CHAPTER 2. MINIMUM DEMANDS FOR DEFORMATION-CONTROLLED UNIAXIAL TENSILE TESTS

Prepared by Jan G.M. van Mier (1) and Viktor Mechtcherine (2)
(1) ETH Zurich, Institute for Building Materials, 8093 Zurich, Switzerland
(2) TU Dresden, Institute for Building Materials, 01062 Dresden, Germany

1. INTRODUCTION

This document is a result of intensive and partly controversial discussions during and between the meetings of RILEM TC 187-SOC about the experimental determination of the stress-crack opening curve for concrete in tension from uniaxial tension tests. On several important issues an agreement could be achieved between the actively participating committee members. These issues are formulated here as minimum demands for deformation-controlled uniaxial tension tests. The points, which are still under discussion, are only briefly mentioned in this document.

Since the work of the committee focused on the cohesive crack approach as proposed in [1], the assumptions for this kind of modelling of the concrete failure in tension were regarded as the starting point and one of the major criteria in the evaluation of different testing methods. With regard to the original approach presented in [1], a uniaxial tension test is considered the most direct and reliable method for obtaining the characteristic softening behaviour of concrete. Under the assumption that stresses are uniformly distributed over the specimen cross-section during the entire test, and that there is no effect of the specimen geometry on the obtained stress-crack opening curves, the result of the uniaxial tension tests can be considered providing true material properties. Unfortunately, in reality even the most elaborated uniaxial tension tests can not exclude “structural” effects due to particular test set-ups. Therefore, the softening curve obtained from such tests is always, to a smaller or larger extent a combined material/structural property.

2. MINIMUM DEMANDS FOR DEFORMATION-CONTROLLED UNIAXIAL TENSILE TESTS

2.1 Test set-up and testing equipment

The principle for the recommended test set-up is given in Figure 1, which shows a front and side view of an instrumented prism. In order to be able to measure softening behaviour, the elastic energy release during crack propagation must be minimized, which leads to demands regarding specimen size, the control length of the LVDTs (extensometers) and the
response time of the deformation-controlled loading system (see [2], which includes an overview). These control systems are commercially available; feed-back response times, electro-mechanical or hydraulic components, and stiffness of the loading frame are the most important parameters with regard to the stability of uniaxial tension tests. For the test set-up proposed here, the sample size and control parameters are chosen such that for most commercial systems, and the range of concretes tested, the demands for the test stability can be met. In case of doubt, some preliminary tests must be performed, and possibly adjustment of the control parameters may be needed. In this proposal, such issues will not be discussed, as they are basic to any fracture experiment on softening materials, and in general the adjustments needed are machine dependent.

Figure 1: Test set-up for deformation-controlled experiments on notched prisms; two LVDTs are used for test-control: (a) front view, (b) side view.

### 2.2 Specimen Geometry

The tensile specimen should be large enough to warrant that a representative volume of the material is considered. In order to guarantee test stability, the gross cross-sectional area ($A = BD$) of the prism should be between 50x50 mm$^2$ and 100x100 mm$^2$, as indicated in Figure 1. The preferential specimen length is $L = 2B$. For longer specimens, the “structural” effects like so-called secondary bending would become more pronounced. The reduction of the specimen length to $L = B$ is possible if the handling of the specimen (exactness of positioning, application of the extensometers etc.) enables this. Specimens with $L < B$ are not recommended, since the nearness to the loading platens influences the stress state in the plane of the notched cross-section.

In many countries there is preference for testing cylinders. In principle the deformation controlled uniaxial tensile test can also be conducted using cylinders rather than prisms, where the diameter of the specimen should lie between 50 and 100 mm; the length constraints are similar as mentioned for prismatic specimens (see Figure 2).
Figure 2: Test set-up for deformation-controlled experiments on notched cylinders; 3 LVDTs (at 120 degrees intervals) are used for test-control: (a) side view, (b) top view.

The specimen dimensions mentioned above are suitable unconditionally for testing (gravel) concretes with aggregate size up to 8 mm ($B \geq 50$ mm) or 16 mm ($B = 100$ mm). The aggregate size of 32 mm is large compared to the specimen size, and in general one would have to choose larger specimen sizes. If the specimens with $B = 100$ mm are used for this kind of concrete this may lead to a larger scatter, and the need for repeating the test on samples of the same concrete more often than for finer grained concretes. In general it is recommended to conduct tests until four successful results have been obtained (extending the number of tests to 6-12 when the representative volume demands are impaired; for example testing a 32 mm concrete using specimens with $B = 100$ mm).

In some cases tensile tests on dam concrete (containing sometimes aggregates up to 100-125 mm) must be performed. The size of the specimens should increase proportionally to the size of the maximum aggregate size. The specimens become too large and ease of handling is impaired. It is recommended for specimens with a weight larger than 25 kg to develop tools for handling and placing the specimens in the test set-up. Furthermore the use of specimens with $L = B$ is suggested.

For the ease of the test-control it is suggested to machine two notches in the specimen perpendicular to the tensile loading direction as indicated in Figure 1. The notches are best made using a rotating diamond saw, with a blade thickness up to 3 mm. Two notches must be sawn, one at each side of the specimen as indicated in Figure 1. The combined depth of the two notches ($2a$) should be between 10 and 50% of the specimen width $B$, reducing the effective load-carrying area $bD$ to between $0.9BD$ and $0.5BD$. The minimum notch size is 5 mm. For sake of the test stability, the combined notch depth can best be chosen towards the upper limit of 50% of the specimen width.
The notches should be sawn at the same height, a maximum error smaller than 3% of the specimen width $B$ in vertical alignment can be accepted (see Figure 1c). When the vertical alignment deviates more the specimen should be rejected.

Before testing, all specimen dimensions, i.e. size $H \times B \times D$, notch depth $a$ at both sides, as well as the distance between the notches $b$ should be measured (in [mm]). All dimensions should be determined along the four specimen edges (in case of a prism), or along three radial positions for the height $H$ for cylinders.

2.3 Further demands on the preparation of the specimens and the test parameters

The prismatic specimens should be cast horizontally. The cylinders can best be cast vertically or cored from concrete blocks/members. After de-moulding (or coring), the specimens should be protected against desiccation in order to avoid eigen-stresses caused by moisture gradients. This, for example, may be done by a careful wrapping in vapour impermeable foil. Storage in water is not recommended.

The ends of the specimens should be sawn for a better transmission of load into the specimens. Additionally, abutting faces might be roughened mechanically and cleaned. The cutting must be performed perpendicular to the longitudinal axis of the specimen. The deviation may not be higher than 1.0%, for example 1 mm for $B = 100$ mm, in order to avoid the load eccentricity. Small deviations can be corrected during gluing of the metal plates to the specimen or gluing of the specimens directly into the testing machine.

The recommended deformation rate in the tensile tests on the notched specimens with a gauge length of 30 mm is $3 \cdot 10^{-4}$ mm/s. In case of problems with stability of the test control, the deformation rate may be reduced, which however results in a correspondingly longer testing time. For decreasing the total test duration, the loading rate may be doubled (or even quadrupled (stepwise)) beyond a crack opening $w = 50 \mu m$. This will have only very limited effect on the fracture energy and the shape of the softening diagram.

2.4 Deformation measurement and test-control

For test-control the average deformation measured with 2 or 3 extensometers (preferably LVDTs; alternatively clip-gauges or others) is needed. A dedicated data acquisition system is needed to warrant continuous measurement without halting the load for measurement purposes. In addition to the deformations (separate measurement of each LVDT, plus the average), the axial load and the time must be recorded.

The recommended position of the LVDTs is shown schematically in Figure 1. Here the minimum number of 2 LVDTs is drawn, one at each side over the notch. For cylinders the best option is using three LVDTs glued at 120 degrees intervals on the surface of the cylinder, as indicated in Figure 2. The measurement length is the centre-to-centre distance of the blocks used for fixing the LVDTs to the specimen’s surface. Note that the LVDTs should be positioned as closely as possible to the specimen’s surface in order to avoid serious deviations due to rotation of the two specimen sides with respect to each other (this may, for example, occur during crack growth from one side, which is rule rather than exception in disordered materials like concrete, at least at a certain stage of the test). The LVDTs should not touch the specimen’s surface at any time during the test.

The measurement length $l_{\text{meas}}$ is simultaneously also the control length. This length should be small enough to warrant stability throughout the test. It is recommended to limit the control/measuring length to 30-50 mm.
2.5 Test evaluation

The following simple evaluation procedure can be used for the estimation of the cohesive crack model parameters directly from the curves measured in the uniaxial tension tests. Some major critical comments are given at the end of this paper (cf. Concluding remarks).

The mean load-deformation curve is used for the derivation of the softening behaviour of concrete. Stress is derived by dividing the load by the effective cross-section of the sample. The effective area must be taken as $bD$ for prisms or $\frac{1}{4}\pi(D-2a)^2$ for cylinders. In order to derive crack-opening values $w_i$ in the post-peak regime, the elastic deformations must be subtracted from the measured displacements $\delta_{\text{meas}}$. It can be approximately done using the following formula:

$$w = \delta_{\text{meas}} - \frac{\sigma}{E} l_{\text{meas}}$$

where $E$ = modulus of elasticity

$l_{\text{meas}}$ = gauge length.

The obtained stress-crack opening curve (cf. Figure 3) can be considered as an approximation of the characteristic softening behaviour of concrete (please note the Concluding Remarks). From this curve, characteristic values for cohesive crack models can be derived.

![Diagram](image)

Figure 3: Derivation of the tensile strength $f_t$ and fracture energy $G_F$ from measured $\sigma$-$\delta$ relation.

The fracture energy $G_F$ can be calculated from the area under the stress-crack opening curve:

$$G_F = \int \sigma(w) dw$$

The tensile strength $f_t$ is calculated by dividing the load at peak through the effective load-carrying area.

3. CONCLUDING REMARKS

3.1 Effect of the boundaries

The problem of defining the correct boundary conditions remains an important point of the ongoing debate, since the choice of rotational freedom of the loading platens affect the tensile strength $f_t$, fracture energy $G_F$ and the shape of the softening curve, see [3], [5].
It seems that none of the boundary conditions can be rated as ideal. The test where loading platens can freely rotate provides a lower tensile strength, a lower fracture energy and a smoother softening curve (cf. Figure 4b). However, after the crack formation, the deformation distribution over the cross-section becomes more and more non-uniform. In the tests with fixed loading platens (i.e. prevented to rotate), the deformation distribution is uniform throughout most of the experiment (except during the steep part of the softening curve), the tensile strength is higher, as is the fracture energy. Depending on the size and shape of the specimen as well as on the stiffness of the machine a smaller or larger bump is observed in the softening regime (cf. Figure 4a). The test set-up proposed in [7], which compensates for the specimen rotations, might provide the most uniform deformation distribution over the cross-section. It is however not fully clear, how these adjustments affect the crack development. Furthermore, this set-up is too elaborate to be recommended for consideration as standard test.

Basically these observations underscore the introducing remarks to this document. Further details can be found in [3] and [5].

Figure 4: Boundary condition effect on the shape of the softening diagram in tension: P-δ relations obtained from uniaxial tension tests conducted between (a) freely rotating platens and (b) fixed (non-rotating) loading platens (after [5]).

3.2 Effect of the specimen size

The tensile strength and fracture energy are size dependent (see for example [4]). With increasing sample size, the fracture energy $G_F$ increases, but seems to approach an asymptotic value. The estimate for the fracture energy on smaller samples must be considered conservative, but safe. Larger specimens tend to behave more brittle than smaller specimens when the control length is scaled, see Figure 5. A correct evaluation of the test result would include a complete scaling theory, which cannot be provided to date.
3.3 Effect of the notches

Plain concrete is a notch-sensitive material, i.e. the tensile strength obtained from tensile tests on notched specimens is generally lower than the corresponding value obtained for un-notched specimens, see for example [6]. Therefore, the values obtained using the proposed procedure would be on the safe side with regard to the prediction of the carrying capacity of concrete members. However, in some cases, for example for the calculation of the minimum demand on steel reinforcement, the use of too low values of concrete tensile strength is not appropriate.

Furthermore, the notches hamper the direct measurement of the Young’s modulus in tension, which is needed for cohesive crack models as well. This material parameter should be obtained preferably from the tensile tests on un-notched prisms or cylinders, with the same size constraints as mentioned above. Alternatively, existing standardized testing procedures might be used, which implies loading of cylinders in compression.

REFERENCES