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Stability of ancient masonry towers: Moisture diffusion, carbonation and size effect

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Abstract

Moisture diffusion and carbonation influence the behavior of multiple-leaf ancient masonry walls, producing during centuries a redistribution of stresses from the core of lime mortar concrete to the external cladding of stiff masonry. This is likely one of the causes of long-time damage of some ancient masonry towers. With these motivations, coupled processes of moisture diffusion, carbon dioxide diffusion and carbonation reaction are analyzed numerically. Due to the absence of models and data for lime mortar, one of the simplest models proposed for Portland cement concrete is adapted for this purpose. The results reveal the time scales of the processes involved and their dependence on wall thickness (size). It is found that the temporal scale is set mainly by diffusion of moisture trough the massive concrete wall and is only slightly modified by carbonation. Moisture evolution in time is needed for stress analysis that is relegated to a subsequent paper.

Keywords: C Carbonation; A Humidity; C Diffusion; C Long-term performance; Tower

1. Introduction

In 1989, eight centuries after its construction, the Civic Tower of Pavia (Fig. 1a), Italy, collapsed suddenly, with imperceptible warning signals . This dramatic event was only the last in a series of failures of masonry towers built in Europe between the 11th and 14th centuries. Other examples are the collapse in 1902 of the Campanile in San Marco Square in Venice (whose present day structure is a replica of its predecessor [1]) and the collapse of the bell tower of the church of St. Magdalena in Goch (Germany) in 1992. In addition, there are plenty of ancient towers that are seriously damaged. After many centuries of uneventful existence, their surfaces are now seen to develop systems of growing vertical cracks propagating through mortar joints and also cutting through the bricks of masonry walls. This problem affects towers built with solid brick walls (e.g., Campanile in San Marco Square, Monza Cathedral, Torrazzo in Cremona), as well as multiple-leaf walls (e.g., Civic Tower of Pavia, Ravenna Tower, Tower of St. Giustina in Padua).

Multiple-leaf walls consist of two external layers (claddings) of good coursed masonry 150 to 250 mm thick, filled up by 1 to 4 m of a particular ancient concrete consisting of lime mortar, river gravels and recycled bricks (Fig. 1b,c). Ancient lime concrete is different from modern Portland cement concrete. Sometimes, the rubble is disordered and loose. In other cases, it consists of ordered layers of bricks and gravel alternating with thick layers of lime mortar. Fissures in these walls or the tendency of the external layers to spall off were discussed by some authors (e.g. [2–5]). They observed that, for Pavia Tower as well as most others, the foundation settlements, overloads, lightning effects and chemically induced decay must be excluded as the causes of cracking. Also, the average stress due to the weight of these towers is high but generally not critical. For instance, in the case of the Civic Tower of Pavia, which serves here as a paradigm, the average vertical normal stress at the base was only 1.1 MPa, while the average uniaxial compressive strength of the core was measured to be about 3.0 MPa [5]. Three-dimensional

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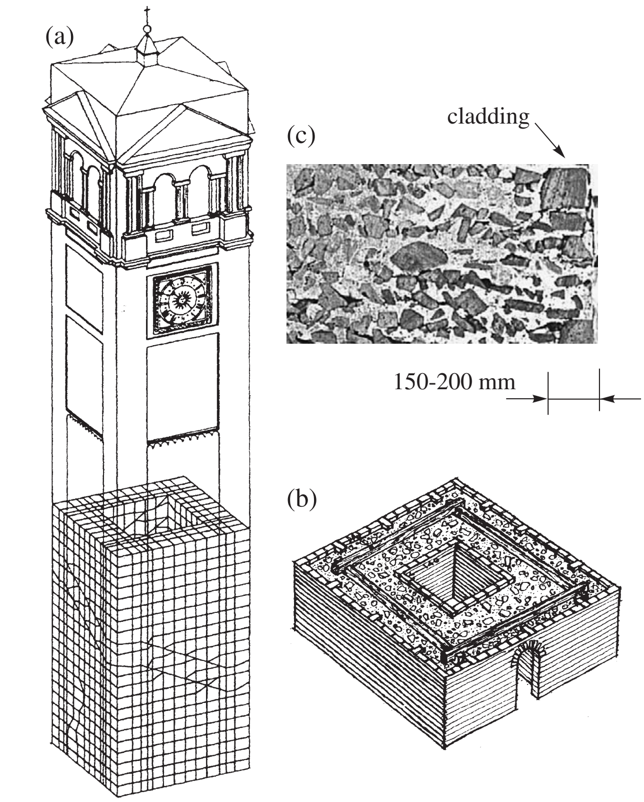

Fig. 1. Ancient tower: (a) geometry and finite element mesh of the Civic Tower of Pavia, Italy (after [5]); (b) typical cross section; (c) photo of the masonry wall of the Civic Tower of Pavia.

nonlinear finite element analyses were conducted (Fig. 1a) and showed that a severe stress concentration exhausting the compression strength existed at the base of the staircase, near the entrance to the tower [5]. However, although the ruins confirm that stress concentration might have triggered local failure, neither the overall collapse after centuries nor the development of crack patterns in the cladding many years before the collapse [5] could be explained by these finite element analyses.

To explain failure, it is necessary to take into account the effect of time. Specimens taken from Pavia ruins and from others ancient walls were tested under constant compression stresses for long time [6,7]. The compression strain at constant stress equal to 40–50% of compressive strength increased in time and was accompanied by growth of splitting microcracks. The strain–time curve at constant stress had the form of a creep curve with secondary and tertiary creep phases [7], which must be explained by damage microcracks growth (and must be sensitive to the lateral confining stress). Researchers modelled this time-dependent behavior by a viscoelastic-damage law [8] and used it for finite element analyses. Computations showed that the damage zones produced by stresses concentration propagate in time up to failure of the structure [9]. During centuries, this damage growth was probably intensified by fatigue effects due to cyclic stresses produced by wind and bell ringing. Up to depth $d<\sqrt{6ct_p}$ (Eq. (7) in [10], c = thermal diffusivity, about 1 mm^2 s^{-1}, t_p = fluctuation period), which is 0.7 m for $t_p = 1$ day and all wall thickness for $t_p = 1$ year, the material also suffers cyclic stresses due to temperature fluctuations in the environment, different at various sides [11].

Most importantly, in massive walls, especially multiple-leaf walls, the stress distribution is nonuniform and evolves in time. Time effects arise from creep, drying, and carbonation. For this problem, a comprehensive mathematical model is still missing. Its development is the objective of this study.

2. Nature of long-term processes involved and failure scenario

The nonuniform stresses caused in multiple-leaf walls by shrinkage, creep and carbonation evoke similarities with modern multi-layer masonry walls, in which the effects of moisture diffusion, drying and creep are known to cause microcracks due to redistribution of stresses among the different layers [12]. Such phenomena must be expected also in the walls of ancient towers. The cladding, consisting of stone or brick masonry, creeps and shrinks very little. For this reason, shrinkage and creep of the core (basic creep plus drying creep) must cause gradual transfer of stresses from the core to the cladding. Further stress transfer in the horizontal cross section can also be caused by volume changes due to carbonation of lime concrete, which slowly propagates from the outside to the inside of the core. Why should these processes take centuries?

The temporal scale is set by the diffusion of moisture through the massive wall, and is somewhat modified by carbonation. The half-time of diffusion processes is known to be proportional to the square of thickness. The ancient concrete appears to have roughly similar diffusion properties as modern low-strength concrete and, for a 0.15 m thick wall of such concrete, the drying half-time is about 2 years. So, for 2.80 m thick wall of ancient concrete, the half-time is expected to be about $(2.80/0.15)^2 \times 2 \approx 700$ years. This is confirmed by the evidence that very thick ancient walls built centuries ago are still far from completely dry and carbonated.

As hypothesized by Bažant and Ferretti [13], during the initial stage of drying, concrete near the exterior cladding shrinks and undergoes additional creep due to drying. This causes tensile stress increments, which must be balanced by compressive stress increase in the central portion of the wall. The stresses in concrete, though not those in the cladding, relax due to creep. During the terminal stage of drying, the central portion of the wall shrinks and additionally contracts due to drying creep. This reduces compressive stresses in the central portion, which must be balanced by an increase of compressive stresses both in the cladding and in the concrete near the cladding. The resulting increase of compressive stress may cause secondary creep, tertiary creep and compression failure of the surface layer of the wall, which can take the form of either crushing of the cladding with the adjacent concrete, or delamination buckling of the cladding.

In either case, the compression failure would not be simultaneous because compression failure is not plastic but softening so the failure cannot be simultaneous, as typical of plasticity, but must localize and propagate transversely. Transverse propagation is governed by fracture mechanics, i.e. by the energy release rate. As is well known, this rate may be calculated for constant load or