EFFECT OF DEFORMATION HISTORY ON STEEL-REINFORCED HPFRCC FLEXURAL MEMBER BEHAVIOR

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Abstract

High-performance fiber-reinforced cementitious composites (HPFRCCs) show promise for use in seismic applications. Structural configurations varying in geometry and material properties have been investigated to understand their behavior and failure modes under reverse cyclic loading. The influence of cyclic deformation history on component performance has not been investigated. Variations in deformation history may influence multiple cracking behavior or strain accumulation in steel reinforcement. This study investigates the behavior and failure modes of steel-reinforced HPFRCC flexural members subjected to different reverse cyclic deformation histories. Parameters of the loading protocol under investigation include the presence or absence of initial pulses, the amplitude of initial pulses, and the number of cycles per step. The results of five nominally identical flexural members of reinforced Engineered Cementitious Composite (ECC), a type of HPFRCC, tested to failure under varying loading protocols are presented herein.

All specimens reached between 12-17% drift with little strength degradation prior to failure by longitudinal reinforcement fracture. Small inelastic initial deformation pulses increased tensile strain accumulation in the reinforcement, whereas larger initial pulses led to high strains that quickly reduced with splitting crack formation and subsequent debonding. Cracking was more well-distributed when a larger number of cycles were applied prior to crack localization.

1. INTRODUCTION

High-performance fiber-reinforced cementitious composites (HPFRCCs) exhibit strain hardening in uniaxial tension [1]. Steel reinforced HPFRCC structural members have been proposed as a replacement for reinforced concrete to enhance seismic performance (see for example, a summary in [2]). Past studies of reinforced HPFRCC members subjected to reverse cyclic loading have included a variety of specimen geometries and test setups with varied levels of confinement from stirrups, as well as varied fiber volume fraction and type, and axial load [e.g., 3-5].

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9) The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.
Deformation histories have varied between previous studies, making direct comparisons difficult. A systematic study of deformation history on reinforced HPFRCC component response has yet to be conducted. Natural uncertainty between ground motions that induce cyclic deformations in structures suggests researchers should select a deformation history that is representative, yet conservative in laboratory testing of structural components and systems [6].

Variations in deformation history have been shown to significantly impact the behavior and failure of reinforced concrete specimens. Hwang [7] found that ultimate failure was influenced more by the number of large amplitude excursions imposed on reinforced concrete beams than the number of small ones. Specifically, larger excursions (to 4% drift) deteriorated the concrete, while smaller excursions (to 2% drift) did not cause meaningful deterioration. Kawashima and Koyama [8] tested flexurally dominant reinforced concrete columns without axial load with deformation histories that varied in the number of cycles per step. The deformation histories with fewer cycles per step resulted in a larger ultimate deformation, which was attributed to less cumulative damage to the concrete core and its ability to resist load. Lukkunaprasit and Thepmangkorn [9] found that specimens exposed to deformation histories with a relatively large step size (twice yield drift), exhibited in general, more ultimate specimen ductility than specimens subjected to deformation histories with step sizes half as large. For a given level of drift, the deformation history with the larger step size exposed the specimen to less cumulative plastic deformation, and thus, less cyclic deterioration of the concrete core.

In well-designed reinforced concrete members subjected to reverse cyclic loading, failure typically occurs over numerous cycles as the concrete core degrades and loses the ability to resist compression and shear. Understanding how reinforced concrete specimens behave under different cyclic deformation histories, however, does not imply direct understanding of reinforced HPFRCC specimen behavior under the same loads.

Reinforced HPFRCC specimens behave differently than reinforced concrete members in the strain compatibility between steel and the cementitious matrix [10-11]. High bond in reinforced HPFRCCs has been shown to limit splitting cracks [12], which then limits debonding of the reinforcement. Lack of debonding leads to relatively short unbonded lengths, which can cause reinforcement fracture at lower deformation levels in reinforced HPFRCC than reinforced concrete specimens [13]. Under cyclic loading, a dominant crack may form at high levels of drift as fibers begin to pull-out of the cementitious matrix. Large initial pulses that lead to crack localization and fiber pull-out relatively early in the deformation history may alter specimen behavior when compared to an experimental deformation history consisting of incrementally increasing cycles. The amplitude of the pulse may also dictate whether splitting and debonding occurs in conjunction with crack localization. Characteristics of the deformation history after crack localization are also expected to affect strain localization and accumulation in the reinforcement, which may ultimately control failure if governed by fracture of the steel reinforcement.

This study investigates reinforced HPFRCC flexural member behavior when subjected to four reverse cyclic loading protocols. Cracking behavior, hysteretic performance, and strain in the steel reinforcement were recorded. The impact of varying the cyclic deformation histories on reinforced HPFRCC specimen behavior and failure modes is presented.
2. METHODS AND MATERIALS

Eight reinforced HPFRCC specimens have been tested to date and the results of five are reported herein. The test set up and specimen dimensions are shown in Figure 1. All specimens were designed as symmetric, flexural elements consisting of a cantilever beam cast monolithically with an enlarged base. Geometry and materials were nominally identical in all specimens. In cross-section, each beam was 127 mm wide by 178 mm in height. Four deformed mild steel longitudinal reinforcing bars of 13 mm diameter with a nominal yield strength of 420 MPa were placed at each corner. The effective depth of the reinforcement was 152 mm providing a reinforcement ratio of 1.3%. Smooth, 3mm diameter steel wire stirrups were spaced at 75 mm throughout the cantilever beam and into the enlarged base. The nominal yield strength of the stirrups was 690 MPa.

The type of HPFRCC used in this study was Engineered Cementitious Composite (ECC). The ECC mix design is shown in Table 1. The silica sand had a 0.10 mm effective size, and the polyvinyl (PVA) fibers supplied by Kuraray Co. Ltd. were 12 mm long with a 15 μm diameter and they represented 2% of the composite by volume. The specimens were moist cured for seven days and then air cured at room temperature before being tested on day 28 ± 2 days. The ECC achieved an average compressive strength of 42 ± 5 MPa at 28 days based on tests of four 100 mm x 200 mm cylinders per specimen.

The naming convention of each specimen indicates the material (ECC), the reinforcement ratio (1.3%), and a descriptor indicating the applied deformation history. One specimen (ECC-1.3-M) was tested monotonically to failure. The other four specimens were tested cyclically, each with a different deformation history. The deformation history applied to ECC-1.3-CF followed the protocol proposed by the Federal Emergency Management Agency (FEMA) with incrementally increasing cycle amplitude and two cycles per step [14]. The first step was 0.15% drift, which ensured each specimen would be subjected to several elastic...
excursions prior to yield. The deformation histories of the other three reverse cyclically loaded specimens were variations to the FEMA protocol. One variation reduced the number of cycles per step from two to one (ECC-1.3-CMF) to investigate variations in strain accumulation and drift at fracture of the reinforcement. The second and third variations of the FEMA protocol involved beginning with two initial pulses. It was hypothesized that initial pulses could cause crack localization in the ECC leading to different cracking behavior, strain accumulation, and drift at fracture of the reinforcement. The two initial pulse amplitudes investigated were 2.5% and 7% drift (ECC-1.3-C2.5PF and ECC-1.3-C7PF, respectively). Each pulse was a full cycle of symmetric positive and negative displacement.

A hydraulic actuator attached to a strong column applied load to the specimens at a rate of 0.0167% drift per second where drift was equal to the horizontal displacement measured at the point of loading divided by the 760 mm span length. The specimen base was bolted to a wide flange section, which was fixed to the strong floor (Figure 1). Lateral translation and bending out of plane were restrained. Two of the four longitudinal reinforcing bars of each specimen were instrumented with three strain gages located 5 cm into the joint, 5 cm above the joint, and 15 cm above the joint (Figure 1) for a total of six strain gages. A string potentiometer at the level of the actuator was used to monitor displacement. While not reported herein, specimen deformation and strain were also monitored through a series of 12 mm black-colored dots painted on the specimen and an image analysis technique.

Table 1: ECC mix design (per cubic meter)

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type II/V Portland Cement</td>
<td>547</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>656</td>
</tr>
<tr>
<td>Silica Sand</td>
<td>438</td>
</tr>
<tr>
<td>Water</td>
<td>312</td>
</tr>
<tr>
<td>PVA Fibers</td>
<td>26.0</td>
</tr>
<tr>
<td>High Range Water Reducer</td>
<td>2.74</td>
</tr>
<tr>
<td>Viscosity Modifying Admixture</td>
<td>0.613</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

Table 2 presents the drifts at which response characteristics of interest were observed specimen during testing. Yield refers to the drift at which the specimen stiffness changed abruptly as observed from the slope of the hysteretic curve. Crack localization refers to the drift at which one crack exceeded 0.1 mm wide. First splitting refers to the drift at which splitting cracks were first visible to the eye. In all tests, the experiment was terminated due to fracture of the reinforcement.

The specimens that exhibited the most cracking were ECC-1.3-CF followed by ECC-1.3-CMF. Cracking was the sparsest for the two specimens subjected to initial pulses. All specimens developed the first observed crack between 0.15% and 0.30% drift. Additional cracks, less than or equal to 0.1 mm wide, formed with increasing drift until localization. All specimens experienced crack localization at similar drifts after which strain was concentrated at the dominant crack. When comparing ECC-1.3-CF to ECC-1.3 CMF at crack localization, ECC-1.3-CMF had been subjected to half the number of cycles as ECC-1.3-CF, and therefore cracking was more saturated in ECC-1.3-CF. Crack localization occurred within the initial
pulses for ECC-1.3-C2.5PF and ECC-1.3-C7PF. Thus, for those two specimens, the FEMA protocol cycles were applied after the fibers had begun to pull out of the cementitious matrix and did not induce any new cracks.

Fiber pull-out caused by the initial pulses did not limit the ultimate drift. ECC-1.3-C2.5PF and ECC-1.3-C7PF underwent one additional deformation level before fracture when compared to the two cyclic specimens without initial pulses. The increase in ultimate drift from 12% to 17% for the specimens subjected to initial pulses was likely related to shear sliding that became evident near 12%. Bar kinking due to shear sliding may have been less severe in the specimens subjected to initial pulses due to local damage of the ECC around the reinforcement from early crack localization in the deformation histories followed by repeated cycling. At the time of strain gage failure, ECC-1.3-C7PF had the lowest strain in the reinforcement among all specimens, and it had been relatively constant in the cycles leading up to strain gage failure. On the other hand, reinforcement strain in ECC-1.3-C2.5PF was higher than all cyclic specimens except ECC-1.3-CF, and was accumulating with each cycle up until strain gage failure. This widely different strain in the reinforcement at strain gage failure indicates behavior other than pure flexure played an important role in fracture of the reinforcement. Alternate specimen designs are being investigated in a follow-on study.

Table 2: Drift levels of various response characteristics

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Drift (%)</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Yield</td>
<td>Crack localization</td>
<td>First splitting</td>
<td>Splitting cracks &gt; 0.5 mm wide</td>
</tr>
<tr>
<td>ECC-1.3-M</td>
<td>1.5</td>
<td>2.0</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>ECC-1.3-CF</td>
<td>1.5</td>
<td>2.2</td>
<td>1.6</td>
<td>8.5</td>
</tr>
<tr>
<td>ECC-1.3-CMF</td>
<td>1.5</td>
<td>2.2</td>
<td>3.1</td>
<td>6.1</td>
</tr>
<tr>
<td>ECC-1.3-C2.5PF</td>
<td>1.5 during pulse</td>
<td>3.1</td>
<td>6.1</td>
<td>17</td>
</tr>
<tr>
<td>ECC-1.3-C7PF</td>
<td>1.5 during pulse</td>
<td>during pulse</td>
<td>during pulse</td>
<td>17</td>
</tr>
</tbody>
</table>

Figure 2 shows the hysteretic response for each specimen with the monotonic response plotted as a dashed line in each plot for reference. The “X’s” indicate fracture of one of the longitudinal reinforcing bars, which concluded the test. The hysteretic behavior of all the specimens was similar. While pinching due to shear sliding can be observed to begin at drifts near 12%, there were some differences between specimens. ECC-1.3-CF began pinching during the second 12% cycle whereas ECC-1.3-CMF completed the 12% cycle and experienced slight pinching during the 17% cycle. ECC-1.3-C2.5PF began pinching in the second 12% cycle, and the pinching increased during the 17% cycles. With the most plastic deformation post-crack localization of any of the specimens tested, slight pinching began in ECC-1.3-C7PF sooner than the other specimens. ECC-1.3-C7PF experienced pinching in the second 8.5% cycle and it grew more pronounced until failure at 17%.

The hysteretic responses indicate strength degradation measured from the first to second cycle at each step was minor for all specimens subjected to two cycles per step, including the specimens subjected to initial pulses. Strength reduction in ECC-1.3-C7PF between the first 7% pulse and the first time drift reached 7% in the FEMA protocol was 6.8% indicating that the large number of small cycles that followed the two larger initial pulses had little effect on the specimen’s strength.
Figure 3 shows the tensile strain in the reinforcement measured 5 cm above the joint superimposed over each specimen’s cyclic deformation history. Reinforcement strain is represented by a line connecting the peak tensile strains measured during each cycle on the side of the specimen that ultimately experienced fracture. Strain gauges in all specimens failed prior to reinforcement fracture as indicated by the gray boxes in Figure 3.

Comparing ECC-1.3-CF to ECC-1.3-CMF, the number of cycles per step had a small effect on strain accumulation in the reinforcement as expected. Reinforcement strain remained elastic during the early cycles and increased sharply at 1.5% drift when it yielded (as was also seen in the monotonically loaded specimen). Strain continued to increase with each subsequent step up to strain gage failure. Strain accumulated more quickly in ECC-1.3-CF than in ECC-1.3-CMF due to the multiple cycles per step as indicated by the slightly steeper line in Figure 3a than Figure 3b (note that the drift amplitude follows the same slope between Figure 3a and Figure 3b to facilitate slope comparisons). The increase in strain accumulation did not impact ultimate drift (both failed at 12% drift). Splitting was expected to reduce strain in the reinforcement. Splitting cracks exceeded 0.5 mm wide in all specimens at nearly the same drift at which strain gages failed in all specimens with the exception of ECC-1.3-C7PF, making the impacts of the splitting cracks difficult to observe. The 2.5% pulses subjected to ECC-1.3-C2.5PF were large enough to cause yield and flexural crack localization, but no splitting was observed. Consequently, reinforcement strain rose to 1.3% during the initial pulses, then remained at that same level until cyclic amplitudes exceeded that of the 2.5% pulses as shown in Figure 3c. As cyclic amplitudes increased throughout the remainder of the deformation history, strain in the reinforcement also increased until strain gage failure.
The larger initial pulses had a different effect on reinforcement strain. The reinforcement strain measured in ECC-1.3-C7PF began to reduce near 5% drift within the first pulse (Figure 3d) as the result of a splitting crack that exceeded 0.1 mm in width. By the end of the first pulse, the reinforcement strain reduced from its peak of 6.2% to 4.4% as the splitting crack grew to 0.5 mm wide. Strain in the reinforcement did not increase beyond what was reached during the initial pulse, and remained at 2-3% up to strain gage failure at 8.5% drift.

When comparing ECC-1.3-C2.5PF and ECC-1.3-C7PF, splitting cracks that reduce strain in the reinforcement did not form when the initial pulse amplitude was 2.5% (15% of the monotonic drift capacity), but did form when the pulse amplitude was 7% (45% of the monotonic drift capacity). The larger initial pulses caused splitting cracks, which reduced reinforcement strain to a constant value up to strain gage failure. The smaller pulses led to a gradual increase in strain in the reinforcement up to 6% when the strain gages failed.

4. CONCLUSIONS

The results of five steel reinforced ECC flexural members subjected to varying reverse cyclic deformation histories have been presented. Based on these results, it was found that deformation histories affect specimen behavior in several ways. Crack saturation was dependent on the number of cycles imposed on the specimen prior to crack localization. The more cycles prior to crack localization, the more cracks developed. Specimens in this study subjected to initial pulses had the least amount of cracks because localization occurred within the first two (pulse) cycles.

Strain in the longitudinal reinforcement was also affected by different deformation histories. Using a FEMA protocol, multiple cycles at the same step increased strain accumulation in the reinforcement relative to a similar protocol with only one cycle per step. Initial displacement pulses measuring 15% of the monotonic drift capacity also resulted in
strain accumulation in the reinforcement when followed by the same FEMA protocol. Two initial displacement pulses measuring 45% of the monotonic drift capacity generated splitting cracks that debonded the reinforcement from the cementitious matrix and reduced strain in the reinforcement. Reinforcement strain remained constant during the subsequent FEMA protocol up to failure of the gages.

The specimens without initial pulses achieved an ultimate drift of 12% while those with initial pulses reached 17%. The increase in ultimate drift capacity to 17% is attributed to differences in bar kinking behavior caused by shear sliding that became prominent in the specimens near 12% drift. A study investigating the impact of reinforcement ratio on trends in sensitivity to different deformation histories is under investigation.

REFERENCES