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Smart materials for accelerated bridge construction in high seismic zones

M. 'Saiid' Saiidi[1], Sebastian Varela[2], and Mostafa Tazarv[3]

[1] Professor, Dept. of Civil and Environmental Engineering, University of Nevada, Reno, NV, USA
[2] PhD Candidate, Dept. of Civil and Environmental Engineering, University of Nevada, Reno, NV, USA
[3] Post-doctoral scholar, Dept. of Civil and Environmental Engineering, University of Nevada, Reno.

ABSTRACT: This paper summarizes the results from investigations aimed at developing novel details for ABC columns that can be used in zones of high seismic hazard. Smart materials such as engineered cementitious composite (ECC), ultra-high performance concrete (UHPC), fiber-reinforced polymers (FRPs), shape memory alloys (SMAs), and elastomeric elements were used to resist earthquakes, reduce column damage, residual drift and loss of lateral and vertical load capacity under intense earthquake loading. Results suggest that the novel details that were proposed could be an alternative for prefabricated bridge elements for use in accelerated bridge construction (ABC) in high seismic zones, potentially reducing costs both in the short term due to expedited construction and in the long term as bridge closure, repair or replacement work needed after an earthquake would be minimized.

1 INTRODUCTION

Accelerated Bridge Construction (ABC) refers to a series of design and construction techniques aimed at minimizing service disruption, traffic delays and associated monetary losses during the construction phase of highway bridges. In ABC, precast bridge members are typically manufactured at an off-site plant and transported to the job site, where well-orchestrated logistical operations are carried out in order to assemble the bridge and put it to service in very short periods of time. ABC not only provides advantages and direct cost savings in terms of reduced traffic disruption and faster construction speeds, but also allows a higher quality control on structural members and materials as well as safer on-site construction practices.

Although all these benefits have been observed in ABC projects successfully completed in regions of low seismicity throughout the United States, transportation agencies are still hesitant about using ABC techniques in high seismic zones. This is because concerns exist about the performance of ABC members and their connections under lateral seismic loads, and doubts about whether or not these members are capable of displaying a behavior comparable to that observed in conventional cast-in-place (CIP) reinforced concrete construction. In CIP bridge systems, bridge column members are specifically designed and detailed to undergo extensive inelastic behavior and withstand earthquake loading by means of hysteretic energy dissipation. This typically results in good seismic performance of bridge systems in terms of collapse prevention, but could render the bridge inoperative as large residual drifts in the columns can occur due to extensive concrete spalling and plastic strains in the steel reinforcing bars.

In order to address these issues, extensive experimental and analytical studies have been conducted at the University of Nevada, Reno to develop and study ABC column members that could be used in regions of high seismicity and yet remain functional with minimal or no damage. In order to achieve the goal of ABC, different types of connections and precast members were studied. Superior seismic performance of ABC column models was achieved by using several smart materials that are able to accommodate large drifts and experience minimal or no damage.

2 SMART MATERIALS FOR DAMAGE MITIGATION AND SERVICEABILITY AFTER EARTHQUAKES

2.1 Engineered Cementitious Composite (ECC)

ECC is a grout-like cementitious material that consists of fine aggregates, Portland cement, special admixtures, and Polyvinyl Alcohol (PVA) fibers that give it superior ductility in tension and compression. One of the most important features of ECC for seismic applications is its ability to resist large compressive strains without completely losing its capacity. The fibers inside ECC provide self-confinement, preventing the material from spalling even in the absence of transverse reinforcement, Fischer and Li, (2002), contrary to the behavior exhibited by conventional concrete with comparable compressive strength. All of these properties make ECC a very suitable option for replacing the concrete in the plastic hinge region of bridge columns in order to reduce the extent of apparent damage and lateral load degradation, as demonstrated in the studies by Varela and Saiidi (2014), Saiidi and Wang (2006), Saiidi et al. (2009), Cruz-Noguez and Saiidi (2013), and Varela and Saiidi (2015), amongst others.

2.2 Ultra-high performance concrete (UHPC)

UHPC is a class of fiber reinforced concrete with a minimum specified compressive strength of 150 MPa (22 ksi), which is significantly higher than that of conventional concrete. Similar to ECC, UHPC is made of special admixtures that combined with steel fibers give it improved ductility and strength in tension and compression as well as enhanced durability in comparison to conventional concrete. As summarized later in this paper, the studies by Tazarv and Saiidi (2014) revealed that UHPC could be used to effectively reduce the required development length for steel reinforcing bars inside grout-filled duct type connections, therefore allowing for these types of ABC connections to be used in bridges with shallow cap beams and footings.

2.3 Fiber-reinforced polymers (FRPs)

Originally developed mostly by the aviation industry, FRPs are composite materials made of a polymer matrix and reinforcing fibers, and they typically have a very high tensile strength while also being very light. Common FRPs used in civil engineering applications include Carbon fiber-reinforced (CFRPs) and Glass fiber-reinforced (GFRPs) polymers and they can used in the form of wrapping fabrics for the retrofit of existing structural elements, or as jackets or tubes forming outer shells that can act as both stay in place formwork and provide structural reinforcing to a concrete member. FRPs are very appealing for ABC column members due to their many advantages including lightweight and ease of transportation, cleaner and safer formwork, and less reinforcement congestion while providing high ductility, strength, and confinement.

2.4 Superelastic Shape Memory Alloys (SMAs)

SMAs are materials that have the unique ability to undergo large deformations and recover their shape either through heating (shape memory effect) or upon stress removal (superelastic effect). Nickel-Titanium (NiTi) superelastic SMA used in the form of longitudinal reinforcing bars inside the plastic hinge region of bridge columns has been found to be effective in reducing the residual drifts of the columns after intense earthquake loading, Saiidi and Wang (2006), Saiidi et al. (2009), Cruz-Noguez and Saiidi (2013), Varela and Saiidi (2014b). This is because this type of alloy displays a flag-shaped hysteretic behavior that provides self-centering to the columns (see Figure 1a), meaning these columns could stay functional after being subjected to a strong earthquake.

Although previous studies have demonstrated the good performance of bridge columns with NiTi SMA and ECC, it can be expensive to use NiTi in the practice due to the high cost of Titanium, an absence of established bridge engineering market, and because NiTi is very difficult to machine. An emerging Copper-Aluminum-Manganese (CuAlMn) superelastic SMA (Figure 1b) has been reported to have comparable superelastic properties to most NiTi SMAs at only a fraction of the cost due to relatively lower cost of Copper, lower production cost, and easier machinability. In the study by Varela and Saiidi (2014) this emerging type of SMA was used at a larger scale for the first time, and it was found to be also feasible alternative to keep bridges functional after strong earthquakes.

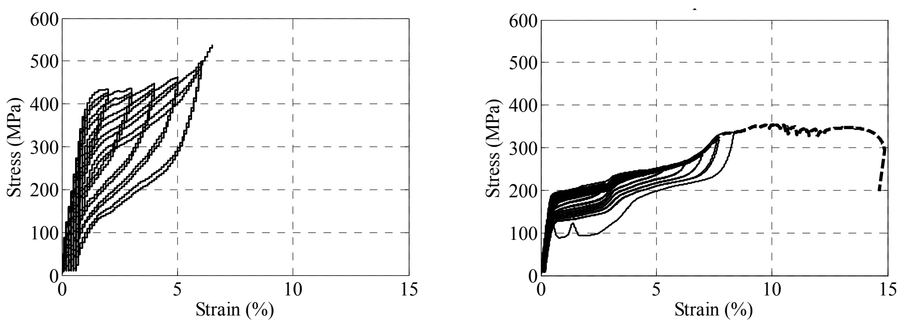


Figure 1. Cyclic tensile stress-strain behavior of superelastic SMA bar samples: a) (Left) NiTi – Varela and Saiidi (2015) b) (Right) CuAlMn – Varela and Saiidi (2014).

2.5 *Elastomeric elements*

As an alternative to ECC, the concrete in the plastic hinge region of bridge columns could be replaced by rubber in order to mitigate damage and loss of lateral load capacity and reduce residual drifts. The underlying idea is to take advantage of lower stiffness of the rubber in order to increase the fundamental period of the column and shift it to a region of lower spectral acceleration ordinates. This is similar to the concept of seismic isolation, but in this case the elastomeric elements are designed to primarily work in flexure rather than shear. This concept was originally developed by Kawashima and Watanabe (2006), who used a combination of post-tensioning to provide self-centering and high damping rubber placed in the plastic zone of a CIP bridge column. Motaref et al. (2010) also investigated this concept by testing two third-scale segmental post-tensioned column models on a shake table, one with a built-in elastomeric plastic hinge element and the other with concrete in the plastic hinge region. Their tests demonstrated that the rubber elements minimizes damage, increases ductility and energy dissipation and reduces residual drifts.

3 APPLICATION OF SMART MATERIALS FOR ABC COLUMNS UNDER SEISMIC LOADING

3.1 *Experimental studies on the bond strength of UHPC-filled duct connections*

The structural performance of UHPC-filled duct connections was investigated by Tazarv and Saiidi (2014), who tested 14 large-scale pullout specimens under tensile loading (Fig. 2). The objective of these tests was to determine the bond strength of UHPC-filled duct systems. The tests variables were the steel reinforcing bar embedment length, bar size, duct diameter, number of ducts, and bundling of bars. Straight #8 (Ø25 mm) and #11 (Ø36 mm) Grade 60 (420 MPa) bars were used with embedment lengths of $3d_b$, $5d_b$, $8d_b$ and $12d_b$ where d_b is the bar diameter. Corrugated metal ducts with nominal sizes of 75 mm, 100 mm, and 125 mm were used. The test specimens were designed in two groups to determine the bond strength of the duct (group I) and the bar bond strength (group II).

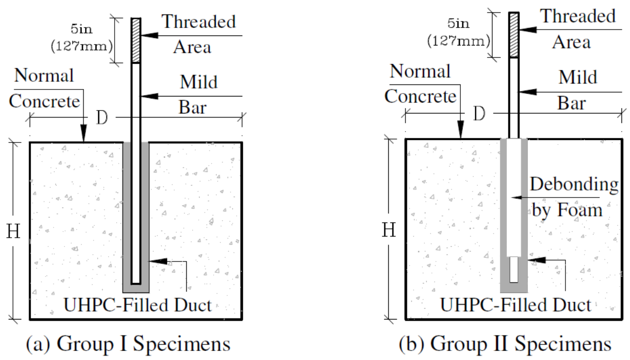


Figure 2. Schematic view of pullout test specimens, Tazarv and Saiidi (2014).

It was found that the effect of bar bundling, bar size, and multiple ducts was negligible on the bond performance, but the size of the duct had a significant effect on the bond strength. The bond strength of the bars inside UHPC was found to be eight times higher than in conventional concrete, meaning that the required bar development length could be much shorter thus allowing for UHPC-filled duct connections to be utilized for shallower footings and/or cap beams. Based on test data, simple design equations were proposed in order to determine the required embedment length of mild steel bars inside UHPC-filled ducts.

3.2 *Experimental studies on half-scale column models*

In the second phase of the study by Tazarv and Saiidi (2014) two half-scale cantilever column models incorporating UHPC-filled duct connections at the base of the columns were tested under slow reversed cyclic loading. These models also incorporated smart materials as well as novel connection details and were designed to have comparable flexural capacity to the ABC models that had been tested earlier by Haber et al. (2013), who also tested a benchmark CIP model for comparison purposes. The novel details for ABC columns with smart materials tested by Tazarv and Saiidi (2014) are shown schematically in Fig. 3. Both models were made of precast concrete footings and hollow column shells. The shell in PNC was made of reinforced concrete in its entirety, and had protruding steel bars at the bottom that were inserted into UHPC-filled ducts that were provided in the footing.

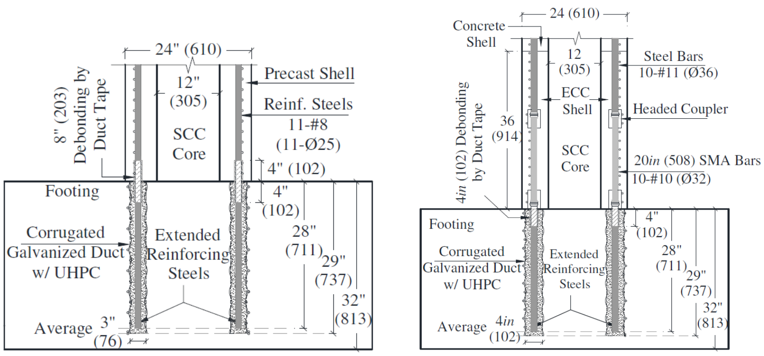


Figure 3. Plastic hinge details of the half-scale ABC column models tested by Tazarv and Saiidi (2014). Left: PNC, right: HCS.

The other model (HCS) incorporated longitudinal NiTi SMA bars in the plastic hinge region that were connected to the mild steel reinforcing bars using headed couplers. The core in both PNC and HCS was filled with self-consolidating concrete (SCC), but the shell of HCS was made of ECC over a height equal to 1.5 times the column diameter (914 mm) above the footing and of reinforced concrete elsewhere. Duct tape wrapping was used in a portion of the longitudinal steel reinforcing bars to spread bar yielding in order to avoid premature bar failure.

The damage state after 10% drift in both models tested is illustrated in Fig. 4, along with that for the benchmark CIP model tested by Haber et al. (2013). The failure mode in all column models was fracture of longitudinal steel bars. Fig. 4 shows that PNC plastic hinge damage was similar to that of CIP, showing the effectiveness of UHPC-filled duct connections. In agreement with previous studies, ECC and SMA significantly reduced the apparent damage in HCS, where damage was limited to spalling of the cover ECC with no spirals exposed or SMA bars buckled even after subjecting the column to cycles of 12% drift.

The measured lateral force-drift hysteretic response of the models tested revealed that both PNC and HCS showed stable hysteresis with no loss of capacity up to the point when rupture of the first longitudinal bar occurred. Although the lateral load capacity measured for HCS in each cycle was approximately the same as that of CIP, its unloading behavior was different and hysteretic energy dissipation was less in comparison to CIP due to the flag-shape hysteretic response of NiTi SMA. The measured residual drifts after subjecting the models to a maximum drift of 10% were about 7% for CIP, 7.5% for PNC and about 1% for HCS, demonstrating once more the effectiveness of superelastic SMA bars as a self-centering mechanism.

3.3 Experimental studies on detachable quarter-scale column models

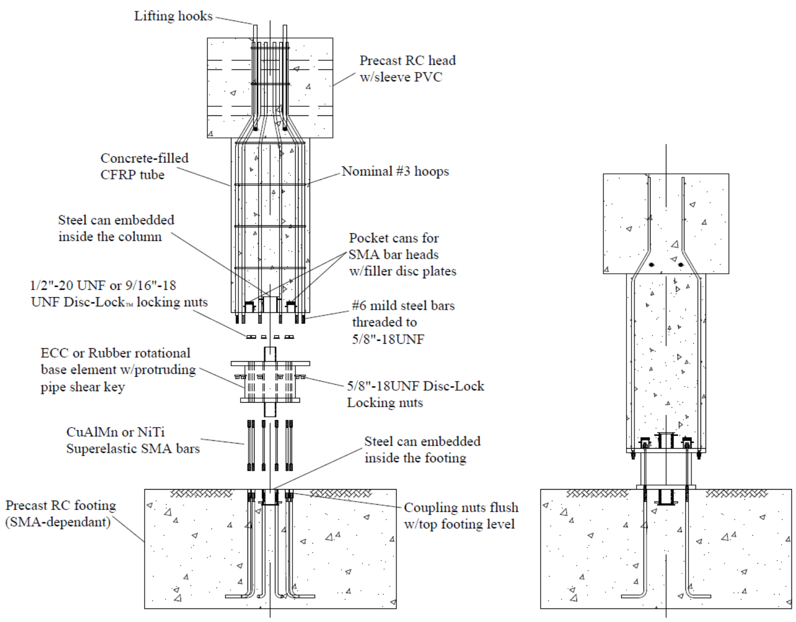
As part of an ongoing research project at the University of Nevada, Reno details for novel ABC columns that not only are able to stay functional after intense earthquakes but also be detachable were developed and tested (Varela and Saiidi 2014b). The concept of a bridge column designed for disassembly (DfD) was adopted in order to facilitate component reuse and material recycling at the structure's end-of-life, thus reducing the energy consumption and carbon footprint during material extraction and manufacture. This is especially important for RC bridges, considering that CO_2 emissions due to cement production have been found to account for 5% of the global anthropogenic carbon dioxide emissions, Worrel et al. (2001). An exploded view of the components of the quarter-scale DfD models that were designed and tested, as well as that of the assembled column is shown in Figure 5.

(a) (b) (c)

Figure 4. Plastic hinge damage at 10% drift: a) CIP, Haber et al. (2013), b) PNC, c) HCS.

The models were comprised of a precast footing with embedded threaded couplers, a rubber or ECC plastic hinge base element, NiTi or CuAlMn SMA bars that were inserted into the base elements, and an upper column body made of a concrete-filled CFRP tube. The column body and footing were completely detachable from the base elements and were designed to remain elastic, while the base elements and inner SMA bars dissipated energy with minimal or no damage under large drift demands. Bolted connections were used to provide force transfer from the upper column body onto the footing. Flexural capacity and self-centering of the columns was achieved by using the removable unbonded SMA bars inside the base elements. The experimental variables combined were the SMA type and the material of the plastic hinge element. The model corresponding to the rubber and CuAlMn SMA combination was not tested as analytical pre-test studies suggested that this combination would result in a very weak and excessively flexible column having only minimal energy dissipation. Therefore, the 3 combination of variables resulted in a total of 6 column tests corresponding to testing of the 3 ‘virgin’ column models, and then re-testing of their reassembled versions. Complete inspection and disassembly of the column components was carried out after testing of the ‘virgin’ models. Then, each of the column models was reassembled and retested. Since the DfD concept adopted is meant to allow for reuse and disassembly of column elements, it was desired to study the implications of reusing plastic hinge elements that had already been subjected to large drift demands. The column models were tested dynamically on a shake table. A near-fault record from the 1-17-1994 Northridge, California earthquake was simulated in order to maximize the chances of causing residual displacements to the models. Further details about the design and construction of column models as well as testing procedure can be found in Varela and Saiidi (2014b).

All of the column models were subjected to large (>5%) drift demands, which could be expected to be experienced by a bridge during an intense earthquake. Figure 6 shows the damage state of the plastic hinge region for each of the models tested at the end of the largest earthquake run applied. In general, damage consisted of limited and repairable spalling and cracking of unconfined ECC, and some NiTi SMA bars that were slightly buckled inside the rubber element. No damage was observed on the rubber element itself. Reassembled models were able to reach the same capacity of the ‘virgin’ columns but exhibited lower stiffness.



(a) (b)

Figure 5. DfD column concept. (a) Exploded view (b) Assembled column.

(a) (b) (c)

Figure 6. Plastic hinge damage at the end of the last earthquake run of reassembled models. a) NiTi+ECC, b) NiTi+rubber, c) CuAlMn + ECC.

All of the measured residual drifts were very small (less than 0.5%) in spite of the relatively large drift demands. The loss of lateral and vertical load-carrying capacity for all the models was minimal. None of the SMA bars ruptured, and there was no distress in any of the footings or in the column body. Since the assembly and reassembly process in all of the models was easy and fast, it was concluded that the DfD concept proposed had the potential to be adopted for sustainable ABC columns in high seismic zones.

4 CONCLUSIONS

This paper presented highlight of several investigations aimed at developing novel details for ABC columns in high seismic zones. Smart materials were used to successfully improve the seismic performance of these columns and increase the likelihood for them to stay functional after an intense earthquake. This would not only allow ABC to be used in high seismic zones but would also reduce costs associated with bridge downtime, repair, and maintenance in the long term.

5 ACKNOWLEDGMENTS

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