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► To cite this version:

A Chaker, Amna Rekik, A Langlet, Ridha Hambli. Micro-mechanical model accounting for creep and damage of masonry. ICSCES2021, Jul 2021, Aracona, Italy. <hal-03527572>

HAL Id: hal-03527572

<https://hal.science/hal-03527572v1>

Submitted on 16 Jan 2022

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Micro-mechanical model accounting for creep and damage of masonry

A. Chaker¹, A. Rezik¹, A. Langlet¹, and R. Hambli¹

Univ. Orléans, Laboratoire de Mécanique Gabriel LaMé, Unité de recherche EA 7494,
France

aida.chaker@univ-orleans.fr, amna.rezik@univ-orleans.fr,
andre.langlet@univ-orleans.fr, ridha.hambli@univ-orleans.fr

Abstract. The main objective of this paper is to predict numerically the viscoelastic behaviour of damaged masonry accounting for the creep of its both components (bricks and mortar). Creep functions of bricks and mortar joints are assumed to follow the Generalized Maxwell (GM) model. The proposed semi-numerical model is based on two steps. The first one estimates the creep behavior of the microcracked mortar by coupling the brittle Griffith's theory to the Ponte-Castañeda & Willis homogenization scheme. The second step consists to apply the finite elements method to predict the local behaviour of a loaded masonry wall. The proposed model is validated with analytical solution available for homogeneous panel submitted to vertical compressive load. Two cases are considered for comparison purpose: masonry with elastic bricks and viscoelastic ones.

Keywords: Masonry, creep, microcrack, Finite element method

1 Introduction

Masonry is a traditional building material made up of bricks and mortar. It is still adopted nowadays thanks to its low cost and high resistance. Various numerical models were proposed recently to predict the mechanical behaviour of masonry structures [1, 8, 9]. An experimental and numerical study were carried out by Choi et al. [6] in order to investigate the creep of masonry. It was then demonstrated that the Modified Maxwell (MM) model presents well the mortar creep behaviour better than other rheological models (Burgers, Feng, Ross and USBR). Accordingly, the MM's model will be used herein to model the mortar creep phenomenon. While, the brick's creep effect was neglected in the majority of previous works. Sayed-Ahmed et al. [12] proved that bricks present the origin of 20% of the total masonry creep. In this study, it is proposed to account for this phenomenon.

Moreover, notice that presence of microcracks due to creep or external conditions (temperature, moisture, etc.) is a possible origin for the masonry collapse. Accordingly, accounting for presence of microcracks should better reproduce the masonry's real behaviour. The study of the the combining effect of creep and

damage on masonry is rarely investigated in the litterature [7, 11]. Rezik [10] proposed a 2D finite elements (FE) model based on periodic homogenization and the Ponte Castañeda & Willis (PCW) model [3] was used to assess rigorously mortar's cracks interactions and their spatial distribution.

This paper aims to estimate the local behaviour of the microcracked viscoelastic masonry structure using the FE method inspite of periodic homogenization procedure. Only the behaviour of the mortar is homogenized using the PCW model. The proposed model accounts for the creep of both components (mortar and brick) following the Generalized Maxwell rheological model. Results of the proposed model are validated for the case of masonry wall subjected to compressive loads by comparison with analytical available solution and numerical one provided in Rezik [10]. Hereafter we provide the basic steps on which relies the proposed model as well as some first results obtained for a compressed masonry wall.

2 Creep properties of the microcracked mortar based on the PCW model

This section provides a rigorous assessment of the effective creep properties of the microcracked mortar accounting for cracks interactions, their spatial distribution and state (opened). This step is based on the coupling, in the symbolic space, between the brittle Griffith's theory and the Ponte Castañeda & Willis analytical homogenization model [3]. The symbolic effective stiffness tensor \tilde{C}^* of the mortar reads:

$$\tilde{C}^* = 3\tilde{k}_{PCW}^*J + 2\tilde{\mu}_{PCW}^*K \quad (1)$$

J and $K = I - J$ are respectively the spherical and deviatoric fourth-order projectors. Whereas, \tilde{k}_{PCW}^* and $\tilde{\mu}_{PCW}^*$ are respectively the effective bulk and shear moduli given by:

$$\begin{aligned} \tilde{k}_{PCW}^* &= k_m^* \left(1 - \frac{48d_c (1 - (\nu_m^*)^2)}{27(1 - 2\nu_m^*) + 16d_c(1 + \nu_m^*)^2} \right) \\ \tilde{\mu}_{PCW}^* &= \mu_m^* \left(1 - \frac{480d_c (1 - \nu_m^*) (5 - \nu_m^*)}{675(2 - \nu_m^*) + 64d_c(4 - 5\nu_m^*)(5 - \nu_m^*)} \right) \end{aligned} \quad (2)$$

where

$$k_m^*(p) = k_R + \frac{1}{\frac{1}{k_M} + \frac{p\eta_M^s}{3}}; \mu_m^*(p) = \mu_R + \frac{1}{\frac{1}{\mu_M} + \frac{p\eta_M^d}{2}}; \nu_m^* = \frac{3k_m^* - 2\mu_m^*}{6k_m^* + 2\mu_m^*} \quad (3)$$

As in the symbolic space, the apparent mortar's behaviour is linear, its effective Poisson's ratio is obtained as follows:

$$\tilde{\nu}_{PCW}^*(p, d_c) = \frac{3\tilde{k}_{PCW}^* - 2\tilde{\mu}_{PCW}^*}{6\tilde{k}_{PCW}^* + 2\tilde{\mu}_{PCW}^*} \quad (4)$$

Since the mortar's viscoelastic behaviour is assumed to follow the MM's rheological model at the safe and cracked states, then its properties in the symbolic space can be expressed as follows:

$$\begin{aligned} k_{MM}^* &= k_R(d_c) + \frac{pk_M(d_c)\eta_M^s(d_c)/3}{k_M(d_c) + p\eta_M^s(d_c)/3} \\ \mu_{MM}^* &= \mu_R(d_c) + \frac{p\mu_M(d_c)\eta_M^d(d_c)/2}{\mu_M(d_c) + p\eta_M^d(d_c)/2} \end{aligned} \quad (5)$$

Using theorems on the initial and final values given by:

$$\lim_{p \rightarrow 0} f^*(p) = \lim_{t \rightarrow \infty} f(t) \quad , \quad \lim_{p \rightarrow \infty} f^*(p) = \lim_{t \rightarrow 0} f(t) \quad (6)$$

it is possible to identify the MM's coefficients of the microcracked model at long and short terms as shown in Rezik [10]. Finally, the mortar's creep function reads:

$$\begin{aligned} \tilde{J}_{MM}(t, d_c) &= \frac{1}{9k_R(d_c)} \left(1 - \frac{k_M(d_c)}{(k_R(d_c) + k_M(d_c))} e^{-t/\tau_{MM}^s(d_c)} \right) \\ &+ \frac{1}{3\mu_R(d_c)} \left(1 - \frac{\mu_M(d_c)}{(\mu_R(d_c) + \mu_M(d_c))} e^{-t/\tau_{MM}^d(d_c)} \right) \end{aligned} \quad (7)$$

where the characteristic times of the spherical and deviatoric parts of the Modified Maxwell model are given by:

$$\begin{aligned} \tau_{MM}^s(d_c) &= \frac{\eta_M^s(d_c)(k_R(d_c) + k_M(d_c))}{3k_R(d_c)k_M(d_c)} \\ \tau_{MM}^d(d_c) &= \frac{\eta_M^d(d_c)(\mu_R(d_c) + \mu_M(d_c))}{2\mu_R(d_c)\mu_M(d_c)} \end{aligned} \quad (8)$$

In the following, for the microcracked mortar, we adopt a power-law time evolution law for the accumulated damage according to the Weibull's failure rate as proposed in Shrive et al [13]:

$$d_c(t) = \sum_{i=t_0}^t \frac{100\eta}{\tau_D} \left(\frac{t}{\tau_D} \right)^n \quad (9)$$

where $t_0 = 400$ (*days*) presents the initiation time of damage. The constant τ_D refers to the apparition of the most damage set here equal to 800 days. The coefficients of the damage evolution function are given by: $\eta = 0.3$ and $n = 10$.

3 Illustrative example : case of a compressed masonry wall

As a first example of illustration of the proposed model, we investigate hereafter the case of a compressed wall as shown on Figure-1. All computations are carried

out under 2D plane stress assumption using the finite element software Cast3M. This wall, with length $L = 1550\text{ mm}$ and height $H = 1040\text{ mm}$, is meshed with refined quadratic "QUA8" elements with 8 nodes. Brick's dimensions are: length $a = 250\text{ mm}$, height $b = 50\text{ mm}$ and thickness $s = 120\text{ mm}$. They are assumed to be uncracked with a constant Poisson's ratio: $\nu_b = 0.15$ and a time-dependent Young's modulus:

$$E_b(t) = \frac{1}{J_{MM}^b(t)} = \frac{7990.83}{1 - 0.5327e^{-1.60017 \cdot 10^{-1}t}} \quad (10)$$

On the other hand, thicknesses of bed and head mortar joints are assumed to be equal to 10 mm. The mortar is assumed to be damaged with opened cracks. It's Young's and Poisson's ratio are given respectively by:

$$\begin{aligned} \tilde{E}_{PCW}(t, d_c) &= \frac{1}{\tilde{J}_{MM}(t, d_c)} \\ \tilde{\nu}_{PCW}(t, d_c) &= \frac{-0.185394 + d_c(0.369141 + 0.2d_c)}{-0.926971 + d_c(0.369141 + d_c)} \end{aligned} \quad (11)$$

where, the six parameters of the mortar's creep function are provided in Table-1.

Table 1. Identified mortar's creep coefficients following the PCW model (case of opened cracks)[10]

$k_R (MPa)$	$k_M (MPa)$	$\eta_s (MPa.s)$
$-1025.81 + \frac{1442.55}{0.703125 + d_c}$	$-3251.97 + \frac{4573.08}{0.703125 + d_c}$	$-5.98466 \cdot 10^9 + \frac{8.41593 \cdot 10^9}{0.703125 + d_c}$
$\mu_R (MPa)$	$\mu_M (MPa)$	$\eta_d (MPa.s)$
$-769.358 + \frac{2028.58}{1.31836 + d_c}$	$-2438.98 + \frac{6430.89}{1.31836 + d_c}$	$-2.99233 \cdot 10^9 + \frac{7.88993 \cdot 10^9}{1.31836 + d_c}$

3.1 Validation step: case of a masonry wall with rigid bricks

This part aims to investigate the sensibility of the proposed model to the mesh refinement. For this purpose, we made comparison between results provided by the semi-numerical model and solutions available for a compressed wall (Figure (1)-a) at safe [4] and damaged [10] states. It is worth noting that there is no analytical solution for a damaged masonry structure, which argued our choice to validate the semi-numerical model at the safe and damaged states by comparison respectively with the Cecchi and Tralli analytical solution [4] and a numerical solution based on the coupling between the PCW model and periodic homogenization procedure applied to the masonry [10]. Bricks are assumed to be safe and rigid, however, the mortar is viscoelastic following the MM's rheological model [6].

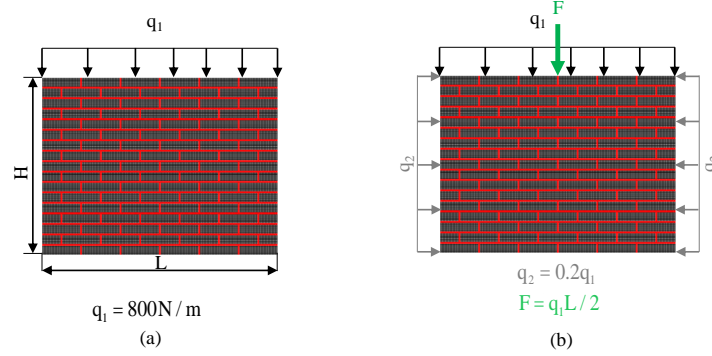


Fig. 1. Masonry wall subjected to: (a) distributed vertical compression (b) and a lateral compression with a concentrated load F

Recall that the analytical solution of the wall vertical displacement under vertical distributed compressive load, derived by Cecchi and Sab [4], takes the form:

$$u_y(x, H, t) = \frac{Q_1 H}{A_{2222}^F(t) \cdot L \cdot s} = \frac{q_1 H}{A_{2222}^F(t)} \quad (12)$$

where, Q_1 and $q_1 = Q_1/L \cdot s$ present respectively the vertical distributed load and the pressure applied at the top of the masonry wall. $A_{2222}^F(t)$ is given by:

$$A_{2222}^F(t) = \frac{(a + e_h) K_h(t)}{e_h} ; K_h(t) = \frac{E_m(t)}{(1 + \nu_m)(1 - 2\nu_m)} \quad (13)$$

Temporal evolutions of the vertical displacement u_y on the top of the wall are presented in Figure-2. It can be noticed that the displacements are similar for cases of masonry with safe and microcracked mortar when $t < 600$ (days). Notice that for this range of time, the absolute error between the semi-numerical model and the analytical solution (safe state) is lower than 7%. After that, this error increases to reach 29.9% at $t = 900$ (days) when comparing damaged state to the safe one. This difference can be explained by the relaxation of the microcracked mortar Young's modulus $\tilde{E}_{PCW}(t, d_c(t))$ (see equation (11)-a). While, the error between the obtained semi-numerical solution and the numerical solution [10] is lower than 2.8%.

3.2 Case of damaged wall : elastic and viscoelastic bricks

The objective of this section is to study the local behaviour of a masonry wall and to compare this result when considering elastic and viscoelastic bricks. This wall is subjected to distributed compressive loads and a vertical concentrated load (F), as depicted on Figure-1(b). Elastic and viscous properties of the brick are shown on Table-2. Its Young's modulus $E_b(t)$ is defined in equation (10).

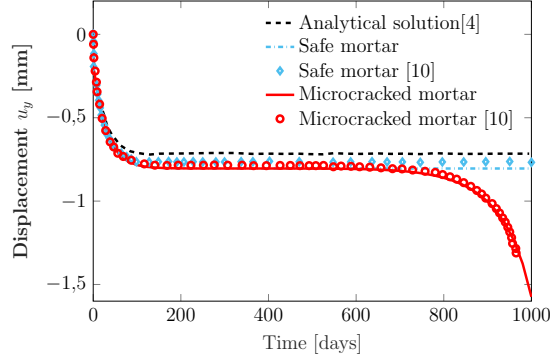


Fig. 2. Temporal evolutions of vertical displacement u_y at the top of the wall

Table 2. Elastic and viscous properties of bricks [2, 5]

E_0 (MPa)	ν_b	τ_M (days)
17100	0.15	33.8

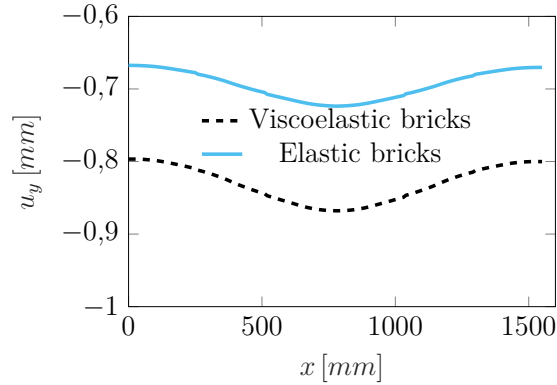


Fig. 3. Distribution of the vertical displacement u_y at the middle height along the x-axis of the wall: Elastic and viscoelastic bricks

The distribution of the vertical displacement u_y at the middle height along the x-axis of the wall ($y = H/2$) are illustrated in Figure-3. It can be observed that, the displacement is negative and reaches its maximum at the point application of the concentrated load F . Results show a significant difference when comparing walls with viscoelastic and elastic bricks. The mean value of the absolute error is

around 29.596 %. It can be concluded that brick's creep increases the deformation of the masonry.

4 Conclusions

This work aims to develop a multi-level model for damaged masonry accounting for creep of both components : mortar and bricks. This model is based on the coupling between the brittle Griffith's theory, a relevant homogenization scheme (PCW) and the finite elements method. It was validated by comparison with analytical and numerical results available in the litterature. At last, comparison made between masonries at safe and damaged states, with elastic and viscoelastic bricks show that the risk of failure increases with the presence of brick's creep and microcracks in the mortar joints. To improve the proposed model, it can be interesting to consider the interface between bricks and mortar in futur works.

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