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RESISTANCE OF FLEXURAL REINFORCED CONCRETE MEMBERS AFTER REPAIR WITH EPOXY RESIN

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SUMMARY

A series of specimens were tested to investigate the mechanism of the increase in flexural resistance of epoxy repaired reinforced concrete members. Epoxy injection and epoxy mortar filling methods were applied to repair the damaged reinforced concrete specimens in flexure. Contribution of the strain hardening and strain aging of steel, the tensile or compressive reinforcement by epoxy resin and the change in the location of the neutral axis of the critical section, to the increase in resistance after repair, was discussed.

INTRODUCTION

Damage investigations after recent large earthquakes in Japan reported that approximately 10 percent of reinforced concrete buildings, on the average, suffered intermediate to severe damage in the severely shaken areas and required some repair work, strengthening or demolition (Ref.1). The Building Standard Law and accompanying Law Enforcement Order in Japan, revised in 1981, emphasizes the importance of ductility of a structure. 'Ductility' implies that a structure deforms well into an inelastic range. Hence, some repair work will be required if the structure performs as designed during a strong earthquake motion. The most popular repair work both in research and practice of this country is the application of epoxy resin because of its strong material properties and easy handling. Reinforced concrete members, failed in flexure and repaired with epoxy resin, are observed to develop flexural yield strength higher than the virgin specimens. The reason of this increase should be clarified in order to evaluate the strength and ductility of repaired members for the earthquake resistance.

FLEXURAL RESISTANCE OF SECTION AFTER REPAIR

Consider flexural resistance of a critical section of a reinforced concrete beam under pure bending moment without axial load. At flexural yielding, the yield moment M_y is expressed as i.e.,

$$M_y = a_t \cdot f_y \cdot j \tag{1}$$

where, a_t = area of tensile reinforcement, f_y = yield stress of tensile reinforcement, and j = distance between tensile and compressive resultants.

Equation (1) is expressed in differential form;

$$dM_y = da_t.f_y.j + a_t.df_y.j + a_t.f_y.dj \tag{2}$$

The first term in Eq.(2) represents the contribution of increase in effective area of tensile reinforcement. The epoxy resin and epoxy mortar with high tensile strength (Fig.1), penetrating around reinforcing steel or replacing crushed or spalled concrete by repair work, can carry tensile stress effectively. Thus, the contribution of the epoxy resin and epoxy mortar may be included in the increase in effective area of tensile reinforcement. The second term in Eq.(2) represents the contribution of increased yield stress of the tensile reinforcement. The increase in yield stress after repair may be developed by (a) the strain hardening of steel through large inelastic deformation during the previous loading, and (b) the strain aging at reloading a couple month after the repair. The strain aging is a fundamental property of mild steel to develop a higher yield point and plateau when reloaded after scores of days from a virgin monotonic test; i.e., point A of reloading curve in Fig.2 is appreciably higher than point B of the previous unloading point in the virgin test. The third term in Eq.(2) represents the contribution of the change in the location of the compressive and tensile resultant forces. The third term may or may not increase the flexural resistance because the distance between the two resultants may decrease after repair. It should be investigated to identify which of the three terms in Eq.(2) gives a dominant contribution to the increase in flexural resistance by epoxy repair.

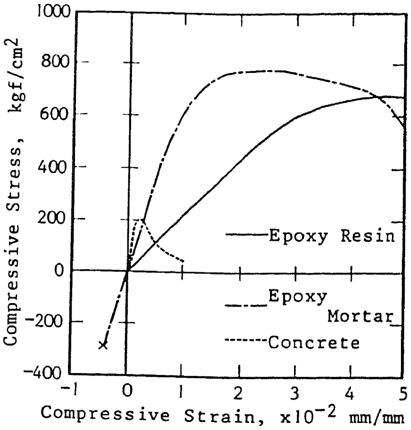

Fig.1 Stress-Strain Curve of Epoxy Resin and Epoxy Mortar

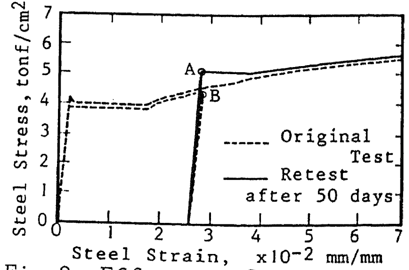

Fig.2 Effect of Strain Aging on Steel Stress-Strain Relation (SD30, D16)

EXPERIMENTAL STUDIES

Repair Method Two methods were used to repair damaged reinforced concrete beam members in flexure; i.e., (a) epoxy injection method and (b) epoxy mortar filling method. In the epoxy injection method, low viscous epoxy resin was slowly injected into a crack under continuous low pressure. The epoxy resin was observed to penetrate into a crack and along the longitudinal reinforcement recovering the bond between concrete and reinforcement. The epoxy mortar filling method was used to replace crushed or spalled concrete by epoxy mortar, which was epoxy resin mixed with very fine aggregates. The epoxy mortar was able to stick onto the concrete or steel surface and be formed into any shape to restore the lost concrete. Mechanical properties of epoxy resin and mortar are shown in Fig.1. The tensile strength of epoxy resin and epoxy mortar was 340 kgf/cm^2 and 290 kgf/cm^2, respectively.

Test Series Three series A, B and C of tests were conducted to investigate the mechanism of the increase in resistance after repair. Cross sections of the specimens and loading method in each test were illustrated in Fig.3 and in Fig.4, respectively. Test series A and B employed monotonically loading, and test series C was conducted under positive and negative cyclic loading. The objective of test series A was to identify the cause of increase in resistance after repair by the epoxy injection method. Three half-scale specimens A1, A2 and A3 were tested. Two specimens A2 and A3 were specifically designed for the longitudinal reinforcement to yield at the same critical sections before and after repair work by reducing

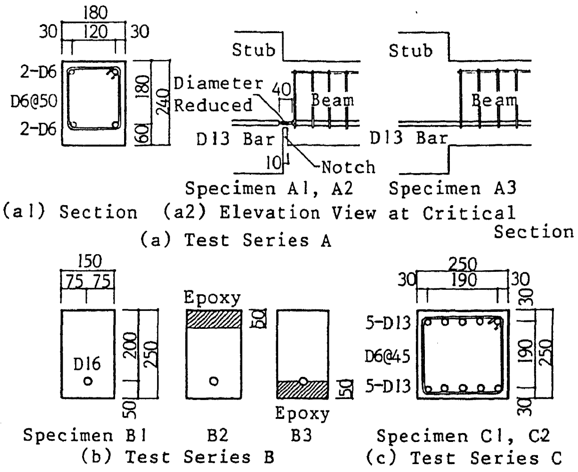

Fig.3 Cross Section of Specimens (Unit,mm)

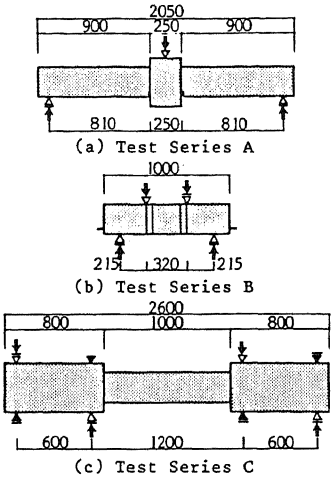

Fig.4 Loading Procedure

the diameter of longitudinal reinforcement at critical section so that the effect of the strain aging could be observed in the test. Specimens A2 and A3 were repaired after virgin testing, while specimen A1 was left without repair in order to reveal the effect of the strain aging. Test series B was carried out to investigate the contribution of epoxy in the epoxy mortar filling repair method to the resistance under uniform bending moment. In test series C, the increase in yield resistance after repair was studied under reversal loading. Material properties in each series of tests are listed in Table 1.

Table 1 Material Properties in Each Series of Test

	Test series	A	B	C
Concrete	Compressive Strength Fc (kgf/cm2)	180	314	359
	Splitting Tensile Strength (kgf/cm2)	15	25	33
Longitudinal Reinforcement	Yield Stress (tonf/cm2)	4.68	3.90	4.68
	Yield Strain (mm/mm)	0.0022	0.0018	0.0022
	Strain at Strain Hardening (mm/mm)	0.0220	0.0177	0.0220
	Tensile Strength (tonf/cm2)	5.76	-	5.76

STRAIN HARDENING AND STRAIN AGING

The behavior of specimens A1 and A2 is carefully compared to study the effects of the strain hardening and the strain aging on the increase in resistance by repair. The load-deflection relationship is shown in Fig.5, in which dashed lines and solid lines represent the relations observed in the tests before repair (called tests A1 and A2) and after repair (called tests RA1 and RA2), respectively. The relations of tests RA1 and RA2 were plotted from residual points of corresponding tests A1 and A2. Solid circles in Fig.5 represent "yield points" where the stiffness changed suddenly during loading. The yield resistance during tests RA1 and RA2 was higher than the yield resistance during the corresponding virgin tests A1 and A2 attributable to strain hardening. Furthermore, the yield resistance of both specimens RA1 and RA2 was even higher than the maximum resistance observed at the unloading point during the corresponding virgin

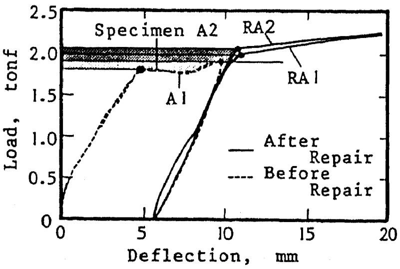

Fig.5 Load-Deflection Relationship

tests. The increase in specimen A1 must be attributable to the strain aging because the specimen was not repaired. The load was plotted in Fig.6 with respect to the strain in the longitudinal reinforcement at critical section. Note that the resistance is closely associated with the stress in the longitudinal reinforcement. The increase in yield resistance after repair from the maximum resistance before repair was 3 percent in specimen A1 and 4 to 8 percent (different on the two sides of the column stab) in specimen A2; the average increase rate of about 5 percent coincided with the increase rate by the strain aging in the material tests. The contribution of injected epoxy resin to the yield resistance was judged minor.

The location of resultant compressive force was calculated from observed strain distribution in compressive zone at critical region (Fig. 7). The height of compressive resultant force at yielding was found to change little in specimen A2 before and after repair. The effect of change in distance between compressive and tensile resultants was judged to be insignificant. Therefore, the yielding resistance of a repaired flexural member increased, provided that the same section yields before and after repair, caused by the increase in the yield resistance of longitudinal steel by the strain hardening and the strain aging.

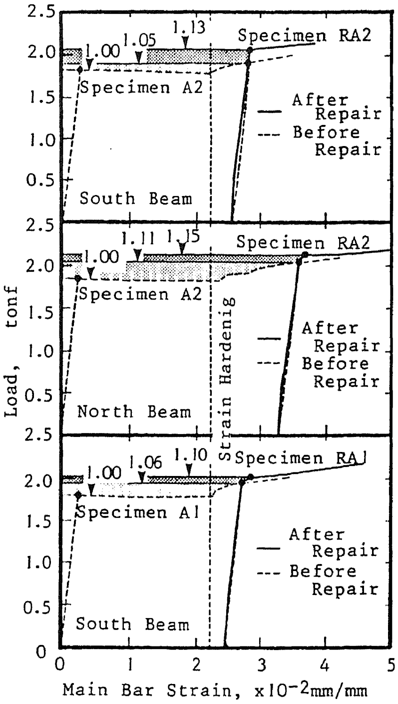

Fig.6 Load-Main Bar Strain Relationship

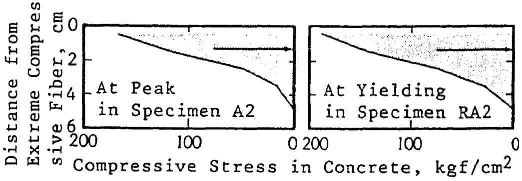

Fig.7 Compressive Stress Distribution and Location of the Resultant

Specimen A3 was fabricated with normal reinforcement without reducing the diameter of longitudinal reinforcement at critical section. The yield resistance of this specimen after repair was almost equal to the load at the unloading point in the virgin test. Crack patterns and strain distribution along the longitudinal reinforcement immediately before unloading in the virgin test and at the yielding after repair is shown in Fig.8. The resistance before repair was controlled by the bending resistance at the critical section, while the yielding after repair probably took place near one of new cracks outside of the critical section. The shift in the location of yielding can be explained by the increase in steel resistance at the previously yielded localities due to "strain aging", and no increase at previously elastic localities. In order to develop an increased resistance of a member after repair under monotonic loading, the same localities of the longitudinal reinforcement must yield before and after repair.

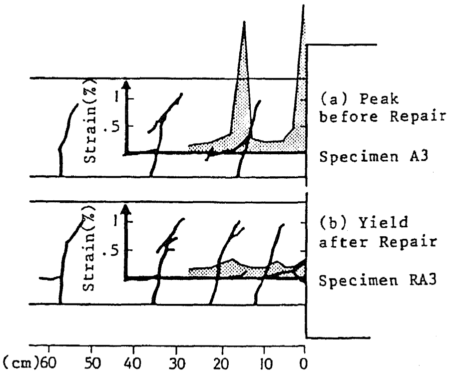

Fig.8 Crack Patterns and Strain Distribution of Main Bar

The resistance was also observed to increase under reversal loading. Load-deflection relation obtained from test series C (specimen C2 and RC2)is shown in Fig.9. The stiffness and resistance deteriorated due to bond split failure before repair, but the behavior was reasonable after repair because the epoxy was effective to improve bond around deformed bar reinforcement (Ref.2). The resistance after yielding of repaired specimen was significantly higher than the maximum resistance before repair. Though crystalline mechanisms of the strain aging under monotonic loading were explained by the dislocation theory, the strain aging of the steel under load reversals has not been clarified. The characteristics of the strain aging was studied using D13(SD35) bars, used in test series C. The effect of strain aging was not observed under tensile and compressive inelastic stress reversals. However, the resistance of repaired specimen was significantly higher than the maximum resistance of the corresponding virgin test. The resistance before and after repair was plotted with respect to the longitudinal reinforcement strain at the critical section in Fig.10. In the same figure, the stress-strain relationship under monotonic loading of a D13(SD35) bar is plotted after the steel stress was normalized to the yielding load of specimen C2. The load of specimen C2 did not increase as much as the steel stress increased due to strain hardening during the virgin test probably because the bond deterioration shifted the location of the neutral axis. But, after repair, the member resistance above yielding agreed favorably with the normalized steel stress in the strain hardening. Therefore, under reversal loading, the significant enhancement of resistance after repair must be associated with the strain hardening in the longitudinal reinforcement.

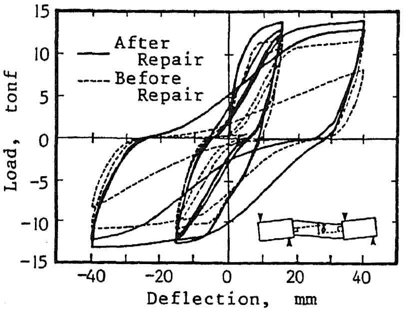

Fig.9 Restoring Force Characteristics

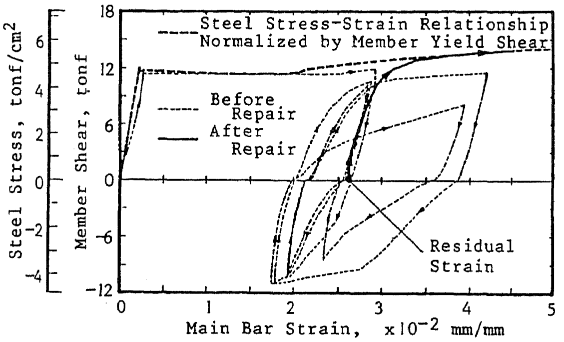

Fig.10 Effect of Steel Stress on Member Resistance

TENSILE RESISTANCE OF EPOXY

In test series B, specimen B3 was prepared to simulate the repaired condition by placing the epoxy mortar over one-fifth of the section from the bottom to investigate the tensile resistance of epoxy mortar fiber. Crack patterns after test is shown in Fig.11. Although this specimen failed abruptly in shear outside the mid-span test region, the resisting moment at failure exceeded the yield moment observed in specimen B1 with no epoxy mortar layer. The longitudinal strain at the bottom of the epoxy mortar layer reached 0.0014 at the maximum resistance. This value was considerably smaller than the strain of 0.0039 at tensile fracture of epoxy mortar. The section was analyzed using the flexural theory and observed material properties to estimate the stiffness and resistance of specimen B3 up to tensile fracture of the epoxy resin at the bottom. The observed and calculated moment-curvature relations are compared in Fig.12. The calculated curve agrees favorably with the

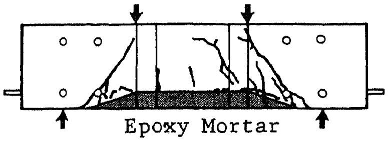

Fig.11 Crack Patterns of Specimen B3

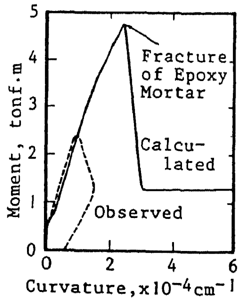

Fig.12 Observed and Calculated Moment-Curvature Relation

observed one. The calculated resistance continued to increase to reach twice the observed maximum resistance. Thus the epoxy mortar filling can carry a significant tensile force to increase the flexural resistance of the new repaired section.

LOCATION OF NEUTRAL AXIS

The change in resistance of specimen B2 by replacing the crushed concrete in compression zone by the epoxy layer was examined. The moment-curvature relation of specimen B2 is shown in Fig.13, in which a dashed line represents the relation of specimen B1 with no epoxy layer. Specimen B2 exhibited the stiffness before yielding and the resistance after yielding lower than specimen B1. The section was analyzed by assuming plane section remain plane, and by using the material characteristic obtained in the test. The calculated distance between the compressive and tensile resultants at a curvature was shorter in specimen B2 than that in specimen B1 (Fig.14). As the epoxy mortar was more flexible than the concrete, the distance between the resultants was closer and the location of the neutral axis lower. Therefore, the epoxy mortar to replace damaged concrete is not effective to recover the stiffness and resistance when it resists compressive stresses. However, this fact does not always mean that the epoxy mortar is not effective to recover the member ductility.

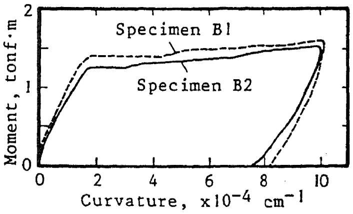

Fig.13 Observed Moment-Curvature Relation

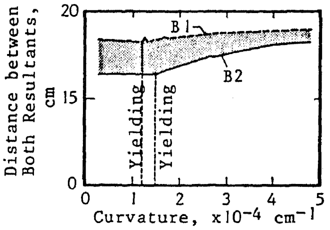

Fig.14 Distance between Compressive and Tensile Resultants

CONCLUSION

Resistance of reinforced concrete components repaired with the epoxy resin and the epoxy mortar was discussed. In case of flexural yielding in one direction, the yield resistance of the repaired section increased due to the strain aging of the longitudinal reinforcement. The epoxy mortar resists tensile stresses and also increases the flexural resistance. However, the increase in section resistance does not always increase the resistance of the member capacity because the adjacent weaker section may yield prior to the enhanced section. In case of cyclic reversal loading into an inelastic range, the resistance of repaired flexural member increases due to the strain hardening of longitudinal reinforcement, provided that the ability to carry compressive stresses is restored in the hinged zone.

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