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DYNGMIC TESTING ON CIRCULAR RC BRIDGE COLUMNS RETROFITTED AND REPAIRED WITH SHAPE MEMORY ALLOYS

D. Jung[(1)], B. Andrawes[(2)]

[(1)] *Graduate Research Assistant, University of Illinois at Urbana-Champaign, djung10@illinois.edu*
[(2)] *Associate Professor, University of Illinois at Urbana-Champaign, andrawes@illinois.edu*

Abstract

RC bridge columns are required to maintain their functionality after strong seismic events without collapsing. Many existing bridges constructed based on old seismic design provisions lack the sufficient lateral confinement and are exposed to risk of severe column damage. Seismic damage of bridge columns may interrupt the immediate use of the bridge or lead to the collapse of the bridge under subsequent seismic events. As a new retrofit/repair technique for vulnerable RC columns, the application of Shape Memory Alloys (SMAs) in applying active confinement at plastic hinges has gained great interest recently. The substantially improved seismic performance of RC columns retrofitted and repaired with SMA spirals was proven in previous quasi-static cyclic tests. This experimental study aims to explore the effectiveness of using SMA spirals as retrofit and repair tool for RC columns through a series of shake table dynamic tests. Two 1/6-scale circular RC columns are tested under bidirectional earthquake loading. One of the specimens is retrofitted with SMA spirals, while the other specimen remains in the as-built condition. After moderate damage was imposed to the as-built specimen under seismic excitations, emergency repair is performed with SMA spirals followed by sequential seismic loading. Experimental results indicate that SMA spirals can effectively mitigate the damage and enhance the performance of RC columns under strong sequential ground shakings.

Keywords: Active confinement; Shape memory alloys; Concrete; RC Column; Retrofit; Shake table5

1. Introduction

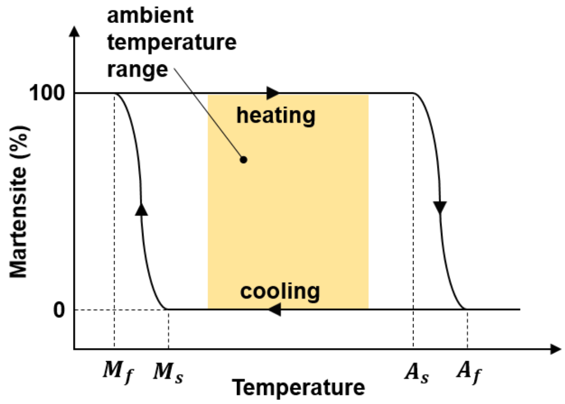
As one of the most critical components, affecting the structural integrity of the entire bridge system, RC bridge columns are required to resist damage and maintain their functionality when subjected to devastating seismic events. Through extensive experience and in-depth research, enormous advances have been made in the field of seismic design of RC bridge columns in recent decades. However, many existing RC bridge columns designed according to old seismic provisions before 1971 were constructed without taking careful seismic detailing into account. Especially, those RC columns which are lightly reinforced in the transverse direction are characterized with inadequate flexural ductility due to lack of sufficient confinement, which could lead to severe brittle damages during strong seismic events. These seismically deficient RC columns pose a serious threat to the bridges which may lead to a significant loss of lives and properties. The likelihood of disruption of transportation network and delay in emergency aids supply through the bridges would also increase. Therefore, effective retrofit and repair strategies need to be developed to mitigate severe seismic damages and to restore the functionality of the bridge in a reliable and rapid manner.

As a way to improve the flexural ductility of seismically vulnerable RC columns, application of external supplemental confinement has been investigated in many studies. The concrete confinement techniques developed up to date can be divided into two types, namely, passive confinement and active confinement. If concrete is passively confined, the confinement pressure is activated when the confined concrete is axially loaded and expanded laterally due to Poisson's effect, causing the confining material to be stressed. Steel jackets and fiber reinforced polymer (FRP) wraps are the most widely used materials for passive confinement and their applications have been extensively studied by Priestly et al. [1, 2], Daudey and Filiatrault [3], Xiao and Wu [4], Saadatmanesh et al. [5], Haroun and Elsanadedy [6] among many others. Active confinement pressure on the other hand is a type of lateral prestressing pressure which is applied without relying on concrete dilation. Active confinement exhibited better performance than its passive confinement counterpart in increasing concrete ductility under compression and delaying damages in concrete. The use of active confinement for RC columns has been explored recently by researcher such as Gamble et al. [7], Saaticoglu and Yalcin [8], Yamakawa et al. [9], and Nesheli and Meguro [10]. Most of these studies focused on utilizing conventional materials such as steel strands or FRP straps. However, it is quite demanding and impractical to implement active confinement technique using the conventional materials since excessive mechanical hardware, labor and time are needed to apply sufficient prestressing force. To overcome these issues, Shin and Andrawes [11, 12] explored a new active confinement technique utilizing shape memory alloy (SMA) spirals for RC columns. This technique relies on the thermally triggered shape memory effect of SMA material to apply large external active confinement pressure. Sufficient active confinement pressure is readily developed without special tools and labor once the SMA spirals are heated. The capability of the SMA spirals to enhance the seismic capacity of the RC columns was investigated experimentally by Shin and Andrawes [13]. Shin and Andrawes [14] also implemented the SMA confinement technique to rapidly repair severely damaged RC columns and tested the repaired RC columns under quasi-static lateral cyclic loading.

While the enhanced seismic capacity of RC columns retrofitted or repaired with the new SMA spirals was verified through quasi-static cyclic tests, such tests were not adequate to assess the dynamic responses of the columns induced by earthquakes. The realistic earthquake loading cannot be represented by the predetermined displacement loading protocol of those tests. Therefore, this study aims to evaluate the effectiveness and feasibility of the new SMA confinement technique in performing seismic retrofitting and emergency repair on RC bridge columns through a series of bidirectional shake table tests conducted at the U.S. Army Construction Engineering Research Laboratory (CERL).

2. Background on Active Confinement using SMA

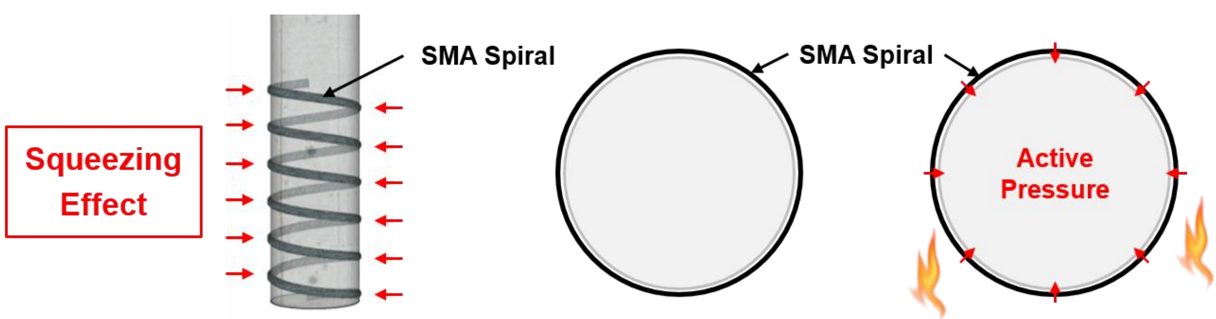
The active confinement technique using SMA is based upon the shape memory effect (SME), a characteristic of SMAs exhibited with heat application, which can generate high recovery stress (prestress) exploited to apply confinement pressure. Fig. 1 briefly depicts the principle of the SME which is closely associated with the phase transformation at the atomic level from the martensite phase to the austenite phase triggered by heat. Below the martensite finish temperature (M_f), SMA remains fully in the martensite phase as illustrated in Fig. 1.a. As the temperature of the SMA increases, the austenite phase starts to form at the austenite start temperature (A_s) and fully develops above the austenite finish temperature (A_f). If the SMA in the martensite phase is subjected to excessive deformation and then unloaded, it will sustain large residual strain. When the SMA is heated above A_f, the phase transformation activates the SME, enforcing the deformed SMA to recover its original shape. If the SMA is constrained and not able to recover its original shape, large recovery stress (prestress) would develop and maintain until the SMA is released.



(a) Thermal hysteresis (b) Thermomechanical behavior

Fig. 1 – Thermal hysteresis and thermomechanical behavior of SMAs

Figure 2 illustrates the application of SMA spirals implemented in this study to provide active confinement pressure for the plastic hinge zone of RC columns. First, prestrained SMA wires (6% strain) are wrapped around the plastic hinge zone of the column in the spiral form, and are fully anchored to the column to develop the maximum constraint. If the SMA spirals are heated using a propane torch, the elongated SMA spirals will attempt to contract to retrieve its original length. However, the constraint provided by the column hinders the SMA spirals from recovering the original length, and causes the recovery stress (prestress) to be developed within the spirals, applying the uniformly distributed radial confinement pressure to the column as a direct result. To avoid any chances of confinement pressure loss due to fluctuations in the ambient temperature, the NiTiNb SMA is chosen for this application considering its wide thermal hysteresis [15]. As illustrated in Fig. 1.a, the wide thermal hysteresis of NiTiNb allows it to maintain recovery stress as the ambient temperature remains above the martensite start temperature (M_s), which typically around -50 ˚C for NiTiNb.

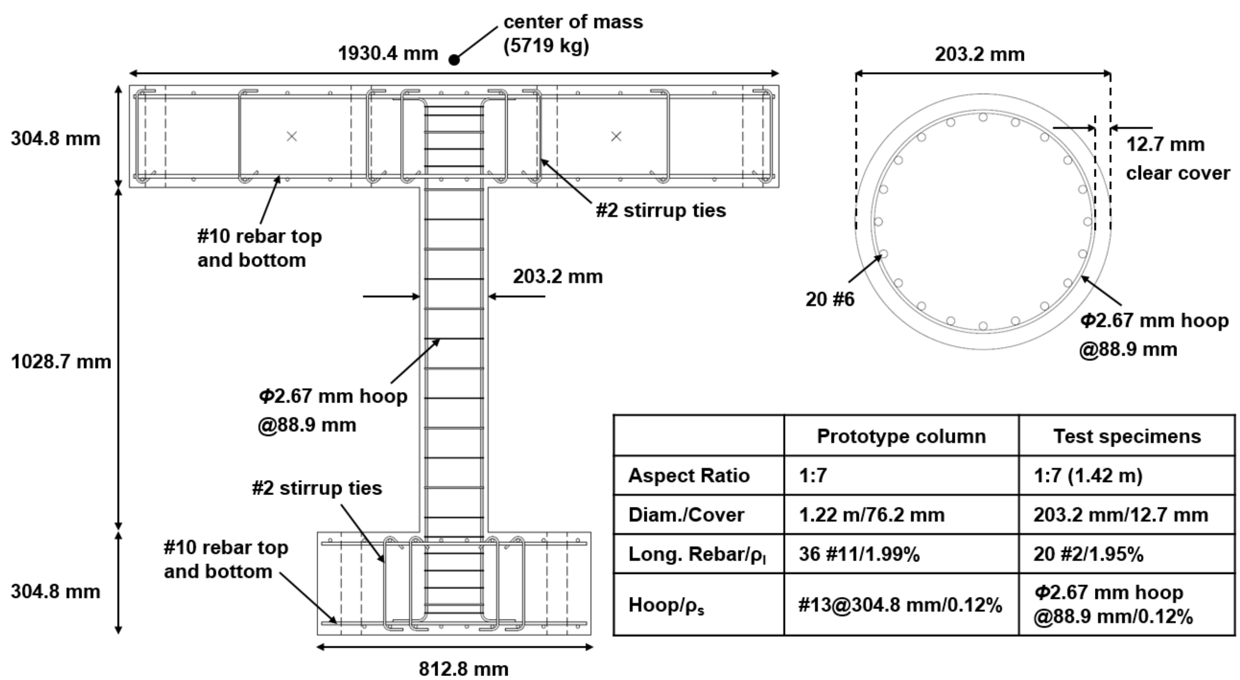


(a) (b) (c)

Fig. 2 – Application of active confinement pressure using SMA spirals: (a) prestrained SMA spirals applied at the plastic hinge zone of a RC column, (b) cross section before heating, and (c) cross section after heating

3. Design of Test Specimens

Two identical 1/6-scale RC cantilever columns were designed based on a prototype RC column constructed before 1971 according to old seismic design provisions. Fig. 3 shows the design of the test specimens. The RC columns had circular cross section with a diameter of 203.2 mm, in which 20 No. 6 (6.35 mm diameter) reinforcing bars were placed, corresponding to a longitudinal reinforcement ratio (ρ_l) of 1.95%. For the transverse reinforcement, 2.67 mm diameter steel hoops were sparsely placed at every 88.9 mm along the height of the columns, which reflected insufficient flexural ductility of the prototype column. The volumetric ratio of the transverse reinforcement (ρ_s) of about 0.12% falls far short of the standard of modern seismic design provisions. The footings (812.8 mm × 812.8 mm × 304.8 mm) and caps (1930.4 mm × 1168.4 mm × 304.8 mm) were reinforced with No. 10 (9.525 mm diameter) longitudinal reinforcing bars and No. 6 (6.35 mm diameter) ties. The target compressive concrete strength was 35 MPa.



	Prototype column	Test specimens
Aspect Ratio	1:7	1:7 (1.42 m)
Diam./Cover	1.22 m/76.2 mm	203.2 mm/12.7 mm
Long. Rebar/ρ_l	36 #11/1.99%	20 #2/1.95%
Hoop/ρ_s	#13@304.8 mm/0.12%	Φ2.67 mm hoop @88.9 mm/0.12%

Fig. 3 – Design of test specimens

To investigate the performance of SMAs, one test specimen (COL-1) was provided with SMA spirals in the plastic hinge zone, while the other specimen (COL-2) remained in the as-built condition. The retrofitted column (COL-1) was confined under a target active pressure of 2.07 MPa by wrapping 2.67 mm diameter NiTiNb alloy spirals with 8 mm spacing along a height of 305 mm. In the absence of any guidelines on the use of active confinement technique for seismic retrofit of RC columns, specifications on FRP column casing system suggested by the California Department of Transportation (Caltrans) were utilized in this study. According to Caltrans, FRP jackets are required to provide a confinement pressure of 2.07 MPa at a radial dilating strain of 0.004 when applied to the plastic hinge zone of the column [16]. Caltrans also recommended lateral confinement to be applied along a height of 1.5 times the diameter of the column (i.e. 1.5 × 203.2 = 304.8 mm) [17]. The fundamental period of the test specimens measured from a sine sweep vibration test were about 0.5 sec in the longitudinal and lateral directions. The longitudinal and lateral directions in this study indicate "south-north" and "east-west" directions, respectively.

4. Test Description and Procedure

4.1 Test setup

Fig. 4 shows the shake table test setup at CERL. The Triaxial Earthquake and Shock Simulation (TESS) has a 3.66 m × 3.66 m table which is controlled by hydraulic actuators installed in the longitudinal, lateral and vertical directions for six-degree of freedom motions. Because of time restriction, the testing for both columns was completed within one day. Both columns were set up on the table and tested simultaneously under equivalent bidirectional test motions in the longitudinal and lateral directions. Each test specimen supported the 16013.6 N concrete cap and six 6672.3 N steel plates at the top and had inertia mass of 5719 kg and axial load of 56047.4 N, reaching about 5% of the target compressive capacity of the column. The effective height of the column from the top surface of the footing to the center of mass is about 1.42 m with an aspect ratio of 7. To avoid direct collision between the column cap and the shake table, a safety frame was installed to catch the columns in case of collapse during the tests.

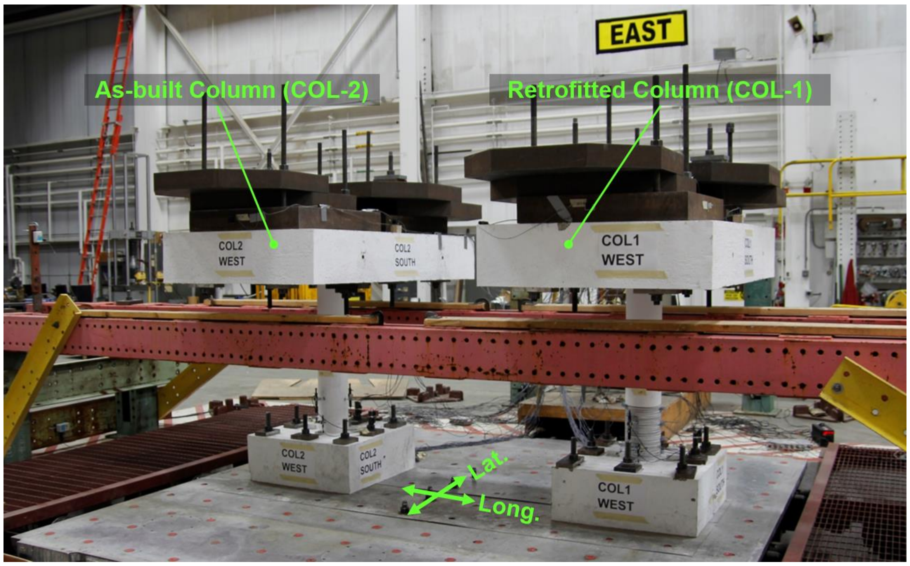


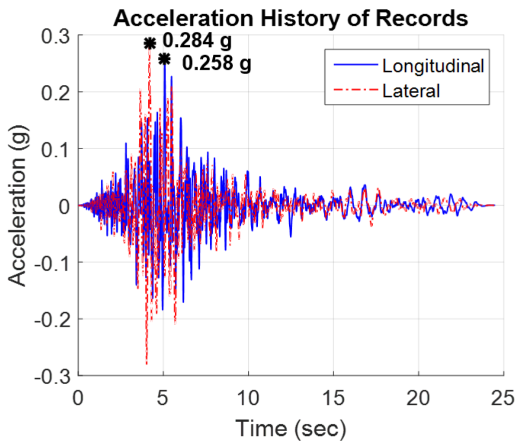
Fig. 4 – Shake table test setup at CERL

4.2 Instrumentation

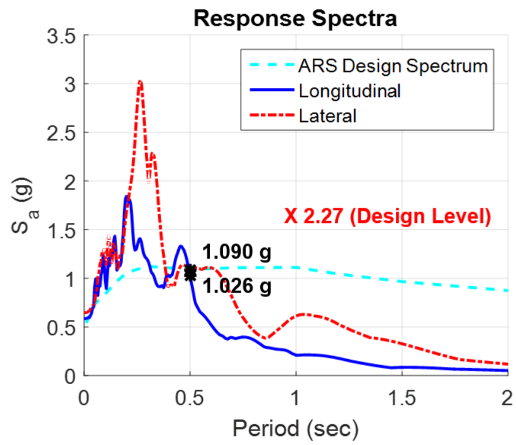
Acceleration and displacement responses were measured to obtain the global response of the specimens. The relative translational acceleration responses between the center of mass and the footing of each specimen were measured by accelerometers in the longitudinal and lateral directions. Accelerometers measuring the vertical accelerations at the edges of the column caps provided rotational acceleration responses of the column caps. Cable extensometers installed at the top and the base of the columns measured the relative displacement of the column top with respect to the bottom in the longitudinal and lateral directions. Linear extensometers were set up between threaded rods penetrating the columns at 76.2 mm and 152.4 mm above the base to measure deformation of the columns near the base. Strain gauges were attached on the steel hoops and along the longitudinal reinforcing bars at 0, 76.2, 152.4 and 228.6 mm above the base.

5. Selection of Ground Motions

The two horizontal components of the Foster City - APEEL 1 station records of the 1989 Loma Prieta earthquake were selected as the test motions. To avoid shear failure of the test specimens which lacked transverse reinforcement during the tests, the ground motions which did not induce high shear force were selected by performing nonlinear dynamic analyses. The selected records were preprocessed to be used for the tests. Considering the similitude laws for the scaled specimens, both records were first scaled in the time axis with a factor equal to the square root of the length scale ($\sqrt{6} \approx 2.45$) [18]. Fig. 5.a shows the ground motions scaled in the time axis. The unwanted frequency components of the records were removed through band-pass filter with a range of 0.01 ~ 25 Hz using Butterworth filter. Depending on specific target levels, the amplitudes of the both acceleration records were also scaled with the same scaling factors. In the scaling process, a design response spectrum defined by Caltrans ARS curve [17] was used to obtain a design earthquake by assuming that the RC columns were located at the station site of the records with a soil type E (shear wave velocity 116.35 m/s). The spectral acceleration, S_a of the records was scaled until it matched the design response spectrum at the fundamental period of the columns (0.5 sec.) as illustrated in Fig. 5.b. The selected scaling factor was used to obtain the design earthquake which was further scaled to reach each target level of the test sequence as discussed in the following section.



(a) Time axis scaling



(b) Amplitude scaling

Fig. 5 – Preprocessing of ground motions

6. Test Sequence

The dynamic tests were divided into two phases and each phase had three test runs. The test sequence and the target level of each test run are presented in Table 1. The equivalent scaling factor was used for both components of the test motions. The design earthquake defined in the earlier section was further scaled for the test motions and used to indicate the seismic intensity of the test motions.

Table 1 – Test sequence and target levels

	Run #	Earthquake	Target Level (scale factor)	PGA (g)
Phase 1	Run 1	Foreshock 1	Elastic level (+30%)	[0.080,0.086]*
	Run 2	Foreshock 2	Minor concrete spalling in COL-2 (+175%)	[0.464,0.501]
	Run 3	Foreshock 3	Severe concrete spalling in COL-2 (+200%)	[0.530,0.573]
Emergency repair of specimen COL-2				
Phase 2	Run 4	Main shock	Design level (+227%)	[0.596,0.644]
	Run 5	Aftershock	–0.80 × Design level (–182%)	[0.481,0.052]
	Run 6	Shock 1	+1.25 × Design level (+284%)	[0.752,0.813]

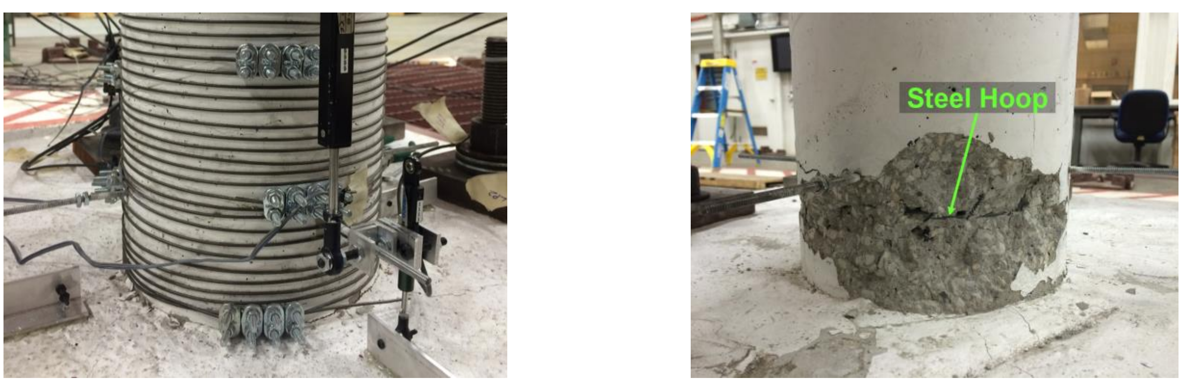
*[longitudinal,lateral]

The two objectives of phase 1 were to investigate how the seismic damage of the SMA retrofitted column was mitigated by observing the responses of the SMA retrofitted (COL-1) and as-built (COL-2) columns, and to cause some level of damage to COL-2 needed to evaluate the feasibility and effectiveness of the SMA confinement technique applied to emergency repair of seismically damaged RC columns in phase 2. The test motions used in phase 1 with the relatively low level intensity were denoted as “foreshocks”. The elastic level earthquake was first applied to identify the dynamic responses of the specimens in the elastic range and to check if the data acquisition system was working properly. The damage states of the test specimens under the higher level test motions were closely monitored after each test run. After test run 3, an emergency repair was conducted to rapidly repair the damaged column (COL-2) using the SMA spirals. The detailed repair procedure is discussed further in the following section. Phase 2 focused on the capability of the SMA repair technique to enhance the seismic performance of the damaged column (COL-2) under the sequential earthquake scenario, i.e. a “main shock” followed by an “aftershock” with an assumption that the design earthquake represented the main shock. For the scaling factor of the aftershock, one of the scaling factors used by Li and Ellingwood [19] to obtain aftershocks, 80% of the main shock, was selected. The negative scaling factor of the aftershock indicates that the test motions for the aftershock were applied in the opposite directions in order to perform the tests without collision with the safety frame by avoiding excessive accumulation of residual column drifts. The test motions increased again to 125% of the design earthquake after the aftershock.

7. Test Results and Analysis

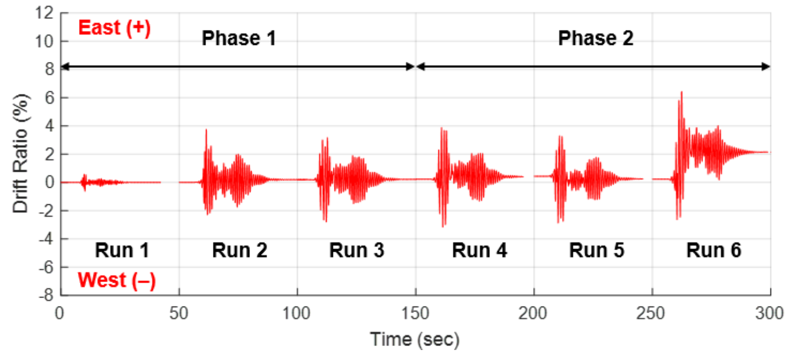
7.1 Phase 1 results

The elastic level earthquake loading was applied during test run 1 in phase 1. Both test specimens showed quite similar dynamic responses globally and no signs of major damages were observed. Only hairline cracks at the interface with the footing and the column were commonly seen for both columns, which were quite negligible. The initially reported damage was minor spalling of cover concrete on the east side of COL-2 near the base when recording the maximum drift of 3.65% in the lateral (east) direction during test run 2. Several hairline cracks newly formed on the west side of COL-2. Under test run 3, more severe concrete spalling occurred on the northeast side of COL-2 near the base. COL-2 lost cover concrete and exposed steel hoop in the damaged area ranging about 101.6 mm and 279.4 mm in height and width, respectively. After test run 3, COL-2 was slightly tilted in the lateral (east) direction with a residual drift of 0.89% caused by the elongation of the longitudinal reinforcing bars. The damage condition of COL-1 was closely monitored however only several hairline cracks in the concrete were observed without any significant damage even after test run 3. The maximum and residual drifts of COL-1, were 3.76% and 0.22% in the lateral (east) direction in phase 1. The maximum drift of COL-1 was quite similar to that of COL-2 but large discrepancies existed in the local damage conditions and the residual drifts between the two specimens. The damage conditions of the specimens in the plastic hinge zones after test run 3 are shown in Fig. 6. The large elongation of the reinforcing bars of COL-2 is expected to be caused by the loss of concrete in the plastic hinge zone shown in Fig. 6.b, which in turn reduced the lever arm for the bending acting on the circular section and imposed higher demand on the bars. The time history of the relative column drifts are shown in Fig. 7.

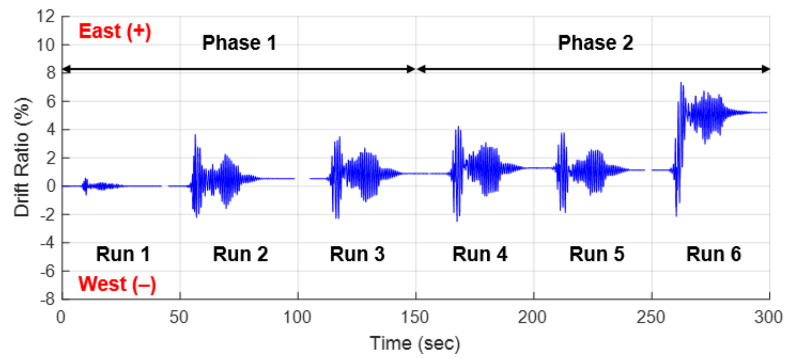


(a) COL-1 (b) COL-2

Fig. 6 – Damage conditions of test specimens after test run 3



(a) COL-1



(b) COL-2

Fig. 7 – Time history of the relative column drifts in the lateral direction

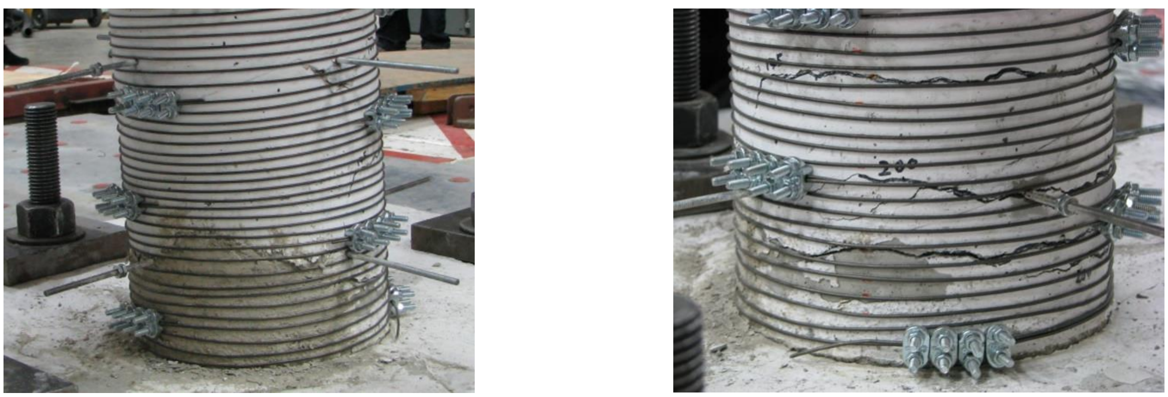
7.2 Emergency Repair Procedure for Damaged Column (COL-2)

A three step emergency repair procedure using SMA spirals was implemented for COL-2. First, the damaged region was cleaned by removing any concrete debris. In the second step, the damaged region was filled with rapid set mortar grout to quickly recover the original cross sectional area of the column. The compressive strength of the applied mortar evaluated according to ASTM Standard C109 [20] were about 18 and 28 MPa at one and three hour curing time, respectively. After waiting about one hour until the applied mortar developed a certain level of strength, the plastic hinge zone of COL-2 was provided with SMA spirals wrapped with 8 mm spacing up to 305 mm column height to generate a target active confinement pressure of about 2.07 MPa. Only about 2 hours and 30 minutes was taken for the repair process and the dynamic testing of phase 2 started in about 3 hours and 15 minutes after the repair process started.

7.3 Phase 2 results

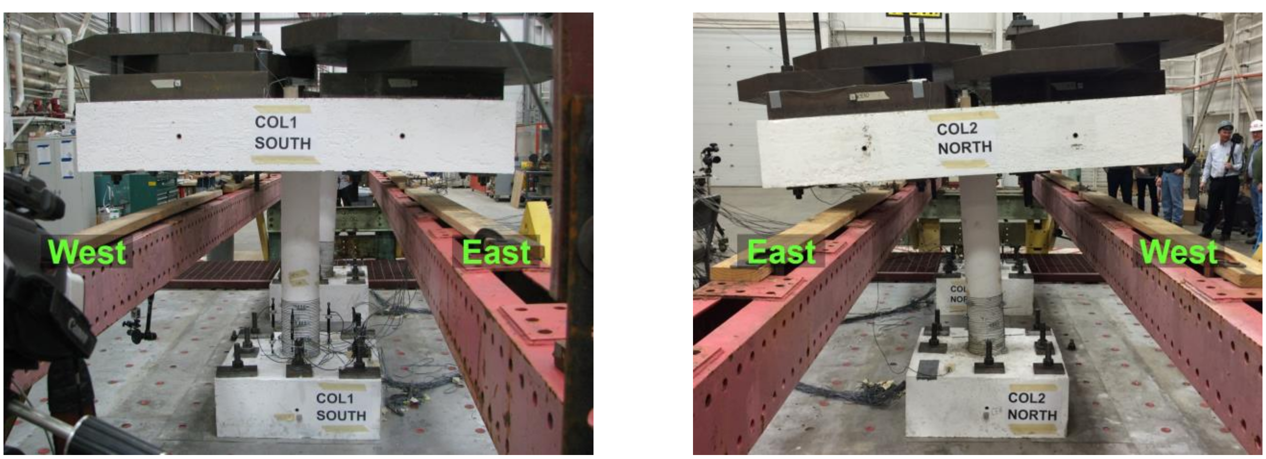
Phase 2 of the dynamic testing started from the design earthquake (227% of the Loma Prieta record) after the repair process was completed. In test run 4, both COL-1 and COL-2 successfully survived the design earthquake considered as the main shock. Only small concrete flakes were observed in the plastic hinge zones of both columns. In the global responses, both COL-1 and COL-2 had the maximum column drifts of about 4% in the lateral direction. The residual drift of COL-2 increased to about 1.27% in the lateral (east) direction, tilting further in the east direction because of the damage accumulation in the longitudinal reinforcing bars while COL-1 had a residual drift of 0.39% in the east direction. In test run 5, the aftershock motions, 80% of the design earthquake (-182% of the Loma Prieta record), were applied in the opposite directions to control the undesirable residual drift of the specimens as mentioned earlier. No further damages were reported for both columns in the plastic hinge zones. Due to the opposite directions of the applied test motions, the residual drift of both columns did not increase further. In test run 6, test motions equal to 1.25 times the design earthquake (284% of the Loma

Prieta record) were applied. The damage observations of the confined regions of both columns were similar to what had been reported in previous tests in phase 2. More concrete flakes were generated in the confined regions of the columns without serious concrete damages. The concrete damages in both columns were effectively minimized by the SMA confinement. However, the global responses of the column specimens exhibited differences, compared to the previous test runs. COL-1 and COL-2 recorded the maximum column drifts of 6.4% and 7.3% in the lateral direction, respectively, much greater than the 4% column drifts recorded in test run 4. Especially, the residual drifts of COL-1 and COL-2, 2.1% and 5.2%, respectively, in the lateral direction, increased significantly from 0.39% and 1.27% recorded in test run 4. The dramatic changes in the column drifts in test run 6 can be mainly attributed to the low cycle fatigue behaviors of the reinforcing bars as a direct consequence of the large number of inelastic strain reversals experienced by the bars under the repeated dynamic loading in phase 1 and 2. The time history of the relative column drifts in the lateral direction for both columns are presented in Fig. 7. Fig. 8 shows the damage condition of COL-2 after test run 6 in the confined region. The cracks developed on the west side of COL-2 opened further in Fig. 8.b due to elongation of the reinforcing bars. Fig. 9 clearly shows the residual drifts of COL-1 (captured from the south) and COL-2 (captured from the north) in the lateral direction after test run 6.



(a) Northeast side (b) Northwest side

Fig. 8 – Damage condition of COL-2 in the plastic hinge zone after test run 6



(a) COL-1 (b) COL-2

Fig. 9 – Residual drifts of the test specimens after test run 6

8. Conclusions

The feasibility and efficacy of the application of active confinement technique using SMA spirals to retrofit and repair RC columns were investigated through bidirectional earthquake simulation tests. The dynamic testing was conducted in two phases. In phase 1, two reduced scale RC circular columns, one (COL-1) retrofitted with the SMA spirals and the other (COL-2) in the as-built condition, were tested to assess the damage mitigation effect of the SMA retrofitted under the seismic excitations. Under test motions scaled up to 200% of the selected ground motions, severe cover concrete spalling occurred in the plastic hinge zone of COL-2, while no noticeable damage was observed in COL-1, which clearly proved that the SMA confinement can effectively protect the concrete from spalling or crushing. The maximum column drifts in the lateral direction of COL-1 and COL-2 in phase 1 were comparable (3.76% and 3.65%, respectively). However, the residual column drift of COL-1 and COL-2 in phase 1 were 0.22% and 0.89%, respectively, yielding a large difference. This observation implies that the SMA confinement does not just reduce the concrete damage but also prevents progressive shift of the damage in the steel reinforcing bars. The damaged column (COL-2) was rapidly repaired by conducing emergency repair procedure using SMA spirals for 2 hours and 30 minutes. The seismic performance of the SMA repaired column (COL-2) was evaluated under the sequential earthquake scenario along with COL-1 in phase 2. Both COL-1 and COL-2 survived the main shock followed by the aftershock. No more severe concrete damages threatening the structural integrity of the column were observed in the confined regions of both specimens, indicating that the repair procedure using SMA spirals played a crucial role in minimizing further concrete damages and restoring the seismic capacity of the damaged column against threat of subsequent seismic events. Under the test motions of 1.25 times the design earthquake in test run 6, the dynamic responses of COL-1 and COL-2 were greatly affected by the low cycle fatigue behaviors of the reinforcing bars subjected to the repeated inelastic strain reversals. The residual drifts of COL-1 and COL-2 dramatically increased to 2.1% and 5.2%, respectively, due to the elongation of the reinforcing bars. The result suggests that the seismic performance of RC columns with sufficient external confinement can be highly governed by the low-cycle fatigue behavior of reinforcing bars. Even with high maximum column drifts greater than 6%, only small pieces of concrete flake were observed and the SMA spirals successfully provided active pressure for the confined regions of both specimens until the testing was completed.

9. Acknowledgements

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10. Copyrights

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