SWELLING DAMAGE MECHANISM FOR CLAY-BEARING SANDSTONES

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Abstract

Some sedimentary stones contain clays that swell upon wetting, and this can lead to damaging stresses. The most commonly observed damage mechanism in the field with clay bearing sandstones is that of buckling, where the surface delaminates from the bulk of the stone. In this study, we compare experimental results to theory in the prediction of buckling and find that buckling occurs above a critical flaw aspect ratio. Because of the large size of the aspect ratio, we also explore a potential flaw growth mechanism based on subcritical deflections created by varying wetting patterns.

Keywords: clay swelling, sandstone deterioration, buckling

1. Introduction

Swelling clays are a well known source of damage in many engineering problems such as tunneling and soil stability (Barton et. al 1974, Mohamed 2000). In the field of conservation, swelling clays can exist as part of the cement of sedimentary stones often used in historic buildings and monuments, and they have been identified as a potential source of deterioration by many authors (Jiménez Gonzalez et al. 2002, Delgado Rodrigues 2001, Franzini et al. 2007). The presence of clays can also create many small pores, which can also lead to damage from frost or salt crystallization. Swelling clays can cause damage from the evolution of stresses during wetting and drying cycles that are on the order of the stone's strength, and can be estimated in the limiting case of a very thin wet or dry layer by the following (Jiménez Gonzalez et al. 2004):

$$\sigma_{d/w} = \pm \frac{E_{d/w}\varepsilon_s}{1-\nu} \qquad (1)$$

where $\sigma_{d/w}$ = drying or wetting stress, $E_{d/w}$ = dry or wet Young's modulus for the stone, ε_s = swelling strain, and ν = Poisson's ratio, usually estimated to be about 0.25. The stress can be positive or negative, depending on whether a wetting or a drying cycle is occurring; because wetting places the thin layer in compression relative to the rest of the stone, wetting stresses are negative (compressive). Typically the Young's modulus is on the order of GPa and the swelling strain can be anywhere from 0.3 to 3 mm/m, which will produce stresses on the order of MPa, close to the strength of stones. Because stones are much weaker in tension than in compression, most damage is expected to occur during a drying cycle, which would resemble mud cracking. However, most damage observed actually resembles buckling, as seen in Figure 1. This damage is expected to occur during wetting cycles.

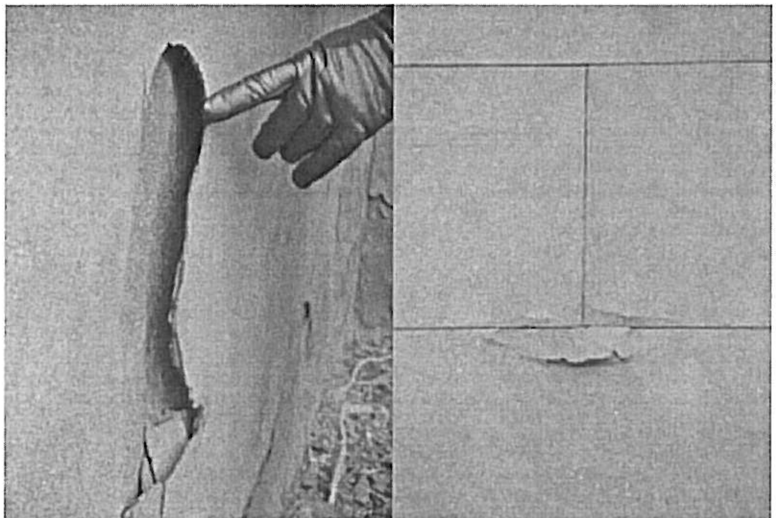

Figure 1: Buckling damage observed on the Victoria Mansion, a 19th century mansion in Portland, Maine, USA, constructed out of Portland Brownstone, an expansive clay-bearing sandstone found on many historic structures in the northeastern US.

Buckling is a failure mode characterized by sudden failure of a slender object due to a large buildup of compressive stress. In the case of the swelling stone, the failure occurs in a thin layer already detached from the stone surface that suddenly "peels" away from the rest of the stone, as seen in Figure 2.

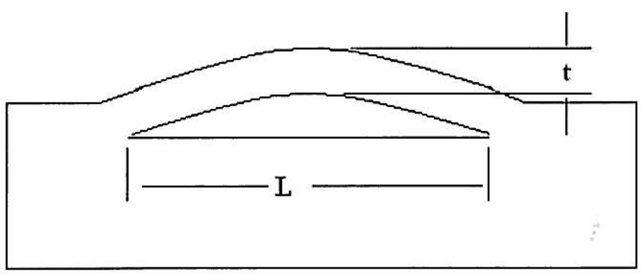

Figure 2: Schematic demonstrating buckling. *L* is the length of the flaw, *t* is the depth from the surface of the stone to the flaw.

It is necessary for a preexisting flaw to have caused the initial detachment, and this could come from salt crystallization damage, frost action, or already present imperfections in the bedding of the stone. The problem of surface buckling of a thin, circular plate with fixed perimeter was analyzed by Hutchinson (1996), and from his analysis it can be shown that buckling will occur at a critical aspect ratio:

$$A_{crit} = \frac{\pi}{3\varepsilon_s} \tag{2}$$

where A_{crit} = the buckling aspect ratio (*L/t*, as seen in Figure 2) and ε_s is the strain in the plate, which in this case is the swelling strain. Thus the critical aspect ratio for buckling can be estimated if the swelling strain is known. It is the goal of the present study to test this condition for buckling in swelling stones.

2. Materials & Methods

2.1 Materials

For this study, Portage bluestone was obtained from Endless Mountain Quarry (Susquehanna, PA, USA). This stone was selected because it has a high swelling strain, and the large swelling strain means a smaller critical aspect ratio. Samples were cut into slender rectangular plates of approximately 20 cm length, 4 cm width, and varying thicknesses on the order of a few millimeters. The thicknesses varied in order to vary the length to thickness aspect ratio necessary to test the buckling theory.

2.2 Stone characterization

The swelling strain, sorptivity, Young's modulus, and porosity of the stone were measured. The swelling strain was characterized by measuring the swelling of a prismatic sample using a Dynamic Mechanical Analyzer (DMA, from Perkin Elmer, USA) with an accuracy of +/-0.2 μm. The sorptivity was measured by suspending a stone sample below a balance, contacting a known cross sectional area with water, and monitoring the mass uptake as a function of time using a computer. The porosity was measured via vacuum impregnation. The Young's modulus was measured using a homemade static 3-point bending setup in which the load and deflection were monitored on a wet or dry sample. Finally, because this stone (like most sedimentary stones) demonstrates anisotropy due to bedding orientation, the properties were measured only in the orientation of interest.

2.3 Buckling Experiment

Buckling experiments were performed by restraining the ends of the stone samples both laterally (with rigid end members) and vertically (with clamps). The setup is pictured in Figure 3.

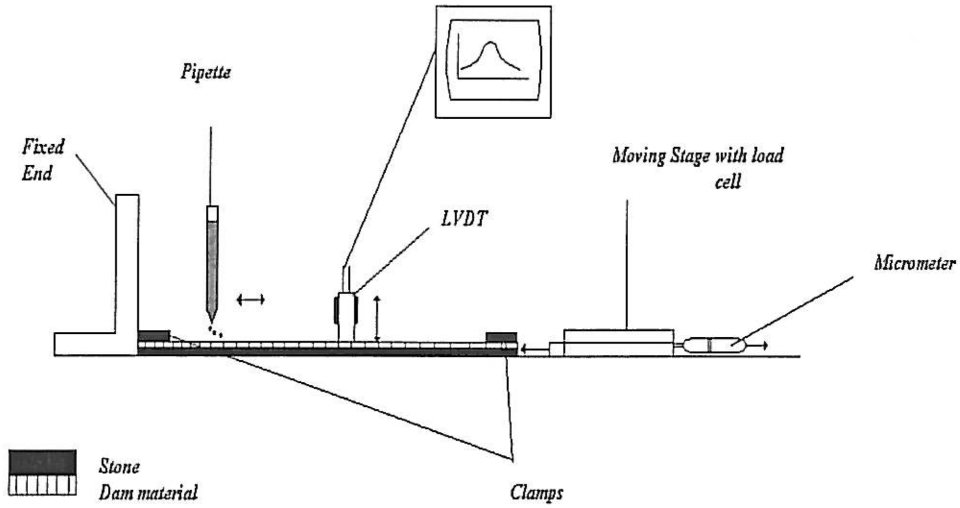

Figure 3: Setup for buckling experiments.

One end of the sample was restrained with a translating stage coupled to a force gauge in order to ensure that the same force was applied to the end for each experiment. The length, L, was controlled by the clamp distance, and was approximately 20 cm. The displacement at the center of the sample was monitored with a linear variable differential transducer (LVDT, from Macrosensors, Pennsauken, NJ, USA). A "dam" was made using a silicone sealant around the edges of the sample to control the wetting, and wetting was performed by slowly adding water from a pipette across the length of the sample until full saturation was achieved.

3. Results

For the Portage bluestone, the swelling strain was 0.81 mm/m. The sorptivity was 0.0152 g/cm $min^{1/2}$, and the porosity was 4.4%. The Young's modulus was 30 GPa dry and 13 GPa wet.

The results of the buckling experiments are shown in Figure 4. The critical aspect ratio as calculated by equation (2) is marked on the plot. It can be seen that above the critical aspect ratio, deflections are on the order of hundreds to thousands of microns, demonstrating buckling.

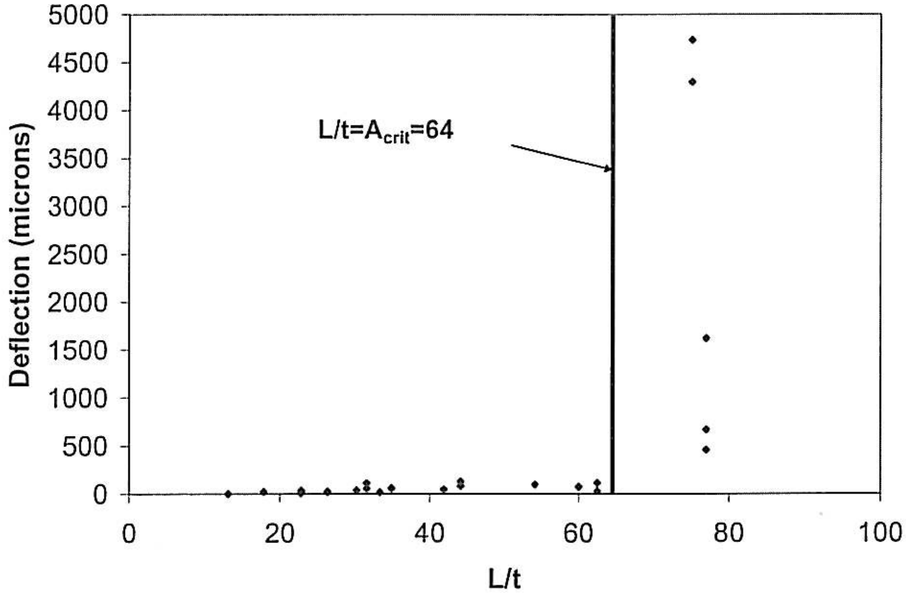

Figure 4: Deflection measured in microns versus aspect ratio (*L/t*) for Portage bluestone in the buckling experiments.

4. Discussion

The results of the buckling experiment demonstrate that buckling occurs above the critical aspect ratio for the Portage bluestone used in this study, in accordance with the theory. There were difficulties in cutting long thin samples to test the theory at the higher aspect ratios, which explains the lack of data (as well as the apparent grouping of particular aspect ratios) at aspect ratios above about 40. Additionally, the very thin samples (very high aspect ratios) were quite fragile and would often fracture under the restraints. Nevertheless, the magnitudes of the deflection are so high and the increase so sudden between the data on opposite sides of the critical aspect ratio that it is evident that buckling has occurred.

The extremely high critical aspect ratio, however, is a point of concern. It is difficult to believe that the stone has preexisting flaws with such high aspect ratios when it is installed from the quarry. There must be a flaw growth mechanism that allows a flaw to grow to a critical size where it can then cause buckling failure. To examine this possibility, the data at lower aspect ratios was examined more closely, as seen in Figure 5.

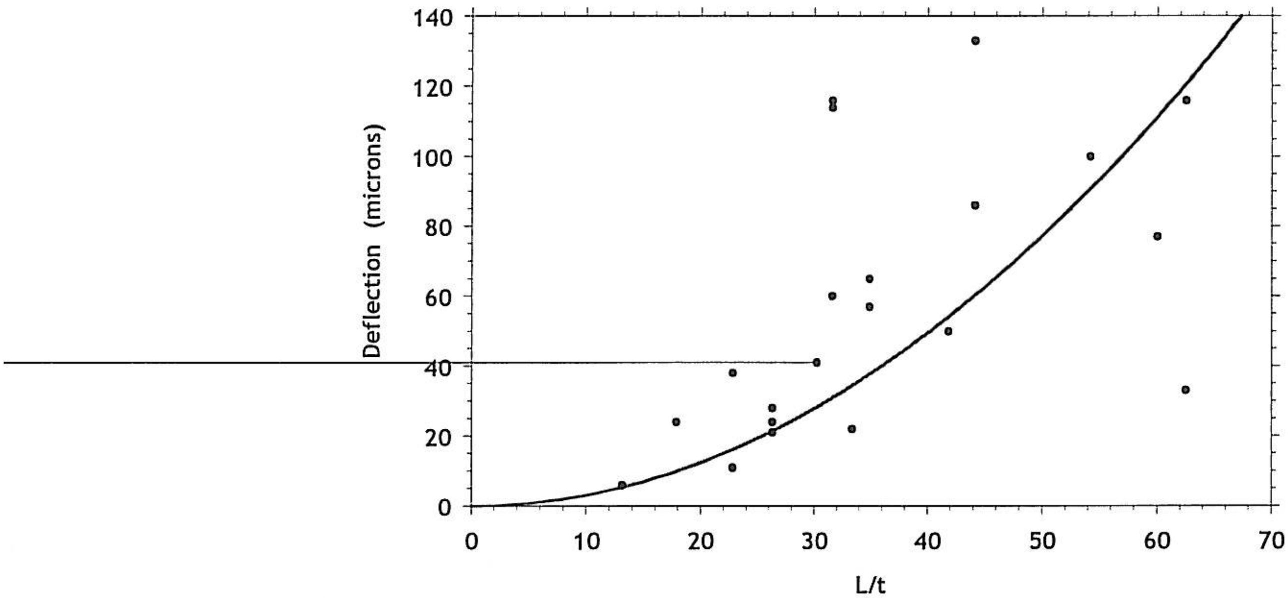

Figure 5: Subcritical deflection of Portage bluestone. The curve indicates the dependence of deflection on the square of the aspect ratio. Significant scatter in the data is due to the details of the wetting pattern.

From the plot, it can be seen that subcritical deflections (deflections at aspect ratios lower than the critical aspect ratio) can be rather significant. The deflections are on the order of tens to hundreds of microns, and are too large to be explained as free swelling in the direction perpendicular to the plate thickness.

Bloom & Coffin (2001) analyzed the problem of a thin, circular plate with fixed perimeter subjected to various thermal distributions, and found that if the thermal gradient varied through the plate, then a bending moment is formed that can result in a deflection. Thermal stresses are analogous to hygric stresses, so the thermal problem is easily adapted to this problem. The deflection varies according to the equation

$$\frac{w}{t} = A^2 \varepsilon_s \Omega(u) \tag{3}$$

where w/t is the vertical deflection normalized by the thickness of the plate, A is the aspect ratio (L/t), ε_s is the swelling strain, and $\Omega(u)$ is a function that depends on the wetting distribution. $\Omega(u)$ is equal to zero when the wetting is uniform, meaning that there is no deflection in the case of a uniform application of water. This is virtually impossible to achieve, as there will naturally be gradients formed as the water is applied from one side of the sample to the other. This is also what is expected in nature, as a stone's wetting pattern during a rainstorm is expected to be nonuniform. The dependence of the deflection on the square of the aspect ratio is also shown by a curve drawn in Figure 5, but the data show significant scatter from the curve due to the dependence on the random nature of the wetting pattern. From the same analysis, the bending moment formed is:

$$M_r = -E\varepsilon_s t^2 \mu(u) \tag{4}$$

where M_r = bending moment, E = the Young's modulus, t = plate thickness, and $\mu(u)$ is a function analogous to $\Omega(u)$ in equation (3). Once again, wetting gradients lead to variations in the bending moment. These subcritical deflections and bending moments may generate stresses large enough to propagate a flaw at the crack tip. This point is currently under investigation by numerical simulation, as it may be the mechanism necessary to grow a flaw to a critical (buckling) aspect ratio.

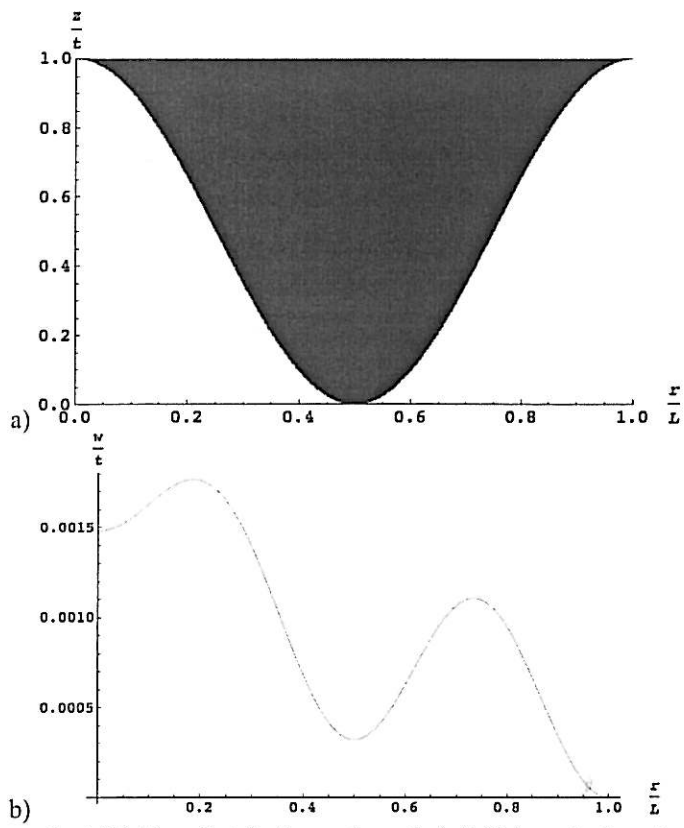

Figure 6: a) Wetting distribution, where dark field is wetted portion of stone. The center of the circular flaw is at distance normalized by flaw radius (*r/L*) equal to zero, and *z/t* is the axial coordinate normalized by the flaw depth. b) Vertical deflection normalized to flaw depth (*w/t*) versus normalized flaw radius. Calculated using properties of Portage bluestone (ε_s= 8e-04, ν = 0.25) and using aspect ratio $A = L/t = 10$.

The effect of a nonuniform wetting distribution on the subcritical deflection was simulated using *Mathematica*® to evaluate the equations given by Bloom & Coffin (2001), and the results are shown in Figures 6a-b. It is clear that the wetting distribution has a large effect on subcritical behavior. The effect of varying wetting patterns on the stress distribution is also under investigation using numerical methods.

5. Conclusion

The results of this study demonstrate that above a particular flaw aspect ratio, buckling failure will occur in swelling sandstone. However, that aspect ratio is very high and unlikely to be found in quarried sandstone, so a potential mechanism by which flaws can grow from a subcritical to a critical size has been identified and is currently under investigation. This mechanism is dependent on the details of the wetting distribution and might generate stresses sufficient to grow flaws. Finally, it should be noted that treatments that reduce swelling stress have been identified (Wendler et. al 1991, Gonzalez et. al 2004) and their efficacy in reducing damage via this mechanism is also being investigated.

Acknowledgment

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6. References

Barton, N., Lien, R., & J. Lunde. 1974. Engineering classification of rocks for the design of tunnel support. Rock Mechanics and Rock Engineering, 6 (4) 189-236.

Bloom F. & D. Coffin. 2001. Handbook of Thin Plate Buckling and Postbuckling. Chapman and Hall. London.

Delgado Rodrigues, J. 2001. Swelling behaviour of stones and its interest in conservation. An appraisal. Materiales de Construcción, 51 (263-264) 183-195.

Franzini, M., Leoni, L., Lezzerini, M., & R. Cardelli. 2007. Relationships between mineralogical composition, water absorption and hydric dilatation in the 'Macigno' sandstones from Lunigiana (Massa, Tuscany). Eur. J. Mineral., 19 113-125.

Jiménez Gonzalez, I., Higgins, M. & G.W. Scherer. 2002. Hygric swelling of Portland Brownstone. Materials Issues in Art & Archaeology VI, MRS Symposium Proc. vol. 712, eds. P.B. Vandiver, M. Goodway, and J.L. Mass, 21-27. Warrendale, PA.

Gonzalez, I.J. & G.W. Scherer, 2004. Effect of swelling inhibitors on the swelling and stress relaxation of clay bearing stones. Env. Geo., 46, 364-377.

Hutchinson, J.W. 1996. Mechanics of Thin Films and Multilayers. Technical University of Denmark Report.

Mohamed, A.M.O. 2000. The role of clay minerals in marly soils on its stability. Eng. Geo., 57 (3-4) 193-203.

Wendler, E., Klemm, D.D. & R. Snethlage. Consolidation and hydrophobic treatment of natural stone. Proc. from 5th International Conference on Durability of Building Materials and Components, 203-212. London.