J. Materials, Conc. Struct., Pavements, JSCE, No. 613/V-42, 309-318, 1999 February

BOND PROPERTIES OF CONCRETE JOINTS AND SIZE EFFECT

Norihiko KURIHARA[1], Minoru KUNIEDA[2], Yuichi UCHIDA[3] and Keitetsu ROKUGO[4]

[1]Member of JSCE, Dr. of Eng., Research Associate, Dept. of Civil Eng., Musashi Institute of Technology (1-28-1, Tamazutsumi, setagaya-ku, Tokyo 158-8557, Japan)
[2]Member of JSCE, M. of Eng., Research Associate, Dept. of Civil Eng., Gifu University (1-1, Yanagido, Gifu, 501-1193, Japan)
[3]Member of JSCE, Dr. of Eng., Associate Professor, Dept. of Civil Eng., Gifu University (1-1, Yanagido, Gifu, 501-1193, Japan)
[4]Member of JSCE, Dr. of Eng., Professor, Dept. of Civil Eng., Gifu University (1-1, Yanagido, Gifu, 501-1193, Japan)

The bond properties of concrete joints in different conditions were investigated through tension softening diagrams in addition to conventional flexural bond strength. Conditions to obtain good bond properties were clarified. The size effect on the flexural bond strength was discussed. The fracture energy (area under the tension softening diagram) was a more sensitive index than the conventional flexural bond strength for the evaluation of concrete joints. The wash-out method combined with a paper sheet containing retarder was efficient to obtain a rough joint surface and good bond properties. The size effect on the 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 remarkable.

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

1. INTRODUCTION

The tension softening diagram, which is the relationship between the transfer tensile stress and the crack opening in a fracture process zone of concrete, is one of the efficient fracture mechanics parameters. Numerical analysis with a tension softening diagram can well describe the fracture behavior of concrete. Although it is a tension property, as illustrated in **Fig. 1**, the diagram has usually been determined from easy bending tests of beam specimens instead of direct tensile tests, which are more difficult to be performed. It should be stressed that the tension softening diagram is the direct tension property including the tensile strength and the fracture energy.

The performance based design method is expected to be one of the advanced approaches to spread throughout the world in the coming future. The performance of structures must be well required and then rightly evaluated through appropriate methods. In the discussion of the failure behavior of structures, the whole load-displacement curves including the elastic region, the peak (ultimate) and also the post-peak region, as illustrated in **Fig. 2**, seem to be necessary for future advanced design approaches. Constitutive relations such as the tension softening diagram are needed for the numerical analysis of the whole failure behavior of structures.

Because good bond properties are required for concrete joints in many cases, many investigations have been carried out[1)-3)]. The roughness of the joint surface[4)], the mix proportions of concrete and the

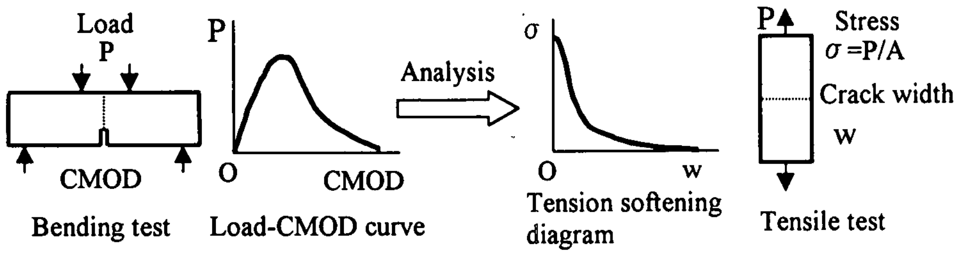


Fig. 1 Determination of tension softening diagram from bending test

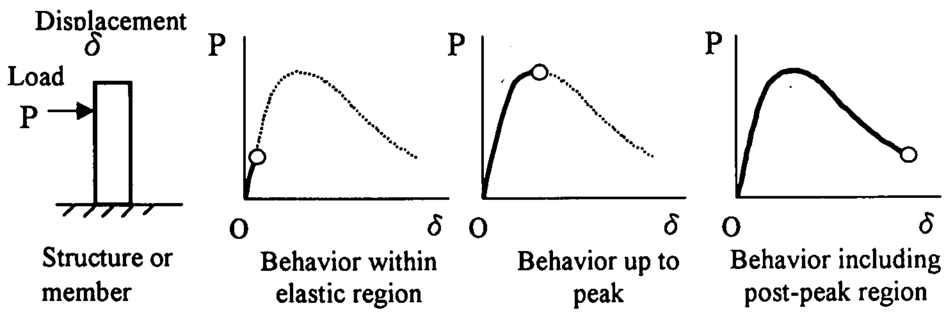


Fig. 2 Failure behavior

Table 1 Test conditions

Test	Series		Kinds of concrete, Old & New	Direction 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]

construction methods are the main factors affecting the bond properties. Flexural bond strength has been used as an index to evaluate the bond properties at concrete joints. It is known that there is a size effect on the flexural strength and that the flexural strength of large specimens can not be well predicted based on results of small specimens. The performance of the concrete joint must be more appropriately

Table 2 Mix proportions of concrete

Kinds 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

Kinds 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

evaluated.

In this study, the bond properties of concrete joints were evaluated by means of the tension softening diagrams and the fracture energy, which is the area under the diagram, in addition to the conventional flexural bond strength. Conditions to obtain good bond properties were investigated. The size effect on the flexural bond strength was discussed. The results of our preliminary studies[5),6)] are included in the first half part of this study.

2. OUTLINES OF EXPERIMENTS AND ANALYSIS

(1) Specimens

The test conditions are summarized in **Table 1**. Thirteen series of tests were 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 made by a concrete saw or by an embedded plastic plate at the tension side. The specimens were made of normal concrete. Mix proportions of old and new concrete are shown in **Table 2**. The properties of the concrete are tabulated in **Table 3**.

The main factors in Test I were the direction of joint surfaces and the surface treatments including the placement of mortar between old and new concrete. The specimens were 100×200×1200 mm (width × depth × length) and had a joint at the center except for 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, a fracture surface after bending tests was adopted as a joint surface. No roughening treatment was done on the joint surface of Series HN. In Series HS, VS, VSM and VSK, the joint surface was roughened by washing out surface mortar, where the hardening was delayed by placing 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 on the joint surface of old concrete before pouring new concrete in Series VSM and VSK, respectively.

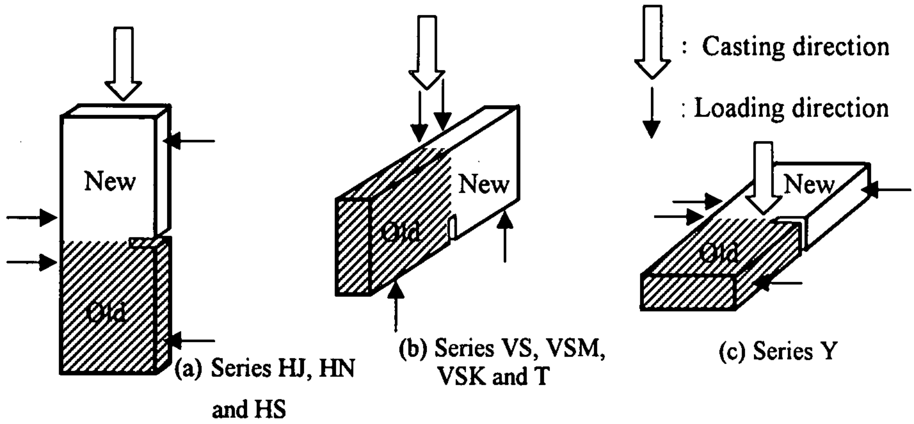


Fig. 3 Casting direction and loading direction

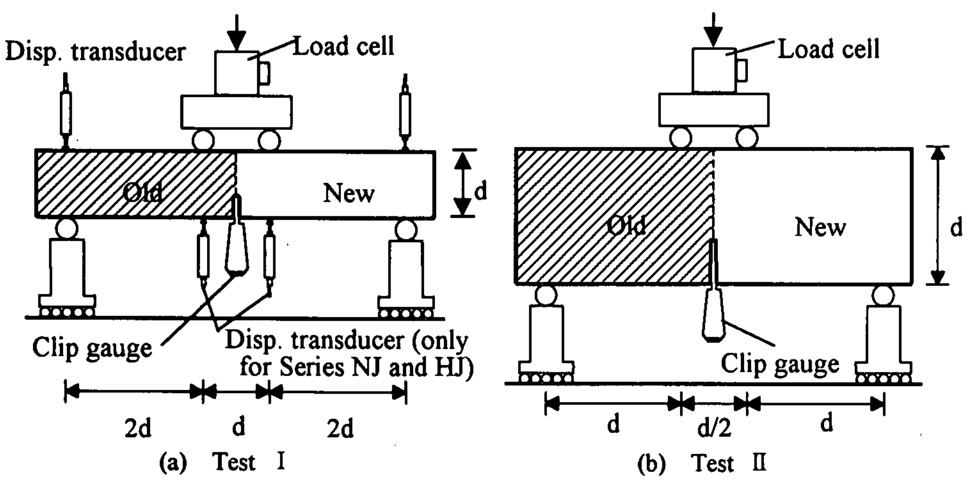


Fig. 4 Test setup

In Test II, the effect of specimen size on both the flexural bond strength and the shape of tension softening diagrams was examined using different size specimens: 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) Bending test

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 load applying points in Series NJ and HJ.

(3) Determination of tension softening diagrams

The poly-linear approximation analysis method[7)] combined with the finite element analysis with a fictitious crack model[8)] was used for the 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. The program was revealed to everyone in a committee report[9)] and was distributed through the Internet.

3. EFECT OF JOINT SURFACE CONDITIONS (Test I)

(1) Load-displacement curves and load-CMOD curves

The test results of Series NJ (with no joint) and

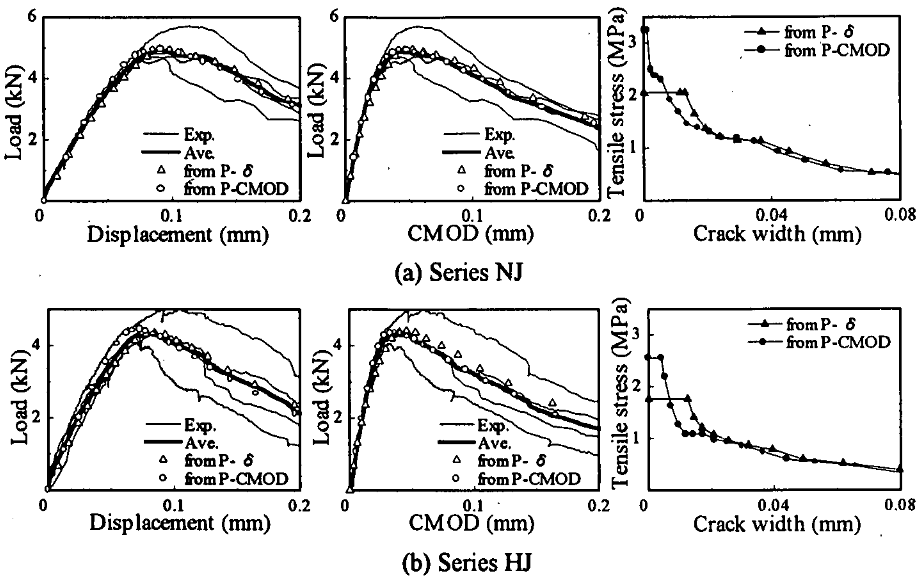


Fig. 5 Test results of Series NJ and HJ

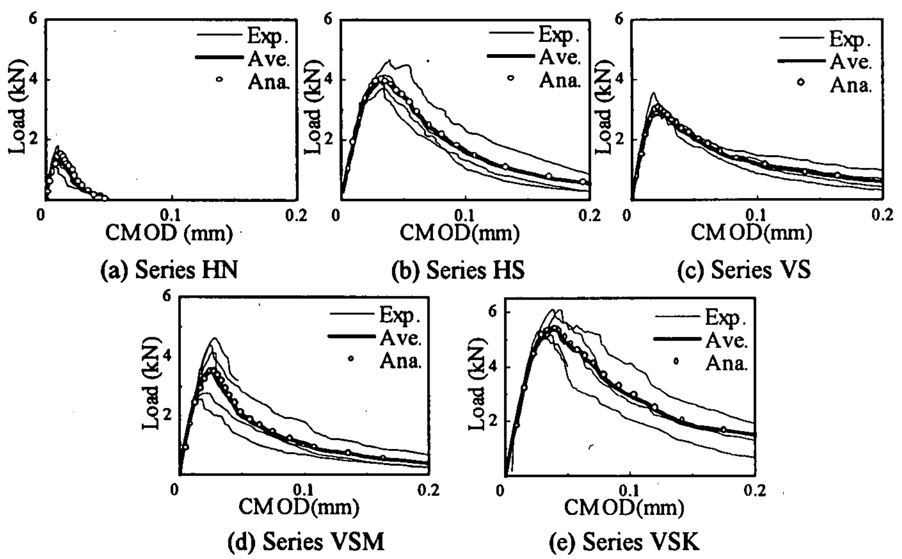
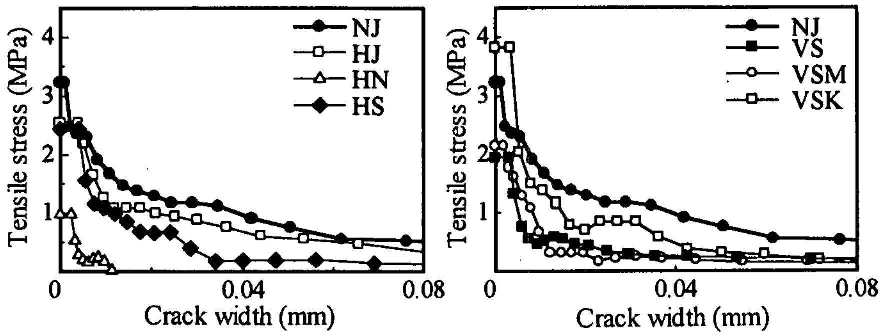


Fig. 6 Load-CMOD curves of Series HN, HS, VS, VSM and VSK

HJ (with a joint) are shown in **Fig. 5**, where measured curves are given 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 these two kinds of diagrams, shown in the right-hand side of **Fig. 5 (a)** and **(b)**, are similar with each other for each series, the stress at the softening start point of the diagram determined from load-CMOD curves was close to the tensile strength given in **Table 3**. It is considered that the softening diagram determined from the load -displacement curve is inferior in accuracy to that determined from load-CMOD curve, because the measured load point displacement includes measurement errors such as the settlement of the



(a) Series NJ, HJ, HN and HS (b) Series NJ, VS, VSM and VSK

Fig. 7 Comparison of tension softening diagrams

Table 4 Flexural strength and fracture energy

Series	Age (days)		Flexural strength* (MPa)	Fracture energy (N/m)		Ratio to Series NJ	
	Old	New		P-δ **	P-CMOD***	Flexural strength	Fracture energy 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

* : Calculated from maximum load
** : 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

support or the local deformation at the loading point. The load-displacement curve and the load-CMOD curve were simulated through FEM with the determined diagrams and are plotted 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 determination of tension softening diagrams than the load-displacement curve because of the simplicity in measurement. For this reason, only load-CMOD curves were used in other series in this study.

(2) Shape of tension softening diagrams of Test I

The load-displacement curves of the rest series of Test I and the averaged curves are presented in **Fig. 6**. The determined tension softening diagrams of all series of Test I are given in **Fig. 7**. The simulated results are also plotted in **Fig. 6**. It is seen from **Fig. 7** that the tension softening diagrams can 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 duplication of fracture surfaces as a form for concrete products requiring good bond properties.

The shape of the diagram of Series VSK, where high strength mortar was put between old and new concrete, was also close to that of Series NJ. It has been known that the placement of mortar on a joint surface is effective for good bonding. From the

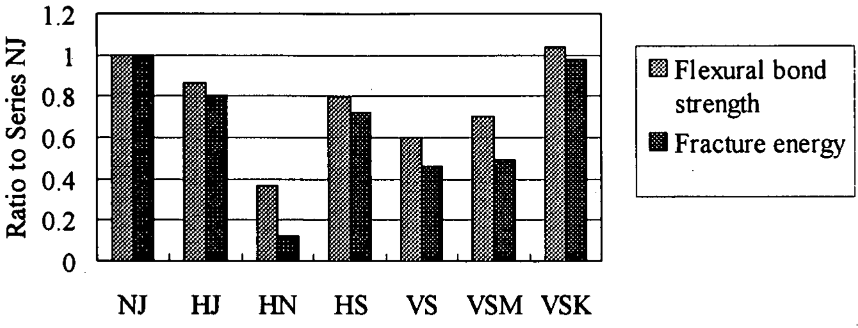


Fig. 8 Ratios of flexural bond strength and fracture energy of each series to Series NJ

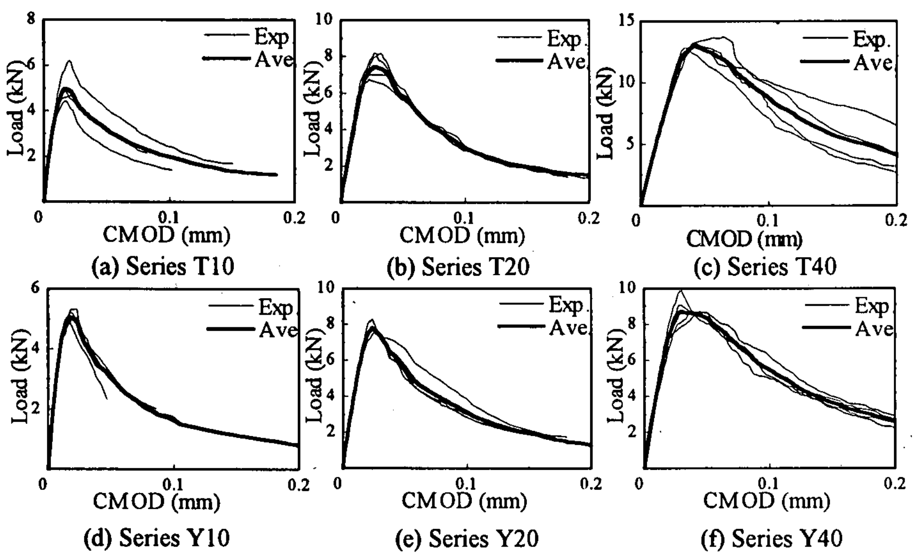


Fig. 9 Load-CMOD curves of Series T and Y

comparison of VSM and VSK, it is seen that the higher the mortar strength, the better the bond property at joints.

(3) Flexural bond strength and fracture energy

The flexural bond strength and the fracture energy of each series are tabulated in **Table 4**. The flexural bond strengths were calculated in consideration of the moment induced by the weight of a specimen and loading apparatus. The fracture energy was defined as the area under the tension softening diagram up to the crack width of 0.02 mm in this study. Further discussions will be needed for selection of the 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 the flexural bond strength and the fracture energy of each series to 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 was a more sensitive index than the conventional flexural bond strength for the evaluation of bond properties of concrete joints. It is seen from results of Series HJ, HN and HS, that the wash-out method combined with a paper sheet having retarder was effective to obtain 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 less effect of bleeding. The bar chart of Series VSM and VSK in **Fig. 8** also indicates that the use of the high strength mortar between old and new concrete gave better results.

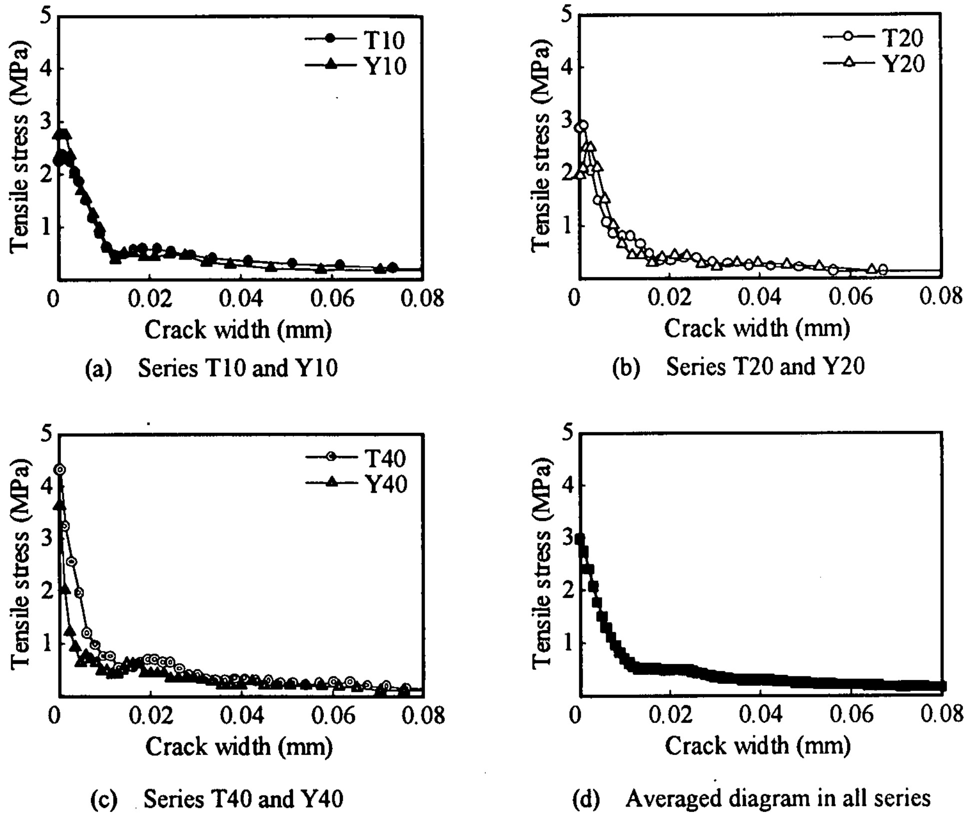


Fig. 10 Tension softening diagrams of Series T and Y

Table 5 Flexural bond strengths of Test II

Beam depth (mm)	Flexural bond strength (MPa)		
	Measurement		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)**

4. EFFECT OF SPECIMEN SIZES (Test II)

(1) Shape of tension softening diagrams of Test II

In **Fig. 9**, individual load-CMOD curves of Series T and Y are shown by thin lines and the averaged curves by thick lines. The determined tension softening diagrams of each series are shown in **Fig. 10**. The shapes of the diagrams were similar with each other irrespective of the specimen size, except for Series Y40, where the stress was slightly lower than others. It was not made clear whether this was an experimental scatter or the essential nature. However, we can conclude that the size effect on the shape of the tension softening diagram was not remarkable in the rage of this study.

(2) Size effect on flexural bond strength

The experimental flexural bond strengths with the increasing specimen size are tabulated in **Table 5**, together with the analytical results up to the beam

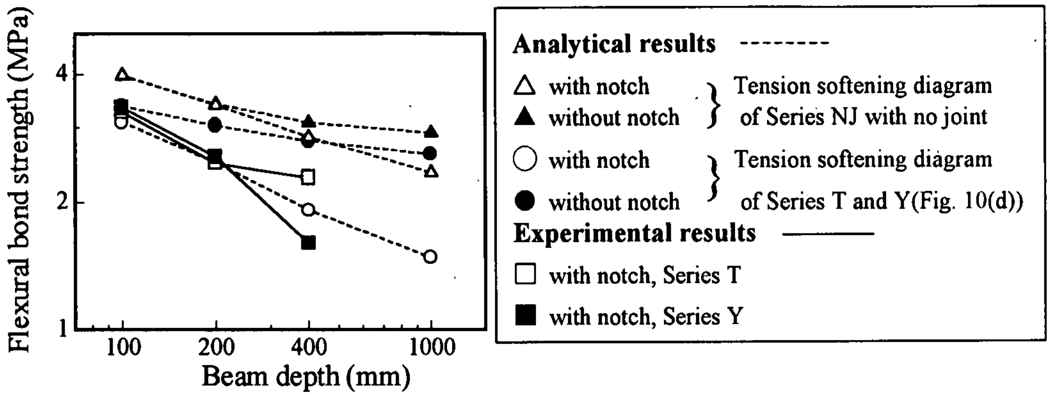


Fig. 11 Size effects on flexural bond strength

depth of 1,000 mm. The averaged diagram shown in **Fig. 10 (d)** was adopted in the numerical analysis. The 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 with the diagram. For beam specimens with and without a notch up to the beam depth of 1,000 mm, the flexural bond strengths were calculated using the tension softening diagram of Series T and Y (**Fig. 10 (d)**) and are shown by broken lines in **Fig. 11**. The experimental results are also shown by solid lines in **Fig. 11**. In addition, the flexural strengths of beam specimens with no joint were calculated using the diagram of Series NJ for comparison and are 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) with an increase in the beam depth. On the other hand, the flexural strength of notched beam specimens decreased remarkably with the increasing beam depth. The decreasing rate for jointed specimens was larger than that for specimens with no joint. It can be observed that the strength of notched beam specimens approaches the solutions of LEFM, when the specimen becomes very large. Additional experimental data are needed for the detailed discussions.

5. CONCLUSIONS

The tension softening diagrams determined from both load-displacement curves and load-CMOD curves were similar. We concluded that the load-CMOD curve was more suitable for the determination than the load-displacement curve because of the simplicity in measurement.

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

The wash-out method combined with a paper sheet having retarder was effective to obtain good bonding. The horizontal joint surface had a better bond property than the vertical one. The use of the higher strength mortar between old and new concrete gave better results. The joint on a fracture surface had a good bond property.

There was a size effect on the flexural bond strength at concrete joints. The size effect was predicted through a numerical analysis with tension softening diagrams. The effect of size on the shape of the tension softening diagram was not remarkable. The numerical analysis with tension softening diagrams was efficient to discuss the fracture behavior of concrete beyond experiments.

REFERENCES

1) Kokubu, M. : Tests on construction joints of concrete, *Proc. of JSCE*, No.8, pp.1-24, 1950 (in Japanease).
2) Adachi, I. and Kobayashi, K. : Construction joint of concrete structures using shot blasting technique, *Proc. of JSCE*, No.373/VI-5, pp.64-73, 1986 (in Japanease).
3) Moriwaki, T., Tsuji, Y., Hashimoto, C. and Nakajima, T. : Characteristics for strength of construction joint using polymer-modified mortar as joint materials, *Proc. of JSCE*, No.538/V-31, pp.15-26, 1996 (in Japanease).
4) Kamada, T., Kunieda, M., Kurihara, N., Nishida, Y. and Rokugo, K. : Evaluation of roughness of joint concrete surface and bond properties, *Fracture Mechanics of Concrete Structures*, AEDIFICATIO Publishers, pp.1645-1654, 1998.
5) Kurihara, N., Ando, T., Uchida, Y. and Rokugo, K. : Evaluation of bonding properties of concrete joint by means of tension softening diagrams, *Proc. of the Japan Concrete Institute*, Vol. 18, No.2, pp.461-466, 1996 (in Japanease).
6) Nishida, Y., Kunieda M., Kurihara N. and Rokugo K. : Evaluation of bonding properties of concrete joint, *Proc. of the Japan Concrete Institute*, Vol. 19, No.2, pp.129-134, 1997 (in Japanease).
7) Kitsutaka, Y. : Fracture parameters for concrete based on poly-linear approximation analysis of tension softening diagram, *Fracture Mechanics of Concrete Structures*, AEDIFICATIO Publishers, pp.199-208, 1995.
8) Uchida, Y., Kurihara, N., Rokugo, K. and Koyanagi, W. : Determination of tension softening diagrams of various kinds of concrete by means of numerical analysis, *Fracture Mechanics of Concrete Structures*, AEDIFICATIO Publishers, pp.17-30, 1995.
9) JSCE : The size effect and the tension softening diagram of concrete, Concrete Technical Series 18, *JSCE*, 1997 (in Japanese).
10) Alvaredo, A.M. and Torrent, R.J. : The effect of the shape of the strain-softening diagram on the bearing capacity of concrete beams, *Materials and structure*, Vol. 20, pp.448-454, 1987.

(Received June 5, 1998)

コンクリート打継ぎ部の付着性能と寸法効果

栗原哲彦・国枝 稔・内田裕市・六郷恵哲

条件の異なる打継ぎ部の付着性能について，従来から用いられている曲げ付着強度に加えて，引張軟化曲線を用いて検討を行い，良好な付着性能を得るための条件を明らかにした．コンクリート打継ぎ部の曲げ付着強度の寸法効果についても検討した．破壊エネルギー（引張軟化曲線下の面積）は，打継ぎ部の付着性能に対して，従来から用いられている曲げ付着強度に比べてより敏感な指標であった．凝結遅延剤シートを用いた洗出し法により，打継ぎ面を粗くし，良好な付着性能を得ることができた．引張軟化曲線を用いた数値解析により，打継ぎ部の曲げ付着強度の寸法効果を適切に表現することができた．なお，引張軟化曲線の形状に対し，寸法の影響は明確には認められなかった．