Innovative materials for bridge seismic design

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Abstract

Shape memory alloys (SMAs) are unique alloys that have the ability to undergo large deformation, but can recover deformations fully after the loads. The primary objective of this study was to investigate the seismic performance of RC columns with SMA longitudinal reinforcement in the plastic hinge area. Another target was to evaluate seismic performance and damage in a repaired SMA-reinforced column using engineered cementitious composites (ECC). Two quarter-scale spiral RC columns with SMA longitudinal reinforcement in the plastic hinge area were designed and constructed for shake table testing at the Large Scale Structure Laboratory of the University of Nevada, Reno. The shake table data showed that SMA RC columns were able to recover nearly all of the post-yield deformation and that the use of ECC reduced the concrete damage substantially, thus requiring minimal repair even after very large earthquakes. Keywords: shape memory alloy, seismic performance, deformation, engineered cementitious composites, plastic hinge.

1 Introduction

Reinforced concrete structures in seismic regions are susceptible to collapse and severe damage due to excessive lateral displacements. The basis of conventional seismic design is to yield steel in order to dissipate energy while encountering permanent deformation due to plastic properties of post-yield steel reinforcements. Shape memory alloys (SMA) are unique alloys that have the ability to undergo large deformations, but can return to their undeformed shape by heating or through removal of the stress. Therefore if SMA can be used as reinforcement in seismic design, it can yield under strains caused by seismic loads but potentially recover deformations at the end of earthquakes. The University of Nevada, Reno (UNR) and others have conducted analytical and
experimental studies to determine the SMA performance in structural engineering applications (Ocel et al. [1]; Ayoub et al. [2]; Johnson et al. [3]).

The low tensile strain capacity of conventional concrete is the cause of early damage and the need for repair. Its brittleness has caused numerous and catastrophic failures of substandard buildings and bridges in recent earthquake events. Alternative technologies promise to improve the performance of concrete materials. One such technology involves a family of engineered cementitious composites (ECC). Some researchers have conducted analytical and experimental studies on the repair performance with ECC (Li et al. [4]).

This study makes use of SMA and ECCs. Two specimens were designed and constructed for shake table tests. The objective of the study was to investigate the seismic performance of reinforced concrete columns with SMA longitudinal reinforcement in plastic hinge area and to determine the effectiveness of superelastic SMA bars in reducing the permanent displacements. Another target was to evaluate damage in a repaired SMA-reinforced column using ECC. The study also included extensive analytical studies that are not included in this article due to space limitations.

2 Test specimen and experimental process

Two RC columns with SMA longitudinal reinforcement in the plastic hinge area were designed and constructed for shake table testing at the Large Scale Structure Laboratory of University of Nevada, Reno.

2.1 Materials

Two kinds of innovative materials were used in this research: superelastic shape memory alloys and engineered cementitious composites.

SMAs are a class of alloys that display several unique characteristics, including shape memory effects, pseudo-elasticity, and high damping characteristics. The interest in SMA in structural engineering applications has been growing over the last several years. During deformation, SMA undergoes phase transformations instead of intergranular dislocations as typically found in metals. These phase transformations refer to spontaneous shifts between martensitic and austenitic crystal forms. Nickel-Titanium (NiTi) alloy is the most used SMA. It is a compound of NiTi, whose transformation temperature can range between -100 °C and +110 °C. It has great shape memory strain (up to 8%), is thermally stable, and has excellent corrosion resistance. In this study, the superelastic properties occurring in the austenitic phase of the SMAs, specifically NiTi rods (55.9% Nickel, 44.1% Titanium) were investigated. The transformation temperature is approximately 0 °C.

The total length of NiTi rod was 355.6 mm. The ends were threaded. In the middle 203 mm part, the diameter was reduced to 12.7 mm. One NiTi rod was tested in a MTS load frame in the Large Structures Testing Lab at UNR. The measured yield stress of NiTi rod was approximately 379.2 MPa. Stress strain curves of NiTi rod are shown in Fig. 1. An ultimate strength of 903.5 MPa was specified by the manufacture.
Figure 1: Test stress strain curve for shape memory alloy.

(a) Test setup

(b) Highlighted cracks

Figure 2: ECC sample beam flexure test.
ECC is a high performance fiber-reinforced cementitious composite designed with micro-mechanical principles. Different from fiber reinforced concrete (FRC), fine sand and tailored polymer fiber must be chosen for ECC. Special micro-mechanics based design methodology is the key point to mix ECC. The FRC interface is not controlled while chemical and frictional bonds control ECC interface for bridging properties, which enable ECC strain hardening behavior verses tension softening seen in FRC.

In this study, PVA fiber was selected to mix in ECC. Figure 2(a) shows ASTM beam flexure tests. Beam dimensions were 25.4 mm by 25.4 mm by 127 mm. Note that many cracks were formed in the ECC beams and that the cracks were thin and distributed (Fig. 2(b)). In contrast flexural failure of plain concrete or mortar beams is usually associated with a single crack. A typical measured stress strain curve is shown in Fig. 3. The thickness of the sample was 7.6 mm. High strain capacity was achieved. ECC compression tests (Cylinder: 152 mm diameter and 305 mm height) showed compression strength of 74 MPa.

2.2 Specimens

Two, quarter-scale columns were tested, SMAC-1 and SMAC-2. Specimen SMAC-1 was a new column and SMAC-2 was a column that was repaired using ECC. To compare SMAC-1 and SMAC-2 performance with conventionally reinforced RC columns, scale and dimension were chosen to match specimen SC-CAL tested in a previous study by Mortensen and Saiidi [5]. An axial load of 623 kN was selected corresponding to an axial load index of 0.25.

The aspect ratio of the column was 4.5, which was chosen to ensure flexure-dominated behavior (Fig. 4). From Paulay and Priestley’s equation, 215 mm was
calculated out for plastic hinge length (Paulay [6]). The column longitudinal reinforcement consisted of 15 bars spaced evenly in a circular pattern. NiTi rods were used in the plastic hinge area. Steel couplers were used to connect NiTi rods and #5 bar (Ø15.9 mm). Transverse reinforcement was #6 galvanized spiral wire with a diameter of 4.9 mm and spacing 40 mm.

Figure 4: Specimen detail.

After SMAC-1 was tested on the shake table, its plastic hinge was repaired with ECC. The repaired area was designed to restore strength of the hinge concrete and to reduce damage relative to SMAC-1. The repair height was approximately 254 mm from the top of the footing.

2.3 Test setup and testing program

Figure 5(a) shows the experimental setup for the specimen. The columns were attached rigidly to the shake table and to the inertial system. A steel beam was bolted to the top of the column head and the hydraulic ramp system was attached to apply the axial force. A large number of displacement transducers,
Accelerometers, and strain gages were attached to the specimen and connected to a data acquisition system.

(a) Test setup                                (b) ATC-32D earthquake record

Figure 5: Test setup and input earthquake.

An artificial ground motion from the Applied Technology Council 32 documents [7] for soil type D (ATC-32-D) was chosen to be the input shake table motion for the large number of high amplitude motions, and because it represents a collection of motions on medium stiff soil. The ATC-32-D motion had a peak ground acceleration (PGA) of 0.44g and was active for 20 seconds (Fig. 5(b)). Each specimen was subjected to a series of scaled motions the amplitudes of which were progressively increased. SMAC-1 experienced eleven excitations, ranging from 15% (run 1) to 300% (run 11) of the ATC-32-D record. For SMAC-2, four more runs were applied. As a result for repaired column, the maximum excitation was 400% (run 15) of the ATC-32-D record.

3 Experimental results

3.1 Specimen SMAC-1

First minor flexural cracks appeared after run 3 in the lower 200 mm of the column. After run 6 (PGA 0.66g) concrete spalling occurred on the both sides of the column at the about 150 mm from the top of the footing (Fig. 6 (a)). As shown in Fig. 7 (a) wires could be seen and more spalling occurred after run 8 (PGA 0.99g). The test was stopped to prevent reinforcement failure and to keep the column in a repairable state. Figure 8 shows displacement histories for different runs. Note that the maximum displacement was nearly constant in the last three runs. The maximum top displacement was 66 mm, which corresponded to a maximum column drift ratio of 4.8%. The residual displacements in SMAC-1 were less than 1.3 mm during the shake table test.
3.2 Specimen SMAC-2

First minor flexural cracks appeared after run 3 on the south side of the specimen. After run 6 small cracks were seen on the bottom and some vertical cracks appeared, as shown in Fig. 6(b). Most cracks were mainly on the top boundary of the ECC and the old concrete. During run 8 (Fig. 7(b)), more cracks were observed on the bottom part. Minor spalling of ECC took place but the fibers held the piece. During run 11, delamination happened on the ECC top boundary with old concrete. For run 12-15, only a few new cracks were formed. The test was stopped after run 15 when the capacity of SMAC-2 dropped. Figure 8(b) shows displacement histories for different runs. From run 8, the maximum displacements started at the same level, with an average of 69 mm. The maximum top displacement was 78 mm, a drift ratio of 5.7%. The residual displacements in SMAC-2 were less than 3.3 mm during the shake table test.

Figure 8 shows the displacement comparison for two SMA columns and SC-CAL. The SMA RC columns withstood larger earthquake amplitudes than the conventional columns. The maximum displacement was only 66 mm (drift ratio of 4.8%) for specimen SMAC-1 after run 11 while it was 135 mm (drift 9.8%) after the last run (run 8) in specimen SC-CAL. For SMAC-2, the maximum column displacement was 78 mm (drift 5.7%). The residual displacements were less than 3.3 mm for SMA columns during the test. While for SC-CAL, the residual displacement was 45 mm during run 7 and this increased to 135 mm shortly before failure in run 8.
3.3 Performance comparisons of SMA and steel RC columns

As stated before, SC-CAL was a conventional steel RC column tested with the same shake table testing program as those of SMAC columns. Figure 6 compares the columns after run 6 (PGA 0.66g). Considerable concrete spalling occurred in SC-CAL, some concrete spalling occurred in SMAC-1, and no spalling was observed in SMAC-2. During run 8 (Fig. 7), SC-CAL totally failed while only cover concrete spalling occurred in SMAC-1, and no spalling was seen in SMAC-2. Significant cover concrete spalling occurred in SMAC-1 while a little spalling was observed in SMAC-2 even after run 15.

![Displacement histories for specimens.](image)
4 Conclusions

The following conclusions were made based on the experimental and analytical results.
1. The SMA reinforced concrete columns were superior to the conventional steel RC columns in limiting relative column top displacement. The maximum column drift was only 4.8% for specimen SMAC-1 after run 11 while it was 9.8% after the last run (run 8) in specimen SC-CAL. For SMAC-2, the maximum column drift was 5.7% after run 15.
2. The SMA RC columns were superior to the conventional columns in limiting residual displacements. The residual displacements in SMAC-1 were less than 1.3 mm during the test. While for SC-CAL, the residual displacement was 45 mm during run 7 and this increased to 135 mm shortly before failure in run 8. For SMAC-2, the residual displacements were less than 3.3 mm during the test.
3. The SMA RC columns withstood larger earthquake amplitudes than the conventional columns. During run 8 (PGA 0.99g) SC-CAL failed, while only cover concrete failure was observed for SMAC-1 after run 11 (1.32 g). SMAC-2 withstood an earthquake with PGA of 1.76g.
4. The performance of ECC as a repair material was satisfactory. It exhibited only limited damage even under large-amplitude motions. The maximum displacement and residual displacement were close to those of the as built SMA reinforced column.

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References


