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DEVELOPMENT OF UNBONDED BAR REINFORCED CONCRETE STRUCTURE

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SUMMARY

The Unbonded Bar Reinforced Concrete (UBRC) structure is newly developed and proposed as the high seismic performance structure. The UBRC structure consists of a conventional RC structure and unbonded bars. These bars can add the stable positive post-yield stiffness to the load-displacement hysteresis loop of the original RC structure. And this post-yield stiffness can be changed easily by the adjustment of bar parameters (area, length, location etc.). In order to evaluate the seismic performance of UBRC structures, cyclic loading tests and pseudodynamic tests were carried out. From the results, it was found that UBRC structures exhibit the stable seismic response even under strong earthquakes and the residual deformation is small because of the elastic restoring force by the unbonded bars. Next, the two-level seismic design method for structures with the post-yield stiffness is proposed. According to the design method, the compact section structures can be realized. Applying the UBRC structure to a railway rigid-frame viaduct bridge, the compact section pier can be satisfied with the require performance of the two level seismic design. These results lead the conclusion that UBRC structures can improve the seismic performance of concrete structure easily and economically.

INTRODUCTION

Not only civil engineers but also citizens had a great impact from the collapse and the severe damage of many concrete bridges in Hyogo-ken Nanbu Earthquake. In the restoration operation, not only seriously damaged piers but also slightly damaged piers with large residual deformation were subject to reconstruction. From the detail survey results after the earthquake, in 591 piers of the non-serious damage level, 129 piers had to be reconstructed because the residual deformation was over 15cm [1]. Nowadays, the important infrastructures are required to have not only the high strength and the high ductility but also the usability and the repairability after earthquakes.

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In this study, the Unbonded Bar Reinforced Concrete (UBRC) structure is proposed as the high seismic performance structure. This structure has the stable post-yield stiffness of the load-displacement relationship and it might be the rational structure under the two level seismic design method. In this paper, at first the structure and the concept are presented, and in order to investigate the fundamental characteristics, the cyclic loading and the pseudodynamic tests were carried out. Next showing the rational seismic design using the post-yield stiffness, the application to the railway structure is presented.

UNBONDED BAR REINFORCED CONCRETE STRUCTURE

The UBRC structure consists of a conventional RC pier and unbonded high-strength bars [2,3] (Figure 1). The both ends of the bars in the basic UBRC structure are anchored in the body of the RC structure. As we shall see later in Figure 2, the active elastic range of bars ban be shifted to larger deformation range if the gap is installed at the bottom end of the bars. Since this structure is reinforced by not only the re-bars but also unbonded bars, it is called Unbonded Bar Reinforced Concrete (UBRC) structure.

The characteristics of the UBRC structure are explained from the viewpoint of the load-displacement skeleton curve (Figure 2). The load-displacement relationship of a conventional RC structure is the perfectly elasto-plastic model [4]. When elastic members are installed in the RC structure, it is possible to obtain the structure with the post-yield stiffness. The UBRC structure has the positive and the stable post-yield stiffness even in the large deformation. In order to obtain the stable post-yield stiffness in the large deformation, it is necessary to guarantee that the bars behave in the elastic manner. Therefore not only the high-strength material is used for the bars, but also the unbonding treatment is performed.

The effect of the unbonding treatment is shown in Figure 3. In the small deformation, the strain of longitudinal bars shows the triangle distribution along the height of the pier as same as the moment distribution. When the deformation becomes large, the longitudinal bars would yield at the bottom of the pier and the plastic hinge zone is formed. On the other hand, the strain distribution of the unbonded bars is constant because the bars behave independent of the RC member except for the anchors. Therefore since the whole length of the bar can resist the deformation of the RC member effectively, the strain of the bars becomes small. That is, the bars hardly yield. By this fact, the unbonded bar can behave in an elastic manner even in the large deformation, and the UBRC structure can show the stable post-yield stiffness.

For the UBRC's bars, a high-strength material is used to avoid a yielding. But in general the high-strength material is very expensive, and it is sometimes difficult to adopt it from the economical viewpoint. Since the most important characteristic of the UBRC structure is the post-

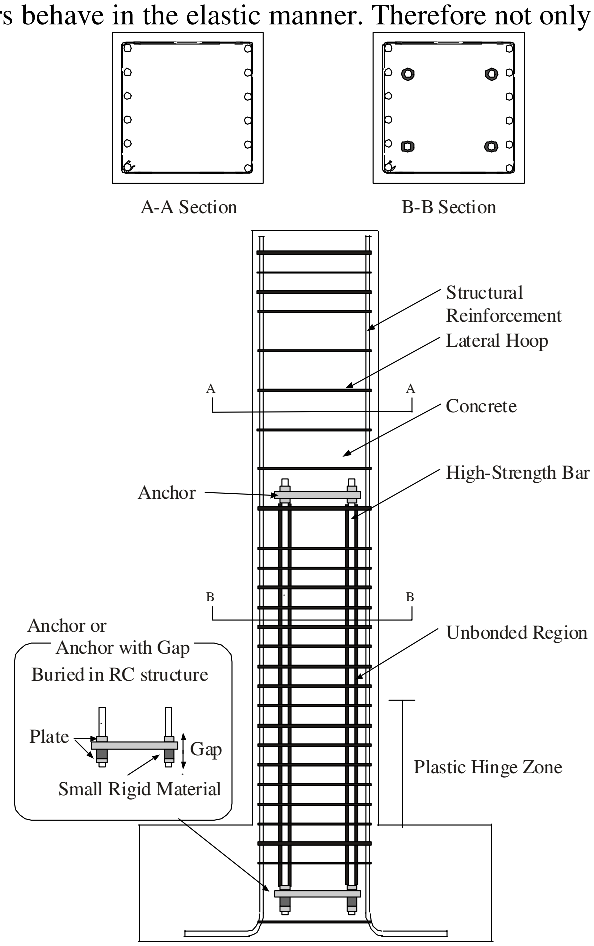


Figure 1 : Conceptual Model of UBRC Structure

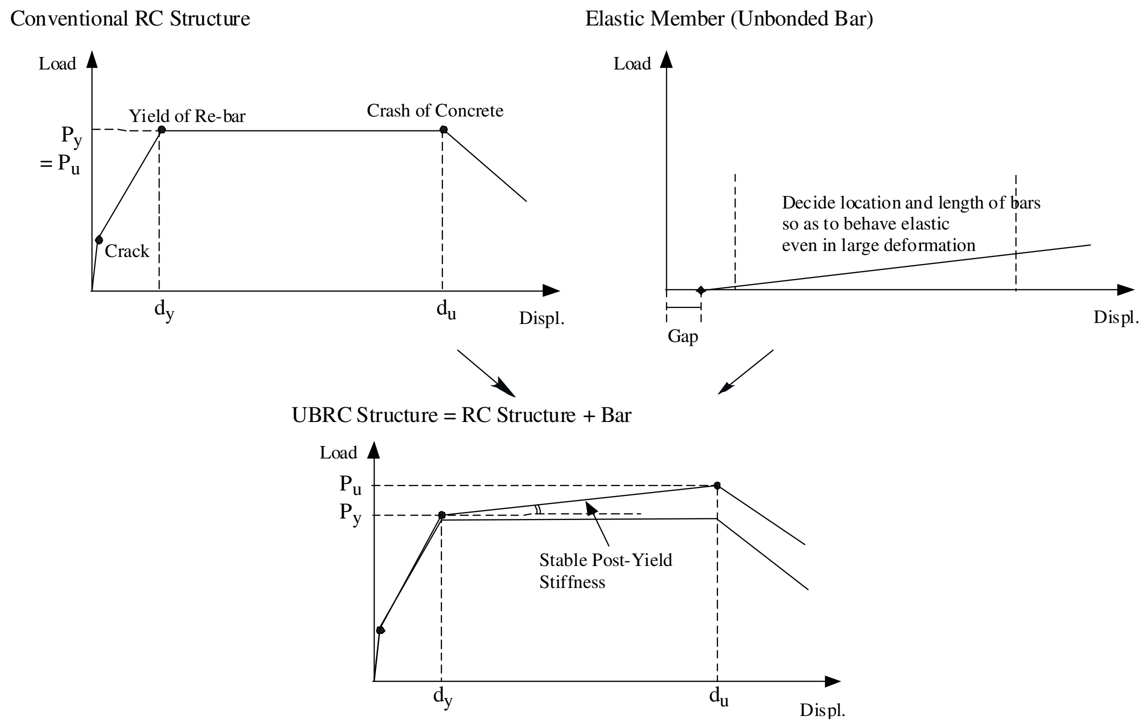


Figure 2 : Effect of Installation of Elastic Bars

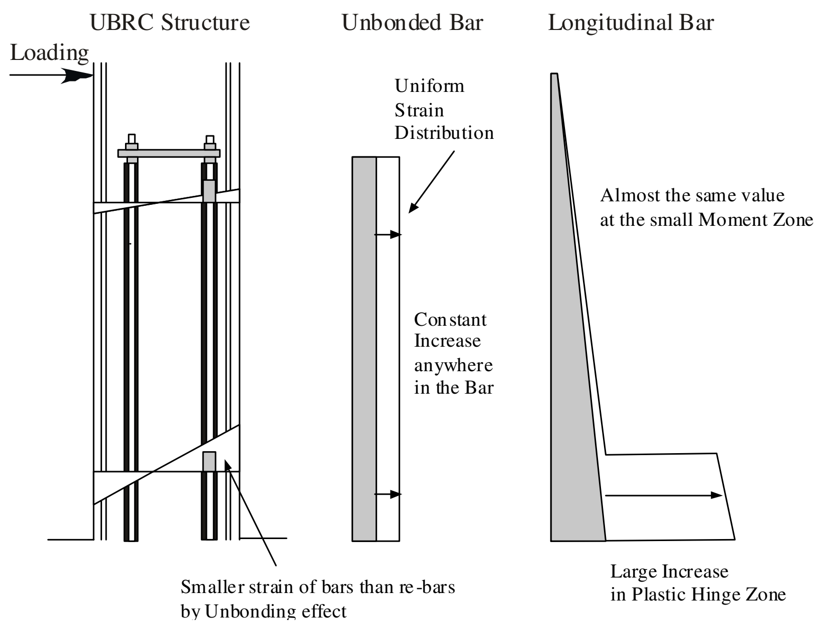


Figure 3 : Effect of Unbonding Treatment of Bars

yield stiffness in the large deformation, the effect of the bars in the small deformation is not so important. Therefore the gap is installed at the one end of the bars and controls the active elastic range of the bars (Figures 1, 2). With the gap, the UBRC structure can be realized by using the conventional material for bars.

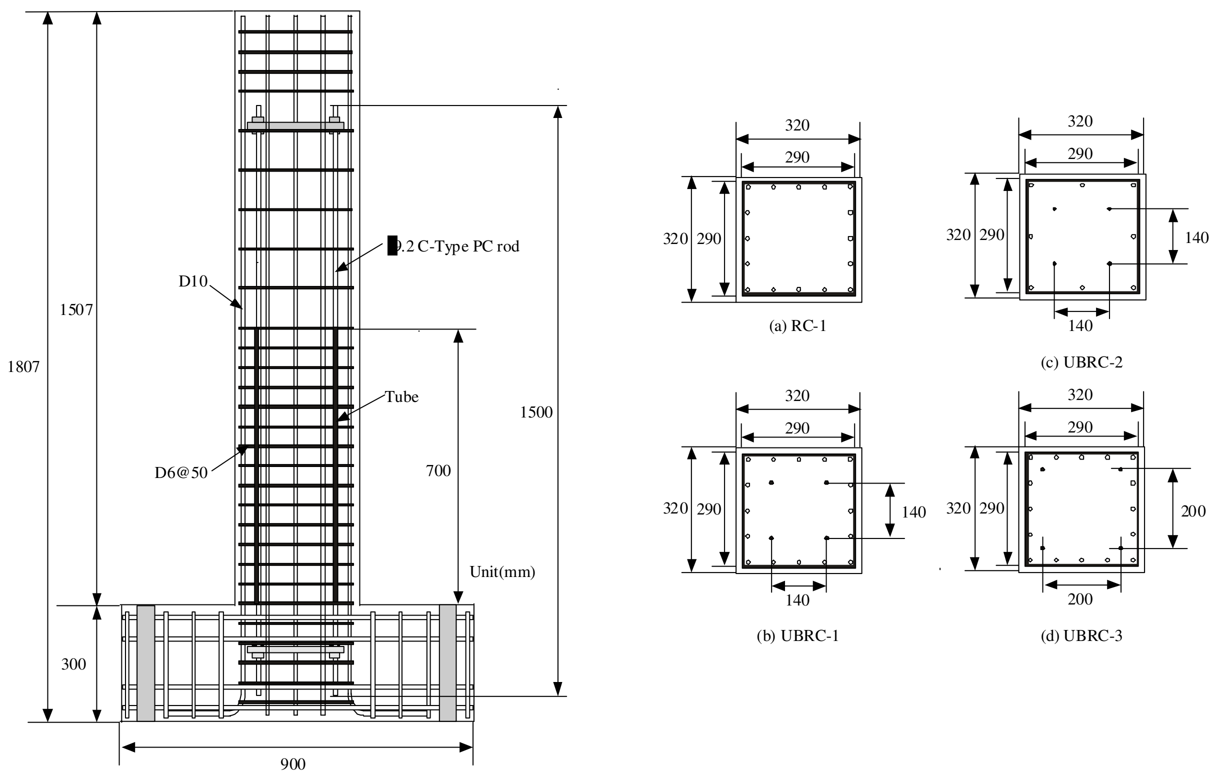


Figure 4 : Test Units

Next, the characteristics of the UBRC structure are explained from the viewpoint of the seismic response. The maximum displacement response of the conventional RC structure becomes large because the post-yield stiffness is almost zero. As the result, the residual plastic deformation after the earthquake becomes large. On the other hand, since the UBRC structure has the positive post-yield stiffness and the elastic members, it can be expected the stable seismic response. Moreover, because the unbonded bars do not yield, they can be expected to have the effective restoring force and reduce the residual deformation.

The UBRC structure can absorb the input energy like a RC structure. In addition to that, the installation of the unbonded bars can stabilize the seismic response and reduce the residual deformation.

FUNDAMENTAL CHARACTERISTICS OF UBRC STRUCTURE

Cyclic loading tests

Test units and loading system

In order to investigate the fundamental effects of unbonded bars, four different pier specimens are prepared. All specimens have the same dimensions, which is 320 mm square cross section, and is about 1500 mm height. Figure 4 shows the arrangement. The high strength PC tendons are used as unbonded bars, of which yielding strain is 5102 μ. And in order to tread the bars with unbonding, the bars installed in tubes. Their both ends are anchored to the piers. RC -1 is the conventional RC model. And UBRC-1 is the specimen with unbonded bars. UBRC-2 has fewer structural reinforcements than RC-1 to investigate roles of structural reinforcements on strength and absorbing energy in the UBRC structure. In order to obtain effects of location of the unbonded bars, UBRC-3 specimen has as same amount of bars as in UBRC-1, but at the different location.

The loading system is shown in Figure 5. In the system, the computer controls horizontal and vertical actuator. In the cyclic loading tests, axial stress was set to 1.46MPa. The horizontal dis-placement is applied at quasi-static rate in cycles with ductility factor of μ=1, 2, etc (δy=5.0mm).

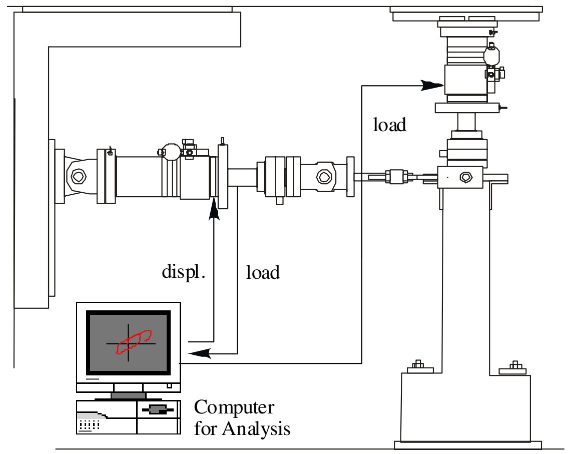


Figure 5 : Loading System

Test results

Figure 6 shows the load-displacement relationships. RC-1 shows almost perfectly elasto-plastic behavior. On the contrary, the others exhibit positive post-yield stiffness. The post-yielding stiffness of UBRC-1 is almost the same as that of UBRC-2, and UBRC-3 shows larger than others. This result suggests that the post-yield stiffness is defined by the location of bars in the section, in spite of the amount of conventional structural reinforcement.

Figure 7 shows the residual displacement, which is defined as the displacement of zero-crossing at unloading on the hysteresis loop from the maximum displacement. Those of the UBRC specimens are smaller than that of RC-1. In other word, even if piers are not prestressed such as PC piers, the residual displacement can be decreased only by installing elastic members in RC piers. The decrease of the residual displacement depends on the amount of unbonded bars. This trend is the same as PC piers.

The hysteretic absorbed energy is shown in Figure 8. From this figure, it is clear that the absorbed energy depends on the amount of structural reinforcement. That is, whereas only UBRC-2 has poor performance of absorbing energy, the others have the same performance in spite of the difference of the bar

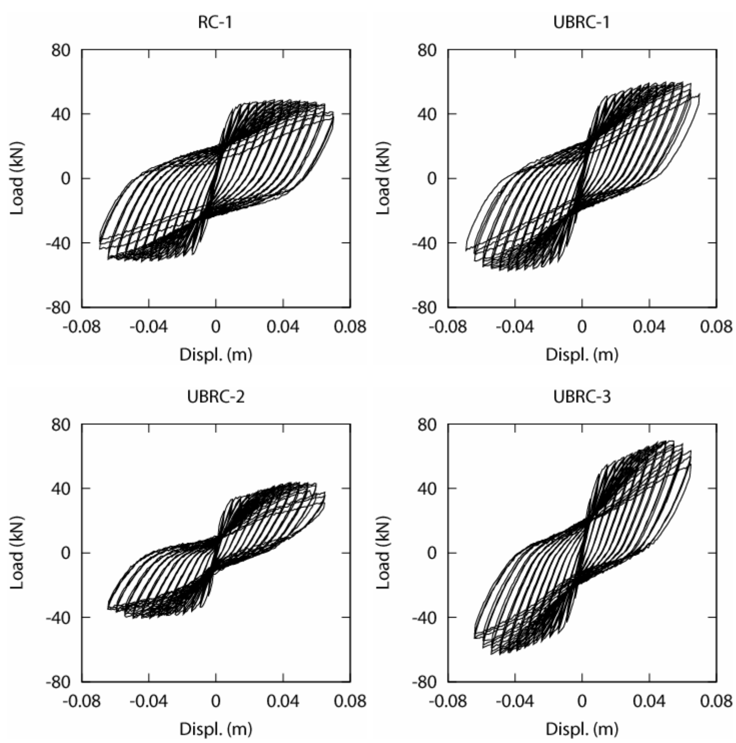


Figure 6 : Load-Displacement Hysteresis Loops

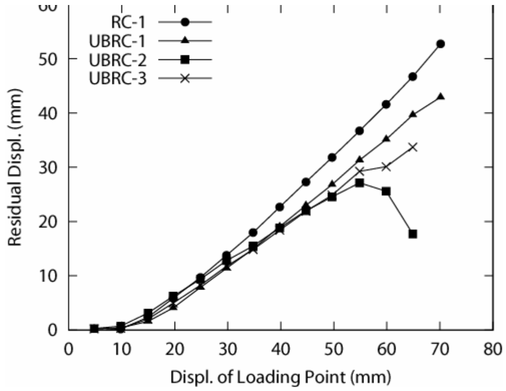


Figure 7 : Residual Displacement

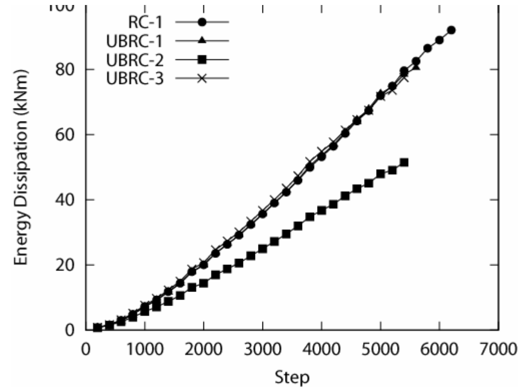


Figure 8 : Amount of Absorbed Energy

arrangement. The figure also exhibits that unbonded bar has no contribution on the energy absorption.

Analytical results for cyclic loading

Since the UBRC structure consists of the RC structure and the unbonded bars, the analytical model is also represented as the combination of the RC pier model (Fiber model) and the unbonded bar model. The UBRC element cannot be satisfied with the Bernoulli's assumption because the behavior of the bars is independent from that of the RC section between the anchors. The bars are deformed following the deformation of the RC element satisfying the compatibility condition. Therefore, the additional axial force and moment due to the unbonded bars are calculated by the compatibility condition of the deformed RC fiber element. And, these forces due to the unbonded bars are loaded at the anchor point of analytical model of UBRC pier.

The analytical results of the cyclic loading of Figure 4 are shown in Figure 9. Comparing with the experimental results, it is found that the numerical analyses can predict the effect of the unbonded bars very well.

Pseudodynamic tests

Prototype bridge and test units

The highway bridge used in this study is shown in Figure 10. The superstructure was the 5 span continuous steel I-girder, and the length of the span was 13 m, 40 m@3 and 13 m. The pier surrounded by the solid line in Figure 10 was selected as the prototype pier, and the behavior in the transverse direction was examined in this study. The pier has a 2.4 m square cross section and a height of 9.6 m [5]. 72-D34 were used as the longitudinal reinforcement and D19 transverse hoops were placed in the pitch of 300 mm. In order to investigate the seismic behavior of the UBRC structures, the pseudodynamic tests were carried out.

In the tests, we constructed three 1/7.5 scale pier models. The specimens had a 320mm square cross section and the loading height of 1.28m (Figure 11). In case of the UBRC pier, PC rods with the unbonding treatment were installed at 110mm from the center of the cross section. Both ends of the bars were anchored in the concrete mechanically.

The Kobe JMA record (NS dir.) (Figure 12) was used as input ground motion. By considering the similarity law, the seismic response of the real size structure is calculated in the computer. The total

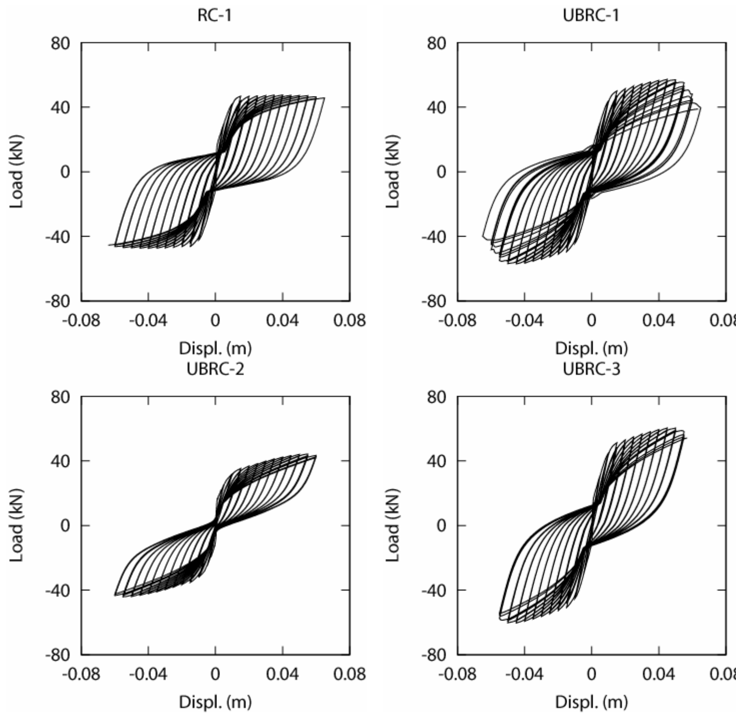
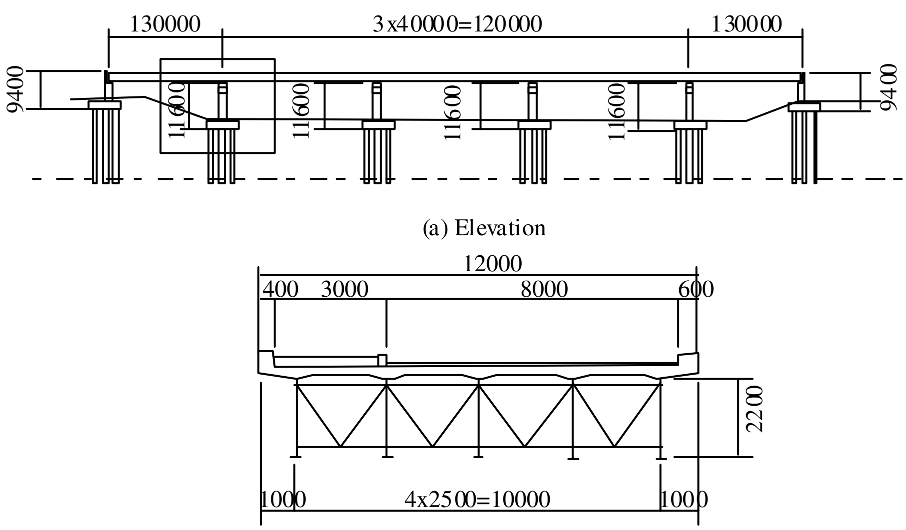


Figure 9 : Analytical results for cyclic loading tests



(a) Elevation

(b) Section of Girder

Figure 10 : Prototype Continuous Girder Bridge

weight of superstructure is 5000kN assuming it is the steel I-shape girder. In the tests, the axial stress was set to 0.88MPa.

Test results

The results of the RC and UBRC units are shown in Figure 13. These results are plotted for the prototype pier. From the load-displacement hysteresis loop of the UBRC unit, the positive post-yield stiffness can be observed. Also, the shape of hysteresis loop had the linearity compared with that of the RC unit. It is found that the effect of the unbonded bars can be recognized as well as the cyclic loading tests.

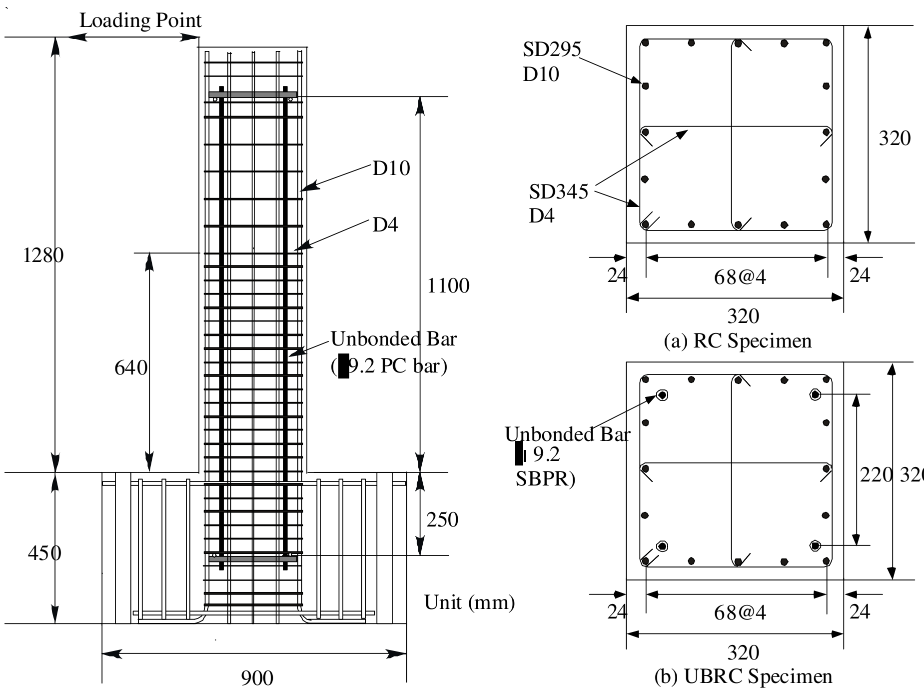


Figure 11 : Test Units

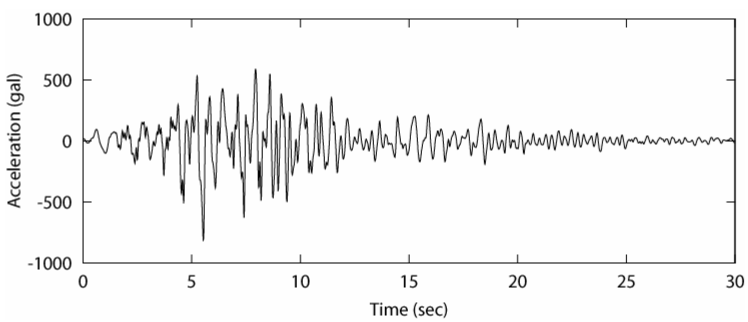


Figure 12 : Kobe JMA record

From the displacement time histories, the maximum responses in both cases of the RC and UBRC units are about 30 cm, and no significant difference in spite of the installation of bars in this case. But during 6, 7 seconds, the UBRC unit returned to the center position whereas the RC unit returned only to about 0.12 m. As the result, the residual displacement of the UBRC unit after the earthquake was only 1.5 cm whereas that of the RC unit was 5 cm. This result shows that by installing unbonded bars, the residual displacement after earthquake can be reduced and the hysteretic behavior can be stabilized.

RATIONAL SEISMIC DESIGN USING POST YIELDING STIFFNESS

After the Kobe earthquake, the two-level seismic design method was proposed. The design takes into account two types of design ground motion. For moderate ground motion (Level 1), bridges should behave in an elastic manner without essential structural damage. For extreme ground motion (Level 2), standard bridges should prevent critical failure, while important bridges should perform with limited damage. The required strength for Level 2 design is usually much higher than that for Level 1. RC piers are modeled as elasto-plastic load-displacement relationship with zero post-yielding stiffness by Highway Design Specifications [4] in Japan. Therefore although the optimal RC pier for Level 1 doesn't satisfy the

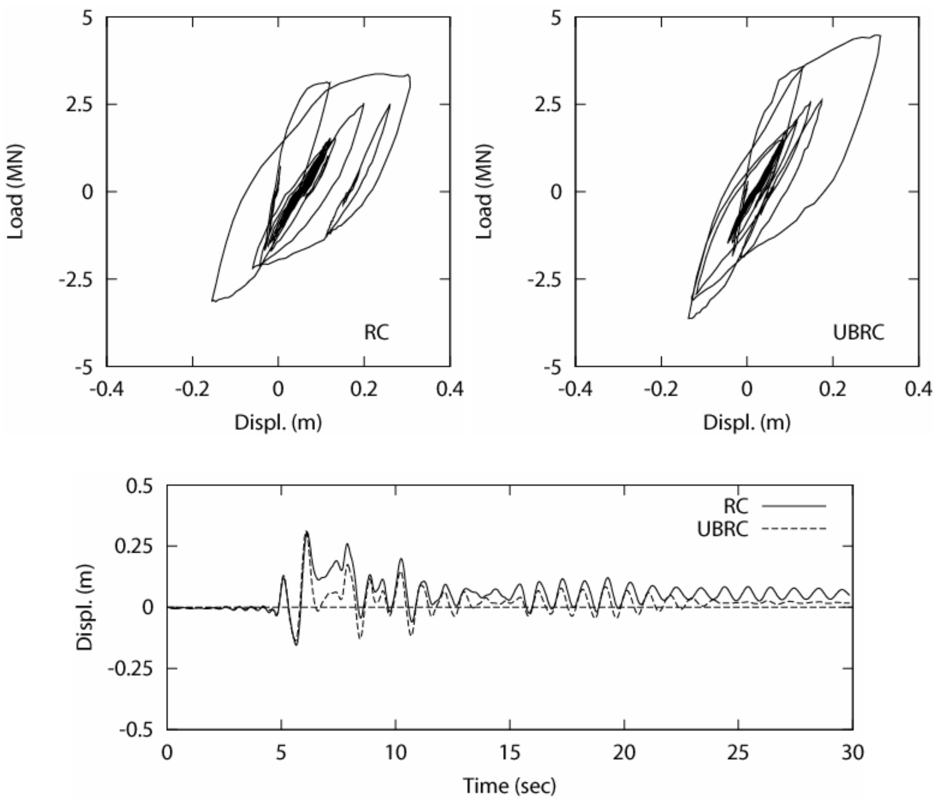


Figure 13 : Results of Pseudodynamic Test

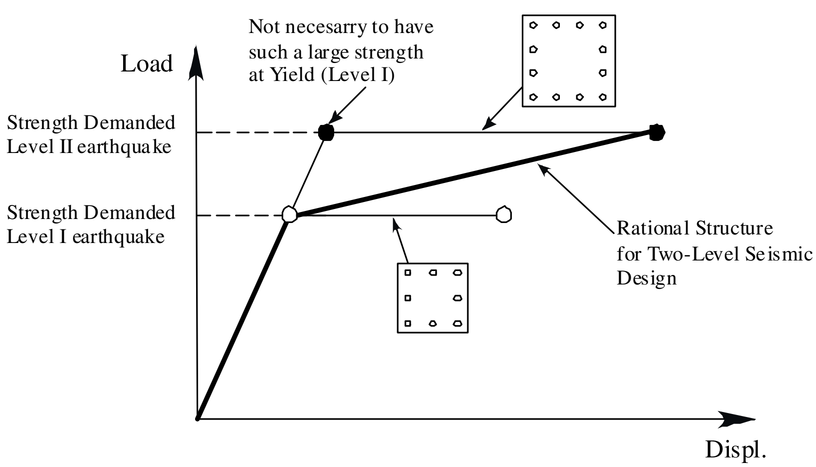


Figure 14 : Rational Load-Displ. Relationship in Two Level Seismic Design Method

requirements of Level 2 design and the section must be enlarged and/or the amount of the reinforcement must be increased. If the post-yield stiffness can be used effectively, the design for Level 2 becomes possible without increasing the section nor reinforcement from those determined by the Level 1 design. The load-displacement relationships with and without post yielding stiffness are schematically illustrated in Figure 14.

Small post-yield stiffness causes the large residual displacement by Level 2 earthquakes, which makes the repair works difficult after earthquakes. Therefore, the Specification recommends that the residual displacement evaluated by the following equation should not be larger then 1% of the height of piers.

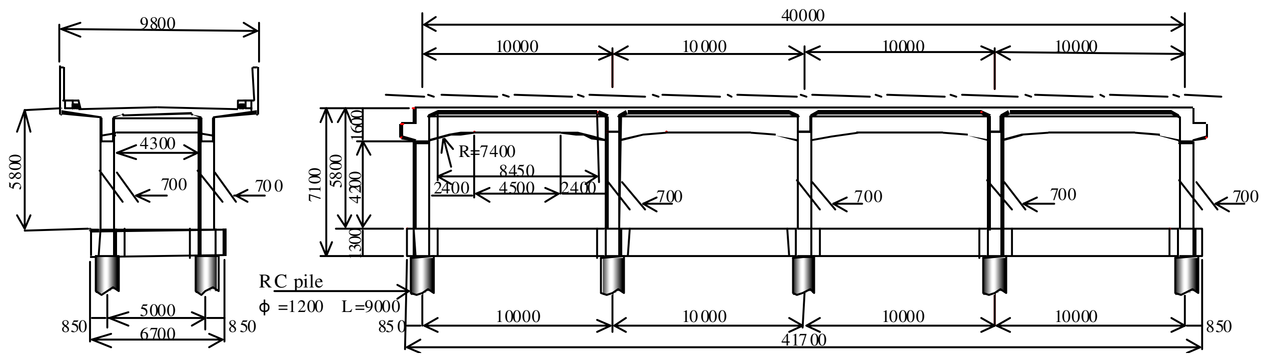


Figure 15 : Railway rigid frame viaduct bridge

$$\delta_R = c_R(\mu_R - 1)(1 - r)\delta_y$$

in which $\delta_R =$ residual displacement of a pier after earthquake, $c_R =$ modification factor, $\mu_R =$ response ductility factor of pier, $r =$ ratio between the pre and post-yield stiffness, $\delta_y =$ yield displacement. It is easily understood from this equation that the larger the ratio r is, the smaller the residual displacement becomes. That is, the piers with large value of r become to have higher seismic performance.

APPLICATION FOR RAILWAY STRUCTURE

Railway Rigid Frame Viaduct and Preliminary Design

The prototype railway rigid frame viaduct is the beam-slab style (Figure 15). In general, the rigid frame viaduct of the railway structure has the large amount of the reinforcement compared with the road highway bridges. Applying the UBRC structure to the viaduct, the reduction of the reinforcement is examined satisfying the two level seismic design [6].

In the seismic design of the railway structure, corresponding to the presumed levels of repair and reinforcement of structures that may be required after an intense earthquake, the seismic performance can be categorized into 3 levels as follows:

- Seismic Performance I: capability of maintaining the original functions without any repair and no excessive displacement occurring during an earthquake.
- Seismic Performance II: capability of making quick recovery of the original functions with repairs after an earthquake.
- Seismic Performance III: capability of keeping the overall structure in place without collapse during an earthquake.

For moderate earthquakes (called L1 earthquakes), the structural seismic performance I should be satisfied by all structures. For severe earthquakes (called L2 earthquakes), the seismic performance II should be satisfied by the important structures.

At the beginning of the preliminary design, the RC pier for L2 earthquakes is designed. The RC pier has a 700 mm square cross section and has 24-D32 longitudinal bars (Figure 16). The longitudinal bar ratio is

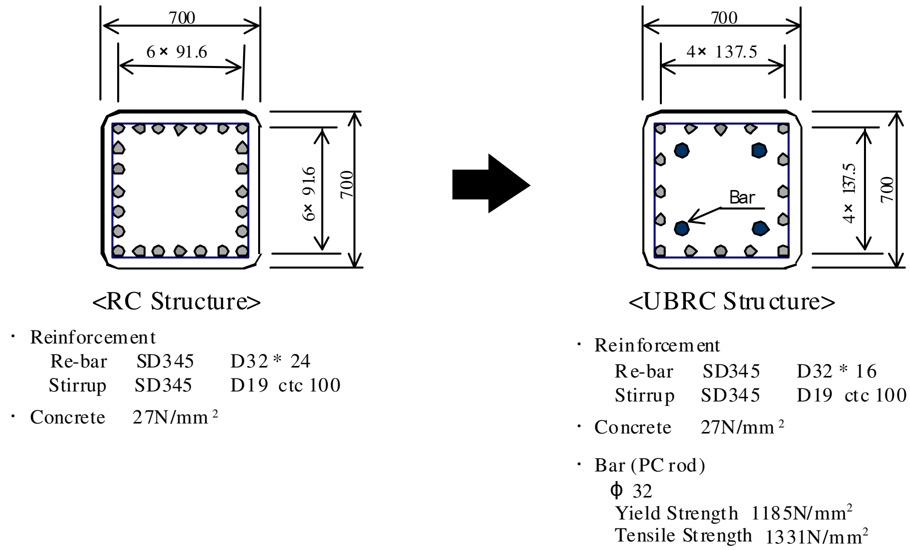


Figure 16 : Cross Section of RC and UBRC structure

about 3.9 %. On the other hand, the design for L1 earthquakes only requires 16-D32 longitudinal bars in the section (2.6 %). Therefore, for the design concept of the UBRC pier,

- Only the RC member can be satisfied with Seismic Performance I.
- The combination of unbonded bars and the RC member can be satisfied with Seismic Performance II.

Under this design philosophy, the UBRC cross section is decided as Figure 16.

Although it is also possible to reduce the cross section of the UBRC pier, but in consideration for the workability, in this preliminary design, the cross section is set to be the same as the RC member designed by L1 earthquakes.

Test Units and Test Procedure

In order to verify the performance of the UBRC pier designed according to the two level seismic design method, the cyclic loading tests were carried out. In these tests we constructed scaled models of the half pier of the rigid frame so as to become the similar moment distribution because the test setup is for single column specimens.

The RC test unit was the 1/2.1875 scale model of the RC pier in the preliminary design for L2 earthquakes (Figure 17). The number of longitudinal bars and the width between the bars were precisely scaled down. The UBRC test unit was also the 1/2.1875 scale model of the UBRC pier. The arrangement of the longitudinal bars was decided by the section designed by L1 earthquakes, and the configuration of unbonded bars was decided so that the maximum strength becomes larger than that of RC pier designed by L2 earthquakes. The longitudinal bars of the UBRC unit were fewer than the RC unit, and the 4-ϕ17 PC rods were placed in the corner of the cross section. Since the work space became large, the construction work became very easy. The analytical skeleton curves are shown in Figure 18. In the yield state, the restoring force of the UBRC unit is lower than that of the RC unit, but in the large deformation (0.05 m), the UBRC unit becomes stronger than the RC unit. In short, in this structure, the elastic behavior under L1 earthquakes was guaranteed by the RC structure and the required strength of L2 earthquakes was guaranteed by the post-yield stiffness due to the unbonded bars.

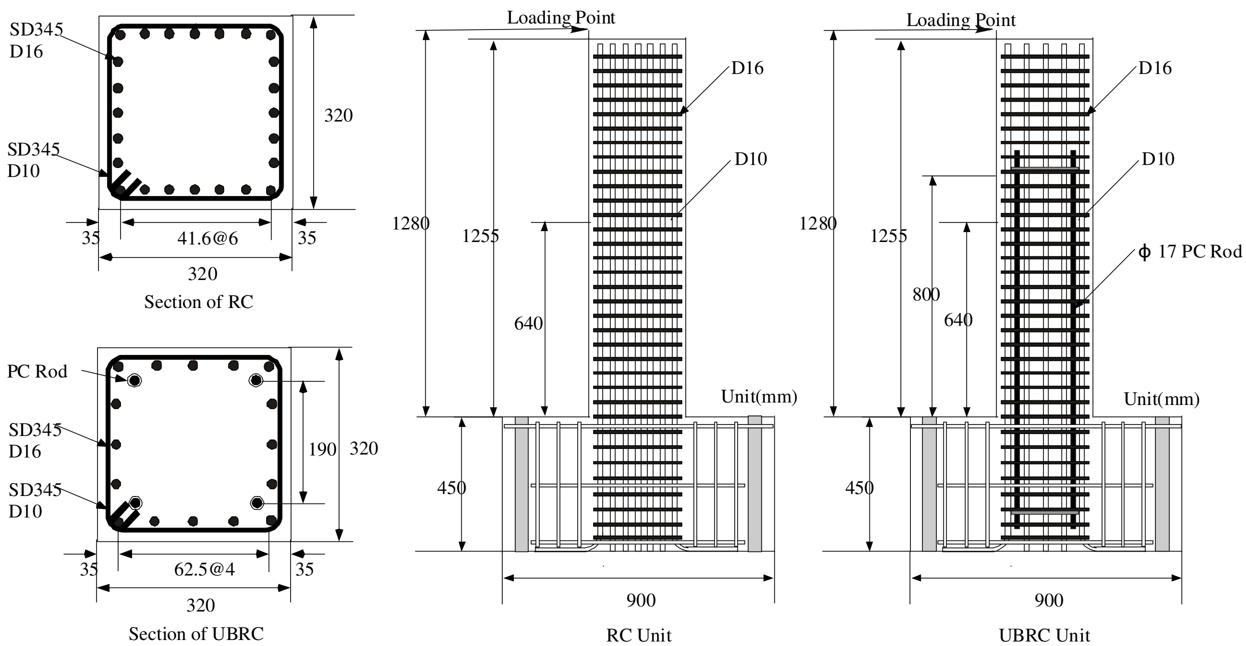


Figure 17 : Test Units

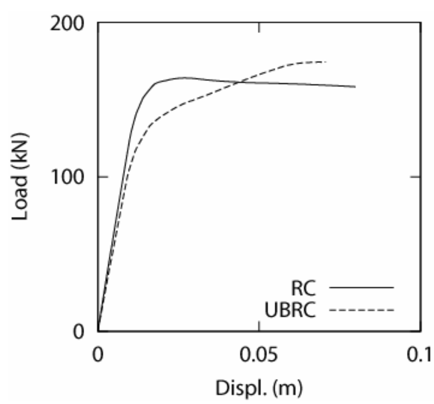


Figure 18: Analytical Skeleton Curves

In the experiments, the horizontal displacement was applied in cycles to displacement ductility factor each of $\mu = 1, 2$, etc. ($\delta y = 6$ mm). The axial stress was 1.24 MPa calculated from the superstructure of the prototype bridge.

Test results

Load - displacement hysteresis loop

The hysteresis loops of the RC and UBRC unit are shown in Figure 19. In case of the RC unit, the restoring force tended to deteriorate gradually after the maximum force (183 kN at the displacement of 0.041 m). On the other hand, the restoring force of the UBRC unit was 171 kN at the displacement of the maximum state of the RC unit, and it increased gradually up to 186 kN at the displacement of 0.077 m along to the stable post-yield stiffness branch. This result was satisfied with the required performance of L2 earthquakes.

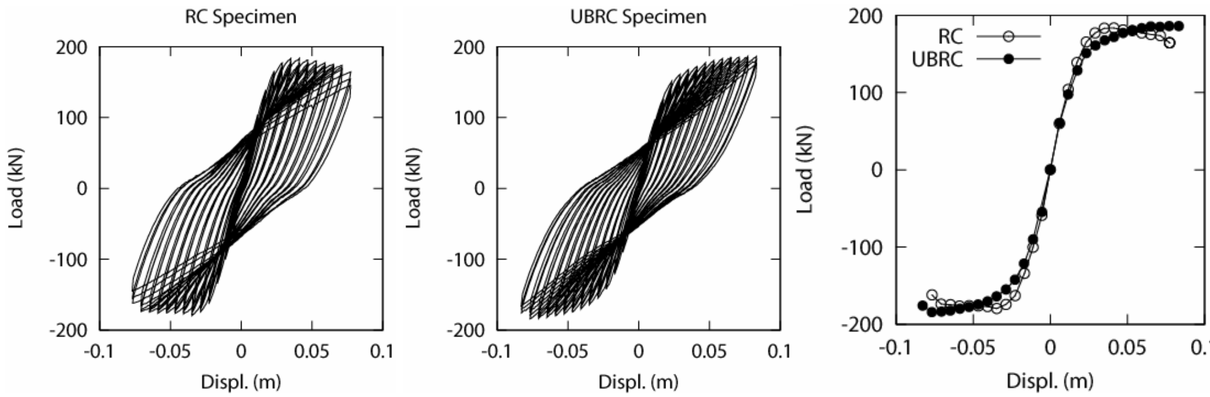


Figure 19: Load-Displacement Hysteresis Loops and Skeleton Curves

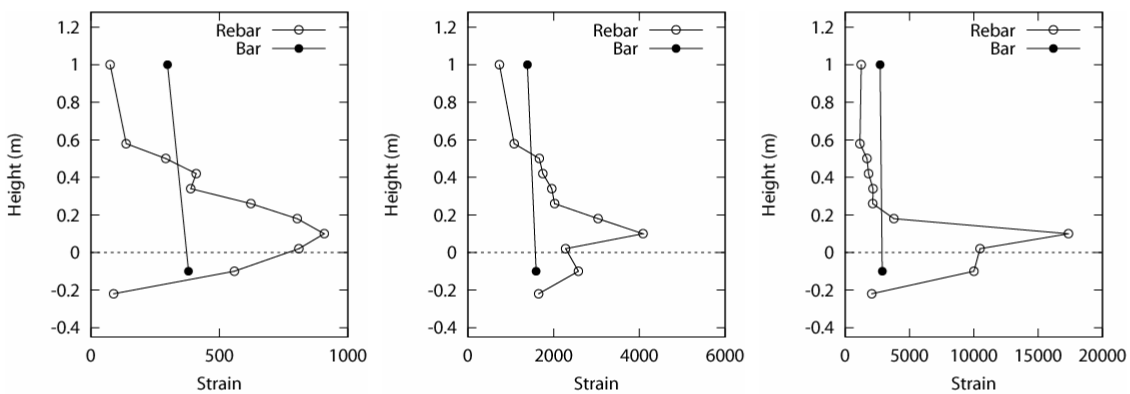


Figure 20 : Strain Distribution of Bars and Re-bars

And, the longitudinal bars of the UBRC unit yielded during the first 2 - 3 input cycle, at which the restoring force was 97 - 128 kN. Since the required strength for L1 earthquakes was 92 kN, this UBRC unit was also satisfied with the performance for L1 earthquakes.

From the results, it is found that the designed UBRC pier behaves in the elastic manner under L1 earthquakes and the restoring force at the ultimate state is satisfied with the performance for L2 earthquakes in spite of small amount of longitudinal reinforcement.

Unbonding Effect

Figure 20 shows the snapshots of the strain distribution of the unbonded bar and the longitudinal bar of the UBRC unit during the loadings (at 1st, 3rd, 5th cycle). If the bars bond to the concrete perfectly, the strain distribution becomes triangle (see the results of longitudinal bars). But the strain distribution of the unbonded bars became constant even in the deformation whereas the longitudinal bar had yielded and the plastic hinge zone was formed. And, finally in this test, the bars remained in elastic. From the results, it is clear that the unbonded bars treated by the tube can worked well even in the large deformation.

Residual Displacement

The comparison of the residual displacements is shown in Figure 21. Since the restoring force of the UBRC unit was smaller than that of the RC unit in the small deformation, the residual displacements were almost the same. And as the deformation became large, the residual displacement of the UBRC unit

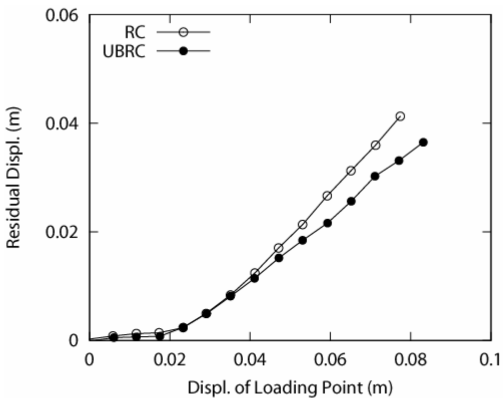


Figure 21: Residual Displacement

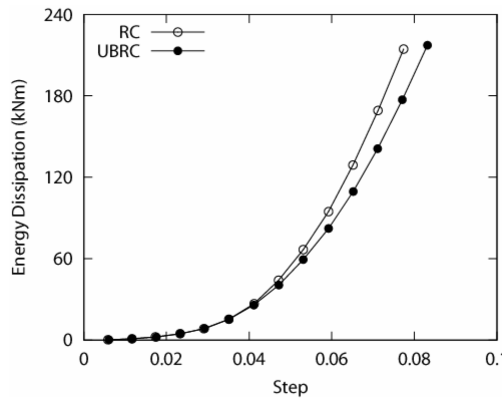


Figure 22: Absorbed Energy

became smaller than that of the RC unit. This phenomena can be acceptable because we want to avoid the large residual displacement over the 1 % of the height. This result suggests that the elastic restoring force due to the bars worked well.

Performance of Absorbing Energy

The accumulation of absorbed energy is shown in Figure 22. Since the amount of longitudinal reinforcement of the UBRC unit was lower than that of the RC unit, the capacity of the energy absorption of the UBRC unit was inferior to the RC unit. This result seems to show that the UBRC pier has the low seismic performance, but it is not true. The large amount of hysteretic absorbed energy means the large plastic deformation of the pier. For the concrete structure, it means to be the yield of the longitudinal bars and the crush of the concrete. If the structure with small failure has the equivalent seismic performance of the RC structure, the structure has advantage for the usability and the repairability after earthquakes. Since the UBRC structure can be satisfied with the required performance in the load-displacement relationship, the UBRC structure has the high seismic performance.

CONCLUSION

In this study, the UBRC structure was proposed as the high seismic performance structure in the next generation, and the concept and background were described. And, the cyclic loading and pseudodynamic tests were carried out in order to obtain the fundamental performance. Furthermore the applications of the UBRC structure to the railway bridge pier are presented. From this study, the following results are obtained:

- By installing the unbonded bars, it is possible to easily realize the RC structure with the stable post-yield stiffness.
- The UBRC structure has small residual displacement in comparison with the conventional RC structure by the bar effect.
- The capacity of the energy dissipation is only depend on the amount of longitudinal reinforcement, and never change due to the installation of bars. That is to say, the optimal amount of longitudinal reinforcement for the UBRC structure is the equivalent to that of RC structure in order to expect the energy dissipation.
- From the results of the cyclic loading tests, it can be obtained the equivalent results to the principle got by installing the elastic member into RC structures. This structure can be realized only by

installing unbonded bars into RC structure. Therefore this structure can be constructed with simple and easy construction works and low cost.

- From the results of the pseudo dynamic tests, it is found that the seismic response of the UBRC structures is stable. Especially the residual deformation after earthquakes is certainly small by the combination of the small maximum deformation and the effect of elastic members.
- In the pseudo dynamic tests it is also recognized the bars' effect (stable post-yield stiffness and the small residual deformation). Considering with the easy construction and the low construction cost, the UBRC structure has the high seismic performance.
- The philosophy of the two level seismic design method can be realized easily and rationally by applying UBRC structures with the stable post-yield stiffness.
- The railway RC structures have large amount of longitudinal reinforcement, but applying UBRC structures, the amount of reinforcement can be reduced. Since the RC part of the UBRC structure is decided by L1 earthquakes, it has the economical section. And cooperating with the unbonded bars, it can resist L2 earthquakes. The reduction of reinforcement also make the construction work easy.

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