A comparison in tension softening curves obtained by a uniaxial tension test and a 3-point bending test with an inverse analysis

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ABSTRACT: In order to obtain tension softening curves, the authors carried out both the uniaxial tension test and the 3-point bending test with different types of concrete: normal concrete, highly-flowable concrete and high-early-strength concrete. For the uniaxial tension test, a specially designed gear system was adopted for avoiding secondary flexure. For the 3-point bending test, inverse analysis was done. The tension softening curves obtained by both tests were compared and found to be roughly similar, on each type of concrete. However, since the accuracy of the inverse analysis procedure, which uses test results of the 3-point bending test for obtaining tension softening curves, is limited, the original uniaxial tension test with the elimination of secondary flexure, as proposed by the authors, is more effective for obtaining the tension softening curve of concrete.

1 I INTRODUCTION

The phenomenon of concrete fracture is analyzed numerically by computer using a tension softening curve, which is the relationship between tensile stresses and crack widths after the peak load. The analysis of concrete fracture is helpful to investigate size effects for the design of concrete structures and so on. Ideally, a uniaxial tension test would be the best for obtaining the tension softening curve, but unfortunately no standard procedure has been established yet. The reason is that a uniaxial tension test is very difficult to perform, because it is necessary to achieve uniform strain (stress) conditions on the surfaces of a specimen in order to obtain accurate tension softening curves. The occurrence of secondary flexure caused by local softening during tension loading must be avoided, but it is impossible to avoid it in the ordinary simple uniaxial tension test. Thus, several alternatives such as combining a 3-point bending test and an inverse analysis procedure have been used. However, since the tension softening curves obtained by such procedures have not been compared with those by the uniaxial tension test carried out under desirable test conditions, the accuracy of the tension softening curve obtained by using the inverse analysis method is unknown.

In this study, in order to obtain tension softening curves, both the desirable uniaxial tension test and the 3-point bending test were carried out with different types of concrete: normal (ordinary) concrete, highly-flowable (self-compactable) concrete and high-early-strength concrete. For the uniaxial tension test, a specially designed gear system was adopted for avoiding secondary flexure. Then the tension softening curves obtained by both tests were compared.

2 EXPERIMENTAL MATERIALS AND METOHDS

2.1 Materials and specimens

Four types of concrete, which were two types of normal concrete (normal concrete A and normal concrete B), highly-flowable concrete, and high-early-strength concrete, were applied in both the uniaxial tension test and the 3-point bending test. For both tests, several prismatic specimens of $100 \times 100 \times 400$ mm with notches, which were made from the same batch of concrete on each type of concrete, were used. The details of notches are described in Sections 2.2 and 2.3.

Regarding the proportion of concrete mixture, coarse aggregate of 20 mm maximum size was used for the four types of concrete. The water-to-cement ratio and unit cement content were 50% and 165 kg/m^3 for normal concrete A, 65% and 178 kg/m^3 for normal concrete B, 31% and 180 kg/m^3 for highly-flowable concrete, and 55% and 198 kg/m^3 for high-early-strength concrete, respectively. The compressive strength and tension strength of each concrete at 28-day age under water curing, were 34.1 MPa and 2.7 MPa for normal concrete A, 32.0

MPa and 2.6 MPa for normal concrete B, 44.2 MPa and 3.9 MPa for highly-flowable concrete, and 42.2 MPa and 3.5 MPa for high-early-strength concrete, respectively.

2.2 *Original uniaxial tension test*

In order to directly obtain the accurate tension softening curve while avoiding secondary flexure, the original uniaxial tension test (Akita et al. 1998) was carried out instead of the ordinary simple uniaxial tension test.

Figure 1 shows the view of the original apparatus, which consists of steel arms, steel rods and adjusting gears, etc. around the four faces of the specimen, for the original uniaxial tension test. Figure 2 shows the details of the original apparatus. By tuning each adjusting gear, the stress (strain) at each surface of the central part of the specimen becomes uniform under tensile loading. The ends of the specimen were glued at aluminum plates. Each specimen of this test had different depths of notches (range of 5-25 mm) at the central part of the specimen (see Fig. 1).

The application of tensile loading was controlled by the average strain (deformation) of the four faces of the testing specimen, using a closed-loop loading system. The strain (deformation) of each of the four faces was measured by four extensometers, which were set at the central part of each surface of the specimen (see Fig. 1).

From these experiments, the relations between applied tensile load and average deformation of the four faces, which is nearly equal to the deformation of each face, were obtained.
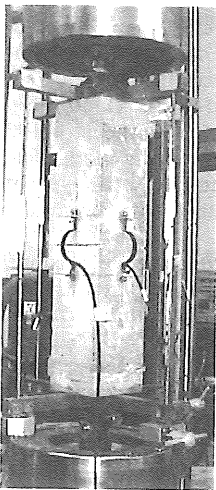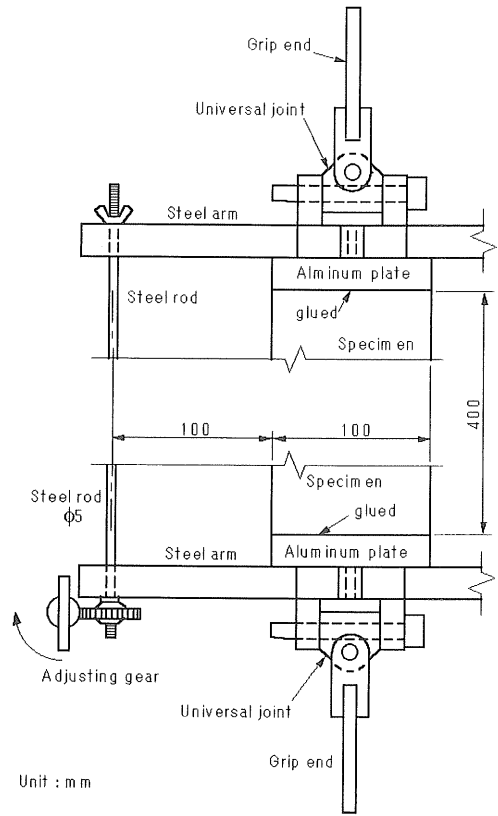

Figure 2. Original apparatus for uniaxial tension test.

2.3 *3-point bending test*

In order to indirectly obtain the tension softening curve by using inverse analysis, the 3-point bending test was carried out.

Figure 3 shows the view of the bending test. The test specimen has a notch depth of 50 mm. The post-

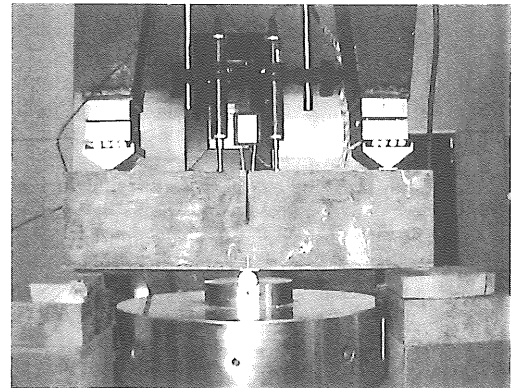Figure 1. Setup for original uniaxial tension test.

Figure 3. Setup for 3-point bending test.

peak behavior is obtained by only displacement control in loading. Therefore the application of loading was controlled by the crack mouth opening displacement (CMOD), using a closed-loop loading system. From these experiments, the relations between applied load and CMOD were obtained.

In this study, for protecting the expensive clip gauge over the crack mouth, which measured CMOD, after breaking a specimen, the loading and support points were set upside down in comparison to ordinary bending tests (see Fig. 3).

3 EXPERIMENTAL RESULTS

3.1 *Uniaxial tension test*

3.1.1 *Results of original uniaxial tension test*
Figure 4 shows a typical load-deformation relationship (*P-d* curve) for normal concrete A. Several *P-d* curves of each type of concrete were obtained by the original uniaxial tension test.
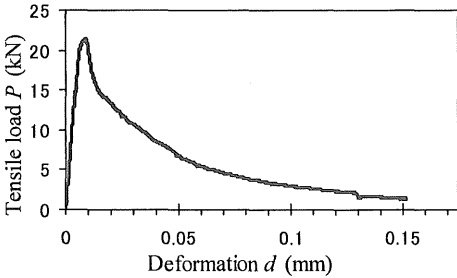
Figure 4. Load – deformation curve (uniaxial tension test).

3.1.2 *Tension softening curve by uniaxial tension test*
In order to obtain the tension softening curve (tensile stress − crack width relationship), Equation 1 was used with *P-d* curves (e.g. Fig. 4), which were measured by the original uniaxial tension test.

$$w = d - \frac{PL}{EA} - d_r \qquad (1)$$

where w = crack width; d = observed deformation; P = applied tensile load; L = measuring length; E = Young's modulus; A = cross sectional area of ligament; and d_r = residual deformation when the load decreases to 0.

Figures 5-8 show the tension softening curves calculated by using Equation 1 and the results of the uniaxial tension test on the four types of concrete. For each type of concrete, since the proposed tension softening curves of different depth of notches are almost the same, these curves show no distinction between different notches of specimens.

From Figures 5-8, it is obvious that each tension softening curve is similar for each type of concrete.
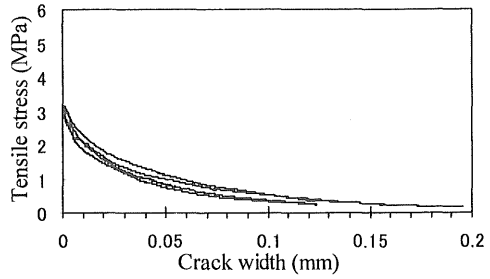
Figure 5. Tension softening curves obtained by uniaxial tension test (normal concrete A).
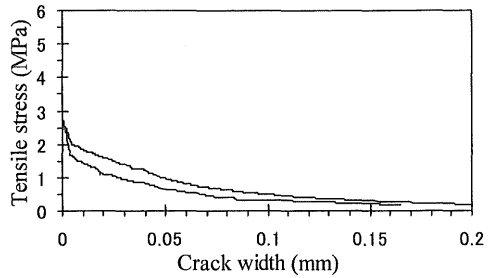
Figure 6. Tension softening curves obtained by uniaxial tension test (normal concrete B).
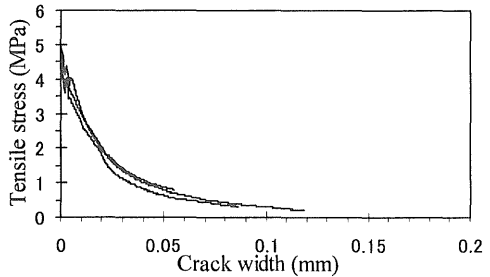
Figure 7. Tension softening curves obtained by uniaxial tension test (highly-flowable concrete).
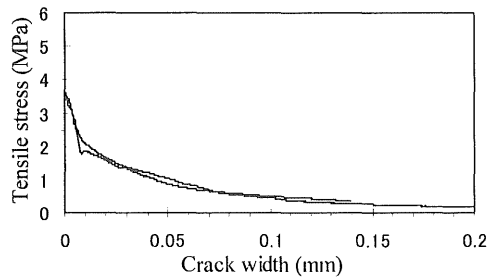
Figure 8. Tension softening curves obtained by uniaxial tension test (high-early-strength concrete).

Namely, the influence of differences in both the test specimens and testing error is small for the same concrete. Therefore, the original uniaxial tension test

with the elimination of secondary flexure, as proposed by the authors, is effective in obtaining the tension softening curve as the property of the corresponding concrete.

3.2 3-point bending test

Figures 9-12 show load-CMOD relationships for the four types of concrete, which were obtained by the 3-point bending test.

From Figures 9-12, it is obvious that each load-CMOD curve is not similar on each type of concrete. The difference of values of tensile yield load is especially not small on each type of concrete. Therefore the tension softening curves, which were derived by inverse analysis using these load-CMOD curves, will be different between test specimens, even if concrete specimens made from the same batch are used for the tests. Namely, it will be difficult to obtain a single tension softening curve as the property of the corresponding concrete.

4 TENSION SOFTENING CURVE BY INVERSE ANALYSIS

In this study, inverse analysis including the polylinear approximation analysis method proposed by Kitsutaka (1995), with the fictitious crack model and finite element method (Hillerborg et al.1976), was employed to obtain the tension softening curve.

Figures 13-16 show the tension softening curves obtained by inverse analysis using the results of the 3-point bending test (Figs 9-12) on the four types of concrete. Because some load-CMOD curves of the 3-point bending test were inadequate for inverse analysis, some tension softening curves could not be obtained by inverse analysis. Therefore, the number of curves, which corresponds to the number of specimens, is different between the figure of load-CMOD curves and that of tension softening curves on each type of concrete (e.g. between Figures 10 and 14 for normal concrete B).

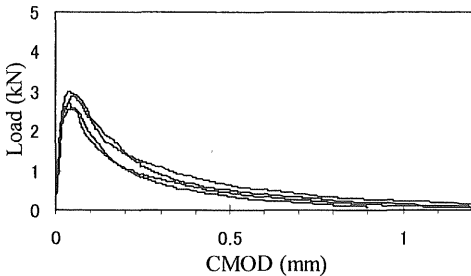From Figures 13-16, it is obvious that each ten-

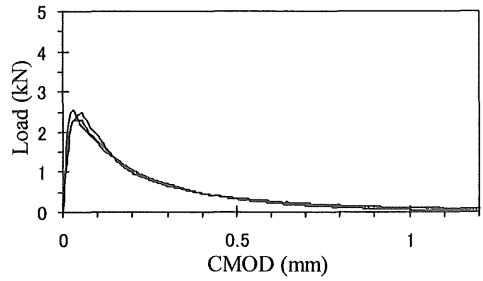Figure 9. Load–CMOD curves obtained by 3-point bending test (normal concrete A).

Figure 10. Load–CMOD curves obtained by 3-point bending test (normal concrete B).
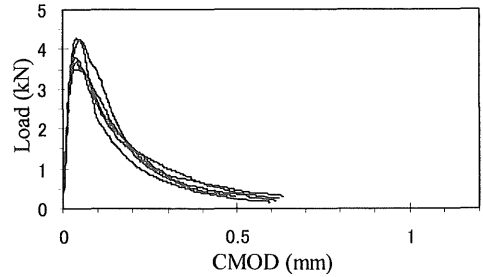

Figure 11. Load–CMOD curves obtained by 3-point bending test (highly-flowable concrete).
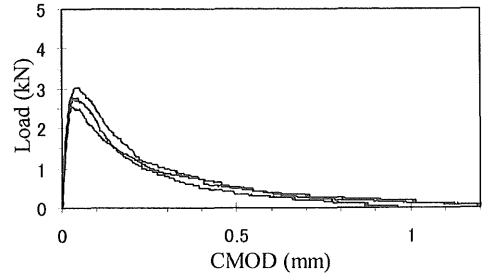

Figure 12. Load–CMOD curves obtained by 3-point bending test (high-early-strength concrete).
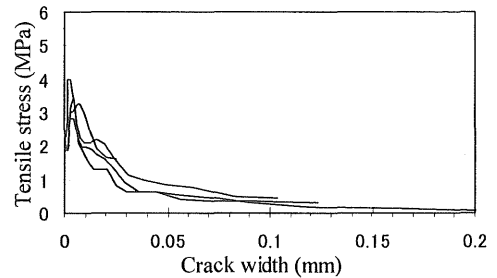

Figure 13. Tension softening curves obtained by inverse analysis (normal concrete A).

sion softening curve is not similar on each type of concrete. The curves of each specimen for the same concrete are clearly dispersed. This is due to the in-
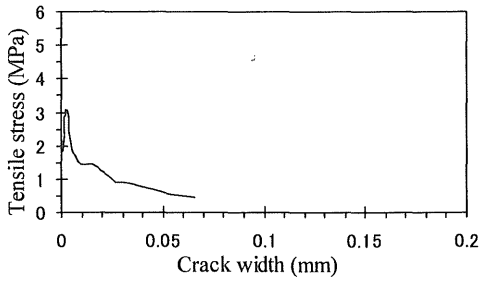
Figure 14. Tension softening curve obtained by inverse analysis (normal concrete B).
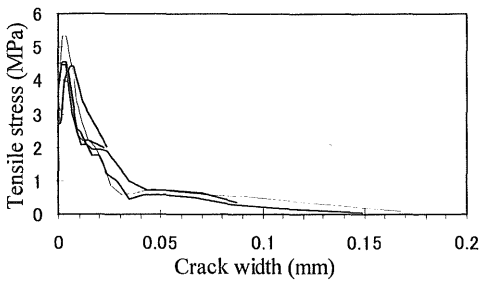

Figure 15. Tension softening curves obtained by inverse analysis (highly-flowable concrete).
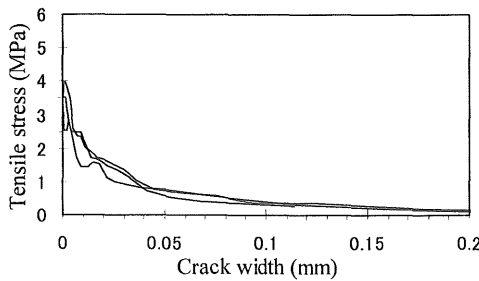

Figure 16. Tension softening curves obtained by inverse analysis (high-early-strength concrete).

fluences of differences of test results of the 3-point bending test caused by differences of test specimen and testing errors. This phenomenon cannot be avoided, even if both the same batch of concrete and the same testing condition are used for several specimens. Therefore, it is difficult to determine the tension softening curve as the property of the corresponding concrete by inverse analysis using test results of the 3-point bending test.

5 COMPARISON OF TENSION SOFTENING CURVE

Figures 17-20 compare tension softening curves obtained by the uniaxial tension test and the 3-point bending test with inverse analysis on the four types

of concrete: normal concrete A, B, highly-flowable concrete and high-early-strength concrete. One or two curves of typical tension softening curves in each of Figures 5-8 and 13-16, are indicated in Figures 17-20.

The comparison of the tension softening curves obtained by both procedures shows that the curves on each type of concrete are roughly similar. However, there are differences between the curves. The curves of the inverse analysis procedure are wavy, while those of the uniaxial tension test show a monotonous decrease, because the uniaxial tension test is designed to control the tension loading by the tensile strain of the specimen.

As a result, it is thought that the curves obtained by inverse analysis do not accurately reflect the material characteristics for an analysis of concrete fracture.

6 CONCLUSIONS

In order to obtain the tension softening curves, both the original uniaxial tension test and inverse analysis with 3-point bending test were carried out for four types of concrete which are frequently used in construction sites. Tension softening curves obtained by both procedures were compared for each type of concrete. As a result, the following are proposed for each type of concrete.
– The tension softening curves, obtained by the original uniaxial tension test with the elimination of secondary flexure, are similar. Namely, the influence of both differences of test specimen and testing error is small.
– The tension softening curves obtained by inverse analysis with 3-point bending test are not similar. The curves of each specimen were clearly dispersed. This is due to the influence of the test results of the 3-point bending test. Namely, the influence of both differences of test specimen and testing error is large in the 3-point bending test.
– The comparison of the tension softening curves obtained by both procedures shows that the curves are roughly similar.
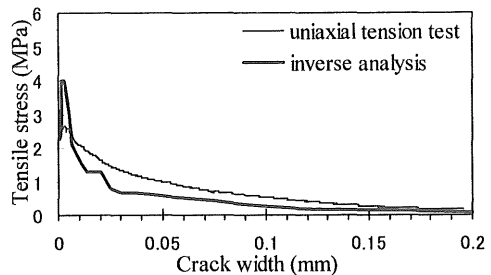

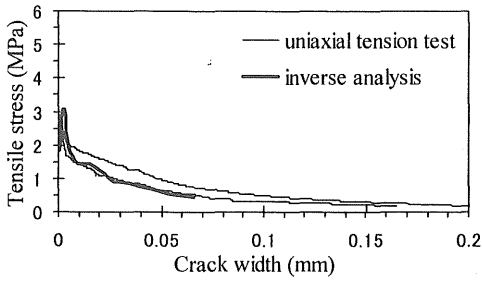Figure 17. Comparison in tension softening curves (normal concrete A).

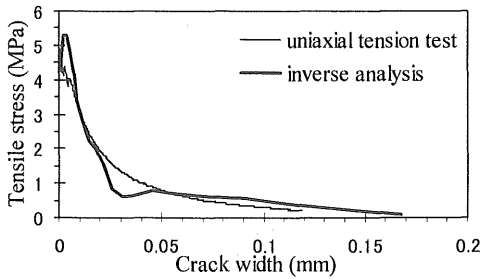Figure 18. Comparison in tension softening curves (normal concrete B).

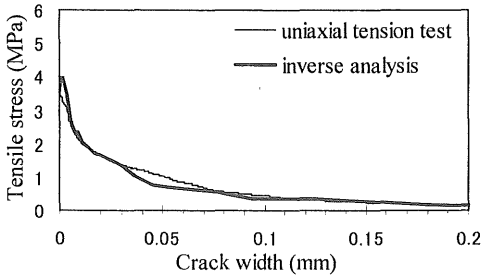Figure 19. Comparison in tension softening curves (highly-flowable concrete).

Figure 20. Comparison in tension softening curves (high-early-strength concrete).

Some tension softening curves of the inverse analysis procedure are wavy, while those of the uniaxial tension test show a monotonous decrease.

Consequently, since the tension softening curves obtained both methods are roughly similar, it is thought that both the original uniaxial tension test and inverse analysis with 3-point bending test are effective in obtaining the curves. However, because the accuracy of the 3-point bending test is limited, it is difficult to determine a single tension softening curve as the property of the corresponding concrete by inverse analysis with the 3-point bending test. Therefore, the original uniaxial tension test with the elimination of secondary flexure is more effective in obtaining the tension softening curve of concrete.

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