BOND PROPERTIES OF CONCRETE JOINTS AND SIZE EFFECT

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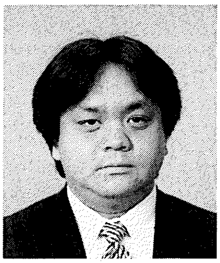
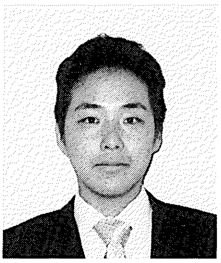
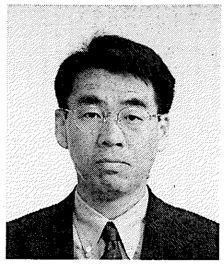
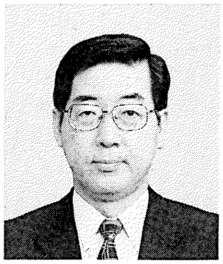

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The bond properties of concrete joints under different conditions are investigated using tension softening diagrams in addition to the conventional flexural bond strength approach. The conditions that yield good bond properties are clarified. The size effect on flexural bond strength is also discussed, and the fracture energy (area under the tension softening diagram) is shown to be a more sensitive index than conventional flexural bond strength for the evaluation of concrete joints. The wash-out method combined with a retarder-impregnated paper sheet was found to be an efficient means of obtaining rough joint surfaces and good bond properties. The size effect on strength was well predicted through numerical analysis with tension softening diagrams. The effect of size on the shape of the determined tension softening diagram was not notable.

Keywords: *concrete joint, flexural bond strength, size effect, tension softening diagram*

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1. INTRODUCTION

Performance-based design is an advanced design method that is expected to come into widespread use in the near future. The performance of structures must be accurately specified and then correctly evaluated using appropriate methods. In discussing the failure behavior of structures, the complete load-displacement curve including the elastic region, the peak (ultimate load), and also the post-peak region seems likely to be required in such advanced design approaches, as illustrated in **Fig. 1.** Constitutive relations such as the tension softening diagram will be needed to allow numerical analysis of the overall failure behavior of structures.

The concrete tension softening diagram, which describes the relationship between transfer tensile stress and crack opening in a fracture process zone, is one of the efficient parameters of fracture mechanics. Numerical analysis using a tension softening diagram is able to accurately describe the fracture behavior of concrete. Although it is a tension property, the diagram has usually been determined from simple bending tests on beam specimens as illustrated in **Fig. 2** instead of by direct tensile tests, which are more difficult to perform. It should be stressed that a tension softening diagram is a direct tension property that includes tensile strength and fracture energy.

Because good bonding is often required for concrete joints, many investigations of bonding properties have been carried out [1,2,3]. The roughness of the joint surface [4], the concrete mix proportions, and the construction method are the main factors affecting the bond properties. Flexural bond strength has commonly been used as an index to evaluate bond properties at concrete joints. It is known, however, that there is a size effect on flexural strength and that flexural strength in the case of large specimens cannot be well predicted on the basis of results for small specimens. Thus there is a need for a more appropriate approach to evaluating the performance of concrete joints.

In this study, the bond properties of concrete joints are evaluated by means of tension softening diagrams and fracture energy, or the area under a tension softening diagram, in addition to the conventional flexural bond strength approach. The conditions under which good bond properties are attained were investigated. The size effect on flexural bond strength is also discussed. The results of our preliminary studies [5,6] were given in the first part of this study.

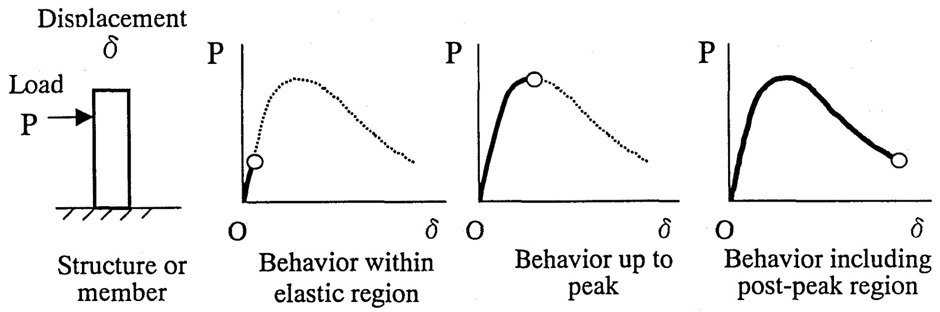

Fig. 1 Failure behavior

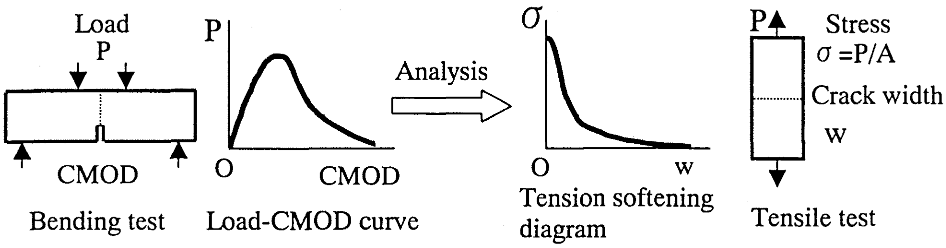

Fig. 2 Determination of tension softening diagram from bending test

2. OUTLINE OF EXPERIMENTS AND ANALYSIS

2.1 Specimens

The test conditions are summarized in **Table 1**. Thirteen series of tests were each divided into two parts: Test I and Test II. Each series consisted of 4 or more beam specimens. A notch of 1/3 of the specimen depth was cut using a concrete saw or by embedding a plastic plate in the concrete on the tension side. The specimens were made of normal concrete. Mix proportions of the existing and new concrete are shown in **Table 2**. The properties of the concrete are tabulated in **Table 3**.

Table 1 Test conditions

Test	Series		Type of concrete, Existing&New	Orientation of joint surface	Surface treatment	Number of specimens	Specimen size (mm), Width×Depth×Length[Span]
I	NJ		②	–	–	4	100×200×1200[1000]
	HJ		② & ③	Horizontal	Fracture surface	4	
	HN		① & ②		Without treatment	7	
	HS		① & ②		Wash-out	5	
	VS		② & ④	Vertical	Wash-out	5	
	VSM		② & ④		Wash-out+ Mortar	5	
	VSK		② & ④		Wash-out+ High strength mortar	5	
II	T	10	⑤ & ⑥	Vertical	Wash-out	4	100×100× 400[250]
		20				4	100×200× 600[500]
		40				4	100×400×1200[1000]
	Y	10	⑤ & ⑥	Vertical	Wash-out	4	100×100× 400[250]
		20				4	100×200× 600[500]
		40				4	100×400×1200[1000]

Table 2 Mix proportions of concrete

Type of concrete	Air content (%)	W/C (%)	Unit weight (kg/m³)				
			Water W	Cement C	Fine ag. S	Coarse ag. G*	Admixture**
①	2.0	50.4	173	343	789	1031	1.026
②	2.5	50.4	172	341	787	1029	1.024
③	2.2	50.6	172	340	785	1026	1.021
④	2.9	50.3	171	340	782	1022	1.017
⑤	3.3	50.6	171	338	781	1014	1.009
⑥	3.1	50.4	171	339	782	1023	1.018

* : Crushed stone, Maximum size 15mm
** : AE water reducing agent

Table 3 Properties of concrete

Type of concrete	Strength (MPa)			Young's modulus (GPa)	Age (days)
	Compression	Tension	Flexure		
①	45.5	3.52	4.09	27.8	13
	43.7	3.47	5.19	29.4	31
②	42.7	3.85	4.31	31.2	12
	46.5	3.74	5.59	29.1	30
③	41.7	3.48	4.13	31.8	14
④	54.0	4.22	5.90	31.0	28
⑤	48.0	3.05	5.06	32.0	33
⑥	50.5	3.11	4.94	31.9	32

The main factors in Test I were the orientation of joint surfaces and the surface treatment applied, including the placement of mortar between the existing and new concrete. The specimens were 100×200×1200 mm (width × depth × length) and the joint was at the center except in the case of Series NJ. The joint surface was taken to be horizontal for Series HJ, HN, and HS and vertical for the rest, as sketched in **Fig. 3**. In Series HJ, the fracture surface resulting from bending tests was adopted as the joint surface. No roughening treatment was done on the joint surface in the case of Series HN. In Series HS, VS, VSM, and VSK, the joint surface was roughened by washing out the surface mortar, with hardening delayed by lying on a paper sheet containing retarder. Normal-strength mortar (cement : water : sand = 1.0 : 0.35 : 2.35) and high-strength mortar (cement : water : sand = 1.0 : 0.27 : 1.8) were placed over the joint surface of the existing concrete before pouring the new concrete in Series VSM and VSK, respectively.

In Test II, the effect of specimen size on both flexural bond strength and the shape of the tension softening diagram was examined using specimens of different sizes: 100, 200, and 400 mm in depth. As shown in **Fig. 3**, the loading direction was parallel to the casting direction in Series T, but perpendicular in Series Y. The joint surface was roughened by the above-mentioned wash-out method.

2.2 Bending tests

As illustrated in **Fig. 4**, four-point bending tests were carried out. The applied load and the crack mouth opening (CMOD) were recorded for all series. The displacement (deflection) of the beam was also measured at loading points in Series NJ and HJ.

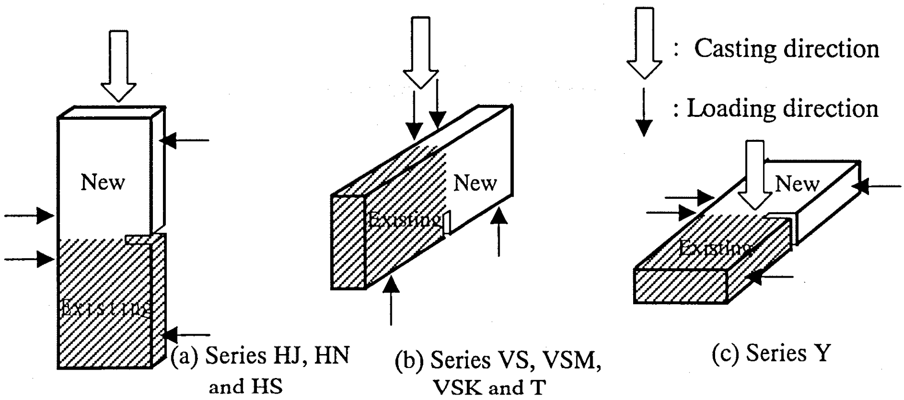

Fig. 3 Casting direction and loading direction

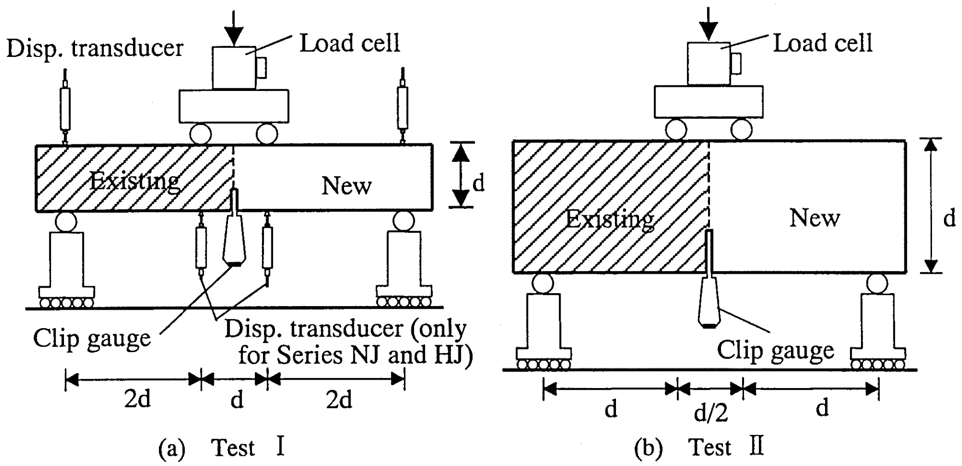

Fig. 4 Test setup

2.3 Determination of tension softening diagrams

The poly-linear approximation analysis method [7] combined with finite element analysis using a fictitious crack model [8] was used for determination of the tension softening diagrams. The shape of the diagram was determined step by step, so that the analytical load-CMOD (or -displacement) curve agreed with the experimental one. This program was made available to all in a committee report [9] and was distributed through the Internet.

3. EFFECT OF JOINT SURFACE CONDITIONS (Test I)

3.1 Load-displacement curves and load-CMOD curves

The test results for Series NJ (with no joint) and HJ (with a joint) are shown in **Fig. 5**, where the measured curves are indicated by thin lines and the averaged curve by a thick line. The tension softening diagrams were determined from both the averaged load-displacement curve and the averaged load-CMOD curve. Whereas the diagrams obtained by these two methods, which are shown the right-hand diagrams in **Fig. 5 (a)** and **(b)**, are similar for each series, the stress at the softening start point of the diagram as determined from the load-CMOD curves was close to the tensile strength given in **Table 3**. It is inferred that the softening diagram determined from the load-displacement curve is inferior in accuracy to

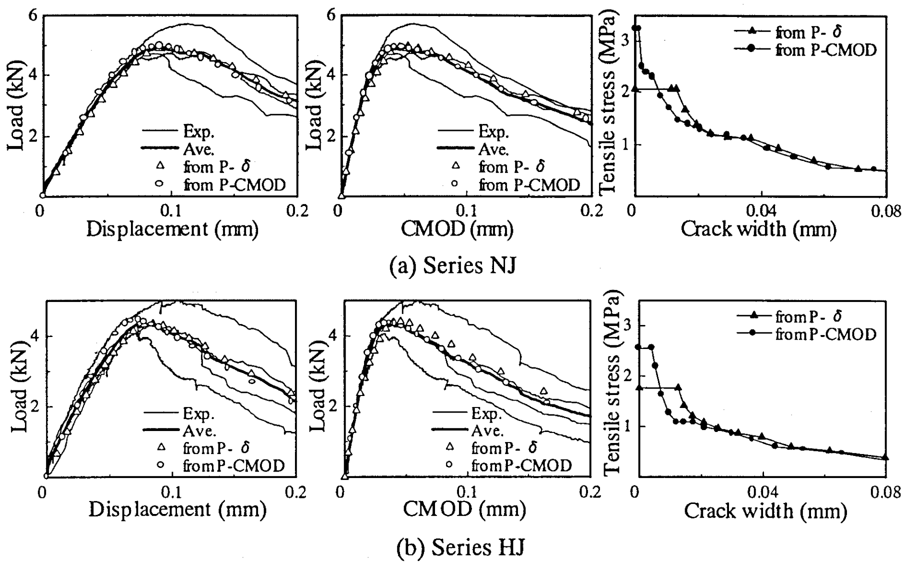

Fig. 5 Test results for Series NJ and HJ

that determined from the load-CMOD curve, because the measured loading point displacement includes measurement errors such as the settlement of the support and local deformation at the loading point. The load-displacement curve and the load-CMOD curve were simulated using FEM with the two determined tension softening diagrams and are plotted as triangle and circular points in **Fig. 5**. The numerical results were in good accordance with the experimental results. It can be concluded that the load-CMOD curve is more suitable for determining tension softening diagrams than the load-displacement curve because of the simplicity in measurement. For this reason, only load-CMOD curves were used in the other series in this study.

3.2 Shape of tension softening diagrams of Test I

The load-displacement curves of the rest of the Test I series and the matching averaged curves are presented in **Fig. 6**. The determined tension softening diagrams of all the Test I series are shown in **Fig. 7**. The simulated results are also plotted in **Fig. 6**. **Figure 7** shows that the tension softening diagrams can be used to visually distinguish the difference in bond properties.

In the case of Series HJ, where new concrete was placed on the fracture surface after bending tests, the shape of the diagram was close to that of Series NJ with no joint. It would be effective to use a simulated fracture surface as a form for concrete products requiring good bond properties.

The shape of the diagram for Series VSK, where high-strength mortar was placed between the existing and new concrete, was also close to that of Series NJ. It has long been known that mortar on the joint surface effectively improves bonding. From a comparison of VSM and VSK, it is seen that the higher the mortar strength, the better the bond property at joints.

3.3 Flexural bond strength and fracture energy

The flexural bond strength and fracture energy of each series are tabulated in **Table 4**. The flexural bond strengths were calculated in consideration of the weight of the specimen and

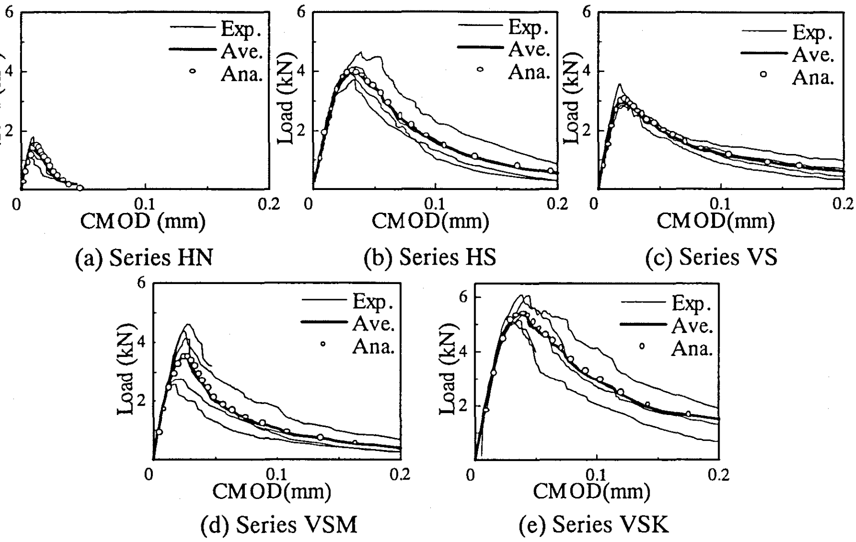

Fig. 6 Load-CMOD curves for Series HN, HS,VS, VSM, and VSK

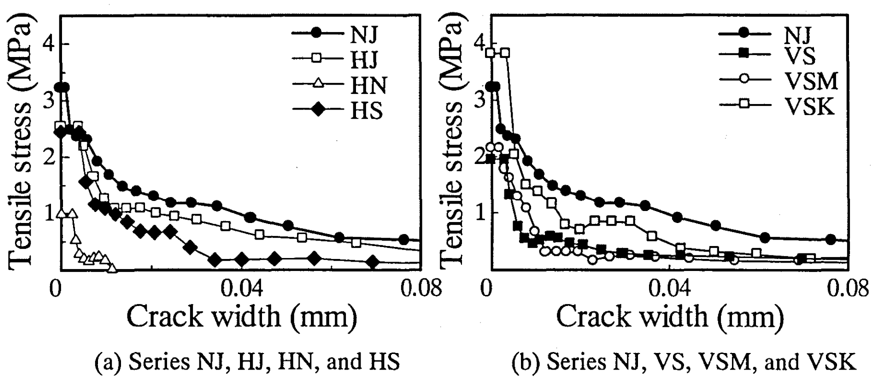

Fig. 7 Comparison of tension softening diagrams

the loading apparatus. The fracture energy was defined in this study as the area under the tension softening diagram up to a crack width of 0.02 mm. Further discussion is needed to select a suitable limit for the crack width. It is known that the area under the diagram for narrower crack width has a larger effect on the flexural strength [10]. The ratios of flexural bond strength and fracture energy of each series to the Series NJ with no joint are shown in **Table 4** and indicated in **Fig. 8**.

It is clear from **Fig. 8** that the fracture energy is a more sensitive index than conventional flexural bond strength for evaluation of the bond properties of concrete joints. Further, it is seen from results of Series HJ, HN, and HS that the wash-out method combined with a retarder-impregnated paper sheet is effective for obtaining a rough surface and good bond properties. The horizontal joint surface of Series HS had better bond properties than the vertical one of Series VS due to the reduced effect of bleeding. The bar chart for Series VSM and VSK in **Fig. 8** also indicates that the use of the high strength mortar between existing and new concrete gives better results.

Table 4 Flexural strength and fracture energy

Series	Age (days)		Flexural strength (MPa)	Fracture energy (N/m)		Ratio to Series NJ	
						Flexural strength	Fracture energy
	Old	New		P-δ *	P-CMOD**		P-CMOD
NJ	12		3.67	41.2	37.0	1.00	1.00
HJ	30	14	3.18	35.3	29.7	0.87	0.80
HN	31-32	30-31	1.34	–	4.5	0.37	0.12
HS	31-32	30-31	2.93	–	26.8	0.80	0.72
VS	129-130	28-29	2.19	–	16.9	0.60	0.46
VSM	129-130	28-29	2.57	–	18.3	0.70	0.50
VSK	129-130	28-29	3.80	–	36.2	1.04	0.98

* : Area under tension softening diagram determined from load-displacement curve until crack width becomes 0.02 mm

** : Area under tension softening diagram determined from load-CMOD curve until crack width becomes 0.02 mm

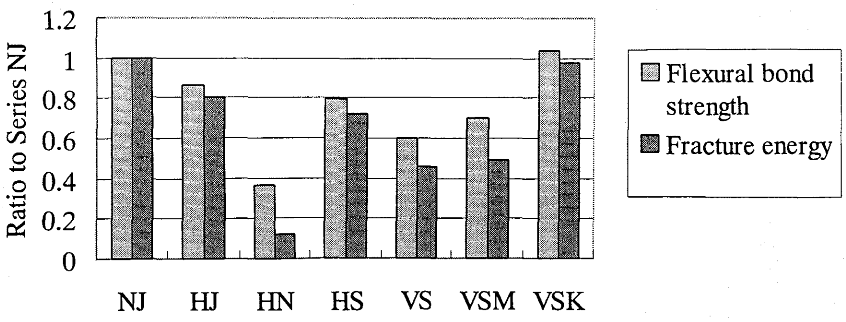

Fig. 8 Ratios of flexural bond strength and fracture energy of each series to Series NJ

4. EFFECT OF SPECIMEN SIZE (Test II)

4.1 Shape of tension softening diagrams in Test II

In **Fig. 9**, the individual load-CMOD curves for Series T and Y are shown by thin lines and the averaged curves by thick lines, respectively. The determined tension softening diagrams for each series are shown in **Fig. 10**. The shapes of the diagrams are all similar irrespective of specimen size, except in the case of Series Y40, where the stress was slightly lower than the others. It is not clear whether this is a result of experimental scatter or the essential nature of the specimens. However, we can conclude that the size effect on the shape of the tension softening diagram is not particularly significant within the range of this study.

4.2 Size effect on flexural bond strength

The experimental flexural bond strengths with increasing specimen size are tabulated in **Table 5**, together with the analytical results up to a beam depth of 1,000 mm. The averaged diagram shown in **Fig. 10 (d)** was adopted in the numerical analysis. A size effect on the flexural bond strength was recognized. Good accordance was observed between the experimental and analytical results.

One of the advantages of the tension softening diagram is that we can discuss the fracture behavior of concrete beyond the range of experiments through a numerical analysis based on

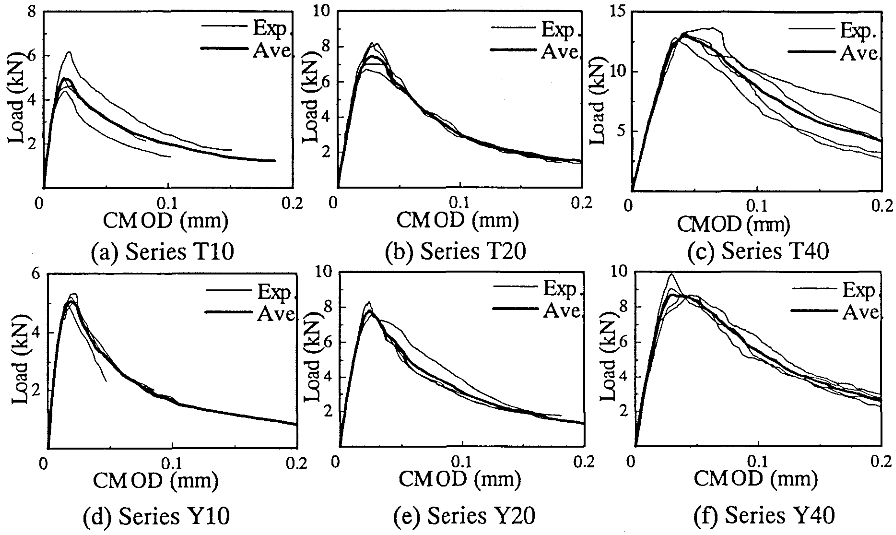

Fig. 9 Load-CMOD curves for Series T and Y

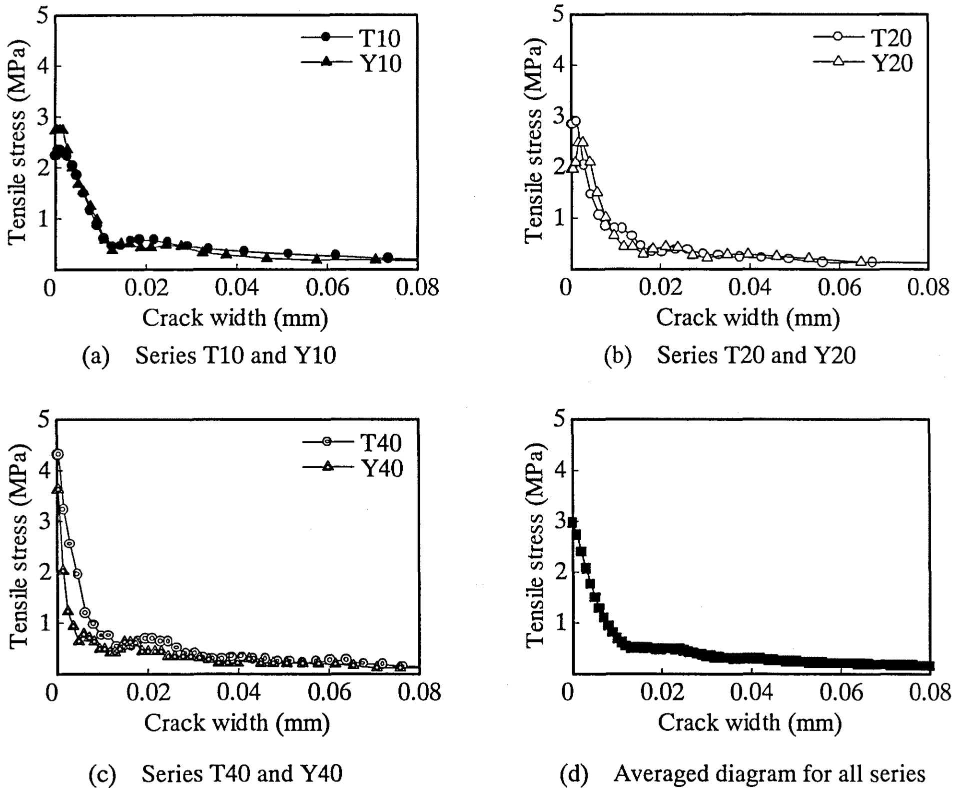

Fig. 10 Tension softening diagrams for Series T and Y

Table 5 Flexural bond strength in Test II

Beam depth (mm)	Flexural bond strength (MPa)		
	Experiment		Analysis*
	Series T	Series Y	
100	3.26	3.34	3.09
200	2.47	2.56	2.48
400	2.28	1.60	1.92
1000	-	-	1.48

* : Using averaged tension softening diagram shown in **Fig. 10(d)**

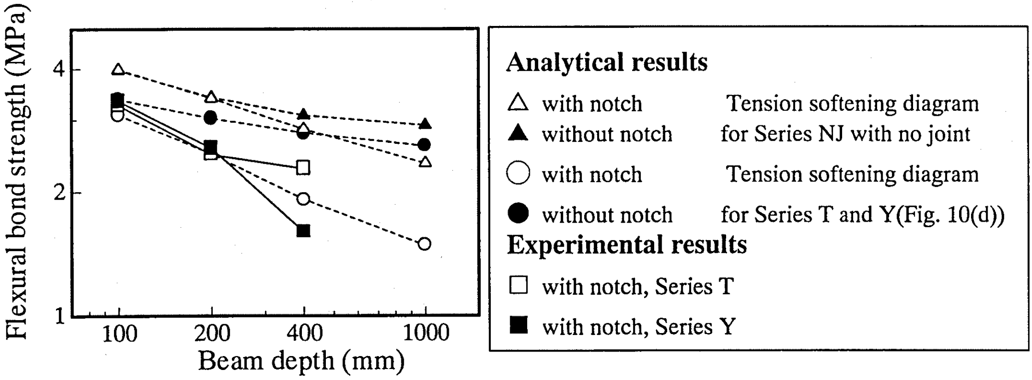

Fig. 11 Size effect on flexural bond strength

the diagram. For notched and non-notched beam specimens up to a beam depth of 1,000 mm, the flexural bond strengths were calculated using the tension softening diagram for Series T and Y (**Fig. 10 (d)**). The results are shown by the broken lines in **Fig. 11**. The experimental results are also shown in **Fig. 11** by solid lines. In addition, the flexural strengths of beam specimens with no joint were calculated using the diagram for Series NJ for comparison, and these are also shown in **Fig. 11**. The flexural strength of beam specimens with no notch tended to approach the tensile strength (stress at the softening start point) as the beam depth increased. On the other hand, the flexural strength of notched beam specimens decreased remarkably with increasing beam depth. The rate of decrease for jointed specimens was greater than that for specimens with no joint. It should be noted that the strength of notched beam specimens approaches the solutions given by linear elastic fracture mechanics when the specimen becomes very large.

5. CONCLUSIONS

Tension softening diagrams determined from load-displacement curves and from load-CMOD curves were similar. We conclude that the load-CMOD curve is more suitable for the determination of these curves than the load-displacement curve because of the simplicity in measurement.

The bond properties of concrete joints treated in different ways can be characterized by the shape of the tension softening diagrams. The fracture energy (area under the diagram) proves to be a more sensitive index than the conventional flexural bond strength for the evaluation of the bond properties of concrete joints.

The wash-out method combined with a retarder-impregnated paper sheet is an effective way to achieve good bonding. Further, horizontal joints had better bond properties than the vertical ones, and the use of higher strength mortar between the existing and new concrete gives better results. Joints on a fracture surface have particularly good bond properties.

There was a size effect on flexural bond strength at concrete joints. This size effect was predicted through a numerical analysis based on tension softening diagrams. The effect of size of specimen on the shape of the tension softening diagram was not particularly notable, and numerical analysis with tension softening diagrams was found to be an efficient way to discuss the fracture behavior of concrete beyond the experimental regime.

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