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DEVELOPMENT OF THE COLLAPSE DIRECTION CONTROL DEVICE TO IMPROVE ANTI-CATASTROPHE PERFORMANCE OF A VIADUCT

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ABSTRACT

This paper proposes a new "Collapse Direction Control Device," or CDC device, that is intended to be installed to a rigid-frame viaduct. The proposed device assured the direction of the final collapse of a viaduct so as not to interfere the residential areas and/or yard for repair, by which the anti-catastrophe performance of the structure would be improved. In this research, two different types of the real CDC devices were proposed, and shaking table tests of the viaduct models incorporating these devices were performed. The one was the block type device attached to the slab-column corners. The other one was wire type device connecting mid of the column and slab. These arrangements made it possible to give asymmetric force-displacement character to the structure according to the direction of motion, by which the response would be guided to the designated direction.

It was observed from series of the tests that all specimens having both block and wire type CDC devices were finally collapsed to the designated direction. It was also confirmed from inertial force versus horizontal displacement relations that they showed asymmetric behavior and displacement gradually accumulated toward the desirable direction as increasing the input acceleration. It consequently followed that the proposed block and wire type CDC devices were able to control the direction of collapse.

Keywords: Collapse Direction Control Device; Anti-Catastrophe; Shake Table Tests

1. INTRODUCTION

Resilience engineering has been recognized as a marked paradigm shift from ordinary safety engineering and reliability engineering to mitigate unwanted outcomes, injuries, and losses due to uncertainties. Bruenau et al. (2003) and Hollnagel et al. (2006) defined resilience as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions. In earthquake engineering, design codes have repeatedly been revised in accordance with the results of reconnaissance of structural damages and ground motion records observed in several devastating earthquake events (MLIT and RTRI, 2012). To have a possible end to such endless revision of seismic codes based on unexpected damages and mitigating actions, a paradigm shift relying on the concept of resilience engineering is necessary (Saitoh et al. 2015, Honda et al. 2017). In this study, it is primarily admitted that the collapse of structures could occur due to unexpected large ground motions despite possessing sophisticated knowledge from historical earthquake events pertinent to the seismic design. In this situation, to consider appropriate ways for reducing human casualties, to have working places for quick recovery, and to avoid blocked roads due to collapsing structures is rational for enhancing resilience in structures and neighboring societies. This concept is compatible with one of the important strategies of resilience defined by Zolli

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and Healy (2014) as “a disturbance in one part does not disrupt the whole”. The current study categorizes methodologies for constructing resilient structures for collapse such as - 1) controlling space, region, and direction of collapse; 2) controlling duration of collapse; 3) holding safety space in structure, and 4) having alternatives or replaceable units. This study focuses on methodology for controlling the direction of collapse (see Figure 1). In this research, two different types of new devices are proposed to realize such control on the direction of collapse, and the efficacy of the proposed device was confirmed through shake table tests. The developing new device is referred to as “collapse direction control” device or CDC device in the following discussions.

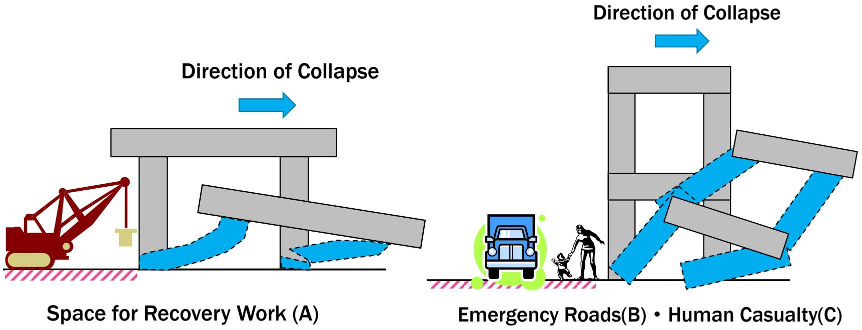


Figure 1. Resilient structures controlling the direction of collapse

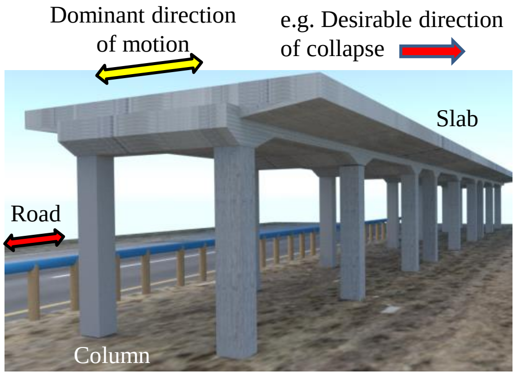


Figure 2. Overview of a rigid frame viaduct

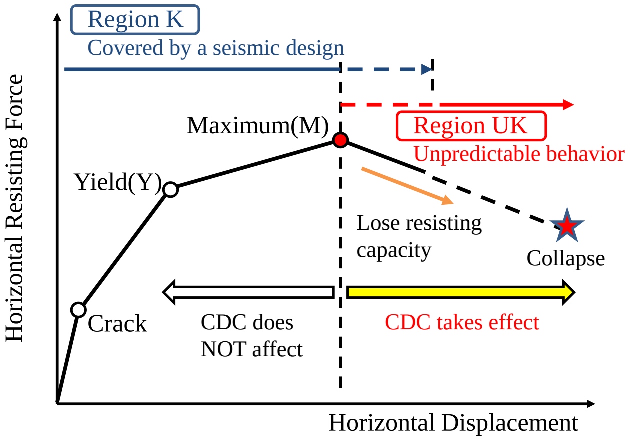


Figure 3. Schematic of a nonlinear behavior

2. COLLAPSE DIRECTION CONTROL (CDC) DEVICE

2.1 Basic Concept

The fundamental design concept of the CDC device is summarized in this chapter. In developing a new device to be applicable to the real structures, a rigid frame viaduct as shown in Figure 2 was selected as a target structure, since there are numerous number of viaducts in use for both railway and road structures.

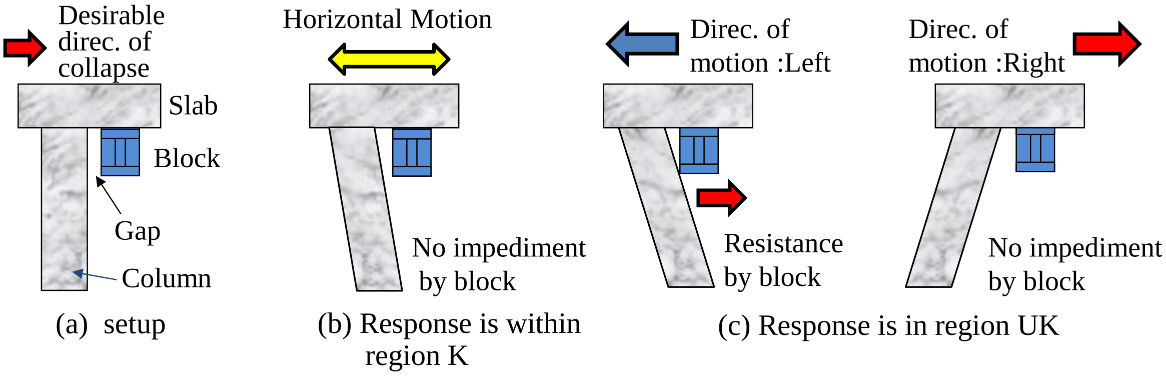
Figure 3 shows the general nonlinear behavior of a rigid frame viaduct. The structure would be resilient enough to enable rapid repair after an earthquake, if its response is restrained below the maximum resisting displacement (point M). Even if the response slightly exceeds point M, a structure whose response is in region K in Figure 3 would be still safe enough to avoid a total collapse. Actually, in the general seismic design, structures are designed so that its response is in region K under designated design motions, by which the safety and restorability performances are met. On the contrary, structure gradually loses its resisting capacity and goes to a total collapse in the region UK in Figure 3. Such an occasion might take place if the earthquake exceeds the predetermined level. In the region UK, failure behavior would vary depending on the material and/or geometric properties of the structure as well as characteristics of an earthquake, and one could hardly estimate the direction of collapse.

The aim of the CDC is to artificially control this direction of collapse in the region UK. In order to realize such a control, asymmetric inelastic response of structures needs to be generated by employing a device, for the accumulation of residual responses in the desired direction. In addition, the device should not interfere the inherent behavior of the structure if its response is in region K so as not to disturb the ordinal seismic design and avoid unexpected damage of the structure. Moreover, such a viaduct has been constructed alongside long-distance road and/or in highly populated area. It follows that the device should come with a simple mechanism and economical enough to employ to significant amount of structures simultaneously. In order to meet such demands, as possible options, following two devices were proposed (Saitoh et al., 2015).

2.2 Proposed Devices Realizing the CDC

2.2.1 Block-type device

Figure 4 shows a proposed device consisting of a rigid block. The block is connected to the beam slab while it maintains a small gap from the column. As shown in Figure 4(c), the rigid block acts as a restraint when the column is displaced in the undesired direction. It has, however, no effect on the movement of the column in the opposite direction. As a consequence, the residual displacement is accumulated in the desired direction. Herein, the reason for allowing a small gap from the column is to avoid changing the failure pattern due to an extra constraint from the block if the response is in the region K in Figure 3 (see Figure 4(b)).

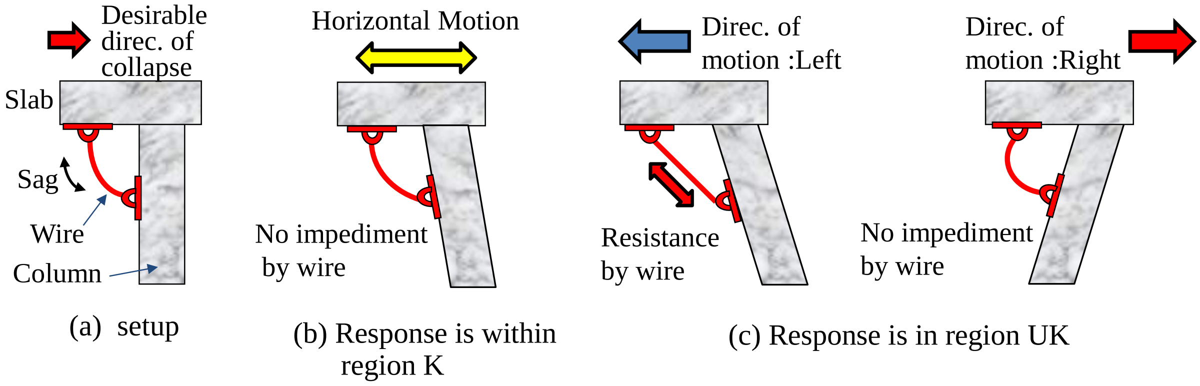


(a) setup (b) Response is within region K (c) Response is in region UK

Figure 4. Device with block for controlling the direction of collapse

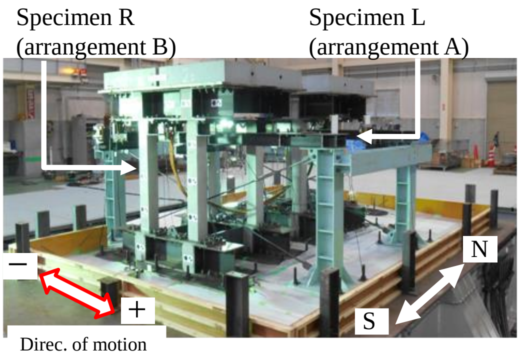
2.2.2 Wire-type device

Figure 5 illustrates another idea of control device. A flexible wire is placed in between the column and the beam slab as a connecting element with a small amount of sag. As shown in Figure 5(c), when the column (after its strength deterioration) is displaced in an undesired direction, tension force is developed in the wire. Such generated internal forces in the wire restricts the movement of the column in the undesired direction; the movement in the opposite direction is free. As a result, residual displacement is accumulated in the desired direction. The reason for providing the relaxation in the wire is to avoid changing the failure pattern due to additional tension force from the wire if the response is in the region K in Figure 3 (see Figure 5(b)).

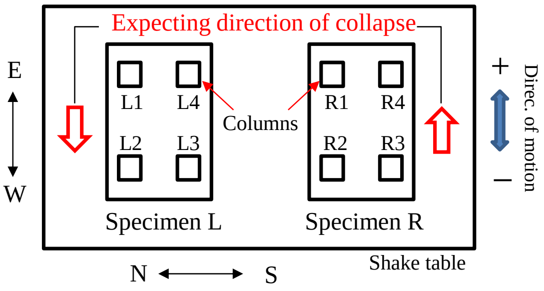


(a) setup (b) Response is within region K (c) Response is in region UK

Figure 5. Device with wire for controlling the direction of collapse

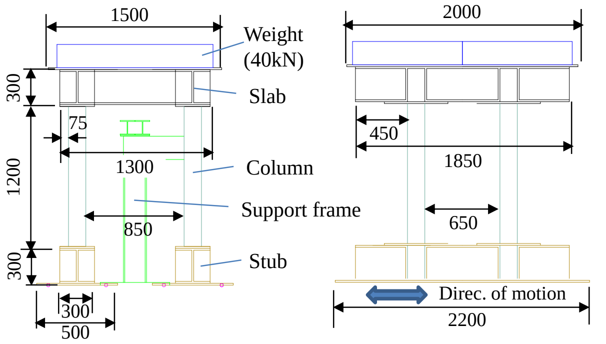


(a) Test setup

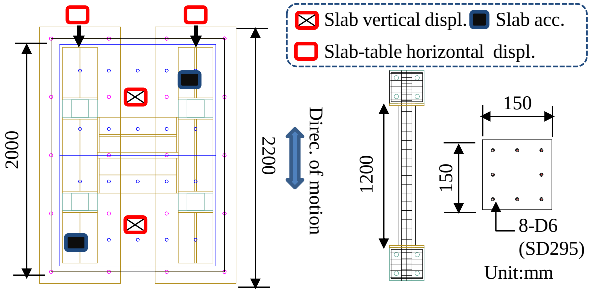


(b) Arrangement of specimens (top view)

Figure 6. Test setup



(a) Side view (b) Side view(direc. of motion)



(c) Top view with measurements (d) Pre-casted column

Figure 7. Schematic of the test specimen

3. VERIFICATION TESTS OF CDC DEVICES USING SHAKE TABLE

3.1 Test Setup

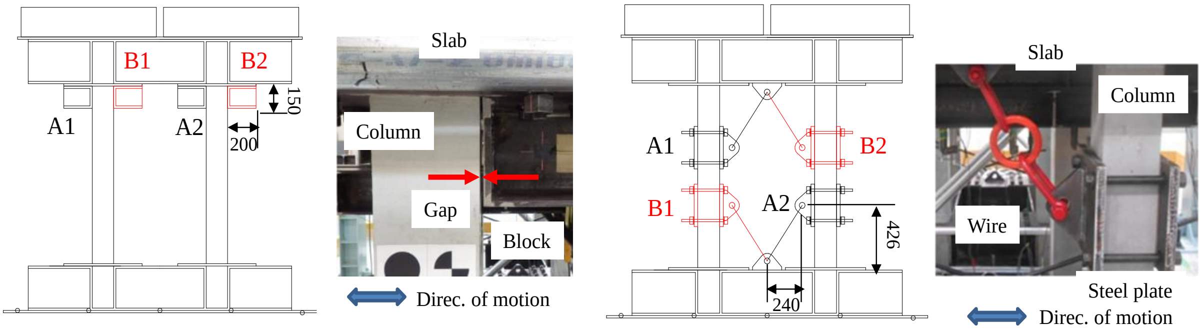
The effectiveness of proposed devices shown in Chapter 2 was investigated by a shake table test. In the series of tests, two identical rigid frame viaduct models were constructed on the table as shown in Figure 6, and excited until they came to a complete collapse. The proposed devices were embedded in these two specimens so that their directions of collapse were different each other. The effectiveness of the device was then confirmed by checking whether two specimens would collapse in opposite directions and their directions would agree with predetermined ones.

3.2 Viaduct Model

As shown in Figures 6 and 7, a rigid frame model consisted of a steel-made slab and four pre-casted reinforced concrete columns were constructed. The size of a slab was W2000 mm x D1500 mm x H300 mm. The top and bottom of the column were inserted in slab and stub, respectively. The size of a column was W150 mm x D150 mm x H1200 mm with reinforcing bars of 8-D6 (SD295). The dead weight on the column was given by mounting a bunch of steel blocks of 40kN on the slab. Consequently, total dead weight was 48.5 kN, and corresponding section stress on the column was 0.54N/mm^2.
The yielding seismic coefficient of the specimen was restrained up to approximately 0.6, considering the maximum loading capacity of the shake table. In addition, the specimen was designed so that no brittle shear failure took place and the final failure mode was a bending mode, where plastic hinges formed at every top and bottom of columns would invoke a total collapse. In addition, the supplemental supporting frames were placed on the shake table for the safety measure, preventing the fall down of a slab after specimen was totally collapsed.

3.3 CDC Devices

The schematics of the proposed block-type and wire-type devices are shown in Figure 8. In the block-type device, the height of the block was identical to the column width (=150mm) that corresponds to



(a) Block-type device (b) Wire-type device

Figure 8. Arrangements of CDC devices (arrangement A:A1&A2/ arrangement B:B1&B2)

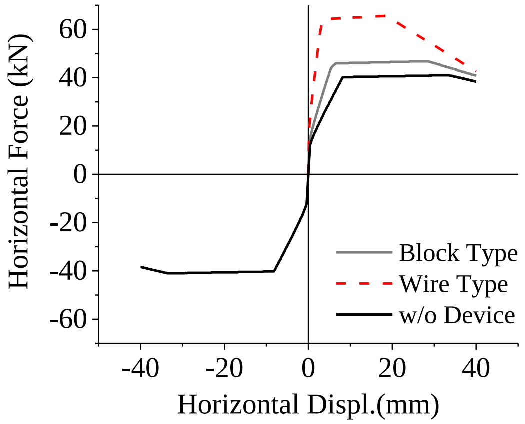


Figure 9. Nonlinear behavior of specimens with and without CDC device

Table 1. Test cases and corresponding loading accelerations – frequencies to the shake table

Case	Block Type		Case	Wire Type	
B1	2Hz-500gal	---	W1	2Hz-500gal	---
B2	2Hz-750gal	---	W2	2Hz-750gal	L
B3	2Hz-750gal	---	W3	2Hz-750gal	---
B4	2Hz-1000gal	---	W4	1Hz-750gal	R
B5	2Hz-1500gal	---			
B6	1Hz-750gal	L,R			

the plastic hinge length of the column. In addition, the device was placed so that the device was horizontally distant from the column. This gap was intended to introduce so that the device would take effect after the viaduct would be suffering from the response exceeding the maximum resisting displacement. The block was placed on the slab with a gap of 4mm from the column. It was determined as horizontal deformation at an edge of the block (150mm below the slab) when the maximum displacement of the specimen reached a maximum resisting limit. It was calculated by the preliminary numerical simulations mentioned in the next section.

In the wire-type device, the wire was attached via steel plates in between the slab/stub and a middle of column where acting moment due to horizontal inertial force is negligibly small. Due to the same reason as the gap of block-type device, a small initial sag was introduced so that tensile force would act when the maximum displacement of the specimen reached a maximum resisting limit.

The arrangements of the proposed devices with regard to block-type and wire-type are also shown in Figure 8. As illustrated in the figure, devices were placed as a combination of A1 and A2 for arrangement A, whereas B1 and B2 for arrangement B. According to the concept of the device mentioned in Figures 4 and 5, direction of collapse in arrangement A was presumed to be in the left-hand side of Figure 8. On the contrary, the collapse direction will be in the right-hand side in case of arrangement B. In the following discussion, specimens with CDC arrangements of A and B are referred to as Specimen L and Specimen R, respectively. It was expected from the polarity of the measuring displacement and arrangement of specimens shown in Figure 6 that the specimen L would collapse in minus direction whereas specimen R in plus direction.

3.4 Nonlinear Behavior of Specimens with CDC Devices

The preliminary static nonlinear analysis was carried out to design the viaduct model and comprehend the nonlinear behavior of the specimen with CDC devices.

First, the viaduct without the CDC devices was expressed by a plane frame, and nonlinear momentcurvature relations were given to the column beam according to the arrangement and material properties of reinforcing bars and concrete. The compressive strength of the concrete was 30 N/mm^2 from the preliminary element tests. The nonlinear behavior of the viaduct model was calculated by gradually inducing the horizontal inertial force at the slab. The arrangement and material of the reinforcing bars were then determined by a trial-and-error basis so as for the yielding seismic coefficient to be the desirable level, say, 0.6.

Next, the nonlinear behavior of the specimen with the CDC device was calculated. The effect of the block-type device was expressed that the restraining length of the column top and bottom (=1D) due to the block were replaced by a rigid beam. In the wire-type device, the placed wires were expressed by a truss model. The arrangement A was assumed to compose the model with the CDC devices.

Figure 9 depicts the nonlinear horizontal force versus displacement relations with and without the CDC devices. In this figure, the CDC devices take effect if the deformation goes in plus direction. As shown in the figure, maximum resisting force without the CDC devices was 41.0 kN. On the contrary, they were increased to 46.8 kN and 65.6 kN in cases block-type and wire-type devices were embedded, respectively. It follows that the CDC devices alter the nonlinear behavior from symmetric to asymmetric, whereby it would be expected to accumulate the response and damage to the desirable direction whose resisting capacity is smaller. In addition, it was also confirmed that all specimens did not show brittle failure mode, as expected, regardless of with and without the CDC devices.

3.5 Measurement and Excitation Plans

For data acquisitions, absolute accelerations of slab and table as well as relative displacement between slab and table in horizontal and vertical directions were mainly measured. This arrangement is shown in Figure 6(b). The collapsing behavior was also acquired by equipping the high-speed video cameras.

Two specimens, L and R, were simultaneously excited by an acceleration control mode. A five set of sinusoidal waves with supplemental ascending and descending motions at beginning and ending of the excitation was selected as input wave. Since the input motion itself was symmetric, one could identify that the effect of the supplemental CDC devices would mainly contribute to the resulting collapse directions. The maximum acceleration of the excitation was gradually increased until both specimens came to a total collapse. The excitation frequency was selected as 2.0 Hz corresponding to the resonance frequency when the maximum displacement response of the specimen is about to exceed the maximum resisting capacity. In the final case, however, the frequency was decreased to 1.0 Hz to accelerate the deformation and made the specimens collapse. The series of test condition carried out is summarized in Table 1. In this table, capital “L” and “R” represent the test cases where the collapse of the specimen L and/or R took place.

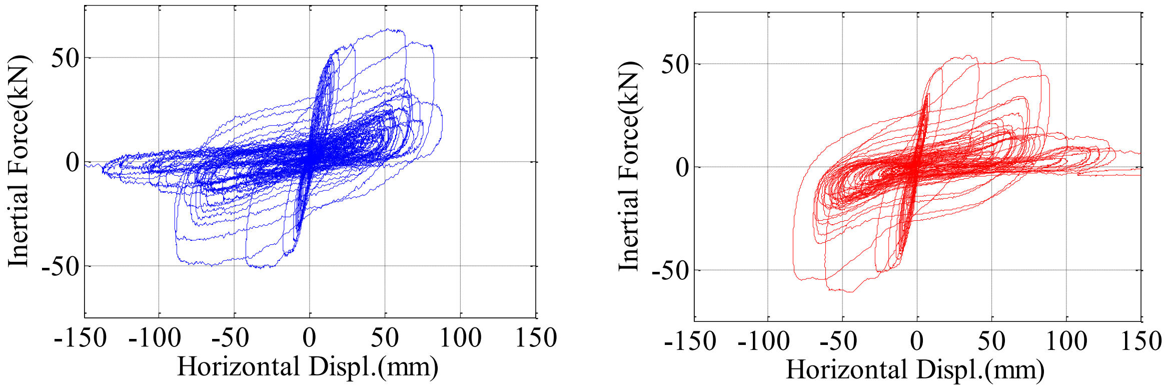
4. TEST RESULTS AND DISCUSSIONS

4.1 Block-Type CDC Device

Figure 10 shows the horizontal force versus displacement relations with respect to specimens L and R. In this figure, results of all test cases shown in Table 1 are depicted in the same graphs. The horizontal force was calculated by multiplying the absolute acceleration of the slab to the mass of slab and additional weight. Figure 11 shows the relative displacement time histories as tests proceeded. Also, Figure 12 shows the horizontal versus vertical displaements of the slab to comprehend the damage of the column.

It is observed from Figures 10 and 11 that specimen L accumulated its displacement to the negative direction, whereas specimen R in positive direction. It follows that the block-type device successfully guided the directions of collapse to the predetermined ones. Finally, specimens L and R collapsed in minus and plus directions, respectively.

In order to comprehend the progressive failure according to the maximum induced acceleration, Figure 13 shows the horizontal force versus displacement relations in cases of B2 and B5 in Table 1. It is found that the specimens show almost symmetric behavior in Case B2. On the contrary, in case B5, the specimens deform large enough to contact the block device, and the device restrains the accumulation of the displacement. Figure 14(a) shows the snapshot of the specimen R in mid of excitation (case B4).



(a)Specimen L (b)Specimen R

Figure 10. Inertial force – horizontal displacement relations (Block-type: all test results are depicted)

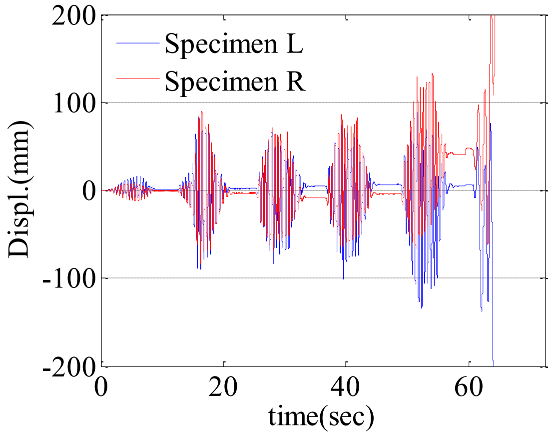


Figure 11. Comparison of horizontal displacement (Block-type)

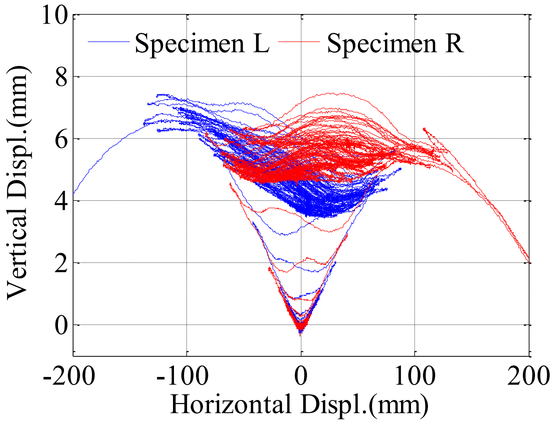
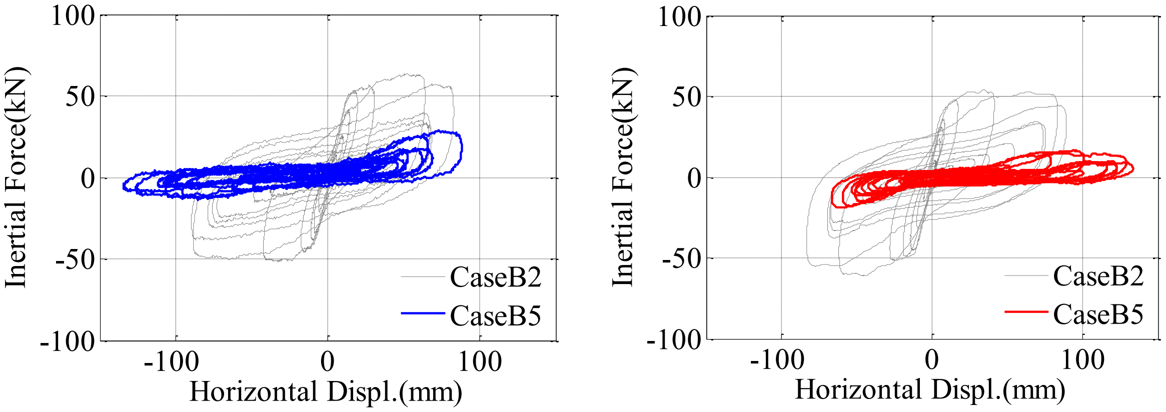


Figure 12. Comparison of vertical – horizontal displacements (Block-type)

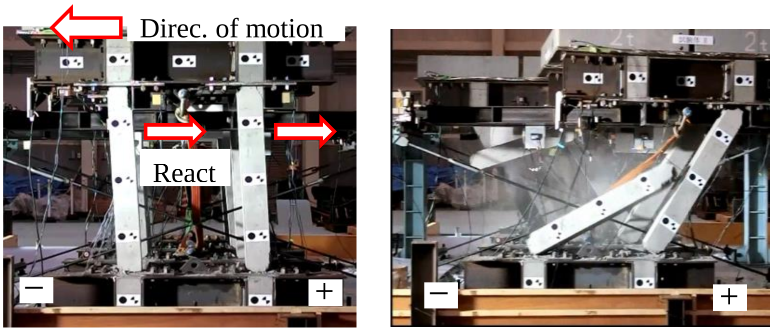


(a)Specimen L (b)Specimen R

Figure 13. Inertial force – horizontal displacement relations (Block-type: representative cases)

It was found that the plastic hinges were formed at every top and bottom of columns. It is a desirable failure process in a seismic desing of a rigid frame viaduct. It was also observed that the attached blocks restrained the deformation of column if the direction of displacement was opposite to the desirable collapse direction.

Finally, the two specimens were totally collapsed simultaneously in case B6. Figure 14(b) shows the corresponding snapshot when the specimen R collapsed. It was found from the observation of tests that the breaking of reinforced bars invoked the collapse of the specimen. This failure mechanism is also confirmed from Figure 12 that the vertical displacement of the slab was uniformly increased up to 7mm where the final collapse took place. It follows that the reinforced bars connecting columns and slab were also exposed to the constant tensile force until they broke.



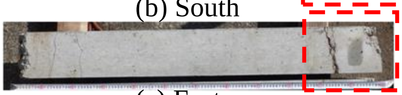
Specimen R
(a) In mid (Case B4)

Specimen R
(b) Collapse (Case B6)

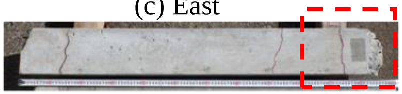
Figure 14. Snapshots in mid of shaking and final collapse

(a) North

(b) South

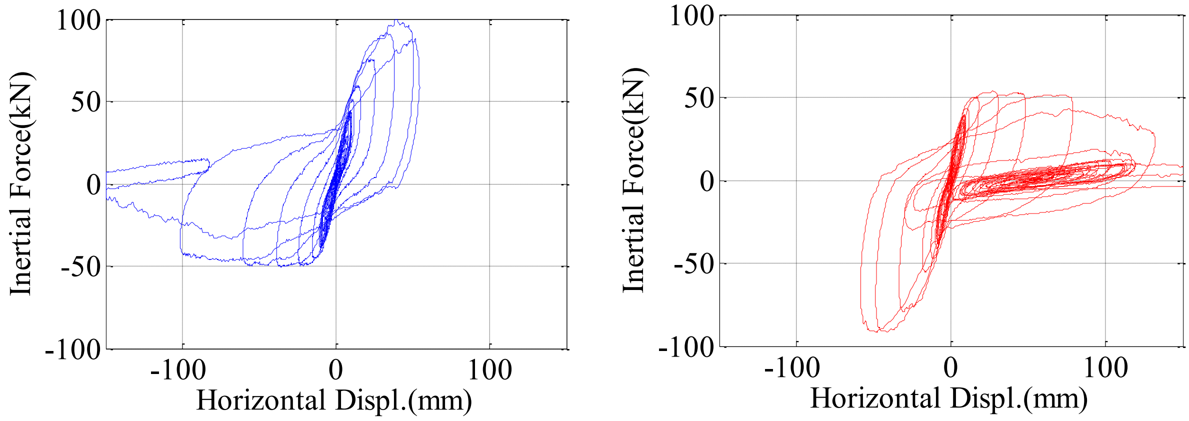


(c) East



(d) West

Figure 15. Damage of column (No.R4)



(a)Specimen L

(b)Specimen R

Figure 16. Inertial force – horizontal displacement relations (Wire-type: all test results are depicted)

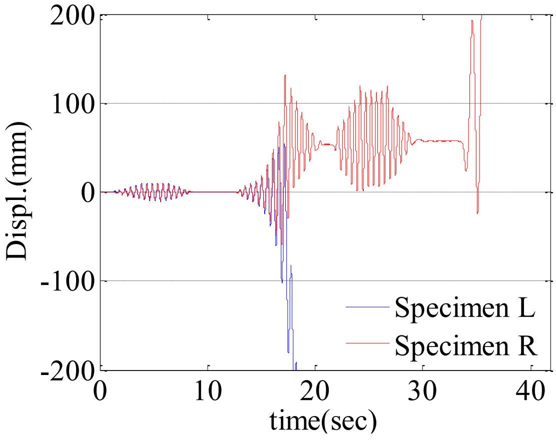


Figure 17. Comparison of horizontal displacement (Wire-type)

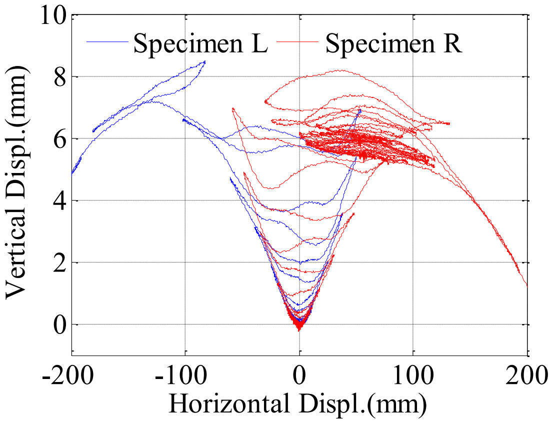
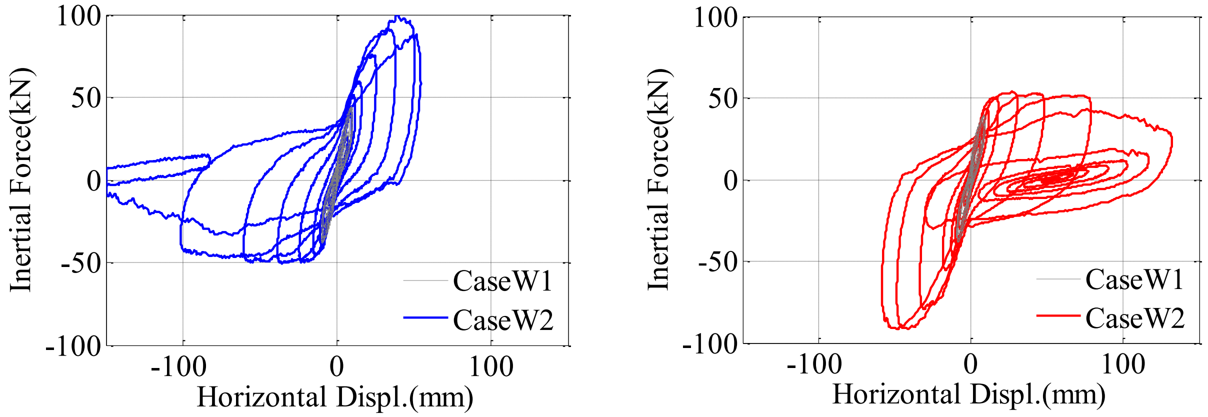


Figure 18. Comparison of vertical – horizontal displacements (Wire-type)

In addition, Figure 15 shows the damage of the R4 column in Figure 6(b) as a representative result. It is found from Figure 15(c) that the large round crack is observed where the block device was contacted (dotted area). It consequently follows that the acting force due to the block should be somehow distributed by introducing the buffering materials when it comes to the application to the real structures.

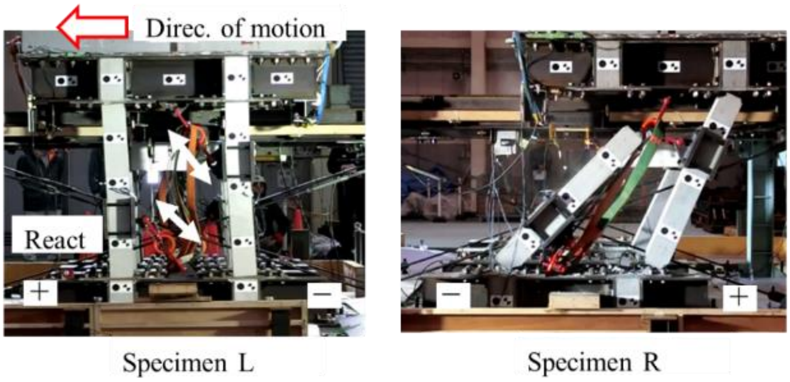
4.2 Wire Type CDC Device

In the same manner as block type device, Figure 16 shows the horizontal force versus displacement relations with respect to specimens L and R. Figure 17 shows the relative displacement time histories as



(a)Specimen L (b)Specimen R

Figure 19. Inertial force – horizontal displacement relations (Wire-type: representative cases)



(a) In mid (Case W2) (b) Collapse (Case W4)

Figure 20. Snapshots in mid of shaking and final collapse

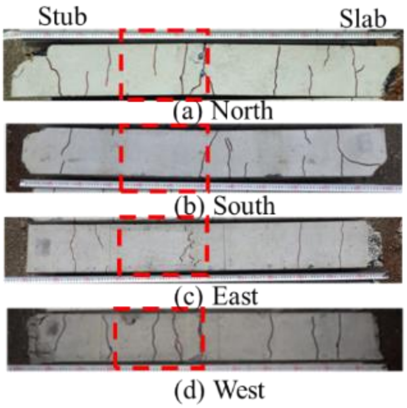


Figure 21. Damage of column (No.R4)

tests proceeded. Also, Figure 18 shows the horizontal versus vertical displaements of the slab to comprehend the damage of the column.

It is observed from Figures 16 and 17 that the wire-type CDC device also guided the collapse to the desirable direction, say, specimen L in a negative and specimen R in a positive direction. Figure 19 illustrates the horizontal force versus displacement relations with regard to cases W1 and W2 as representative results. It is observed that both specimens were almost intact in case of W1, whereas specimen L collapsed in case W2. It should be noted that block-type device did not collapse under same excitation as case W2. It follows that the difference of the failure behavior arose from the difference of the restraining mechanism between block and wire type devices. From Figure 18, vertical displacement of specimen L at case W2 reached approximately 7mm, large enough to cause the breaking of reinforced bars. It consequently follows that the wire-type device applied more tensile force toward bars compared to the block-type device. The constraining behavior found in Figure 20(a), specimen L in mid of case W2 excitation, intuitively shows that the wire instantaneously constrained the motion of the column when deformed. The impact force due to the action of wire would result in the rapid collapse of the specimen. Although specimen R did not collapse in case W2, it possibly due to the variation of initial sag of wire.

The collapsed specimen L was removed after case W2 excitation and continued the tests. Consequently, specimen R also collapsed in case W4. Figure 20(b) shows the corresponding snapshot when the specimen R collapsed. Figure 21 shows the remaining R4 column in Figure 6(b). The red dotted area shows the location where the wire was installed. Since the wire was attached to the column using a steel plate, damage cracks were distributed throughout the column as seen in Figure 21.

4.3 Summary of the Tests

It was confirmed through series of tests that proposed CDC devices, both block-type and wire-type, successfully controlled the direction of collapse to the designated ways. The specimen with a block-type devices endured the repetitive motion, whereas less vulnerable against total failure in case of wire-type device due to the larger constraint force induced to the column.

On the contrary, block-type device induced the partial damage on the column because the resisting force was acted in line with the block edge. The wire-type device, however, distributed the damage to the column since the resisting force was acted through the plane steel plate. It consequently follows that despite the proposed devices are both promising in realizing the collapse direction control, several improvements to decrease the damage to the column should be needed in the further research.

5. CONCLUSIONS AND FURTHER REMARKS

This study focused on methodology for controlling the direction of collapse of a viaduct in order to improve the anti-catastrophe performance under unexpected earthquakes. Two different types of new CDC devices were proposed to control direction of collapse, and efficacy of the proposed device was confirmed through shake table tests. Several conclusions are summarized and remarked as follows:

(1) A concept of new "Collapse Direction Control Device," or CDC device intended to be installed to a rigid-frame viaduct was proposed. The device assures the direction of the final collapse under unanticipated large earthquakes so as not to interfere the residential areas and/or yard for repair, by which the anti-catastrophe performance of the structure would be improved.

(2) Two different types of devices were proposed to realize the collapse direction control. The one was the block type device attached to the slab-column corners. The other one was wire type device connecting mid of the column and slab. Those CDC devices made it possible to give asymmetric force-displacement character to the structure according to the direction of motion, by which the response would be guided to the designated direction. In addition, these devices would take effect only if the structural response exceeds the predetermined level in the seismic design in order to avoid altering the presumed failure pattern.

(3) It was confirmed through series of tests using scaled viaduct models and symmetric sinusoidal motions that proposed CDC devices, both block-type and wire-type, successfully guided the direction of collapse to designated ways. The specimen with a block-type devices endured the repetitive motion, whereas less vulnerable in case of wire-type device due to the larger constraint force induced to the column. On the contrary, block-type device induced the partial damage on the column because the resisting force was acted in line with the block edge. The wire-type device, however, distributed the damage to the column since the resisting force was acted through the plane steel plate. It consequently follows that despite the proposed devices are both regarded as promising in realizing the collapse direction control, several improvements to decrease the damage to the column should be needed in a further research.

6. ACKNOWLEDGMENTS

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