Flexural Bond Strength and Fracture Energy Tests of Concrete Joint Using Simple Beam Specimen Connected with Concrete Adhesives

Ryo Yamashita[1*], Masaya Okano[2**], Yukio Hiroi[1], Takashi Yamamoto[2] and Toyo Miyagawa[2]

[1]*IHI Construction Service Co., Ltd., JAPAN*
[2]*Kyoto University, JAPAN*
[*]*Minato-machi 1-4-1, Naniwa-ku, Osaka, JAPAN 556-0017,*
ryo_yamashita@iik.ihi.co.jp, yukio_hiroi@iik.ihi.co.jp
[**]*Kyoto-daigaku-katsura, Nishikyo-ku, Kyoto, JAPAN 615-8540,*
okano.masaya.82x@st.kyoto-u.ac.jp, yamamoto.takashi.6u@kyoto-u.ac.jp,
miyagawa@sme.kuciv.kyoto-u.ac.jp

ABSTRACT

Flexural bond strength and fracture energy tests were conducted to understand the basic flexural properties of the construction joint bonded with concrete adhesives for strengthening design of existing concrete bridges. The flexural bond strength tests were conducted for two types of joint, bonding hardened concrete to freshly-mixed or hardened concrete. Epoxy resin adhesives, acrylic polymer dispersion, and polymer modified cement grout were selected as the binders. The fracture energy tests were carried out in order to obtain more detailed information regarding tension softening. As a result, it was found that the binders for freshly-mixed concrete were not effective in terms of improving the bond strength when the joint surfaces were intentionally roughened by the use of concrete retarder. On the other hand, the epoxy adhesives for hardened concrete increased the load carrying capacity compared to the concrete placed monolithically because the fracture energy with them became higher.

Keywords. Adhesive, Flexural Bond Strength, Fracture Energy, Joint, Tension Softening

INTRODUCTION

For strengthening design of existing concrete bridges, it is often necessary to place concrete bracket in order to newly construct load supporting point such as the anchorage system of external tendon for strengthening main girder as shown in **Fig. 1**. In the current design codes, the primary steel reinforcement is required to transfer the external load on the concrete bracket to the main structure. For the design of new concrete structures, placing the primary reinforcement is not a significant concern. For the strengthening design of existing concrete structures, however, it is necessary to place post-installed anchors or prestressing bars and it is preferable to avoid cutting the existing rebar and the prestressing tendon at the time of drilling holes to place the anchors. Therefore, the design flexibility for the strengthening design is highly restricted. To solve this issue, the bracket structure without the primary steel reinforcement is being studied. The static loading tests for the bracket structure indicated that the surface preparation by chipping hammer was effective to improve the bond strength but it was only 32% compared to the flexural strength of concrete placed monolithically (Yamashita, 2012). Thus, applying concrete adhesive such as epoxy resin to the joint could be one of the choices to increase the bond strength. Concrete adhesives are used when the bond strength at the joint is required and the strength is commonly evaluated by pull-off test with direct tension. In case post-installed concrete bracket is structurally connected to the existing girder, however, its flexural bond strength is more important while limited research was carried out on this purpose to this date. Therefore, flexural bond strength and fracture energy tests were conducted to understand the basic flexural properties of the construction joint bonded with concrete adhesives.

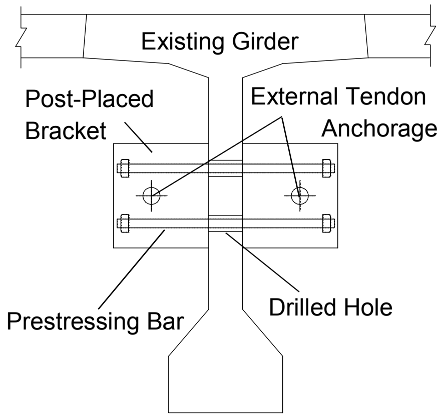

Figure 1. Cross section of girder strengthening by external tendon

FLEXURAL BOND STRENGTH TEST

Testing Overview. The flexural bond strength tests were conducted for two types of joint, bonding hardened concrete to freshly-mixed concrete (hereinafter "Type A") or hardened concrete (hereinafter "Type B"). The test specimen was a simple beam with the dimensions of 100 x 100 x 400 mm and tested by third-point loading in accordance with JIS A 1106 (Japanese Standard Association, 2006) as shown in **Fig. 2**. The joint surfaces were intentionally roughened by the use of concrete retarder. Epoxy resin adhesives, acrylic polymer dispersion, and polymer modified cement grout were selected as the binders. The test cases are shown in **Table 1**. The epoxy resin adhesives were used for both joint types whereas the acrylic polymer dispersion was used only for Type A joint and the polymer modified cement grout was used only for Type B joint.

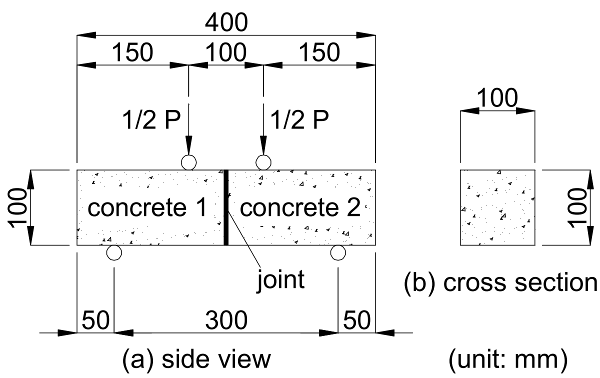

Figure 2. Flexural bond strength test

Table 1. Test cases for flexural bond strength test

test case	joint type	number of specimen	binder	note
AE1	hardened-to-freshly mixed concrete joint (Type A)	3	epoxy resin (type 1)	supplier A
AE2		3	epoxy resin (type 2)	supplier A
AE3		3	epoxy resin (type 3)	supplier B
AA		3	acrylic polymer dispersion	supplier B
AN		3	no binder	-
BE1	hardened-to-hardened concrete joint (Type B)	3	epoxy resin (type 4)	supplier A
BE2		3	epoxy resin (type 5)	supplier A
BG		3	polymer modified cement grout	supplier B
M	monolithically placed	9*	-	-

*Test specimens were made by three times of concreting and specimen M was made at each time.

Materials. The concrete mixture proportion and the material test results are shown in **Tables 2 and 3**, respectively. The material properties of the binders are shown in **Table 4**.

Test Results. The test results at 8 days of the binder age and the illustration of the notable failure modes are shown in **Table 5** and **Fig. 3**, respectively. The strength was calculated by dividing the bending moment due to the load at failure by the sectional modulus and for each case, the results from three test specimens were averaged. The results of concretes 1 and 2 indicate the strength of the concrete placed monolithically (case M) and concrete 1 is the one placed firstly. Note that concretes 1 and 2 were simultaneously placed for Type B joint.

Table 2. Concrete mixture proportion

maximum aggregate size (mm)	slump (mm)	water-cement ratio (%)	air content (%)	unit weight (kg/m^3)				
				water	cement	sand	gravel	admixture
15	80	40.0	7	170	425	780	861	1.063

Table 3. Concrete material test results

joint type	compressive strength (MPa)		splitting tensile strength (MPa)		elastic modulus (GPa)	
	concrete 1	concrete 2	concrete 1	concrete 2	concrete 1	concrete 2
Type A	60.3 (22 days)	50.3 (8 days)	3.89 (22 days)	3.33 (8 days)	36.8 (22 days)	35.0 (8 days)
Type B	64.0 (30 days)		4.42 (30 days)		39.0 (30 days)	

* The days in parenthesis indicate the concrete age at testing.

Table 4. Material properties of binders

property	unit	epoxy resin					APD*[1]	PMCG*[2]
		type 1	type 2	type 3	type 4	type 5		
pot life	min.	36	82	30	177	65	NA	NA
tensile bond st.*[3]	MPa	2.1	2.6	4.3	5.0	3.6	1.6	2.3
compressive st.	MPa	87	NA*[4]	71	85	43	NA	31
elastic modulus	MPa	2870	NA	2540	4910	2450	NA	NA
tensile shear st.	MPa	18	NA	29	25	17	NA	NA

*1 acrylic polymer dispersion, *2 polymer modified cement grout, *3 strength, *4 no data available
All the properties here were the reference values from the tests by the suppliers at 7 days of age.

Table 5. Results of flexural bond strength tests (at 8 days of binder age)

test case	flexural bond strength (MPa)			observed failure mode
	jointed one	concrete 1	concrete 2	
AE1	2.43	5.93	4.07	interface failure between concrete 2 and epoxy adhesive (**Fig. 3** (a))
AE2	1.81			
AE3	2.65			
AA	2.36			interface failure between concretes
AN	2.27			
BE1	6.98	6.09		concrete and epoxy failure (**Fig. 3** (b))
BE2	6.78			concrete failure (**Fig. 3** (c))
BG	2.40			interface failure between concrete and grout

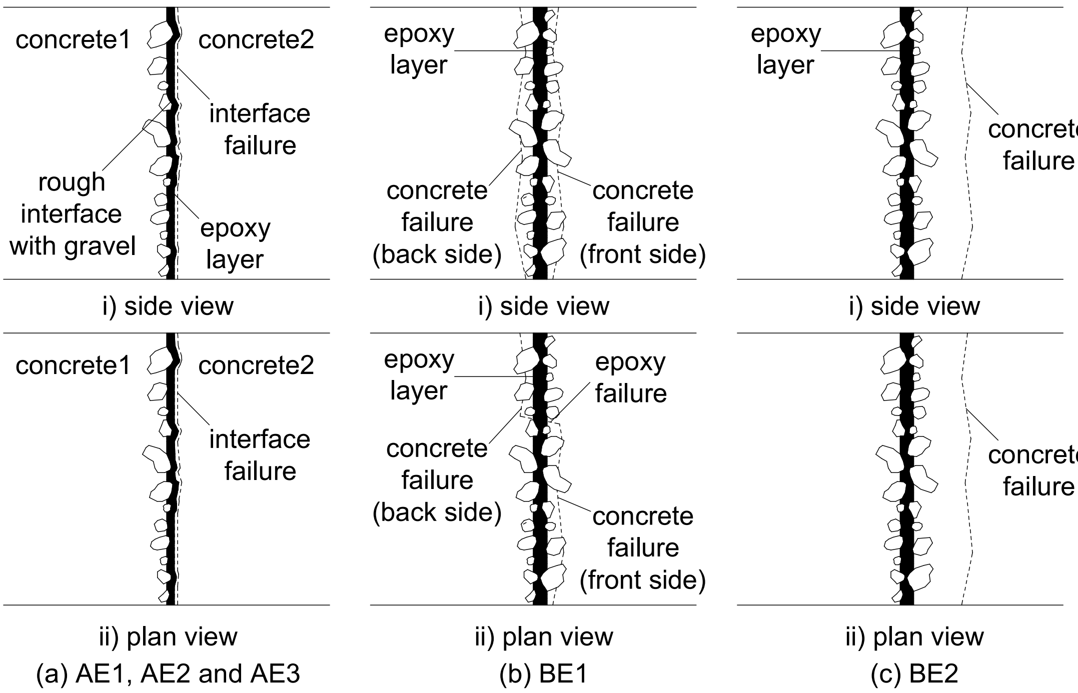

Figure 3. Schematic illustration of notable failure modes

For Type A joint, which is the test cases where the initial letter starts with A, no remarkable difference in the flexural bond strength could be seen. Considering that the strength results from two factors, which are the chemical adhesion of the material and the mechanical locking due to the surface roughness, the followings can be said:

(1) Since the surface preparation was carried out by using the concrete retarder that was cleanly washed out about 2 to 3 mm in depth, the surface roughness and cleanness were in good conditions so that the strength of the joint without any binder (AN) was relatively high. The strength was 2.27 MPa that corresponded to 56% of M, concrete monolithically placed (4.07MPa).

(2) The result of AA with the acrylic polymer dispersion was not different from AN. The purpose of applying the dispersion was to reduce water absorption at the interface as a primer but no remarkable effect was confirmed in this study.

(3) The epoxy resin adhesive types 1 and 3 (AE1 and AE3) slightly improved the strength and type 2 (AE2) seemed ineffective when compared to AN. Based on the observed failure mode, it can be assumed for the reasons that the surface roughness for freshly-mixed concrete decreased due to the application of the epoxy adhesive (**Fig. 3** (a)) and the mechanical locking became less effective although the chemical adhesion itself increased. As a result, the flexural bond strength did not change so much against AN.

For Type B joint, which is the test cases where the initial letter starts with B, the strengths of BE1 and BE2, with the epoxy adhesive types 4 and 5, were higher than M, and the strength of BG was close to AN. The failure of BG occurred at the interface between the concrete and the grout and that was similar failure as AN; thus, the strength was also close to it. Focusing on BE1 and BE2, the strengths were similar but the failure modes were different. Cracks occurred in concrete and no interface failure was observed in both cases. The crack in BE1 was close to the interface and the epoxy resin was vertically ruptured whereas the crack in BE2 was apart from the interface and any damage around the interface was not confirmed as shown in **Figs. 3** (b) and (c). For the possible reason of the difference, the stiffness of the epoxy resin should be considered. The elastic modulus of the epoxy type 4 used for BE1 was 4910 MPa and it was nearly twice of the epoxy type 5 used for BE2, 2450 MPa. It was possible that the higher the elastic modulus of the epoxy resin was, the more the stress concentrated around the interface. To understand the flexural behavior in detail especially for tension softening, the fracture energy tests including BE1 and BE2 were decided to be conducted.

FRACTURE ENRGY TEST

Test and Analysis Overview. The fracture energy tests were carried out in order to obtain more detailed information regarding tension softening. The test specimen was a notched beam with the overall dimensions of 100 x 100 x 400 mm and tested by center-point loading in accordance with JCI-S-001-2003 (Japan Concrete Institute (JCI), 2003) as shown in **Fig. 4**. The joint types of AE1, AN, BE1, BE2 and M shown in **Table 1** were selected as the test cases. Note that four test specimens for each joint type were prepared for the fracture energy tests. The fracture energy can be calculated by the area of the load-crack mouth opening displacement (hereinafter "CMOD") curve and the CMOD was measured up to 2 mm by a clip-type displacement transducer. The CMOD control loading was carried out with the displacement transducer. The test setup is shown in **Photo 1**. The tension softening curve was estimated by the multi-linear approximation analysis and the computer program based on finite element analysis available at JCI's website (http://www.jci-net.or.jp) was used for it (Kurihara, 1996). In the analysis, a discrete crack that was supposed to include all the effects of concrete, epoxy adhesive and their interface was modelled at the mid-span and the other elements for concrete were assumed to be uniform and elastic material because it would be difficult to exactly model the interface behavior in micro level (Kunieda 2001).

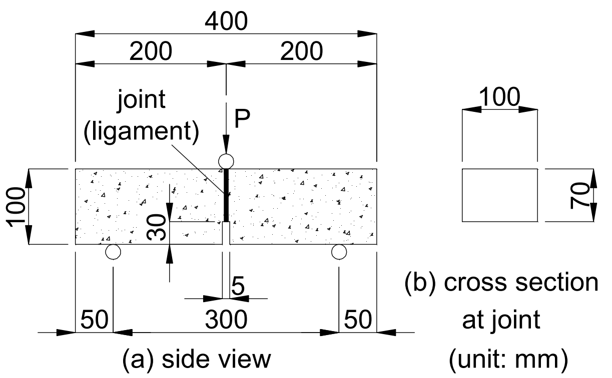

Figure 4. Fracture energy test

Photo 1. Test setup

Materials. The same concrete mixture proportion and the epoxy adhesives as the flexural bond test were used. The compressive strength, elastic modulus, splitting tensile strength, and flexural tensile strength of the lately placed concrete at testing day were 56.5 MPa, 38.1 GPa, 4.32 MPa, and 5.06 MPa, respectively. The material ages of the epoxy adhesives at testing were 8 days for AE1 and 15 days for BE1 and BE2.

Test Results. The load-CMOD relationships for each case and the comparison of the averages from all the cases were shown in **Fig. 5**, where the unstable results obtained were eliminated and as a result, there is no case having four results. The average line was calculated and smoothed by focusing on the loads at the same CMOD. Table 6 shows the summary of the averaged results including the fracture energy up to 2 mm of CMOD.

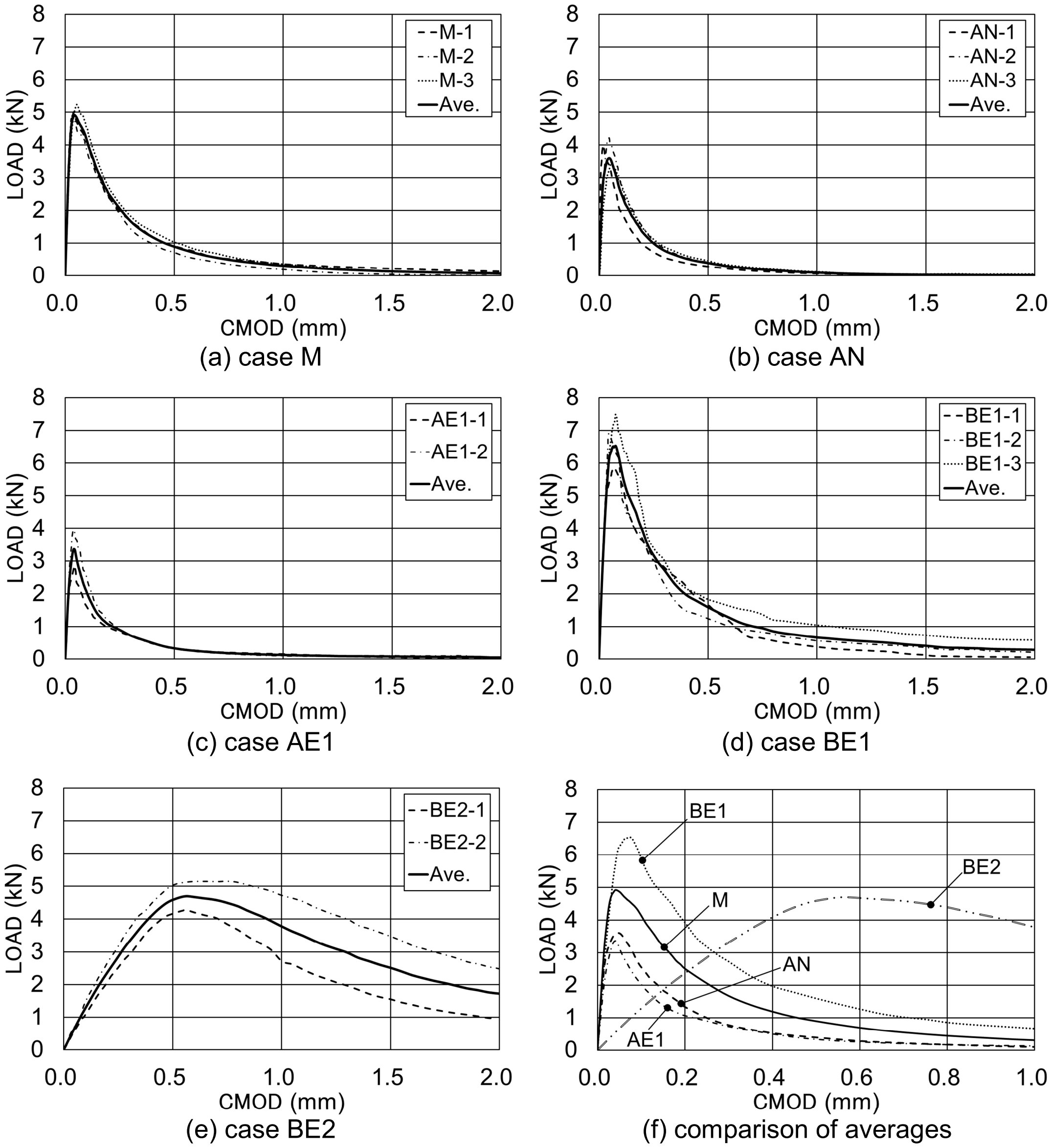

Figure 5. Load-CMOD relationships

Table 6. Summary of averaged results

case	fracture energy at CMOD 2 mm (N/mm)	maximum load (N)	CMOD at max. load (mm)	load at CMOD 2mm (N)	flexural bond strength*1 (MPa)
M	0.182 (1.00)*2	4912 (1.00)	0.040	44	4.43
AN	0.095 (0.52)	3605 (0.73)	0.048	16	2.87
AE1	0.090 (0.49)	3361 (0.68)	0.040	13	2.81
BE1	0.289 (1.59)	6533 (1.33)	0.076	285	5.72
BE2	0.644 (3.54)	4697 (0.96)	0.560	1722	4.17

*1 The flexural bond strength was simply calculated by dividing the bending moment due to the maximum load by sectional modulus of the joint for reference.

*2 The values in parenthesis indicate the ratio to case M.

As shown in **Fig. 5** (f) and **Table 6**, the results of cases AN without adhesive and AE1 with epoxy resin type 1 were similar, which corresponded to the flexural bond test results. The load-CMOD curves for AN and AE1 were in the envelope of case M as expected. On the other hand, the remarkable difference can be seen in the results of cases M, BE1 with epoxy resin type 4 and BE2 with epoxy resin type 5. The initial stiffness of BE1 was close to M, but the maximum load of BE1 was 33% higher. The post peak gradients of M and BE1 were similar and consequently, the fracture energy of BE1 was 59% higher than that of M and the load at 2 mm of CMOD for BE1 was also higher. That means BE1 did not reach its failure at 2 mm of CMOD and strictly speaking, the actual fracture energy should be higher. Note that the fracture energy was defined to be the energy consumed by 2 mm of CMOD for the purpose of comparison in this study. Focusing on BE2, the initial stiffness and post peak gradient were gradual and the CMOD at the maximum load and the load at 2 mm of CMOD were much larger than M or BE1. The low elastic modulus of the epoxy resin used for BE2 could be one of the possible reasons. However, the elastic modulus is just a half of the epoxy resin used for BE1; thus, there should be another factor especially for the post peak behavior and it will be discussed in the following section.

Tension softening. The analytical results for the tension softening curve with the averaged load-CMOD relationship were shown in **Fig. 6**, where case M is compared with the design curves calculated according to Standard Specifications for Concrete Structures (Japan Society of Civil Engineers (JSCE), 2007) and Model Code 2010 Final Draft (fib, 2012) to check the validity of the analytical result. As shown in **Fig. 6** (a), the tension softening curve for M was similar to both design curves and fib Model Code seems more applicable for the concrete used in this study.

The tension softening curves for AN and AE1 were within the curve for M and this was thought to be reasonable based on the results mentioned earlier. For BE1 and BE2, the tensile stress did not decrease at the beginning whereas it immediately started decreasing for M. The tensile stress started decreasing at 0.02 mm and 0.10 mm of crack opening for BE1 and BE2, respectively. The ductility of the epoxy resin could be considered for the reason. In the analysis, a discrete crack was modelled and it was the unique factor that could represent inelastic behavior. Therefore, the opening of the discrete crack should include the inelastic displacement of the epoxy resin or the micro level interface failure, if any. Assuming that the epoxy resin showed inelastic elongation without stress decrease immediately after reaching its maximum tensile stress in the physical test, these results shown in **Fig. 6** (b) should be obtained. It could be said for the reason of the difference in BE1 and BE2 that the epoxy resin for BE2 was softer and much more ductile compared to

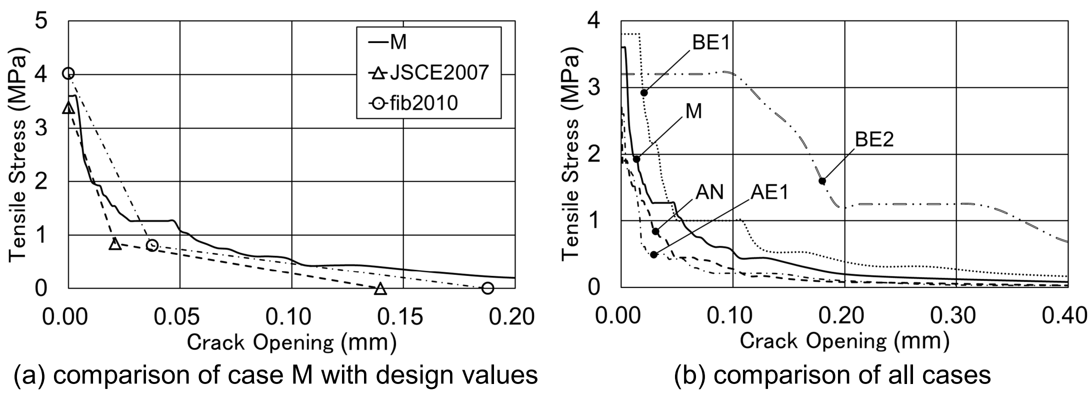

Figure 6. Tension softening curve

BE1. Thus, the difference in the load-CMOD relationship shown in **Fig. 5** (f) was caused. However, it is necessary to conduct a test regarding the ductility of the epoxy resin itself in order to verify these conclusions.

CONCLUSIONS

The following conclusions are obtained based on the experimental and analytical results.
(1) The acrylic polymer dispersion for the hardened-to-fleshly-mixed concrete joint and the polymer modified cement grout for the hardened-to-hardened concrete joint were not effective to increase the flexural bond strength in the scope of this study.
(2) The epoxy resin adhesive was also not effective to improve the flexural bond strength at the hardened-to-fleshly-mixed concrete joint in case the joint surface was intentionally roughened by the use of concrete retarder. For the reason, it was estimated that applying epoxy adhesive increased the chemical adhesion but decreased the mechanical locking effect and as a result, the effect could not be confirmed.
(3) The epoxy adhesive increased the flexural bond strength and the fracture energy of the hardened-to-hardened concrete joint. Since the fracture energy increased, the joint with the epoxy adhesive can absorb more energy and the load carrying capacity was even better than the concrete placed monolithically.
(4) Tension softening curve for the hardened-to-hardened concrete joint with the epoxy adhesive was affected by the elastic modulus and the ductility of the epoxy resin. In this study, two types of epoxy adhesive were used for the joint. One of them showed similar and better behavior as the concrete placed monolithically. The other one showed much more ductile behavior and consequently, the fracture energy was higher.

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