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TENSILE STRAIN FOR FAILURE OF OVER-CONSOLIDATED CLAY

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ABSTRACT: This paper presents strain criteria for tensile failure in over-consolidated kaolin clay. The results were obtained by performing 4-point bending tests on consolidated kaolin clay beams. Load controlled and strain controlled tests were performed on clay beams with varying initial suction to understand the strain criteria for crack initiation in clay. Strains in the clay were obtained by Particle Image Velocimetry (PIV) analysis of digital images of the clay beam and suction measurements were obtained from pore pressure and tension transducers (PPTTs) installed within the clay beams. Results from this investigation showed that the threshold tensile strain to cracking in kaolin clay decreased from about 4% at 15 kPa of initial suction to about 1.5% at 100 kPa of initial suction. Further details are presented in Thusyanthan et al. 2007 [1].

Keywords: Tensile strength; cracking; over-consolidated clay

1. INTRODUCTION

Tensile strength of clay is an important phenomenon that that affects many facilities such as in dams, embankments and landfill clay liners. It is also an important factor

Early work on triaxial extension tests was performed by Parry [2] on saturated Weald clay. This work demonstrated that the failure points of saturated clay in both drained extension tests and undrained extension tests (in which the backpressure has been elevated to maintain positive pore water pressures) satisfy Hvorslev's failure concept. Further tension tests on clay were carried out by Bishop and Garga [3], using a modified triaxial cell. They performed drained tension tests on 'intact' samples of London clay to obtain tensile and compressive strengths expressed in terms of effective stress and the corresponding failure strains. Since these tests were carried out in the absence of negative pore pressure, it was entirely reasonable that the investigators looked to rock mechanics principles based on "true cohesion" to analyse the results. Adopting this fracture mechanics (FM) point of view, modified Griffith crack theory was used to devise a ratio of drained

tensile strength to unconfined drained compressive strength in the range 0.144 to 0.178, closely comparable with their test results. More recently, fracture mechanics and Griffith's theory have been applied to evaluate crack growth in unsaturated compacted clays [4], saturated clays [5], and crack tip stress in saturated soils [6].

Ajaz and Parry [7] continued to work towards a strength of materials (SOM) criterion for tensile crack initiation by performing direct tension, unconfined compression and bending tests on two unsaturated compacted clays in order to investigate the stress-strain characteristics leading up to Since this research predated the cracking. development of high capacity tensiometers, stress analysis of their results can only be performed in terms of total rather than effective stress. However, the work of Ajaz and Parry [7] clearly demonstrated that the tensile strain at failure increased with an increase in clay moisture content, both above and below the Proctor optimum for the two compacted clays, irrespective of the type of tension test. Tensile strain at failure in a bending test was shown to increase with water content from 0.5% at a water content of about 22% to 1.5% at water content of about 35%. These values fall within the range of tensile strain at failure extracted from the literature by Lagatta et al. [8] of 0.07% in dam embankments to 4.4% in landfill clay liners. However, the necessity of relying on moisture content to describe the state of the clay in this work irreversibly combines and smears the effects of void ratio and unsaturated effective stress on the observed tensile behaviour, thus eliminating the possibility of deriving a SOM criterion for crack initiation.

This paper presents an investigation into the stressstrain criteria for cracking in clays by performing 4point bending tests on consolidated kaolin clay beams [9]. The clay beams were obtained from specimens of kaolin clay one dimensionally consolidated to a stress of 500 kPa or 250 kPa. Load controlled and strain controlled tests were performed on clay beams with varying initial suction to understand the stress-strain criteria for crack initiation in clay. Tensile strain to cracking was measured by performing PIV analysis [10] on the digital images of the beams being subjected to bending, while the suction was measured by Pore Pressure and Tension Transducers (PPTTs) installed at three different locations within the beams.

2. EXPERIMETAL WORK

Load controlled and strain controlled 4-point bending tests were carried out on beams trimmed from E-grade kaolin clay which had been onedimensionally consolidated either to 500 kPa (type-A beams) or to 250 kPa (type-B beams).

E-grade kaolin clay powder was thoroughly mixed with an equal mass of water under vacuum to produce a slurry. The kaolin slurry at 100% water content was then one-dimensionally consolidated to an effective stress of 500 kPa or 250 kPa in a consolidation rig (Fig. 1). Beams 320 mm long (transverse to the consolidation loading) and of 80 mm cross-section, weighing 4 kg, were cut from the consolidated clay specimens. All beams were wrapped in polythene and stored in air-tight containers prior to testing. The E-grade kaolin clay has a liquid limit of 51% a plastic limit of 30% and permeability of the order of 10^{-9} m/s.

Prior to testing a beam, it was removed from the airtight container and three PPTTs (one near the compression face, one near the tension face and the other in the middle of the beam) were installed at the mid-length of the beam by slowly drilling from one end of the beam. The PPTTs were saturated under vacuum prior to installation. The details of the saturation process are described in Take and Bolton [11]. Fig. 2(a) shows the location of PPTTs in the clay beam. A wooden framework and an aluminium guide were used to ensure that the drilling alignment and depth were correct (Fig. 2(b)&(c)) with the beam protected against evaporation by a polythene cover. The PPTTs were installed on a diagonal of the cross section of the beam in an attempt to mitigate their tendency to weaken the cross-section. The PPTTs were inserted into the drilled holes, back filled with clay slurry and allowed to set. After the installation of PPTTs, the pore pressure was monitored to ensure that it was uniform before the polythene cover was removed. The elevation face of the beam which would face the digital camera was dusted with dyed fine sand. This gives the surface some texture which is required for good PIV analysis of the beam images.



Fig. 1. Consolidated clay specimen of E grade Kaolin clay (320 mm \times 80 mm \times 80 mm)



(a) PPTT locations in the clay beam





(b) PPTT installation (c) Clay beam ready for testing Fig. 2. Clay beam dimensions and PPTT locations

2.1. Particle Image Velocimetry (PIV) Analysis

experimental The investigation of cracking described in this paper concentrates on the stressstrain behaviour of the mid-span of the beam where the bending moment was uniform at its maximum value. The evolution of the magnitude and distribution of the longitudinal bending strain, ε , at this location was precisely measured using the noncontact digital image correlation technique of Particle Image Velocimetry (PIV). This technique is described by White et al. (2003)[10] and allows the precise determination of soil displacements though a series of digital images without resorting to predefined target markers, instead operating on the visual image texture of the soil (colour, grain orientation, etc.) In this application, the grain size of the soil, E-grade Kaolin, ensured that the natural texture of the material could only be seen at the microscopic level. Thus, using the technique described by Take (2003)[12], an artificial texture was applied to the elevation face of the beam using with dyed fine sand. As shown in Fig. 3, the resulting image texture is a high contrast black and white random pattern ideal for PIV analysis.

As PIV operates on image texture rather than predefined target markers, the displacement of any location throughout the beam could be measured. In this application, 33 pairs of 32x32 pixel measurement patches were defined in the digital image on either side of the mid-span of the beam throughout the full height.



b)

Fig. 3. Test setup and digital image of central region

Thus, these pairs of displacement nodes can be thought of as thirty-three virtual strain gauges and can be used to calculate the longitudinal strains throughout the depth of the beam by dividing the horizontal movement of the two patches making up each pair by the original distance between the patches.

Digital images of the beams were captured every 10s during flexural testing by two 4 Megapixel digital cameras: one focussed on a wide field of view to observe the behaviour of the entire beam and the other zoomed to capture the detailed behaviour of the mid-span. As shown in Fig. 3, a thin glass sheet containing a grid of black control makers at known locations was placed in front of the beam to provide a reference coordinate system visible in both cameras. This coordinate system was then used to improve the precision of the measured strains using photogrammetric camera calibration to remove camera errors such as the variation in scale factor due to imperfect camera positioning, radial and tangential lens distortion, and refraction [10].

2.2. Testing Procedure

All the beams initially registered suction in the range 15 kPa to 30 kPa after the equilibration of PPTTs. This suction increased slowly as the beams were allowed to air dry for different periods to obtain various values of initial suction. An air fan was used to speed up the drying process for beams

requiring high suction for testing. Beams were rotated at regular intervals to facilitate uniform drying from all sides. This was confirmed by the uniform readings of the PPTTs. Load-controlled and strain-controlled bending tests were performed on the beams with various initial suctions. 30 mm diameter perspex rods were used to apply load to the clay beams in the direction of their initial onedimensional consolidation. Table 1 summarises the tests carried out.

Type of 4 point	Test	Initial suction	
bending tests	name	(kPa)	
Load controlled tests	AL15	15	
on clay type-A beams.	AL45	45	
(20N every 3 min.)	AL75	75	
	AS25	25	
	AS45	45	
Strain controlled tests	AS62	62	
on clay type-A beams	AS75	75	
	AS82	82	
	AS80	80	
	AS100	100	
	AS102	102	
	BS15	15	
Strain controlled tests	BS22	22	
on clay type-B beams	BS45	45	
	BS46	46	
	BS65	65	
	BS92	92	

Table 1. Summary of the test	Table	1.	Summary	of the	tests
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Load-controlled tests were carried out on 3 beams of type-A (consolidated to 500 kPa). A step load of 20 N was applied to the beam at intervals of 180s. Strain controlled tests were performed using a motorised actuator. The motorised actuator was used to apply the load on the beam at a uniform displacement rate of 0.23 mm/min. Pore pressure readings from all 3 PPTTs were recorded throughout the tests.

Two digital cameras were mounted facing the beams, one to capture the central region of the beam and the other to capture the entire beam, as the beam was subjected to bending. The digital images were captured every 10 s during the test. These images were used in particle image velocimetry (PIV) analysis [10] to obtain the displacement vectors in the beam. A thin glass sheet, with a grid of black markers at known locations, was positioned very close to the beam. These markers acted as control targets to normalise the PIV analysis.

3. RESULTS

All the beams failed by tension cracking near the mid-span of the beam (Fig. 4). The load and hence the bending moment experienced by the beams increased up to the onset of cracking. After the initiation of a tension crack the load decreased and the crack grew through the beams. Complete collapse of the beams was observed once the crack had propagated through about two thirds of the beam thickness. From the recorded data, only data of significance is presented here. A complete set of the data is given in [1 & 9].



Fig. 4. Failure by crack initiation.

3.1. Strain at Crack Initiation

The development of longitudinal strain at the midspan of the beam obtained from PIV analysis of beams AL15 and AS45 is shown in Fig. 5 and Fig.6. Strain was obtained every 10s, however for clarity strains are shown every 50s in Fig. 5&6. It is clear that the strain profile, until near the initiation of a crack, is linear with depth for both the load controlled and strain controlled test. Strain plots of all the other beams also showed a linear variation of strain with depth until near crack initiation. This demonstrates that plane sections remained plane in the clay beams subjected to bending.



Fig. 5. Strain at the centre of the beam AL15, every 50s



Fig. 6. Strain at the centre of the beam AL45, every 50s

The measured tensile strains in all the beams at the initiation of a crack are plotted against the initial suction in Fig. 7. The results indicate that the tensile strain required for crack initiation in clays is significantly affected by the initial suction present in the clay. At low suction values the clay requires strains on the order of 4% to initiate cracking. At higher values of suction, the tensile strain required for crack initiation has decreased from 4% to about 1.5% at a suction of 100 kPa. Equation (1), which fits the experimental data well, can be used to predict the strain required for crack initiation in kaolin clay.

$$\varepsilon_{crack} = 14s_i^{-0.5} \tag{1}$$



Fig. 7. Percentage tensile strain to initiation of crack.

3.2. Bending Moment

The strain distributions in all the beams were very close to being linear, and straight regression lines were obtained by the method of least squares. The gradients of these lines were used to calculate the curvatures of the beams during the bending test. The bending moment applied to the beams was calculated from the applied loading and the weight of the beam. Fig. 8 shows the graph of applied bending moment versus curvature for three type A and type B beams upon failure. The initial bending moment was due to the self weight of the beams and was approximately 1 Nm for all the beams. It is evident from Fig. 8 that, for both type A and type B beams the bending strength of the beam increases with the suction present in the beam. Higher suction means higher mean effective stress in the beam, resulting in a higher bending strength. Higher suction in the beam also results in higher initial tangent bending stiffness as can be seen from Fig. 8.



Fig. 8. Bending moment vs curvature of clay beams.

It is also clear that the curvature induced up to crack initiation and to failure increases with decreasing suction in the beam.

3.3. Pore Pressure Measurements

Pore pressure measurements from PPTTs were recorded throughout all the tests. The recorded pore pressure variation versus time and applied bending moment from test AL45 is shown in Fig.9. The immediate effect of every increment of bending was a pore pressure increase on the compression side and a decrease on the tension side, as would be expected from the changes of total stress. Each of these changes then tended to decrease with time under constant bending moment, as would be expected by considering transient flow due to the induced excess pore pressure gradient. As stresses increased, the negative pore pressure increments due to tension exceeded the positive increments due to compression, and the PPTT at the neutral axis correspondingly begins to register a build up of increasingly negative pore pressures. This indicates that the influence of shear-induced excess pore pressure is not symmetrical. Additional negative pore pressures, due to suppressed dilation are induced on the tension side.

It is evident from Fig.9 that the process of bending the clay beam was partially drained. Although there was negligible evaporation, there clearly was some progressive internal drainage from the compression side to the tension side. Measured pore pressures and total stresses can be used to obtain the effective stresses in the beam. This can be used to find the effective stress criteria for tensile failure. Details of effective stress analysis and effective stress based criteria for crack initiation this given in [1 & 9].



Fig. 9. Pore pressure vs time in beam AL45.

4. CONCLUSIONS

Cracking in clay is an important phenomenon that affects the strength and permeability of clays in many facilities such as in dams, embankments and landfill clay liners. This study investigates the stress-strain criteria for tensile cracking in clays by performing 4 point bending tests on consolidated kaolin clay beams. Load controlled and strain controlled tests were performed on clay beams with varying initial suctions to understand the stressstrain criteria for crack initiation in clay. Strains in the clay were obtained by particle image velocity (PIV) analysis of digital images of the clay beam and suction measurements were obtained from pore pressure and tension transducers (PPTTs) installed with in the clay beams.

Results from this investigation showed that bending of clay beams induces a linear strain distribution in the clay beams up to near the initiation of cracking, and that the tensile strain to crack initiation decreases with increases in initial suction in the clay. Tensile strain to cracking decreased from about 4% at15 kPa suction to about 1.5% at 100 kPa suction.

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