DUCTILITY IMPROVEMENT OF HIGH STRENGTH CONCRETE COLUMNS USING HYBRID CONFINEMENT

Pratik Sharad Deogekar\textsuperscript{1} and Bassem Andrawes\textsuperscript{2}

ABSTRACT

The usage of high strength concrete (HSC) in reinforced concrete (RC) bridge columns in earthquake prone regions is hindered due to the brittle nature of HSC. Passive lateral confinement does not improve the ductility efficiently since HSC exhibits low lateral expansion under axial loads. This leads to an increase in the amount of transverse steel required which causes reinforcement congestion. Concrete-filled fiber tubes (CFFT), manufactured using fiber reinforced polymer (FRP) sheets confine concrete externally overcoming reinforcement congestion problems. However, due to the passive nature of CFFT confinement, the low efficiency persists. Active confinement, applied using shape memory alloy (SMA) spirals confines concrete more efficiently than passive confinement. Hence, this research study investigates the application of active confinement using SMA spirals in the plastic hinge region of CFFTs to attain higher ductility in HSC columns. The resulting hybrid confinement in the plastic hinge region, which is a combination of passive CFFT confinement and active SMA confinement, is studied experimentally by subjecting concrete cylinders wrapped with FRP and SMA spirals to cyclic axial compression and comparing their behavior with FRP wrapped cylinders. Test results indicate that the additional active SMA confinement delays the rupture of FRP jacket. Post the FRP rupture, the SMA spirals remain intact and aid the concrete cylinders in attaining ultimate axial strains which are more than 3 times the ultimate strain of FRP confined cylinders. Next, a numerical study is undertaken to study the pushover behavior of CFFTs confined with SMA spirals in their plastic hinge region. The drift capacity of CFFT column is seen to increase significantly on addition of a limited amount of SMA.

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Ductility Improvement of High Strength Concrete Columns using Hybrid Confinement

Pratik Sharad Deogekar¹ and Bassem Andrawes²

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The usage of high strength concrete (HSC) in reinforced concrete (RC) bridge columns in earthquake prone regions is hindered due to the brittle nature of HSC. Passive lateral confinement does not improve the ductility efficiently since HSC exhibits low lateral expansion under axial loads. This leads to an increase in the amount of transverse steel required which causes reinforcement congestion. Concrete-filled fiber tubes (CFFT), manufactured using fiber reinforced polymer (FRP) sheets confine concrete externally overcoming reinforcement congestion problems. However, due to the passive nature of CFFT confinement, the low efficiency persists. Active confinement, applied using shape memory alloy (SMA) spirals confines concrete more efficiently than passive confinement. Hence, this research study investigates the application of active confinement using SMA spirals in the plastic hinge region of CFFTs to attain higher ductility in HSC columns. The resulting hybrid confinement in the plastic hinge region, which is a combination of passive CFFT confinement and active SMA confinement, is studied experimentally by subjecting concrete cylinders wrapped with FRP and SMA spirals to cyclic axial compression and comparing their behavior with FRP wrapped cylinders. Test results indicate that the additional active SMA confinement delays the rupture of FRP jacket. Post the FRP rupture, the SMA spirals remain intact and aid the concrete cylinders in attaining ultimate axial strains which are more than 3 times the ultimate strain of FRP confined cylinders. Next, a numerical study is undertaken to study the pushover behavior of CFFT columns confined with SMA spirals in their plastic hinge region. The drift capacity of CFFT column is seen to increase significantly on addition of a limited amount of SMA.

Introduction
Reinforced concrete (RC) bridge columns built using high strength concrete (HSC) can sustain high axial loads which reduces the total number of columns required in the bridge system and permits the use of larger spans. However, HSC exhibits brittle behavior under the application of

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axial loading [1–3] which limits its application in earthquake prone regions. Transverse steel reinforcement is typically used to improve ductility of HSC by providing lateral confinement [4]. The transverse reinforcement confinement is designated as passive since it is generated after the concrete expands laterally under axial loads which induces tension in the confining reinforcement. Passive confinement exhibits low efficiency when confining HSC because HSC experiences lower lateral dilation under axial loading as compared to normal strength concrete (NSC) [5]. This increases the amount of transverse steel required to improve the ductility of HSC [6,7] and leads to reinforcement congestion. As an alternative to traditional steel transverse reinforcement, concrete filled fiber tube (CFFT) [8,9], manufactured using fiber reinforced polymer (FRP) sheets, confines the concrete externally and eliminates any congestion problems. However, since the confinement provided by CFFT is passive in nature, the amount of confinement required to achieve the requisite ductility is high. Active confinement is a more efficient alternative to passive confinement for confining HSC [10,11] since it is generated independent of concrete lateral expansion. Lateral prestressed steel strands [12] and prestressed FRP belts [13] have been proposed for application of active confinement in concrete. However, the excessive mechanical hardware and labor associated with these techniques has proven to be an impediment to their implementation on actual structures.

To overcome the problems associated with implementation of active confinement, Andrawes and Shin [14] proposed and studied the application of lateral thermal prestressing using shape memory alloy (SMA) spirals to confine concrete. The superiority of active confinement applied using SMA spirals over passive FRP confinement in improving concrete ductility has been well established [15–17]. SMA spiral confinement also requires less time and labor for its application in comparison to FRP confinement. However, the relatively high material costs associated with SMA, has proven to be a deterrent to its application in the field. To combine the higher efficacy of SMA spiral confinement, with the lower cost of FRP, a hybrid confinement that combines them was experimentally tested for NSC [16] and encouraging results were obtained. The scheme was also applied in plastic hinge region of reduced scale NSC columns [18] and subjected to lateral cyclic loading. The hybrid confined column displayed significantly higher drift capacity than the NSC column confined only with FRP. Although hybrid confinement has been established as an efficient means for confining NSC, no study has been conducted till date to explore the performance of hybrid confinement when applied to HSC. Hence, experimental tests are conducted on concrete cylinders confined with hybrid confinement applied using a combination of SMA spirals and FRP sheets. Their performance is compared with concrete cylinders confined only with FRP sheets. Since the main objective of this research was to use it as means to confine HSC bridge columns built using CFFT, the material level experimental results are used to numerically model HSC CFFT columns which have been wrapped with SMA spirals in their plastic hinge region. The HSC CFFT columns with SMA spirals are subjected to a pushover analysis and their drift behavior is compared with CFFT columns without any SMA confinement.

**Background on SMA-FRP Hybrid Confinement**

The hybrid confinement proposed in this research combines passive confinement applied using FRP and active confinement applied using SMA spirals. Its application is illustrated in Figure 1. The concrete core is wrapped with layers of fiber fabric impregnated with epoxy resin. After the curing of the epoxy resin, the fabric transforms into a rigid FRP shell. After this, prestrained SMA wires are wrapped around the FRP shell in a spiral form and the two ends of the wire are connected
to a previous turn of the spiral to form closed loops at either end. The SMA spiral is then heated to trigger the shape memory effect (SME), due to which a SMA can memorize its shape prior to deformation. The SME, which characterizes the thermo-mechanical behavior of all SMAs, occurs because the SMA exhibits two microstructural phases, namely martensite and austenite, and alternates between them depending on the prevailing thermo-mechanical conditions. When SMA in the martensite phase is subjected to high tensile deformation and unloaded it stores residual strains. After the prestrained SMA is heated, it undergoes a phase transformation to austenite which results in the SMA trying to release the stored residual strains to regain its undeformed state. The prevention of this strain recovery results in the generation of a tensile stress in the SMA. Hence, when the prestrained SMA spirals wrapped around the FRP confined concrete are heated they try to release the prestrain. However, the rigid FRP confined concrete core prevents the shape recovery and generates tensile stresses in the SMA spiral. This prestresses the concrete core laterally and applies confinement which is designated as active since its generation is not due to the lateral expansion of concrete. To retain the active confinement, SMA spirals must not revert back to the martensite phase. Hence, wide hysteresis NiTiNb SMA spirals, which transform back to martensite under temperatures well below the ambient temperature [19] are used to apply the active component of active confinement.

![Diagram of SMA-FRP hybrid confinement](image)

**Figure 1. Implementation of SMA-FRP hybrid confinement**

### Experimental Tests

**Test Setup**

Two unconfined, 3 FRP confined and 2 hybrid confined cylinders, having a diameter of 152.4 mm and height of 305 mm, were tested under cyclic axial compression. For all the confined cylinders, the passive confinement was provided using glass FRP (GFRP) sheets with a thickness of 0.22 mm/ply, elastic modulus of 17900 MPa and ultimate strain of 2.1%. In the case of hybrid confined cylinders, the additional active SMA confinement was provided using SMA spirals made using NiTiNb wires of 1.9 mm diameter, with a prestrain of 0.06, which results in a recovery stress of 550 MPa on thermal activation [17]. The details of the tested cylinders are presented in Table 1. In the specimen designation, the first letter indicates whether it is NSC (N) or HSC (H). Next, it is...
indicated whether the cylinder is unconfined (UC) or confined (C). For the confined cylinders, the next number indicates the number of FRP layers. Furthermore, for the hybrid confined cylinders, the SMA spiral pitch is given by the last number. 2 NSC cylinders were tested as control specimens since guidelines for external FRP confinement have been established only for NSC bridge columns [20]. One NSC cylinder (N-UC) was kept unconfined while the other cylinder (N-C-11) was wrapped with 11 GFRP layers to provide a lateral passive confinement of 2.07 MPa at a radial dilating strain of 0.004 as suggested by the current Caltrans’ guidelines [20]. The number of FRP layers required to apply the desired passive confinement were calculated based on established guidelines [20]. Next, the experimental testing of HSC cylinders with a strength of 64 MPa at the day of testing was undertaken. Similar to the NSC cylinders, an unconfined HSC cylinder (H-UC) and a HSC cylinder with an 11 layer FRP scheme (H-C-11) were tested. However, since previous research has shown that confinement required in HSC is higher [2], a HSC cylinder wrapped with 23 FRP layers (H-C-23) which applied twice the lateral confinement applied in NSC was also tested. In the end, 2 hybrid confined HSC cylinders (H-C-11-27 and H-C-11-14) were tested. In these cylinders, passive confinement component of 2.07 MPa was augmented with SMA active confinement of 0.69 MPa (H-C-11-27) and 1.38 MPa (H-C-11-14). The pitch of the SMA spiral required to apply the desired active confinement were calculated based on previous research work [17]. An important point to note is that a higher SMA spiral pitch results in a lower confinement. Hence, H-C-11-27 has lower active confinement than H-C-11-14.

Table 1. Details of the tested concrete cylinders

<table>
<thead>
<tr>
<th>Specimen Designation</th>
<th>Unconfined Concrete Strength a (MPa)</th>
<th>Number of FRP Layers</th>
<th>Passive Confinement b (MPa)</th>
<th>SMA Pitch (mm)</th>
<th>Active Confinement (MPa)</th>
<th>Total Confinement (MPa)</th>
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</thead>
<tbody>
<tr>
<td>N-UC</td>
<td>36</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N-C-11</td>
<td>36</td>
<td>11</td>
<td>2.07</td>
<td>-</td>
<td>-</td>
<td>2.07</td>
</tr>
<tr>
<td>H-UC</td>
<td>64</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H-C-11</td>
<td>64</td>
<td>11</td>
<td>2.07</td>
<td>-</td>
<td>-</td>
<td>2.07</td>
</tr>
<tr>
<td>H-C-23</td>
<td>64</td>
<td>23</td>
<td>4.14</td>
<td>-</td>
<td>-</td>
<td>4.14</td>
</tr>
<tr>
<td>H-C-11-27</td>
<td>64</td>
<td>11</td>
<td>2.07</td>
<td>27.0</td>
<td>0.69</td>
<td>2.76</td>
</tr>
<tr>
<td>H-C-11-14</td>
<td>64</td>
<td>11</td>
<td>2.07</td>
<td>14.3</td>
<td>1.38</td>
<td>3.45</td>
</tr>
</tbody>
</table>

a at the day of testing
b when the radial dilating strain is 0.004

All the specimens underwent force-controlled loading till 42.7 MPa at a loading rate of 0.25 MPa/s. This initial force controlled loading portion, was followed by unloading and subsequent cyclic loading which were displacement controlled. The displacement controlled loading was applied at a strain rate of 0.25%/min. During each cycle, the maximum axial strain during loading was incremented by 0.75% till specimen failure. During each unloading cycle, the specimens were unloaded till a compressive stress of 9.6 MPa to prevent unnecessary specimen movement which occurs at low axial load levels. The axial movement of the specimen was obtained using two external LVDTs and the readings of the LVDTs were corrected using an axial extensometer which was installed for the first loading cycle.

Test Results
Failure Mode

Figure 2 shows the state of the concrete cylinders confined with different confinement schemes at the time of failure. The unconfined NSC cylinder (Fig. 2a) experienced limited vertical cracking before it failed while the unconfined HSC cylinder (Fig. 2b) failed catastrophically through the formation of large vertical cracks running between the top and bottom of the cylinder. The catastrophic failure resulted in the cylinder breaking into individual fragments and can be attributed to the brittle nature associated with HSC. All the FRP confined NSC (Fig. 2c) and HSC (Fig. 2d) cylinders failed through the rupture of the FRP jacket in the form of single vertical crack. No cracks were observed in the FRP confined specimens before the sudden failure due to FRP jacket rupture. The hybrid confined cylinders, experienced gradual and vertical cracking of the FRP jacket at 3-4 locations (Fig. 2e). The presence of SMA spirals facilitated the gradual cracking and ensured that post the rupture of the FRP jacket, the concrete cylinder was able to sustain significant axial load. The failure of the hybrid confined cylinders occurred when the SMA spiral ruptured at significantly high axial strain levels (Fig. 2f). The presence of cracks in the FRP jacket in a hybrid confinement scheme provide a visual warning well in advance of the complete failure due to SMA spiral rupture. Thus, they provide visual distress signs unlike traditional FRP confinement which fails suddenly with catastrophic consequences.

Envelop Curve Comparison

To compare the effect of passive and hybrid confinement on the ductility improvement of NSC and HSC, the envelope curves obtained from the cyclic axial testing of the 7 cylinder specimens are shown in Figure 3. Unconfined NSC (N-UC) exhibited an ultimate strain of 0.035 while unconfined HSC (H-UC) exhibited an ultimate strain of 0.0027. Both N-C-11 and H-C-11 were confined with 11 FRP layers and exhibited ultimate strains of 0.0110 and 0.0056, respectively. Thus, when subjected to the same level of FRP confinement, HSC (H-C-11) experienced a substantially lower improvement in ductility in comparison to NSC (N-C-11). When the passive confinement in HSC was doubled from 2.07 MPa (H-C-11) to 4.14 MPa (H-C-23), substantial strength gain was obtained. However, the ultimate strain increased only by 36% from 0.0056 (H-C-11) to 0.076 (H-C-23) and was still 31% less than the ultimate strain of N-C-11. Thus, the increase in passive FRP confinement of HSC did not translate into substantial improvement in
ductility which implies that to obtain the desired ductility in HSC using FRP confinement alone, a very thick jacket would be required.

Next, the axial stress strain behavior of hybrid confined cylinders (H-C-11-27 and H-C-11-14) is considered. The rupture of FRP jacket in these cylinders took place gradually and its onset and completion corresponded to distinct strain levels which are indicated in Figure 3. The onset and completion of FRP rupture in H-C-11-27 occurred at axial strains of 0.0082 and 0.0109. Thus, H-C-11-27 had a higher FRP rupture strain than H-C-23, despite being confined with 33% lesser total confinement. This could attributed to H-C-11-27 having 25% of its total confinement applied in the active form from SMA spirals which prestressed the FRP jacket and delayed its rupture. Also, the FRP rupture completion in H-C-11-27 was able to achieve an axial strain level equal to the ultimate strain of N-C-11. When the active component of hybrid confinement was increased from 0.69 MPa (H-C-11-27) to 1.38 MPa (H-C-11-14), the higher lateral prestressing of the FRP jacket from the increased active confinement resulted in FRP rupture onset and completion occurring at higher axial strain levels of 0.0106 and 0.0148, respectively. Also, the strength loss before the rupture of FRP in H-C-11-14 was lower in comparison to H-C-11-27. After the complete rupture of FRP jackets, the hybrid confined cylinders were able to sustain a constant residual stress due to the presence of SMA spirals. The ultimate failure occurred due to rupture of SMA spiral at axial strains of 0.0281 (H-C-11-27) and 0.0295 (H-C-11-14), respectively. The higher active confinement component in H-C-11-14 compared to H-C-11-27, resulted in a 38% higher residual stress.

**Cyclic Response of Hybrid Confined Cylinders**

The complete cyclic behavior of hybrid confined cylinders is crucial to evaluate its performance under earthquakes. Hence, cyclic axial compression curves of the two hybrid confined cylinders (H-C-11-27 and H-C-11-14) is presented in Figure 4. Both these cylinders underwent 4 cycles and exhibited linear behavior during reloading. The reloading stiffness reduced with increase in unloading strain. However, even at high unloading strains of 2.5%, H-C-11-27 and H-C-11-14
exhibited reloading stiffness which were 57% and 54% of their respective initial elastic stiffness. Thus, substantial axial stiffness was retained by the hybrid confined cylinders at high axial strain.

![Cyclic axial stress-strain curves for a) H-C-11-27 and b) H-C-11-14](image)

**Figure 4.** Cyclic axial stress-strain curves for a) H-C-11-27 and b) H-C-11-14

**Pushover Behavior of HSC CFFT Confined with SMA**

The implementation of the hybrid confinement in actual bridge columns can be attained by wrapping the plastic hinge region of HSC CFFT with SMA spirals. This creates a hybrid SMA-FRP confinement in the plastic hinge region, which is the region that gets subjected to the highest inelastic demands. CFFT columns with SMA confinement in plastic hinge region were numerically modeled and their pushover performance was compared with CFFT columns without any SMA confinement in the plastic hinge region. The physical attributes of the CFFT bridge column numerically modeled in this research study are shown in Figure 5.

![Schematic of CFFT column confined with SMA](image)

**Figure 5.** Schematic of CFFT column confined with SMA

The CFFT bridge columns considered had a diameter of 1.52 m, height of 9.12 m and were modeled as cantilevers fixed at the base (refer Figure 5). 26 rebars of 43 mm diameter were used
to provide longitudinal reinforcement of 2% and an axial load equal to 10% of the gross section capacity based on unconfined concrete strength was applied and held constant during the pushover analysis. 7 bridge columns with the characteristics described in Table 2 were considered. No internal steel reinforcement was provided in any of these columns. N-UC and H-UC represent NSC and HSC bridge columns without any confinement. These fictitious columns are included to quantify the improvement in drift obtained by the various confinement schemes. N-CFFT-1, H-CFFT-1 and H-CFFT-2 are CFFT columns without any SMA confinement in the plastic hinge region having the same passive confinement as applied in N-C-11, H-C-11 and H-C-23. The material behavior of these CFFT tubes throughout their length was modeled using the axial stress response of the corresponding concrete cylinder. H-CFFT-SMA-1 and H-CFFT-SMA-2 represent HSC CFFT columns wrapped with SMA spirals in their plastic hinge region. In both these columns, the CFFT tube applies the same confinement as H-C-11. Hence, their material behavior above the plastic hinge is characterized by the stress-strain response of H-C-11. In the plastic hinge region of H-CFFT-SMA-1 and H-CFFT-SMA-2, the SMA spirals apply the same amount of active confinement as applied in H-C-11-27 and H-C-11-14, respectively. Hence, the material behavior of the CFFT-SMA HSC columns in the plastic hinge region is described by these cylinders. All the columns were modeled in OpenSees [21] using ElasticMultilinearMaterial model and subjected to a pushover analysis. This material model allows the inputting of custom envelope curves without considering any plastic strain accumulation which did not present a concern since the columns were subjected to monotonic pushover analysis.

Table 2. Confinement characteristics of columns subjected to pushover analysis

<table>
<thead>
<tr>
<th>Column Designation</th>
<th>Material Stress Strain Behavior</th>
<th>Unconfined Concrete Strength (MPa)</th>
<th>CFFT Passive Confinement (MPa)</th>
<th>SMA Active Confinement (MPa)</th>
<th>Yield Strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-UC</td>
<td>N-UC</td>
<td>36</td>
<td>-</td>
<td>-</td>
<td>1037</td>
</tr>
<tr>
<td>N-CFFT-1</td>
<td>N-C-11</td>
<td>36</td>
<td>2.07</td>
<td>-</td>
<td>1057</td>
</tr>
<tr>
<td>H-UC</td>
<td>H-UC</td>
<td>64</td>
<td>-</td>
<td>-</td>
<td>1298</td>
</tr>
<tr>
<td>H-CFFT-1</td>
<td>H-C-11</td>
<td>64</td>
<td>2.07</td>
<td>-</td>
<td>1313</td>
</tr>
<tr>
<td>H-CFFT-2</td>
<td>H-C-23</td>
<td>64</td>
<td>4.14</td>
<td>-</td>
<td>1341</td>
</tr>
<tr>
<td>H-CFFT-SMA-1</td>
<td>H-C-11-27</td>
<td>64</td>
<td>2.07</td>
<td>0.69</td>
<td>1312</td>
</tr>
<tr>
<td>H-CFFT-SMA-2</td>
<td>H-C-11-14</td>
<td>64</td>
<td>2.07</td>
<td>1.38</td>
<td>1310</td>
</tr>
</tbody>
</table>

The results of the pushover analysis are presented in Figure 6. The drift ratio represented in the figure represents the displacement of the top of the cantilever column as percentage of its total height. The application of the Caltrans’ recommended FRP confinement increased the ultimate drift ratio of NSC column from 1.28% (N-UC) to 3.68% (N-CFFT-1). However, when the same scheme was applied in HSC the ultimate drift only improved from 1.12% (H-UC) to 2.05% (H-CFFT-1). Even the CFFT tube applying double the lateral pressure recommended by Caltrans on HSC columns (H-CFFT-2) could only achieve an ultimate drift of 2.81% which was 24% lower than ultimate drift of the NSC CFFT (N-CFFT-1). The CFFT columns confined with SMA spirals in the plastic hinge region attained very high ultimate drift ratios of 4.09% (H-CFFT-SMA-1) and 5.21% (H-CFFT-SMA-2), respectively. Also, post the rupture of FRP jackets (indicated in Figure 6), the hybrid CFFT columns underwent minimal loss in lateral load capacity. In fact, the loss in
lateral capacity at failure for both the SMA confined CFFT columns was only 18% of their peak lateral load capacity. Thus, the sudden loss in axial stress capacity of hybrid confined cylinders (refer Figure 3) did not translate into significant loss in the lateral load capacity at a global level since the loss in axial stress was restricted to concrete fibers along the circumference.

![Pushover curves of analyzed columns](image)

**Figure 6. Pushover curves of analyzed columns**

**Conclusions**

Passive FRP confinement and active SMA confinement was combined to test a novel hybrid confinement scheme for HSC. The confinement scheme was tested experimentally at the material level and the results were used to model CFFT HSC columns confined with SMA spirals in their plastic hinge region. The major conclusions of the research work are:

- Applying the Caltrans’ recommended FRP confinement (2.07 MPa) resulted in an ultimate strain in HSC which was only 51% of the ultimate strain in NSC. However, in hybrid confined cylinders the addition of minimal SMA active confinement (0.69 MPa) prestressed the FRP jacket and delayed its rupture to the axial strain achieved in NSC.
- Supplementing 2.07 MPa of passive FRP confinement with just 0.69 MPa of active SMA confinement in HSC resulted in an ultimate strain of 0.0281 which was 3.7 times the ultimate strain of HSC confined with FRP confinement of 4.14 MPa.
- In the hybrid confined specimens the rupture of the FRP jacket occurred well in advance of the ultimate failure to SMA spiral rupture and provided warning signs.
- Hybrid confined specimens retained significant reloading stiffness at high axial strains.
- Application of SMA spirals in the plastic hinge region of HSC CFFT columns increased their ultimate drift ratios by as high as 154%.

**References**