DAMAGE RESISTANCE OF REINFORCED CONCRETE STRUCTURES THAT UTILIZE HIGH PERFORMANCE HYBRID FIBER REINFORCED (HYFRC) COMPOSITES

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Abstract
The paper focuses on the effect of multi-scale crack control from the micro-to the macrolevel in hybrid fiber reinforced concrete (HyFRC) composites on performance enhancement and damage resistance when concrete structures are subjected to corrosion as well as seismic loading conditions. Deterioration of reinforced concrete structures is intimately related to cracking and the rate at which water and aggressive agents are able to penetrate the concrete. For the corrosion study, flexural beam specimens containing steel reinforcing bars were prepared with plain concrete and HyFRC matrices and tested under equivalent, cyclic load based demands and corrosion is initiated by ponding salt water on the tensile surface. Corrosion initiation and propagation rates were determined from periodic polarization resistance and galvanic current flow measurements. Longer times to corrosion initiation and lower active corrosion rates were observed in the HyFRC beam specimens when compared to the reinforced specimens containing plain concrete matrices. To investigate the effect of HyFRC on seismic performance and post-earthquake damage resistance, 1:4.7 scale HyFRC bridge columns were tested statically under uni-directional cyclic loading. Compared to conventional reinforced concrete columns of same dimensions the HyFRC columns exhibit superior damage resistance and better load carrying capacity at half their transverse reinforcing ratio.

1. INTRODUCTION
Concrete structures are deteriorating at a much faster rate than expected resulting in a massive need for repair and premature replacement. The deterioration of concrete is mainly associated with mechanical loading and chemical reactions which cause the concrete to crack. Cracks allow more water and aggressive agents to enter the concrete, thereby accelerating deterioration and shortening the service life of concrete structures. One way to reduce deterioration is by making the concrete highly impermeable to prevent these aggressive agents from infiltrating the concrete. However, to increase the durability of concrete structures low permeability is a necessary but not sufficient condition. Crack control and crack resistance is equally important and paramount in order to reduce the deterioration of concrete structures. Hence, a hybrid fiber reinforced concrete composite (HyFRC) was chosen as an effective means to control cracking from the micro-to the macrolevel. Experimental results on flexure and tensile property of HyFRC reinforced with conventional steel reinforcing bars is briefly
discussed. In regards to damage resistance the paper is divided into two parts. The first part discusses the effect of HyFRC on corrosion. Plain and HyFRC beam specimens containing steel reinforcing bars were tested under equivalent, cyclic load based demands and corrosion is initiated by ponding salt water on the tensile surface. Corrosion initiation and propagation rates were determined from periodic polarization resistance and galvanic current flow measurements. The second part of the paper discusses the effect of a self-compact hybrid fiber reinforced concrete (SC-HyFRC) on damage resistance due to seismic loading. For this experiment 1:4.7 scale bridge columns were built with SC-HyFRC and tested statically under uni-directional cyclic loading conditions.

2. FIBER HYBRIDIZATION AND MECHANICAL PROPERTIES OF STEEL REINFORCED HYFRC

In HyFRC fibers of various sizes and material composition are used in order to provide a continuous crack resisting mechanism [1, 2]. Poly-Vinyl Alcohol (PVA) fibers were chosen for the micro level and steel fibers were chosen for the macro. Since cracks initiate as microcracks due to expansive deterioration processes such as corrosion, alkali silica reaction and frost damage, these microcracks are influenced at onset by the PVA microfibers. Once microcracks coalesce and become macrocracks, these macrocracks are then bridged by steel macros to resist further propagation and crack opening. The flexure properties of unreinforced, reinforced HyFRC and reinforced plain concrete beams (15cmx15cmx60cm) are shown in Figure 1a [2]. The average pure tensile behavior of steel reinforced SC-HyFRC dogbone specimens (81mm in thickness, 850 mm in length) is shown in Figure 1b [3]. The steel reinforcement in these SC-HyFRC specimens was 1.9%. Grade 60 #4 bars were also tested in direct tension for comparison (dashed line in Figure 1b). The SC-HyFRC was utilized in 1:4.7 scale bridge columns. All specimens were wet cured for 7 days followed by 21 days of dry curing. The fiber properties and mix design of the HyFRC are described in reference [1].

![Diagram a) Midpoint Displacement vs Load Capacity](image1.png)

![Diagram b) Tension vs Strain](image2.png)

Figure 1. Performance of Reinforced HyFRC in a) Flexure [2] and b) Tension [3].
3. DAMAGE RESISTANCE OF STEEL REINFORCED HYFRC DUE TO CORROSION

Reinforced Plain and reinforced HyFRC beams specimens (150mm x 150mm x 600mm) were subjected to a flexural load level of 42.3 kN (9.5 kips) and then exposed to a corrosive environment. The load of 42.3 kN was chosen based on the performance of the reinforced plain concrete specimens as shown in Figure 1a while not exceeding the yield strength of the rebar. Five complete cycles of loading from 0 to the 42.3 kN load level and back were performed on 3 samples of each type of material. The results of the cyclic load tests are provided in Figure 2a and b. The “C” designation represents the reinforced plain concrete specimens while the “H” designation represents that of the reinforced HyFRC.

Immediately following the cyclic load tests, the tension surfaces of the beam specimens were examined in order to characterize the state of cracking and these results are included in Figure 2. The reinforced plain concrete specimens showed localized, transverse surface cracks ranging from 300 – 400 µm in width. Surface cracking was not detectable in the HyFRC specimens.

After cyclic loading the tensile surfaces were ponded with a salt water solution to investigate the effect of cracking/crack resistance on corrosion. For corrosion monitoring, the electrochemical cell was created by placing a saturated calomel electrode (SCE) directly into the ponding dam (Figure 3). The SCE was used as the reference electrode. The top most #3 (9M) rebar was used as the working electrode (WE) and the two #4 (12M) bottom bars were
connected and used jointly as a counter electrode (CE). The beam elements were stored in a hot chamber at 50°C at 50% RH in between corrosion monitoring periods.

Corrosion monitoring was carried out through a series a direct current (DC), potentiodynamic measurements. Polarization resistance (PR) measurements were performed in a similar manner to that specified in ASTM G59-97. Upon removal from the hot chamber, specimens were immediately clipped in to the potentiostat and the corrosion potential (a.k.a. open circuit potential) $E_{oc}$ was recorded at equilibrium. The corrosion potential $E_{oc}$ and the estimated corrosion current density $i_{corr}$ based on the polarization resistance $R_p$ measurements were measured periodically through an 80 week monitoring period.

**Figure 3. Embedded Cell for Corrosion Monitoring Experiments**

Electrochemical data are plotted as discrete points for each specimen representing the discrete nature of the proposed monitoring technique. The continuous line represents an idealized average behavior through the discrete data points. The values for the corrosion potential $E_{oc}$ and the total corrosion current density $i_{tot}$ are given in Figure 4a and b. The values for $i_{tot}$ are normalized against the entire exposed surface area of the WE.

Comparison between the different electrochemical monitoring techniques reveals consistency among the measurements. Specimens with more negative $E_{oc}$’s (the “C” type specimens) showed higher $i_{tot}$. The average difference ranges between a factor of 8-10 along the corrosion monitoring interval. Corrosion in the reinforced plain concrete specimens was significant enough such that corrosion products were visible at the crack surface.

A series of destructive tests were conducted to characterize the material post corrosion behavior after 9 months of Cl- induced corrosion from salt water ponding. Monotonic, 4 point flexure tests were performed on 2 of the 3 samples for each material type and these results are presented in Figure 5.

Note that cyclic flexural tests up to a load level of 42.3 kN (9.5 kips) were conducted on these specimens prior to salt solution ponding [see Figure 2(a) and (b)] and that the load level was chosen so as to maximize the reinforced plain concrete cracked displacement while not exceeding the yield strength of the rebar. In Figure 5 the yield point of the rebar is highlighted as engineering design parameters (EDP) for both the reinforced plain concrete and reinforced HyFRC specimens. For both of the reinforced plain concrete specimens, the yield point of the rebar fell below the 42.3 kN (9.5 kip) mark, suggesting that significant section loss from corrosion had occurred where the rebar bridged the crack. In specimen C2, the post-yield flexural stiffness began to flatten near a displacement demand of 3 mm so flexural
testing was continued until rebar fracture occurred at an ultimate displacement of 3.1 mm. Following the flexure tests, the rebar was extracted from the beam specimens for visual and gravimetric assessment. Corrosion product deposition was observed over 87% and 99% of the exposed top surface area of the bars in specimens C2 and C3 respectively with a region of localized section reduction at or adjacent to the location of the visible surface crack. In the HyFRC specimens corrosion product deposition was observed in the central region of the bar (area of highest tensile demand during cyclic loading) covering 24% and 28% of the exposed surface area for specimens H2 and H3 respectively. The digital scans of Figure 6 were of specimens C2 and H2 and represented the region of greatest damage to the rebar. From a qualitative perspective it is apparent that significantly more damage is visible on the C2 specimen. Note that C2 fractured during post corrosion flexural testing so it becomes difficult to differentiate between necking due to plastic deformation of the bar and section reduction due to localized corrosion at the crack. The remnants of a bar rib are visible across the fracture surface of C2 so it is apparent from a comparison of the surrounding ribs that a significant degree of localized corrosion was in fact happening at the point of fracture.
4. DAMAGE RESISTANCE OF SC-HYFRC BRIDGE COLUMNS DUE TO SEISMIC LOADING

Two 1:4.7 scale bridge columns built using SC-HyFRC were tested under uni-directional static cyclic loading. The design of the two specimens different in terms of the location where the majority of nonlinear deformations developed. The first specimen was designed to rock at the column’s base foundation interface. The second specimen was designed to form a plastic hinge at its base. The column diameter of both specimens was 16 inches and the aspect ratio of column height to column diameter was 7. The longitudinal $\rho$ and vertical reinforcing steel ratio $\rho_v$ of both columns was 1.2% and 0.37%, respectively. Due to the internal confinement capacity of HyFRC the vertical reinforcing ratio was reduced from 0.75% (for conventional concrete columns) to 0.37%. Figure 7a shows an elevation view of the test set-up. The lateral load was applied using two horizontal actuators inclined at 45 degrees. Two vertical actuators were used to apply a constant vertical load for the duration of the test. The vertical load was applied through a spreader beam placed at the top of the test specimens. Figure 7b shows a photo of the test setup. The foundation of each test specimen was anchored to the strong floor using four post-tensioned DSI rods.

The performance of the SC-HyFRC versus a plain concrete column of same dimension tested by Terzic [4] is shown in Figure 8. Although Terzic’s specimens had the same $\rho$RIR of 1.2%, they had a $\rho$RvR of 0.75%, which was two times larger compared to the specimens reported here. One of the major differences in performance between Terzic’s specimens and the SC-HyFRC test specimens was in the spalling resistance of the concrete cover at similar
drift ratios. Whereas extensive spalling was observed in Terzic’s specimens at a drift ratio of 4% (see Figure 8 (b), with concrete spalling up to a height equal to the diameter of the column above the top of the foundation, very limited spalling was observed at a similar drift ratio of 3.6% in SC-HyFRC test specimens as shown in Figure 8 (a).

Figure 8. Damage states of Bridge Columns at similar drift ratio: (a) SC-HyFRC bridge column at drift ratio of 3.6%; (b) Plain Concrete bridge column at drift ratio of 4% [4].

5. CONCLUSION
Damage resistance of reinforced HyFRC exposed to corrosion and seismic loading conditions was investigated. To study the effect of cracking/crack resistance on corrosion behavior, cyclic flexure tests were conducted on reinforced concrete beams composed of HyFRC and plain concrete in order to induce surface cracking. For a specified load demand in excess of the plain concrete and below the yield strength of the rebar, the HyFRC flexural specimens showed a high propensity for crack resistance (no surface cracks were visible as opposed to the reinforced plain concrete). Corrosion behavior was then monitored by ponding salt solution on the cracked surface and higher corrosion rates (measured by polarization resistance) by nearly 1 order magnitude were observed in the reinforced plain concrete specimens. The observed increased corrosion rates were confirmed by direct gravimetric analysis of the bars after removal. The damage resistance of SC-HyFRC bridge columns when exposed to seismic loading conditions was compared with identical size columns built with conventional concrete. Despite half the transverse reinforcing ratio the SC-HyFRC exhibit a superior damage and spalling resistance compared to conventional plain concrete columns. In summary, the crack resistance provided by the fibers in HyFRC composites can reduce i) the corrosion rate of embedded rebar in beam elements cracked by flexural loading and ii) reduce the damage of bridge columns when exposed to earthquake loading.

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