

CRACK STABILITY IN UNIAXIAL TENSILE TESTS

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ABSTRACT

In a series of uniaxial tensile test on single-edge-notched sandstone specimens, the effect of stiffness of the test set-up on the stability of crack propagation were studied. A specimen is loaded between cables to minimize restraint in the boundary conditions. Variation of cable length represents a variation of the machine stiffness. The cable length is 200 mm, 150 mm, 100 mm and 50 mm respectively. The tests were conducted under closed-loop deformation control. A new control system based on the maximum deformation rate near the notch was developed to achieve a stable test. A long distance microscope was employed to trace the crack propagation and the location of the crack tip. The results show that the cable length does affect the stability of crack propagation. In general, local instabilities occur inevitably for all four different cable lengths. In the cable test the loading situation is defined very well, and with known location of the crack tip, very accurate inverse analysis of softening stress-crack opening relation becomes possible.

KEYWORDS

Uniaxial tensile test, cable, deformation rate control, crack stability, energy balance, secondary flexure

INTRODUCTION

Many fracture models of brittle or quasi-brittle materials need tensile properties as input parameters. Uniaxial tensile tests are commonly used to determine these properties and parameters in such materials. The measurement of tension softening behavior often requires a single crack stably propagating through the specimen. In order to maintain stability after the peak load the tests can be controlled by LVDT's and the PID settings of the regulation amplifier. However, despite the feed back system, instability appears to occur frequently, like sudden load drop and snap-back in load-deformation diagrams. Crack stability in an experiment can be affected by several factors as composition of material, stiffness of test set-up, response of control system, boundary condition, loading rate, specimen size and measuring length of the control LVDT. Some attempts have been made to investigate the stability problems in a test of quasi-brittle material, such as [1,2,3,4]. However, the subject is still far from being well understood.

Freely rotating boundary conditions provide a clear loading condition for a specimen and allow for the propagation of a single crack. Flexure of hinged specimens has been identified as an important aspect of their post-peak failure behavior [5,6]. However, it is difficult to make perfect hinges and often some small constraint will be imposed in one or more directions. Since this constraint is fundamentally unknown it can be difficult to reproduce experimental results by fracture mechanics analysis or by means of finite

element computations. To further reduce the effects of constraints, cable supports have been developed and tested.

The objective of the study is to obtain a better understanding in the causes of instability in uniaxial tensile tests on brittle or quasi-brittle materials. A series of tensile tests has been performed on single-edge-notched sandstone specimens that were loaded between cables. Four different cable lengths were tested, which represent different stiffness of a test set-up. Some interesting phenomena observed from the test are reported.

SPECIMEN AND TEST SET-UP

Specimen Preparation

In this study, Yellow Felsler sandstone was used to produce the specimens. This type of sandstone consists of clay matrix and aggregate particles (mostly quartz and feldspar) with size of 0.05 ~ 0.7 mm [7]. All the specimens were sawn from one large block in the same direction. The size of the specimen is 90*45*10 mm. The width is chosen as 45 mm in order to assure that the whole area where the crack is expected to propagate could be completely covered by the view of a long distance microscope. The thickness is chosen small so that three-dimensional effects could be avoided as much as possible. A single notch with 5 mm depth and 2 mm width was sawn for initiating a crack. After sawing, the specimens were stored in the lab for longer than 6 weeks in order to obtain constant moisture content. Furthermore, in order to improve visibility of the crack under a long distance microscope, the surfaces of the specimens were brightly painted before testing.

Test Set-up

The uniaxial tensile tests have been conducted in a servo-controlled hydraulic test machine (10 kN Instron 8872) as shown in figure 1. A specimen was glued on platens and loaded between two cables in order to eliminate boundary effect as much as possible, and to allow for the propagation of a single crack. In this series of test, four different cable lengths were used to investigate the effect of the stiffness of the set-up on the stability of crack propagation. The selected cable lengths are 200 mm, 150 mm, 100 mm, 50 mm, respectively. Three to five LVDT's were mounted on the specimen to measure the deformation in the middle region of a specimen where a crack is expected to develop. The vertical measuring length for a specimen is 15 mm. When five LVDT's were used, three of them were positioned on the rear face and two on the front face (microscope side) of the specimen to allow the microscope to follow the crack tip.

In addition, the vertical displacements of the top platen and bottom platen were measured in order to observe the rotation of the platens during crack propagation. For this purpose, two aluminum discs were connected to the rectangular specimen platen to provide for a sufficiently large measuring area. Three LVDT's are pointed to the upper disc and another three pointed to the bottom disc. A special frame has been built to mount these six LVDT's.

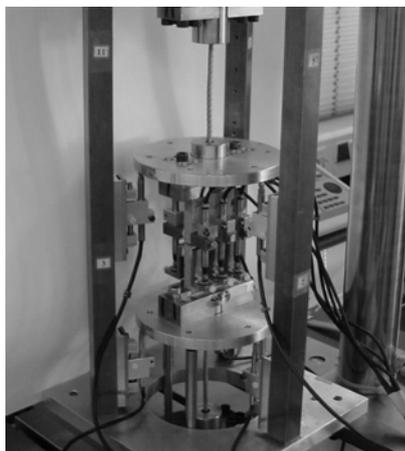


Figure 1: Test set-up

The control method plays a crucial role in the whole loading procedure to obtain a stable test. In earlier tests done by Van Vliet [9], the maximum deformation at any time was used as control variable. This system allowed for stable crack propagation studies in large sandstone and concrete specimens (up to 2400 mm long). Drawback was that manual adjustment of the PID settings was needed with decreasing stiffness of a fracturing specimen. In the present study, a new control system has been developed in which the system continuously compares the deformation rates of the two LVDT's close to the notch. Either of these LVDT's is active. The inactive LVDT will become active whenever its deformation rate is larger than that of the active LVDT plus some threshold value. For example, in Figure 2(a), LVDT 10 and LVDT 13 are the controlling LVDT's mounted next to the notch. LVDT 13 is at the front side of the specimen (microscope side) and LVDT 10 is at its rear side. Figure 2(b) shows which control signal being active at a specific moment in time. When output value is 0.95 the LVDT 10 provides the control signal and when the output value is 0.1 the LVDT 13 provides the control signal. The test results show that this control system gives a stable tensile test and it is even capable to handle snap-back behavior.

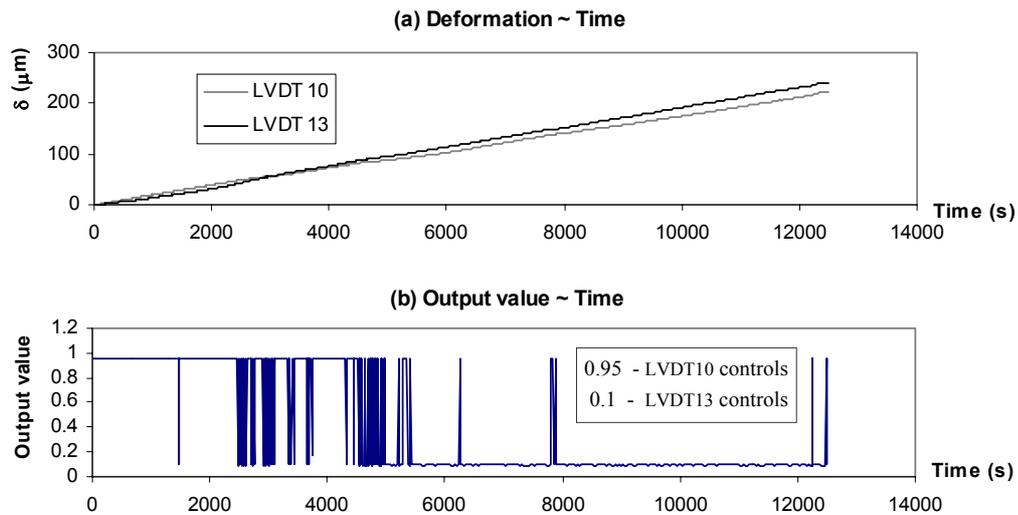


Figure 2: Control signal

In order to trace the crack propagation and location of the crack tip, a long distance optical microscope (Questar, QM100 MK-III) is employed in combination with a CCD camera. Reference [8] gives a detailed technical description on the Questar remote measuring system.

Horizontal Displacement of Cables

Theoretically, when a specimen is loaded in uniaxial tension through cables, no horizontal displacement will occur during crack opening. However, considering imperfections in the test set-up, it was felt that this should be checked. Therefore, a number of tensile tests were conducted in which the horizontal displacements of the cables were measured.

The longest cable (200 mm) was selected, which may show the most significant horizontal displacement. The horizontal displacements at the top of the lower cable were measured in-plane and out-of-plane of the specimen by means of two inductive transducers. This type of transducer uses a magnetic field to measure the distance between a cable and the head of the transducer. In order to distinguish between systematic errors and the real horizontal displacement of the cable, tests have been performed by loading both sandstone specimens (including cracking) and an aluminium specimen (deforming elastically without cracking). The results are shown in Figure 3 and table 1.

The results of sandstone tests show that the measured horizontal displacements of the lower cable are much smaller than in the aluminium tests. This indicates that the opening of a crack in the specimen does not introduce a horizontal displacement of the cables. The measured displacements are due to the elongation and rotation of the cable under tensioning. Therefore, in the subsequent experiments and data interpretation, it is assumed that the external load is properly aligned during the whole loading process.

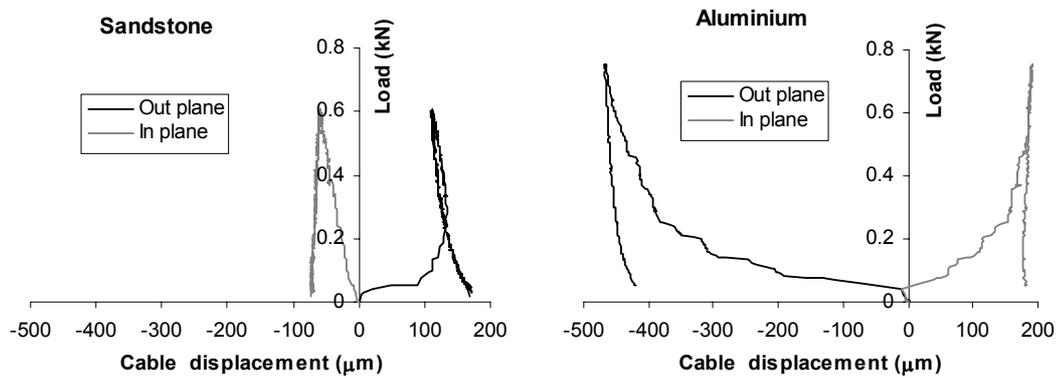


Figure 3: Load-cable displacement diagrams

TABLE 1
CABLE DISPLACEMENTS FROM TESTS OF ALUMINIUM AND SANDSTONE

Material	Test No.	Horizontal displacement of the cable (μm)	
		In-plane	Out-of-plane
Aluminium	Cable02	183.3	---
	Cable03	196.7	449.4
Sandstone	SS11	50.0	162.1
	SS13	73.4	171.3

EXPERIMENTAL RESULTS AND DISCUSSIONS

To investigate the effect of the cable length on stability of crack propagation, a series of 37 tests has been performed with cable length of 200 mm, 150 mm, 100 mm and 50 mm respectively. In these tests, the specimens were loaded in uniaxial tension under a constant loading rate of $0.02 \mu\text{m/s}$ until a sudden failure occurred. The following shows the typical results obtained from the successful tests.

Crack Propagation

For all the tests, load-deformation diagrams were recorded, which show that the shapes of the curves are not visibly affected by the cable length. By means of a remotely controlled long distance microscope, the crack path was followed during the whole loading procedure. The location of the crack tip was recorded under the selected magnification of the microscope. In most of the tests the cracks initiated at the notch and propagated straight through the middle area of the specimens, as shown in Figure 4. In the figure, the image has been enhanced to make the crack better visible. No correlation between the crack pattern and the cable length was observed. When the maximum deformation measured near the notch is approximately $150 \mu\text{m}$, the crack propagation speed slows down gradually. Furthermore, when the deformation reaches about $200 \mu\text{m}$, the crack opening continues to increase, but the crack tip appears to stop almost completely. Apparently, at this stage the stiffness of the intact segment becomes very low, and the eccentricity is large. Bending dominates the specimen behavior. The two segments of the specimen beyond the crack mainly rotate around the center of the intact area.

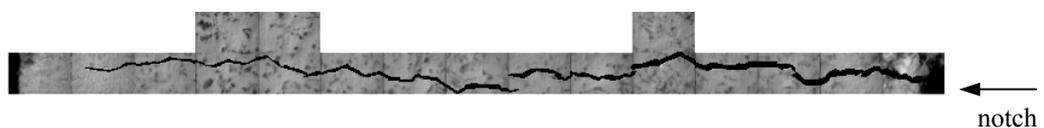


Figure 4: Example of the recorded crack pattern

Representative load-deformation diagrams for the tests using four different cable lengths are presented in Figure 5 (a) to (d). In these curves, δ is the average of the deformations measured by the two LVDT's close to the notch.

In general, it appears that the longer cables (200 and 150 mm) give a more stable crack propagation and larger crack opening at failure than the shorter ones (100 and 50 mm). This could be explained from the (small) flexural stiffness of the cables. Particularly the short cables have some flexural stiffness and provide some constraint in the out-of-plane direction.

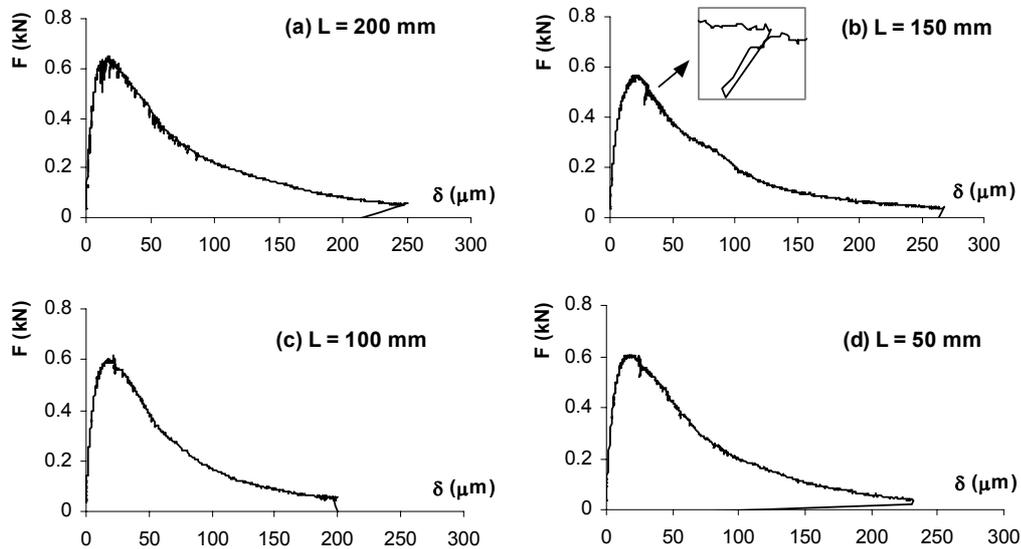


Figure 5: Load-deformation diagrams for four different cable lengths and an example of enlarged instability (snap-back) shown in the inset

Instability Phenomena

Local instabilities are visible in a load-deformation diagram as small dips. Tests with longer cables appeared to contain more instability than tests with the shorter cables (Figure 5). Evidently, in the longer cables more energy is stored which makes the set-up less sensitive to corrections of the control system. The control system first attempts small corrections but when these show to have little effect it will over-react and reduce the force strongly, producing a dip. In all tests the tail parts of the curves show to be smoother than the rest of the diagram. The reason is that at this stage the residual stiffness of the specimen becomes small due to the development of the crack, the stiffness of the cables does not dominate the control system any longer. The current control system therefore was considered an improvement to an earlier control system based on the maximum deformation in specimens used in [9].

A common feature of all load-deformation curves is that substantial drops are present around the peak-load. This indicates that the system experiences considerable changes at this stage. Just before the main crack formed, the biggest amount of strain energy is stored in the system of specimen and cables that requires higher sensitivity to react any sudden changes. When a crack is initiated a qualitative change occurs in the specimen. A big amount of energy releases suddenly at a high rate, and the system is not fast enough to follow the correction of the control system. As a consequence, over-reaction occurs in the system that results in bigger drops in the load-deformation diagrams.

Another distinct point showing instability is at the final stage just before failure. This behavior is possibly dominated by the secondary bending moment formed in the intact area in front of the crack tip due to gradually increased load eccentricity during crack propagation. In a uniaxial tensile test between cables, the stress distribution at the cross section of a crack can be schematized as shown in Figure 6 (a), (b) and (c) for subsequent stages of crack propagation. The stress at crack tip is assumed as tensile strength according to the fictitious crack model. Stress in the intact area in front of the crack tip is distributed linearly, whereas in the area behind the crack tip, the stress distribution follows softening behavior.

As the location of the applied force in the cable is exactly known (hardly any horizontal displacement of the loading cables were observed) and the location of the crack tip at failure is known to some accuracy, the test can be used for extracting softening data of the material to a high degree of accuracy. At present the analysis is in progress. As a result of the eccentric loading on the cracked specimen (Figure 6c) the area in front of the visible crack tip is loaded by the force F_{int} and the bending moment M_{int} . This situation will be used to assess the conditions just before final catastrophic failure.

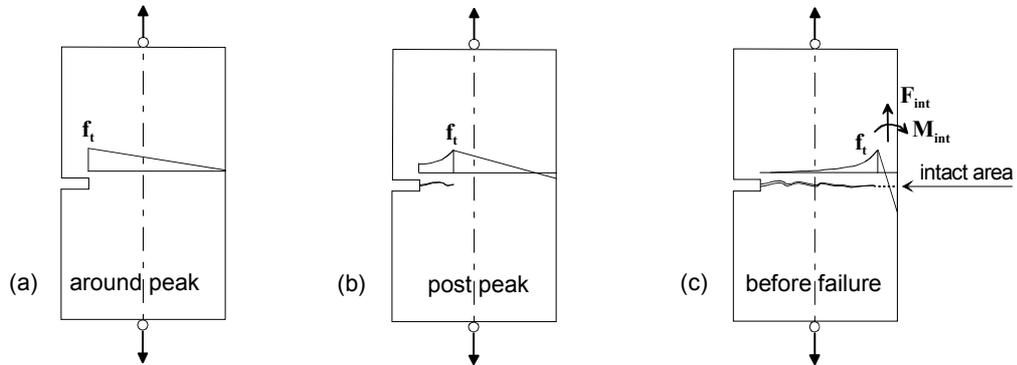


Figure 6: Stress distribution at different crack stages

CONCLUSIONS

1. The current control system, which is based on the rate of crack opening at the notch tip, is very well suited for obtaining stable load-deformation diagrams under uniaxial tension irrespective of the machine stiffness. The machine stiffness was varied through a variation of the length of the cables through which the specimen was loaded.
2. The tests showed local instabilities, which were successfully handled by the control system except for the catastrophic failure at large crack openings.
3. The loading situation in the specimen is very clear. The point of load application is well defined, and since the tip of the crack is known to some accuracy, inverse analysis of tension softening properties of the tested material is possible with high accuracy.

ACKNOWLEDGEMENTS

This research was supported by Dutch Technology foundation (STW) and the Priority Program Materials Research (PPM). The authors are indebted to Allard Elgersma for his invaluable assistance in carrying out the experiments.

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