

3. Collapse prediction and creep effects

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Abstract

The recent collapse of famous historical constructions attributed mainly to the time-dependent behaviour of masonry has driven the attention of the technical community over this issue. Numerical analyses in which units and mortar are individually represented have proven to be of great interest to understand the phenomena at the level of the masonry constituents. Nevertheless, before analysing the influence of long-term effects, it is important that numerical models are able to adequately reproduce the behaviour under short-term compression as it provides a solid basis to correctly capture the response under sustained stresses. Reproduction of short-term behaviour remains, however, unresolved in literature. A contribution is given in the present paper by considering a standard continuum model and a discrete particle model to represent units and mortar. The particle model has showed clear advantages. In addition, the results of an experimental investigation on the creep behaviour of regular ancient masonry including both short-term and long-term creep tests are provided together with a careful discussion of the results.

3.1 Introduction

The collapse of the Pavia Civic Tower in 1989 was a motive of great concern for the public authorities and for the technical community. The collapse rapidly became a focus of interest among masonry researchers and several masonry blocks were recovered from the ruins for mechanical and physical/chemical laboratory testing, Binda *et al.* [1]. Such tests permitted to identify the time-dependent mechanical damage of the tower walls due to high sustained loading as a possible main cause of collapse.

The tower of Pavia is not an isolated case and several other famous examples can be referred, such as the collapse of the St. Magdalena bell-tower in Goch,

Germany, in 1993, the partial collapse of the Noto Cathedral, Italy, in 1996, and the severe damage exhibited by the bell-tower of the Monza Cathedral, Italy.

Masonry creep depends mainly on factors such as the stress level and the temperature / humidity conditions but cyclic actions, such as wind, temperature variations or vibrations induced by traffic or ringing bells, in the case of bell towers, have a synergetic effect, increasing material damage. For these reasons, high towers and heavily stressed columns are the structural elements where time-dependent damage can severely occur, Anzani *et al.* [2].

Traditionally, three creep stages can be recognised. A *primary* stage where the creep rate decreases gradually, a *secondary* stage where the creep rate remains approximately constant and a *tertiary* stage where the creep rate increases rapidly towards failure. A sufficiently high stress level must be applied so that the two last stages are initiated. In the secondary stage, diffuse and thin vertical cracking propagates and coalesces into macro-cracks that may lead, possibly, to creep failure of the material. Creep of cementitious materials is generally attributed to crack growth and interpartical bond breakage due to moisture seepage. In fact, under sustained loading, forced moisture redistribution can occur in the pore structure of the material causing debonding and rebonding of the micro-structure particles, Bazant [3]. In the case of concrete or new masonry, if drying shrinkage is occurring simultaneously to creep, the time-dependent deformation is increased due to a coupled effect known as the *Pickett effect*, Pickett [4]. Time-dependent deformation in a constant hygral and thermal environment, and in the absence of cracking, is denominated by *basic creep*, see *e.g.* Neville [5], and the reader is referred to Van Zijl [6] for a comprehensive discussion on the viscous behaviour of masonry.

For low stress levels, below 40 to 50% of the compressive strength, only primary creep is present and creep deformation can be assumed proportional to the stress level. References on masonry creep within the elastic range are rather abundant in literature, [7,8,9]. On the contrary, creep under high stresses, even in the case of concrete, is not a sufficiently debated issue, [10,11,12]. The fact that standard design methods for new structures are based on linear elastic material hypothesis has contributed to diminish the interest of researchers on this topic. However, ancient masonry structures are often working under low safety margins according to modern safety regulations. This can be due to inadequate knowledge of mechanics or structural modifications that occurred along centuries, resulting in overweighting of the structure and rendering importance to non-linear creep.

Detailed modelling approaches in which units and mortar are individually represented are of great interest to understand the phenomena occurring at the constituents level. In particular, insight over stress redistribution and damage growth occurring under sustained loading can be provided. However, before introducing long-term effects, knowledge on the short-term behaviour and on governing failure mechanisms is of fundamental importance. Nevertheless, numerical prediction of the short-term response of masonry based on the properties of the constituents remains unresolved, Pina-Henriques and Lourenço [13]. In Section 3.2, a contribution to provide reliable predictions of

the compressive strength of masonry and a discussion on the failure mechanisms observed are addressed. A standard continuum model, based in plasticity and cracking, and a particle model developed in discrete settings have been considered to represent units and mortar. In Section 3.3, an experimental investigation on the behaviour of ancient masonry under high compressive stresses is described and its results are carefully analysed. Standard uniaxial compression tests, short-term creep tests and long-term creep tests were considered with the aim of presenting a comparative discussion.

3.2 Short-term compression: Failure analysis and collapse prediction using numerical simulations

3.2.1 Brief description of adopted experimental results

Binda *et al.* [14] carried out deformation controlled tests on masonry prisms with dimensions of $600 \times 500 \times 250 \text{ mm}^3$, built up with nine courses of $250 \times 120 \times 55 \text{ mm}^3$ solid soft mud bricks and 10 mm thick mortar joints. Three different types of mortar, denoted as *M1*, *M2* and *M3*, have been considered and testing aimed at the evaluation of the compressive properties of the prisms. For each type of mortar, a total of three prisms were tested.

The tests were carried out in a uniaxial testing machine MTS[®] 311.01.00, with non-rotating steel plates and a maximum capacity of 2500 kN. The applied load was measured by a load cell located between the upper plate and the testing machine, while the average vertical displacement was recorded with the machine in-built displacement transducer, permitting to capture the complete stress-strain diagram, including the softening regime.

The characteristics of the masonry components in terms of compressive strength f_c , flexural tensile strength f_t , elastic modulus E and coefficient of Poisson ν are given in Table 3.1. The results obtained for the prisms are given in Table 3.2. Prisms *P1*, *P2* and *P3* were built with mortars *M1*, *M2* and *M3* of increasing strength, respectively. The experimental failure patterns found were rather similar despite the type of mortar used, Frigerio and Frigerio [15]. Figure 3.1 depicts the typical failure pattern.

Table 3.1: Mechanical properties of the masonry components, [14].

Component	E [N/mm^2]	ν [-]	f_c [N/mm^2]	f_t [N/mm^2]
Unit	4865	0.09	26.9	4.9
Mortar <i>M1</i>	1180	0.06	3.2	0.9
Mortar <i>M2</i>	5650	0.09	12.7	3.9
Mortar <i>M3</i>	17760	0.12	95.0	15.7

Table 3.2: Mechanical properties of the masonry prisms, [14].

Prism type	Mortar type	E [N/mm^2]	f_c [N/mm^2]
<i>P1</i>	<i>M1</i>	1110	11.0
<i>P2</i>	<i>M2</i>	2210	14.5
<i>P3</i>	<i>M3</i>	2920	17.8

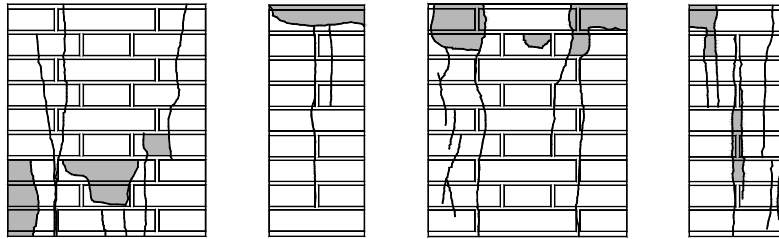


Figure 3.1: Typical experimental failure patterns, [15]. The shaded areas indicate spalling of material.

3.2.2 Continuum model

The simulations were carried out resorting to a *basic cell*, i.e., a periodic pattern associated to a frame of reference, see Figure 3.2, in which units and mortar were represented by a structured continuum finite element mesh. However, in order to reduce computational effort only a quarter of the basic cell was modelled assuming symmetry conditions for the in-plane boundaries, see Figure 3.3. The dimensions of the components are equal to the ones used in the experiments. It is emphasised that the followed approach is only approximate of the real geometry and that the obtained numerical response is phenomenological, which means that a comparison in terms of experimental and numerical failure patterns is not possible. In particular, splitting cracks usually observed in prisms tested under compression, [16], boundary effects of the specimen and non-symmetric failure modes are not captured by the numerical analysis. Nevertheless, most of these effects control mainly the post-peak response, which is not the key issue in the present contribution.

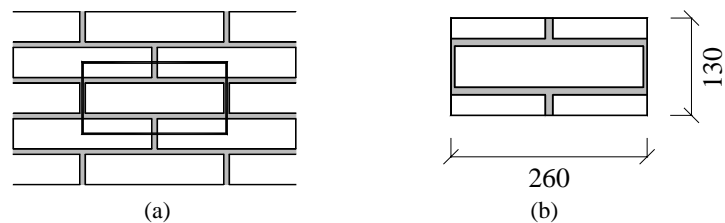


Figure 3.2: Definition of *basic cell*: (a) running bond masonry and (b) geometry.

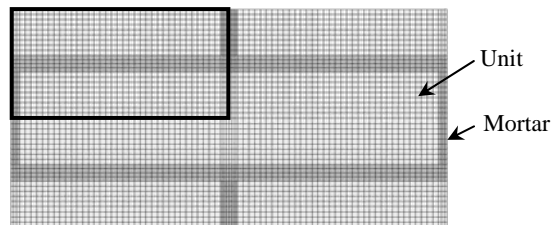


Figure 3.3: Continuum model used in the simulations (only the indicated quarter was simulated, assuming symmetry conditions).

Three different plane approaches have been considered taking into account the out-of-plane boundaries, namely: (a) plane-stress *PS*, (b) plane-strain *PE* and (c) an intermediate state, here named enhanced-plane-strain *EPE*. This last approach consists in modelling a thin out-of-plane masonry layer with 3D elements, imposing equal displacements in the two faces of the layer. Full 3D analyses with refined meshes and softening behaviour are unwieldy, and were not considered. Moreover, recent research indicated that enhanced-plane-stress analysis provides very similar results, Berto *et al.* [17]. *EPE* response is always between the extreme responses obtained with *PS* and *PE*. For this reason, *EPE* is accepted as the reference solution for the continuum simulations and only its results are considered in this paper. A complete description of the continuum simulations can be found in Pina-Henriques and Lourenço [18].

Modelling of the cell in *EPE* was carried out using approximately 900 20-noded brick elements with 6650 nodes, totalling 13300 degrees of freedom (note that the tying adopted for the out-of-plane degrees of freedom mean that, basically, a 2D model is used). $3 \times 3 \times 3$ Gauss integration was used. The material behaviour was described using a composite model including a traditional smeared crack model in tension, specified as a combination of tension cut-off (two orthogonal cracks), tension softening and shear retention, [19], and a Drucker-Prager plasticity model in compression, [20]. The inelastic behaviour exhibits a parabolic hardening / softening diagram in compression and an exponential-type softening diagram in tension. The material behaves elastically up to one-third of the compressive strength and up to the tensile strength.

In order to reproduce correctly the elastic stiffness of the masonry prisms, the experimental elastic modulus of the mortar E must be adjusted by inverse fitting. In fact, the mortar experimental stiffness leads to a clear overstiff response of the numerical specimens. This can be explained by the fact that the mechanical properties of mortar inside the composite are different from mortar specimens cast separately. This is due to mortar laying and curing and represents a severe drawback of detailed micro-models. The material properties adopted, including the adjusted mortar stiffness values E^* are fully detailed in Table 3.3. Here, c is the cohesion, f_t is the tensile strength, ϕ is the friction angle, ψ is the dilatancy angle, Gf_t is the tensile fracture energy and Gf_c is the compressive fracture energy. The value adopted for the friction angle was 10° (a larger value in plane-stress would implicate an overestimation of the biaxial strength) and, for the dilatancy angle, a value of 5° was assumed, [21]. The values assumed for the fracture energy have been based in recommendations supported in experimental evidence, [22,23], and practical requirements to ensure numerical convergence.

Table 3.3: Inelastic properties given to masonry components.

Component	$E^{(1)}$ [N/mm ²]	c [N/mm ²]	f_t [N/mm ²]	$\sin \phi$ [-]	$\sin \psi$ [-]	Gf_t [N/mm]	Gf_c [N/mm]
Unit	4865	11.3	3.7	0.17	0.09	0.190	12.5
Mortar <i>M1</i>	355	1.3	0.7	0.17	0.09	0.350	2.7
Mortar <i>M2</i>	735	5.3	3.0	0.17	0.09	0.150	10.0
Mortar <i>M3</i>	1065	39.9	12.0	0.17	0.09	0.600	23.0

⁽¹⁾ In the case of mortars, the values refer to the adjusted stiffness values.

3.2.3 Particle model

The 2D particle model proposed to represent the micro-structure of units and mortar consists in a phenomenological discontinuum approach based on the finite element method including interface elements. The discontinuous nature of the masonry components is considered by attributing a fictitious micro-structure to units and mortar, which is composed by linear elastic continuum elements of polygonal shape (hereafter named *particles*) separated by non-linear interface elements. All inelastic phenomena occur in the interfaces and the process of fracturing consists of progressive bond-breakage. This is, of course, a phenomenological approach, able, nevertheless, to capture the typical failure mechanisms and global behaviour of quasi-brittle materials. For a detailed discussion of the model, including proposals for selection of numerical data, sensitivity studies, fracture processes and failure mechanisms, and size effect studies, the reader is referred to Pina-Henriques and Lourenço [13]. There, it is also shown that the compressive and tensile strength values yielded by the model can be considered as particle size and particle distortion independent for practical purposes.

The constitutive model used for the interface elements was formulated by Lourenço and Rots [24] and is implemented in the finite element code adopted for the analyses, [20]. The model includes a tension cut-off for tensile failure (mode I), a Coulomb friction envelope for shear failure (mode II) and a cap mode for compressive failure. Exponential softening is present in all three modes and is preceded by hardening in the case of the cap mode. Micro-structural disorder is considered in the model by the irregular geometry of the particles and by attributing to particles and interfaces randomly generated material properties, according to a Gaussian distribution, for given values of the average and coefficient of variation of the material parameters.

The particle model simulations were carried out employing the same basic cell used for the continuum model, see Figure 3.2. The particle model is composed by approximately 13000 linear triangular continuum elements, 6000 linear line interface elements and 15000 nodes, see Figure 3.4. Macro homogeneous symmetry conditions have been assumed.

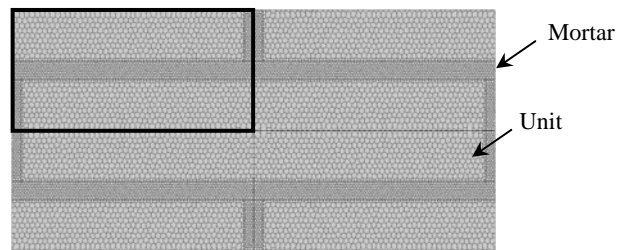


Figure 3.4: Particle model of the masonry cell (only the quarter indicated was simulated, assuming symmetry conditions).

The material parameters were defined by comparing the experimental and numerical responses of units and mortar considered separately. Each material was modelled resorting to specimens with the same average particle size, mesh distortion and dimensions of the masonry components used in the composite model (basic cell).

Given the stochastic nature of the model, five simulations were performed for each masonry component assuming equal average values for the model material parameters. The parameters were obtained, whenever possible, from the experimental tests described in Section 3.2.1 but most of the inelastic parameters were unknown and had to be estimated. For the particles average elastic modulus E , values larger than the experimental ones had to be adopted due to the contribution of the interfaces deformability, characterized by k_n and k_s , to the overall deformability of the specimen. This correction is necessary despite the high dummy stiffnesses assumed.

On the contrary, the values adopted for the interfaces tensile strength f_t are slightly lower than the experimental tensile strength of the specimens, given the contribution of the interfaces shear strength due to the irregular fracture plane. The cohesion c was taken, in general, equal to $1.5 f_t$, [25]. However, quite low experimental ratios between the compressive and tensile strengths were reported for the units and mortars considered here, with values ranging between four and eight. Due to this reason, cohesion values lower than $1.5 f_t$ had to be adopted for mortars *M1* and *M2*.

The values for the friction coefficient $\tan\phi$ were adopted so that the numerical compressive strength showed a good agreement with the experimental strength. The values assumed for mode I fracture energy G_{fI} have been based in recommendations supported in experimental evidence, [23,26]. For mode II fracture energy G_{fII} , a value equal to $0.5 c$ was assumed, with the exception of the very high strength mortar *M3*, for which a lower value equal to $0.3 c$ was adopted. The complete material parameters adopted are given in Table 3.4 and, for such input, the response obtained is given in Table 3.5.

Table 3.4: Values assumed for the material parameters (in brackets, the coefficient of variation is given in %).

		Unit	<i>M1</i>	<i>M2</i>	<i>M3</i>
Particles	$E^{(1)}$ [N/mm ²]	6000 (30)	355 (30)	750 (30)	1200 (30)
	ν [-]	0.09 (0)	0.06 (0)	0.09 (0)	0.12 (0)
Interfaces	k_n [N/mm ³]	1×10^4 (0)	1×10^4 (0)	1×10^4 (0)	1×10^4 (0)
	k_s [N/mm ³]	1×10^4 (0)	1×10^4 (0)	1×10^4 (0)	1×10^4 (0)
	f_t [N/mm ²]	3.40 (45)	0.75 (45)	3.50 (45)	10.50 (45)
	G_{fI} [N/mm]	0.170 (45)	0.038 (45)	0.175 (45)	0.525 (45)
	c [N/mm ²]	5.10 (45)	0.30 (45)	0.70 (45)	15.75 (45)
	G_{fII} [N/mm]	2.55 (45)	0.15 (45)	0.35 (45)	3.15 (45)
	$\tan\phi$ [-]	0.10 (45)	0.00 (0)	0.00 (0)	0.10 (45)

⁽¹⁾ In the case of mortars, the values refer to the adjusted stiffness values.

Table 3.5: Numerical response obtained for the masonry components (in brackets, the coefficient of variation is given in %).

	Unit	<i>M1</i>	<i>M2</i>	<i>M3</i>
f_c [N/mm ²]	27.2 (2.7)	3.2 (5.0)	12.7 (5.4)	95.8 (4.4)
f_t [N/mm ²]	3.61 (1.4)	0.64 (4.7)	2.70 (4.2)	11.62 (6.6)
E [N/mm ²]	4786 (1.9)	1309 (1.4)	5632 (3.0)	17176 (3.1)

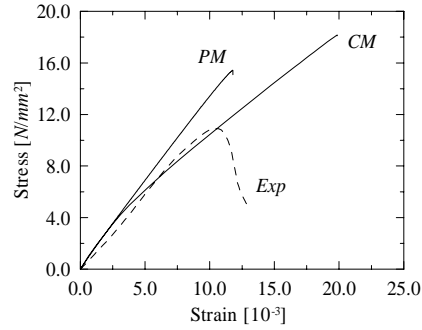
3.2.4 Discussion of the results

The numerical results obtained for the masonry prisms considering the mortar experimental Num_E and adjusted Num_E^* stiffnesses are given in Table 3.6, where f_c is the compressive strength and ε_p is the peak strain. In addition, the prisms experimental results are shown for a better comparison. It is noted, however, that the reference solution for the numerical simulations is the solution provided by Num_E^* . Figure 3.5 depicts the experimental and numerical stress-strain diagrams.

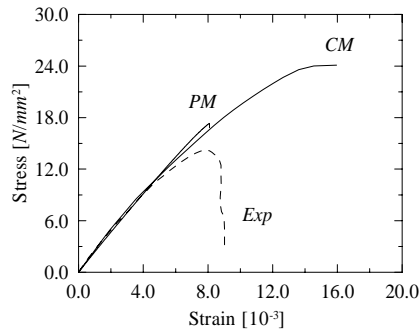
From the given results, it is clear that the experimental collapse load is overestimated by the particle and continuum models, and that the predicted strength is affected by the mortar stiffness, especially in the case of the particle model. However, a much better agreement with the experimental strength and peak strain has been achieved with the particle model, when compared to the continuum model. In fact, the numerical over experimental strength ratios ranged between 165 to 170% in the case of the continuum model while in the case of the particle model, strength ratios ranging between 120 and 140% were found. The results obtained also show that the peak strain values are well reproduced by the particle model but large overestimations are obtained with the continuum model. For this last model, experimental over numerical peak strain ratios ranging between 190 and 510% were found.

Table 3.6: Experimental results Exp and numerical results using experimental Num_E and adjusted Num_E^* mortar stiffness values.

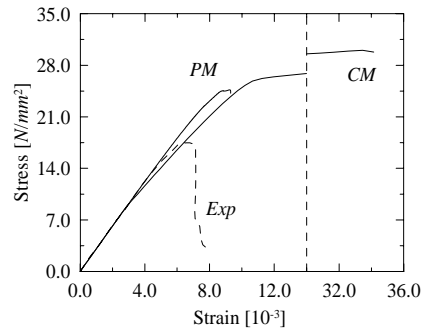
Prism type		Continuum model			Particle model		
		<i>P1</i>	<i>P2</i>	<i>P3</i>	<i>P1</i>	<i>P2</i>	<i>P3</i>
f_c [N/mm ²]	<i>Exp</i>	11.0	14.5	17.8	11.0	14.5	17.8
	<i>Num_E</i>	19.8	24.2	31.0	15.5	19.3	30.8
	<i>Num_E*</i>	18.2	24.1	30.0	15.4	17.3	24.6
ε_p [10 ⁻³]	<i>Exp</i>	10.5	7.9	6.6	10.5	7.9	6.6
	<i>Num_E</i>	10.6	9.7	8.4	5.4	4.6	6.2
	<i>Num_E*</i>	19.9	16.0	33.5	11.8	8.1	8.9



(a)



(b)



(c)

Figure 3.5: Numerical and experimental stress-strain diagrams, using adjusted mortar stiffness values, for prisms: (a) *P1*, (b) *P2* and (c) *P3*. In the diagrams *CM* stands for continuum model, *PM* for particle model and *Exp* for experimental data.

Failure patterns are an important aspect when assessing numerical models. The (incremental) deformed meshes near failure using the continuum and particle models are depicted in Figure 3.6 to Figure 3.8 for prisms *P1* to *P3*, respectively. In case of the continuum model, the contour of the minimum principal plastic strains is also given for a better interpretation of the mechanisms

governing failure. It is noted that despite the fact that only a quarter of the basic cell has been modelled, the results are shown in the entire basic cell to obtain more legible figures.

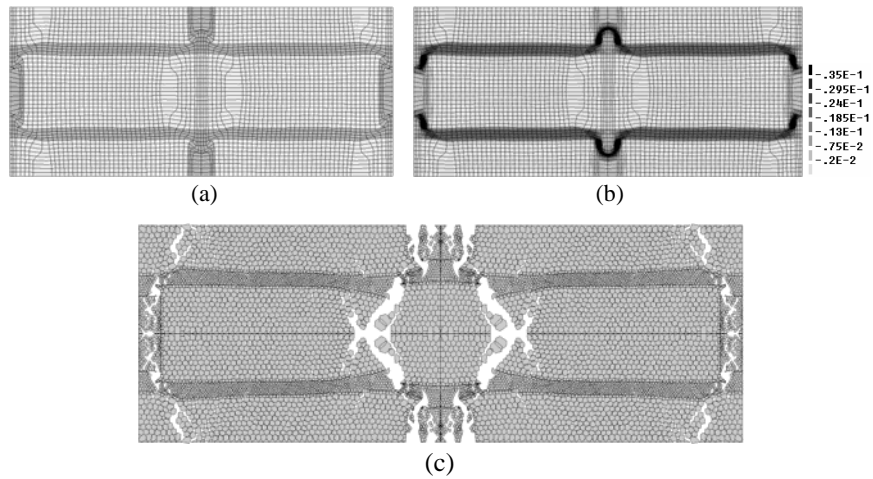


Figure 3.6: Results at failure for prism $P1$ using the continuum model: (a) deformed (incremental) mesh and (b) minimum principal plastic strains; and using the particle model: (c) deformed incremental mesh.

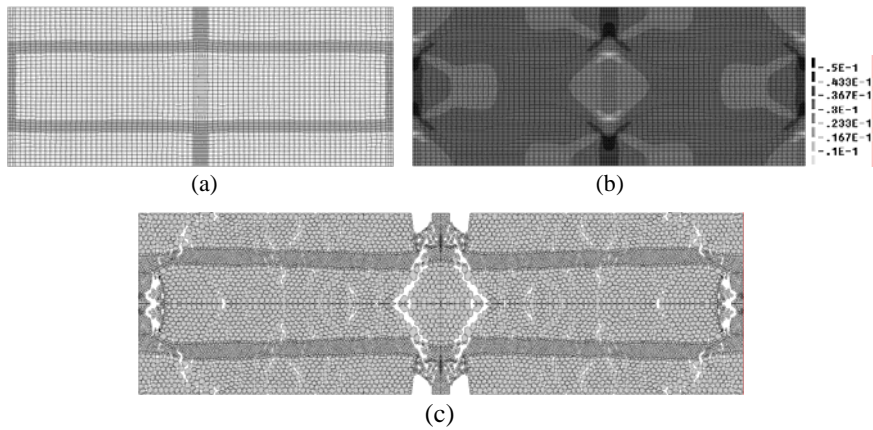


Figure 3.7: Results at failure for prism $P2$ using the continuum model: (a) deformed (incremental) mesh and (b) minimum principal plastic strains; and using the particle model: (c) deformed incremental mesh.

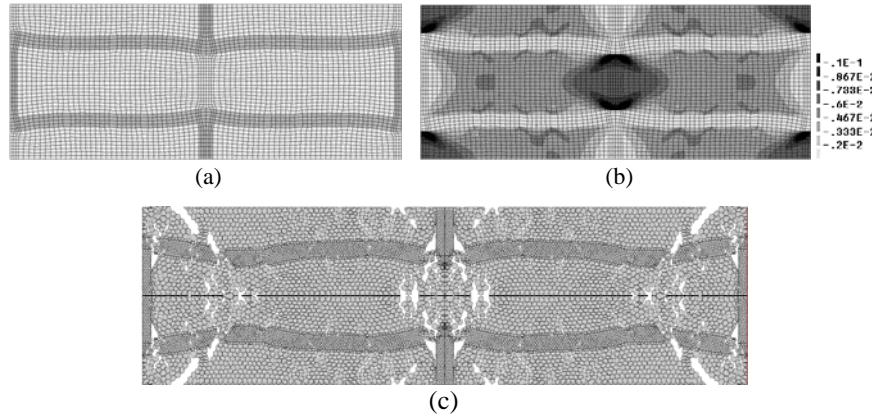


Figure 3.8: Results at failure for prism *P3* using the continuum model: (a) deformed (incremental) mesh and (b) minimum principal plastic strains; and using the particle model: (c) deformed incremental mesh.

The numerical failure patterns obtained are similar for both continuum and particle models. Even if the proposed particle model approach is phenomenological, the failure patterns resemble well typical compression experimental patterns observed in the face of masonry specimens. In the case of prism *P1*, failure occurs mainly due to the development of vertical cracks in the centre of the units and along the head-joints, being the mortar in the bed-joints severely damaged. Prism *P2* fails due to diffuse damage developing in units and mortar in a rather uniform manner. In the case of prism *P3*, diffuse damage is also present but localized crushing of the units can be clearly observed at one-half and one-sixth of the length of the masonry units.

3.3 Long-term compression: Experimental assessment

3.3.1 Tested specimens

The experimental investigation was carried out on ancient masonry prisms due to the difficulty of producing laboratory specimens that correctly represent the material typically found in historical masonry structures. Major obstacles to fabricate specimens are mortar carbonation, hardening or setting, which have a significant influence on the viscous behaviour of masonry and cannot be adequately reproduced in new specimens. On the other hand, the high cost and very limited number of ancient masonry specimens available for destructive testing are obvious. Because the previous experience with similar materials in the scientific community is not frequent, see e.g. [2], the current testing program was much relevant but represents a learning process. In particular, recommendations for testing such specimens could only be given at the end of the testing program.

The experimental investigation carried out focuses on regular coursed brick masonry specimens *Pre* recovered from the ruins of the belfry of the Pavia Civic Tower. The dimensions of the specimens were $(200\pm 5) \times (200\pm 5) \times (330\pm 20) \text{ mm}^3$. Before subsequent testing under compression, the loaded faces of the prisms were regularized with a cement based mortar layer approximately 10 mm thick. In all tests, Teflon sheets were introduced between the prisms and the loading plates to minimize restraining frictional stresses. A summary of the tests performed is given in Table 3.7.

Table 3.7: Quantity of specimens n for each type of test.

	Compression	Short-term creep	Long-term creep
n	4	4	6

3.3.2 Standard compression tests

Standard compression tests were conducted in four specimens. The tests were partly carried out in University of Minho (specimens *Pre_1* and *Pre_2*) and in Politecnico di Milano (specimens *Pre_3* and *Pre_4*). The specimens had to be tested with different test setups according to the conditions locally available at each laboratory. In this way, the tests performed in University of Minho were carried out in a uniaxial hydraulic testing machine with non-rotating steel plates and a maximum capacity of 2000 kN. The load was monotonically increased under displacement control at a rate of 4 $\mu\text{m/s}$. The applied load was measured by a load cell located between the upper plate and the testing machine, and displacements in the specimens were recorded by two vertical inductive displacement transducers HBM (10 mm range), positioned at two different faces of the prisms and by two horizontal transducers positioned at the other two faces.

The tests performed in Politecnico di Milano were carried out using a uniaxial servo-controlled MTS[®] 311.01.00 testing machine, with non-rotating steel plates and a maximum capacity of 2500 kN. Loading was applied under displacement control at a rate of 1 $\mu\text{m/s}$. The applied load was recorded by a load cell and displacements were measured with one vertical and one horizontal displacement transducers GEFTRAN PY2-10 (10 mm range) positioned at each face of the prisms. For all tested specimens, longitudinal displacements were measured over approximately 200 mm span and transversal displacements over about 150 mm span.

The results obtained are illustrated in Figure 3.9. Here, the negative sign is adopted for contraction (longitudinal or vertical strains ε_v) and the positive sign is adopted for elongation (transversal or horizontal strains ε_h). It is noted that the null horizontal deformations exhibited up to the peak load in the case of specimen *Pre_1* can be explained by the fact that only two horizontal transducers per specimen were used. Table 3.8 gives a summary of the test results in terms of the elastic modulus E , compressive strength f_c and peak strain ε_p . The elastic modulus was calculated as the average slope of the stress-strain diagram between 30 and 50% of f_c . It is noted that the elastic modulus is the

parameter showing the largest coefficient of variation, approximately the double of the values found for the strength and peak strain.

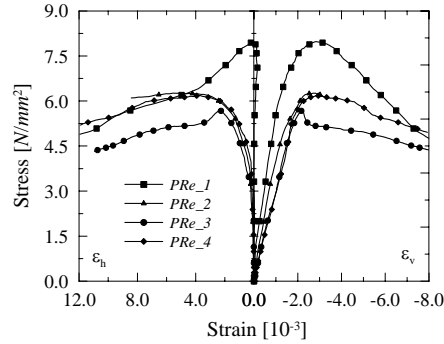


Figure 3.9: Stress-strain diagrams obtained from standard compression tests.

Table 3.8: Results obtained from standard compression tests. In brackets, the coefficient of variation is given.

Specimen	E [N/mm^2]	f_c [N/mm^2]	ϵ_p [10^{-3}]
<i>PRe_1</i>	4980	8.0	2.7
<i>PRe_2</i>	4515	6.3	2.9
<i>PRe_3</i>	2510	5.7	2.2
<i>PRe_4</i>	2720	6.2	3.0
Average	3680 (34%)	6.6 (15%)	2.7 (13%)

3.3.3 Short-term creep tests

Experimental setup

Short-term creep tests were carried out at Politecnico di Milano using, again, the uniaxial servo-controlled MTS[®] 311.01.00 testing machine. The experimental tests considered in this Section are part of an extensive testing program under development at the Politecnico di Milano, which is thoroughly described in Chapter 2. The displacements in the specimens were recorded by a vertical and a horizontal displacement transducer GEFRAN PY2-10 (10 mm range) positioned in each face of the prisms, in a total of eight transducers per specimen. Vertical transducers measured the average longitudinal deformation over approximately 200 mm span and horizontal transducers measured the average transversal deformation over approximately 150 mm span.

Testing program

A total of four specimens were tested for short-term creep. In standard creep tests, a specimen is subjected to a constant load and strain is recorded at subsequent times. Reproduction of the test with a series of different loads gives a family of creep curves, which characterize the creep behaviour of the material. However, in the case of ancient masonry, this procedure has severe drawbacks due to the high scatter of the material strength and the limited number of

specimens available. To overcome these problems and to obtain as much information as possible from each specimen, a stepped load-time diagram has been applied to the specimens.

The specimens were tested by applying successive load steps of 0.30 N/mm^2 at intervals of eight hours. In this way, failure could occur either during the loading phase (short-term failure) or during sustained loading (tertiary creep). An attempt to obtain creep failure of the specimens was pursued by increasing the duration of the last steps whenever the strain rate was similar to the values observed in previously tested specimens. This issue will be further addressed in Section 3.3.5.

Test results

Figure 3.10a depicts the average vertical (longitudinal) and horizontal (transversal) strains obtained, respectively ε_v and ε_h . Figure 3.10b illustrates, as an example, the time-stress-strain diagram for specimen *Pre_5*, which provides a detailed description of the results. In addition, Table 3.9 gives a summary of the experimental results in terms of the elastic modulus E , peak stress f_c' and time to failure T , which corresponds to the duration of the creep test. The values for the elastic modulus E were calculated as an average from the second to fourth load steps (0.30 to 1.2 N/mm^2).

The sample is too small to extract any conclusion. Nevertheless, the comparison between the average standard compression strength ($f_c = 6.6 \text{ N/mm}^2$) and the average short-term creep strength ($f_c' = 4.9 \text{ N/mm}^2$) seems to indicate that damage growth due to sustained loading influenced the results. In terms of average elastic modulus, the difference is rather small.

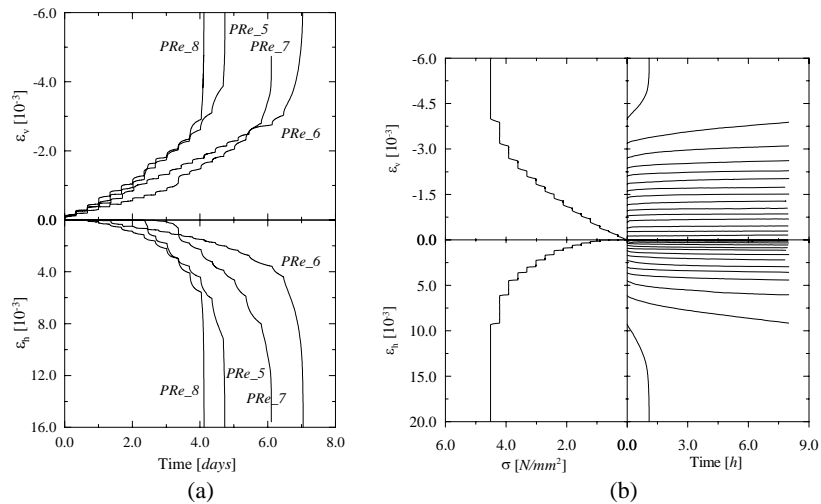


Figure 3.10: Results obtained from short-term creep tests: (a) strain-time diagrams for all tested specimens and (b) time-stress-strain diagram for specimen *Pre_5*.

Table 3.9: Results obtained from short-term creep tests. In brackets, the coefficient of variation is given.

Specimen	E [N/mm ²]	f_c' [N/mm ²]	T [days]
<i>Pre_5</i>	2700	4.50	4.7
<i>Pre_6</i>	3185	5.70	7.0
<i>Pre_7</i>	4075	5.40	6.1
<i>Pre_8</i>	3815	3.90	4.1
Average	3445 (18%)	4.9 (17%)	5.4

With respect to crack patterns, thin and diffuse vertical cracks developed in the specimens during testing but large cracks and spalling were only observed at failure. This failure mode is particularly dangerous as it can lead to erroneous conclusions about the safety level of existing structures. Figure 3.11 illustrates, as an example, the failure pattern for specimen *Pre_7*.

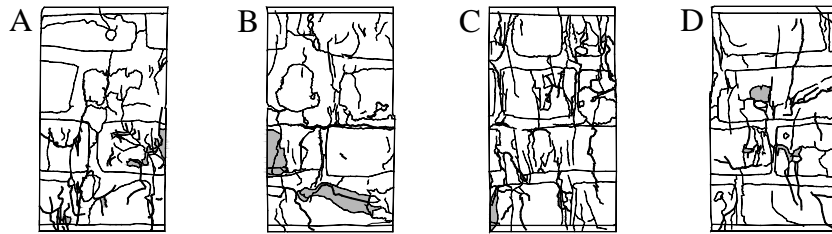


Figure 3.11: Failure pattern for specimen *Pre_7*. Shaded areas indicate spalling / loss of material.

3.3.4 Long-term creep tests

Experimental set-up

Long-term creep tests require specific testing equipment able to keep the load constant for long periods. In this study, three steel frames were specially designed and built to perform the tests conducted at University of Minho, see Figure 3.12a,b. Each frame includes two loading steel plates, a hydraulic jack, a pressure gauge and a gas reservoir to stabilize the applied load. The lower steel plate was fixed, while the upper plate was hinged. The equipment was designed to test two prisms simultaneously, separated by a steel plate. Upon failure of one of the specimens, the equipment is unloaded to remove the failed specimen and re-loaded with the remaining specimen. Further references on long-term creep tests can be found in [27].

Longitudinal and transversal deformations were measured on each face of the prisms with a removable strain-gauge LASER ELECTRONIQUE TP, see Figure 3.12c. Longitudinal deformations were measured over three mortar bed-joints with an approximate span of 250 mm, while transversal deformations were measured over one head-joint with an approximate span of 145 mm. In addition, one inductive transducer HBM (10 mm range) per specimen was employed in the longitudinal direction to act as control of the strain-gauge measurements. It is

noted that in the face of the specimen where the transducer was placed, the transversal displacement was not measured. In this way, the average longitudinal displacement of each specimen results from four strain-gauge measurements, while the transversal displacement results from three strain-gauge measurements. The tests were carried out under controlled conditions of temperature ($22 \pm 2^\circ\text{C}$) and humidity ($55 \pm 10\%$), which were recorded by a data logger TESTOSTOR 175-2.

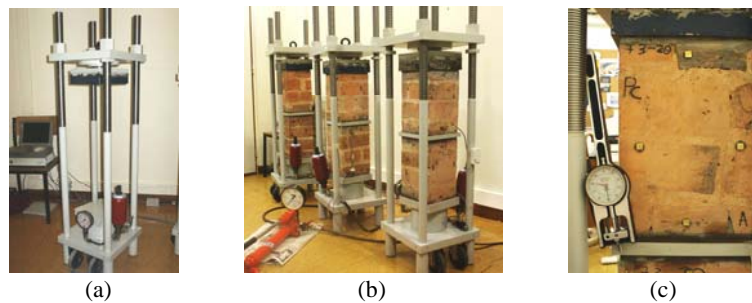


Figure 3.12: Testing apparatus: (a) hydraulic frame, (b) specimens under testing and (c) removable strain gauge and contact seats glued to the specimen.

Testing program

The tests were conducted on six specimens. As in short-term creep tests, the load was applied by successive steps and kept constant for a given period. Two different load histories have been considered in order to better define future testing programs in similar specimens. A total of two prisms were tested by applying an initial stress of 1.50 N/mm^2 and successive steps of 0.65 N/mm^2 . The initial load step corresponds, approximately, to 25% of the compressive strength f_c obtained from the standard compression tests described in Section 3.3.2, while further load steps correspond, approximately, to 10% of f_c . The duration of each period under constant load was of three months.

The other four specimens were initially loaded at 4.10 N/mm^2 (approximately 60% of f_c) with subsequent load increases of 0.65 N/mm^2 (about 10% of f_c), applied at intervals of six months. Both load histories adopted have been defined in order that the estimated duration of the tests would be of about two years.

Test results

Figure 3.13a illustrates the average vertical (longitudinal) and horizontal (transversal) strains obtained for prisms tested with constant load periods of three months. Table 3.10 gives a summary of the experimental results obtained.

For specimens tested with constant load periods of six months, Figure 3.13b shows the average strain-time diagrams obtained for all tested prisms. In addition, Table 3.11 gives a summary of the results. Figure 3.14 illustrates, as an example, the strain evolution at each face of specimen *Pre_12* and, also, the time-stress-strain diagram for the same specimen. From Figure 3.14a it is

possible to observe that the strain evolution is different at each face of the prism. This behaviour is typical of compression tests in quasi-brittle materials but, in the present experiments, such feature is more salient due to the hinged upper loading plate. Another important aspect is that in some specimens cracks suddenly arise during constant load steps, resulting in a strain jump in the strain-time diagram, see e.g. the diagrams of specimen *Pre_10* at 325 days or *Pre_11* at 450 days shown in Figure 3.13a and Figure 3.13b, respectively.

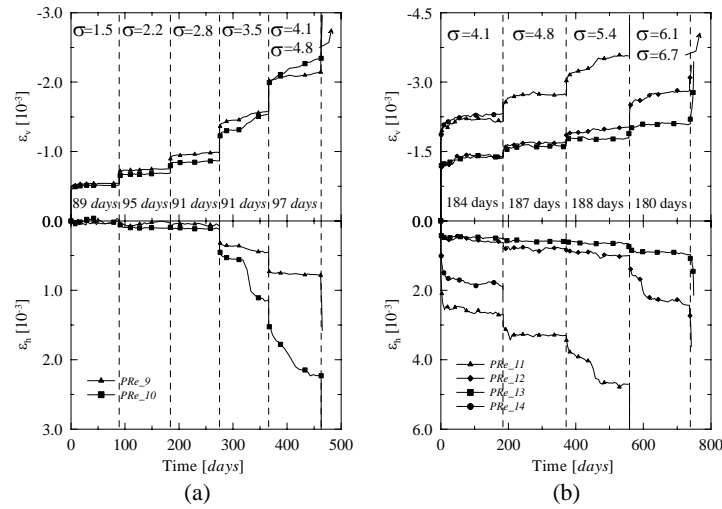


Figure 3.13: Strain-time diagrams obtained from long-term creep tests: (a) constant load periods of three months and (b) constant load periods of six months. σ stands for applied stress in N/mm^2 .

Table 3.10: Results obtained from long-term creep tests with constant load periods of three months.

Specimen	E [N/mm^2]	f_c' [N/mm^2]	T [days]
<i>Pre_9</i>	5055	4.75	465
<i>Pre_10</i>	4380	4.75	464
Average	4718	4.8	464

Table 3.11: Results obtained from long-term creep tests with constant load periods of six months. In brackets, the coefficient of variation is given.

Specimen	E [N/mm^2]	f_c' [N/mm^2]	T [days]
<i>Pre_11</i>	3720	6.05	559
<i>Pre_12</i>	5055	6.70	742
<i>Pre_13</i>	4345	6.70	749
<i>Pre_14</i>	3270	4.75	184
Average	4100 (19%)	6.0 (15%)	558

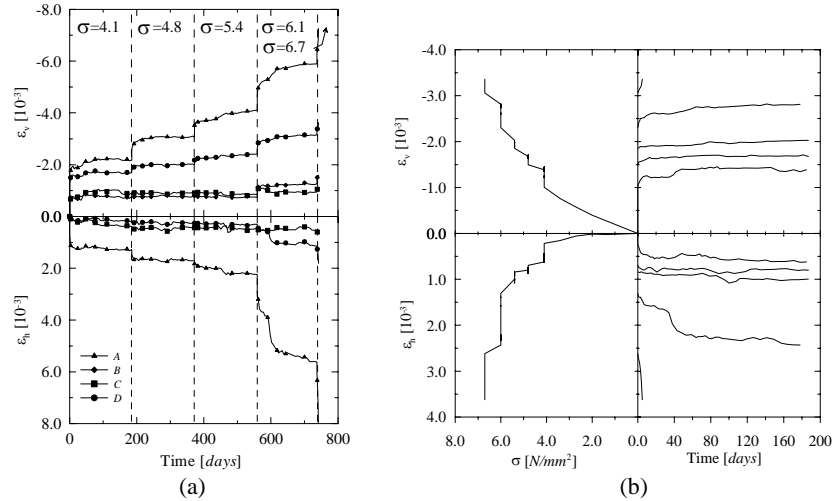


Figure 3.14: Results from long-term creep tests on specimen *PRe_12* (constant load periods of six months): (a) strain evolution for each face and (b) time-stress-strain diagram. σ stands for applied stress in N/mm^2 .

The values obtained for the compressive strength are within the range obtained for the standard compressive strength and short-term creep tests. Displacements recorded with the transducers employed (one per specimen) were found to be in agreement with the strain-gauge measurements.

Figure 3.15 depicts the crack pattern evolution for specimen *PRe_13* as an example. Again, diffuse vertical cracks developing during testing have been observed, with large cracks and spalling occurring near failure. It is noted that the specimens with lower values of f_c' presented the most diffused crack patterns. Severe non-uniform distribution of damage can be observed along the four faces of the specimens, confirming the results shown in Figure 3.14a.

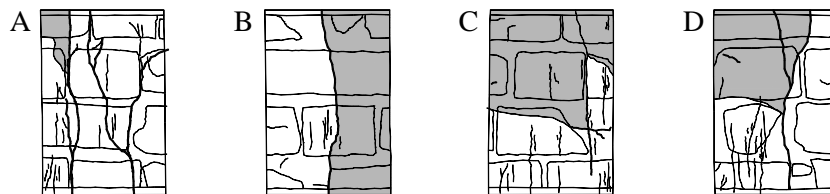


Figure 3.15: Failure pattern for specimen *PRe_13*. Shaded areas indicate spalling / loss of material.

3.3.5 Discussion of the results

The short-term compressive strength f_c of each prism tested in creep is, of course, unknown and can only be estimated. In this Section, the peak stress values f_c' obtained from the creep tests are considered as a close estimate of the

compressive strength f_c . Even if, in reality, the compressive strength f_c does not correspond to f_c' , such values remain the closest estimate in a material as heterogeneous as the one addressed in this study.

Figure 3.16 illustrates the evolution of the creep coefficient, defined as the ratio between the creep strain and the elastic strain, calculated from the short-term and long-term creep tests results. For each specimen, the creep coefficient was calculated considering all creep diagrams at low stress levels (below 45% of f_c'). It is further noted that the creep coefficient obtained from short-term creep tests was calculated from the average of the four tested specimens while the values obtained from long-term creep tests result from the average of the two specimens tested with constant load periods of three months. In the remaining four specimens tested in long-term creep, a first load step of approximately 60% of f_c was applied and, thus, such tests cannot be used to calculate creep coefficients.

Creep coefficients of approximately 0.10 and 0.15 were found at the end of 8 hours and 90 days of sustained loading, respectively, confirming that most creep strain occurs at an early stage. Another important aspect is that the creep coefficient found at the end of 90 days is significantly lower than the values recommended by EC6 [28] for masonry made with clay units, which range from 0.5 to 1.0. This can be explained by the fact that EC6 values refer to new masonry, where maturation of mortar is in an initial stage and, also, because the specimens tested had already been under service loads for approximately five centuries prior to testing.

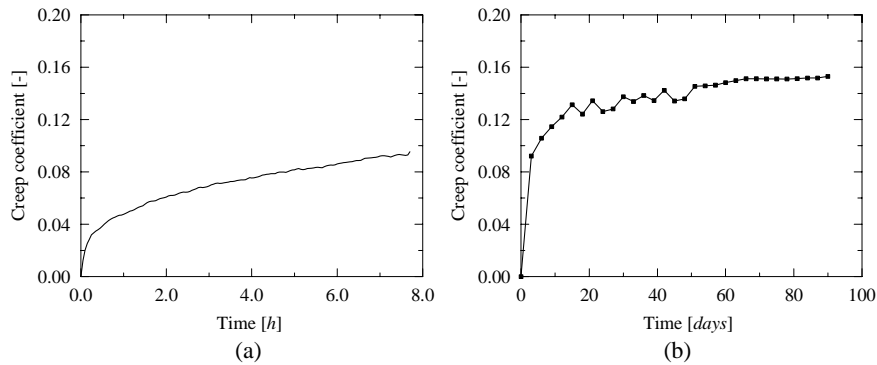


Figure 3.16: Variation of the creep coefficient with time obtained from: (a) short-term creep results and (b) long-term creep results (constant load periods of three months).

Figure 3.17 shows the strain rate evolution, vertical $\dot{\epsilon}_v$ and horizontal $\dot{\epsilon}_h$, versus the applied stress over strength ratio σ/f_c' for specimens tested in short-term creep. Strain-rate values were calculated between the sixth and eighth hours of each constant load step. It is expected that vertical strain rate values would be negative and horizontal strain rate values positive but some exceptions were found. This can be explained by minor variations in the applied load or changes

in the environmental conditions. Such values have been considered equal to zero in the strain-rate diagrams shown in the rest of this Section.

In Figure 3.17a three phases can be distinguished: for low stress levels (up to 50% of f_c'), the vertical strain rate is approximately constant and rather low; for medium stress levels (between 50% and 80% of f_c'), the vertical strain rate increases at a moderate pace; and, for high stress levels (over 80% of f_c'), a remarkable growth of the strain rate stress can be observed. The existence of three distinct phases had also been reported by Mazzotti and Savoia [29] on short-term creep tests performed on concrete specimens. Figure 3.17b shows that beyond 50% of f_c' , crack growth initiates, influencing the creep behaviour of the material.

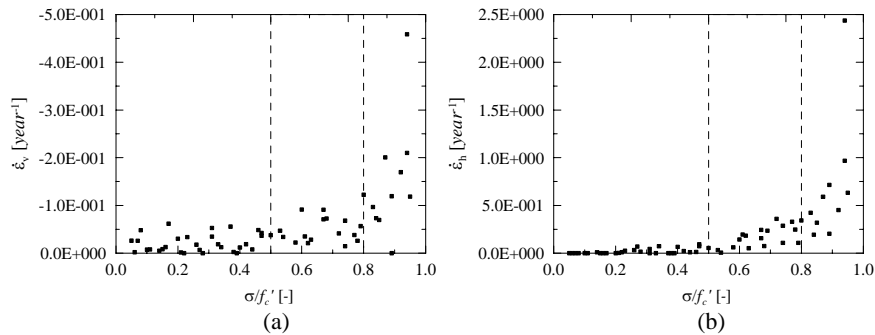


Figure 3.17: Strain rate evolution versus applied stress over strength ratio for short-term creep tests: (a) vertical strain rate and (b) horizontal strain rate.

Figure 3.18 and Figure 3.19 illustrate the strain rate evolution versus stress over strength ratio for long-term creep tests with constant load periods of three months and six months, respectively. Strain rates were calculated from the average results over the last 30 days in the case of the tests with constant load periods of three months and over the last 90 days in the case of the tests with constant load periods of six months.

It is noted that the number of results is scarce and further testing is needed to better fundament the observations made. Nevertheless, the difference between the strain rate values obtained from short-term creep tests and long-term creep tests is striking. In fact, strain rates ranging from zero to $-5.0 \times 10^{-1} \text{ year}^{-1}$ were observed in short-term creep tests while in long-term creep tests, values ranging from zero to $-1.0 \times 10^{-3} \text{ year}^{-1}$ were found. The results obtained from the two types of test seem therefore not comparable. Furthermore, primary creep seems not extinguished at the end of 8 h under sustained loading and, thus, secondary creep rates measured from short-term creep tests must be interpreted carefully.

Another important aspect is that secondary creep was observed to initiate between 60 and 70% of f_c' . It is further noted that larger strain rate values were obtained for the prisms tested with constant load periods of three months, stressing the scattered nature of the masonry tested.

An hyperbolic least squares fit of the experimental data obtained from the long-term creep tests with constant load periods of six months was computed, which can be quite useful in calibrating non-linear creep models. The hyperbolic curve adopted is in the following form

$$\dot{\epsilon} = \frac{0.4a}{1 - \sigma/f_c} + a \quad (1)$$

which yields zero for $\sigma/f_c = 0.6$ and has a vertical asymptote for $\sigma/f_c = 1.0$. From the least squares method, $a = -6.76 \times 10^{-5}$ for the vertical strain rate and $a = 1.19 \times 10^{-4}$ for the horizontal strain rate.

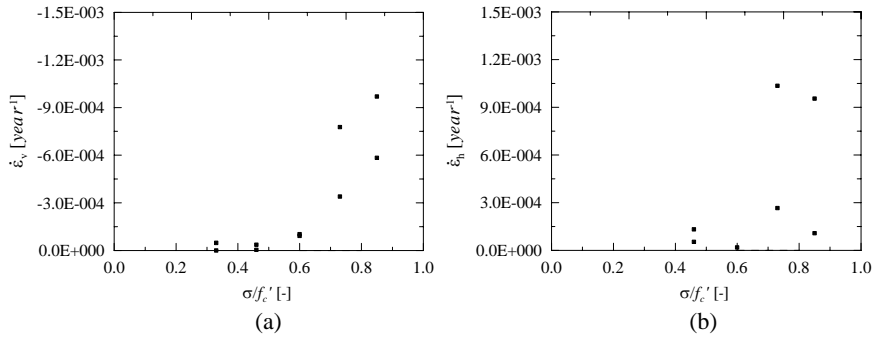


Figure 3.18: Average strain rate over the last 30 days versus applied stress over strength ratio for long-term creep tests (three months steps): (a) vertical strain rate and (b) horizontal strain rate.

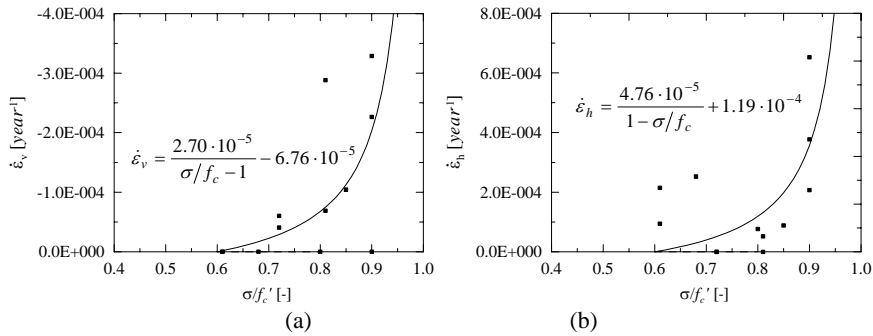


Figure 3.19: Average strain rate over the last 90 days versus applied stress over strength ratio for long-term creep tests (six months steps): (a) vertical strain rate and (b) horizontal strain rate.

The striking difference between strain rate values in short-term and long-term creep tests draws attention over what should be the minimum duration of constant load periods when conducting creep tests at high stress levels. A reasonable criterion is believed to be keeping the load constant until only

secondary creep is present, i.e. until a fairly constant strain rate is attained. For this purpose, the vertical and horizontal strain rates were calculated for each 15 days period of the total 180 days constant load steps, as illustrated in Figure 3.20. It is noted that only results corresponding to load levels larger than 60% of f_c' were considered. The results obtained indicate that the strain rate gets approximately constant after 70-80 days in the case of longitudinal strains and after 30-40 days in the case of transversal strains.

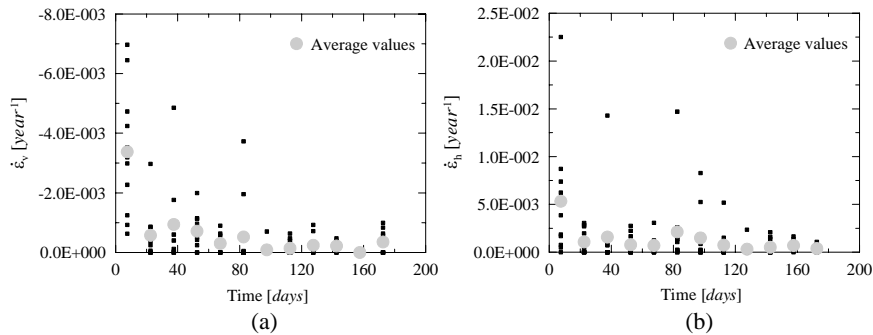


Figure 3.20: Strain-rate evolution in time for applied stresses larger than 60% f_c' : (a) vertical strain rate and (b) horizontal strain rate.

3.4 Conclusions and future work

The ability of standard continuum models, based on plasticity and cracking, and of a particle model, consisting in a phenomenological discontinuum approach, to reproduce the experimental compressive behaviour of masonry has been addressed. The comparison between the obtained numerical results and experimental results available in literature allow to conclude that discontinuum models show clear advantages when compared to standard continuum models in predicting the compressive strength and peak strain of masonry prisms from the properties of the constituents. Further investigation on models able to provide reliable predictions of masonry compressive strength, accounting for the discrete nature of the masonry components, is therefore suggested.

The creep behaviour under high stresses of ancient regular masonry specimens recovered from the collapsed Civic Tower of Pavia has been also analysed. Standard compression tests, short-term creep tests and long-term creep tests have been conducted. From experimental practice, it is possible to conclude that creep tests on ancient masonry prisms should be carried out by applying the load in successive steps, at a given time interval, starting from a low stress level. In this way, a throughout description of the viscous behaviour of the material can be obtained. Creep tests in which the load is applied in a single step are inadequate in the case of ancient masonry due to the high scatter in the mechanical properties and to the small number of specimens usually available.

The time period between successive load steps should be sufficiently long to extinguish primary creep. In fact, the evolution for different stress levels of the

strain rate associated to secondary creep can only be evaluated in such a way. From the results obtained on the regular masonry prisms tested, a minimum time period under sustained loading of 70 to 80 days should be adopted. For this reason, remarkable differences were observed between secondary creep rates calculated from short-term or long-term creep tests. Short-term creep results should, therefore, be interpreted carefully. Finally, it should be stressed that secondary creep was found to initiate at 60 to 70% of the compressive strength. A hyperbolic fit to describe the evolution of secondary creep rate with the applied stress-level has been suggested in the present study.

Suggestions for future work include further creep tests so that an adequate characterization of the material can be obtained, given the wide scatter associated to ancient masonry. With respect to the masonry constituents, experimental results on the non-linear creep behaviour of units and mortar are nearly absent in literature, [30], meaning that further investigation is required. In terms of numerical modelling, the development of suitable 3D models for viscous inelastic behaviour is still needed in order to include time-dependent effects in the numerical simulations of failure.

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