- Technical Paper -

ENHANCING SHEAR CAPACITY BY CONTROLLING BOND OF REINFORCEMENT

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ABSTRACT

An experimental study was carried out in order to investigate the behavior of bond controlled RC beams to enhance its shear capacity. A total number of twelve beams with various parameters such as bond conditions, dimensions, and reinforcement details were tested. The results clearly suggested that by unbonding the longitudinal bars shear capacity can be greatly enhanced while the failure mode mainly depends on the dimensions and reinforcement details. The behavior of unbonded RC beams can be predicted by a Strut-and-Tie model.

Keywords: reinforced concrete, beam, bond, shear capacity, flexural capacity

1. INTRODUCTION

Among the various types of failure mechanisms in RC structures, shear failure is the most dangerous one due to its catastrophic nature. Moreover, several strong earthquakes in the past few decades have shown that the RC structures are vulnerable in seismic action [1,2]. Particularly, the shear failure of the structure is the matter of prime concern due to its sudden and brittle in nature. In recent years, design earthquake loads in Japanese design codes have been drastically increased [3]. To satisfy the seismic performance required by new design codes, an enormous amount of shear reinforcements have to be provided. It is therefore important to look for some alternative methods to improve shear capacity without relying heavily on shear reinforcement alone.

Kani [4] explained the mechanism of diagonal shear failure by considering the effect of bond. He explained that with the lack of bond, no interchange of forces exists between the steel bars and concrete except at the bar end (anchorage) region. The concrete body therefore remains mainly under diagonal compression with a straight diagonal thrust line. The stress condition in such a concrete body is rather favorable so that diagonal failure of reinforced concrete beam without bond cannot be expected. Swamy et al. [5] examined the influence of the surface condition of the tensile steel on shear resistance. Bonded and unbonded beams were found to represent two quite different modes of structural behavior. Ikeda and Uji [6] performed a large number of experiments on specimens with various shear-span-to-depth (a/d) ratios. The results showed that in the range of a/d ratio greater than 2.5, unbonding of longitudinal bars lead to the complete change in failure mechanism from shear to flexure.

Though there have been some significant research, the influence of member geometry and reinforcement details on the behavior of unbonded members are far from being well understood. The main objective of this research, therefore, is to investigate the behavior of unbonded beams with various dimensions and reinforcement details.

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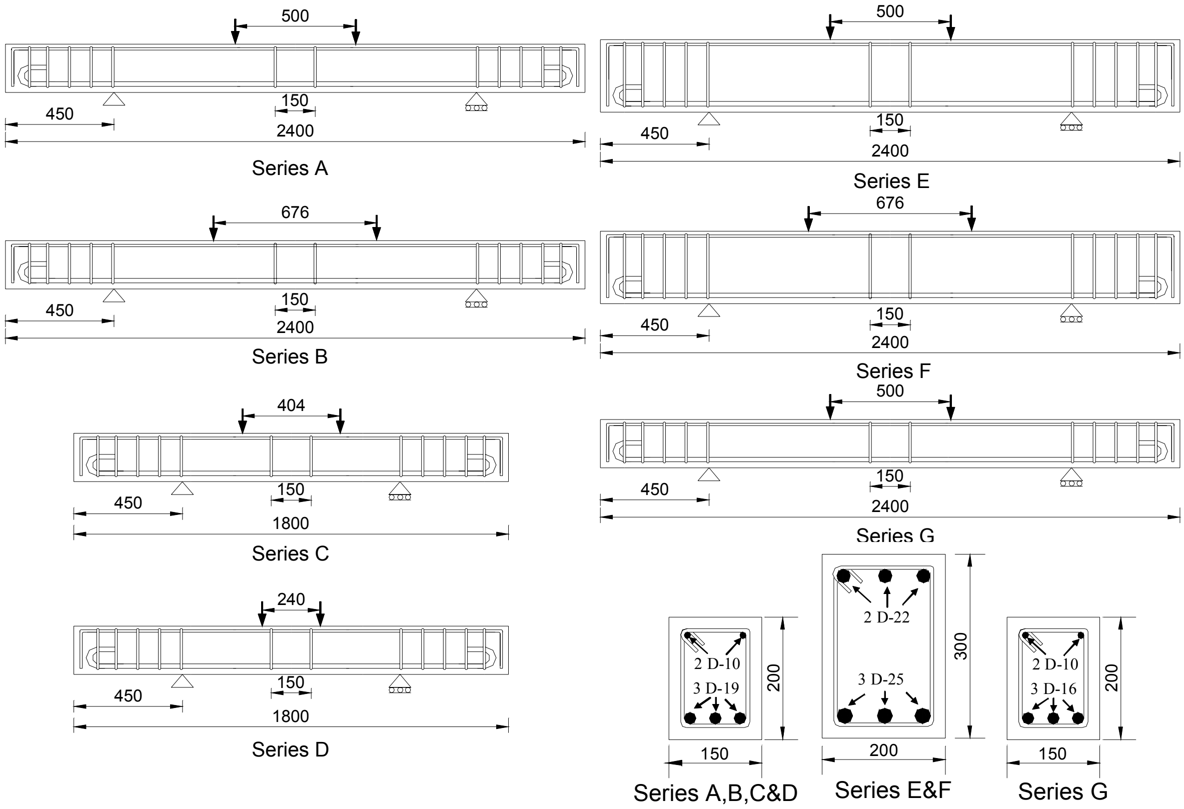


Fig. 1 Geometric Details of Test Specimens

2. TEST PROGRAMS

A total number of twelve specimens with various bond conditions, dimensions, a/d ratios, and reinforcement details were tested.

2.1 Details of Test Specimens

The geometric details and reinforcement arrangements of the test specimens are shown in Fig. 1 and Table 1. The properties of concrete and reinforcing bars are shown in Table 2 and Table 3 respectively. In each series, control and unbonded specimens are designated by using numerical suffixes of 1 and 2 respectively.

Table 1 Details of test specimens

Series	a/d	Tensile reinforcement	Compression reinforcement
A	3.0	3-D19	2-D10
B	2.5	3-D19	2-D10
C	1.5	3-D19	2-D10
D	2.0	3-D19	2-D10
E	1.6	3-D25	3-D22
F	1.9	3-D25	3-D22
G	3.0	3-D16	2-D10

The specimens were divided into seven series depending on their depths and shear-span-to-depth (a/d) ratios.

The specimens with perfect bond were purposely designed to have a much higher flexural strength compared to shear strength in order to insure shear failure so that the enhancement of shear capacity with the change in bond condition of the longitudinal bars could be investigated. Stirrups were therefore not provided in the shear span. Specimens of a severe condition with pre-existing cracks in shear span were investigated in Series G.

Three numbers of reinforcing bars were provided as longitudinal reinforcements. Long anchorage regions of 450 mm with a large number of shear reinforcements with the diameter of 6 mm were provided at both ends to prevent undesirable anchorage failure.

Unbonding of longitudinal bars was achieved by the use of spiral sheath. Before placing the concrete, the length of longitudinal bars between two supports was inserted into the sheath. The location of the sheath was properly fixed and the both the end of the sheath were made water tight by applying silicon gel.

2.2 Test Setup

The test setup of the specimen was as shown in Fig. 2. All beams were tested under four-point loading. a/d ratio was varied with series by adjusting the position of loading point. Load cell was used to measure the load applied on the specimen through hydraulic jack. Displacement of the specimen at mid span was measured by using Linear Variable Differential Transformer (LVDT). Initiation and propagation of cracks were monitored by visual inspection during testing.

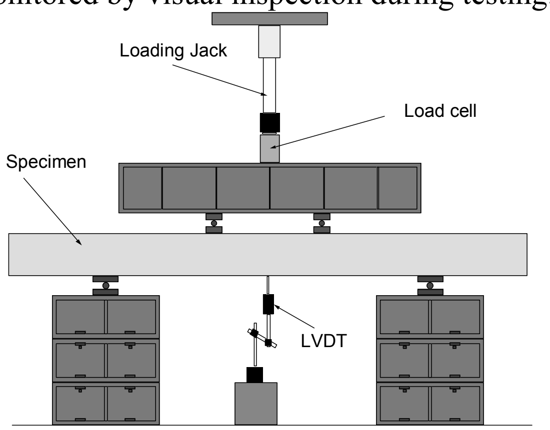


Fig.2 Test Setup

Table 2 Yield strength of reinforcing bars

Bar type	Series	Yield strength (N/mm^2)
D-6	all	335
D-10	A,B,C,D,G	361
D-16	G	385
D-19	A,B	371
D-19	C,D	716
D-22	E,F	383
D-25	E,F	720

Table 3 Compressive strength of concrete

Sp.	Strength (N/mm2)	Sp.	Strength (N/mm2)
A-1	36.0	A-2	37.9
B-1	38.2	B-2	37.9
C-1	35.1	C-2	35.3
D-1	35.1	D-2	35.3
E-2	38.6	F-2	34.3
G-1	36.0	G-2	31.0

2.3 Materials

The concrete used was ready-mixed, normal weight concrete with a 20 mm maximum size coarse aggregate and an average slump of 15 cm. Table 2 shows the yield strength of the various reinforcing bars while Table 3 shows the compressive strength of the concrete on the day of the loading test.

3. EXPERIMENTAL RESULTS

3.1 Load-Displacement Curves

Load-displacement curves of all the tested specimens are shown in Fig. 3.

In series A with a/d ratio of 3.0, as expected, the control specimen failed in shear while by unbonding the longitudinal bars the failure mode changed to flexure with increased load carrying capacity. The failure in specimen A-2 was caused by the crushing of concrete at compression zone before yielding of longitudinal bars. Similar results were obtained in Series B with a/d ratio of 2.5. The final failure was due to the crushing of concrete at compression zone after the yielding of longitudinal bars.

In the specimens with very small a/d ratio of 1.5, investigated in Series C, the failure of control specimen occurred due to the crushing of concrete at compression zone. Hence even with unbonding longitudinal bars the load carrying capacity was virtually unchanged. By unbonding, however, no cracks occurred at shear span. In Series D with a/d ratio of 2.0, the control specimen failed in shear whereas by unbonding the longitudinal bars, the failure mode changed from shear to flexure.

From the previous series it was observed that with unbonding of longitudinal bars, the specimens were prevented from undesirable shear failure. In Series E and F the compression zone was made stronger by adding compression steel and providing high strength longitudinal bars. The results from both the series showed that with stronger compression zone and longitudinal reinforcements, failure mode of unbonded specimens becomes shear compression. The failure occurred due to the crushing of concrete at shear span just outside the loading point.

Behavior of the specimen with much severe condition was investigated in Series G. Unbonded specimen with pre-existing cracks

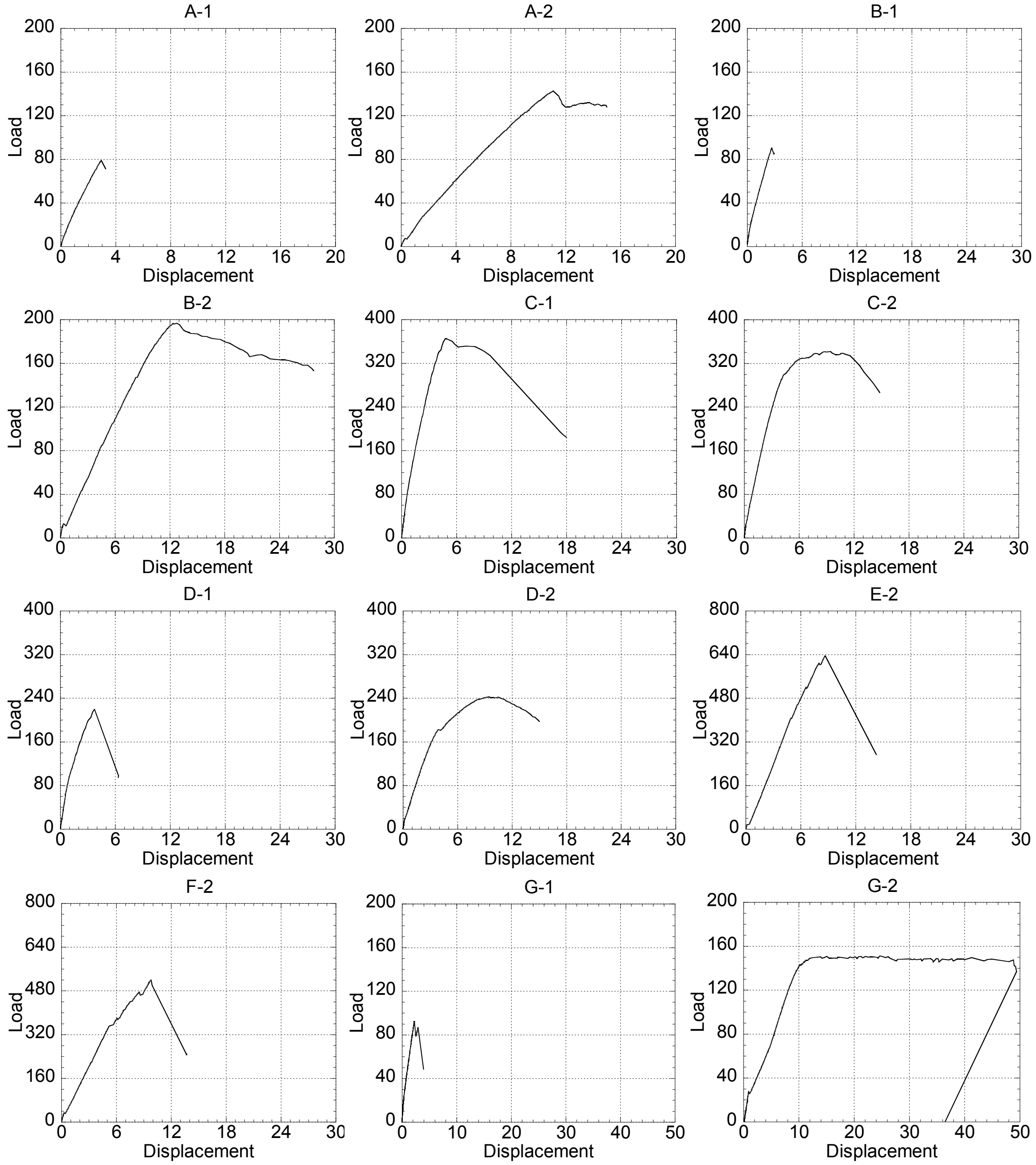


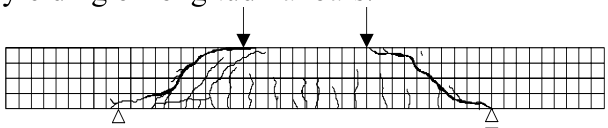
Fig.3 Load-displacement curves Units: Load - kN, Displacement - mm

in the shear span was tested. The results showed that, despite having pre-existing cracks in shear span, the unbonded specimen failed in flexure with enhanced load carrying capacity while its bonded counterpart showed a brittle shear failure.

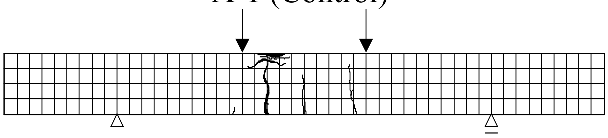
3.2 Crack Pattern

Fig. 4 shows the crack patterns of all the tested specimens at ultimate state. In Series A specimen A-1 failed in shear due to the occurrence of diagonal shear cracks while in Specimen B-2 no cracks occurred at shear span and the failure was due to the crushing of concrete at compression region. Similar pattern was also observed in Series B and Series D. In Series C with a very small a/d ratio, initially the diagonal shear cracks appeared in specimen C-1 while the final failure was caused by crushing of concrete at compression zone. In the unbonded specimen C-2, no cracks occurred at shear span and failure was due to crushing of concrete at compression zone.

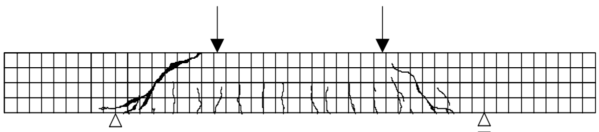
In the unbonded specimens of Series E and Series F, first the vertical cracks appeared at the tensile zone of constant moment region. Since the tensile reinforcement and the compression zone of the concrete was strong, in the later stage, cracks also started to appear at shear spans. The final failure was due to the crushing of concrete at shear span. In series G the control specimen failed in shear with the occurrence of diagonal shear cracks. In the unbonded specimen with pre-existing cracks at shear spans, initially the pre-existing cracks opened with the increase in applied load. Once the crack in concrete occurred at the mid-span, however, the pre-existing cracks were closed. The final failure was due to the crushing of concrete at compression zone followed by the yielding of longitudinal bars.



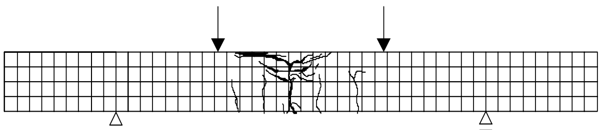
A-1 (Control)



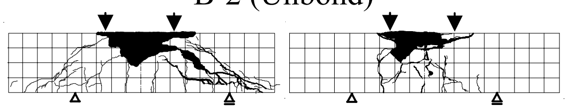
A-2 (Unbond)



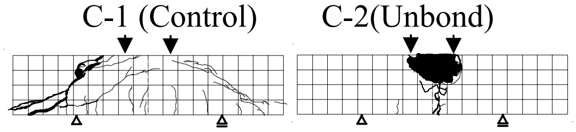
B-1 (Control)



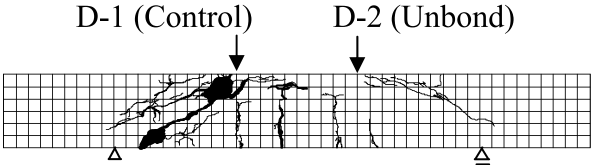
B-2 (Unbond)



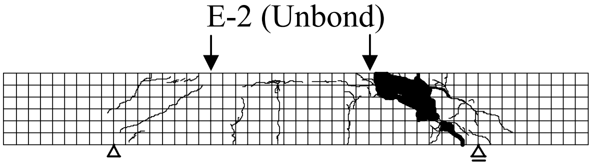
C-1 (Control) C-2(Unbond)



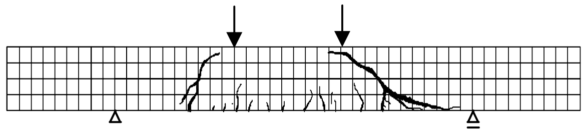
D-1 (Control) D-2 (Unbond)



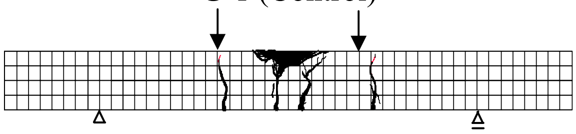
E-2 (Unbond)



F-2 (Unbond)



G-1 (Control)



G-2 (Unbond)

Fig. 4 Crack patterns at failure

4. STRUT-AND-TIE MODEL

The behavior of unbonded beam can be explained by Strut-and-Tie Model (STM) as shown in Fig. 5. W_c is the width of horizontal strut compression. W_{s1} and W_{s2} are the width of strut at top and the bottom ends of the inclined strut respectively. In STM struts are usually symbolized using broken lines, and ties are usually denoted using solid lines as shown in Fig. 6.

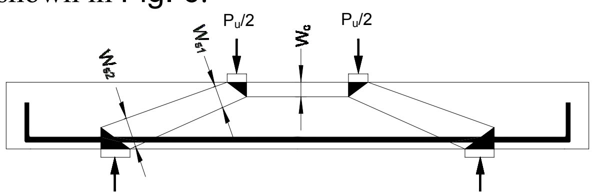


Fig. 5 STM of unbonded beam

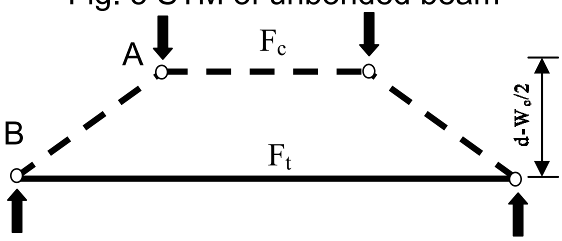


Fig.6 Line diagram of the STM

Fig.7 shows the force equilibrium at nodes A and B.

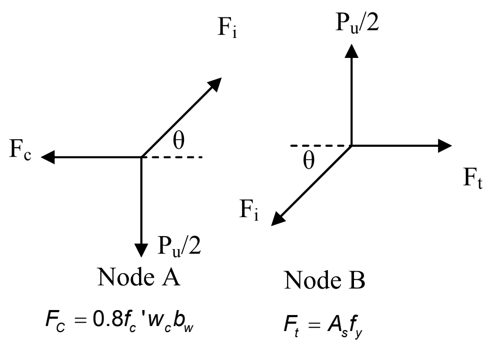


Fig.7 Force equilibrium at nodes

From the force equilibrium at the mid span, F_t must be equal to F_c in magnitude.

From the line diagram shown in Fig. 6 forces in the members can be evaluated when the width of horizontal compression stress is known. The width of the horizontal strut is necessary in evaluating the inclination of the diagonal strut.

The width of the compression strut was assumed to be 50 mm for Specimens A-2 and B-2. The force in the tie was then evaluated by using STM. The force was converted into strain by utilizing the mechanical properties of the reinforcing bars. The results obtained from the analysis were then compared with the experimental results. The comparisons in both specimens are shown in Fig. 8. The uppermost point of the computed value shows the ultimate load obtained from STM. The results thus showed that the STM results in terms of both ultimate load and load-steel strain stiffness agree well with the experimental results following the careful selection of the width of horizontal compression strut.

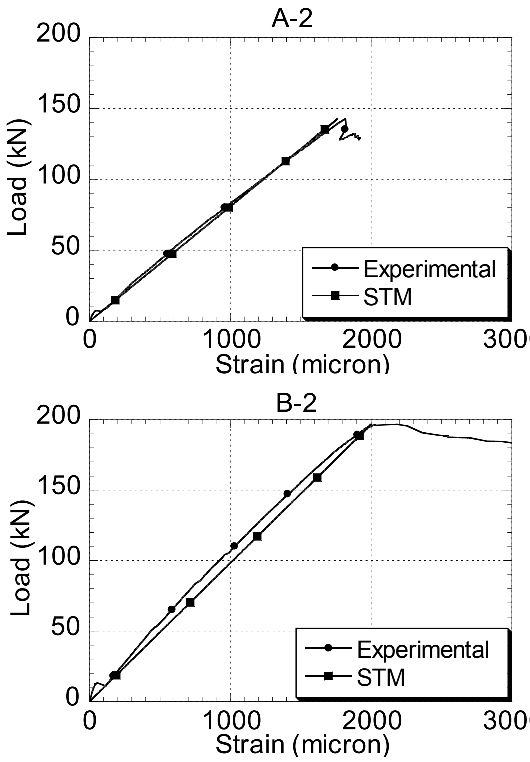


Fig.8 Comparison between STM and experimental result for A-2 and B-2

5. CONCLUSIONS

In order to investigate the behavior of RC beams with the bond controlled reinforcements, a total number of twelve specimens were tested. From the experimental results, following conclusions were drawn:

(1) Altering the bond condition can drastically change the behavior of RC beams.
(2) By completely unbonding longitudinal bars failure mode of beam can be changed from diagonal shear to ductile flexural or shear compression one.
(3) Even the beams with pre-existing flaws in the shear span, the failure mode still remains to be in flexural mode for the beams with unbonded bars.
(4) Behavior of unbonded beams can be approximated by STM with proper assumption of strut widths.

REFERENCES

[1] H. Okamura: Japanese Seismic Design Codes Prior to Hyogoken-Nanbu Earthquake, Cement and Concrete Composites, Vol. 19, pp. 185-192, 1997
[2] M. Hamada: Seismic Code Development for Civil Infrastructures after the 1995 Hyogoken-Nanbu (Kobe) Earthquake, Proceedings of Optimizing Post-Earthquake Lifeline System Reliability, Technical Council of Lifeline Earthquake Engineering, ASCE, pp.922-924, 1999
[3] Standard Specification for Design and Construction of Concrete Structures (Seismic Design), Japan Society of Civil Engineers, 2002
[4] G. N. J. Kani: The Riddle of Shear Failure and its Solution, ACI Journal, Vol. 61, No. 4, pp. 441-467, April 1964
[5] R. N. Swamy, A. Andriopoulos, and D. Adepegba.: Arch Action and Bond in Concrete Shear Failures, Journal of the Structural Division, Proc. of the ASCE, Vol. 96, No. ST6, pp. 1069-1091, 1970
[6] S. Ikeda and K. Uji: "Studies on the Effect of Bond on the Shear Behavior of Reinforced Concrete Beams", Proc. of JSCE, pp. 101-109, 1980