論文

MITIGATION OF EARTHQUAKE DAMAGE OF RC STRUCTURES BY CONTROLLING BOND OF REINFORCEMENT

Govinda Raj PANDEY*1, Hiroshi MUTSUYOSHI*2, Kiyotaka SUGITA*3, Hiroki UCHIBORI*4

ABSTRACT: An experimental investigation was carried out to examine the enhancement of seismic performance of RC structures such as shear strength and ductility by controlling bond of longitudinal reinforcements. Six RC columns with different bond conditions were tested under reversed cyclic loading. Experimental results showed that the failure mode at the ultimate state can be changed from shear to flexure by reducing bond strength of reinforcing bars. It was also observed that shear strength and ductility of RC columns reinforced with unbonded bars were significantly improved compared to those of columns reinforced with ordinary deformed bars.
KEYWORDS: Reinforced concrete, column, seismic behavior, unbonded bars, bond, shear, ductility

1. INTRODUCTION

The main aim of seismic resistant design of reinforced concrete structure is to achieve ductile behavior so that the structure can undergo large inelastic displacement without significant loss of the load carrying capacity. The experiences from the recent severe earthquakes, however, give numerous examples of catastrophic shear failure leading to the collapse of structures. Based on the field observations, one of the major factors responsible for shear failure in RC bridge pier is inadequacy of lateral ties [1-3]. Though, RC structures are generally designed to fail in flexure at the ultimate state, in case of cyclic loading such as earthquake, more transverse reinforcement is required to prevent shear failure that may occur even after yielding of longitudinal bars [4]. Furthermore, to achieve high ductility, the core concrete has to be confined with additional amount of transverse reinforcement.

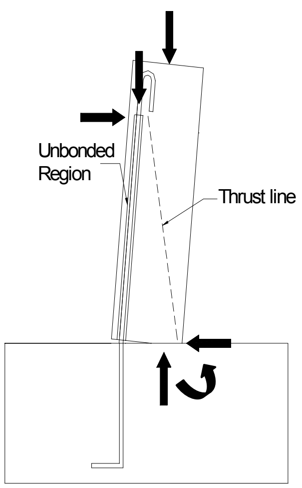


Fig. 1-Concrete Free Body Diagram

To satisfy seismic performance required by current design codes enormous amount of lateral reinforcements have to be provided in RC bridge piers. A large quantity of reinforcement however, makes its arrangement complicated and congested creating constructability problems [5]. It is therefore important to look for some alternative methods to improve shear capacity without relying heavily on transverse reinforcement alone.

Elimination of the bond between longitudinal bar and concrete leads to major change in stress distribution in concrete. Fig. 1 shows concrete free body diagram of a RC column with unbonded longitudinal bars. With no flexural cracks in unbonded region, it is apparent that the concrete body mainly remains under diagonal compression with straight thrust line. Thus, this stress condition does not produce diagonal shear crack, which can eventually enhance the shear capacity of columns [6-9].

The main objective of this research work was, therefore, to investigate the seismic performance of RC columns reinforced with poorly bonded and completely unbonded longitudinal bars.

*1 Graduate School of Science and Engineering, Saitama University, Graduate Student, Member of JCI
*2 Department of Civil and Environmental Engineering, Saitama University, Dr.E., Member of JCI
*3 Graduate School of Science and Engineering, Saitama University, Graduate Student, Member of JCI
*4 Graduate School of Science and Engineering, Saitama University, Graduate Student

2. EXPERIMENTAL PROGRAM

In order to investigate the influence of unbonding reinforcement on seismic behavior of RC columns, six specimens were tested under reversed cyclic loading. Table 1 shows the description of test specimens.

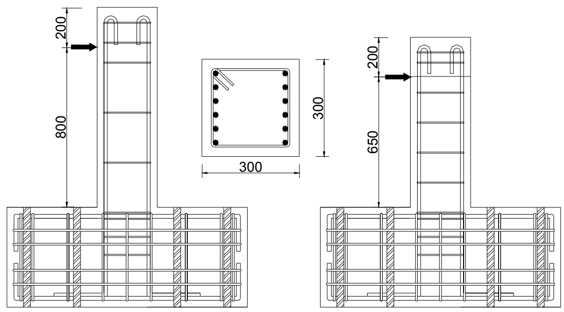
Table 1- Specimen description with experimental parameters

Sp. No.	a/d ratio	Bond condition	Concrete f_c', MPa	Longitudinal bars		Lateral ties	
				A_s	f_y, MPa	Size and spacing	f_{wy}, MPa
A-1	3.0	Ordinary Deformed bars	32.54	12-D16	380.18	D6@250 mm	396.60
A-2		unbonded deformed bars	33.69	12-D16	380.18	D6@250 mm	396.60
A-3		Round bars with grease	34.12	12-φ16	324.06	D6@250 mm	396.60
B-1	2.5	Ordinary deformed bars	28.76	12-D16	380.18	D6@150 mm	396.60
B-2		Unbonded deformed bars	30.47	12-D16	380.18	D6@150 mm	396.60
B-3		Round bars with grease	31.14	12-φ16	324.06	D6@150 mm	396.60

2.1 SPECIMEN DETAILS

Specimens were categorized into Series-A and Series-B depending on their a/d (shear span to depth) radio. Specimens A-1 and B-1 of Series-A and Series-B respectively were purposely designed to fail in shear. The ratio of shear strength to flexural strength for both series was 0.8. Fig. 2 shows details of the test specimen. Twelve bars with diameter of 16 mm were provided as longitudinal bars and the amount was kept constant in both the series. Deformed bars with diameter of 6 mm were used as lateral reinforcement and were proved at the spacing of 250 mm and 150 mm in Series-A and Series-B respectively.

In specimen A-2 and B-2 longitudinal bars from the bottom of column to the loading height were completely unbonded by inserting them into spiral sheaths before casting of the specimens. In specimens A-3 and B-3, however, all deformed bars were replaced by round bars with grease applied on surface to reduce the bond.



A-Series B-Series

Fig. 2-Details of test specimens

2.2 EXPERIMENTAL SETUP AND INSTRUMENTATION

Fig. 3 shows the loading setup. The specimen was fixed on the floor with prestressing rods. Reversed cyclic lateral load was applied at the designated loading point of the column by using an actuator. A constant axial load of 90 kN was applied throughout the experiment in order to maintain the compressive stress of 1 MPa. Axial loading jack was designed to move freely with applied lateral displacement.

Horizontal displacements at three different locations in the column, crack width at the column-footing joint and possible displacement and rotation of the specimen were measured by displacement transducers. Strains in several locations of both longitudinal bars and lateral reinforcement were measured by using strain gages which were already fixed at the desired location before casting concrete.

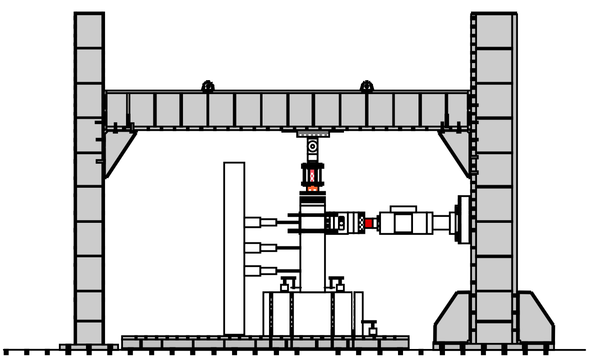


Fig. 3-Experimental Setup

3. RESULTS AND DISCUSSION

3.1 LOAD-DISPLACEMENT CURVE

Load-displacement curve obtained from the experiment for both Series-A and Series-B are shown in Fig. 4. Specimen A-1 failed in shear before yielding of the longitudinal bars. Specimen A-2 with unbonded longitudinal bars completely avoided shear failure and eventually failed due to crushing and spalling of concrete followed by yielding of longitudinal bars. Specimen A-3 with rounds bars applied with grease coating showed better performance with significant improvement in ductility. Unlike A-1, Specimen B-1 failed in shear after the longitudinal bars yielded. With the change in the bond condition, similar to Series-A, Series-B also showed improvement in ductility and complete change in the failure mechanism from shear to flexure.

Pinching effect was clearly visible in the load displacement curves. This effect was attributed to the closure of diagonal shear crack with the load reversal in the case of Specimens A-1 and B-1. On the other hand, pinching in unbonded specimen was due to the closure of large flexural crack at column-footing joint.

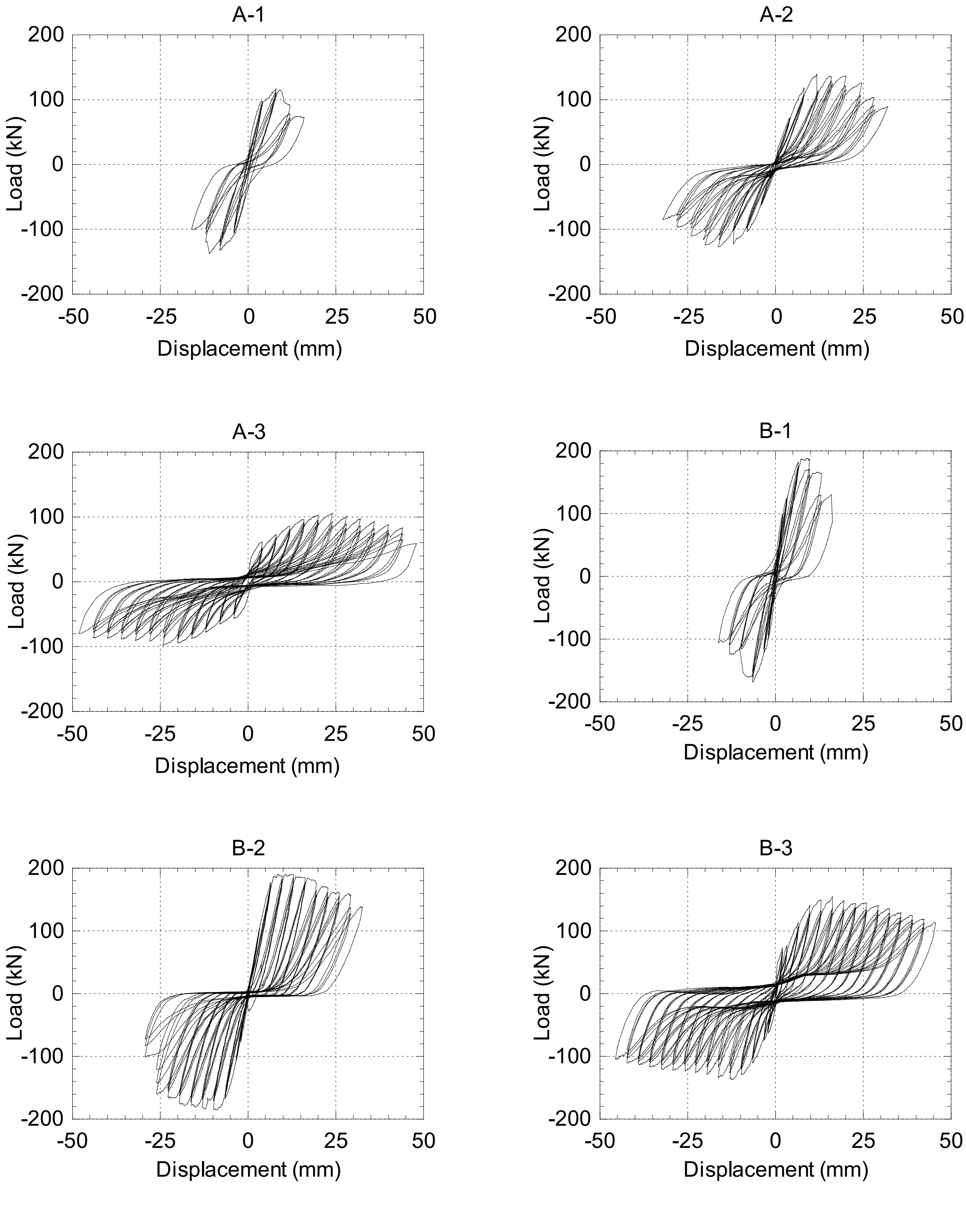


Fig. 4-Load displacement curves of all tested specimens

3.2 FAILURE PATTERN

Fig. 5 shows the crack pattern of all the specimens at failure. In the case of specimens A-1 and B-1, flexural cracks occurred at the several locations on the specimen right from the first cycle. As the number of cycles increased, the crack furthered and then developed to diagonal shear crack. The final failure took place with the wide opening of diagonal crack resulted from the yielding of shear reinforcement. Load-displacement curve clearly shows a typical shear behavior.

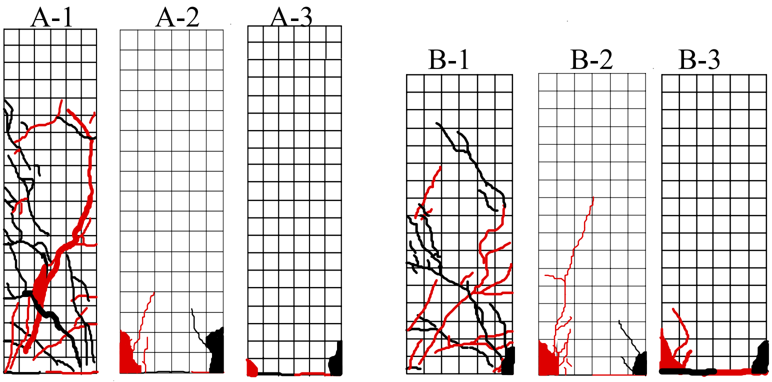


Fig. 5-Crack pattern of specimens at failure

In case of specimens A-2 and B-2, the crack started from the column-footing joint first. With further loading the crack at the bottom increased and propagated upwards. No single crack was formed at the sides of the specimen. The final failure was due to the crushing of concrete followed by yielding of the longitudinal bars.

Specimens A-3 and B-3 also performed in a manner similar to specimen A-2 and B-2. It showed a better performance as the damage was concentrated only at the column-footing joint. The final failure was due to the crushing of concrete followed by yielding of the longitudinal bars.

3.3 ENVELOPE CURVES

Comparison of load-displacement envelope curve in both the series is shown in Fig. 6. The envelope curves in Series-A show that, by unbonding, the load carrying capacity of the specimen was increased due to the complete change in failure mechanism. It was also observed that there was a slight reduction of stiffness due to unbonding but remarkable increase in ductility. The best performing specimen was the one with round bar applied with grease. It showed flexural failure with more ductile behavior. The load carrying capacity of the specimen with round bars, however, seemed to reduce but that was attributed to the lower tensile strength of round bar than that of deformed bars.

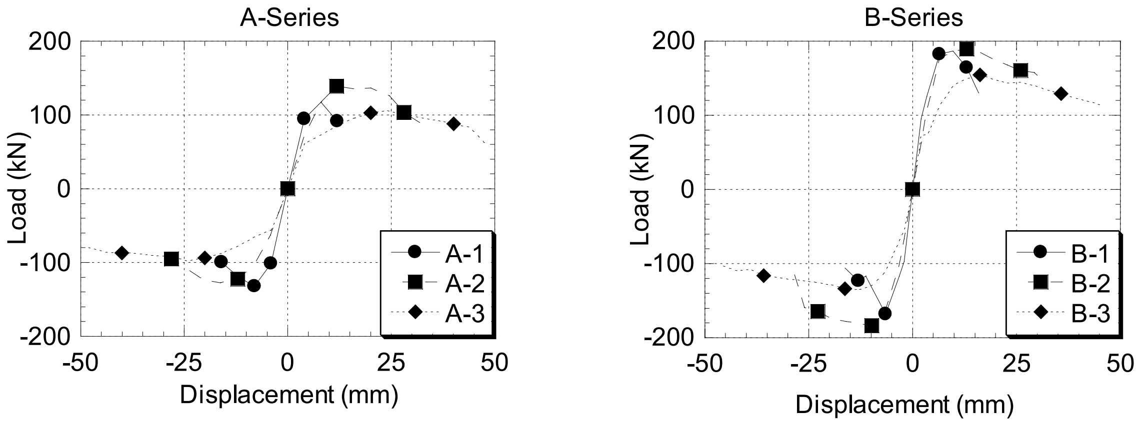
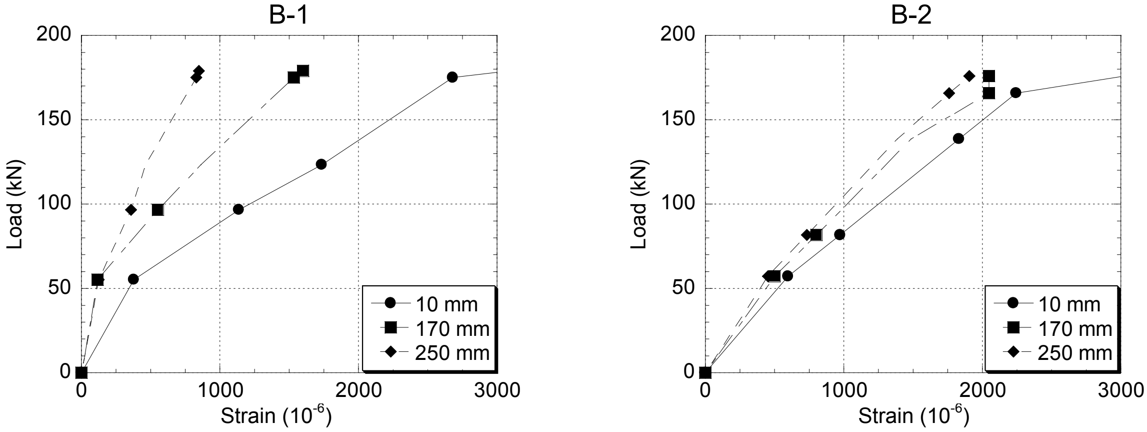


Fig. 6-Load displacement envelope curves

Series-B also demonstrated the similar phenomena. Remarkable improvement in ductility was found in the unbonded specimen with a very little reduction in stiffness and delayed yielding. The performance further improved by replacing the longitudinal bars with round bars applied with grease.

3.4 STRAIN DISTRIBUTION IN LONGITUDINAL BAR

Fig. 7 presents the comparison of strain in the longitudinal bars of specimens B-1 and B-2 at three different locations. The first one was 10 mm above the column-footing joint whereas the second and the third one being at 170 mm and 250 mm above the column-footing joint respectively. Specimen B-1 showed a large difference in the magnitude of strain at those locations. Strain was found to be primarily concentrated near the column footing joint. In the case of specimen B-2, however, the difference was found to be minimal. The strain, instead of concentrating on the critical region, averaged on the whole unbonded length.



(a) (b)

Fig. 7- Comparison of strain at three different locations of longitudinal bars for specimen (a) B-1 and (b) B-2

3.5 COMPARISON OF DISPLACEMENT DUE TO CRACK AT BASE

In order to study the mechanism of the unbonded reinforced concrete column, displacement at the loading point was calculated from the crack width measured at column-footing joint assuming the specimen acts as a rigid body. Fig. 8 schematically shows the relation between crack width c and displacement at the loading point. The calculated displacement was then compared with the measured value.

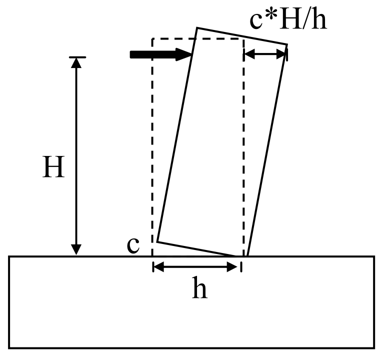
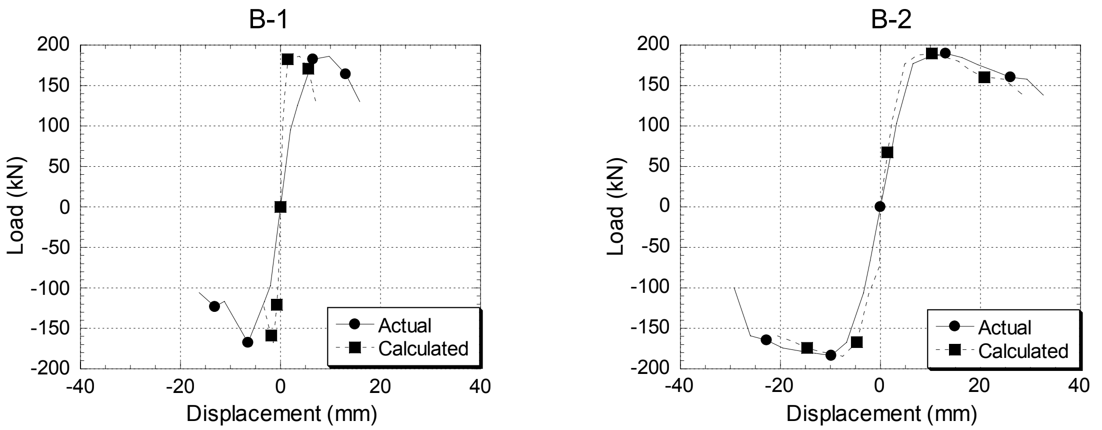


Fig. 8-Displacement due to rigid body rotation

Fig. 9 (a) shows a clear disagreement between calculated and actual displacement. As specimen B-1 failed in shear, majority of the displacement was contributed by flexural and shear deformation. Fig. 9 (b), however, shows that the calculated displacement agreed well with the experimental results in specimen B-2.



(a) (b)

Fig. 9-Comparison of displacement calculated by rigid body analogy with actual value

4. CONCLUSION

Reversed cyclic loading test was carried out on six RC columns with various bond conditions of longitudinal reinforcement. Based on this study following conclusions can be drawn:

1. Unbonding of longitudinal bar can completely change failure mode at the ultimate state from shear to flexure and it remarkably increases the ductility.
2. Due to unbonding, strain in longitudinal bar gets averaged throughout the unbonded length. This results yielding of reinforcing bars to delay. Longer length of unbond further retards yielding.
3. Though both unbonding longitudinal bar and replacing deformed bars with greased round bars improve seismic behavior, the later technique yields better performance which is attributed to the poor bond of longitudinal bar embedded into the footing.
4. Behavior of unbonded specimen is close to a rigid body with damage being concentrated at column-footing joint alone. Upper part of the column does not show significant change in stress due to lateral load

ACKNOWLEDGEMENT

The experiments were conducted at Structural Material Laboratory of Saitama University. The authors would like to acknowledge the co-operation and invaluable suggestions of laboratory members.

REFERENCES

1. Kawashima K., "Seismic Design and Retrofit of Bridges", Proceeding of 12th World Congress on Earthquake Engineering, 2000, 2228.
2. An Z., Maekawa, K. (1998), "Shear Resistance and Ductility of RC Columns after Yield of Main Reinforcement", Journal of Materials, Concrete Structures, Pavements, JSCE No. 585/V-38, February 1998, pp.233-247.
3. Sezen, H. et al., "Performance of Reinforced Concrete Buildings during the August 17, 1999 Kocaeli, Turkey Earthquake, and Seismic Design and Construction Practice in Turkey" Engineering Structures 25 (2003) 103-114, pp.103-114.
4. Dutta, A., Mander, J. B., "Energy Based Methodology for Ductile Design of Concrete Columns", Journal of Structural Engineering, Vol. 127, No. 12, December 2001, pp.1374-1381.
5. Naito, C. J., "Evaluation of Bridge Beam-Column Joints under Simulated Seismic Loading", ACI Structural Journal, Vol. 99, No. 1, January-February 2002, pp.62-71.
6. Kani, G. N. J., "The Riddle of Shear Failure and its Solution", ACI Journal, Vol. 61, No. 4, April 1964, pp. 441-467.
7. Ranasinghe, K., et al., "Cyclic Testing of Reinforced Concrete Columns with Unbonded Reinforcement", Proceedings of JCI, Vol.24, No.2, 2002, pp.1141-1146.
8. Lees, J. M., Burgoyne, C. J., "Experimental Studies of Influence of Bond on Flexural Behavior of Concrete Beams Pretensioned with Aramid Fiber Reinforced Plastics" ACI Structural Journal, Vol. 96, No. 3, May-June 1999, pp.377-385.
9. Lees, J. M., Burgoyne, C. J., "Analysis of Concrete Beams with Partially Bonded Composite Reinforcement" ACI Structural Journal, Vol. 97, No. 2, March-April 2000, pp.252-258.