcium silicate bricks, significant increase in strength starts from approx. 300°C, but the strength suddenly drops for temperatures above 700°C. This is most likely related to the volumetric change of siliceous sand, decomposition of the C-S-H phases, as well as to the cracking between C-S-H phases and sand particles.

a) b)

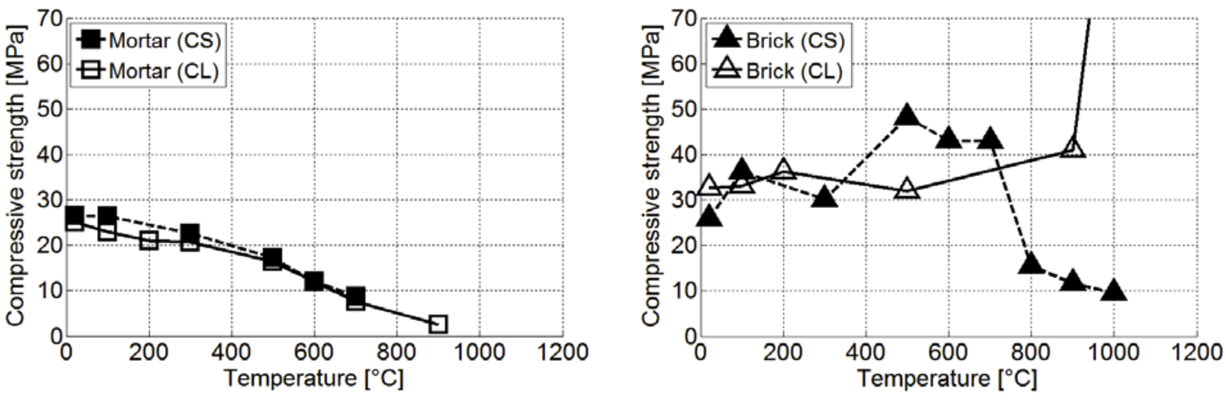


Fig. 3: Degradation of compressive strength after heating – a) mortar and b) brick units

Comparing the relative degradation curves for brick units with that obtained from EN 1996-1-2 (Fig. 1), it is evident that the residual compressive strength of calcium silicate bricks is somewhat higher than the respective hot strength. Particularly pronounced difference between hot and residual strength can be observed for temperatures between 400°C and 700°C.

2.1.2 Residual compressive behavior of masonry prisms

The degradation of compressive strength of the masonry prisms is shown in Fig. 4. In general, it can be stated that both masonry types exhibit relatively good behaviour after exposure to elevated temperatures in terms of residual capacity. The prisms made with calcium silicate bricks display slightly higher compressive strength after exposure to temperatures between 300°C and 700°C than non-heated specimens. However, from 700°C onwards, the residual capacity drops significantly (see dotted line in Fig. 4). The effect of temperature on compressive strength of the prisms made with clay bricks is lower (see solid line in Fig. 4), which is a consequence of more favourable behaviour of the clay brick units after exposure to elevated temperatures.

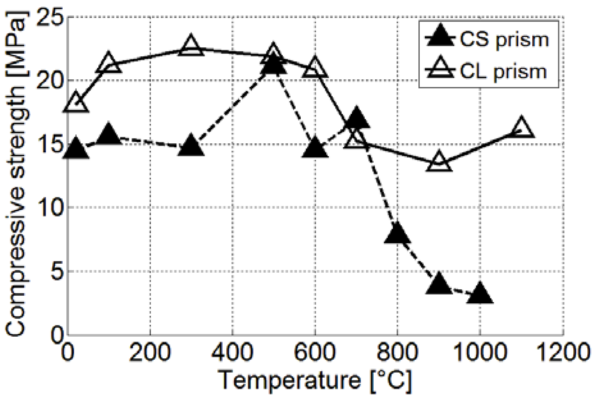


Fig. 4: Degradation of compressive strength after heating - masonry prisms (brickwork)

Examples of normalized stress-deformation curves for the prisms made of clay bricks and calcium silicate bricks are presented in Fig. 5. The prisms made of clay bricks (Fig. 5a) experience a marked degradation in stiffness from 500°C onwards, even though the residual compressive capacity remains relatively high. Stiff bricks compress the weak mortar, leading to pronounced deformation of the masonry prisms. The loss of stiffness is even more pronounced for the prisms made of calcium silicate bricks (Fig. 5b), where the stiffness starts to reduce already below 300°C onwards, well before the residual compressive strength drops at all. It is interesting to note that even though the clay bricks are significantly stiffer than the calcium silicate bricks for the entire range of temperature, the masonry prism formed using both type of bricks display similar stiffness. This is attributable to the fact that as the mortar is softer than both types of bricks, the stiffness of masonry is governed by the mortar as it is the least stiff component.

a) b)

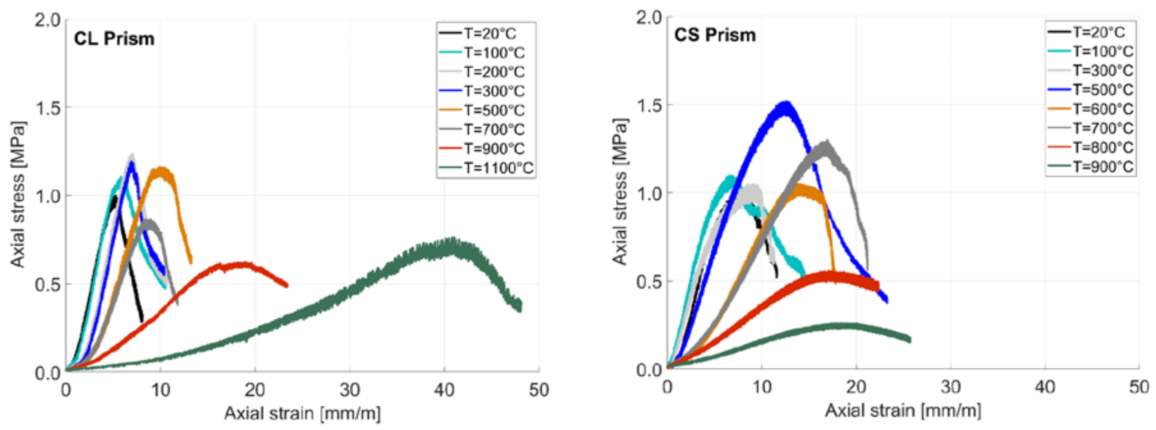


Fig. 5: Normalized stress-strain diagrams for masonry made of clay (CL) and calcium silicate (CS) bricks after exposure to elevated temperature

3. 3D FE NUMERICAL STUDY

The numerical analysis was performed using the 3D FE software MASA [14], which employs microplane model with relaxed kinematic constraint [15] as the constitutive law for quasi-brittle materials. In the framework of the present study, only masonry made of calcium silicate bricks was numerically investigated. The mechanical properties of mortar and brick unit are summarized in Table 1.

Table 1: Mechanical properties of calcium silicate (CS) brick and mortar

Mechanical properties	CS brick	Mortar
Initial tangent modulus [MPa]	8000	5000
Poisson´s ratio	0.15	0.15
Compressive strength [MPa]	21.2	19.8
Tensile strength [MPa]	0.7	1
Fracture energy [J/m^2]	30	35

It is important to note that only the uniaxial compressive strength of the masonry components was known from the experiments. Therefore, the remaining material parameters have been set based on literature data to correctly reproduce experimental results of the prism at room temperature (20°C). The same macroscopic properties were then used to simulate the behaviour of the masonry prism after exposure to elevated temperature (in residual conditions).

Fig. 6 displays the variation of residual compressive strength with temperature assumed in the model for both masonry components. The same as in the experiments, the compressive strength of mortar was kept constant until 100°C and then reduced linearly to zero at a temperature of 1000°C. On the other hand, the compressive strength of the CS bricks was increased initially with increasing temperature and the strength was suddenly reduced for temperatures above 700°C (Fig. 6). These laws were then used in the simulation of the masonry prism.

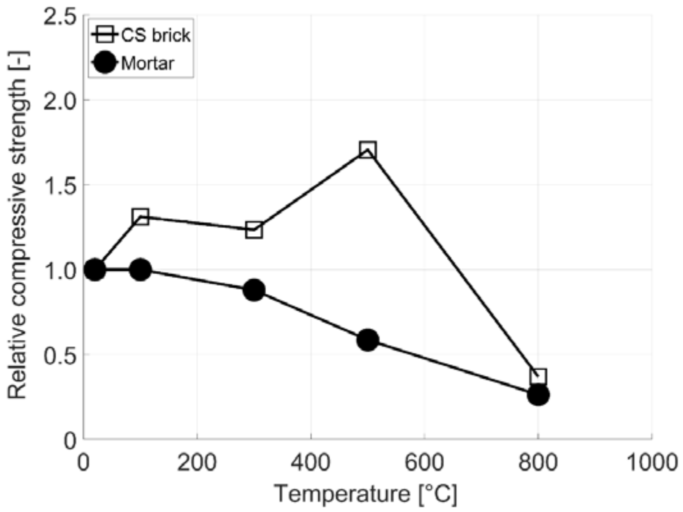
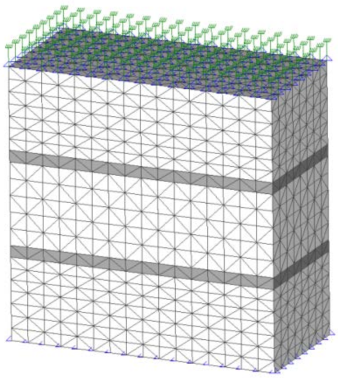


Fig. 6: Degradation of compressive strength after heating – brick unit, mortar

The 3D finite element discretization of the prism is shown in Fig. 7a. Tetrahedral (4-node) solid elements were used to mesh both masonry components. Perfect bond has been assumed between mortar and calcium silicate bricks. Similarly as in the experiments, free expansion of the specimen was allowed during thermal exposure (heating and cooling phase). However, fixed boundary conditions were imposed at the top and the bottom of the specimen for the uniaxial compressive test to simulate the experimental boundary conditions. The vertical load was applied at the top of the prism through displacement control. To get mesh objective results regularization scheme based on the crack band approach [16] was used. Post-heating material behaviour was investigated for the temperature range between 20°C and 800°C. The imposed temperature histories of the environment (ambient air) are shown in Fig. 7b. After thermal exposure, the uniaxial compressive strength of the specimen was measured in residual state.

a) b)



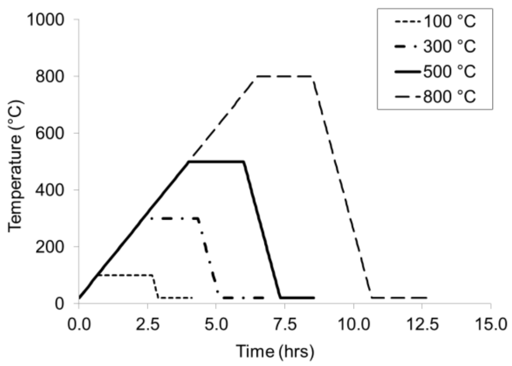
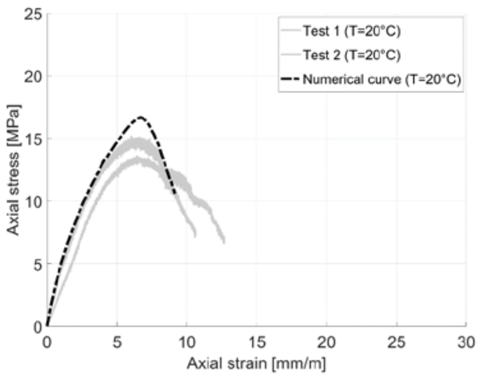


Fig. 7: a) 3D FE discretization of the specimen; b) Temperature history of the environment

Fig. 8 shows the numerical and experimental results for the uniaxial compressive test at room temperature. In Fig. 8a, the average axial strain, measured along the specimen height, is plotted against the axial stress for the case of tests at 20°C (no exposure to elevated temperature). The numerical stress-strain curve is in reasonably good agreement with the experimental one. Also, the crack pattern numerically obtained at the end of the compressive test (Fig. 8c) is very similar to that experimentally observed (Fig. 8b).

a) b) c)



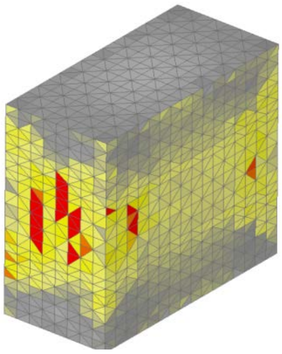


Fig. 8: a) Uniaxial stress-strain curve for calcium silicate brick prism (T = 20°C); Crack patterns in the calcium silicate prism - b) experiment; c) numerical simulation

Fig. 9 shows the numerical and experimental results for the uniaxial compressive test after heating. The variation of relative compressive strength with temperature is shown for the prism made of calcium silicate bricks. As can be seen, the numerical (dashed) and experimental (continuous) curves show a very similar trend.

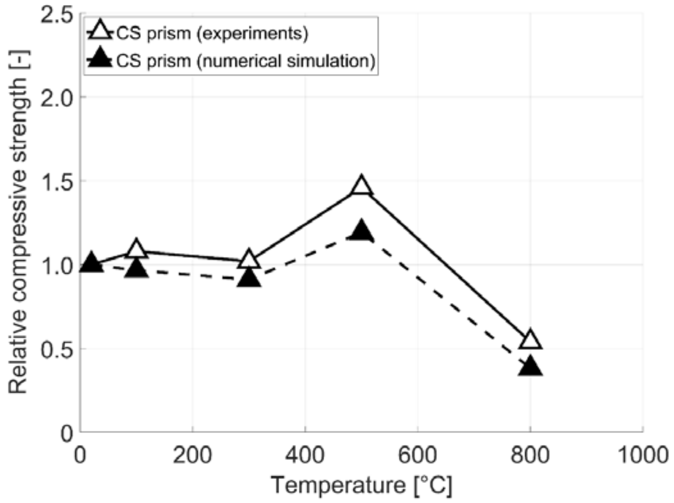


Fig. 9: Degradation of compressive strength after heating –masonry prism

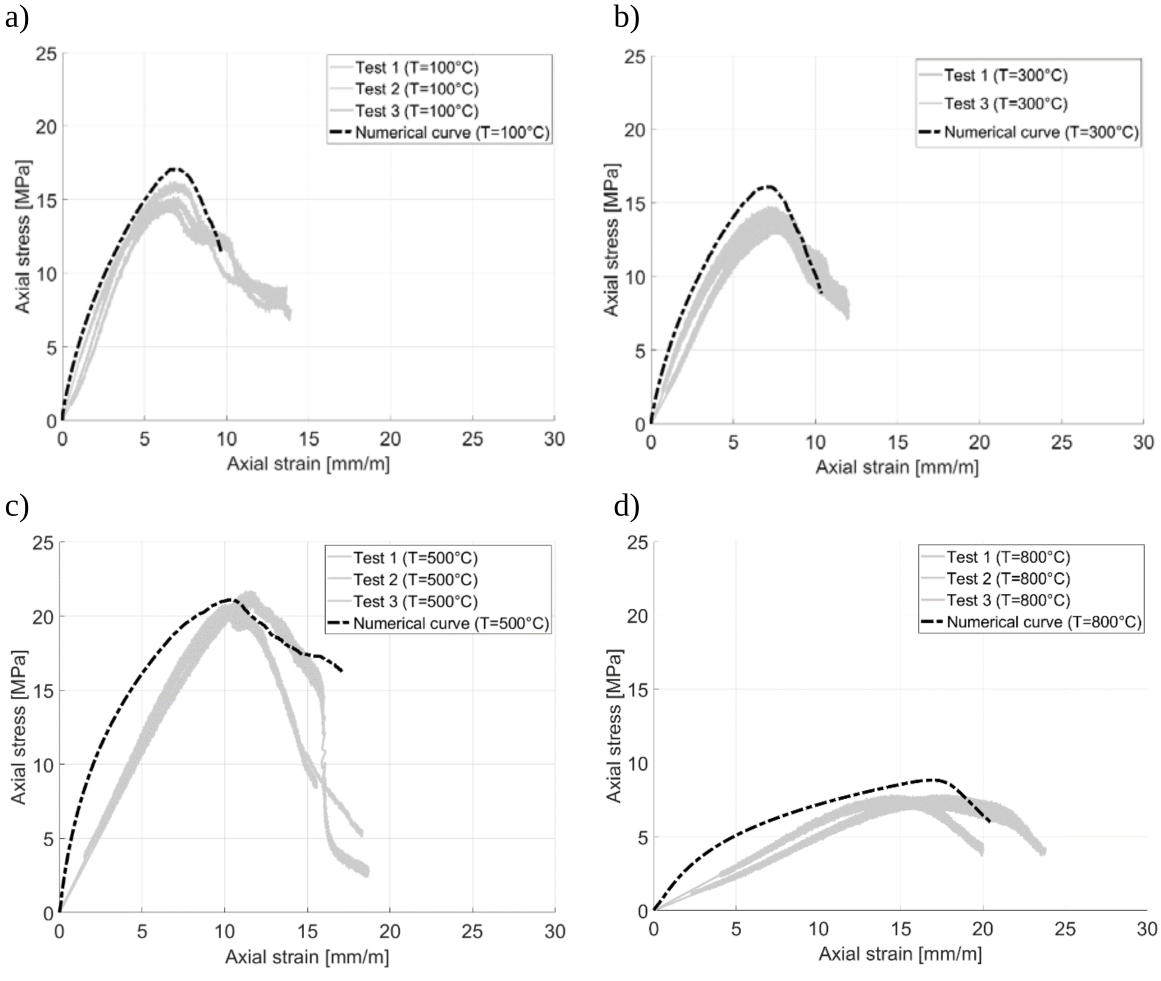


Fig. 10: Stress-strain curves for prism made of calcium silicate bricks after exposure to elevated temperature

The results of numerical simulations compared with the experimental results in terms of uniaxial stress-strain curves are shown in Fig. 10 for the exposure temperatures of (a) 100°C, (b) 300°C, (c) 500°C and (d) 800°C. The numerical (dashed) curves show a good agreement with the experimental ones, for all analysed cases. The model is able to realistically reproduce the variation of both residual compressive strength and stiffness with increasing temperature. As shown in the experiments, the increasing compressive strength of the prism up to 500°C is governed by the increasing strength of the calcium silicate brick (Fig. 10c). Conversely, the gradual degradation of mortar properties is reflected in loss of the stiffness with increasing temperature. Upon compressive loading after exposure to very high temperatures (above 700°C) a strong degradation of both masonry components leads to a significant loss of compressive strength and stiffness in the prism (Fig. 10d).

4. CONCLUSIONS

In the present work, the residual behaviour of masonry after exposure to elevated temperatures was experimentally investigated and numerically simulated. The main motivation for the performed tests was to provide more information for the assessment of fire-damaged masonry structures. It was found that the residual compressive strength of both masonry types is relatively good and more favourable than the current code provisions for hot state behaviour. However, mainly due to strong degradation of mortar, the residual stiffness is significantly influenced by the exposure to elevated temperatures. The numerical investigations were carried out based on 3D finite element modelling and utilizing temperature dependent microplane model for quasi-brittle materials as the constitutive law. The numerical modelling approach seems promising and is able to replicate the residual compressive behaviour of masonry system after exposure to elevated temperatures reasonably well.

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