

EXPERIMENTAL STUDY OF A DIAGONALLY REINFORCED BEAM WITH WELL REPAIRABILITY

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ABSTRACT

Since the Great Hanshin Earthquake, the demands of people who own buildings have changed: they want to use the buildings again with small repair cost. This requires good repairability of RC members. A beam with diagonal reinforcements is very ductile, however, the diagonal reinforcements yield on the tension side only because concrete struts will work with them on the compression side. When the diagonal reinforcements yield under tension, tension stress is applied to the concrete along the whole length by bond stress. This increases the number of concrete cracks. The results of this experimental investigation demonstrated that unbonded diagonal reinforcements are an effective means to reduce damage to short beams and have the same energy dissipation ability as bonded ones. A small design at the end of the beam can make the diagonal reinforcements yield on the compression side, and not increase the beam length.

Keywords: RC structure, damage control, diagonally reinforced beam, earthquake resistance design

INTRODUCTION

The goal of the earthquake resistant design of any country is to protect life in very severe earthquakes by providing for buildings with strength and toughness to resist collapse. After big earthquakes such as the Great Hanshin Earthquake, however, the demands of people who own buildings have changed: they want to use the buildings again with small repair cost. This requires good repairability of RC members.

For reinforced concrete buildings with a “shear core”, short beams are connected the shear walls as shown in Figure 1. To satisfy the ductility demand of the beams, diagonal reinforcements have been used [1]. Many experimental studies were carried out in Japan on using diagonal reinforced beams as members of a tube structure [e.g. 2,3]. Although these beams showed very ductile behavior, the number of concrete cracks was very large and damage to the beams prevented repair works. In those beams, the diagonal reinforcements yield on the tension side only because concrete struts work with them on the compression side. This increases the number of concrete cracks, and increases the beam length. Repair works are thus laborious.

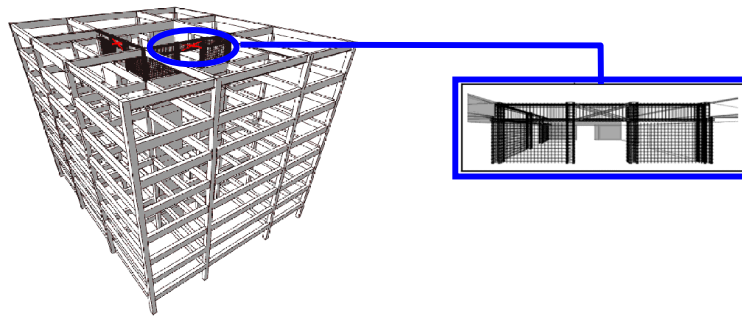


Figure 1: Short beams in a reinforced concrete buildings with shear core

The working stress of diagonal reinforcements is constant with respect to the overall length, so there is no need for bond stress between the diagonal reinforcements and concrete. Unbonded diagonal reinforcements are one solution to reduce the number of concrete cracks. A small design at the end of the beam can make the diagonal reinforcements yield on the compression side. This means the ability to absorb energy will increase and the beam length will not increase.

This paper describes a study on short beams with diagonal reinforcements to reduce concrete cracks and thus improve reparability.

EXPERIMENTAL PROGRAM

Test specimens

The dimensions of the specimens are shown in Figure 2. All beams had eight diagonal reinforcement bars with four longitudinal reinforcement bars and web reinforcements. The section is 200 mm thick, 400 mm high, and 1000 mm long. The overall length of the specimen is 2800 mm with end stubs of 400 mm thickness, 1400 mm height and 900 mm length at both ends. These dimensions are one third scale of the prototype structure shown in Figure 1.

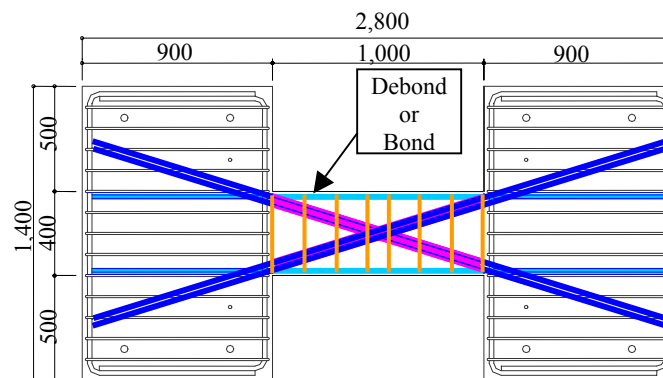
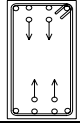
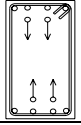
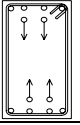
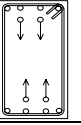
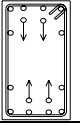


Figure 2: Dimensions of Test Specimens

The primary experimental parameter is the bond of diagonal reinforcements, and the second is the amount of web reinforcement as shown in Table 1. The diagonal and longitudinal reinforcements in the web are the same in all specimens. Specimens #1 and #2 are common diagonal reinforcement beams, and specimens #3, #4 and #5 are beams with unbonded diagonal reinforcements. The amount of web reinforcement provided for #1 and #3 is consistent with the current AIJ standard [4, experimental equation]. For #2 and #4, the amount is calculated according to the AIJ design guidelines [5, truss model equation] with

R=1/50 inelastic rotational ability. For #5, the amount at both end parts is doubled. In the design, the concrete compressive strength was assumed to be 48 N/mm² ($\sigma_B=54$ or 51 N/mm²), the yield stress of the main reinforcement was assumed to be 390 N/mm² ($\sigma_y=476$ or 459 N/mm²), and the yield stress of the web reinforcement was assumed to be 295 N/mm² ($\sigma_y=372$ N/mm²).

Table 1 : List of specimens

| Specimen | No.1 | No.2 | No.3 | No.4 | No.5 |
|---------------------------------|---|---|---|--|---|
| Section |  |  |  |  |  |
| b×D(mm) | 200×400 | | | | |
| | 54 | 51 | 54 | 51 | 51 |
| Parallel | 2-D16 | | | | |
| X Shape | 4-D16 Bond | 4-D16 Bond | 4-D16 Unbond | 4-D16 Unbond | 4-D16 Unbond |
| σ_v (N/mm ²) | 476 | 459 | 476 | 459 | 459 |
| P _t (%) | 1.51 | | | | |
| Web | 2-D6 @150 | 2-D6 @100 | 2-D6 @150 | 2-D6 @100 | 2-D6 @100/@50 |
| σ_v (N/mm ²) | 372 | | | | |
| P _w (%) | 0.21 | 0.32 | 0.21 | 0.32 | 0.32/0.64 |
| Tested year | 2000 | 2001 | 2000 | 2001 | 2001 |

Unbonded reinforcement

To create debonded reinforcement bars, wax and thin plastic sheets were used. First, dimple parts of a deformed bar were filled by wax, and then the bar was covered by a thin plastic sheet as shown in Figure 3(a)(b) for specimen #3. For specimens #4 and #5, after step 1, the bar was coated by unbond material(butylene rubber), and then covered by a gummed tape. The anchor part (the part in a stub) was untouched.

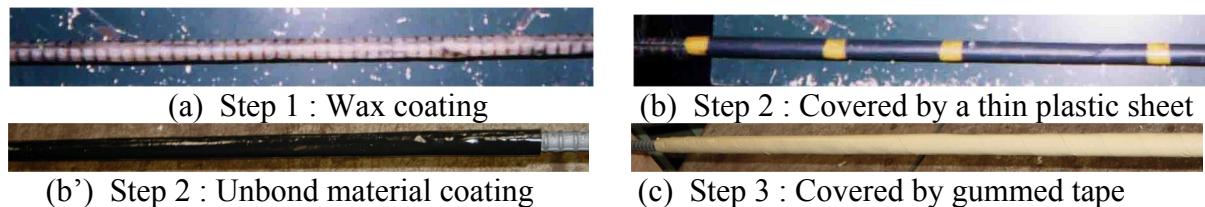


Figure 3 : Unbonded reinforcement bar

Test setup

The bottom of the specimen rotated 90 degrees was bolted to the loading frame. A 500 mm wide by 600 mm deep L shaped loading beam was placed on top of the specimen, and a main hydraulic actuator was attached at mid-height of the beam. Two sub hydraulic actuators were attached at the top to control the level of loading beam as shown in Figure 4. Antisymmetric bending moment was applied to the specimen.

Loading Cycles

Loading cycles as shown in Figure 5 were applied to increase the drift angle R with 3 repeated cycles. Only at the level of $R=1/100$, the loading cycle was conducted with 6 repeated cycles. These were determined by dynamic response analysis for the prototype building shown in Figure 1 during a severe earthquake to satisfy the energy dissipation ability.

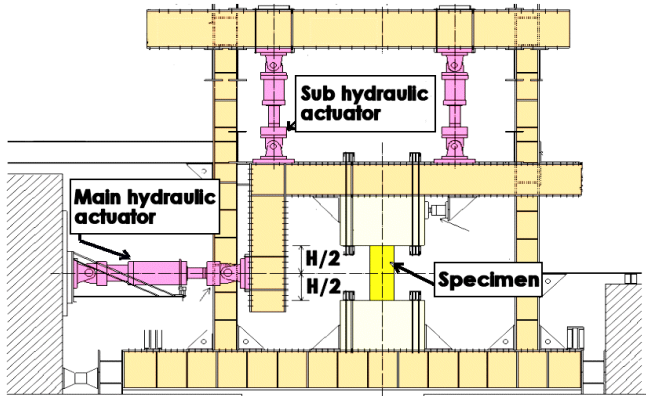


Figure 4 : Test Setup

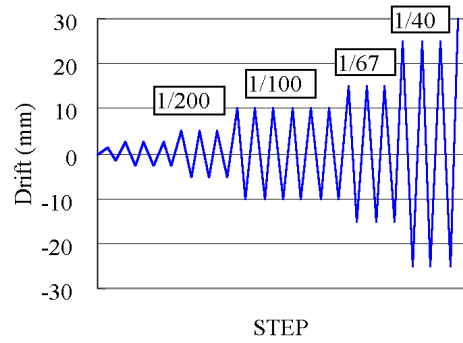


Figure 5 : Loading Cycles

Instrumentation

During the tests, total drift was measured as the displacement difference of the loading stubs. Partitioned axial displacements to calculate bending deformation were measured at both flanges as shown in Figure 6. Shear deformation was calculated by subtracting the calculated bending deformation from the measured total deformation. Strains of reinforcements were also measured by strain gauges mounted in several locations along diagonal reinforcements, longitudinal reinforcements and on the transverse bars.

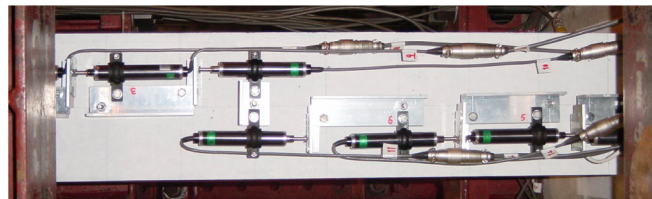


Figure 6 : Measurement of partitioned axial displacements at both flanges

EXPERIMENTAL RESULTS

Crack patterns

During the response in the R=1/700 cycle, bending cracks were observed for all specimens at beam ends. In the R=1/400 cycle, bending-shear cracks were observed. For the specimens with bonded diagonal reinforcements (#1,2), diagonal shear cracks occurred at the center in the R=1/100 cycle. For the specimen with unbonded diagonal reinforcements (#3,4,5), cracks concentrated on both edge parts with no shear crack at the center and the number of cracks was small. Crack patterns in the R=1/100 and final cycles are shown in Figures 7 and 8.

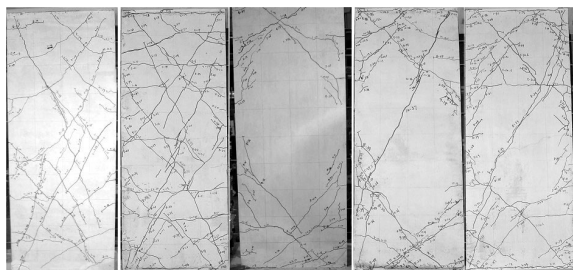


Figure 7 : Crack Patterns (R=1/100)

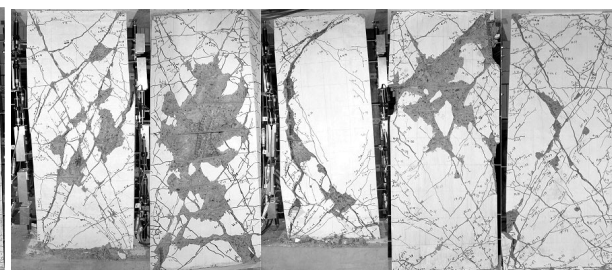


Figure 8 : Crack Patterns (Final)

Load-deflection curves

The load-deflection behaviors of the specimens are shown in Figure 9. Significant differences

are not observed between the hysteretic response of the specimens until the $R=1/40$ cycle. During the response in the $R=1/40$ cycle, strength degradation was observed because of shear yield for specimen #1, of diagonal reinforcements buckling at center in negative loading for specimen #2, of bond failure for specimen #3, and of diagonal shear slip at the end for specimen #4. No degradation was observed for specimen #5.

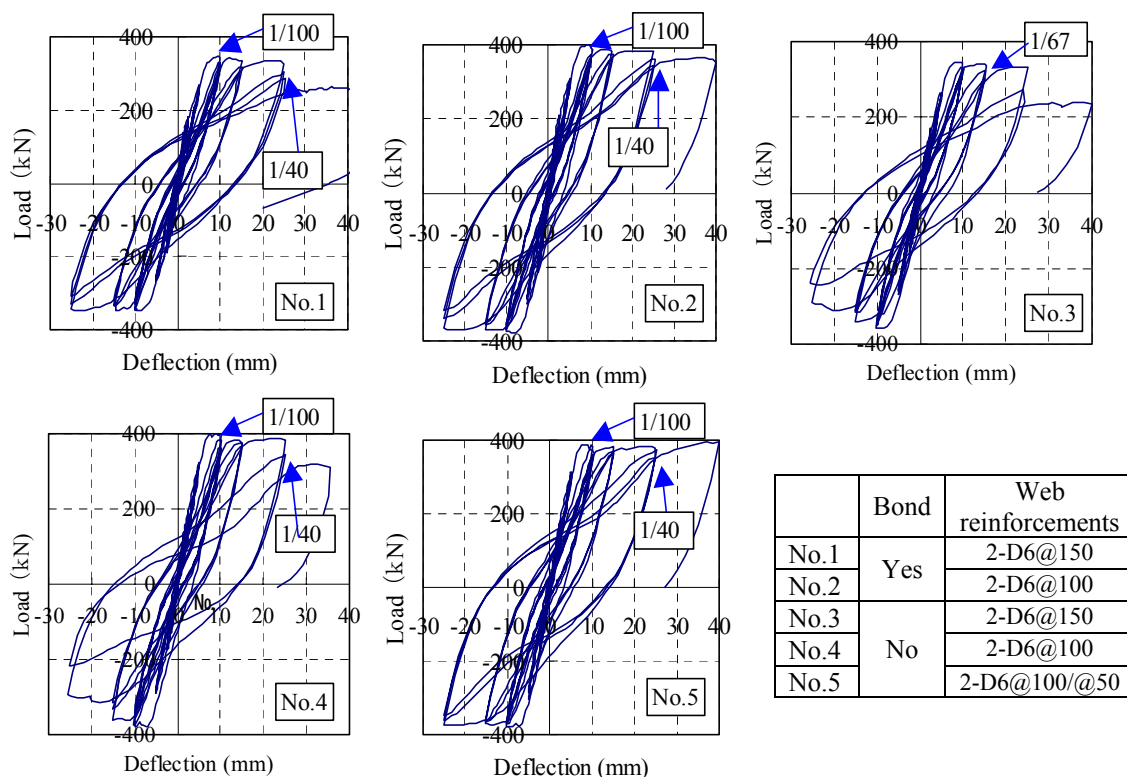


Figure 9 : Load-Deflection Curves

The force-displacement behavior can be predicted based on the assumption that the behavior is the sum of a parallel-reinforced R/C beam and diagonal steel braces. For the R/C beam, the flexural crack M_c and yield strength M_y are calculated by the approximate equations (1) and (2), and the stiffness reduction factor α_y (Secant modulus at yield point/Initial stiffness) is obtained by experimental equation (3) [4].

$$M_c = 0.56 \sqrt{\sigma_B} Z \quad (\text{units: N, mm}) \quad (1)$$

$$M_y = 0.9 a_t \sigma_y d \quad (2)$$

$$\alpha_y = (-0.0836 + 0.159 a/d)(d/D)^2 \quad (3)$$

where, σ_B is concrete strength in N/mm^2 , Z is section modulus, a_t is area of longitudinal tension reinforcement, σ_y is yield strength of steel, d is distance from extreme compression fiber to centroid of tension reinforcement, D is height of beam, and a is the shear span length (M/Q). The diagonal reinforcements are assumed to be the bi-linear system and to act in both tension and compression(cal.1). Additional concrete barace was considered in cal. 2 for shear resistance of confined concrete.

The envelope curves of the test results are compared with the calculated load-deflection relations in Figure 10. Both show good agreement. This approximate calculation method can estimate the load-deflection behavior for diagonally reinforcement beams while fully satisfying the design.

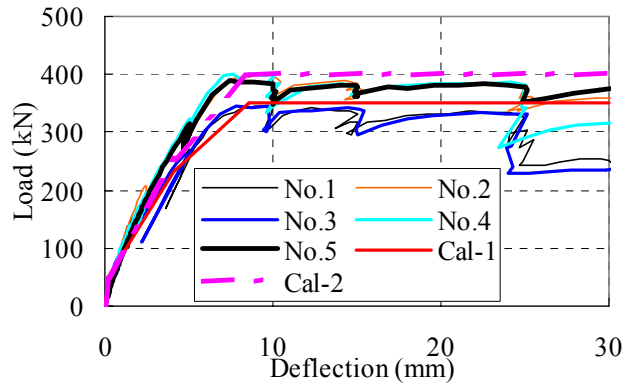


Figure 10 : Load-Deflection Curves

Strain of reinforcements

Figure 11 shows the strain distribution of the diagonal reinforcements at the first peak load in each cycle. Strains of the unbonded reinforcements (#3,4,5) are almost uniform in each cycle even on the compression side, in contrast with the bonded one, in which the strain was

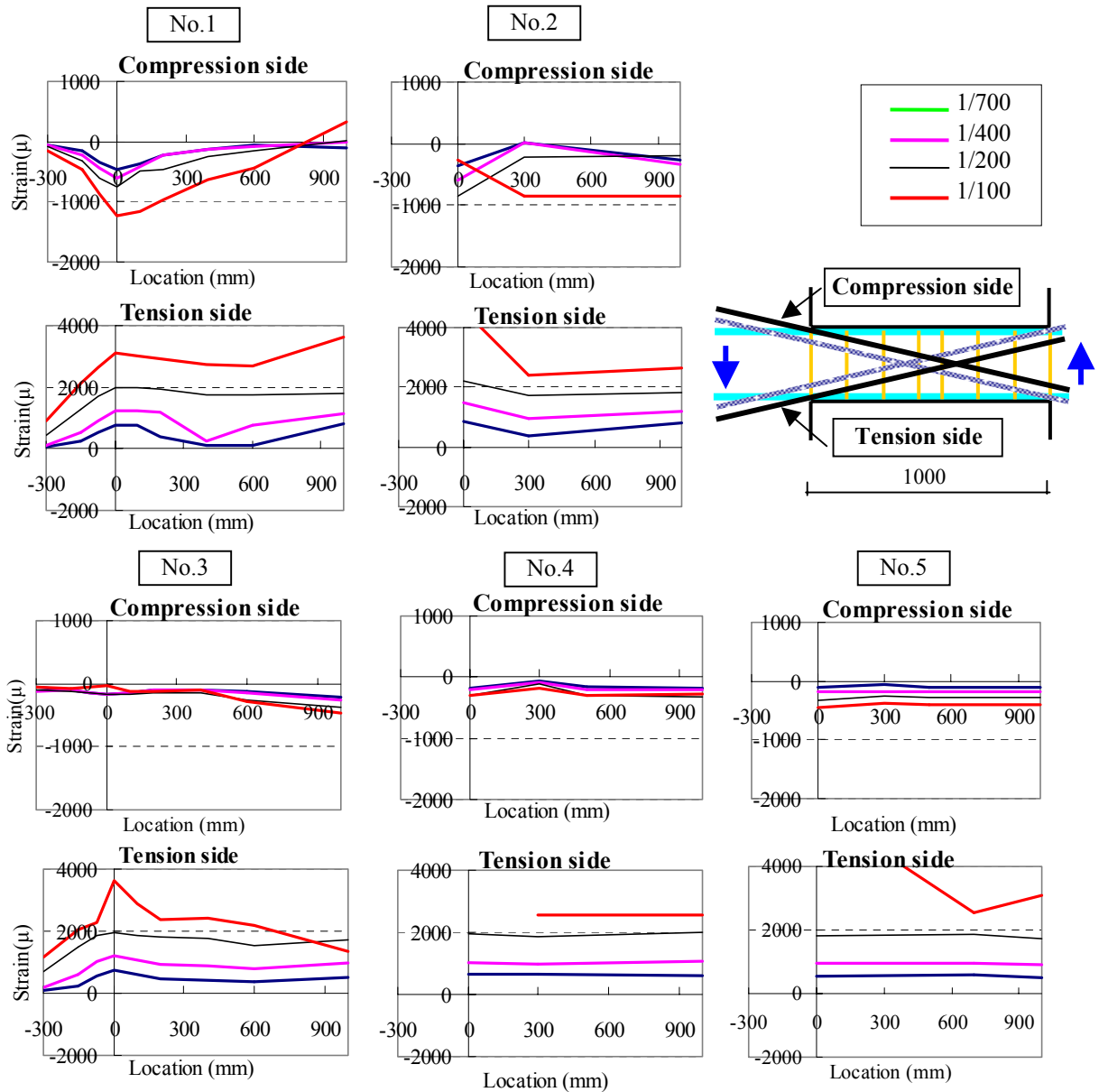


Figure 11 : Strain distribution of diagonal reinforcements

influenced by bending moment on the compression side. The reinforcements yielded during cycle $R=1/200$ to $R=1/100$ for all specimens. Compression strain of specimens #3,4,5 is small because the concrete struts act in compression.

Figure 12 shows the strain distribution of the parallel reinforcements at the first peak load in each cycle. During cycle $R=1/200$ to $R=1/100$, the decline angle of strain distribution on the tension side is larger in specimen #3,4,5 than in #1,2. This is caused by the difference of compression strain of the diagonal reinforcements shown in Figure 11. This means the bond stress in specimen #3,4,5 is larger than in #1,2 and it is a severe value for bond failure.

Figure 13 shows the strain distribution of the web reinforcements at the first peak load in each cycle. Dotted lines on the right side in each figure are drawn assuming symmetry, and were not measured. The web reinforcements yielded at the center of the beam in the $R=1/100$ cycle for specimen #1,2 in contrast with specimen #3,4 which yielded at the end of the beam in the $R=1/67$ cycle. Specimen #5 behaved intermediate between #1,2 and #3,4. These tendencies match the crack patterns shown in Figures 7 and 8.

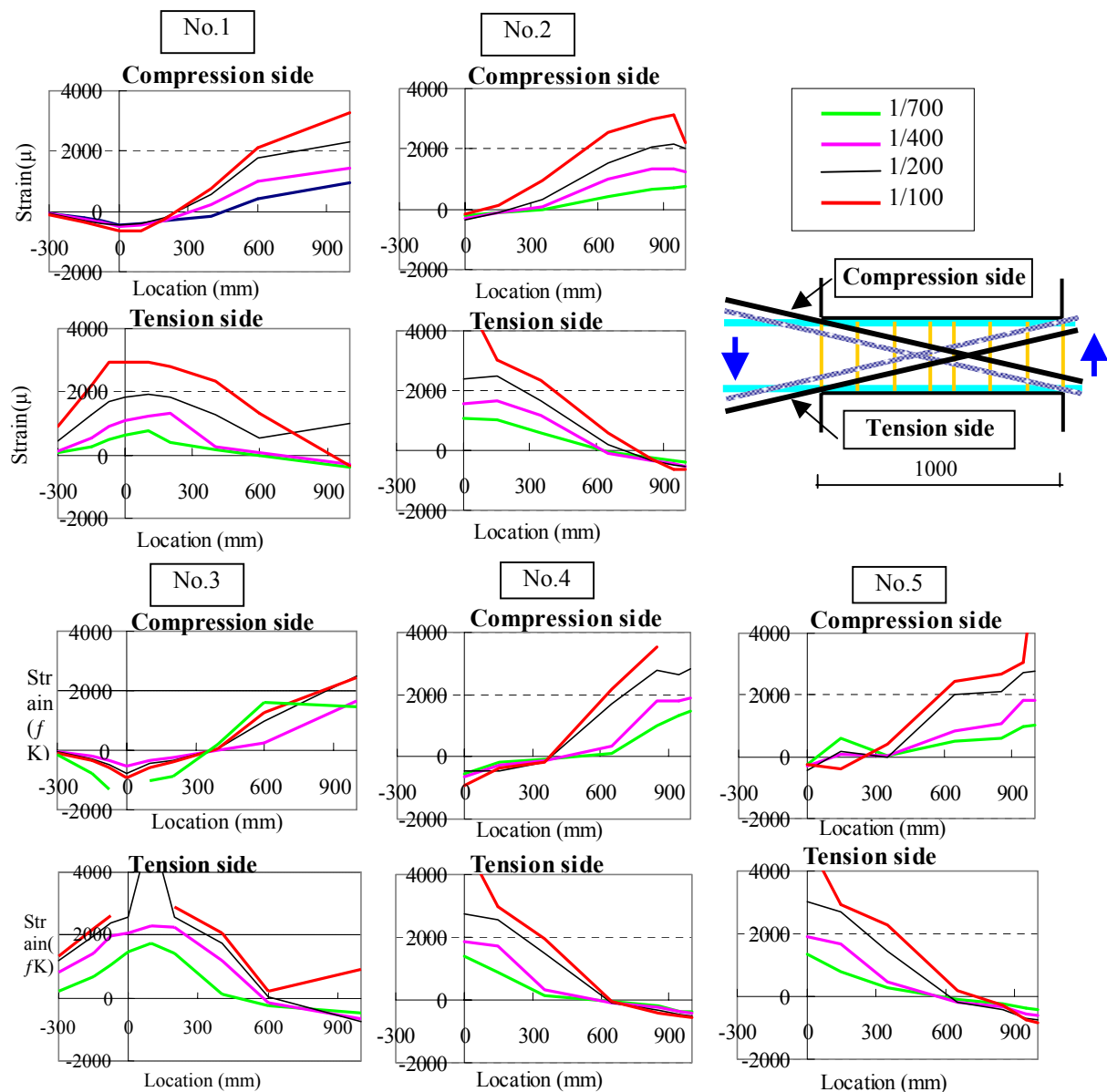


Figure 12 : Strain distribution of parallel reinforcements

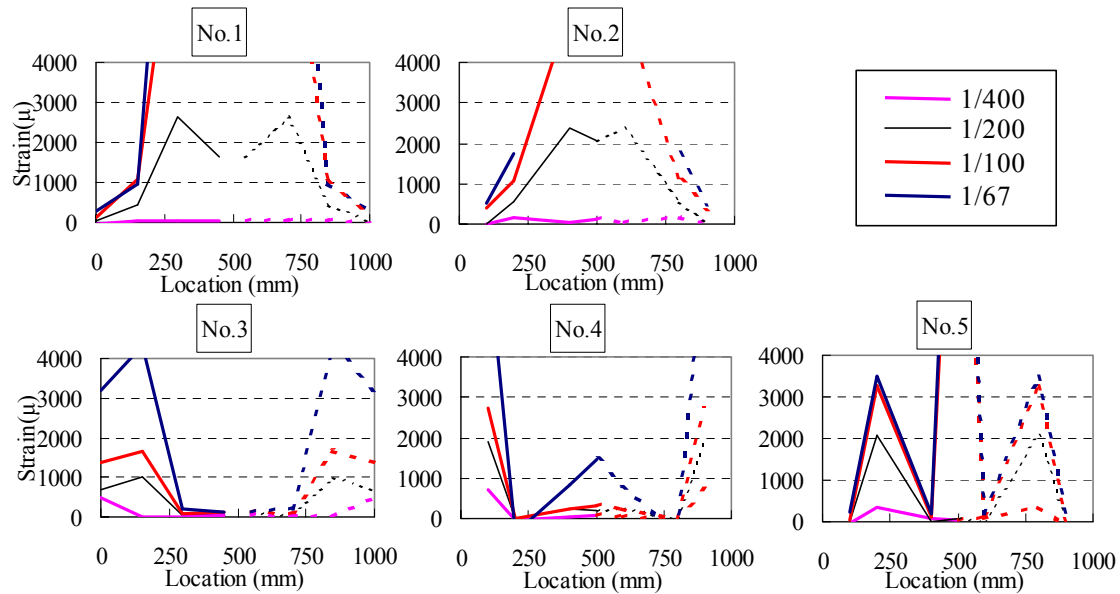


Figure 13 : Strain distribution of web reinforcements

Bending and shear deformation

Bending deformation was calculated by integrating the curvature obtained from the piecewise axial displacement difference of both flanges. Shear deformation was calculated by subtracting the bending deformation from the total deformation.

Figure 14 shows the change of deformation components of bending deformation and shear deformation. The shear deformation part increases with increasing total deformation caused by shear cracks. Specimen #1,2 had shear cracks in the center part, so the shear deformation part becomes much larger than that of specimen #3,4,5 which little cracked in the center. The shear cracks at the end part for specimen #3,4,5 caused a bending hinge at both beam-ends.

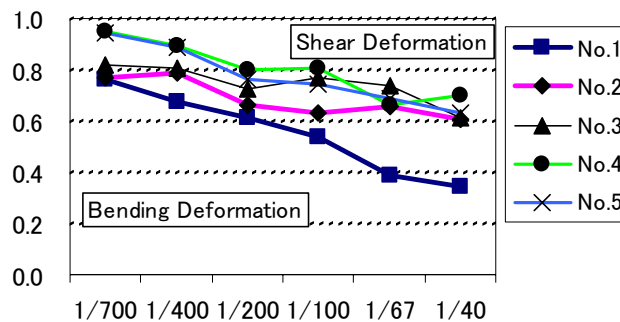


Figure 14 : Changing of deformation component

Axial elongation

Total axial elongation is calculated as the sum value of measured partitioned axial displacements. Figure 15 shows the relation between calculated axial elongation and drift deformation. Until the R=1/200 cycle, the accumulated axial elongation is not measured. At the R=1/100 cycle, the axial elongation increases for all specimens due to yielding of the diagonal and longitudinal reinforcements. The elongation is larger in specimen #3 than in specimen #1 and in specimen #4 than in specimen #2 with same web reinforcements. This difference is caused by the compression strain of the diagonal reinforcements shown in Figure 11. The compression strain of bonded diagonal reinforcement becomes large, because the concrete is compressed by bending, and this compression stress is propagated to the

diagonal bar by bond stress. The unbonded diagonal reinforcements are not influenced by the concrete compression stress, and act only as a compression brace. However, a concrete arch strut acts with them, so the compression stress of the unbonded diagonal reinforcements is small. As accumulated tension stress in the unbonded diagonal reinforcements became large, the axial elongation in specimen #3,4 became large.

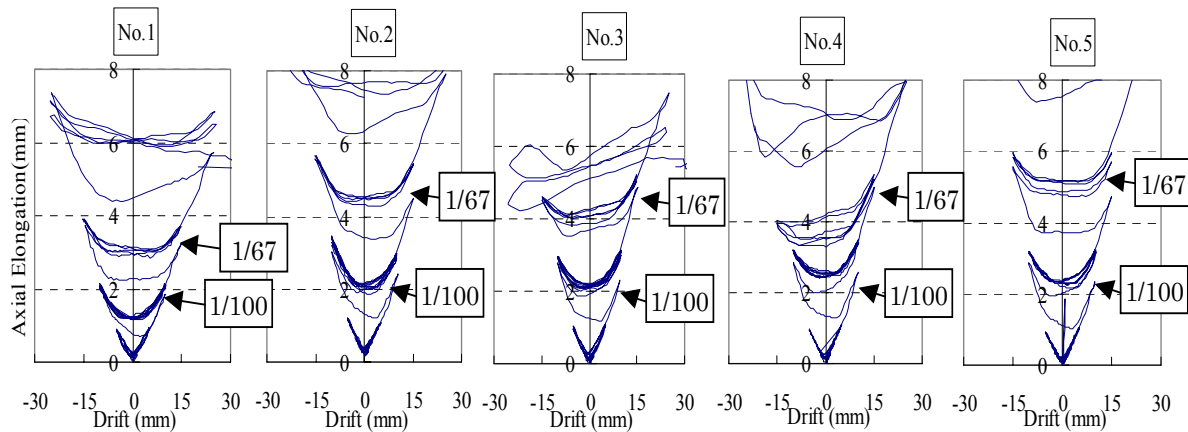


Figure 15 : Relation of axial elongation versus drift

Equivalent damping factor

Figure 16 shows the equivalent damping factor of each specimen calculated from the first half cycle of the applied load – total deflection relationship shown in Figure 9. Significant differences are not observed in the equivalent damping factor between all. This means that the energy dissipation ability is the same, despite the clear difference of crack patterns shown in Figures 7 and 8.

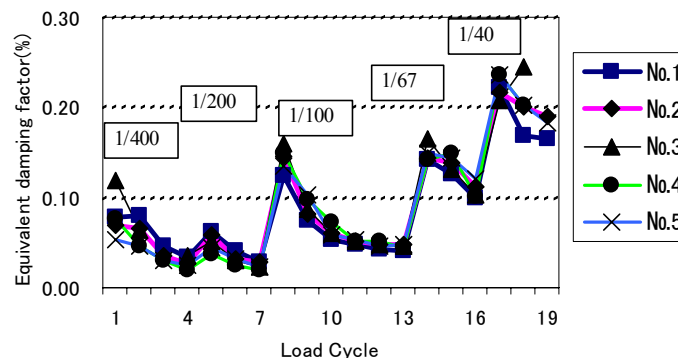


Figure 16 : Fluctuations in equivalent damping factor

CONCLUSIONS

This paper examined the behavior of short beams with diagonal reinforcements to reduce damage during a severe earthquake for good reparability. The main findings are follows:

1. The results of this experimental investigation demonstrated that unbonded diagonal reinforcements are an effective means to reduce the number of cracks for short beams.
2. Significant differences are not observed between the hysteretic response and equivalent damping factor of the specimens. The approximate calculation method (sum of a parallel

reinforced R/C beam and diagonal steel braces) can estimate the load-deflection behavior for diagonally reinforcement beams while fully satisfying the design.

3. Strains of the unbonded diagonal reinforcements are almost uniform in each cycle and free from bending stress.
4. The web reinforcements yielded at the center of the beam for specimen #1,2, in contrast with specimen #3,4 which yielded at the end of the beam.
5. The axial elongation is larger in specimen #3,4 than in specimen #1,2.

This report showed the results of a preliminary study. The project is continuing, and the effectiveness of web reinforcement and more detailed design for compression yield of diagonal reinforcements will be presented in the near future. Furthermore, despite the good agreement of the load-deflection behavior between the tests and the approximate calculation, the strain distribution in the reinforcements was different. This result suggests the possibility of a difference of the load resistance system between bonded and unbonded diagonally reinforced beams. These will be studied by analytical investigations.

ACKNOWLEDGEMENT

This study was carried out as part of the TEDCOM (Typhoon and Earthquake induced Disaster Control and Mitigation) project in Kanagawa University, funded by the Ministry of Education, Culture, Sports, Science and Technology (Frontier Research Program) and Yokohama city (collaboration program between industry, academia, and the government). The opinions and findings do not necessarily represent those of the sponsor.

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