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# Stress–strain curves for masonry materials exposed to fire action

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## ABSTRACT

On the basis of the results obtained by an extended experimental campaign aimed at the mechanical characterization of main masonry materials subjected to fire action, the variation factors of compression strength, ultimate strain in absence of preload and the apparent modulus of elasticity were detected in function of the temperature increasing. A uniaxial constitutive law was performed and validated on the stress–strain readings, allowing subsequent comparisons with the parametric curves proposed by European standards. The error indexes produced by the various constitutive models are also determined and compared. The out-of-plane mechanical behaviour of the horizontal cross sections is then investigated for masonry panels with full units: the adopted method is able to define the axial force-bending moment crushing domains for increasing exposure time to nominal fire, considering different types of stress–strain-temperature constitutive relations.

## 1. Introduction

As shown by past events, the mechanical stability of a masonry wall, in presence of high temperatures, is generally affected by a change in its strength and its stiffness as well as the significant thermal expansion induced. This is particularly relevant in case of compartment walls subjected to fire on only one side: the asymmetric change of strength and stiffness produces an alteration of the compressive stresses, also due to the increased eccentricity, and therefore a decrease of the load-bearing capacity.

Although the response to fire of masonry walls has been studied in the past, as reported by Lawrence and Ghanakrishnan [1] and Byrne [2], only recently experimental results have been compared with those from numerical models. Gnanakrishnan and Lawther [3] developed a simplified plane strain finite element model, obtaining over conservative results. O'Meagher and Bennets [4] produced a computer procedure based on the moment-curvature method of analysis: the thermo-structural model allowed for geometric as well as material non-linearity, and was capable of predicting the thermal bowing of both reinforced and unreinforced concrete walls.

In [5,6], Nadjai et al. reported numerical studies on the behaviour of walls in presence of fire on one side. They assumed preset curves of the compression strength-temperature relation proposed by Abrams in [7] and Thelanderson in [8] and the crushing strain-temperature relation proposed by Terro in [9] as an update to that proposed by Anderberg in [10]: these data were obtained from experimental tests on ordinary concrete specimens.

In more recent works [11,12], Nadjai et al. implemented in their model the solution for the compatibility of the linear flexural strain distributions with non-linear temperature profiles, as presented by O'Connor and Scotney in [13].

In [14], Al Nahhas et al. addressed the case of walls made of hollow bricks, which were subjected to experimental tests and subsequent analytical modeling. The distribution of the isotherms was determined through an energy balance approach by measuring the proportions of convection, conduction and radiation: the temperature-time curves were determined in various points throughout the wall thickness. Another relevant contribution to the experimental investigation of the behavior of clay hollow-brick masonry walls is given by Nguyen and Meftah in [15], where the high performances, detected in terms of exposure time to nominal fire, are presented.

In order to check the experimental results reported in [16] by Shields et al., Dhanasekar et al. [17] carried out numerical analyses on the thermal effects to determine the bowing of panels exposed to fire.

With regard to regulations, the recent adoption of the Eurocodes on structures, in particular the adjustments to EN 1996-1-2

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[18], led to the application of new methods for tabular or analytical design of bearing masonry walls, partially based on the results of a series of experimental trials conducted by Hahn et al. [19]. The analytical methods prescribed in the Eurocodes depend on the knowledge of the ultimate strain and compression resistance as functions of temperature, as well as the main thermal parameters (conductivity, specific heat and density). It should however be noted that some such parameters are significantly influenced by brick humidity, as reported by Nguyen et al. in [20], so caution should be exercised when applying standard diagrams in the design process.

An expanded overview of the state of the art, related to mechanical behavior and properties of masonry exposed to high temperature, is also given by Russo and Sciarretta in [21].

This paper firstly summarizes the experimental campaign presented by Andreini et al. [22] to determine the effects of high temperatures on the mechanical properties of several materials used in masonry walls (blocks, mortars), testing a series of cylindrical specimens (diameter 100 mm–height 200 mm). A special procedure was designed for high temperatures testing between 20 °C and 700 °C. The compressive strength, ultimate strain (in absence of preload), free thermal strain and the equivalent Young modulus were measured for each test and compared with the results obtained from those carried out at room temperature (20 °C).

Subsequently, from stress–strain readings, a uniaxial constitutive law as a function of temperature is proposed, applying specific iterative procedures of non linear regression analysis, for each material and compared to those drawn by European regulations.

The flexural behaviour of the generic wall cross section is also investigated: the method proposed herein is an adaptation of that formulated by Andreini and Sassu [23] with the aim to define crushing domains for the sections of panels subjected to the eccentric axial force acting on various types of masonry exposed to fire on one side. To this end, the temperature distributions across the wall thickness are first taken into account. Then, as the laws governing the decay of the material resistance and axial stiffness as functions of the temperature are known, the wall crushing strain fields are determined in relation to the curvature variation. Lastly, the crushing curves on the plane *N*–*e* (in which *N* is the axial force and *e* is the out-of-plane eccentricity) for increasing exposure time to nominal fire are determined, considering different types of stress–strain-temperature constitutive relations.

## 2. Materials and methods

The experimental campaign concerned about two hundred cylindrical specimens of the following typologies: Clay (CLAY), Aerated autoclaved concrete (AAC), Lightweight concrete (LWC), Façade lightweight concrete (LWC-FV), Lightweight concrete with voulcanic gravel (LWC-LAP), Hydraulic lime mortar, classes M5 and M10 (EN 1996-1-1 classification). The material mix design and the specimens storage conditions are reported by Andreini et al. [22].

The campaign has firstly provided experimental determination of mechanical properties of the several materials in cold conditions: a test procedure, called Cold Mechanical Characterization (CMC), has been developed with an accuracy similar to the EN 771 [24–26] and EN 998 [27,28], detecting the compression stress–strain curve up to the collapse with ambient temperature and humidity.

For the determination of the thermal behaviour of the materials at high temperatures in absence of applied loads, a second preliminary test procedure, called Thermal Characterization of the Transitional Phase (TCTP), has been performed monitoring the temperature in eight points of the test samples, where the thermocouples were applied.

The samples, after having been coated with mineral wool, were placed in a muffle furnace, with a predetermined heating program and then, once they reached an almost uniform temperature distribution inside themselves, were extracted and inserted in a thermally insulated "thermos" of AAC pre-heated at 200 °C to minimize the heat losses.

Finally, the tests that led to the effective determination of mechanical properties at high temperatures were carried out according to the methodology defined Hot Mechanical Characterization (HMC). It consists of a compression test on samples, coated as in TCTP, after having been subjected to a preset heating program. By observing the diagrams of the TCTP of each sample, it was deduced that the mineral wool cover and the AAC thermos limited the heat loss in a period of about 3 min as short as sufficient to run the HMC test. In fact, the maximum temperature reduction, recorded during the TCTP tests, was about of 5% on the lateral surface of the samples and, therefore, had a negligible influence on the results obtained by HMC procedure.

The experimental data furnished, for each sample, the free thermal strain $\varepsilon_{th}$, the coefficient of linear expansion $\alpha_{th}$, the stress–strain couple of values, thus the compressive strength $f_c$ and the ultimate strain $\varepsilon_{cu0}$, in absence of preload. It was also determined the apparent modulus of elasticity $E_b$ (blocks) and $E_m$ (mortar) tangent-secant to the stress–strain curve, for values corresponding to about 40% of the strength $f_c$ for each specimen. Further details are in Andreini et al. [22].

## 3. Uniaxial constitutive law determination

### 3.1. General

In this section the results obtained using the HMC organized by type of material are presented.

The knowledge of the average values of the mechanical properties leads to several continuous functions of temperature. In reference to what is proposed by Terro [9] for fitting the data from concrete specimens, it was chosen to consider a second order polynomial functions, that is:

$$\hat{X}(\theta) = A_0 + A_1\theta + A_2\theta^2, \tag{1}$$

where *X* represents the generic mechanical property depending on the temperature $\theta$. The values of the coefficients $A_i$ for the tested materials are reported by Andreini et al. in [22].

As for reinforced concrete and constructional steel in EN 1992-1-2 [29] and EN 1993-1-2 [30], the reduction factors can be defined dividing the expression (1) for the coefficient $A_0$, that is

$$\hat{k}_X(\theta) = 1 + \frac{A_1}{A_0}\theta + \frac{A_2}{A_0}\theta^2, \tag{2}$$

where $k_X$ represents the ratio between the value of the generic mechanical property at the temperature $\theta$ and the corresponding one at room temperature. The values of the coefficients $A_1/A_0$ and $A_2/A_0$ in the relation (2) for $f_{cm}$, $f_{ck}$, $\varepsilon_{cu0}$ and *E* for each tested material are indicated in Table 1, and the graphs of the functions of temperature are shown in Fig. 1. The coefficients $k_X$ related to CLAY remain roughly constant on the unit value: it confirms how this material be one of the most performing in case of exposure to fire. Furthermore, provided that the block materials present increments of ultimate strain and a reduction of the modulus of elasticity during the elevation of the temperature, the mortars and the AAC show appreciable increases of compressive strength up to a temperature of about 450–550 °C.

It is worth noting that the reduction factors $k_X$ expressed by Eq. (2) could be subjected to strong changes due to the effects of the load induced thermal strain. This aspect has not been