NUMERICAL STUDY ON THE RESIDUAL MECHANICAL PERFORMANCE OF TRADITIONAL BRICKWORK AFTER STANDARD FIRE EXPOSURE

Salvatore Russo¹ and Francesca Sciarretta²

¹Università IUAV di Venezia
e-mail: russo@iuav.it

²Università IUAV di Venezia
scifra@iuav.it

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Abstract. The paper addresses the issues of fire behavior of masonry walls made of traditional/historical component materials (bricks and mortar). There are reasons for coupling investigations on the residual mechanical properties to fire resistance data, aiming at a more complete knowledge of the behavior of a masonry member during and after fire exposure. The paper is part of a research that aims at investigating the relationship between fire and post-fire (i.e. residual) mechanical behaviour of masonry walls, paying attention to scale-related problems and to the possible exploitation of numerical tools to establish simplified approaches. The goal is to establish relationships between fire resistance ratings under exposure and decay in mechanical properties after exposure; the parameter of wall thickness is especially investigated, by choosing four different values (i.e. 12, 25, 38 and 51 cm). This is performed by means of FEM analysis with DIANA 9.4.4 software, simulating a standard ISO 834 fire resistance test followed by a mechanical compressive failure test on each investigated type of wall. The approach, successfully tested against experimental data already available, features a preliminary transient heat flow analysis which gives a numerical prediction of fire resistance after violation of I (Insulation) criterion; then, a staggered heat flow - stress analysis repeats the heating of the wall up to insulation failure and calculates the thermal strain accounting for cracking; finally, a ‘cold’ structural analysis in compression is performed on the thermally-deformed model after cooling. The paper also addresses a way for the extended application of the research outcomes, relying on a simple approach based on the concept of equivalent fire severity.
1 INTRODUCTION

The study of masonry structures subjected to severe actions, like earthquake and fire, is a lively branch of research; this is due to the variety of experimental and numerical issues peculiar of the composite material, and to the need for protection and preservation that very often involves masonry structures [1-3]. Especially for the latter reason, traditional structures, in particular historic and monumental ones, are mostly covered by research about the seismic behaviour [4-7]; besides, the issue of fire effects on masonry structures is very deeply investigated with reference to the behaviour under fire conditions [8-12], meaning the abundant scientific literature about the experimental and numerical research on fire resistance. The available information allows to establish the very good behaviour of masonry structures under fire, due to the high values of thermal inertia that can be attained by masonry members because of the walls’ thickness, density and low conductivity of the component materials. The excellent load capacity under fire conditions (that corresponds to R fire resistance criterion) is of particular relevance; generally, the evidence of fire tests demonstrates that load-bearing masonry members reach fire collapse by violation of E (i.e. integrity) or, in most cases, I (i.e. insulation) criterion. However, the abundant experimental information yielded from fire resistance tests cannot be useful to make inferences about the tested members’ residual structural reliability.

Currently, the residual mechanical behaviour of a masonry structure after fire exposure, covering especially the properties’ decay, can be a very rich research field at its early exploitation [13-18]; it especially applies a concept of fire safety that refers not only to fire endurance but also to post-fire situation. Generally, the maximum temperature of exposure is the main factor that affects the residual mechanical properties of concretes and masonry materials (aside from the parameters that are peculiar to the material); secondly, the duration of exposure, the heating rate and the cooling regime [17] are of relevance. The main difficulties in this field of research chiefly regard the expensiveness and complexity (especially in type and combination of component materials) of masonry testing, and of fire simulation, and the possible sample size dependency of results. On the other hand, there are reasons to search for ways to exploit the great amount of information from fire resistance tests, for instance to find relationships between fire and post-fire performance of masonry walls; this would be very useful for design as well as assessment of structures. Such a goal would surely benefit from experimental research, but this may not be easy and promptly feasible; on the other hand, numerical research would provide useful and quick predictions and/or confirmations about the physical behaviour of the objects of study.

2 FINITE ELEMENT MODELLING

2.1 Research background

Throughout previous research described elsewhere [15], the effect of high temperatures on the residual mechanical properties of traditional masonry samples was assessed experimentally, with reference to a low-medium temperature range (i.e. 300 - 600°C) applied to 25 cm thick wallettes of handmade type bricks and cement mortar. Then, a numerical approach was proposed [18] to investigate the influence of thermal cracks and micro-cracks - supposed to be prevalent over non-mechanical changes due to high temperature exposure - on the residual compressive behaviour of the same wallettes; a 3D finite element model of the sample, based on a micro-modelling approach, was proven suitable for the procedure. In detail, the damage induced by the thermal loading on the exposed surface, previously observed throughout tests (Figure 1), was adequately represented by opportune adopting a
cracking material model; the effect of the thermally induced cracks is clear in the subsequent structural analysis (i.e. a simulated compressive test) and is largely responsible for the mechanical decay of the material (i.e. decrease in compressive strength); the compressive stress-strain graphs of the tested wallettes are shown in Figure 2 to provide a quick look at the experimental behaviour. This model also provided very similar results to the model of a 2 m tall wall stripe of the same thickness and texture. For these reasons, the small model (shown in Figure 3) was adopted to perform the present numerical research.

Figure 1: Experimental observation of mechanical decay after exposure to high temperatures in two wallettes, 1 and 2, sides A (exposed) and B (unexposed).

Figure 2: Experimental behaviour of unexposed (black lines) and 600°C exposed (gray lines) wallettes

Figure 3: The proposed procedure for the numerical assessment of the residual load capacity (A) and the adopted materials’ models (complete stress-strain behaviour, B) [18]
The numerical procedure is here applied to a first attempt of correlation between fire endurance and post-fire residual behaviour, with reference to the compressive regime, accounting for walls of different thickness. The whole procedure means to simulate the residual post-fire behaviour that walls could show after undergoing a standard fire test and getting an endurance rating. To allow comparison with the available information (both experimental and numerical), the same materials and material models as before were adopted; the thickness values thus refer to the width of the handmade type brick, that is 12 cm, and are: 12, 25, 38 and 51 cm (Figure 4). The choice of four values means to investigate as widely as possible the material’s behaviour at varying thickness. The problem, with reference to the adopted numerical procedure, is subdivided as follows: 1) to establish a fire resistance period for the four walls (heat flow analysis), 2) to assess the damage in the walls after the heating period (heat flow-stress analysis), and 3) to assess the performance of the damaged walls under compression (structural analysis).

2.2 HEAT FLOW ANALYSIS

The first step of the present research consists of the numerical assessment of the fire endurance ratings of the four masonry walls of different thickness; the basic ratings of 15, 20, 30, 45, 60, 90, 120, 180, 240 - adopted by the Italian fire building code - are taken as reference and a maximum test duration of 240 min is established; an initial temperature of 20°C is assumed. Following what was previously done on homogeneous models, a transient heat flow analysis with ISO 834 curve input was performed to assess the fire resistance numerically; it was assumed that the violation of the Insulation (I) criterion implies the failure of the masonry member under fire conditions. This means that the analysis is to be stopped as soon as the temperature on the unheated face of the wall rises up to 150°C.

The models consist of eight-nodes brick elements and four-nodes boundary elements for flow analysis, accounting for heat transmission by convection and radiation. Observing the temperature-time graph of Figure 5, the results of the thermal analysis can be appreciated. The thinnest wall (12 cm) fails after 57 minutes and thus can be attributed a I 45 fire endurance rating; in the same way, the 25 cm thick wall, which fails after 178 minutes, gets a I 120 rating. The two thickest walls (51 and 38 cm) behave in a very similar way and both attain I 240. In fact, in both cases the thermal inertia granted by the section size allows the walls to reach the maximum duration; at 240 minutes, the 38 cm thick wall shows a small temperature rise on the unexposed face (i.e. +31°C ); for the 51 cm thick wall, the temperature increase is
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negligible (i.e. +4°C). The results are in a pretty good agreement with available tabulated ratings for similar types of wall [19-21] (Table 1).

Table 1: Fire endurance ratings of the models predicted after FEM heat flow analysis.

<table>
<thead>
<tr>
<th>Thickness (cm)</th>
<th>Present research</th>
<th>EC6 (tables N.B.1.1 and N.B.1.5 [19])</th>
<th>Italian fire design prescriptions [20]</th>
<th>2006 International Building Code [21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>12*</td>
<td>45</td>
<td>≤ 90</td>
<td>30</td>
<td>180</td>
</tr>
<tr>
<td>25**</td>
<td>120</td>
<td>≤ 90</td>
<td>180</td>
<td>&gt; 240</td>
</tr>
<tr>
<td>38**</td>
<td>240</td>
<td>≥ 120</td>
<td>240</td>
<td>&gt; 240</td>
</tr>
<tr>
<td>51**</td>
<td>240</td>
<td>≥ 120</td>
<td>240</td>
<td>&gt; 240</td>
</tr>
</tbody>
</table>

Figure 5. Numerical prediction of fire behaviour of the four walls: time of insulation (I) failure

3 STRUCTURAL ANALYSIS

A phased analysis was run on the models previously described, consisting of a heat flow + nonlinear structural analysis (first phase) and a nonlinear structural analysis (second phase). The nonlinear analyses are performed on the models consisting of twenty-nodes bricks, into which the four-nodes flow brick elements are automatically converted. The two-phases calculation allows to assess the effect of the thermal load on the mechanical properties of the masonry samples after the action of temperature, depending on the different thickness and exposure duration in the four cases. It is worth noticing by now that the four values of thickness allow to appreciate the effect of the same exposure duration (240 min) on walls of different thickness (38 and 51 cm); moreover, with a comparison to already available
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Numerical and experimental data, also the effect of different exposures on the same wall (25 cm thick) will finally be appreciated. The material model input is shown above in the graph of Figure 3. The component materials are supposed, with acceptable simplification for the scale of approach, to be isotropic; the details about the property values are summarised in Table 2.

Table 2. Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>Elastic modulus (N/mm²)</td>
<td>5710</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio of brick</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Compressive strength of brick (N/mm²)</td>
<td>19.17</td>
</tr>
<tr>
<td></td>
<td>Tensile strength of brick (N/mm²)</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion coefficient of brick (°C⁻¹)</td>
<td>4.00 • 10⁻⁶</td>
</tr>
<tr>
<td>Mortar</td>
<td>Elastic modulus (N/mm²)</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio of mortar</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Compressive strength of mortar (N/mm²)</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>Tensile strength of mortar (N/mm²)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Fracture energy of mortar (N/mm) – horizontal joints</td>
<td>17.68</td>
</tr>
<tr>
<td></td>
<td>Thermal expansion coefficient of mortar (°C⁻¹)</td>
<td>6.60 • 10⁻⁶</td>
</tr>
</tbody>
</table>

3.1 Flow-stress analysis (phase 1)

The stepwise heat flow analysis, up to the time of insulation failure, is repeated to provide the input for the nonlinear structural analysis aimed at reproducing the mechanical structural effect of the thermal loading. The criterion for crack opening under thermal loading accounts for the sum of gravity plus thermal stress to equal or exceed the tensile strength \( f_t \); no other superimposed load is accounted for, as it happened during the tests on wallets:

\[ \sigma_G + (E \cdot \alpha \cdot \Delta T) \geq f_t \]

where \( \sigma_G \) is the gravity-induced stress state, \( E \) is the elastic modulus, \( \alpha \) the coefficient of thermal expansion, \( \Delta T \) the temperature difference and \( f_t \) the tensile strength. The final output of the first phase of FEM analysis is shown in Figure 6, in which the concentration of thermal damage (i.e. cracks) on the exposed side is clearly visible.

3.2 Nonlinear structural analysis (phase 2)

The output of the flow-stress analysis worked as input for the subsequent nonlinear structural analysis, aimed at the simulation of a compressive test on the damaged walls after the standard fire resistance test. Since the adopted FEM procedure provides for a quick assessment of the residual behaviour up to compressive strength, the post-peak behaviour is not taken into account. The original properties of reference were assumed on the grounds of the theoretical-experimental information available from previous research work [15], i.e. \( f_c = 9.58 \) N/mm² and \( E = 2723 \) N/mm², with the following stress-strain compressive law:

\[ \frac{\sigma}{f_c} = \frac{2}{3\varepsilon_c} \varepsilon \]

for \( 0 \leq \varepsilon \leq \varepsilon_c \).
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\[
\frac{\sigma}{f_c} = \left(1 - \frac{2\varepsilon_{c1}}{3\varepsilon_{c0}}\right)\varepsilon^2 + \frac{2}{3\varepsilon_{c0}}\varepsilon + \frac{\left(2\varepsilon_{c1} - 1\right)}{\varepsilon_{c1} - \varepsilon_{c0}}\varepsilon^2
\]

for \(\varepsilon_{c0} \leq \varepsilon \leq \varepsilon_{c1}\)

where \(\varepsilon_{c0}\) is the strain value at 2/3 of the compressive strength and \(\varepsilon_{c1}\) is the strain at \(f_c\); the law is plotted in solid line in the graph of Figure 7-1.

The results of the nonlinear structural analysis on the four models are illustrated in the graphs of Figure 7 and listed in Table 3. Observing the graph of Figure 7-1 and Table 3 together, the decay in compressive strength due to exposure to the standard fire tests is very clear in each of the four cases. The decay is lesser (-29%) for the thinnest wall that underwent the shortest exposure duration (57 min); the two thickest ones, both exposed to the maximum duration (240 min), both lose the 47% of compressive strength; the greatest decay (-49%) affects the 25 cm thick wall, exposed for 178 minutes. This is clarified even more by the graph in 7-2, which reports the factor of decay in compressive strength \(f_{c,\text{res}}/f_c\) as a function of the thickness, while not accounting for the different exposure durations. Concerning the elastic modulus, the entity of decay is much smaller, and is maximum in the case of the thickest wall (-16%); the strain value at compressive strength undergoes appreciable decrease in all cases (-47%). All the numerically detected features of residual behaviour, i.e. significant reduction in compressive strength after exposure to a severe fire condition, small (but increasing at increasing exposure duration) reduction in elastic modulus, significant reduction in strain capacity in the pre-peak field, are substantially in agreement with available information from literature and testing and analysis experience [15, 17, 18].

Figure 6. Results of structural analysis: crack pattern after thermal stress (phase 1) and at compressive failure (phase 2)
3.3 Evaluation of results

The severity of fire exposures with different temperature-time paths is a long-time debated issue, especially concerning the disparity between the standard fire curve and the real fires. The oldest method is based on the concept of equal area; that is, equal areas under two fire curves, above a baseline set at 300°C, mean equal severity of exposures. Although this concept is scientifically questionable [22], it is still in use today because of its proven safety; in the following paragraphs, the numerical exposure severity is being linked to the residual compressive strength. This will allow to appreciate (unlike the graph in Figure 7-2) the effects of different exposure durations on walls of the same thickness and, moreover, to compare data from different sources.

The decay of a generic mechanical property \( X \) after fire exposure, i.e. the ratio \( X_{res}/X = k_\theta \) between the decayed and the original property, could be expressed as a function of the maximum exposure temperature \( \theta \), provided that the other relevant factors (namely heating...
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rate, duration at maximum temperature and cooling regime) stay unvaried. Equation (3) was elaborated for the investigated 25 cm wallettes of traditional bricks and cement mortar exposed for 1 hour at maximum temperature, with a heating rate of 19°C/min and natural cooling [15], on the grounds of experimental results:

\[
k_{\theta} = \frac{f_{c,\text{res}}}{f_c} = -(1.0 \times 10^{-6}) \theta^2 + (5.0 \times 10^{-4}) \theta + 0.9898
\]  

(3)

With reference to Figure 8-1, that shows temperature-time graphs at temperatures increasing from 400 to 1000°C (curves A-G at steps of 100°C) keeping the other parameters unchanged, the areas under the time-temperature curves increase. The values of \(k_{\theta}\) that can be yielded from Equation (3) for such maximum temperatures can thus be seen as a function of the area under the respective time-temperature curve A-G.

While recalling the concept of equal area - equal severity, let us define the severity factor \(SF\) as the ratio between the maximum possible and the actual severity of exposure; the former corresponds to the severity of a 240 min (i.e. the maximum resistance rating) exposure to the standard fire ISO 834 - that is represented by the area among the baseline, the ISO 834 curve and line 3 in Figure 8-2 - while the latter is the severity given by the same time-temperature curve over the duration of the specific fire resistance period (Figure 8-2, areas defined by straight lines 1 and 2, see above Section 2.2).

Then, the theoretical-experimental relationship between exposure severity and mechanical decay for the 25 cm thick wallette can be expressed as a function of the severity factor \(SF\) by the following formula:

\[
k_{\theta} = \frac{f_{c,\text{res}}}{f_c} = -0.8317 \, SF + 1.0552
\]  

(4)

that is plotted in dotted line in the graph of Figure 9. The capital letters indicate the curves to which each of the cross markers refer. On the basis of the equivalent severity, this expression allows to compare the prediction of the theoretical-experimental formula to the numerical outcome of the present research, concerning the thickness of 25 cm; the numerical datum clearly confirms the numerical-experimental prediction.

Figure 8. Temperature-time graphs: 1) different maximum temperatures (400-1000°C) with fixed duration, heating and cooling regime, and 2) duration of exposure under ISO 834 curve for the present numerical simulation (line 1: \(t=12\) cm, line 2: \(t=25\) cm, line 3: \(t=38\) and \(51\) cm)
4 CONCLUSIONS

- The numeric study above presented means to investigate the residual post-fire compressive behaviour of traditional brick masonry walls of certified fire resistance; it puts into relationship the fire resistance period and the mechanical decay of walls 12, 25, 38 and 51 cm thick, with reference to compressive strength.

- All the analyses assume the same materials for all models, the standard ISO 834 curve as input and the insulation (I) failure criterion for exposure; in this way, only the thickness affects the time of insulation failure, and consequently dictates the duration and finally the severity of exposure, as demonstrated by the heat flow analysis (phase 1). The calculated durations are 57 (for the 12 cm wall), 178 (25 cm) and 240 (38 and 51 cm) minutes.

- Concerning phase 2, as it was expected, the cracking behaviour of the walls under fire exposure was satisfyingly represented by the models. The greatest decrease in compressive strength (-49%) was attained by the 25 cm thick wall. In fact, although it did not undergo the severest exposure, it showed the most unfavourable combination of thickness and severity of exposure. This is especially noticeable after comparison to the 38 cm thick wall (which lost the 47% in compressive strength after a much longer exposure duration).

- The very slight difference in compressive strength between the two thickest walls (i.e. 38 and 51 cm) can be ascribed to the significant thickness itself, which in both cases
minimizes the incidence of the damaged thickness on the whole resistive cross-section. This inference is confirmed by comparison to the other two models (i.e. 25 and 12 cm thick) and could be supported by further investigation on intermediate values.

- This numerical research proposes factors of original properties < 1 (listed in Table 3) that can be of reference for correlation between fire endurance and residual load capacity; in fact, such factors express the mechanical decay in post-fire condition in the worst case, i.e. after the wall has exceeded its prescribed fire resistance limit. This holds provided that the wall still retains its integrity and (although diminished) structural adequacy. The proposed factors have got a first partial confirmation concerning the thickness of 25 cm, after comparison to theoretical-experimental decay laws previously elaborated by the authors.

- This first consideration allows to assume a certain severity value, independent from the actual time-temperature history, to be related to the halving of compressive strength for the thickness of 25 cm.

- This study will be a ground for a further numerical investigation aimed at assessing relationships between severity and mechanical decay, which will likely focus on the residual compressive strength. The present procedure will be applied with different input curves, to refine the results here obtained and represented in the final graph, with the particular intention of deepening the investigation about all the thickness values and possibly finding experimental confirmation.

REFERENCES


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