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Test methods for determining tension softening diagram for concrete

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ABSTRACT: For predicting crack growth in concrete structures, numerical analyses are widely used in which the tension softening diagram is employed as the constitutive law. The objective of this paper is to discuss potential standard testing methods to determine the tension softening diagram on the basis of a series of experiments, which were carried out using four different types of specimen geometries. In these experiments, besides specimen geometries, the size of specimens and the strength level of the concrete were also changed. General comments on testing methods and data analysis techniques to determine the tension softening diagram are given and further research needs are also discussed.

1 INTRODUCTION

Prediction of cracking to avoid rapid deterioration and fracture of concrete is becoming a major concern in structural concrete design. Since Kaplan (1961) showed the potential applicability of fracture mechanics approach to concrete, there have been many fracture models and testing methods for measuring the fracture properties of concrete proposed. The most accredited contribution to advance the field of fracture mechanics of concrete, is attributed to Hillerborg et al. (1976) who clearly showed the existence of fracture process zone (FPZ) and proposed the fictitious crack model (FCM) to describe the softening properties of concrete under tensile stress. The fracture property of concrete, fracture energy was defined as the area under the curve which relates cohesive stress on the fictitious crack and crack opening displacement (COD).

During these two decades, there were several debates about testing methods and/or data reduction methods for determining more accurate values of fracture properties of concrete. In particular, two main problems have been pointed out for the utilization of the fracture (G_F) as follows: 1) Even for a same value of G_F, different tension softening diagrams may lead to quite different load-displacement curves; 2) G_F was proved to be dependent on the size of specimens. The first problem implies that G_F is not sufficient as the nonlinear material property for simulating crack growth in concrete structures and the tension softening diagram is essential as the constitutive law. The second problem was addressed by Bazant (1984) who proposed a simple formula, to determine the size independent fracture energy (G_f) from the maximum load of the test, the so-called size effect law. Soon after, the RILEM (1985) proposed a standard testing method for determining G_F by means of three-point bending tests on notched beams on the basis of work-of-fracture concept (Nakayama 1965). Few years later, Mihashi et al. (1991a & 1992) showed that the crack growth in the FPZ may be better described by three-dimensional data and that the characteristics of FPZ strongly relate to the heterogeneity of concrete. This relation could explain the size dependency of G_F (Mihashi et al. 1991b). Mihashi and Nomura (1994) also showed that the tension softening diagram derived from the size effect law has a tendency to underestimate the deformability of concrete.

There is a growing consensus that the main objective application of fracture mechanics in structural concrete design is not to obtain the maximum load of plain concrete members but rather to predict crack growth in reinforced concrete structures. Since the early 90's, several commercial programs have been developed, most of which employs the finite element method (FEM) for the structural analyses, in which empirical formulae are used as the tension softening diagram to simulate crack growth in concrete structures. However, though it is clear that the diagram is essential for numerical analyses, standard testing methods for determining the tension softening diagram have not yet been established. In 1998, during an international workshop on quantitative evaluation methods for toughness and softening properties of concrete held in Gifu, Japan, many valuable remarks (Kitsutaka & Mihashi 1998) were given which motivated researchers from three different Institutions in Japan, namely Tohoku Gakuin University (TG), Tohoku Institute of Technology (TI) and Tohoku University (TU), cooperate in order to develop the current study.

In attempting to standardize testing methods, one must bear in mind that the testing method should be simple as to allow testing laboratories with normal facilities to perform it. Besides, it should be also applicable to cementitious composite materials other than ordinary concrete. Particularly for new cementitious materials, existing empirical formulae are not often appropriate and therefore the standardization of test methods is important. Hence the main purposes of this paper are 1) to summarize several points which need to be addressed for standardizing testing methods for determining the tension softening diagram of concrete; 2) to describe and discuss series of experiments using the same mix proportion of concrete and four different testing methods, which were recently carried out separately by the three universities; 3) to discuss the efficient means of interpreting the experimental data in order to determine the suitable tension softening diagram for numerical analyses of concrete structures.

The current experimental study is focused in the following main factors: 1) the effect of specimen geometry: compact tension test, wedge-splitting test, direct tension test and bending test on notched beams; 2) the effect of the specimen size: the height and depth of the specimens were varied in two out of the four geometries; 3) the influence of the concrete strength level: moderate-strength and high-strength concretes.

Uchida and Barr (1998) showed that tension softening curves obtained experimental results of different specimen geometries (i.e. beam, compact compression, and compact tension), were almost identical when they were determined by means of the multilinear approximation analysis method. Based on such results, it was suggested that the problem lies not on the shape of the specimen but on the testing procedure and details, i.e. the preparation of specimens, the loading conditions and the measurement methods. The results presented in the current study, however, showed certain disagreement with this assumption.

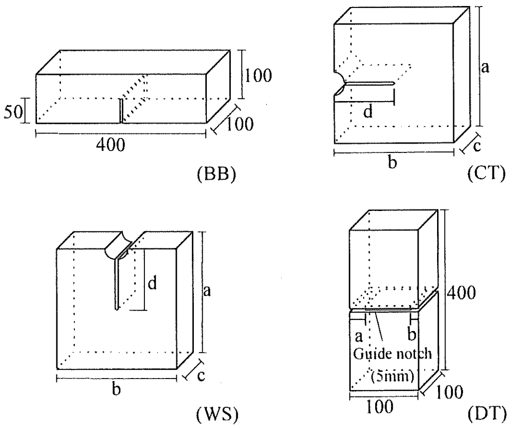


Fig. 1 Specimen geometries and dimensions (mm).

The influences of the maximum aggregate size (d_{max}) and the specimen size exerted on the development of the FPZ were also investigated by Otsuka (1994 & 1998). For getting fully developed FPZ, the size of the CT specimens may need to be more than 10 times larger than the maximum aggregate size. The specimen size also affects the stability of the loading control.

2 EXPERIMENTS (PHASE I)

2.1 *Specimen geometry and test set-up*

Four different testing methods were carried out for this study, namely the compact tension (CT) test, the wedge-splitting (WS) test, the direct tension (DT) test and the three-point bending (BB) test. The dimensions of specimens for BB tests were 100x100x400 mm and notches of 50 mm long were given at the center of the specimens by a concrete cutter. For DT tests, prisms of 100x100x400 mm were employed. The specimen geometries and further details about the dimensions are described in Figure 1 and Tables 1 to 3.

Table 1. Dimensions of compact tension specimens (mm).

Test series	a	b	c	d
CT-100	100	100	100	60
CT-200	200	200	100	110
CT-350	350	350	100	185

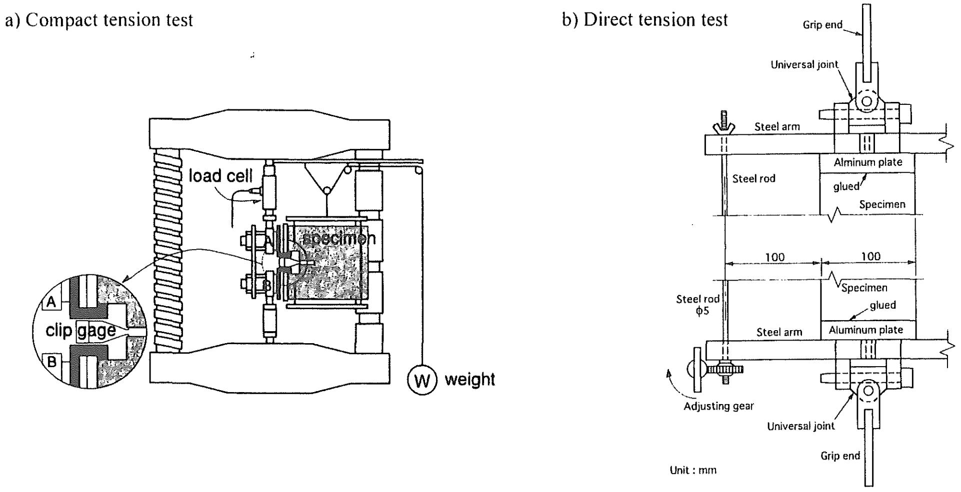
Table 2. Dimensions of wedge-splitting specimens (mm).

Test series	a	b	c	d
WS-100	100	100	100	50
WS-200	200	200	100	100

Table 3. Dimensions of direct tension specimens (mm).

Test series	a	b	guide notch
DT0-1	10	10	5
DT0-2	15	5	5

Figure 2 shows the test set-ups for the CT test and DT test. In the CT test, an external weight was employed to cancel the self-weight of the specimen. In the DT test, an adjusting gear system was attached at the four ends of the steel arms perpendicular to lateral faces in order to allow the


a) Compact tension test

b) Direct tension test

Fig. 2 Test set-up.

control of the associated flexure. All four series of experiments were carried out by a closed-loop loading system.

2.2 *Preparation of specimens*

The specimens consist of concrete made with high-early strength Portland cement and with a water-cement ratio (*w/c*) of 0.55. In the concrete composition, river sand was used as fine aggregate and crushed stone with a maximum size (d_{max}) of 20mm was employed as the coarse aggregate. The concrete mix proportion is described in Table 4 and the material properties of the concrete are presented in Table 5. The specimens were cured under water at 20°C for 14 days before the tests were carried out.

Table 4. Concrete mix proportion (kg/m^3).

w/c	water	cement	sand	aggregate (5-10)	aggregate (10-20)
0.55	198	360	830	553	369

Table 5. Material properties (14 days).

Compressive strength	42.1 MPa
Splitting tensile strength	3.1 MPa
Elastic modulus	26.3 GPa

2.3 *Determination of tension softening diagram*

The tension softening diagram was determined using an approximation method (Kitsutaka et al. 1994, Uchida et al. 1995), in which an inverse analysis is employed to obtain the diagram from the load-displacement curve on basis of the fictitious crack model. In this method, the softening behavior is approximated by the multilinear diagram and the coordinates of the points of the softening diagram are determined step by step with the development of the fictitious crack in the analysis.

2.4 *Results of Phase I and discussion*

Figure 3 shows the tension softening curves obtained from DT0 test series. It may be observed in Figure 3, that although DT0-2 presents a slightly smoother curve than DT0-1, both curves are very similar. Yet the notch lengths of DT0-2 specimens are different on each side while in DT0-1 specimens the notches on both sides have same length. In the case of DT0-1 specimen, the loading plates were controlled by the level arms in order to be kept parallel. In case of DT0-2 test, a small strain gradient of 9x10-4 was employed in order to induce one-direction crack growth, which is believed to be the reason for the smoother curve.

Figure 4 shows load-displacement curves of WS-100 test series and Figure 5 shows the tension softening diagrams determined by the multilinear approximation method for each specimen. Because of the randomness in the direction of the crack growth in the FPZ, there is a scatter among load-displacement curves and each specimen presented a unique tension softening diagram. When the fracture mechanism on the meso-scopic level of the specific specimen is concerned, individual tension softening diagram as shown in Figure 5 may be meaningful. As the constitutive law for a deterministic analysis of concrete structures, however, the average value may be more appropriate. Therefore the multilinear approximation method can be applied to the mean load-displacement curve of each series. Figure 6 shows the tension softening diagrams of WS-100 and WS-200 series determined from the mean load-displacement curves. Both of them are very similar, despite the ligament length of WS 200 is two times longer than that of WS-100.

Figures 7 shows the tension softening diagrams obtained from the CT tests of three different sizes, in which the size effect on the tension softening diagrams is clearly noticed. The large specimens give higher values of G_F because of the larger deformability. This tendency coincides with the findings of Mihashi et al. (1994) and it can be related to the development of FPZ (Mihashi et al. 1992). In Figure 7, a much steeper descending branch than those obtained by other testing methods is observed just after the softening initiates. In addition, the cohesive stress level at COD=0.2mm is higher than those of other test methods.

The tension softening diagrams of BB series is shown in Figure 8 together with that of WS-100 series. Although the ligament length of both series is the same, the first descending portion up to COD=0.05mm of the softening diagram of the WS series are steeper than that of the BB series, though the descending slope of the WS series are still gentler than those of the CT series. It may indicate that the slope of the first descending portion is proportional to the strain gradient near the notch tip and that the CT tests are more sensitive to the load controlling system than the BB and WS tests.

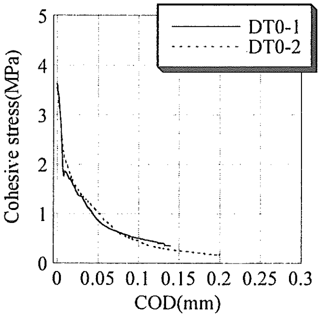


Figure 3. Tension softening curves of DT0 series.

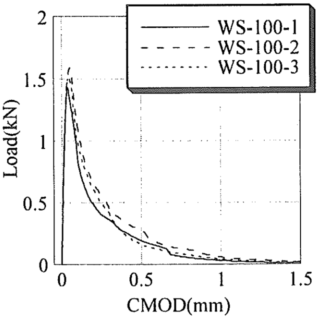


Figure 4. Load-displacement curves of WS-100 series.

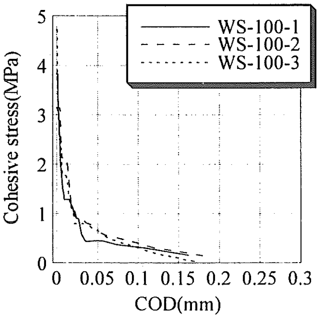


Figure 5. Tension softening diagrams of WS-100 series determined from corresponding load-displacement curves.

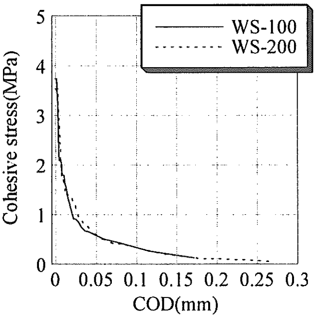


Figure 6. Tension softening diagram of WS-100 and WS-200 series determined from the mean load-displacement curves.

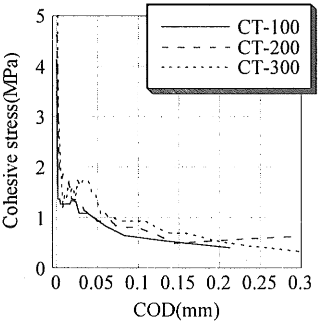


Figure 7. Tension softening diagrams of CT series.

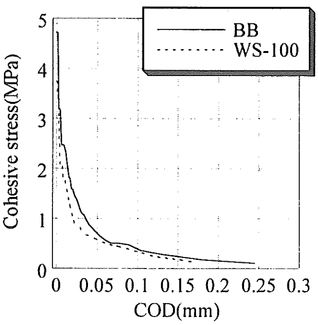


Figure 8. Tension softening diagrams of BB and W-100 series.

3 EXPERIMENT (PHASE II)

3.1 *Outline of Phase II test series*

The experimental study of Phase II was carried out by the TI group on DT specimens. In the Phase II experiments, the influence of concrete strength and notch length on the tension softening diagram was investigated. Ordinary Portland cement was used and the tests were carried out at the age of 28 days. Material properties of concrete used in Phase II experiments are described in Table 6. The notch was varied in four different lengths: 5, 10, 15 and 25mm. The influence of the guide notch of 5mm depth was also studied.

Table 6. Material properties of concrete of Phase II test series.

Test series	DT1	DT2	DT3
Compressive strength (MPa)	44.2	58.8	87.0
Splitting tensile strength (MPa)	3.9	4.1	6.6
Elastic modulus (GPa)	34.6	38.0	41.3

3.2 *Results of Phase II and discussion*

Figure 9 shows the tension softening curves of specimens with guide notches. A stable crack growth was difficult to be obtained for specimens without guide notches, in particular in case of specimens of shorter notches where the test fail in most occasions (Figure 10). The graphs in Figure 9 and 10, display the tension softening curves for concrete of three different strength levels in order to clearly demonstrate this tendency. These results clearly show that sufficiently long notches together with guide notches are very important for direct tension tests.

4 CONVENTIONAL TESTING METHODS

4.1 *Specimen geometry and size*

From a practical point of view, it may be sensible to use a specimen of geometry and size that complies with general purpose testing standards current in practice. In many countries, cylindrical specimens are used in tests for determining the compressive strength and splitting tensile strength. In other countries, cubic specimens are alternatively used for this purpose. Furthermore prisms are widely used for bending test and some other durability tests. Yet when the specimens consist of cores taken from existing structures, cylinders are generally preferred.

In addition, the minimum acceptable specimen size for the given specimen geometry and *dmax* should be cautiously determined in order to allow a fully development of the FPZ.

4.2 *Testing methods and procedures*

Table 7 presents a brief comparison and some remarks on four traditional testing methods. Most current research laboratories are only equipped to perform tests with compressive loading. Hence, under the viewpoint of implementation, either WS tests or BB tests are easier and therefore preferable as the standard test. DT tests are usually difficult to control in a stable manner and very sensitive to the boundary condition. However, DT tests present the advantage of being capable of directly measuring the tension softening curve. This feature is very attractive, in particular to evaluate the fracture properties of newly developed materials since for most cases the existing formulae may not be reliable or even applicable. As it is shown in this paper, the stable crack growth in DT tests can be obtained, if laboratories are equipped with loading machines capable of rigid control and high accuracy, by using some maneuvering to somehow impose stability.

As for research purpose, testing methods are neither ruled nor restricted by codes of practice, there is large flexibility in the choice and thus any testing method or procedure may, in fact, be employed. However, a good compromise would be to carefully adopt testing methods according to the purpose to which they are better suited. For example, CT tests and WS tests are suitable for large specimen tests and therefore for investigating matters related with the size effect.

Since moisture content and distribution influence the fracture mechanics properties, external conditions during the specimen curing and testing need also to be standardized.

4.3 *Data analysis techniques*

Ordinary research laboratories usually are only equipped to perform tests under load control, hence displacement controlled tests are mainly possible in well-equipped testing laboratories. For determining tension softening diagram as well as G_F, stable load-displacement curves including the descending branch are essential.

For determining the tension softening diagram by means of inverse analyses as well as G_F, accuracy of the displacement measurement is very important. For inverse analyses, deformation measurement of any type and at any point may be employed in principle. It is recommended, however, to use the crack mouth opening displacement (CMOD) because ambiguous displacement is often observed around the loading device and supports. Friction and rigidity of rotation in supports as well as in the loading device need to be reduced as much as possible in order to allow the FPZ be naturally

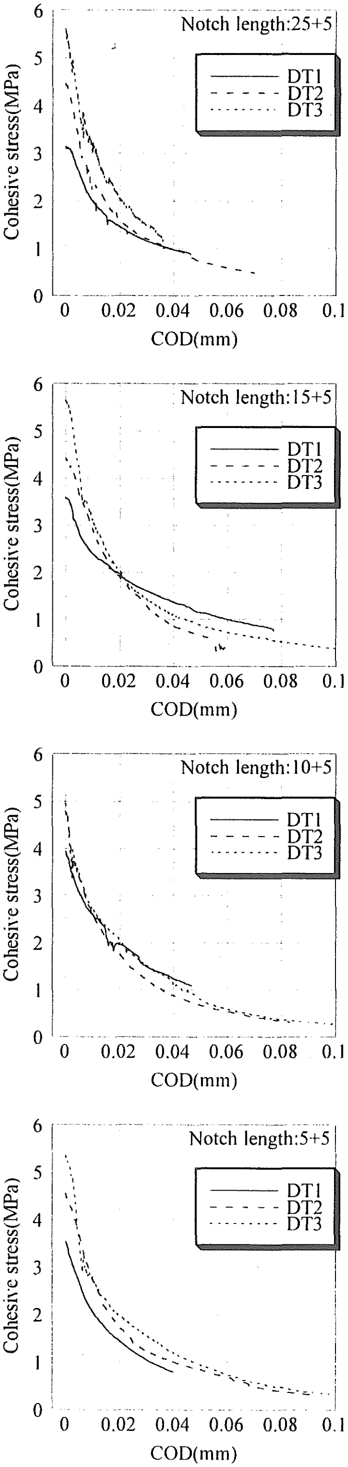


Figure 9. Tension softening curves of DT1~3 with guide notch.

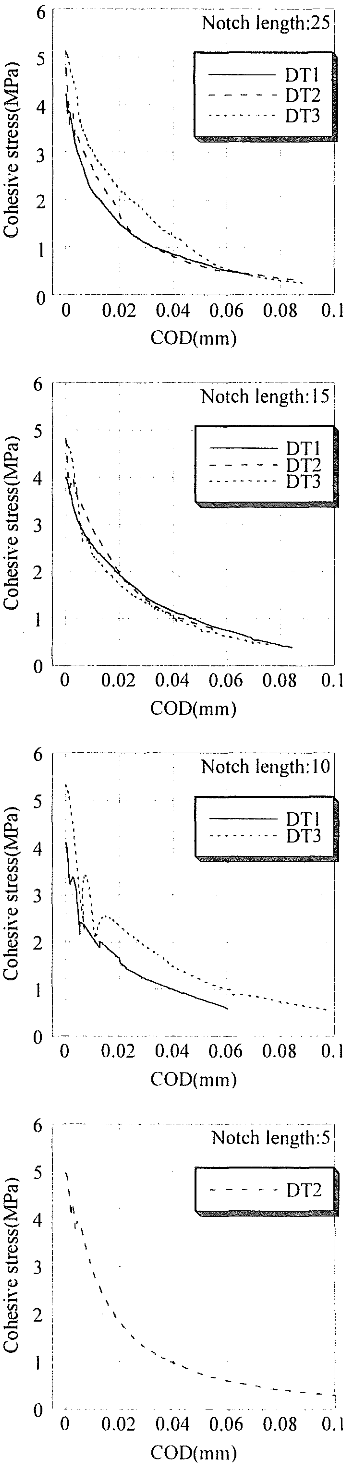


Figure 10. Tension softing curves of DT1-3 without guide notch.

developed. Therefore it seems sensible to establish a standard testing methods for determining the tension softening diagram on different levels of requirement, according to the availability of facilities and the purpose for which they the tension softening diagram is to be used.

In the previously mentioned workshop held in Gifu, a framework of standard procedure to determine the tension softening diagram was proposed by JCI Committee (Kitsutaka et al. 1998). The framework consists of three levels as shown in Table 8.

[Level 1]: Once compressive strength (f_c), tensile strength (f_t) and the maximum aggregate size (d_{max}) are given, a bilinear tension softening diagram may be determined by simple calculation based on empirical formulae (Nakamura et al. 1999) as follows:

$$G_F = 11.4(d_{max} \cdot f_c)^{1/3} \text{ (N/m)} \quad (1)$$

$$s_1 = 0.2 f_t \text{ (MPa)} \quad (2)$$

$$w_1 = 2G_F/(1000 f_t) - 0.2 w_c \text{ (mm)} \quad (3)$$

$$w_c = 5G_F/(1000 f_t) \text{ (mm)} \quad (4)$$

where s_1 and w_1 are, respectively, the values of the cohesive stress and the COD at the collapse, w_c is the critical value of COD. This procedure allows practically all testing laboratories and even designers to obtain a rough approximation of the tension softening diagram of the concrete as well as of G_F.

[Level 2]: The parameters of the tension softening diagram are determined by G_F and f_t which are determined on the basis of the RILEM recommendation (1985) and general standard test, respectively. This method is capable to provide a more accurate approximation for the tension softening diagram than that on Level 1.

[Level 3]: Tension softening diagram is determined from the load-displacement diagram by means of an inverse analysis. For this purpose, computer programs and some kind of numerical treatment and expertise are required to interpret the test data. In addition, a backbone curve is usually necessary. Multilinear curves can approximate practically any kind of tension softening curve.

5 CONCLUDING REMARKS

When an accurate description of the behavior of the softening tension diagram which includes descending branch is required, most conventional testing methods in practice such as BB and WS are

Table 7. Test methods and some remarks.

Test Methods	Advantage(s)	Difficulties & Limitations	Other Remarks
Beam bending test	Easy for loading-control & handling	Inverse analysis for σ-w; Self-weight influence for different sizes; Limited ligament length	Release the friction of supporting points; Reference points in the specimen to measure the deflection
Wedge-splitting test	Easy for loading-control	Inverse analysis for σ-w, crack deviation	Rather steep descending branch
Compact tension test	Easy for changing size of specimens	Inverse analysis for σ-w, crack deviation, self-weight influence	Steep descending branch, Plateau tail in a rather high value
Direct tension test	Direct measurement of σ-w	Unstable cracking	Very sensitive to boundary condition; Reference points in the specimen to measure the deformation

Table 8. Framework of standard procedure to determine the tension softening diagram.

Level	Level 1	Level 2	Level 3
Method	Simple calculation	Simple analysis	Inverse analysis
Shape	Bilinear	Bilinear or function	Function or multilinear
Main purpose	Material property for design code	Constitutive law for analysis	Exact shape evaluation
Data needed	f_c, f_t, d_{max}	f_t, G_F	Load-displacement curves
Procedure	Simple calculation	Calculation from curves obtained by displacement control	Inverse analysis by a computer program
Alternatives			Direct tension test

not capable to provide sufficient data. However, more accurate tests such as DT require much more care in implementation, performing and interpretation of data besides sophisticated equipment, which is only available in more advanced research facilities. Yet simple conventional methods are less sensitive to the testing conditions and therefore producing more uniform results and requiring in general fewer specimens. Hence, at the current stage it seems not sensible the standardization of a single general purpose testing method.

The current experimental study was carried out on four different test methods to determine tension softening diagrams and outlined the advantages, applicability and requirements of such methods. The framework proposed in this study recommend a multilevel standardization of the testing methods to obtain the tension softening diagram according to the purpose for which the diagram is required. Further investigation is still required to determine standard procedures for the test implementation and treatment of the data.

6 FURTHER RESEARCH NEEDS

For the standardization of testing methods for determining the tension softening diagram of concrete, several points are still due to be determined, as for example the suitable size of specimen for a given d_{max}; the treatment of the scatter of load-displacement (or CMOD) curves which leads to discrepancies on tension softening diagrams; the minimum number of test specimens. A large scatter on G_F values is often caused by a long tail of the load-displacement (or CMOD) curve when a large aggregate is by chance located at the end of the crack line in the compressive region, though the crack growth in the heterogeneous media such as concrete should be intrinsically random. Further research needs are also emphasized on the guideline about the range of applicability of the tension softening diagram in Mode I and on how to determine softening diagrams in Mixed Mode fracture if necessary.

7 ACKNOWLEDGEMENT

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