# Research & Development on High Seismic Performance Bridge Structures

by

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ABSTRACT

This paper presents current research and development project on high seismic performance bridge structures in which the seismic performance is significantly enhanced within reasonable cost efficiency than usual structure design. New structural concepts and ideas including high strength structures using high strength materials, high ductility structures using effective confinement measures, high constructibility structures, damage controlled structures, high repairablity structures, and damage detection measures, are briefly presented.

KEYWORDS: Highway Bridges, High Seismic Performance, High Strength Structures, High Ductility Structures

## 1. INTRODUCTION

In the usual seismic design of structures, the structures are designed so that the structures using concrete and steel resist against the design earthquake force. However, it is difficult and is not a reasonable design to prevent the damage completely against strong earthquake ground motions from the viewpoint of cost. Therefore, the ductility design concept has been employed in the usual design of structures, in which plastic hinges is introduced at desirable sections during a large earthquake with low probability to occur and the earthquake energy is absorbed at the plastic hinge sections, then the necessary seismic performance of total structures is attained. Since some damage can not be prevented during a large earthquake, the structures which does not suffer significant damage, and the structures with easy damage detection and high repairability function is effective for the early recovery of the function of damaged infrastructures.

This paper introduces current research and development project on the high seismic performance bridge structures including new structural concepts and ideas such as high strength structure using high strength materials, high ductility structures using effective confinement measures, high constructibility structures, damage controlled structures, high repairablity structures, and damage detection measures.

## 2. CONCEPTS OF HIGH SEISMIC PERFORMANCE BRIDGE STRUCTURE

### 2.1 Basic Concepts

Although there are various aspects on the high seismic performance structures, the following 3 points are considered in this study.

1) Damage free structures or damage controlled structures (Enhancement of elastic limit and/or ultimate limit)

2) Self-diagnosis structures for damage detection (Intelligent structures)

3) High repairablity structures

**Table 1** shows some example ideas for these high seismic performance bridge structures. There are two concepts including the employment of new materials and intelligent materials, and structural modifications.

In this study, the concept 1) in the above as well as high constructibility was focused for the reinforced concrete structures.

### 2.2 Damage Free Structures

To prevent structural damage, there are two general concepts as 1) enhancement of strength and ductility, and 2) reduction of earthquake force.

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The simple way to enhance the strength is to use high performance materials including high strength materials and high elastic materials. The selection and the arrangement of high performance materials are dependent on the objectives on what the enhancement is necessary. For example, as shown in **Table 1**, there are some concepts including high strength structures, high elasticity structures, high rigidity structures, and high ductility structures.

On the other hand, seismic isolation is a typical concept to reduce the seismic inertia force. The improvement of effectiveness of current seismic isolation design is expected. The rubber type isolation bearing is popular for the seismic isolation design, however, a sliding type isolation bearing is much effective to control the seismic force and displacement. If the displacement response can be controlled by appropriate devices, the sliding type isolation can surely control the seismic force to transmit to substructures.

Also, the collision seismic isolation concept, in which the earthquake vibration energy is absorbed by the collision between adjacent girders and/or between girder and abutments, may be applicable to reduce the seismic response of girders then the seismic force to transmit to substructures.

The displacement isolation concept is to prevent falling down of the superstructures even when the large surface fault displacement is developed. The displacement may be developed in 3 dimensionally, i.e., up, down and horizontally. The expansion girders and emergency expansion support seat are applicable against a certain level of the surface fault displacement.

### 2.3 Self-Diagnosis Structures for Damage Detection

Supposing the highway network just after the large earthquake, the emergency patrols are made to detect the outline of damage in the affected area as soon as possible in order to check the safety of the public traffic. At this stage, it is necessary to check the outline of heavy damage of the important facilities and to judge the damage causing the secondary damage and the continuous serviceability in a short time as much as possible. In the current damage inspection, the clear and heavy damage including the crack and slope failure of road surface, significant inclination and crack of substructures of bridges are the points to be detected firstly by visual inspection. Then, the damage degree is judged and the necessary emergency treatment such as route closure is made. However, the complex structures are increasing and the visual inspection is not applicable during night time and is not applicable for structural portion underground or under water in the river and sea. The current judge of the damage degree is made based on the outside visual check, so the accuracy is not the same depending on inspectors. In these cases, it will be effective to use the sensors as shown in **Figure 1**. Just after the earthquake, the patrol team can judge the damage by using the tester system to check the sensor data. It is effective for the earthquake damage investigation to detect the damage easily and objectively by any inspectors.

### 2.4 High Repairablity Structures

As high seismic performance structures with high repairablity concept, there is a possibility to employ the structures with high restoration devices including shape memory materials and the structures with hysteresis characteristics as high secondary stiffness so that the residual displacement be less. For the control of the hysteresis characteristics, for example for reinforced concrete structures, high strength re-bars such as PC rods are applicable.

Also, there is a possibility to employ the damper with self-recovery characteristics to decrease the residual displacement of superstructures. For this purpose, the shape memory materials and mechanical trigger-type dampers are applicable.

## 3. SOME OF EXPERIMENTAL AND ANALYTICAL DEMONSTRATION OF RESEARCH RESULTS

### 3.1 Oval Shape Interlocking Hoops

In order to reduce the amount of re bars and cost of structural members, the columns with interlocking hoops, of which the concept is quite popular in US, are attractive. To widen the application of interlocking hoops, new idea has been proposed to apply the concept for rectangular columns with any shape of section. It is oval shape interlocking hoops which can be applicable for any shape of rectangular columns including square to wall type columns.

Oval shape interlocking hoops enable to make simpler than the usual one as shown as **Figure 2**. Comparing a column with 3 series of circular interlocking hoops, the amount of re-bars can be reduced and the constructibility can be improved.

When the oval shape hoops are employed, the confinement effect may be reduced than the circular hoops because of the decrease of the confinement effect. The experimental study through cyclic loading tests of model columns was conducted to know the difference on the strength and ductility between circular and oval type confinement effect.

**Figure 3** shows the model columns with the scale from the real structure of about 1/3 to 1/5. Five types of specimens were tested and compared. Specimens R and C are rectangular and circular columns with the same confinement effect, respectively. Specimen IL is two circular interlocking columns with bending diameter of 268mm, the distance between two circular hoops of 400mm which is 1.5 times of the bending diameter. On the other hand, Specimens OV-1 and OV-2 have the width of columns of 1200mm and 1400mm, respectively. Two oval interlocking hoops are used. It should be noted that the specimen OV-2 corresponds almost to the width of three circular interlocking hoops.

Longitudinal re-bars of D10 are used and the re-bar ratio in the section is 1%. Hoop ties of D6 are arranged with width of 75mm. The cyclic loading tests were made as shown in **Figure 4**.

**Figure 5** and **Figure 6** show the damage after the experiment and the comparison of the force-displacement relation obtained through the cyclic loading tests. Based on the test results, almost the same ductility performance was obtained for all specimens with rectangular, circular, and three types of interlocking hoops.

3.2 High Constructibility Re-bar Arrangement

Reinforced concrete columns which is expected to have nonlinear behavior during a large earthquake, the hoop and tie re-bars play a role of confinement effect of core concrete and buckling of longitudinal re-bars as well as the effect of shear enhancement. To assure these effects during ductile behavior, the fixing anchorage of hoop and tie re-bars is essential. In the current seismic design specifications, it is generally required to have the 135 or 180 degree hooks at both ends of re-bars. It is important to keep the fixing effect of hoops and ties even when the cover concrete is spalled-off. However, if such fixing hooks are used for both ends of hoops and ties, the constructibility is significantly affected. From the viewpoint of construction, 90 degree hook is much easy to construct. But based on the cyclic loading tests with cross ties with 90 degree hooks, the ductility decrease by a certain level and once cover concrete was spalled-off, the confinement effect of core concrete and longitudinal re-bars were significantly decreased.

Therefore, simple but effective ideas on the fixing anchorage of re-bars with high constructibility are proposed. **Figure 7** (a) shows a oval shape fixing devise to increase the fixing effect of 90 degree hook. **Figure 7** (b) shows a two rings device which has the same anchorage effect of 180 degree hook. The effectiveness of the confinement was tested through cyclic loading tests. **Figure 8** shows the test columns and **Figure 9** shows the fixing devise details. **Figure 10** shows the test results the test results. Almost the same confinement effect was verified to be obtained.

3.3 High Strength Structures

To decrease a section and amount of materials of structures, research on the reinforced concrete structures using high strength concrete and re-bars has been made. In the current design specifications, concrete with the maximum strength of 30N/mm$^2$, and re-bars of SD345 are specified to be used for the construction of substructures. In the research, the use of concrete of strength of 60N/mm$^2$ and re-bars of USD685/785 is focused. The axial compression tests to develop stress-strain model has been was made and the cyclic loading tests of columns were made to develop the ductility evaluation model. The combination of interlocking hoops and high strength materials has been also studied.

To enhance confinement effect and then to increase ductility capability or to decrease the hoops, the arrangement of prestressed cable/rod/precast members instead of usual hoops has been studied. The axial compression tests with prestressing to develop stress-strain model was made and the cyclic loading tests were made to develop ductility evaluation model.

### 3.4 Damage Control Design

To increase the ductility, generally the number of hoop and cross ties is increased to enhance confinement effect. However, the confinement effect exceed a certain level, the plastic hinge length significantly decreases and the damage concentrate in a certain shallow length. It results in the decrease of the ductility characteristics. Therefore, the plastic hinge is introduced not in one section but is distribued in several sections. Then the damage of each section is decreased at thy same displacement capacity. So, the total ductility performance can be enhanced. One method is shown in **Figure 11**, in which the damage control re-bars is arrange to introduce the plastic hinges at two sections. The plastic hinges are controlled and introduced surely in two sections. Other method is the use of unbonded fixing in the footing to increase the ductility by pulling-out characteristics of longitudinal re-bars from the footing. To verify the effectiveness of these idea, the cyclic loading tests were made.

**Figure 12** shows the analytical approach to evaluate the post peak behavior. The modeling or re-bars considering the buckling effects are proposed.

### 3.6 Damage Detection by Intelligent Sensor

Just after the earthquake, to detect the significant damage the visual inspection is made. To judge the damage degree accurately from the outside visual inspection, the knowledge and the experiences on the damage evaluation is required. And if the visual inspection can not be made, the damage evaluation is impossible. To solve these difficulties, the sensor system is studied. The continuous monitoring system is desirable but the maintenance of such system becomes one of the difficulties. Also if the system becomes large, the operation cost becomes high. Therefore, the maximum memorize type sensor or sensor with memory function by low cost is essential to be widely used in the practical. The development of sensor system and the damage detection system is now under development. **Figure 13** shows the shake table test to develop the damage evaluation system. The damage was detected by the change of natural period of structures. **Figure 14** shoes that the ductility response was well evaluated by this system.

## 4. CONCLUSIONS

This paper presents current research and development project on the high seismic performance bridge structures. The concepts andn ideas are briefly introduced and the some of the tests results are demonstrated. The outcome oft these research is expected to be used in the practical use.

## 5. REFERENCES


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Table 1 Possibility of High Seismic Performance Structures

| Category | | Perofornance | Structural Image fo High Perfonnance Strucutres |
|---|---|---|---|
| Damage Free Structures or Damage Controlled Structures | High Perofonnance | High Strength | ･High Bending Strength or High Shear Strength Structures using High Strength Materials (High Strength Re-bars, PC Steel, High Strength Concrete, New Materials, etc.) |
| | | High Stiffness | ･Structure with Wide Elastic Range using High Strength Elastic Materials such as PC Steel and other High Elastic Materials |
| | | Super Elasticity | ･Super Elastic Structure with displacement absotption members/devises |
| | | High Ductility | ･High Ductility Strucutre with enhanced characteristics of confinement of compression side, of tension and low-sycle fatigue in tesnion side<br>･Damage distrebution Structure |
| | Mitigation of Eartqhauhke Effcet | Reduction of Inertia Force ' (Seismic Isolation) | ･High Seimsic Isolation Structures (High Performanec Sliding Isolation Bearing)<br>･Imapact Isolation Structures with collision between girders or between girder and abutment |
| | | Reduction of Effcet of Ground Fault Displacement (Displacement Isolation) | ･Expansion Girder Structure<br>･High Performance Expansion Structure<br>･Support System against Large Fault Displacement |
| Self-Diagnosis Structures | | Self-diagnosis Structures | ･Monitoring Structiure with Sensor Network<br>･Intelligent Structure with Intelligent Materials/Sensors (CFGFRP, TRIP Bars, etc.) |
| High Repairability Structures | | High Repairability struutcre | ･High Recovery Strucutre to decrease Residual Displacement<br>･Structure with High Secondary Stiffness to decrease Residual Displacemet<br>･Damage Distrebution Structure<br>･Self-repairable Materilas to recovery from Residual Displacement |

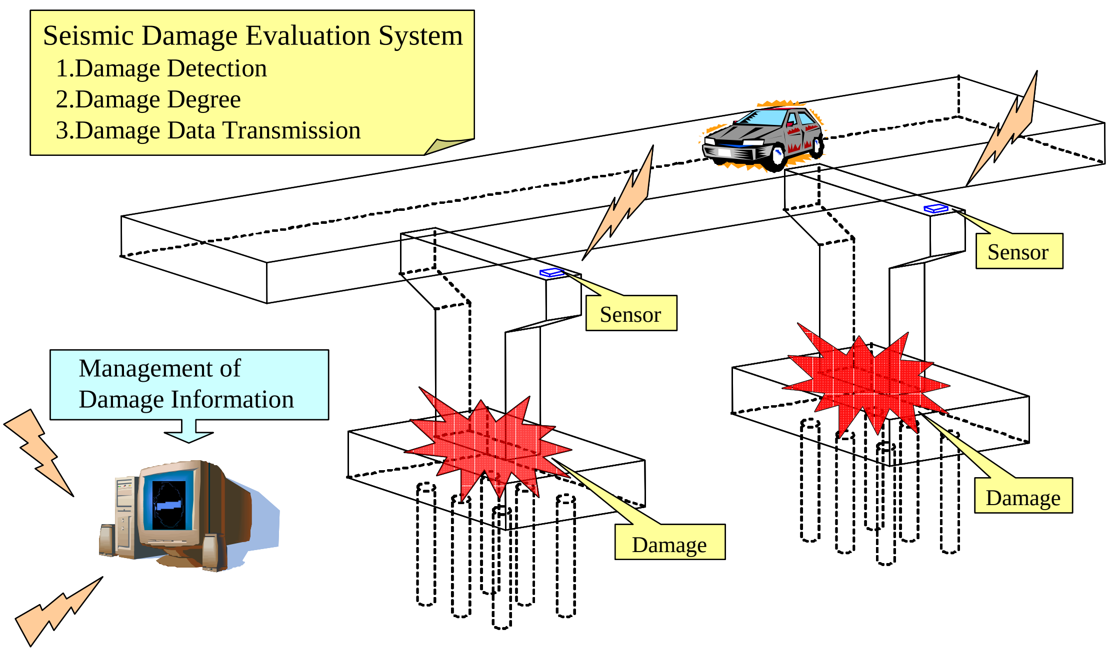



Figure 1 Seismic Damage Evaluation System

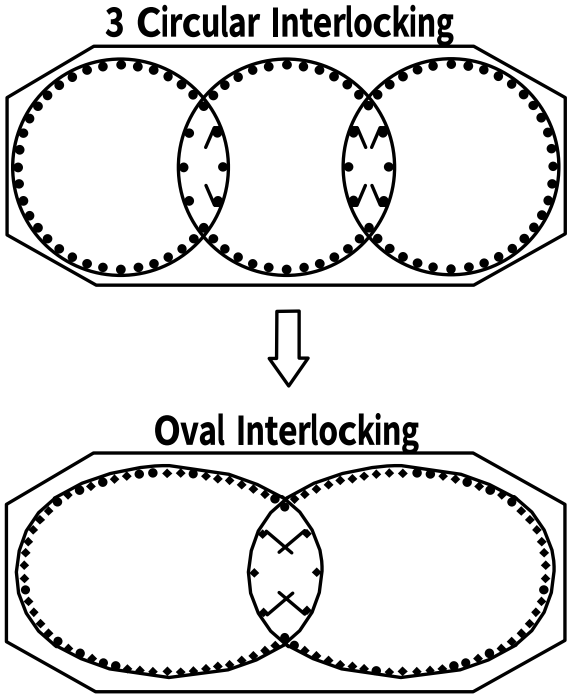



Figure 2 Oval Shape Interlocking Hoop Systems

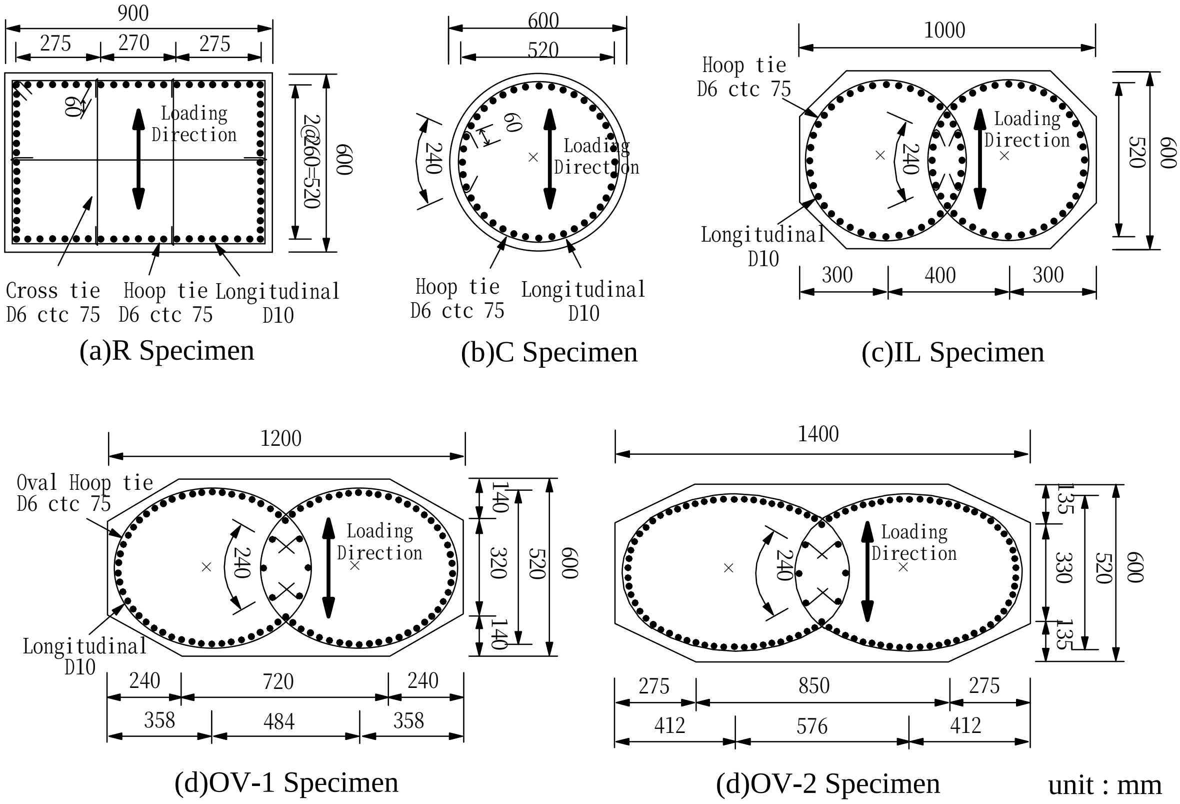
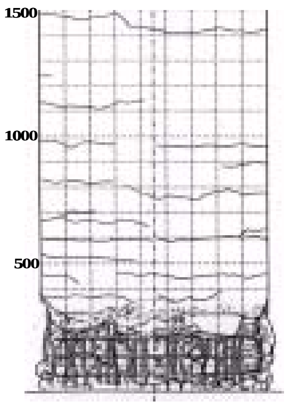
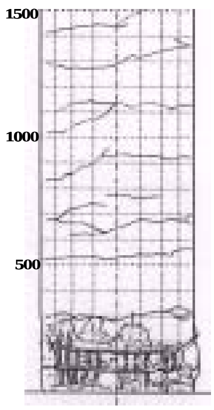



Figure 3 Experimental Specimens

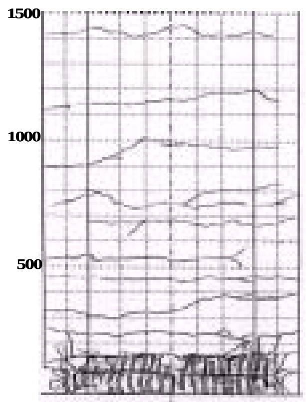
Figure 4 Cyclic Loading Tests



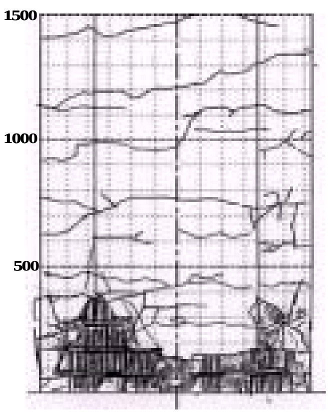

(a)R Specimen



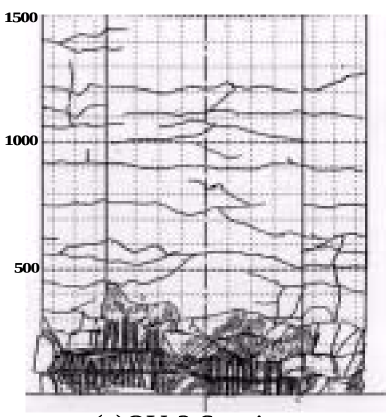

(b)C Specimen




(c)IL Specimen



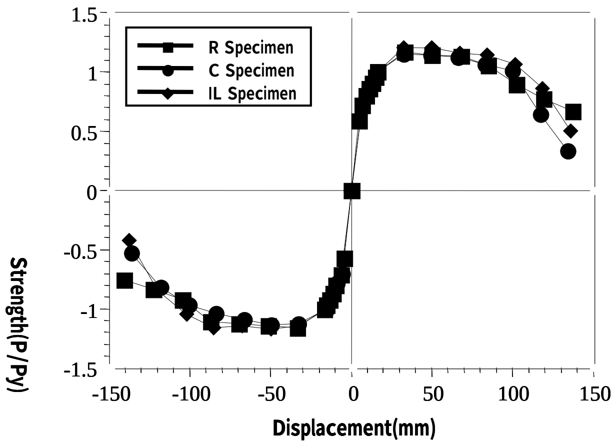

(d)OV-1 Specimen



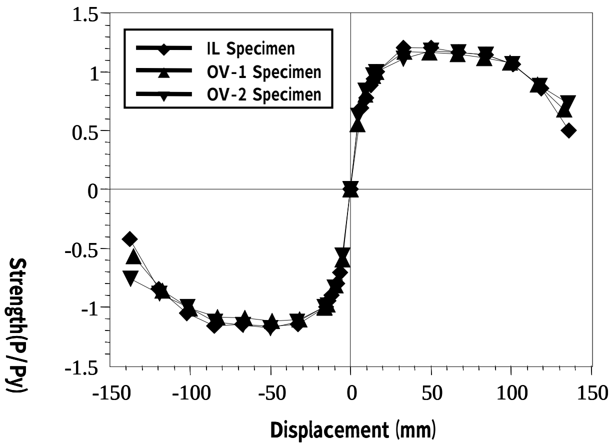

(e)OV-2 Specimen

Unit : mm

Figure 5 Damage after Cyclic Loading

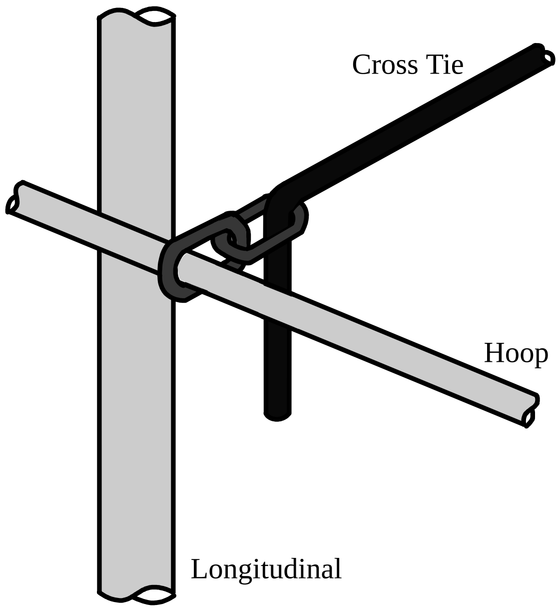



(1) Comparison between
Rectangular and Circular Hoops

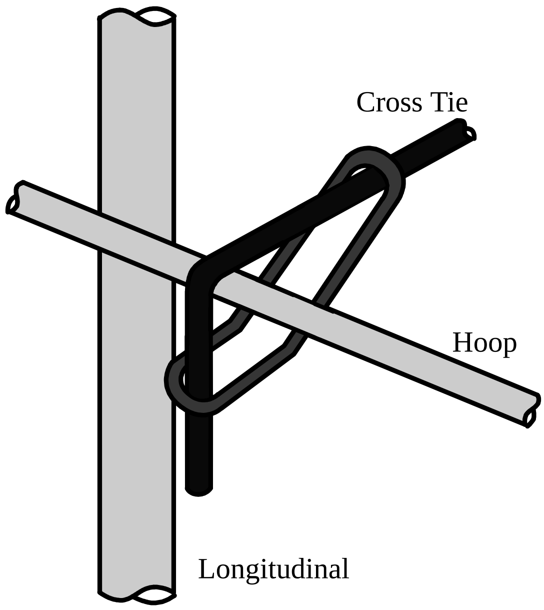



(2) Comparison between
Circular and Oval Interlocking Hoops

Figure 6 Force Displacement Relation




(1) 90 Degree Hook with Oval Ring Type




(2) 90 Degree Hook with Chain Ring Type

Figure 7 High Constructibility Re-bar Details

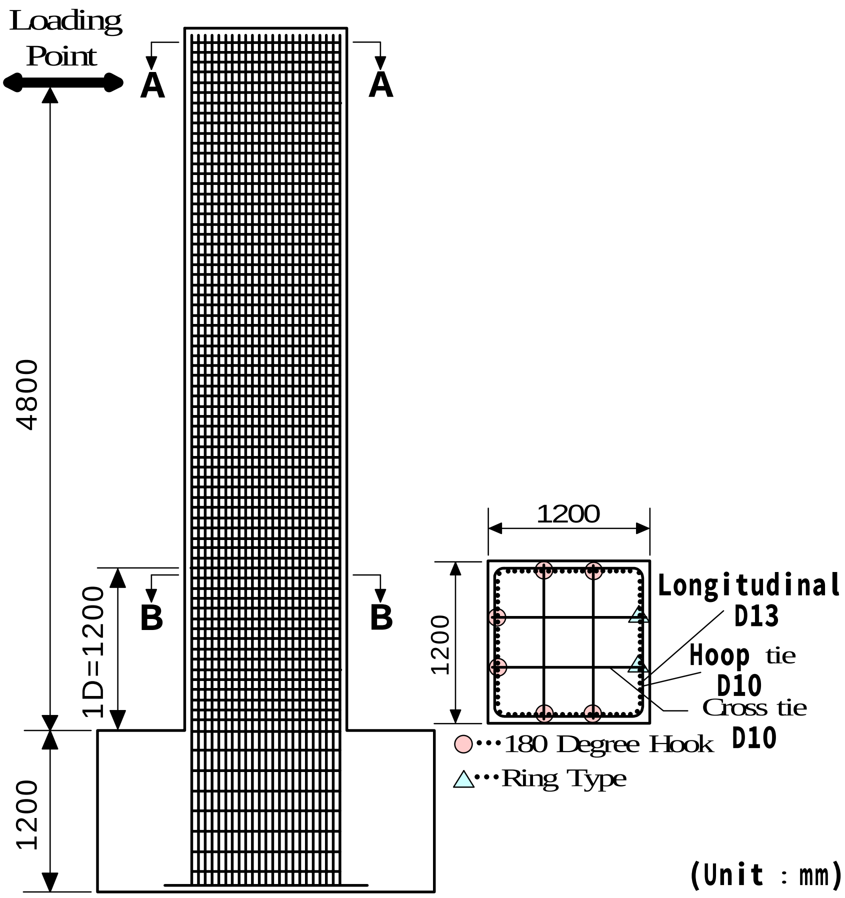
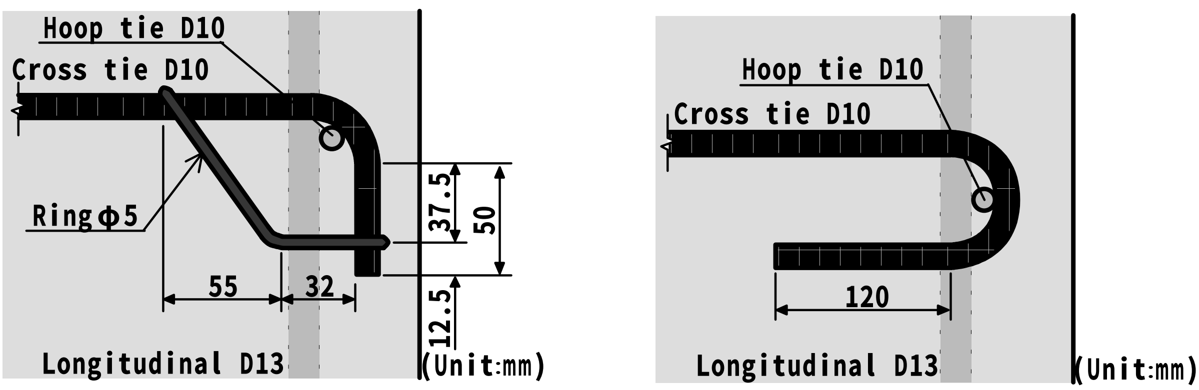



Figure 8 Specimen to Verify Anchorage of Cross ties through Cyclic Loading Test




(a) Oval Ring Type (b) Chain Type

Figure 9 Details of Anchorage of Cross Ties

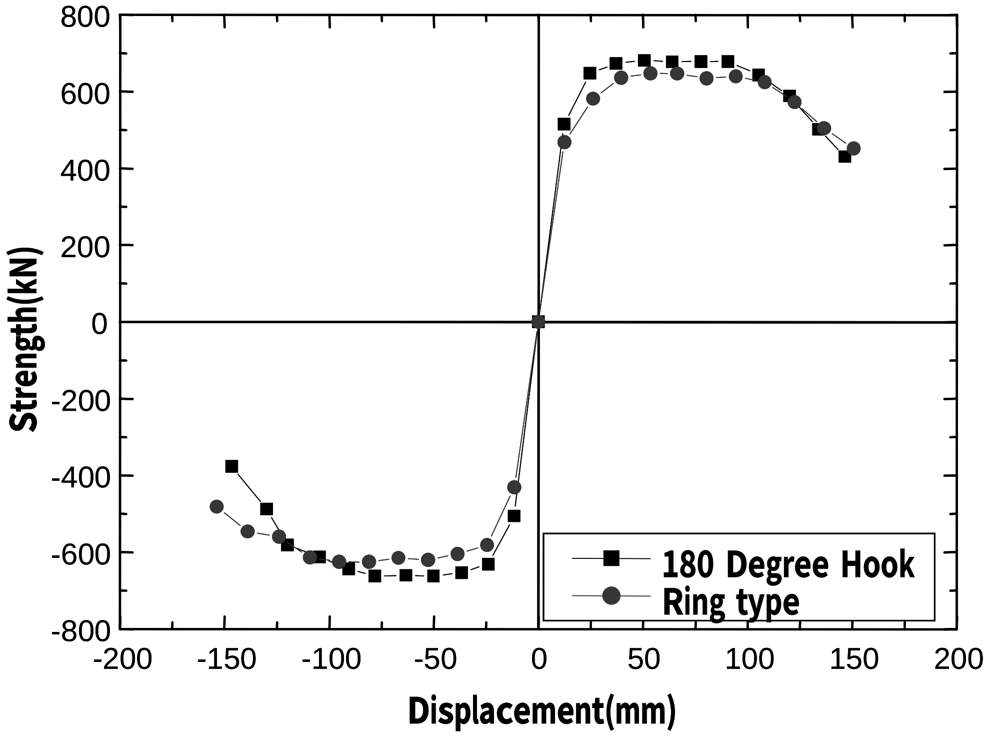
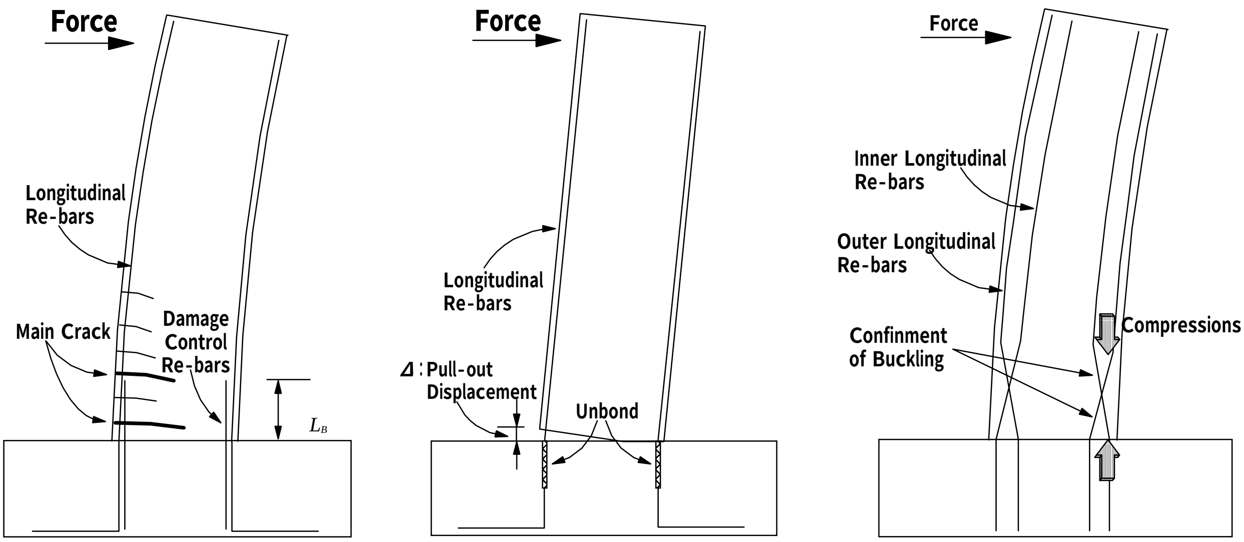



Figure 10 Force Displacement Relation to Verify the Effectiveness of Anchorage of Cross Ties




(a) Damage Control (b) Unbonded Anchorage (c) Cross Longitudinal Re-bar

Figure 11 Damage Controlled Structures and High Ductility Structures

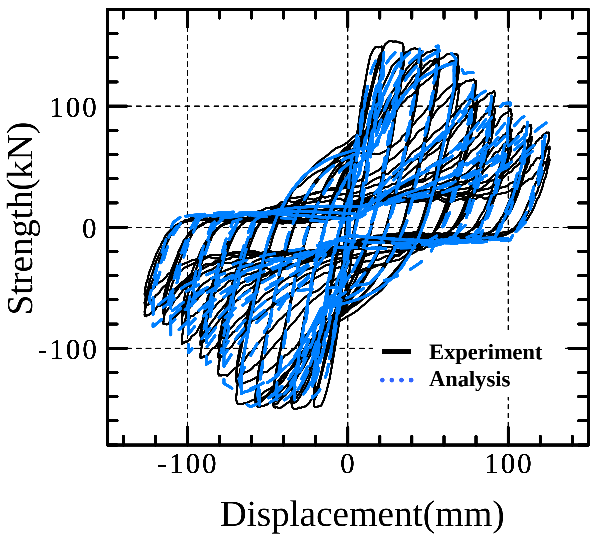


Figure 12 Analytical Approach to Simulate Post Peak Behavior of Reinforced Concrete Structures


(a) Test Set up


(b) Damage at the Bottom of Column
Figure 13 Shake Table Tests to study the Damage Detection of Reinforced Concrete Columns

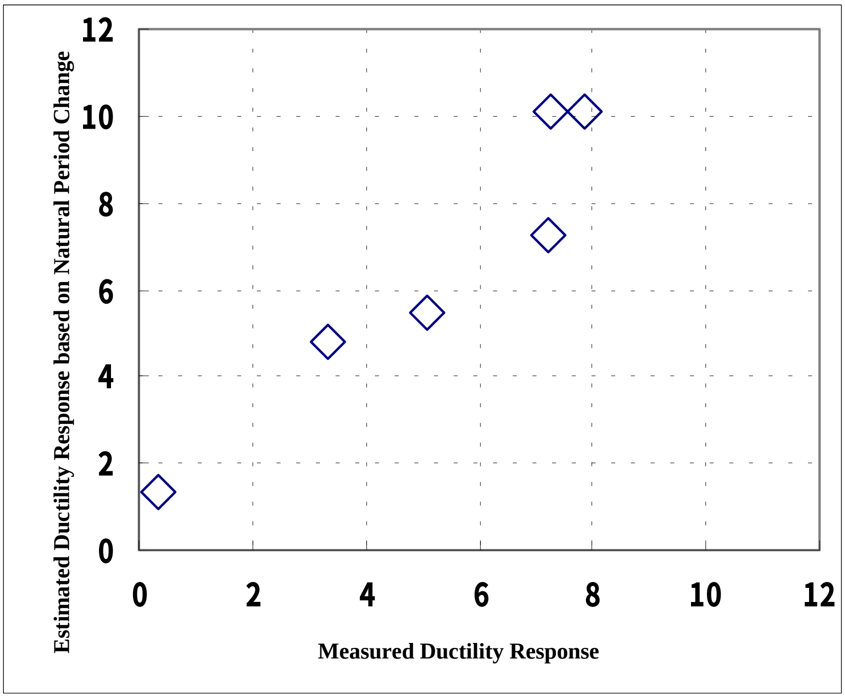



Figure 14 Ductility Estimation by Natural Period Change