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A Multi-Physics and Multi-Scale Approach For Hollow Clay-Brick Masonry

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Abstract — The behavior of mechanically loaded hollow brick masonry walls when exposed to fire is investigated numerically. A multi-scale thermo-mechanical model based on the Arlequin framework is developed. Plate models are used in the brick's walls and coupled to accommodated 3D models in the brick's corners. This is a first achievement in this work. The thermo-mechanical multi-scale coupling and treatment is a second one. Numerical results are given to enlighten our achievements.

Key Words — hollow clay brick masonry, multi-scale, multi-physics, arlequin method.

1 Introduction

Brick masonry is an old building solution that has been used for more than 10,000 years. Still it occupies an important part of the construction market today with new engineering challenges to design bricks, meeting new legal requirements. Therefore, understanding the behaviour of masonry, especially of hollow brick masonry is essential to define reliable processes that could help one designing new products, while assessing the safety of a global building bearing both mechanical and severe thermal loadings. As a matter of fact, building regulations in Europe require that in the event of an inside-fire, masonry walls should provide an adequate barrier to fire for a legal prescribed time to allow the evacuation of the building.
The fire resistance of a mechanically loaded given wall is determined experimentally in specialised laboratories by subjecting this wall to standard costly fire exposition tests. However, due to the variability and uncertainties of the physical and mechanical properties of burnt-clay bricks, but also to the complexity of the structure itself (several geometrical parameters of different length scales) it is prohibitive to design new products meeting the aforementioned legal requirements.

To reduce the experimental tests and to be able to predict the fire resistance of masonry structures, modelling and numerical simulations are the appropriate alternative.

In this work, our goal is the modelling and the simulation of the thermo-mechanical behaviour of hollow clay brick walls when submitted to mechanical and thermal loads. The achievement of this goal is burdensome with regard to the complexity of these structures. Indeed, masonry walls are quite heterogeneous. They rely on hollow clay bricks, mortars and multiple contact interactions. The resulting problem is not only multi-physics but also multi-scale. In fact, in a masonry wall, the geometrical dimensions range from millimetres for the mortar to meters for the wall, going through centimetres for the brick's shards and decimetres for the bricks (see Figure 1).

The existing models often rely on two-dimensional approaches based on macroscopic masonry models, either derived at the macroscopic level or obtained by a homogenization theory (e.g. [1]). In both cases, masonry is considered as an equivalent homogeneous and continuum medium with appropriate macroscopic properties. Thus, these approaches preclude effective three-dimensional thermo-mechanical effects of masonry. More importantly, it precludes detection possible local failures or instabilities.

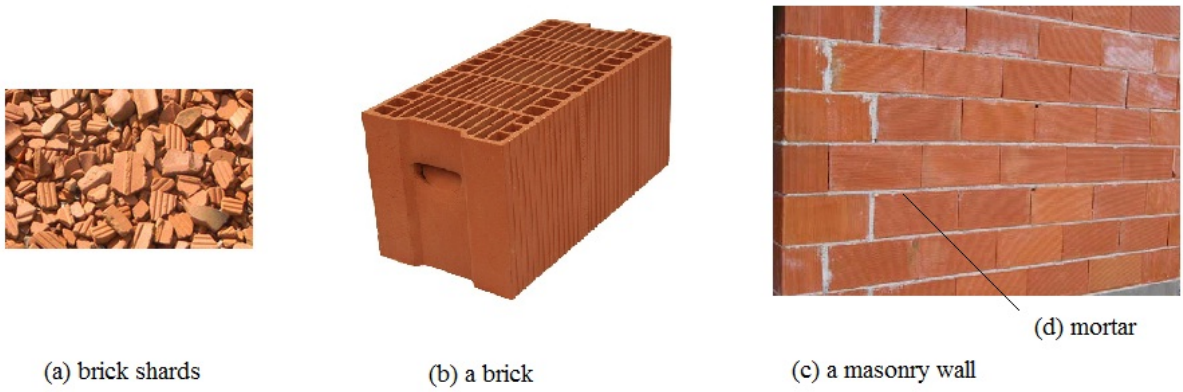

FIGURE 1 – Different length scales in a masonry wall

In this work, a multi-scale modeling for the thermo-mechanical behaviour of a masonry wall, composed of hollow clay bricks and mortars, is developed within the Arlequin framework [2, 3]. For both mechanical and thermal aspects, thin structured models (beam for the 2D case and plate models for the 3D case) are used there where these reduced models are available, namely far from areas of possible stresses of thermal concentrations or singularities. In these zones, local full 2D models (in the 2D case) and 3D models (in the 3D case) are used and coupled to the structure models within the Arlequin framework. A reduced 2D Arlequin model for a brick's section is represented in Figure 2.

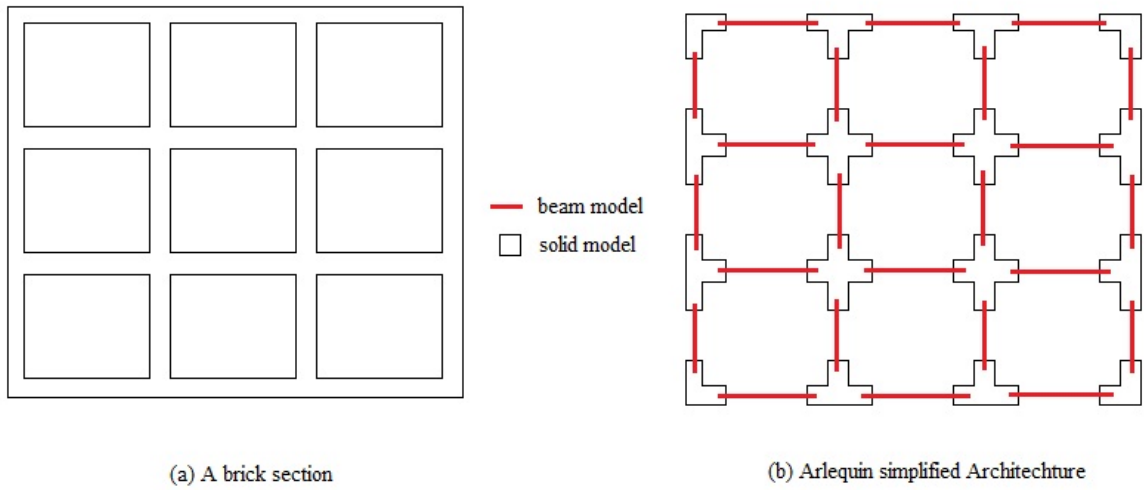

FIGURE 2 – A brick section architecture (a) in the Arlequin framework (b)

2 Arlequin formulation of the thermo-mechanical problem

The Arlequin method [2, 3], is a flexible tool used to conduct multi-scale and multi-model simulations. It is based on three main ingredients : (i) splitting of the domain into overlapping subdomains where different models are considered, (ii) an energy distribution between these models by using weight functions and (iii) a weak coupling of the solutions of the superimposed models in a gluing zone.

For Clarity, we consider the thermo-mechanical problem defined in a domain Ω. The latter is divided into two overlapping subdomains Ω_s to which a 3D model is attached and Ω_p to which a plate model is attached. It is assumed that $\Omega_s \cup \Omega_p = \Omega$ and $\Omega_s \cap \Omega_p = \Omega_c$, the latter being of positive measure. It represents the coupling volume (see Figure 3).

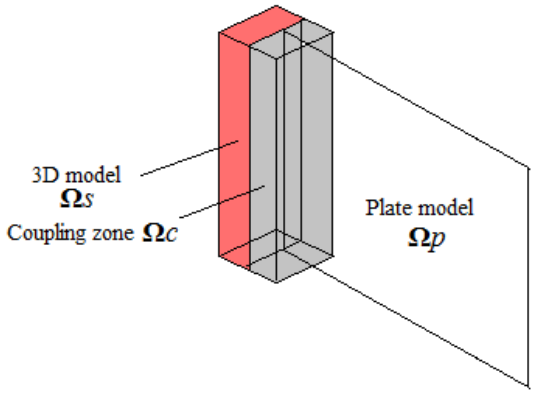

FIGURE 3 – A coupled plate solid model in 3D

Written in the Arlequin framework, the thermo-mechanical problem consists in finding for each positive time t in the interval $]0, t_{\text{study}}]$, the displacement fields $\mathbf{u_s}(t)$ and $\mathbf{u_p}(t)$, the temperature field $T(t)$ and the coupling field $\boldsymbol{\lambda}(t)$ by solving the following system of weak equations :

$$\begin{cases} A_{th}(T,\theta) + C_d(T,\theta) + C_v(T,\theta) + R(T,\theta) = L_{Th}(\theta) & \forall\theta \in W_s \quad (1) \\ A_{m,s}(\mathbf{u_s}, T, \mathbf{v_s}) + C(\boldsymbol{\lambda}, \Pi(\mathbf{v_s})) = L_{m,s}(T, \mathbf{v_s}) + L_{th,s}(T, \mathbf{v_s}) & \forall\mathbf{v_s} \in \mathbf{V_s} \quad (2) \\ A_{m,p}(\mathbf{u_p}, T, \mathbf{v_p}) - C(\boldsymbol{\lambda}, \Pi(\mathbf{v_p})) = L_{m,p}(T, \mathbf{v_p}) + L_{th,p}(T, \mathbf{v_p}) & \forall\mathbf{v_p} \in \mathbf{V_p} \quad (3) \\ C(\boldsymbol{\mu}, \Pi(\mathbf{u_s} - \mathbf{u_p})) = 0 & \forall\boldsymbol{\mu} \in \mathbf{V_c} \quad (4) \end{cases}$$

The thermal behaviour of the structure is governed by the mono-model weak equations (1), in which we have taken into account conduction (Cd), convection (Cv) and radiation(R) phenomenon. (Note that it is possible to use the Arlequin coupling for the thermal problem with no technical difficulties).

The system (2)-(4) governs the mechanical behavior of the structure. Equations (2) and (3) express the equality between the virtual work of internal forces and external forces respectively in the 3D model and in the plate model, with the appearance of a gluing load in the coupling volume Ω_c embodied in the operator C and where the terms $L_{th,s}$ and $L_{th,p}$ denote the thermo-mechanical coupling terms. Equations (4) enforce a weak "equality" between the two solutions us and up in the Arlequin coupling zone.

Notice that :

- unlike the classical Arlequin formulation used in [4] and by following [2], this formulation uses an accommodation operator, denoted Π in the coupling terms. The choice and the relevance of this operator will be discussed during the conference.

- the thermal problem is time dependant whereas the mechanical problem is just quasi-static. The two problems are coupled through thermo-mechanical constitutive laws, but also through mechanical material parameters variation with respect to significantly varying temperature in the wall, during burning.

3 A first numerical test

A first mechanical calculation is performed on a brick cell, the elementary pattern of a hollow brick, without considering thermal effects. The considered structure is assumed to be clamped on its bottom surface and submitted to a uniform density of compressive load on its top surface. The simplified architecture of the pattern within the Arlequin framework is composed of four plates coupled to four 3D solids, located in the corners of the cell (see Figure 4).

In Figure 4, the iso-values of the norm of the displacement field are shown on the deformed shape of the structure.

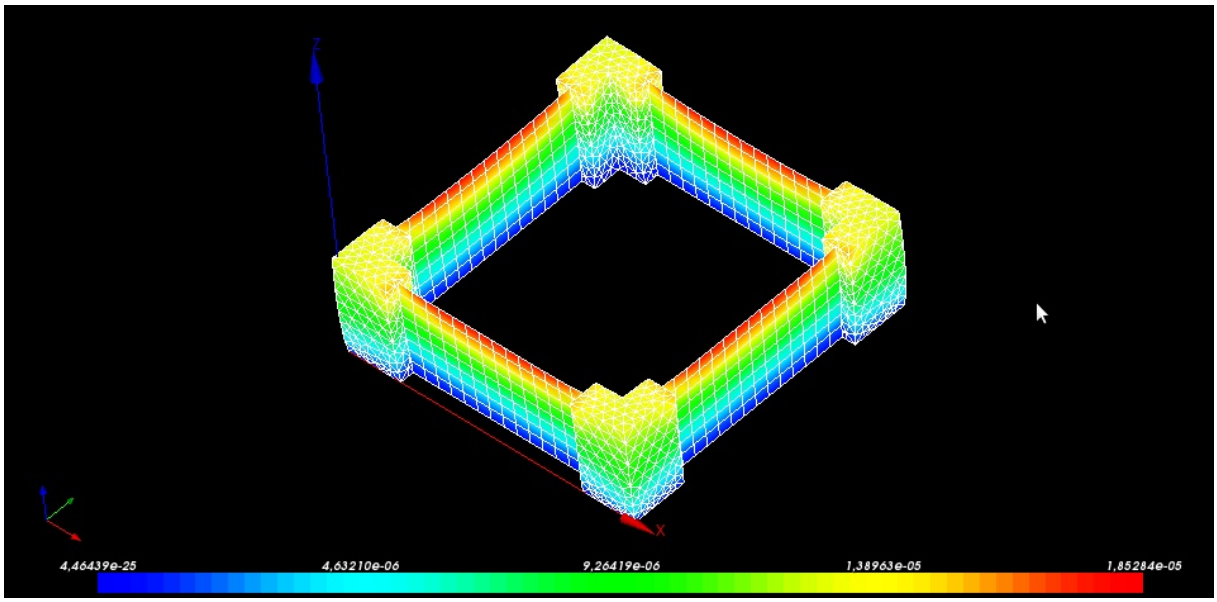

FIGURE 4 – Norm of the displacement field in the cell

Other more involved simulations will be shown during the conference.

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