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Discussion of "Learning from Failure of a Long Curved Veneer Wall: Structural Analysis and Repair" by Paulo B Lourenço and Pedro Medeiros

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Lourenço and Medeiros, in an interesting and valuable paper, describe the failure of the brick-masonry veneer façade of a multi-use public hall in Gondomar, Portugal.

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Damage occurred within two years of construction. The veneer was a single leaf of continuous brick masonry tied to a reinforced-concrete structural wall, and forming a cavity of nominal width 0.07m which was partly filled with foamed polyurethane. The veneer wall was 242m in length × 15m in height, without movement joints, and extended around most of the elliptical perimeter of the building with portions facing north, east and south. From their site investigations and technical analysis, Lourenço and Medeiros attributed the failure primarily to effects of "the irreversible expansion of clay brick", apparent both from cracking and from extensive out-of-plane deformation of the wall, which had widened the cavity to as much as 0.13m. Effects were greater on parts of the wall facing south. The failure analysis made use of a power law proposed by Wilson et al. (2003) to describe how expansive strain develops in fired-clay ceramics with time. Here we comment on recent fundamental work on moisture expansion in brick, and in particular on its temperature dependence, matters of direct relevance to the paper under discussion. Our comments support and extend the conclusions of Lourenço and Medeiros, with which broadly we agree.

Irreversible moisture expansion occurs as a result of slow chemical reactions between components of the fired-clay ceramic and environmental moisture (Hamilton and Hall 2012). The magnitude of the expansion varies strongly with brick mineralogy and kiln firing history, but a predictive model for expansion based on these factors does not yet exist. However, in general, highly crystalline engineering ceramics produced at high kiln temperatures expand less than low fired ceramics with a higher amorphous content. The penalty is that high-fired ceramics tend to be more brittle and prone to cracking. It is now established that the expansive reaction continues indefinitely although at a diminishing rate over all timescales, and therefore there is no well defined time at which it ceases. Recent re-analysis of published data

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(Hall et al. 2011, Hall and Hoff, 2012) shows that the equation $e = at^{1/4}$ accurately describes expansion strain e over periods of time t as long as 65 years. It follows from this equation that expansive strain at 16y is double that at 1y; and three times the 1y value at 81y.

The persistence of the expansion reaction, albeit with a diminishing rate, emphasizes the need to incorporate appropriate movement joints in masonry design. Lourenço and Medeiros mention the possibility of using a "poor mortar" to accommodate some of the expansive strain. The use of weak mortars undoubtedly explains the absence of expansion damage in some much older buildings with thick brick walls. However we consider that in thin brick veneers such as that at Gondomar a weak mortar is potentially dangerous.

It is unfortunate both for design and for failure analysis that the test procedures generally used to characterize clay brick do not provide values of the expansivity a which are needed to apply the equation $e = at^{1/4}$. Accelerated steam tests such as EN772-19 cited by Lourenço and Medeiros are at best semi-quantitative. In our view it is essential to determine the expansivity from measurements of expansion strain made over an appropriate period of time under controlled conditions (Hall and Hoff 2012).

We draw attention also to the important practical matter of the temperature dependence of the moisture expansivity (Hall, Hamilton and Wilson, 2013). The fact that moisture expansion is the direct consequence of a chemical rehydroxylation reaction (Hamilton and Hall 2012) ensures that the expansivity increases notably with temperature. Available data indicate that the activation energy (which controls the temperature dependence) is about 70 kJ/mol. This means, for example, that the expansivity a of any brick material is about 60 per cent greater at a temperature of 30

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°C than it is at 10 °C. Thus if a limit expansion strain (say 1 x 10^{-3}) is reached in a particular material in 50y at 10 °C, the same strain is attained in the same material in only 7y at 30 °C.

It seems likely that its strong temperature dependence explains why moisture expansion is perceived differently in different geographical regions (see for example McNeilly 1985), and generally receives more attention in warmer climates such as Australia, south Asia and Brazil. However in any particular region the magnitude of expansion and the associated damage within individual buildings are influenced by local temperature variations, in particular from solar heat gain. In the Gondomar structure, deformation and cavity expansion were greatest in parts of the structure with a south aspect, where the summer temperatures of the veneer are highest. The influence of aspect here is presumably exacerbated by the open situation of the building, and by the insulation of the cavity where large temperature gradients might be expected. We believe this large gradient acting over a thin veneer may partly explain such dramatic damage over a short period of time. A thicker brick cladding would probably fare better, There are also no doubt seasonal modulations of the expansion. We have shown elsewhere how related thermal effects in the rehydroxylation of archaeological ceramics may be calculated (Hall, Hamilton and Wilson 2013).

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