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A THREE-DIMENTIONAL FINITE ELEMENT MODEL SIMULATING DAMAGE AND CREEP INTERACTION IN MASONRY

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ABSTRACT

It is well established that creep can produce significant effects on the structural behaviour of quasi-brittle materials such as masonry. In addition to increasing deformations, creep can alter the stress distribution within a masonry element significantly. Using simplified mechanical models with step-by-step in time analysis, we have previously concluded that the interaction of creep and damage in masonry can accelerate the failure of masonry elements. In this paper we use a three dimensional finite element model to demonstrate the significance of combining creep and damage on the behaviour of structural masonry. The three-dimensional finite element model enables us to simulate realistic boundary conditions and the effects of Poisson's ratio on creating the out-of-plane constraint stresses which affect grout and brickwork. A cracking criterion is introduced to model crack occurrence. The model permits comparison of the numerous interactions between damage and creep in both grout and brickwork. We identify the significance of such interactions on the long-term behaviour of a masonry column subjected to axial load.

KEYWORDS: masonry, creep, damage, finite element modelling.

INTRODUCTION

Previous research demonstrated that significant creep occurs in masonry structures under sustained loading [1-2]. Creep increases the long term deformation of masonry structures [3]. Moreover, because of the composite nature of masonry (units and mortar), the different creep rates of the mortar and units not only increase long term deformations, but can also alter the stress distribution within a masonry element significantly. Based on our previous investigation [4], creep effects can cause the stress to decrease in one component of the masonry composite structure while the stress increases in the other component. The peak stress value developed at a certain time can be much higher than the elastic stress response to load. Hence, the peak stress may unexpectedly cause material cracking and subsequently, failure. Furthermore, a masonry structure can experience weathering, thermal and other external sources of degradation during its service life [5]. We and others have shown that the interaction of creep and external damage in masonry can accelerate the failure of masonry elements [4-5].

Several two dimensional (2D) linear models have been developed to consider creep [3, 4 and 6]. In this article, in order to simulate realistic boundary conditions and the effects of Poisson's ratio in creating out-of-plane constraint stresses which affect the grout and brickwork, we describe a three dimensional (3D) finite element model of a grouted brickwork column. The finite element model has the ability to indicate crack occurrence by considering a specific cracking criterion. External damage of the outer brickwork is also considered. By assuming different creep ratios of the grout and brickwork, the evolution of the long term stress and cracking locations in the grout and brickwork can be observed.

FINITE ELEMENT MODEL

To demonstrate the significance of creep we consider a square composite masonry column consisting of an external shell of brickwork filled with grout. The total cross-sectional area is 100,000 mm^2, while the section areas of the grout and brickwork are 40,000 mm^2 and 60,000 mm^2 respectively. The height of the column is 1600 mm and axial compression force applied is 1500 kN. Considering the symmetry of the column, only one quarter of the column's section and one half of the specimen's length are modelled. The grout and brickwork are modelled using ANSYS SOLID65 elements [7]. SOLID65 is a solid element with eight nodes, each having three degrees of freedom (DOF) - translations in the x, y and z directions at each node. This type of element can consider cracking and crushing. For the finite element model of the composite column, 720 solid elements in twenty layers were used. The grout component was modelled with 320 elements while the brickwork component was modelled with 400 solid elements as shown in Figure 1. Both materials are assumed to be linear elastic because analysis is performed within serviceability limits. The material properties used for the finite element analysis are presented in Table 1. In order to simulate realistic boundary conditions, the nodes of the top layer of the model were constrained to experience the same displacement in the *z*-direction (along the column length).

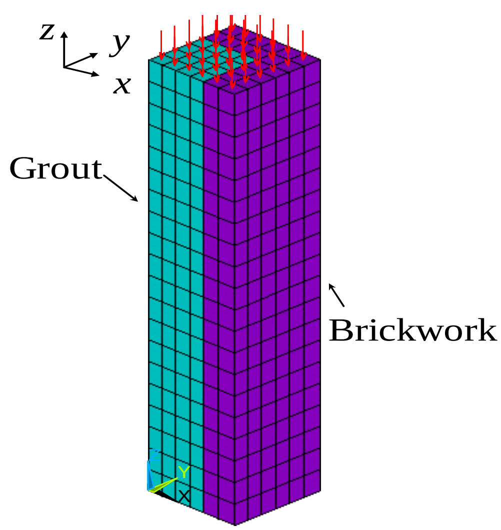


Figure 1: Finite Element Model (Dark-brickwork, Light-grout)

Table 1: Material properties used in finite element analysis

Materials	Poisson's Ratio	Modulus of Elastic	Tensile Strength
Grout	0.3	24 GPa	0.8 MPa
Brickwork	0.2	15 GPa	1.2 MPa

Creep model

To calculate the creep strains of the grout and brickwork, a Kelvin rheological model was used as proposed by others for cementitious materials [8-9], since creep in brickwork is dominated by creep in its mortar joints [3].

$$\varepsilon_c(t) = \frac{\sigma(t)\phi}{E(t)}\left(1 - e^{-t/\tau}\right) \tag{1}$$

where t is the time, $\sigma(t)$ represents the stress at time t, ϕ is the creep coefficient for infinite time and τ represents the time when 63% of the creep has occurred. $E(t)$ is the modulus of elasticity at time t when external damage is considered. If no external damage is considered, $E(t)$ is the initial modulus of elasticity and remains constant. The step-by-step in time analysis of creep is implemented by enforcing both force equilibrium and compatibility between the grout and the brickwork [3].

Damage model

Here we consider the possible effects of external damage due to external weathering and mechanical damage due to overstress. We consider damage here from a continuum damage perspective [10]. A simplified model for external damage is used by decreasing the modulus of elasticity with time [4] as

$$E(t) = \left[1 - D(t)\right]E(t_0) \tag{2}$$

$$D(t) = \beta t^{\beta - 1} \tag{3}$$

$$\beta = 1 + \frac{\ln(D_{\text{in}} / D_{\max})}{\ln(t_{\text{in}} / T_{\max})} \tag{4}$$

where $D(t)$ is damage at time t. D_{in} is the initial level of damage at t_{in}. $D_{\max}$ is the ultimate damage at time $T_{\max}$. $E(t_0)$ is the initial modulus of elasticity before external damage occurs. In the current modelling, since an outer shell of brickwork was used, only external damage to this brickwork was considered. The following values were used for introducing the effect of external damage in the brickwork: D_{in}=0.001, $D_{\max}$=0.32, t_{in}=400 and $T_{\max}$=2000. This means that damage started to occur 400 days after loading and reached its maximum value at 2000 days. Creep effects began from the time of loading.

Cracking model

To consider cracking and crushing of the grout and brickwork, the five parameter model by William and Warkne [11] for cracking and crushing was used. However, in order to simplify the modelling process, the crushing criterion was not considered. The cracking criterion in that model assumes that the element will be cracked whenever a principal stress component exceeds the ultimate uniaxial tensile strength of the material. The uniaxial tensile cracking strengths of the brickwork and grout were taken as 1.2 MPa and 0.8 MPa respectively. The shear transfer coefficients for an open crack and closed crack were both assumed equal to unity. This means there was no loss of shear transfer across the crack face. When an element is deemed to have cracked, the stiffness normal to the element crack face was reduced to zero. Detailed information about William and Warkne's model can be found elsewhere [7, 11].

RESULTS AND DISCUSSION

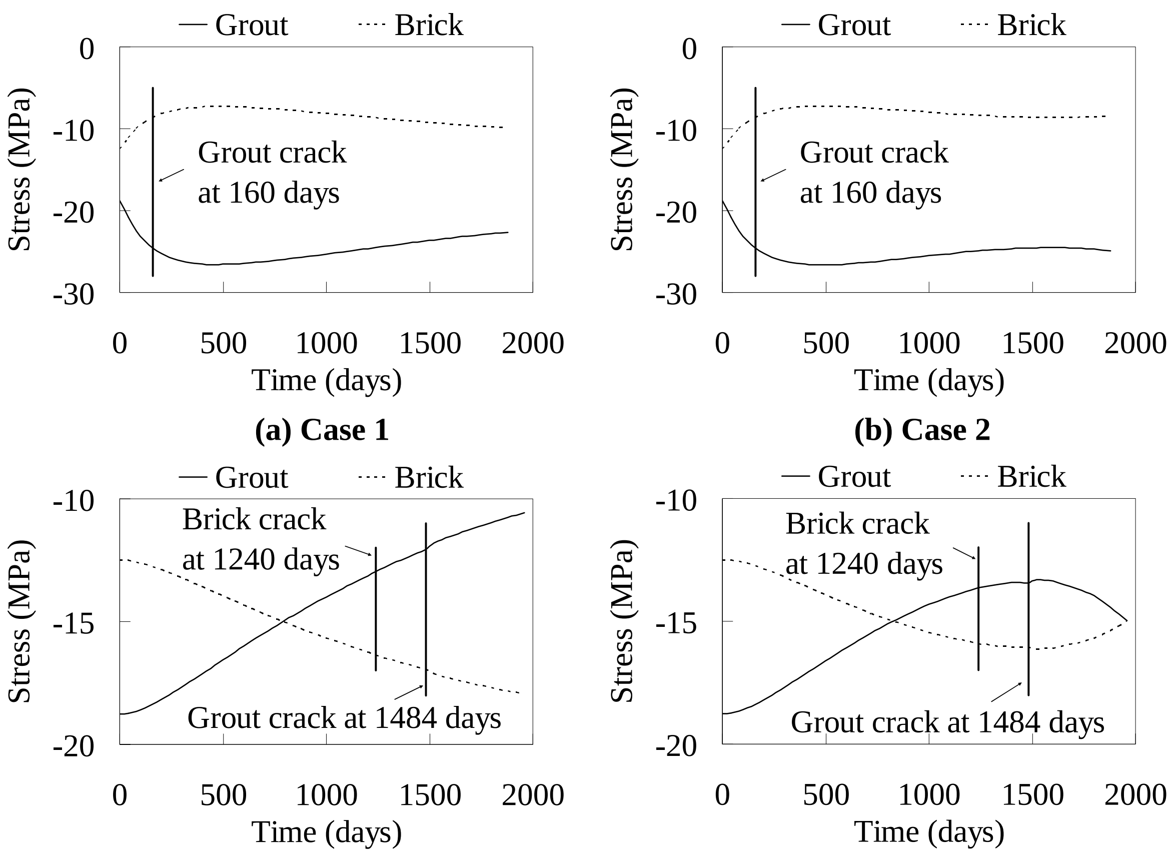
Four analysis cases are listed in Table 2 considering different combinations of creep for the grout and brickwork. In all cases, cracking was considered for both brickwork and grout elements. External damage was considered for brickwork only in cases 2 and 4. The axial stress distribution at the bottom layer in Figure 1 was obtained at each time step and averaged for the brickwork and the grout as shown in Figure 2.

Table 2: Case studies analysed

Cases	Grout				Brickwork			
	Cracking	Damage	ϕ	τ (days)	Cracking	Damage	ϕ	τ (days)
Case 1	Yes	No	2.5	1000	Yes	No	5.0	500
Case 2	Yes	No	2.5	1000	Yes	Yes	5.0	500
Case 3	Yes	No	5.0	1000	Yes	No	2.5	500
Case 4	Yes	No	5.0	1000	Yes	Yes	2.5	500

Yes-considered, No-not considered, Damage indicates external damage

As shown in Figures 2 (a) and (b) for Cases 1 and 2, as the brickwork creeps faster than the grout, the brickwork stress decreases with time while the grout stress increases for 475 days. After that time, as the grout creeps more than the brickwork, so now the brickwork stress increases and the stress in the grout decreases with time. However, as shown in Figure 2 (b) Case 2, when external damage is introduced to the brickwork, and the stiffness of the brickwork decreases because of that damage, the stress in the brickwork begins to decrease again after 1600 days. Thus the grout has to carry increasing compressive stress as the brickwork degrades and offloads its share of the total load to the grout. When cracking is examined, the grout begins to crack 160 days after loading whether external damage is considered or not. The location of the cracking in the grout is indicated by the dashed lines on the cross section shown in Figure 3. On initial loading, the brickwork generates out-of-plane (*xy* plane) confinement (compressive) stresses in the grout which result in a relatively high axial stress in the corner of the grout. This high axial stress in the grout is shown graphically in Figure 4 (a). The compressive stress distribution changes with time due to creep as shown in Figure 4 (b). For Cases 1 and 2, the confining stresses increase until 475 days, when tensile stresses are generated at the corner of grout and cracking occurs. It is worth noting that the brickwork does not crack in either Case 1 or Case 2. With the grout cracking, structural failure of the column becomes a possibility.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

Figure 2: Stress evolution with time in brickwork and grout

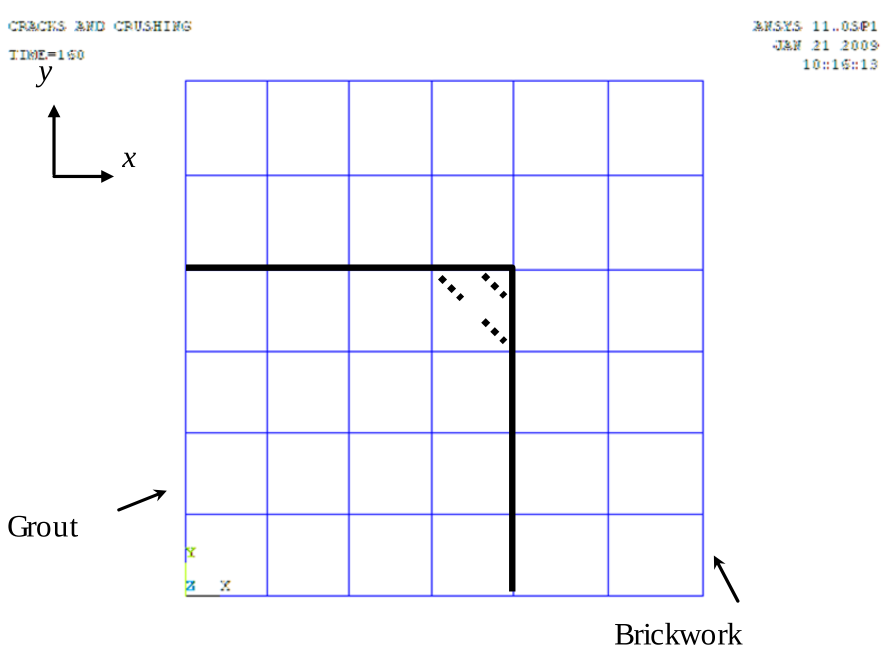
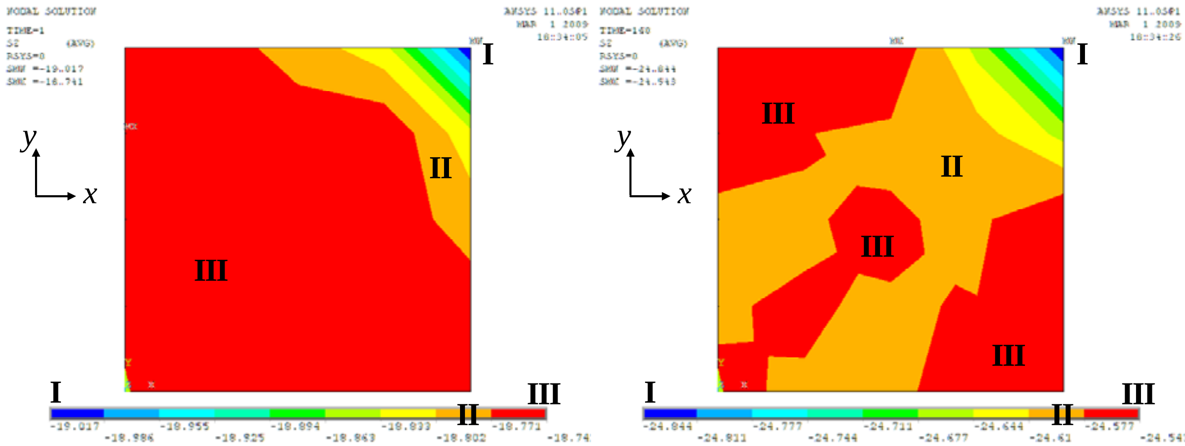


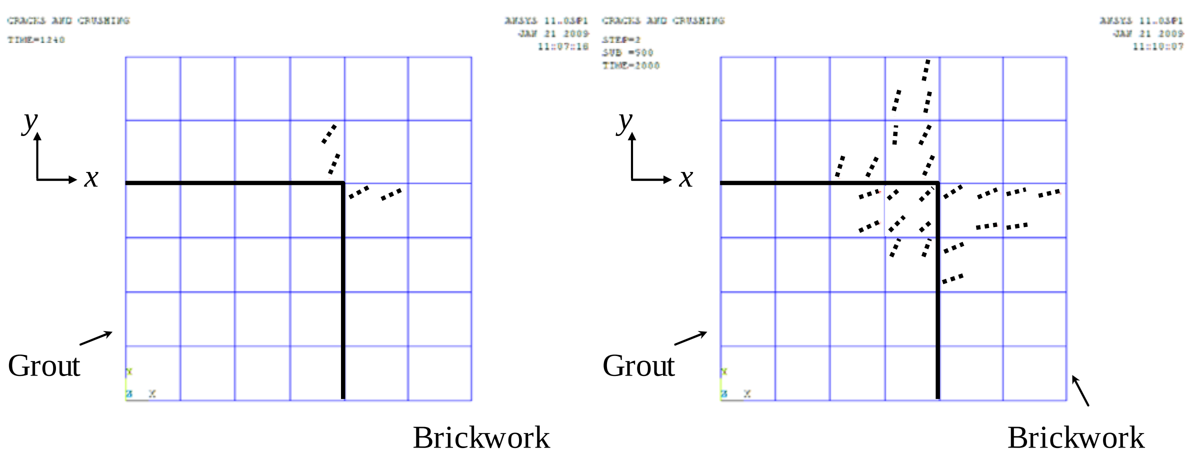
Figure 3: Cracking in the grout at 160 days for Cases 1 and 2



(a) On Initial loading **(b) At 160 days**

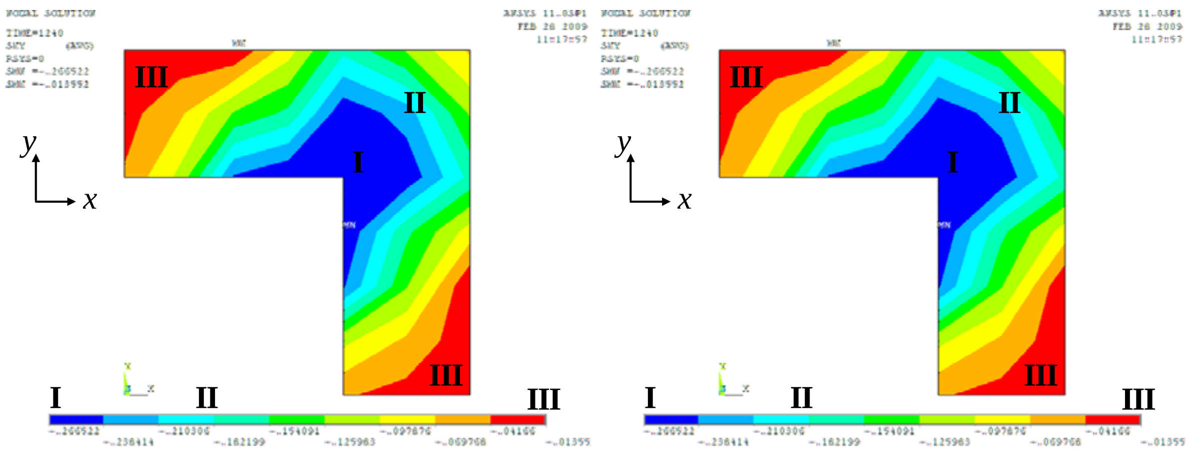
Figure 4: Grout axial stress (*z*-direction) distribution for Case 1

<u>For Cases 3 and 4</u>, as the grout creeps faster than the brickwork, the stress in the grout decreased with time while the stress in the brickwork increased as shown in Figures 2(c) and (d). However, when external damage to the brickwork was introduced, the stress in the brickwork decreased after 1484 days, as shown in Figure 2 (d) for Case 4. For cracking, whether external damage was considered or not, the brickwork near the grout corner began to crack 1240 days after loading. The location of the cracks is shown in Figure 5 (a). Cracking in the brickwork extended and the grout began to crack at 1484 days. The shear stress (σ_{xy}) distributions at 1240 and 1484 days for Case 3 are shown in Figures 6 (a) and (b) respectively. It is obvious that the highest shear stress occurs near the grout corner.



(a) At 1240 days **(b) At 1484 days**

Figure 5: Cracking in grout and brickwork for Case 3 and 4



(a) Time at 1240 days **(b) Time at 1484 days**

Figure 6: Brickwork shear stress (*xy*-direction) distribution for Case 3

An interesting phenomenon that is worth mentioning is that, at 1484 days, the grout began to crack although the axial stress was relatively small. This is attributed to the effects of Poisson's ratio on creating out-of-plane constraining stresses as shown schematically in Figure 7. In both Case 3 and Case 4, the brickwork began to crack at 1240 days while the grout began to crack at 1484 days. The increase in axial stress and the effects of Poisson's ratio result in significant out-of-plane constraining stresses which affect the grout/brickwork interface. This it can be observed that complex composite interactions exist between the components in masonry walls. These interactions should be carefully considered when combining creep and damage effects.

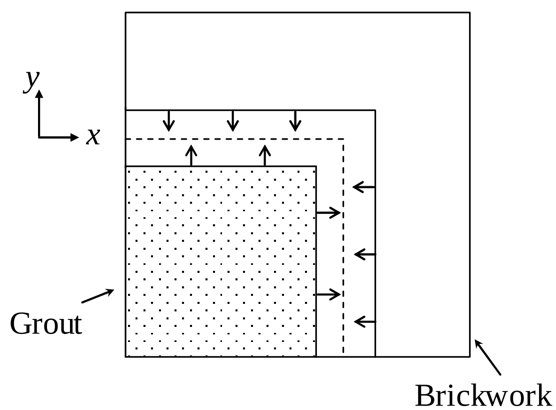


Figure 7: Schematic representation for grout cracking by the constraining stresses

Further improvements in the proposed model are possible. For example, we neglected crushing as a failure criterion to simplify the analysis. Moreover, both material models were assumed to be linear-viscoelastic. The observed cracking justifies consideration of nonlinear viscoplasticity even though the applied stresses are within serviceability limits. Alternatively, the cracking could be deemed to induce a reduction in modulus, like the external weathering damage. Nevertheless, the proposed model demonstrates the relatively high possibility of failure due to cracking considering various combinations of creep and damage in masonry structures.

CONCLUSION

A three dimensional finite element model for a composite masonry column subject to axial compression load was developed. In addition to considering creep and external damage, the proposed model enabled simulation of realistic boundary conditions and demonstrated the possibility of cracking of both materials, given different creep behaviour for the brickwork and the grout and damage affecting the brickwork. The proposed model also showed the need to consider Poisson's ratio and its possible significance on cracking of the grout core of the column. The results indicate that besides creep, out-of-plane constraining stresses can cause the materials to crack and accelerate structural failure. Moreover, external damage can also accelerate failure when combined with creep. Further analysis is underway to provide further insight to such complex behaviour.

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