コンクリート工学年次論文報告集 9-2 1987

[2114] 各種方法によるコンクリートの破壊エネルギーとひずみ軟化曲線の定量化

DIFFERENT METHODS TO DETERMINE FRACTURE ENERGY AND STRAIN SOFTENING OF CONCRETE

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1. INTRODUCTION

The whole failure process as expressed by complete load-displacement diagram has gained interest for huge and important concrete structures such as prestressed pressure vessels, tanks for liquified natural gas, large dams, etc. In order to describe the failure behaviour of concrete in a realistic way, concepts of Fracture Mechanics must be introduced in numerical analysis. The fictitious crack model [1,2] and the blunt crack model [3] have been developed based on the fracture energy concept. RILEM Technical Committee 50-FMC has proposed a recommendation [4], which specifies a method for the determination of the fracture energy G_F of concrete by means of three-point bending tests on notched beams. It has been shown that not only the G_F-value but also the shape of the strain-softening diagram [2,6] is needed for the application in computerized structural analysis [5]. The current status of Fracture Mechanics of concrete is reported in ref. [6].

In this contribution, the fracture energy and the strain-softening diagram of concrete as determined by means of the newly proposed wedge splitting test [11] are presented. These test results are compared with those obtained from the three-point bending test [7] suggested by RILEM recommendation and from the compact tension (CT) test [8]. The effect of the ligament length and the geometry of the specimens on the fracture energy are investigated. Load-displacement curves are numerically predicted with the assumption of a bilinear softening-diagram, and are compared with experimental curves. The G_F-value as obtained from the calculated strain-softening diagram is compared with the G_F-value determined from the load-displacement curve.

2. EXPERIMENTAL PROCEDURES

The dimensions of three different specimens, namely, (a) bending beams, (b) CT-specimens, and (c) wedge splitting cubes, are shown in Fig.1. Characteristics of the test series are given in Table 1. The specimens were cured in water until the test and then were kept humid during the test. The notch was cast for CT-specimens and was sawn for both beams and cubes. Further description of the three different test methods are given below.

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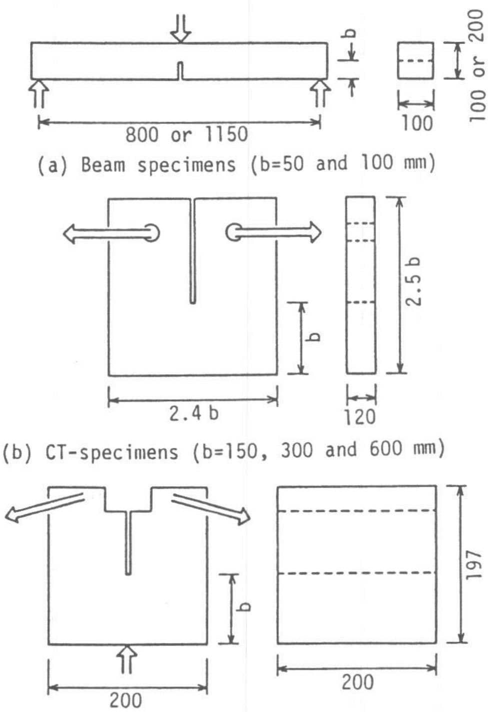
(a) Three-point bending test: Following the RILEM recommendation [4], beam specimens were tested and analyzed. The deflection of the beam measured on the center along the direction of the applied load was recorded during the test. A servo-controlled hydraulic jack was used to perform the test.

(b) CT-test: A servo-controlled hydraulic jack was used. Besides the load, both the displacement in the plane of loading points and the crack mouth opening displacement were measured and recorded. The crack mouth opening displacement was used to control the rate of loading. A more detailed description of the test method is given in refs. [8,10]. The test results on the effect of specimen size are cited in this contribution.

(c) Wedge splitting test: The principle of the wedge splitting test consists in splitting a notched cube by means of a wedge pressed between ball bearings placed on the top of the cube as shown in Fig.2. This testing

Table 1. Characteristics of test series

	specimen		concrete					
type of test	height x length x thickness,(span) [mm]	ligament length [mm]	water-cement ratio	maximum grain size [mm]	compressive strength [MPa]	testing age [days]	number of specimen	time from start to max. load [second]
wedge splitting test	197x200x200	70	0.50	32	35.6	14	5	60
		100					5	50
		130					5	45
		150					3	20
CT-test	375x 360x120	150	0.43	16	42.9	28	6	40
	750x 720x120	300					6	65
	1500x1440x120	600					6	100
three-point bending test	100x 840x100,(800)	50	0.40	16	48.2	28	5	75
	200x1190x100,(1150)	100					5	75



(a) Beam specimens (b=50 and 100 mm)

(b) CT-specimens (b=150, 300 and 600 mm)

(c) Wedge splitting cubes (b=70, 100, 130 and 150 mm)

Fig. 1. Three different types of specimens.

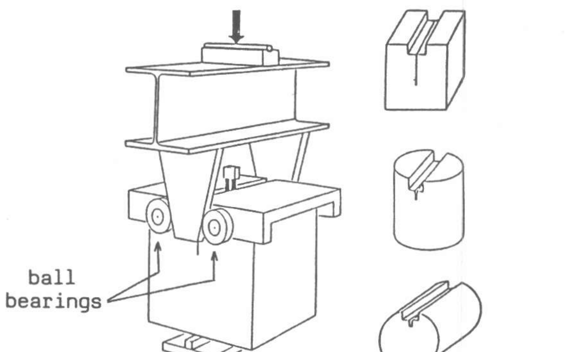


Fig. 2. Loading device for wedge splitting test and different specimen geometries.

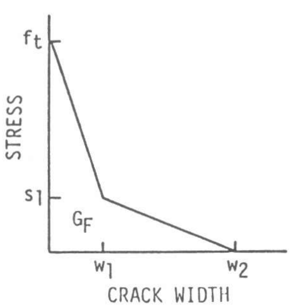


Fig. 3. Bilinear strain-softening diagram.

method is also suitable for cylinders. The test on cubes in this study is controlled by measuring the crack opening displacement using a clip gauge. During the test the applied load and the crack opening displacement are recorded. All tests were carried out on a servo-controlled testing machine. Four different ligament lengths were chosen; 70mm, 100mm, 130mm, and 150mm.

3. BILINEAR STRAIN-SOFTENING DIAGRAM

Generally, it is difficult to measure directly the strain-softening of concrete by uniaxial tensile tests. Therefore only few results exist in the literature. In practical applications simplified models have to be used representing the real strain-softening diagram. The simplest models are a straigth line and a bilinear relation. The bilinear strain-softening diagram is defined by four parameters, f_t, s_1, w_1, and w_2 as shown in Fig.3. The concrete outside the fracture zone is assumed to behave in a linear elastic way.

Based on the fictitious crack model, a finite element module SOFTFIT [5,9] has been developed. This module allows us to determine the essential parameters of the bilinear strain-softening diagram, i.e. f_t, s_1, w_1 and w_2 from experimentally obtained load-displacement curves by means of a data fit.

It is possible to describe the measured load-displacement curve in a realistic way when an approximate bilinear strain-softening diagram is chosen. It has been shown that the calculated load-displacement curve does not depend very sensitively on the exact selection of the parameters of the strain-softening diagram [10]. Therefore, for the case of comparative studies several of the parameters can be fixed. Strain-softening diagram has been determined on the basis of the results obtained with bending beams by means of SOFTFIT. These results are described in detail in ref. [7].

In this study, the bilinear strain-softening diagrams are calculated from measured load-displacement curves of CT-specimens and cube specimens by using a modified version of SOFTFIT in the following way:

- First, f_t of a strain-softening diagram is fixed. It would have been preferable to have tensile strength measured directly.
- Second, the ratio of f_t/s_1 is chosen to be 4 for CT-specimens and 3 for cubes. Other values for the ratio would also lead to satisfying agreement.
- Third, w_1 and w_2 are determined by a data fit in such a way that the difference between measured and calculated maximum loads is less than 1% and the square of the difference between the measured and calculated diagram becomes a minimum.

In this way, a unique bilinear softening diagram can be obtained for each measured load-displacement curve. The fracture erergy G_F is calculated from the area under the strain-softening diagram.

In order to compare the shape of the strain-softening diagrams as determined under different test conditions, the calculated strain-softening values are transformed into a normalized diagram. The stresses are related to the tensile strength f_t and the crack widths w_1 and w_2 are represented by constants C_1 and C_2 defined in the following way:

$$C_1 = w_1 \cdot f_t / G_F \qquad (1)$$

$$C_2 = w_2 \cdot f_t / G_F \qquad (2)$$

4. TEST RESULTS AND DISCUSSION

4.1 LOAD-DISPLACEMENT CURVES

For each series of both the wedge splitting test and the CT-test, a mean curve was determined from the individual curves. The mean curves were treated numerically when determining the parameters of the bilinear strain-softening diagram. Mean curves for cube specimens and CT-specimens are shown in Figs. 4 and 5, respectively, by a solid line with dots. The numerically predicted curves are also shown in Figs. 4 and 5 by a solid line.

4.2 FRACTURE ENERGY

The values for the maximum load and the fracture energy G_F for each series are given in Table 2. The measured fracture energy was determined as the area under the observed load-displacement curve divided by the ligament area. For the measured G_F of beam specimens, the correction for the effect of the dead weight was done according to RILEM recomendation [4]. The calculated fracture energy was determined as the area under the bilinear strain-softening diagram obtained by the numerical method, where the mean load-displacement curve and/or the individual curves were adopted. For CT-specimens, the displacements in different planes were comparatively used for the numerical determination of the fracture energy.

As seen from the results for CT-specimens, the values for the numerically determined fracture energy from the mean curve are in good

Table 2. Results for maximum load and fracture energy.

type of test	ligament length [mm]	maximum load [kN]	fracture energy G_F [N/m] measured [from load-disp. curve]	calculated [from strain-softening diagram] disp. in load acting plane	disp. at crack-mouth mean curve	disp. at crack-mouth average of individual curves
wedge splitting test	70	3.8	98	-	91	-
	100	6.7	104	-	99	-
	130	10.7	111	-	100	-
	150	15.6	119	-	100	-
CT-test	150	7.3	124*	-	116	116
	300	12.6	162	152	155	151
	600	20.7	158	150	150	150
three-point bending test	50	1.19	111	86	-	-
	100	2.51	116	91	-	-

*estimated using the ratio between the displacements at load-acting plane and at crack mouth as determined on the specimens with ligament length of 300mm and 600mm.

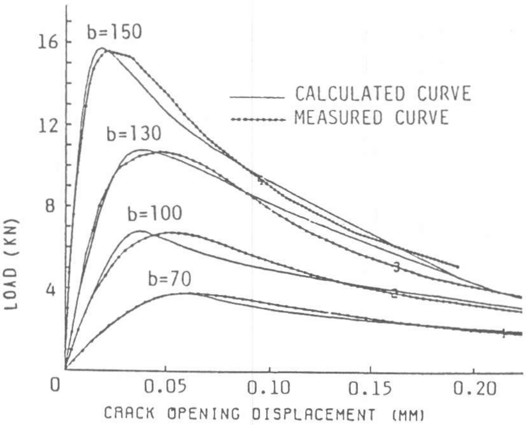


Fig. 4. Load-displacement curves of wedge splitting cubes.

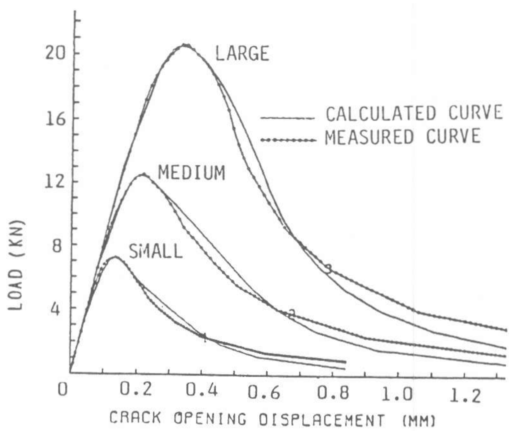


Fig. 5. Load-displacement curves of CT-specimens (displacement was measured at crack mouth).

agreement with the average values of G_F numerically determined from individual curves. Moreover, the numerically determined G_F-values from the data of the two different displacements measured in the load-acting plane and at the crack-mouth agree well with each other. This result proves that the displacement measured at any point along the notch can be used for the numerical determination of G_F.

For the cube specimens and the CT-specimens, the numerically determined G_F-values compare well with the G_F-values as determined directly from the load-displacement curve. The bilinear strain-softening diagram is a first approximation and does not necessarily describe well the real relation for wide crack openings. This part, however, is of minor importance for practical application.

4.3 EFFECT OF LIGAMENT LENGTH AND GEOMETRY

The relations between the ligament length and the measured fracture energy G_F as determined from the load-displacement curve for the beam, CT- and cube specimens are all shown in Fig.6. It is obvious that the fracture energy increases with increasing ligament length up to a limit value which is about 300 mm. For the CT-specimens with ligaments bigger than this value G_F-value turns out to be constant. Similar G_F-values are obtained by the three differnt testing methods, when the ligament length are similar. Therfore, no strong influence of the specimen's geometry on the fracture energy can exist.

4.4 STRAIN-SOFTENING DIAGRAMS

After the introduction of simplifying assumptions, the bilinear strain-softening diagrams have been determined for the cube specimens and the CT-specimens by means of finite element analysis. The subsequently obtained normalized strain-softening diagrams are reported in Fig.7. It can be stated

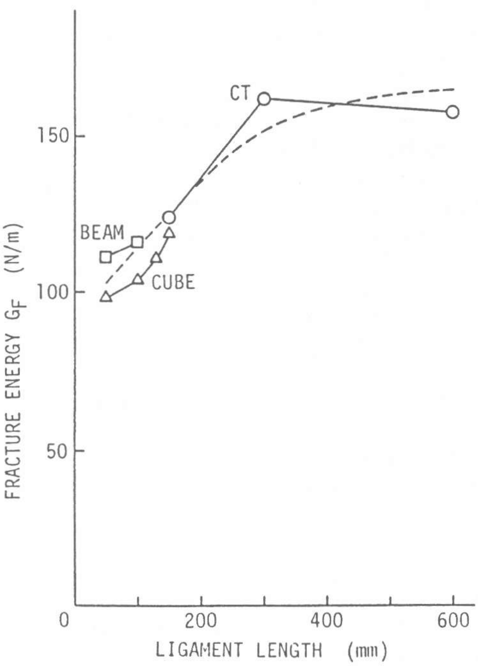


Fig. 6. Ligament length and fracture energy.

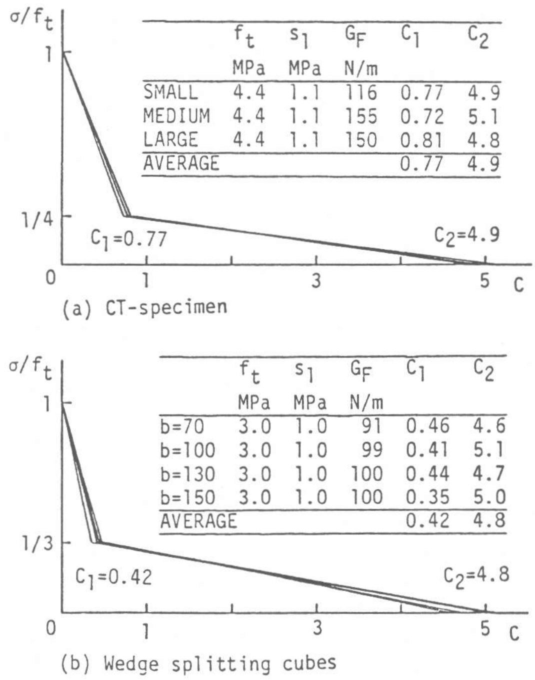


Fig. 7. Normalized strain-softening diagrams.

from Fig.7 that there is no significant influence of the ligament length on the shape of the normalized bilinear strain-softening diagrams. As seen from Figs. 4 and 5, the numerically simulated load-displacement curves (solid lines) by using the strain-softening diagrams in Fig.7 are in good agreement with the measured load-displacement curves (solid lines with dots).

5. CONCLUSIONS

(1) The fracture energy and the strain-softening diagram of concrete can be determined by means of the wedge splitting test as well as the CT-test.

(2) The fracture energy G_F of concrete depends on the ligament length of the specimen. The results indicate that G_F increases with increasing ligament length up to certain limit, then G_F seems to remain constant. For the concretes tested in this project the limit is about 300 mm.

(3) G_F-values as obtained by the three different testing methods agree well for similar ligament length. It can be concluded that no strong influence of the geometry of specimens on G_F exists.

(4) With the assumption of a bilinear strain-softening diagram, load-displacement curves can be calculated by means of FE-analysis and lead to a good agreement with the experimentally determined curves. For the cube specimen and the CT-specimen, the G_F-values as obtained from the calculated strain-softening diagram correspond well to the G_F-values determined directly from the load-displacement curve.

REFERENCES

[1] Hillerborg, A., "A Model for Fracture Analysis," Report TVBM-3005, Div. of Building Materials, Lund Institute of Technology, Sweden, 1978.

[2] Hillerborg, A., "Analysis of One Single Crack," in Fracture Mechanics of Concrete, ed. by F.H. Wittmann, Elsevier, 1983, pp.223-249.

[3] Bazant, Z.P, and Oh, B.H., "Crack Band Theory for Fracture of Concrete," Materials and Structures, Vol.16, No.93, 1983, pp.155-177.

[4] RILEM-Draft-Recommendation (50-FMC), "Determination of Fracture Energy of Mortar and Concrete by Means of Three-Point Bent Test on Nothed Beams," Materials and Structures, Vol.18, No.106, 1985, pp.285-290.

[5] Roelfstra, P.E., and Wittmann, F.H, "Numerical Method to Link Strain Softening with Failure of Concrete," in Fracture Toughness and Fracture Energy of Concrete, ed. by F.H. Wittmann, Elsevier, 1986, pp.163-175.

[6] Mihashi, H., "Survey of Fracture Mechanics of Concrete," Concrete Journal, JCI, Vol.25, No.2, 1987, pp.28-39, (Japanese).

[7] Wittmann, F.H., Mihashi, H., et al, "Influence of Age of Loading, Water-cement Ratio, and Rate of Loading, on Fracture Energy of Concrete," Materials and Structures, (to be published, 1987).

[8] Mihashi, H., Rokugo, K., et al, "Fracture Energy Evalution of Concrete with Compact Tension Test," Contribution to this volume.

[9] Roelfstra, P.E. and Sadouki, H., "Fracture I, Theory and Application," Lab. of Building Materials, Swiss Federal Institute of Technology Lausanne, 1987.

[10]Wittmann, F.H., Rokugo, K., Mihashi, H., et al, "Fracture Energy and Strain Softening of Concrete as Determined by Means of Compact Tension Specimens," Materials and Structures, (to be submitted).

[11]Wittmann, F.H., Brühwiler, E., Rokugo, K., Mihashi, H., "Constitutive laws based on the concept of fracture energy to predict the behaviour of concrete under seismic conditions," Proc. ICFFM-SHANGHAI, 1987.