UNIAXIAL TENSION

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Abstract

This workshop contribution summarizes the requirements on tensile testing of concrete, the testing implications and experiences. It is concluded that the direct tensile test is the most objective tensile test to determine the materials which are needed for analytical and numerical computation.

1 Introduction

There are three established methods to determine mechanical properties of concrete under tensile stress: the splitting (or Brazilian) test, the bending test, and the uniaxial (or direct) tensile test. The splitting test is easy to perform and the results are rather insensitive to environmental actions like humidity and temperature because tensile stresses develop in the interior of the specimen which is little affected. The bending test is also easy to perform. However, moisture and temperature gradients affect the result very much because they act in the most stressed outer fibre of the specimen. Both testing methods assume linear elastic material behaviour to predict cross-sectional stresses from external forces. As soon as non-linear behaviour or cracking starts this assumption is violated. Furtheron, the rate of loading varies within the specimen from zero to a maximum at the point of maximum stress.

The uniaxial test is an attempt to avoid these assumptions and shortcomings, however, with the result of increasing testing inconvenience.

2 Aim of the test

The test is performed to generate values of mechanical properties or functions between some properties. The results should be objective i.e. there should be a theory behind which defines clearly the state of stress and strain and the quantities which can be measured. In a direct tensile test, the initial state of stress is uniaxial with the principal direction parallel to the axis of the specimen. The principal strains are parallel and normal to the axis of the specimen. Stress and strain are uniformly distributed and stress and strain rate are the same at any point.

If the testing devices are accurate and calibrated and the specimen preparation is well controlled the test yields repeatable and reproduceable results.

3 Measured properties

Analytical and numerical computations need constitutive equations for the material characterization, i.e. a complete relation between stress and strain. The uniaxial tensile test can provide Young's modulus and Poisson's ratio for the elastic range which is approximately valid until 0.8 times tensile strength. However, concrete shows during first loading some nonlinearity due to consolidation and creep. Therefore repeated loading is recommended and the elastic constants should be determined after ten cycles in a stress range between about 0.05 and 0.3 times strength (on the analogy of RILEM (1975)). The rate of loading must be controlled. Higher loading rates yield a stiffer response than lower loading rates. Hence, the total strain is composed of the elastic and short term creep deformation as

$$\epsilon = \sigma f \left[\frac{1}{E\ (\tau)} + C\ (t, \tau) \right] \tag{1}$$

with E = Young's modulus, C = creep compliance, t = time, τ = time at loading, f = function of.

Tensile strength is defined as maximum mean stress measured in a direct tensile test (mean stress = force divided by initial cross-section). After having reached the strength strain-softening occurs until complete separation of two specimen halves. The area under the stress displacement curve is called specific fracture energy. The softening (or descending) branch has three features: the shape, the value w_0 and as the consequence of both together with the tensile strength, the fracture energy G_F. G_F is interpreted as the energy necessary to create a complete crack plane.

The ideal picture is blurred by the nonlinear part of the ascending branch. The nonlinearity is attributed to new microcracks and growing micro-cracks which are invisible to the naked eye. Unloading from that part of the curve leads to irreversible strain but not to a distinct and discrete cracking plane. The microcracks are randomly distributed in the specimen. In model terms, it appears like plastic yielding with strain

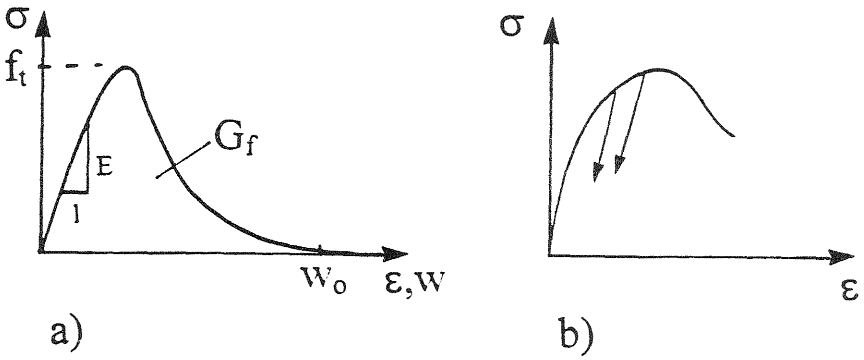

Fig. 1 Tensile stress vs. displacement
a) Complete curve b) Ascending branch with unloading

hardening. However, the mechanism is very different from yielding of metals due to dislocations. This "strain hardening" is a volume effect whereas the softening is due to the gradual weakening of a layer adjacent to the final crack plane, i.e. a local effect.

4 Use of material properties

A few examples will make clear that not all material properties are relevant in practical applications. Two extreme cases are a plain concrete bar under tension and the generation of surface cracks due to eigenstresses.

If a concrete bar is stressed in tension elastic energy

$$W_{el} = \int_{v} \sigma \, d \epsilon \tag{2}$$

is stored which is for a prism of length l and cross-section A equal to

$$W = \frac{1}{2} \frac{\sigma^2}{E} l A.$$

When a macro crack occurs the fracture energy is

$$W_{fr} = A \, G_F \tag{3}$$

By definition, the stress just before fracture was equal to the tensile strength f_t and Eqs. (2) and (3) yield

$$l = \frac{2 \, E \, G_F}{f_t^2} = 2 \, l_{ch} \tag{4}$$

The elastic energy in a bar with length 2 l_{ch} (l_{ch} = characteristic length acc. to Hillerborg) is compensated by the fracture energy. The longer the bar the less important are softening and fracture energy for the fracture of the bar. Since l_{ch} is in the order of 0.1 to 0.5 m for plain concrete real structures are load controlled and behave brittle.

Opposite to this, eigenstresses due to thermal and hygral gradients may lead to displacement controlled cracking. Cracks occur when the maximum stress reaches tensile strength, this may happen at an infinitesimal small crack distance. As soon as a crack occurs elastic energy releases and some cracks may close. Crack depth and crack spacing depend finally on fracture energy and the shape of the softening curve (besides thermal and hygral stresses, of course). In this case, fracture energy is an important material property and cannot be neglected.

In reinforced concrete members, it depends on the amount of reinforcement (reinforcement ratio) whether a load or a displacement controlled situation prevails. The more reinforcement the closer to a displacement controlled situation in tensile loading.

In numerical analyses, for instance in an FE analysis, all material parameters E, f_t, ν, G_F, w_0, shape of the stress-displacement curve are needed as input. The behaviour of a structure is calculated step by step. Instabilities show up when energy release cannot be compensated by fracture energy in a computing interval.

5 Implications to testing

Excentricity, stress concentration, and eigenstresses cause deviations from the ideal, physically correct testing scheme. Fig. 2 shows schematically

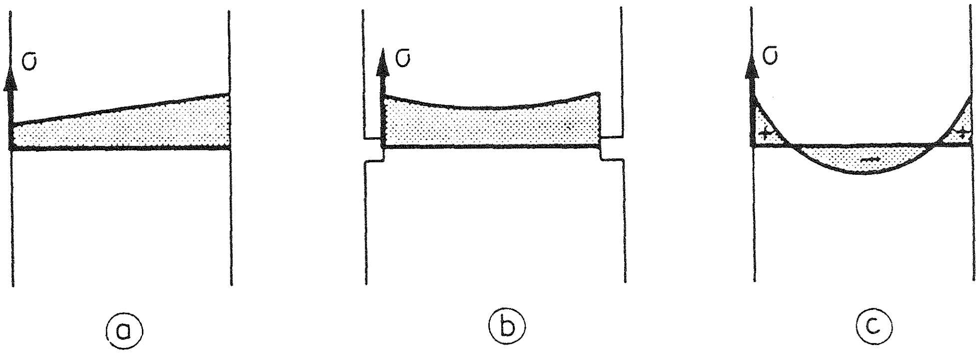

Fig. 2 Non-uniform stress distribution due to
a) Excentricity b) Stres concentration c) Eigenstresses

what happens to the assumed stress distribution. To avoid excentricity the specimen is glued in fixed grips. However, the bending stiffness of the specimen is limited and fixed grips cannot prevent excentric crack opening. A strain softening material cannot stabilize by itself as a strain hardening material does. Numerous results have shown how front and rear side of a specimen behave in a tensile test, Fig. 4 shows an example.

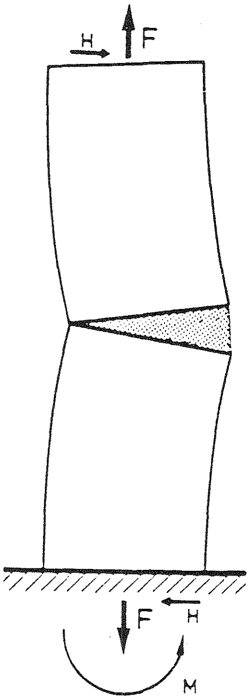

Fig. 3 Bending of specimen leads to non-uniform crack opening

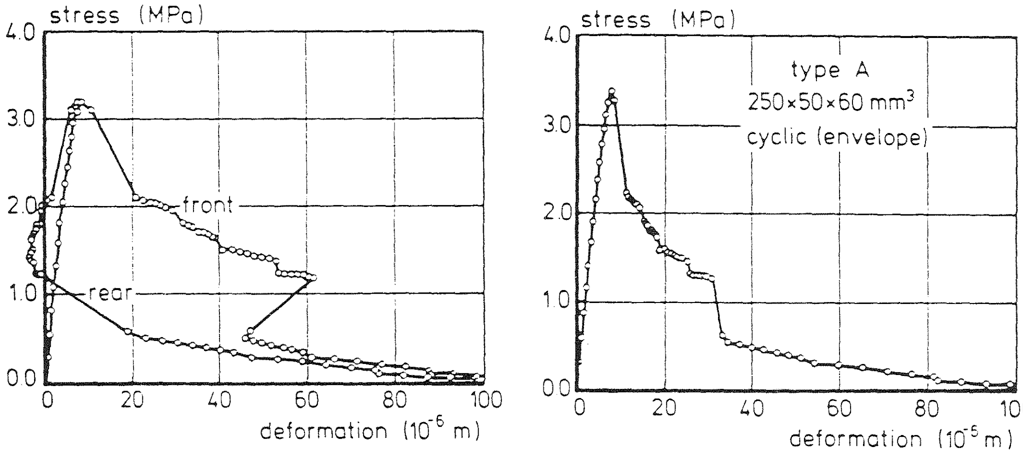

Fig. 4 Typical example of tensile test, Hordijk (1991)
a) Stress-deformation of front and rear side
b) Stress-deformation averaged

Due to bending of the specimen there is a great excentricity. The assumption of uniform stress distribution is violated mostly just after the descending branch has started. The shape of the descending branch is distorted but the G_F value is still acceptable.

Notched specimens have been widely used because the notch acts as crack starter which makes instrumentation and displacement control of a test easier. However, tensile strength is affected by a notch and the size of the specimen plays an important part. Fig. 5 shows an example of two specimens one half as large as the other.

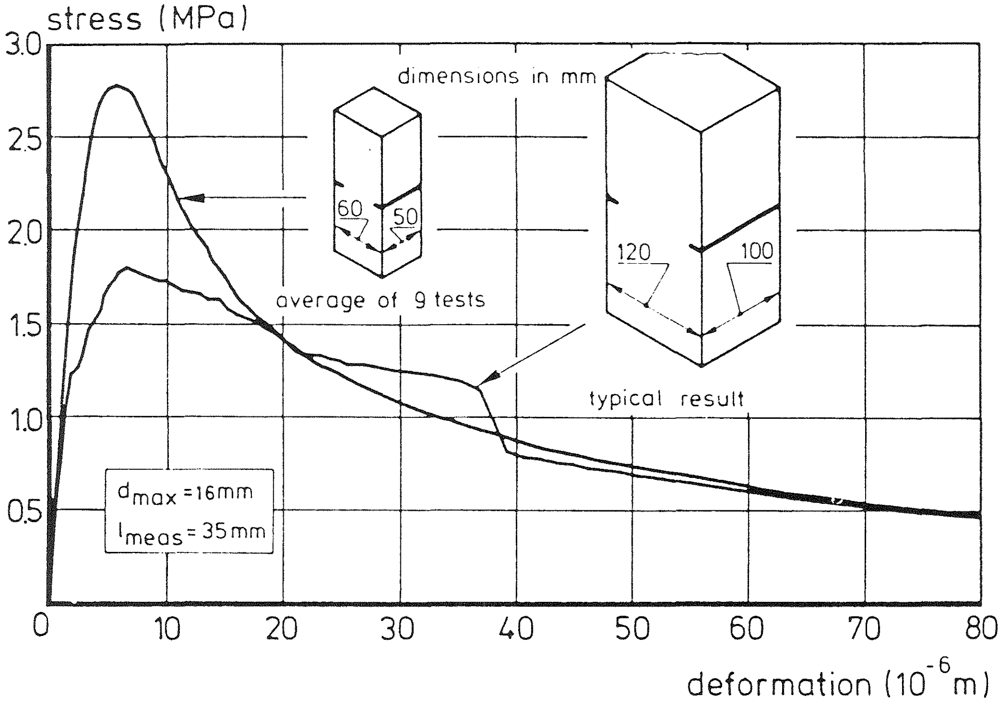

Fig. 5 Influence of size on stress-displacement response, Hordijk (1991)

At the notch tip tensile strength is earlier reached than in the middle of the specimen. That makes that a softening zone grows into the specimen. The larger the specimen the more non-uniform the stress distribution becomes and the lower becomes the apparent tensile strength which is maximum force divided by net cross-section. A better specimen geometry is received when the prismatic specimen has a reduction of cross-section of about 10% along about 50 mm, Middel (1995), where transducers can be placed and where stress-concentration is negligible. The material properties are then determined on a practically un-notched specimen which is less sensitive to size. As the absolute size is concerned the smallest dimension should at least four times the maximum aggregate size.

Drying of a specimen causes non-uniform shrinkage and thus eigenstresses. Superimposed stresses due to loading lead to earlier cracking and hence the apparent tensile strength decreases. To avoid problems the specimens should be kept in the same storage condition seven days prior to testing.

The problems which are encountered at tensile testing have been discussed already by L'Hermite (1955). He proposed a testing device as sketched in Fig. 6 which shows a parallel arrangement of a steel tube and a concrete cylinder.

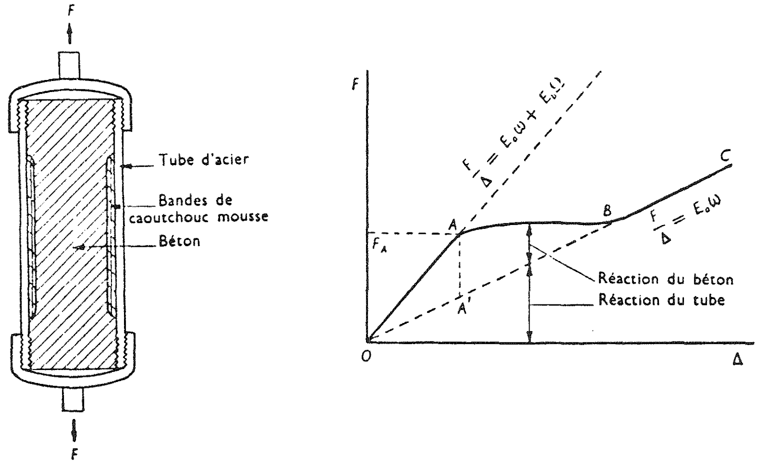

Fig. 6 Testing device for direct tension, L'Hermite (1955)
a) Arrangement b) Force-displacement curve

By subtracting the reaction of the steel tube from the total response one gets the softening curve of plain concrete. This basic idea is still used successfully, Middel (1995). A much more sophisticated arrangement has been designed by Carpinteri & Ferro (1994) consisting of three actuators: number 1 is the main loading actuator, number 2 can compensate in-plane bending, and number 3 counteracts out-of-plane bending. Four extensometers produce displacement signals which are evaluated and automatically used for the control of the three actuators. By this, excentricity in two directions is counteracted and the displacement is forced to be uniform.

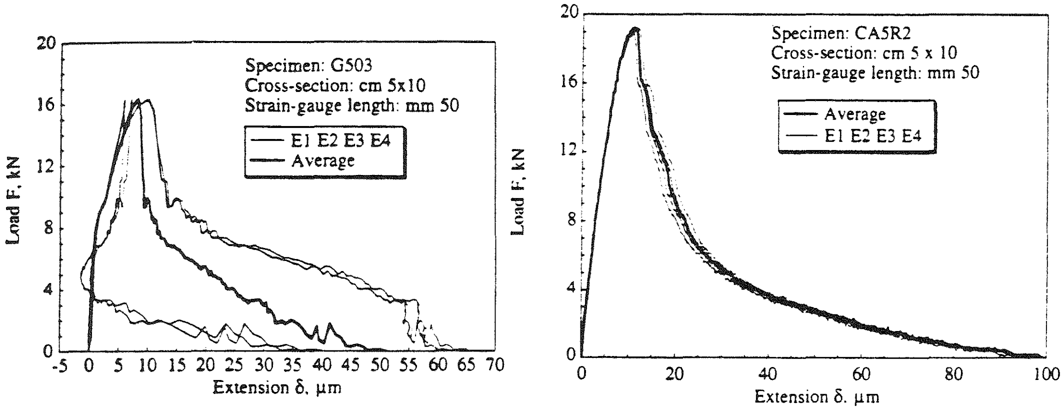

Fig. 7 Results from two tensile tests, Carpinteri & Ferro (1994)

a) One actuator, four extensometers. Bending in two directions is inevitable
b) Three actuators, four extensometers. Excentricity is compensated

The main results are: the maximum stress is larger, the softening branch is smooth with only very little scatter. This means that the results can be called objective as required in chapter 2.

6 Conclusion

The direct tensile test is the most objective test for the determination of tensile properties of concrete. Due to strain softening a test cannot be performed in a self-stabilizing manner. External control is necessary to meet the requirements. Storage conditions and loading rate have to be specified as well as specimen size in terms of cross-section and preferably also in terms of length.

7 References

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