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Bidirectional shake table testing of RC columns retrofitted and repaired with shape memory alloy spirals

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ABSTRACT

Under the extreme threats of strong earthquakes, bridge columns are required to remain functional to ensure the safety and structural integrity of the entire bridge system. However, many existing bridges designed according to old seismic design provisions lack flexural ductility due to insufficient concrete confinement. Lack of confinement in old bridges is often addressed through providing supplementary external passive confinement. Recently, an active confinement technique using Shape Memory Alloys (SMAs) has been proposed as a more effective alternative to conventional passive confinement methods. In this study, the application of SMA confinement in seismic retrofitting and emergency repair of RC bridge columns is examined experimentally through a series of shake table tests. Two 1/6-scale RC columns, retrofitted and repaired with SMA spirals, are tested simultaneously under bidirectional test motions with varying intensity. Test results show that SMA confinement is highly effective in mitigating the seismic damage and improving the seismic performance of retrofitted and repaired RC columns subjected to strong earthquakes.

1. Introduction

The past few decades have witnessed the damage and collapse of several reinforced concrete (RC) bridges across the world due to strong seismic events. Among various types of bridge damage resulting from earthquakes, the failure of RC bridge columns is among the most undesirable since it directly impacts the safety and functionality of the entire bridge system. Despite recent advances in earthquake engineering, many existing RC bridge columns were constructed with poor seismic detailing according to old seismic design provisions prior to 1971. The use of insufficient transverse reinforcement in those old RC columns leads to lack of concrete confinement, which in turn gives rise to the possibility of non-ductile flexural damage at the column's plastic hinge region as observed during large recent earthquakes [1]. The existence of such non-ductile RC columns in a bridge poses a direct threat to the bridge's structural integrity and its post-earthquake functionality, especially if the bridge is subjected to a sequence of strong ground shaking (i.e. Main shock followed by strong aftershocks). Therefore, the importance of pre-earthquake retrofit and post-earthquake emergency repair techniques to maintain and recover the structural integrity of these columns, respectively, cannot be overemphasized. A great research effort has been made over the last few decades to address this issue through providing external supplementary confinement at the column's plastic hinge region. The concrete confinement techniques developed up to date can be divided into two primary types: (1) passive confinement and (2) active confinement. In the case of passive confinement, the confinement pressure is exerted by hoop stresses developing in the lateral reinforcement as a result of the lateral expansion (dilation) of the concrete under loading (i.e. Poisson's effect). Installing external steel jackets or fiber reinforced polymer (FRP) wraps on the column is among the most widely used approaches to provide supplementary passive confinement [2–7]. Unlike passive confinement which inevitably entails a certain level of concrete damage, active confinement pressure is applied as lateral prestressing pressure exerted without the need for concrete dilation, and is therefore continuously maintained. Several studies demonstrated the ability of active confinement to surpass its passive confinement counterpart in increasing concrete ductility under compression and delaying concrete damage. Among these studies is the one by Gamble et al. [8] who used tensioned steel bands and prestressing strands to actively confine full scale circular RC columns. Saaticoglu and Yalcin [9] also tested full scale circular and rectangular RC columns confined with external prestressing strands under lateral cyclic loading. Attempts were also made to actively confine RC columns using prestressed FRP belts/straps [10,11]. One of the drawbacks of using steel strands or FRP straps to apply active confinement is the excessive mechanical hardware, labor

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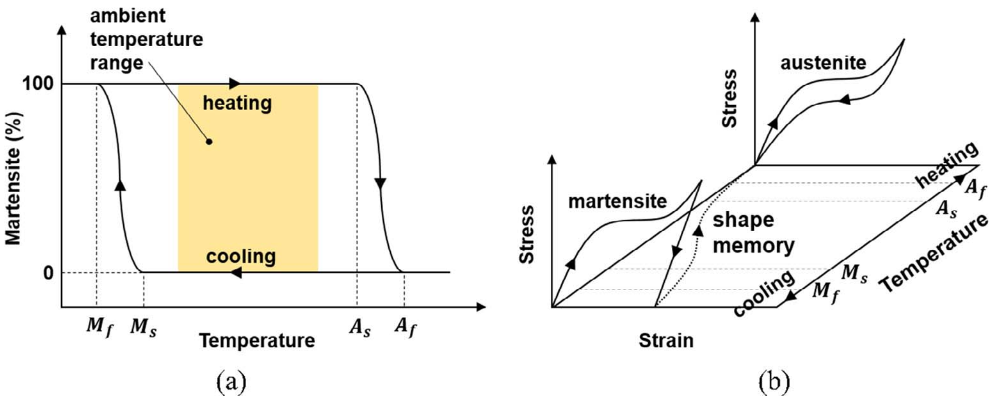

Fig. 1. Thermomechanical properties of SMAs: (a) thermal hysteresis and (b) thermomechanical behavior.

and time needed to apply sufficient prestressing force, which raises serious concerns related to the practicality of active confinement techniques. In an attempt to overcome these issues, researchers proposed using unconventional methods to apply active confinement. For example, Yan et al. [12] utilized expansive cement concrete confined by prefabricated FRP jackets to apply chemically triggered confining pressure to rectangular or square RC columns. Krstulovic-Opara and Thiedeman [13] studied the use of shape memory alloy (SMA) fibers embedded in high performance fiber reinforced concrete to actively confine concrete cylinders. Shin and Andrawes [14,15] proposed and studied the use of thermally prestressed SMA hoops and spirals to retrofit and repair RC columns. These SMA-based techniques focused on exploiting the shape memory effect of SMA material triggered by heat to apply large external active confinement pressure. One of the main advantages of this technique over other active confinement techniques is that a great amount of active confinement pressure is readily developed without special tools and labor once the SMA is heated. The capability of SMA spirals to enhance the seismic capacity of RC columns was investigated numerically and experimentally by Shin and Andrawes [15,16]. They also explored the use of SMA active confinement technique to conduct rapid repair of severely damaged RC columns [17]. Under quasi-static lateral cyclic loading, the repaired RC columns fully recovered their lateral strength and showed enhanced flexural ductility. The previous studies revealed that SMA's excellent confinement capability would enable the use of much less amount of material to provide sufficient ductility capacity for RC columns, compared to steel or FRP used in passive confinement, making it economically feasible. Even at risk of impending seismic events, rapid on-site installation of SMA spirals and immediate pressure activation would not only significantly lower the labor costs but also effectively prevent severe column damages which may lead to a tremendous loss of lives and properties.

While the efficacy of SMA active confinement was proven on the component level through quasi-static cyclic tests, such tests were unable to adequately represent the realistic dynamic responses of SMA retrofitted/repaired columns under seismic excitations. Further, the predetermined unidirectional displacement loading protocol of those tests is quite different from realistic multi-directional seismic loadings. This paper presents the findings of an experimental study that involved a series of bidirectional shake table dynamic tests that were carried out at the U.S. Army Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL) to investigate the dynamic behavior and effectiveness of the new SMA confinement technique as seismic retrofitting and emergency repair method for RC bridge columns.

2. Background on active confinement using SMA

The application of active confinement using SMA takes advantage of the high recovery stress (prestress) induced by the shape memory effect (SME), a phenomenon exhibited by SMAs when subjected to heating. Fig. 1 depicts the thermally triggered SME, which is a direct result of the atomic phase transformation from the martensite phase to the austenite phase. As illustrated in Fig. 1(a), if SMA remains below the martensite finish temperature (M_f), it is fully in the martensite phase. The SMAs start to transform to the austenite phase at the austenite start temperature (A_s) and become fully austenite above the austenite finish temperature (A_f). As depicted in Fig. 1(b), in its martensite phase, SMA experiences large residual strain when unloaded after being excessively deformed. When alloy is heated above A_f, the SME is triggered and the SMA recovers its original shape. If the SMA is constrained and not able to recover its original shape, a large recovery stress (prestress) would develop in the material.

Fig. 2 illustrates how SMA spirals are utilized in this study to confine the plastic hinge of RC columns. First, in the manufacturing factory, SMA wires are elongated to have permanent strain of 6.4% in the martensite phase. The prestrained SMA wires are then wrapped in the form of a spiral around the column's plastic hinge zone where confinement is desired. After anchoring the wires to keep them in place, the SMA spirals are heated using a propane torch. The already deformed SMA spirals will attempt to recover the original length. However, due to the constraint provided by the column, recovery stress (prestress) will

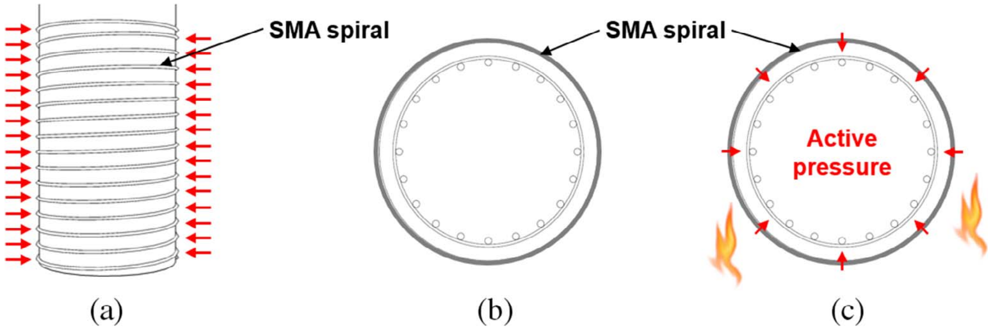

Fig. 2. Application of active confinement using SMA spirals: (a) prestrained SMA spirals wrapped around the plastic hinge zone, (b) cross section before heating and (c) cross section after heating.