16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3444

Registration Code: S-T1474507645

Seismic Performance Evaluation of Damaged RC column Retrofitted by GFRP-Strip Device

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Abstract

Many reinforced concrete (RC) buildings, which were designed and constructed with old seismic-design codes, have been seriously damaged and destructed in both destructive earthquakes and several aftershocks. Several aftershocks may be quite destructive because of the previous damage of the RC building. Therefore, demand for development of rapid-repair methods was increased to prevent possible collapse of RC building during the aftershocks. Partial or total collapse of a RC building under the earthquakes was led by the collapse of columns. Therefore, the main purpose of a seismic retrofitting method is to increase shear capacity of the RC columns. In this study, a GFRP-strip device was proposed to improve the seismic performance of damaged RC columns and was designed to consider easy installation and rapid repair. The GFRP-strip device consists of both GFRP composite strips and aluminum clip-connectors. The shape of the aluminum clip-connectors was designed in three pieces to consider easy installation and rapid repair. Three RC specimens consisted of two columns, which were designed at 75% scale of existing school buildings constructed in the 1980s in South Korea, and were constructed to evaluate the performance of the GFRP-strip device. Two of the RC specimens were pre-tested to take damage before installing the GFRP-strip device. After the pre-test damage was done, the GFRP-strip devices were installed along the plastic-hinge regions on both ends of the test columns. The experimental test results indicate several improvements in seismic performance of damaged columns. These include strength enhancement, failure mode, ductility and hysteretic energy-dissipation capacity. Thus, both the maximum strength and ductility of the retrofitted specimens were increased. Furthermore, accumulated energy-dissipation capacity of the retrofitted specimens was increased. Taking the un-retrofitted RC specimen as a control specimen, the failure behavior of the retrofitted RC specimens was changed from brittle-shear failure to ductile-flexural behavior, which was maintained until the failure of the GFRP-strip devices occurred. Finally, it is shown that the proposed GFRP-strip device developed can be used to improve the seismic performance of damaged RC columns.

Keywords: Damaged RC column, rapid-retrofit method, GFRP-strip device

1. Introduction

Many reinforced concrete (RC) buildings, which were designed and constructed with old seismic-design codes, and had been seriously damaged and destructed in both destructive earthquakes (e.g., in 1967-Caracas, 1968-Tokachi-Oki, 1999-Izmit, 2008-Wenchuan, and 2009-Honduras) and several aftershocks. Aftershocks may be quite destructive because of the previous damage to the RC building. Demand for development of rapid-repair methods was increased to prevent possible collapse of RC building during aftershocks. Partial or total collapse of a RC building under earthquakes was led by the collapse of columns (singly or in groups). The seismic performance of RC column designed by old seismic-design code was governed by shear-failure, so enhanced shear capacity is urgently required for the RC columns. Therefore, the main purpose of a seismic retrofitting method is to increase shear capacity of the RC columns.

Many researchers have proposed some seismic retrofitting methods for the RC columns using external materials. Some researchers have used steel jacketing that could enhance both strength and ductility of RC columns [1-3]. Other materials were also attempted to increase the performance of the RC columns. Fiber reinforced polymer (FRP) has been used as an external strengthening material. Some researchers used it to wrap bridge columns [4-8]. Furthermore, several researchers used a prefabricated jacket method to overcome a reinforcement quality problem. Quality control of prefabricated composite jacket from a manufacturer could be achieved more easily in terms of thickness, amount of epoxy, and curing process [9-13].

In this study, a GFRP-strip device, which consists of both the GFRP composite strip and aluminum clip connectors, was proposed to increase shear capacity of the damaged RC columns. The shape of the aluminum clip-connectors was designed in three pieces to consider easy installation and rapid repair. The design process of the GFRP-strip device was summarized simply. The GFRP-strip device was intended to increase the shear strength of the damaged RC columns and to defend against catastrophic collapse by shear-failure of damaged RC columns. To evaluate the performance of the proposed device, three RC frames were constructed for this research. The RC specimens were designed at 75% scale of existing school buildings constructed in the 1980s in South Korea. Two of the RC specimens were damaged before installing the GFRP-strip device. The two pre-test damage levels were determined using displacement ductility factor. The experimental results of the specimen tests are discussed in terms of strength enhancement, failure mode, ductility and hysteretic dissipated energy.

2. GFRP-strip device

2.1 Description of GFRP-strip device

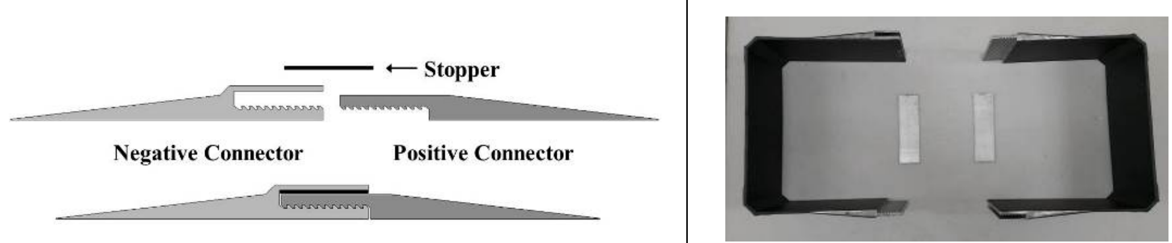
RC structures suffer damage when earthquakes strike. Such damage will make collapse likely from the added stress of aftershocks. Compromised structures need to be repaired before aftershocks arrive to prevent additional damage or to defend against collapse. For these reasons, there is an urgent need for a rapid-repair technology that might prevent possible collapse of damaged structures. The rapid-repair technology must not only be fast, but must also be easy to install in the field. The proposed GFRP-strip device consists of two parts, a GFRP composite strip and aluminum clip-connectors, and is available for easy installation and rapid repair.

2.2 Material properties

Both a glass fiber fabric and a epoxy binding-agent were used to fabricate the GFRP composite. Within each glass fiber fabric ply, 80% of the glass fibers were placed in the longitudinal direction, and 20% in a transverse direction. The tensile strength, elastic modulus and strain at maximum load of GFRP composite were 448 MPa, 38,300 MPa and 0.012, respectively. The aluminum clip-connector consists of three pieces, two connecting parts and a stopper, for easy installation and rapid repair. The dimensions of connecting device shape were determined through FE analyses. ABAQUS 6.11 [14], a general-purpose finite-element program, was used to perform the numerical study. The yield strength, maximum strength, elastic modulus and poisson's ratio of aluminum were 270 MPa, 310 MPa, 70 GPa and 0.33, respectively.

2.3 GFRP-strip device

The GFRP-composite strips were fabricated from 12-ply composite sheet made from glass fibers and epoxy binding agent. Each ply was 0.25 mm thick, making a 3-mm-thick GFRP-composite strip to prevent failure of the aluminum clip-connector. The connection length between the aluminum clip-connector and GFRP-composite strips was calculated according to the strength of the epoxy bond. Figure 1 shows the detail of aluminum clip-connectors and GFRP-strip device used in this study. The width of the GFRP-strip device was 150 mm.



(a) Aluminum clip-connector

(b) GFRP-strip device

Fig. 1 – GFRP-strip device

3. Experimental tests

3.1 RC specimen

Three RC specimens, which were 75%-scale models of actual RC columns of an old school building in Korea, were experimentally constructed in this study, as shown in Figure 2. Each RC specimen had two RC columns representing the frame of the building, which allowed us to test for double curvature behavior. A ready-mix concrete that had 18 MPa of compressive strength at 28 days was used to make RC specimens, since the compressive strength of old school buildings was 18 MPa. For longitudinal reinforcement throughout a vertical member, eight pieces of deformed D16 mm (16 mm diameter) rebar were used. As for transverse reinforcement, eight pieces of D10 (10 mm diameter) deformed rebar fastened with 300 mm spacing in each RC column. The 300 MPa of yield-strength of the reinforcements was applied based on the design method of old school building.

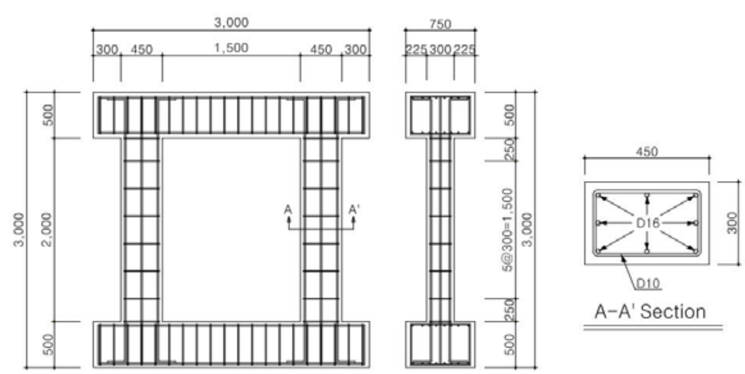


Fig. 2 – Detail of RC specimen (Unit=mm)

There are two retrofitted RC specimens (Retrofitted RC Specimen-1, 2, RRS-1 and RRS-2) and one un-retrofitted RC specimen (Un-retrofitted RC Specimen, URS). The level of damage inflicted upon RRS-1 and RRS-2 was determined by the ductility factor (μ), which depends on the yield displacement corresponding to the first-yield point of the longitudinal rebar. Two kinds of ductility factor (μ=2 and μ=2.5) were used as the pre-test damage level of the RC specimens in this study. In particular, the 2.5-ductility factor (μ=2.5) indicated maximum flexural ductility since it was determined at maximum flexural displacement. After the pre-test damage was done, the GFRP-strip devices were installed along the plastic-hinge regions on both ends of the test columns. The details of the test specimens are summarized in Table 1. The number of GFRP-strip devices was determined according to numerical study, which was considered both design strength and width of GFRP-strip device and the plastic-hinge length of the RC columns, which was assumed to be one-fourth length the column height [15]. Surface of the damaged column was treated before the installation of GFRP-strip device. Epoxy bond was used to install the GFRP-strip device, and was acted as filler between column and GFRP-strip device.

Table 1 – Detail of test specimens

Name of RC specimen	Pre-damage (Ductility factor)	Number of GFRP-strip device
URS	None	None
RRS-1	μ=2.0	6-Set
RRS-2	μ=2.5	6-Set

3.2 Test setup

Figure 3 presents the test setup. Lateral load was imposed at the loading frame of the top block of the RC specimen using a 1,000 kN hydraulic actuator. Four servo-type-hydraulic jacks were used to apply constant axial force which is 486 kN corresponding to 0.1×Ag×fck approximately [13]. To prevent out-of-plane deformation of the RC specimen, four auxiliary guide rollers were installed.

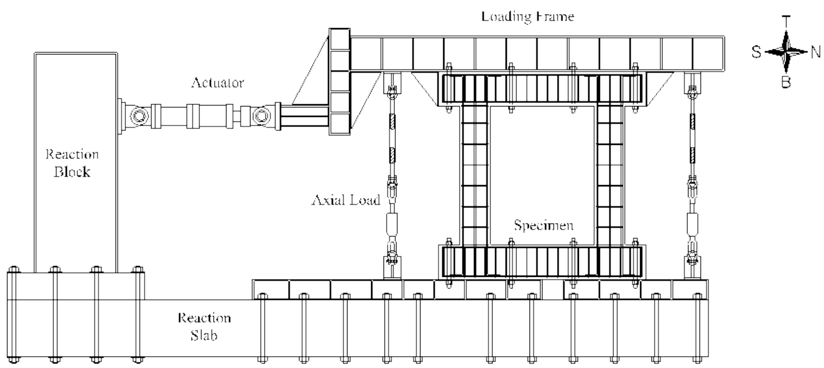


Fig. 3 – Test setup

3.3 Test method and loading protocol

A quasi-static cyclic load was applied to evaluate the seismic performance of the RC specimens. The displacement of the quasi-static cyclic load was increased by 0.5-ductility factor (μ=0.5) in each loading step [13,16]. In order to define the yield-displacement point before the first yield, the displacement load was controlled by 5 mm. The ductility factor (μ) was determined by yield displacement at the first-yield point of the longitudinal rebar. The lateral displacement load was increased by 0.5-ductility factor (increment, μ=0.5), from zero, which was applied to the retrofitted RC specimens after install the GFRP-strip devices.

4. Results and discussion

4.1 Behaviors

The URS specimen was the control specimen used to evaluate the effect of the GFRP-strip device. The RRS-1 and RRS-2 specimens were the damaged specimens which were pre-tested with μ=2.0 and μ=2.5 respectively before installing the GFRP-strip device. Figure 4 presents the load and displacement relationships, as well as load and ductility factor relationships of the three specimens.

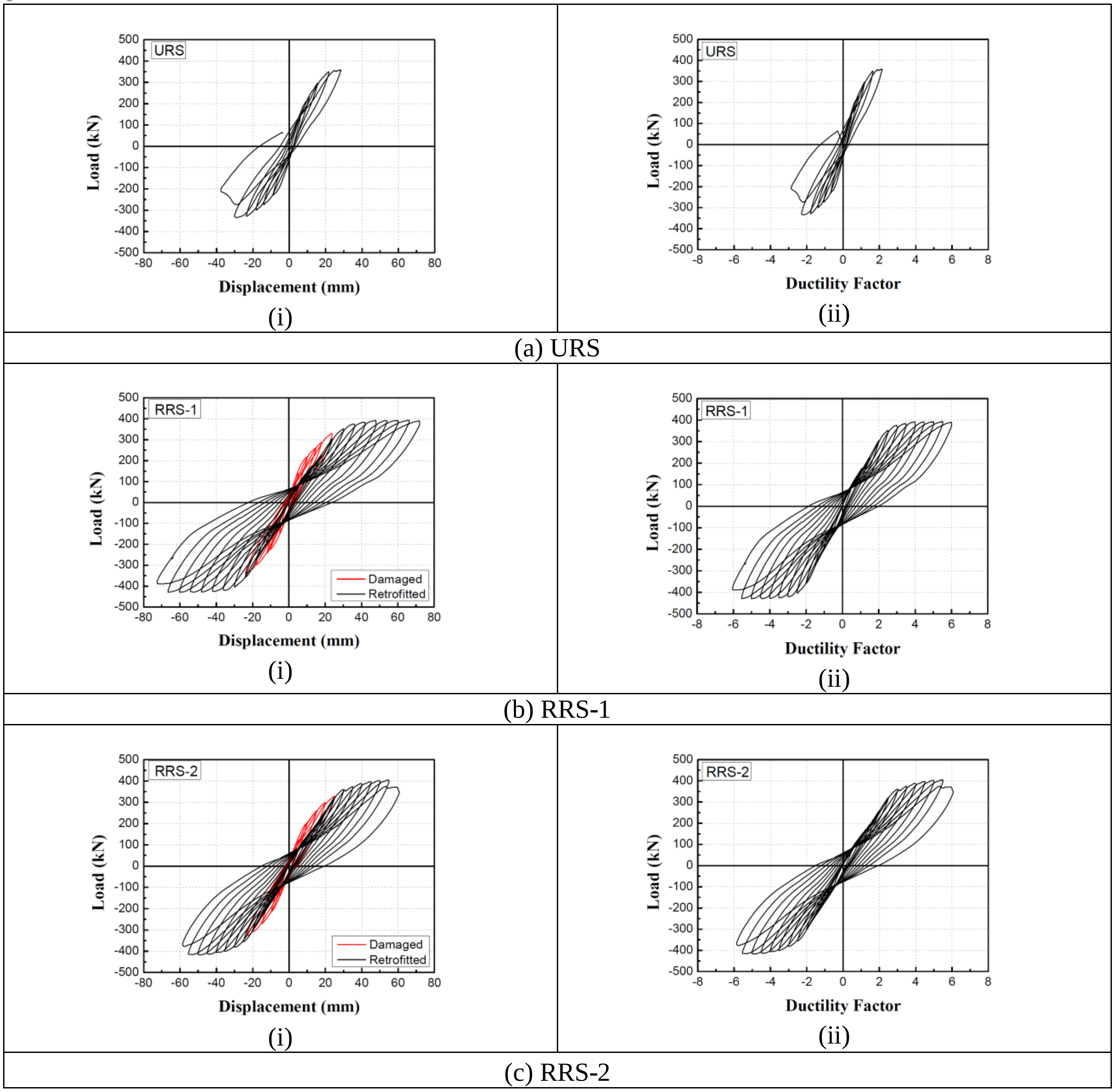


Fig. 4 – Experimental behavior of specimens ((i): Load-displacement, (ii): Load-ductility factor)

4.2 Ductility

Figure 5 plots envelope curves for each specimen. The cycle peak of each specimen was used to make the envelope curve. The peak loads of the RRS-1 and RRS-2 specimens were slightly higher than that of the URS specimen. However, the displacements at peak load were increased. The displacement at peak load of RRS-1 was larger than that of RRS-2, since RRS-2 took more damage than RRS-1 during the pre-test. The maximum displacement was defined as the displacement at 80% of peak load. The experimental test results were summarized in Table 2. From the experimental results, the maximum displacement of the retrofitted specimen (RRS-1 and RRS-2) was approximately two times greater than that of the control specimen. The maximum displacement of the RRS-1 specimen was greater than that of RRS-2 specimen, because the pre-test damage to the RRS-2 specimen was greater. Furthermore, the ductility factor of the retrofitted specimens (RRS-1 and RRS-2) was 2.6 times greater than that of the un-retrofitted specimen (URS). The shear-strength of the URS specimen was slightly less than its flexural strength. The GFRP-strip devices enhanced the shear-strength of the RRS-1 and RRS-2 specimens, so the behavior of the retrofitted specimens changed from shear failure to flexural failure.

Therefore, the proposed the GFRP-strip device is a feasible means to increase the shear-strength of damaged RC columns and to shift their failure behavior from brittle/shear mode to ductile/flexural mode.

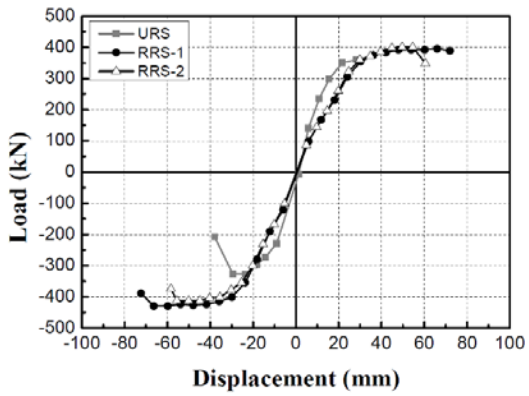


Fig. 5 – Envelope curve

Table 2 – Experimental test results

Specimen (First Yield Disp.)	North Direction			South Direction		
	Peak Load (kN)	Ductility Factor (Disp. at peak, mm)	Ratio	Peak Load (kN)	Ductility Factor (Disp. at peak, mm)	Ratio
URS (13 mm)	359.5	μ = 2.2 (28.7)	1.0 (1.0)	334.9	μ = 2.3 (28.6)	1.0 (1.0)
RRS-1 (12 mm)	393.6	μ = 6.0 (65.9)	2.7 (2.3)	429.6	μ = 6.0 (60.1)	2.6 (2.1)
RRS-2 (10 mm)	405.5	μ = 6.1 (54.5)	2.8 (1.9)	417.6	μ = 5.9 (49.2)	2.6 (1.7)

4.3 Crack distribution

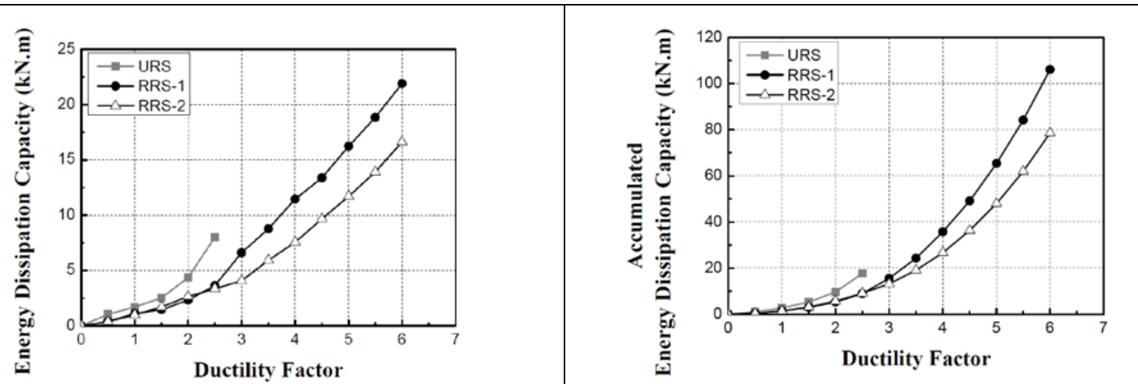
Figure 6 presents the crack distribution of each specimen at final stage or after pre-test. A large diagonal direction crack was observed in the plastic hinge area of the right column on the URS specimen; however, until the final stage, such diagonal direction cracks were not observed in the RRS-1 and RRS-2 specimens, which were retrofitted with GFRP-strip device. Due to the GFRP-strip device, the RRS-1 and RRS-2 specimens were more flexible than the URS specimen. The GFRP-strip device governed this behavior because flexural behavior was maintained before the failure of the GFRP-strip devices was occurred.

(a) URS (μ=2.5) (b) RRS-1 (μ=6.0) (c) RRS-2 (μ=6.0)

Fig. 6 – Final crack distribution

4.4 Hysteric energy-dissipation capacity

The energy-dissipation capacity is one of the parameters used to evaluate the seismic performances of the structure and might be dissipated by hysteretic behavior of the structure. This dissipation is usually called 'hysteretic damping by material inelastic behavior, since it indicates the ability to resist external forces exerted by an earthquake. Greater structural ductility provides greater energy-dissipation capacity. Generally the energy-dissipation capacity of each specimen was calculated as the sum of the area enclosed within the load-displacement hysteresis curves. Figure 7 shows the hysteric energy-dissipation capacity. The accumulated-energy-dissipation capacities are summarized in Table 3. The accumulated energy-dissipation of the RRS-1 specimen was 6.0 times that of the URS specimen. The accumulated energy-dissipation of the RRS-2 specimen was 4.5 times larger than that of the URS specimen. The accumulated-energy dissipation of the RRS-1 specimen was larger than that of the RRS-2 specimen, since the pre-test damage of the RRS-2 specimen was greater than that of the RRS-1 specimen.



(a) Energy-dissipation capacity

(b) Accumulated energy-dissipation capacity

Fig. 7 – Hysteric energy-dissipation capacity

Table 3 – Accumulated-hysteric-energy dissipation of specimens

Specimen	Accumulated Energy Dissipation Capacity (kN·m)	Ratio
URS	17.6	1
RRS-1	106.1	6.0
RRS-2	78.5	4.5

5. Conclusions

In this study, a GFRP-strip device was proposed to improve the seismic performance of damaged RC columns and was designed to consider easy installation and rapid repair. The GFRP-strip device consists of both GFRP composite strips and aluminum clip-connectors. Three RC frames were constructed to evaluate the performance of the GFRP-strip device. Two of the RC specimens were pre-tested to create damage before installing the GFRP-strip device. The experimental test results indicate several improvements in seismic performance of damaged columns. These include strength enhancement, failure mode, ductility and hysteretic energy-dissipation capacity. Thus, both the maximum strength and ductility of the retrofitted specimens were increased. Furthermore, accumulated energy-dissipation capacity of the retrofitted specimens increased 4.5 and 6.0 times, respectively. Taking the un-retrofitted RC specimen as a control specimen, the failure behavior of the retrofitted RC specimens was changed from brittle-shear failure to ductile-flexural behavior, which was maintained until the failure of the GFRP-strip devices occurred. Finally, it is shown that the proposed the GFRP-strip device developed can be used to improve the seismic performance of damaged RC columns.

6. Acknowledgements

This research was supported by a grant (15SCIP-B065985-03) from Smart Civil Infrastructure Research Program (SCIP) funded by Ministry of Land, Infrastructure and Transport of Korean government.

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