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Flexural Failure Behavior of Concrete Beams Repaired by Crack Injection Techniques

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ABSTRACT: This paper presents an experimental work for evaluating the flexural failure behavior of a concrete beam repaired by crack injection techniques. Not only flexural strength but also tension softening diagrams and fracture energy were used for the indices. In addition, a size effect on the flexural strength of the repaired specimens, which is larger than that of original concrete (plain concrete), is observed experimentally. Then the importance of evaluating the cracks in repaired specimens is indicated.

1 INTRODUCTION

Crack injection is a common technique for repairing damaged concrete materials and structures. To evaluate the performance of repaired structures on a life-cycle cost basis, methods for testing and analyzing repair schemes are necessary. Especially, the specimen type, size and boundary conditions in the testing, which affect the test results, should be selected appropriately.

Epoxy is one of the common materials for crack injection methods. The bond strength test of epoxy, which is one of the important performances, is specified in the Japanese Industrial Standard (JIS A 6024: Epoxy injection adhesives for repairing in buildings). The testing method involves a smaller size specimen($40 \times 40 \times 160$mm) compared with existing structures, a specimen made of a mortar, and smooth surface for injection. These testing conditions are useful to carry out the test easily for material users. To evaluate the properties of injected repair materials in existing concrete structures, the testing conditions that reflect the practical conditions in concrete structures, such as size, damage and so forth, should be adopted in the testing method. For example, the crack surface of concrete, which has roughness due to coarse aggregate, should be used for evaluating the bond properties between concrete and repair materials in crack injection techniques.

There are many indices for evaluating the results in testing or analysis. In general, bond strength, which is calculated by using the maximum load in the test, is one of the important indices. However, important properties include not only bond strength at the interface between the concrete and injection material, but also on the fracture properties of the adjacent bulk concrete and the injection material itself.

Kleinschrodt (1989) showed that the flexural strength and fracture energy of the repaired specimens, in which an epoxy was injected into the cracks, became larger than that of the original concrete specimen. Kitsutaka (1992) also applied fracture energy to evaluate the flexural failure behavior of the repaired beams, in which the effects of Young's modulus of injection materials and crack width were investigated.

This paper presents experimental work for evaluating flexural failure behavior of concrete beams repaired by crack injection techniques. Not only flexural strength but also tension softening diagrams and fracture energy were used for the indices. In addition, the size effect on the flexural strength of the repaired specimens is confirmed experimentally.

2 OUTLINE OF EXPERIMENT

2.1 *Test setup for initial loading*

Experimental programs are shown in Figure 1. Mix proportions of concrete are shown in Table 1. The water to cement ratio of the concrete was 0.50. The maximum size of coarse aggregate was 15mm.

Four specimens were tested, each having a depth of 100 (size 1), 200 (size 2) and 300 (size 3) mm. Each specimen has a notch extending over one-third of this depth. For the size 1 specimen, a notch was made by a concrete cutter before the loading test. For the size 2 and size 3 specimens, a plate having a thickness of 3.0mm was embedded at the initial setting of concrete. The original concrete specimens (original specimens) were tested at the concrete

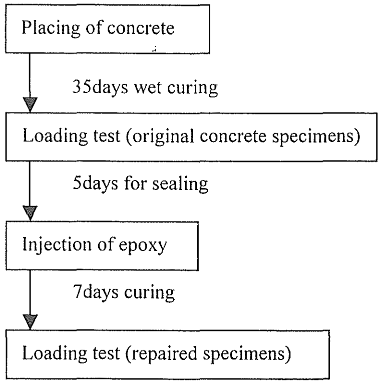


Figure 1. Experimental programs

Table 1. Mix proportions of concrete

W/C	Unit content				
(%)	Water (kg/m^3)	Cement (kg/m^3)	Fine agg. (kg/m^3)	Coarse agg. * (kg/m^3)	Admix-ture ** (kg/m^3)
55.6	161	290	836	1001	0.725

* Maximum size: 15mm

** AE water reducing agent

age of 35 days. As shown in Figure 2, four-point bending tests were carried out, and load versus crack mouth opening displacement (CMOD) under displacement control of the loading apparatus was measured in these tests.

2.2 *Crack injection repair*

After fracturing the original specimens through their ligament length, each specimen half was carefully positioned and joined through epoxy injection so that the epoxy material width (simulated crack width) was about 3mm, as shown in Figure 3. The crack region was sealed to prevent leakage of the epoxy during pressure injection. As shown in Table 2, the type of epoxy used exhibits no shrinkage, has a Young's modulus of 2.0 GPa, and has a flexural bond strength of 7.5 MPa, in accordance with the Japanese Industrial Standard. After curing the epoxy for 7 days, the same type of four-point bending tests was carried out, as shown in Figure 4. Further research is needed to evaluate the relationship between the direction of injection and loading.

2.3 *Determination of tension softening diagrams*

A crack might propagate in repair material, bulk concrete, or interface between the repair material and concrete. However, the only one crack that is not a

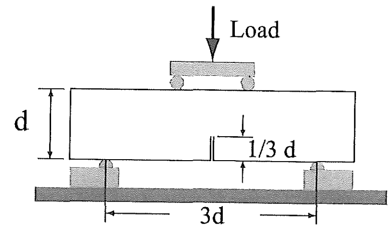


Figure 2. Test setup for original concrete specimens

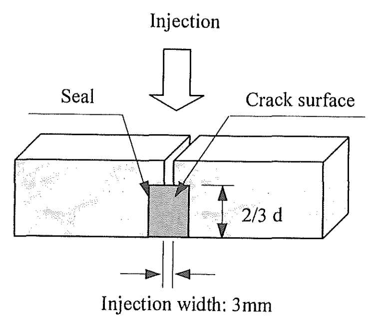


Figure 3. Injection of epoxy

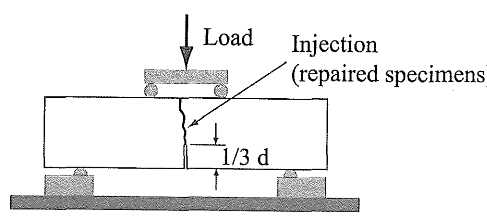


Figure 4. Test setup for repaired specimens

Table 2. Properties of epoxy*

Working time (min.)	50-60
Curing time (hr.)	15
Shrinkage (%)	0.0
Elastic modulus (GPa)	2.5
Bond strength (MPa)	7.5

* Extracted from catalogue

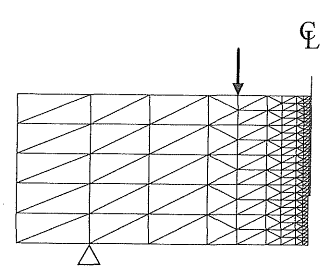


Figure 5. Finite element for inverse analysis

Table 3. Test results

	Original specimens		Repaired specimens		Strength ratio	Fracture energy ratio	Number of specimens
	Flexural strength * (MPa)	Fracture energy $G_f0.01$ (N/m)	Flexural strength * (MPa)	Fracture energy $G_f0.01$ (N/m)			
Size1 (d=10cm)	3.03 (0.17)	18.6	3.84 (0.30)	26.2	1.27	1.41	4
Size2 (d=20cm)	2.60 (0.23)	16.0	3.14 (0.12)	21.7	1.21	1.35	4
Size3 (d=30cm)	2.13 (0.05)	14.6	2.39 (0.10)	16.7	1.12	1.14	4

* Standard deviation is shown in parentheses

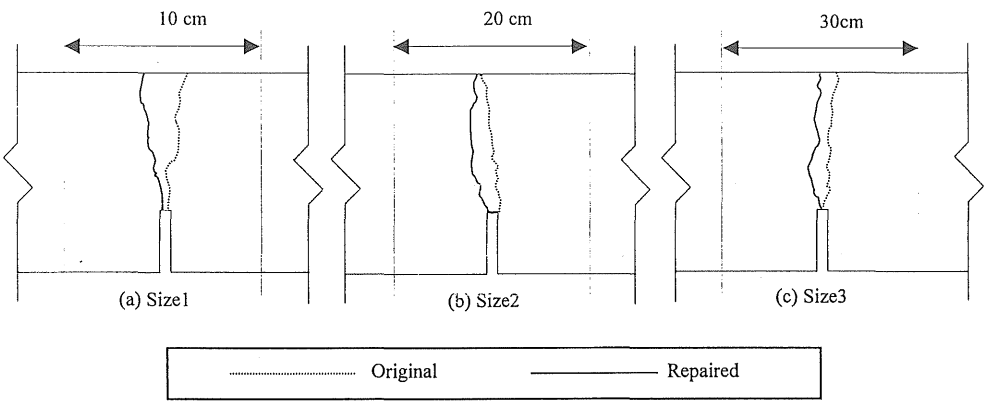


Figure 6. Crack patterns in each specimen

micro crack but a macro (main) one occurs in the repaired specimens. In this study, it was assumed that the main crack consumed all energy represented by the load-displacement relationship. And a tension softening diagram was determined from the average load-CMOD curve through inverse analyses based on a poly-linear approximation method (Uchida et al. 1995). This method is based on the finite element method with a fictitious crack model (Hillerborg et al. 1976). The finite element for this inverse analysis is shown in Figure 5.

3 TEST RESULTS

3.1 *Compressive strength and Young's modulus*

Compressive strength and Young's modulus of the concrete at the age of 47 days, which are measured by using cylindrical specimens measuring ϕ 100 × 200mm, are 30.9MPa and 25.8GPa, respectively.

3.2 *Flexural strength and cracking behavior*

Test results of original and repaired specimens are shown in Table 3. The ratio of the flexural strength

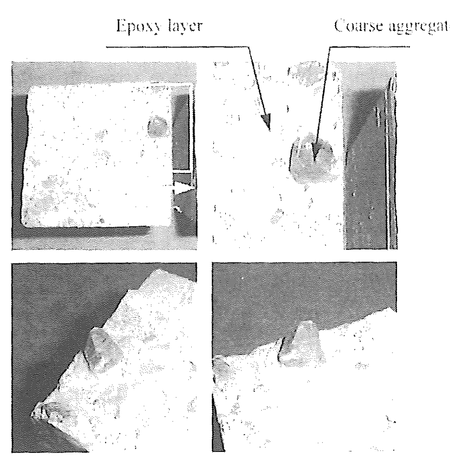
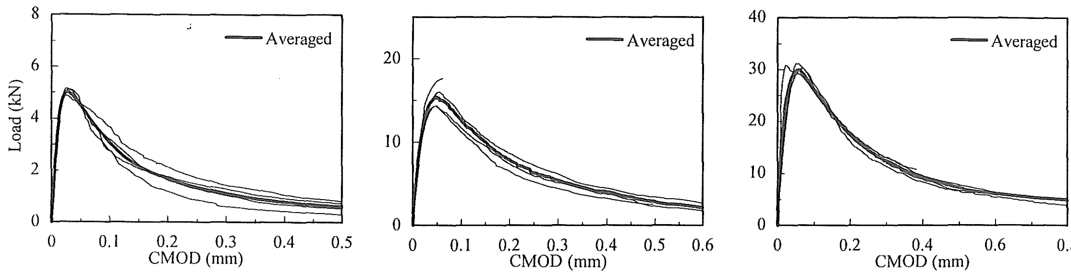


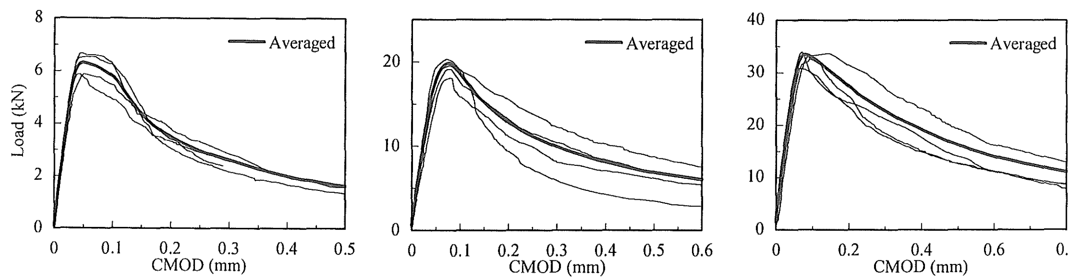
Figure 7. Coarse aggregate as obstacle

of the original specimen to that of the repaired one, which is the strength ratio, is also shown in Table 3. In all cases, the flexural strength of repaired specimens exceeded that of original specimens. And the effect of damaged concrete due to micro cracks



(a) Size 1 (b) Size 2 (c) Size 3

Figure 8. Load-CMOD curves of original concrete specimens



(a) Size 1 (b) Size 2 (c) Size 3

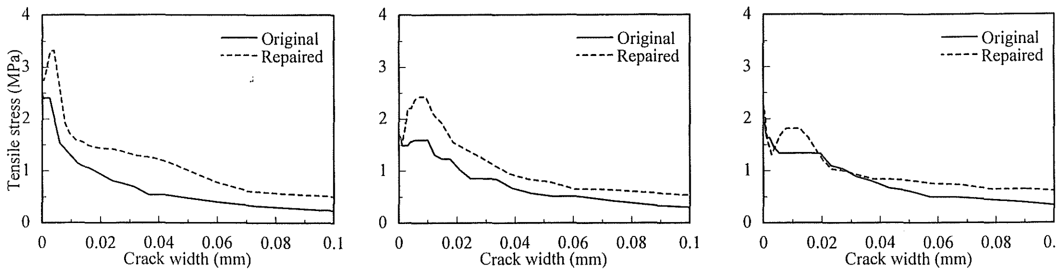
Figure 9. Load-CMOD curves of repaired specimens

(FPZ) in initial loading on the flexural failure behavior of repaired specimens was not observed. For larger specimen sizes, however, the strength ratio became smaller.

Figure 6 shows typical crack patterns seen in these specimens. For ordinary concrete, the relationship between the geometry of cracks and fracture behavior was investigated (Mihashi et al. 1995, Carpinteri et al. 1997, Kamada et al. 1998). In the case of the repaired specimens, cracking behavior depends on the material properties local to the crack such as strengths of the mortar matrix and aggregate, aggregate size, bond properties between epoxy and aggregate and so forth. Figure 7 shows a coarse aggregate that was located between the new fracture surface and previous fracture surface bonded to the epoxy. For the original specimen, a crack propagated from the notch tip. In this crack surface that is an injection surface, broken or unbroken coarse aggregate is in contact with the injected epoxy. Usually the epoxy has a good bonding with the aggregate. Then cracks propagating in the repaired specimens tend to detour away from the repaired (injected) cracks and are also affected by the aggregate size. This cracking behavior imparted higher flexural strength to the repaired specimen. And this behavior also accounts for the larger consumed energy. With the increase of the specimen size, the crack patterns in repaired specimens tended to be similar with those in original specimens, in which the roughness of the crack surface in larger repaired specimens was smoother than that of smaller ones relatively. Then the strength ratio with larger specimen size became smaller.

3.3 *Tension softening diagrams and fracture energy*

The measured load-CMOD curves for the original and repaired specimens are shown in Figure 8 and Figure 9, respectively. And the determined tension softening diagrams of the original specimen and repaired one in each specimen size are also presented in Figure 10. The maximum load and toughness of the repaired specimens are larger than those of the original specimens. The fracture energy up to a crack width of 0.01mm, which reflects resistance of crack propagation and affects the maximum load, is shown in Table 3. This fracture energy of repaired specimens was larger than that in original specimens. In addition, the resistance of crack propagation in smaller repaired specimens, which is represented by means of the fracture energy, was higher than that of larger repaired specimens.



(a) Size 1 (b) Size 2 (c) Size 3

Figure 10. Determined tension softening diagrams

3.4 *Size effect on flexural strength*

The flexural strength of original specimens in each specimen size, as well as those of repaired specimens, are shown in Figure 11. In addition, the analytical results through the finite element method by using the tension softening diagram in size 1 specimen are also presented in Figure 11. Both experimental and analytical results show the size effect. The analytical results of original specimens agreed with the experimental one.

Most papers present the effects of restoration by using smaller repaired specimens. As the specimen size becomes larger, the flexural strength of repaired specimens in the experiment, which is higher than that of original specimens in smaller specimen sizes, approached that of the original specimens. It was observed that effect on flexural strength of repaired specimens was larger than that of original ones. In the test for evaluating the performance of repair methods, in which smaller specimens are used, the crack pattern should be observed carefully, and size effect should be considered appropriately.

4 CONCLUSIONS

In these tests, the following results were obtained:

- The flexural strength and fracture energy of repaired specimens, in which the cracks were injected with the epoxy, were larger than those of the original specimens used for the same tests. The size effect on the flexural strength of repaired specimen was observed, and was larger than that of original one; the complex cracking behavior in the repaired specimens accounts for the larger size effect on flexural strength.
- Tension softening diagrams and fracture energy were effective indices for evaluating the flexural failure behavior of the repaired specimens.
- The effect of damaged concrete due to micro cracks (FPZ) in initial loading on the flexural failure behavior of repaired specimen was not observed.

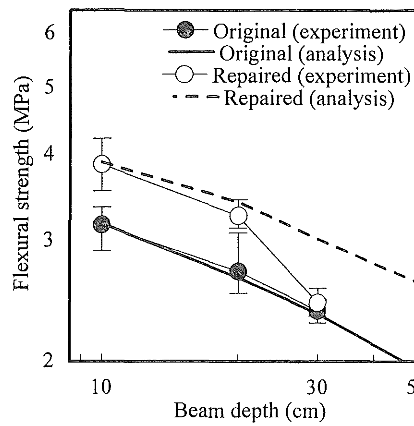


Figure 11. Size effect on flexural strength of original and repaired specimens

The bond property at the interface between repair material and bulk concrete is a fundamental performance for repair. Especially, most paper discussed the importance of the bond properties due to delamination of repair materials. This paper also indicated the importance of evaluating the cracks of the adjacent bulk concrete.

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