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RESILIENT AND SUSTAINABLE BRIDGES OF THE FUTURE

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ABSTRACT: Highlights of several investigations on seismic performance of new generation of bridges are presented. Low-damage materials such as shape memory alloy, engineered cementitious composite, fiber reinforced polymer, and elastomeric rubber pad were incorporated in bridge columns to facilitate construction, enhance performance, minimize damage, reduce permanent deformations, and reduce or totally eliminate the post-earthquake repair costs.

KEY WORDS: Bridge; Low-damage materials, SMA, ECC, FRP, Rubber pad

1 INTRODUCTION

Conventional bridge construction (CBC) in which bridge components are cast in-place has a history of more than a century in the United States. Several months of construction are typically required using CBC techniques to fully build a bridge. Accelerated bridge construction (ABC), in contrast, utilizes advanced technologies and improved planning to facilitate construction and minimize interruption to highway network. Precast components are the essence of ABC. Even though ABC offers many advantages over CBC, precast component connections present a challenge in the moderate and high seismic areas. Low-damage high-performance materials may be used to improve ABC connection performance and to enhance the overall seismic behavior of bridges even under severe earthquakes. This article presents the highlights of several studies in which novel materials and details were explored to develop earthquake-resistant connections and elements. The article also includes a study on design for deconstruction of bridge columns.

2 ADVANCED MATERIALS

2.1 Shape memory alloy (SMA)

SMA is a class of metallic materials with superior properties, which makes it a viable alternative to reinforcing steel. Large strains induced to SMA can be fully recovered by heating (shape memory effect) or unloading (superelastic effect) [1]. Superelastic SMAs has gained more attention for structural engineering applications since they exhibit minimal residual deformations without applying external heat or electrical current. Among many alloys of SMA, Nickel-Titanium (NiTi or Nitinol) alloy is more common because of its high superelastic range, high energy dissipation capacity, low- and high-cycle fatigue properties, and excellent corrosion resistance [2].

Tazarv and Saiidi [3] defined mechanical properties of reinforcing superelastic SMA for structural applications and proposed a method to extract the properties form a ASTM standard test. A simple flag-shape material model (Fig. 1) was proposed and a design specification for reinforcing NiTi superelastic SMA bars was presented. Statistical analyses on a pool of tensile tests showed that reinforcing SMA has 10-20% lower yield strength, 80% lower modulus of elasticity, and slightly higher ultimate stress and strain capacities compared to reinforcing steel.

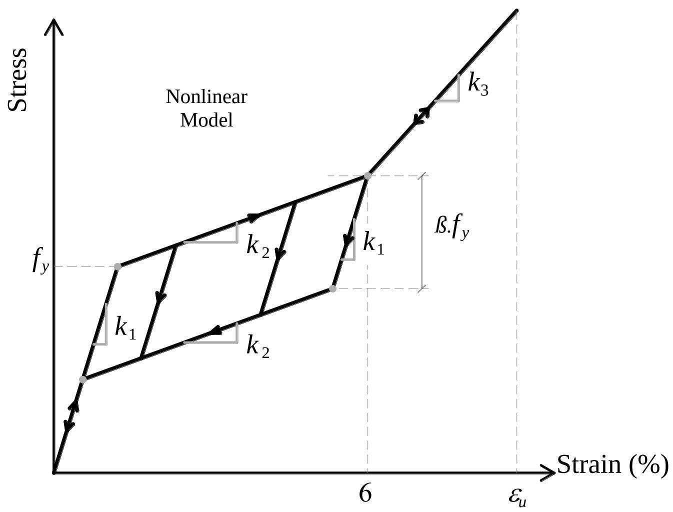


Figure 1. Nonlinear model for reinforcing NiTi superelastic SMA [3]

2.2 Engineered cementitious composite (ECC)

ECC is a class of high-performance fiber reinforced concrete with 4% or more tensile strain capacity. Polyvinyl alcohol (PVA) with 2% volumetric ratio is the most common type of fiber used in ECC mix. Seismic performance of ECC structural components have been studied by several researchers [4, 5, 6, and 7]. A minimal damage of elements incorporating ECC plastic hinge was observed in these studies, and the damage was mainly limited to minor cover ECC spalling.

2.3 Fiber reinforced polymer (FRP)

Even though FRP is linear-elastic and brittle material, satisfactory performance can be achieved when FRP be incorporated as either reinforcement or external jacket in concrete structures. Seismic performance of FRP tubes filled with concrete has been investigated in several studies. A state-of-the-art review on the topic was presented in Bakis et al. [8].

2.4 Elastomeric rubber plastic hinge

Rubber has been widely used in bridge industry for bearings and seismic isolators. Since rubber has a significantly lower stiffness than steel and concrete, it softens the behavior of a structure in an isolator configuration resulting in higher vibration periods thus lower seismic forces. A new application for rubber as an elastomeric rubber plastic hinge for ABC bridge columns was investigated by Motaref et al. [9]. The rubber pad was reinforced with steel shims to reduce bulging of the rubber and prevent buckling of the column longitudinal steel bars (Fig. 2). A high drift ratio capacity with no rubber plastic hinge damage was observed in shake table testing of the column.

3 LOW-DAMAGE PLASTIC HINGES FOR CONVENTIONAL BRIDGE CONSTRUCTION (CBC)

Two 1/3-scale, SMA/ECC bridge columns were tested under slow reversed cyclic loading to failure. ECC was used in entire length of columns but NiTi superelastic SMA bars were used only in plastic hinges (Fig. 3). The test variable in the two columns was the length of SMA bars with 18-*in*. (475-*mm*) bars in one column and 13.5-*in*. (343-*mm*) bars in the other. #4 (Ø13 *mm*) SMA bars were connected at both ends to #5 (Ø16 *mm*) steel bars using mechanical headed bar splices. These column models were cast in-place.

The test results showed that even under 12% drift ratio, the plastic hinge damage of SMA/ECC columns was minor (Fig. 4). Flag-shape hysteretic behavior with negligible residual displacements was observed in both columns (Fig. 5). It was found that displacement capacity of SMA/ECC column with a SMA bar length equal to one column side dimension is 85% higher than a steel-reinforced concrete column and 30% higher than the SMA/ECC column with shorter SMA bars. The drift capacity of the column with long-SMA was 11% versus 6% for the RC column and 8% for the column with shorter SMA bars.

Figure 2. Elastomeric Rubber Hinge [9]

Figure 3. Reinforcing SMA bars used in plastic hinge

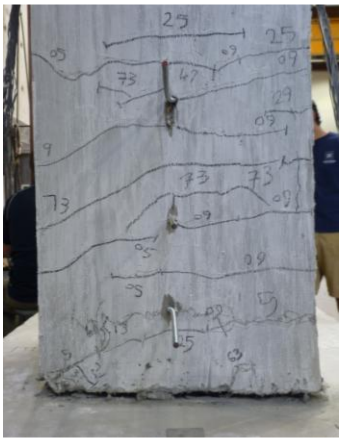


Figure 4. SMA/ECC column plastic hinge damage after 12% drift cycles

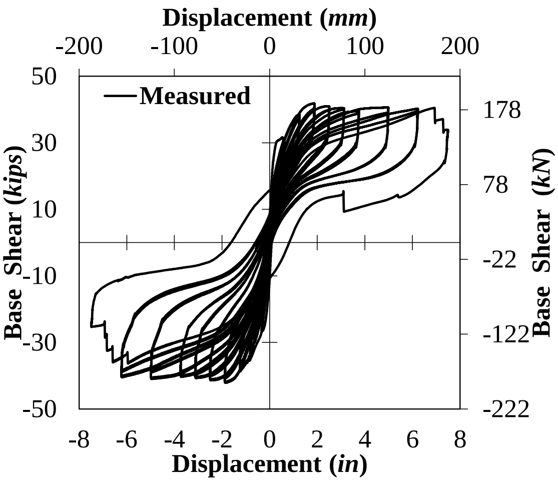


Figure 5. Measured force-displacement hysteresis for SMA/ECC column with long SMA bars

4 LOW-DAMAGE MATERIALS FOR ACCELERATED BRIDGE CONSTRUCTION (ABC)

Low-damage materials may be used in precast bridge columns. Tazarv and Saiidi [10] developed a new ABC connection for precast columns in high seismic zones. Ultra-high performance concrete (UHPC), which is another class of low-damage materials with five times higher tensile and compressive strength compared to conventional concrete, was used to fill the ducts that were installed in adjoining members. Precast member longitudinal bars were secured in ducts before casting UHPC.

A half-scale precast reinforced concrete column was built incorporating eight different materials: conventional concrete, reinforcing steel, reinforcing NiTi superelastic SMA, headed bar couplers, corrugated galvanized metal ducts, UHPC, self-consolidating concrete (SCC), and ECC. The column was connected to the footing by inserting protruded precast column bars in UHPC-filled ducts. #10 (Ø32 *mm*) SMA bars were connected to #11 (Ø36 *mm*) steel bars using headed bar couplers. ECC was used only in the plastic hinge of the column with a depth of 1.5 column diameter. The precast column was hollow-core to facilitate the transportation but it was filled with SCC after installing the shell.

The column was tested under slow cyclic loads. The plastic hinge damage of the SMA/ECC column and a reference cast-in-place (CIP) steel-reinforced column after 12% drift cycles is shown in Fig. 6. The damage in SMA/ECC column was limited to only cover concrete while the core concrete was crushed in the CIP column. The UHPC-filled duct connection exhibited no damage.

(a) SMA/ECC Column (b) Conventional Column

Figure 6. Plastic hinge damage of SMA/ECC and conventional columns after 12% drift cycles

Figure 7 shows the measured lateral force-drift hysteresis of the SMA/ECC and reference columns. A flag-shape behavior with residual displacements that were on average 70% lower than the reference column was observed. It can be seen that low-damage materials incorporated in the precast column improved the seismic performance.

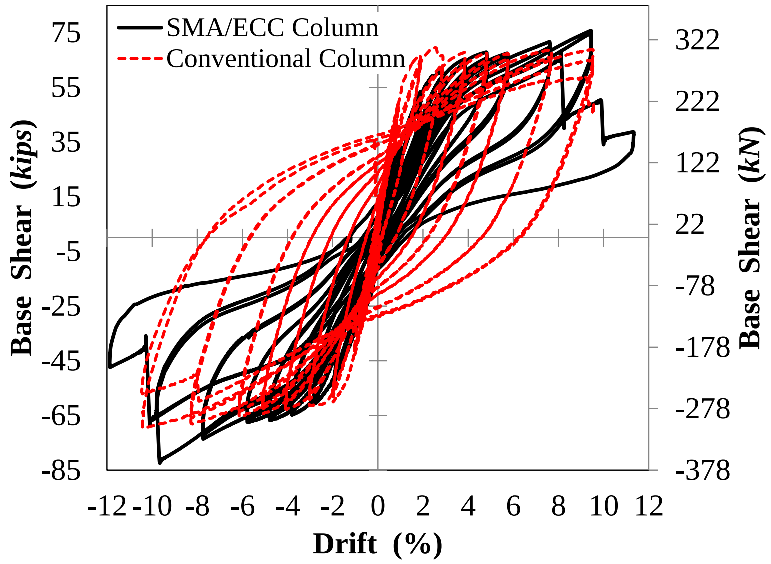
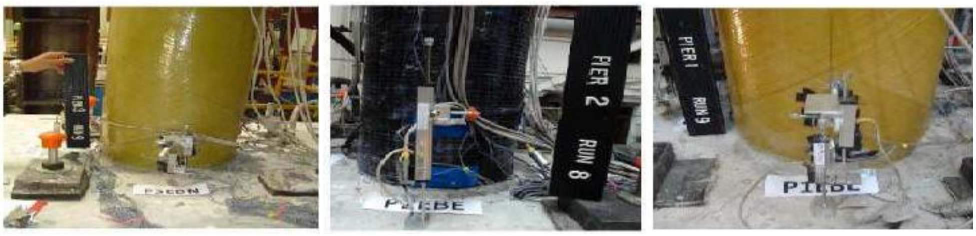


Figure 7. Measured force-drift hysteresis for SMA/ECC and conventional columns

A quarter-scale, four-span bridge model incorporating concrete-filled FRP-tube (CFFT) bents was studied by testing on shake tables (Fig. 8). The total length and the width of the bridge model were 107 *ft* (32.6 *m*) and 7.5 *ft* (2.3 *m*), respectively. The bridge had three two-column bents, each built with different FPR jackets or different ABC techniques. One bent consisted of cast-in-place CFFT columns. The second bent consisted of post-tensioned segmental FRP wrapped columns. The third bent was similar to the first but consisted of precast CFFT columns connected to a precast footing and cap beam using a member pocket and pipe-pine connections, respectively.

The performance of the columns was satisfactory. The bridge withstood a 9.3% drift ratio with minor apparent damage only to the cap beams and the footings (Fig. 9). The seismic performance of all three bents were approximately the same and FRP remained intact with concrete in all columns. All columns showed less than 1% residual displacements but residual displacements of the segmental bent were even smaller than the other bents since posttensioning tendons remained elastic under seismic loads and increased the self-centering tendency of the bent. The ABC connections used in this bridge model successfully transferred the column loads to the footings and maintained the integrity of the bent.

Figure 8. Quarter-scale bridge model on shake Tables



(a) CIP Bent (b) Segmental Bent (c) Precast Bent

Figure 9. Concrete-filled FRP-tube plastic hinge damage after run 9 (under 9% drift ratio)

5 LOW-DAMAGE MATERIALS FOR FUTURE BRIDGES

The form of bridges of the future is imagined by some visionary designers. One example is the bridge by Chetwood, who designed a futuristic bridge (Fig. 10) [11], which is a residential green bridge powered by solar energy. Equally important is the construction techniques that will be used in the future and the performance of bridges of the future under severe events.

Three objectives are sought in the present study for bridges of the future: (1) construct a full bridge in a relatively short time than that the time conventional construction takes, (2) minimize or completely eliminate bridge damage under destructive loads, and (3) totally disassemble the bridge after its lifetime and recycle the components.

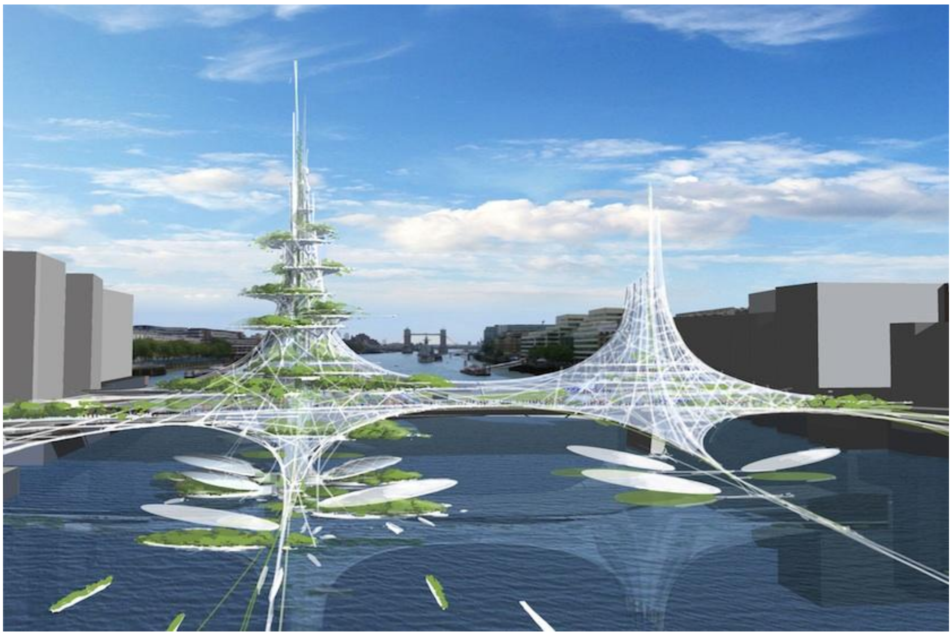
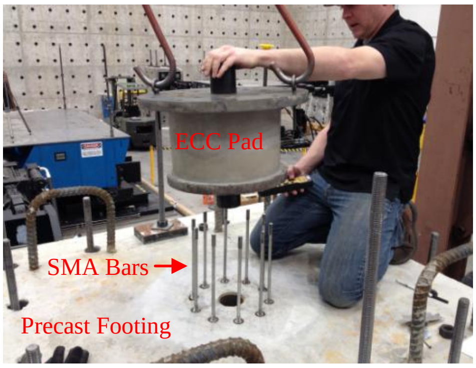


Figure 10. A conceptual bridge of the future [11]

Feasibility of the first two objectives was investigated in the experimental studies presented in previous sections in which satisfactory performance was achieved. In order to study the feasibility of the third objective, seismic behavior of three quarter-scale modular bridge columns using innovative materials and precast segments was investigated.

Each modular column consisted of three segments (Fig. 11): precast footing, pre-fabricated plastic hinge element, and precast column. ECC or elastomeric rubber were used in different plastic hinge elements. Two types of SMA alloy bars, NiTi and an emerging CuAlMn alloy, were passed through plastic hinges to connect the footing to the precast segment of the column, which was built with a concrete-filled FRP tube. Combination of ECC/rubber pad with NiTi/CuAlMn SMA bars resulted in three modular column models. The CFFT segment was designed to remain elastic during ground excitations. Therefore, all nonlinearities were expected to occur only in plastic hinges. Connection of all segments was provided by threaded couplers so the segment could be disassembled after the tests. Each modular column was tested twice by going through these steps: (1) assemble a column model, (2) test the column model on a shake table, (3) totally disassemble the column model including removing of the plastic hinge bars, and (4) retest it under similar loading protocol as step (2).



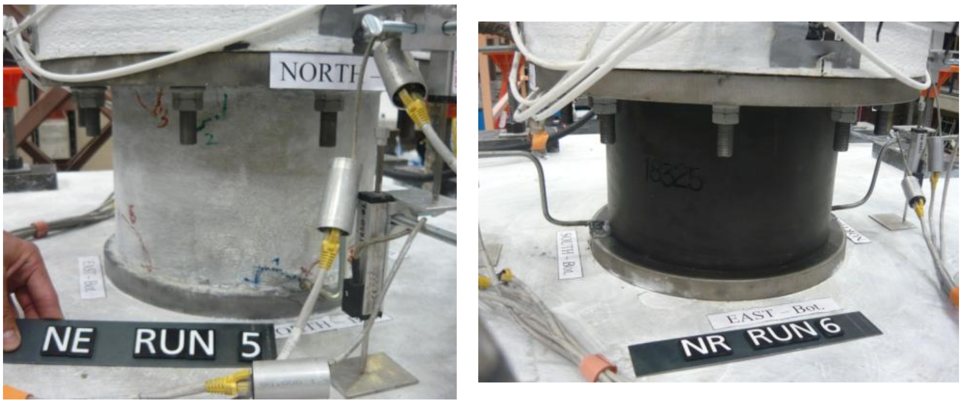
(a) Installing precast ECC Pad

(b) Installing prefabricated rubber pad

(c) Installing precast concrete-filled FRP tube segment

Figure 11. Deconstructible bridge columns incorporating low-damage materials

The tests showed promising results with minimal damage in plastic hinges and no damage elsewhere. ECC plastic hinges reinforced with SMA bars suffered only minor concrete spalling under a motion simulating twice the design earthquake (Fig. 12a). The column with SMA bars and elastomeric rubber plastic hinge exhibited no damage even under 250% design earthquake (Fig. 12b). Since SMA bars were used in all modular columns, negligible residual displacements were observed in testing and retesting stages.



(a) SMA/ECC Plastic Hinge (b) SMA/Rubber Plastic Hinge

Figure 12. Damage of detachable bridge column plastic hinges under 200-250% design earthquake

The columns were disassembled, assembled, and retested. A similar seismic performance with minimal damage was observed in all column models. Fig. 13 shows the SMA/rubber column initial and retested force-displacement curves under 250% of design earthquake. It can be seen that column performance was not affected by disassembling the column into its segments, which confirms the feasibility of the third objective sought for the bridges of the future.

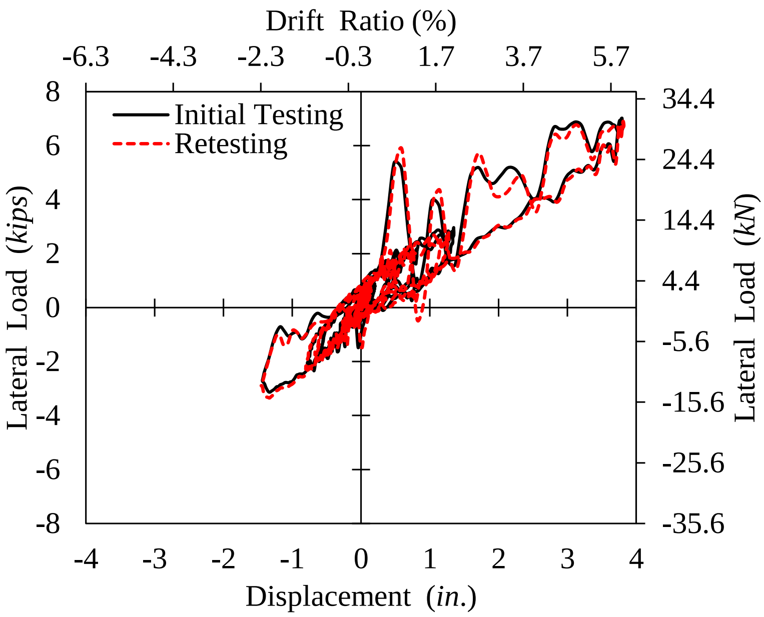


Figure 13. Lateral force-displacement relationships of SMA/Rubber column under 250% design earthquake before and after disassembly

6 CONCLUSIONS

Low-damage materials such as shape memory alloy (SMA), engineered cementitious composite (ECC), fiber reinforced polymer (FRP), and elastomeric rubber were incorporated in large-scale bridge component or complete bridge system test models to accelerate bridge construction and reduce or totally eliminate bridge damage after an earthquake. The summary of experimental investigations were presented. It was found that SMA can substantially reduce bridge column residual displacements and provide equal or improved displacement capacity compared to conventional bridges. ECC can reduce the column damage significantly, and when combined with reinforcing SMA, a superior seismic performance can be achieved. Concrete filled FRP tube columns showed no damage even under large drift demands. The low-damage materials were also exhibited an excellent performance when used in precast bridge components. Three characteristics for the bridges of the future were sought: being fast in construction, being damage-free, and being totally detachable into segments for recycling as bridge components. Feasibility of all three properties was experimentally confirmed in the present paper.

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