FIBER-BASED MODELING OF REINFORCED HPFRCC HINGE REGIONS

H. Tariq¹, E. Jampole² and M.J. Bandelt³

ABSTRACT

Over the last two decades, researchers have conducted various experimental investigations of structural components made with High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) for proof-of-concept seismic applications. Engineered Cementitious Composites (ECC), one type of HPFRCC material, have improved the damage resistance of reinforced concrete elements. Experimental research of reinforced ECC (R/ECC) components have shown higher strength, ductility, and energy dissipation capacity as compared to traditional reinforced concrete components. Developing sophisticated numerical models to predict the nonlinear response of reinforced ECC components can improve the confidence of engineers in using the material, and enhance its practical applications. This paper discusses the calibration of fiber-based models that are used to simulate the response of reinforced ECC beams under various deformation histories. The goal of the calibration is to ensure that the model can capture the component level behavior which includes global force–deformation response. The accuracy of the calibration procedure is evaluated by comparing the numerical parameters with experimental ones in terms of maximum strength, stiffness degradation, and energy dissipation capacity. The numerical results show strong agreement with experimental specimens. Recommendations are provided to calibrate the simulated response of reinforced HPFRCC members subjected to various deformation histories.

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ABSTRACT

Over the last two decades, researchers have conducted various experimental investigations of structural components made with High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) for proof-of-concept seismic applications. Engineered Cementitious Composites (ECC), one type of HPFRCC material, have improved the damage resistance of reinforced concrete elements. Experimental research of reinforced ECC (R/ECC) components have shown higher strength, ductility, and energy dissipation capacity as compared to traditional reinforced concrete components. Developing sophisticated numerical models to predict the nonlinear response of reinforced ECC components can improve the confidence of engineers in using the material, and enhance its practical applications. This paper discusses the calibration of fiber-based models that are used to simulate the response of reinforced ECC beams under various deformation histories. The goal of the calibration is to ensure that the model can capture the component level behavior which includes global force–deformation response. The accuracy of the calibration procedure is evaluated by comparing the numerical parameters with experimental ones in terms of maximum strength, stiffness degradation, and energy dissipation capacity. The numerical results show strong agreement with experimental specimens. Recommendations are provided to calibrate the simulated response of reinforced HPFRCC members subjected to various deformation histories.

Introduction

High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) have been developed over the past two decades with a goal of improving the performance of concrete structures across many applications [1]. HPFRCCs exhibits strain hardening behavior under uniaxial tension characterized by multiple crack formation due to the bridging action provided by fibers across crack planes [2]. Engineering Cementitious Composites (ECC), one class of HPFRCC material, has improved the damage tolerance characteristics over traditional concrete, with tensile strengths in the range of 4-6 MPa and tensile strain capacities exceeding the yield strain of reinforcement [3]. Several experimental studies on HPFRCCs have reflected promising features for seismic applications. For instance, reinforced HPFRCCs have been observed to have higher rotational capacity in beams [4], lower shear and bending deformations in shear walls [5], better damage resistance than reinforced concrete coupling beams even with reductions in reinforcement [6]. The experimental investigations have shown that ECC components absorb more energy and can withstand higher inelastic deformation demand than traditional reinforced concrete. The

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interaction of ECC with steel reinforcement has been studied by Moreno et al. [7] in terms of tension stiffening experiments. The results showed that reinforced ECC (R/ECC) specimens have the ability to resist stresses after the yielding of the rebar. Unlike concrete which had a poor resistance to splitting cracks, ECC was observed to restrain splitting cracks, preventing reinforcement strain distribution once a dominant tensile crack formed and causing the reinforcement to fracture in ECC specimens at lower deformation than in reinforced concrete (RC) specimens. Bandelt and Billington [4] showed that reinforcement fracture is the dominant failure mode in flexure for reinforced HPFRCCs, and deformation capacity of R/HPFRCC is dependent on reinforcement ratio. Frank et al. [8] studied the flexural behavior of R/ECC beams under various deformation histories. The results indicate that the failure mode of R/ECC specimens was governed by reinforcement fracturing as compared to the RC specimens where failure occurred due to concrete crushing. Moreover, the observed lateral strength, ductility and energy dissipation was improved as compared to traditional RC components.

While numerous seismic advantages have been observed in experimental testing of ECC and other HPFRCCs, several challenges, such as cost, design code provisions, and limited numerical simulation tools, among others, have prevented their widespread adoption in practice. The development of numerical simulation tools can improve analysis and design methods for R/HPFRCC structures in practical applications.

This research intends to improve numerical models that are capable of simulating the lateral response of R/ECC beams under cyclic loading up to the point of reinforcement fracture. The fiber-based modeling technique, which is based on distributed plasticity approach [9] was adopted in this research. The material models were adjusted to calibrate the component level response. The goal of the calibration is to ensure that simulation can capture the global force-deformation response. Furthermore, efficiency of the calibration procedure has been evaluated by comparing numerical parameters to experimental parameters: maximum strength, stiffness degradation and energy dissipation capacity.

**Experimental Database**

The experimental data simulated in this study is from a series of 18 cantilever R/ECC beams tested with varying reinforcement ratios, under three deformation histories [8]. The beams were 895 mm in length with cross-sectional dimensions of 165x203 mm. The results have been discussed and analyzed by Frank et al [8]. The simulation of two different configurations with 0.95% and 1.0% longitudinal reinforcement ratios are considered is this paper. The specimen cross-section dimensions and reinforcing details can be seen in Fig. 1. During the experimental test, cyclic displacements were imposed at the tip of the beam, following the protocol proposed by Federal Emergency Management Agency (FEMA) [10]. The deformation was applied incrementally with two cycles per step. The first amplitude step is 0.15% drift, and each step is 40% larger than the previous step. The other two deformation histories began with the initial drift of 2.5% and 7% followed by FEMA deformation protocol (Fig. 2). The same deformation histories were used to simulate the nonlinear response of beams.
A better description of the element inelastic behavior should account for the spread of inelastic deformations into the member. Since nonlinearity may occur at any section of the element therefor fiber-based modeling is adopted in this study to simulate the nonlinear response of R/ECC beams. The numerical modeling of both the specimens was implemented in OpenSees, an open-source platform commonly used to simulate the behavior of structures under seismic loading [11]. The nonlinear response of R/ECC beam was modeled with a force-based fiber beam-column element [9]. The plasticity was distributed throughout the length of the member in the form of integration points. Five integration points were chosen to represent the behavior of R/ECC beams. The control section was assigned to each integration point. Each cross-section was divided into 16 fibers, and fibers were associated with corresponding uniaxial material behavior (i.e. stress-strain response) as illustrated in Fig. 3.
Selection of Material Models and Calibration Process

The hysteretic behavior of the ECC is similar to well confined concrete in compression [12], therefore its nonlinear behavior was modeled with the “Concrete 02” material model [13]. ECC undergoes a pseudo-strain hardening behavior in uniaxial tension after first crack whereas concrete 02 model exhibits linear softening. To capture the ductility of ECC in tension, the post peak response of the ECC was defined by using the same fracture energy obtained from the experimental results. Moreover, the ultimate tensile strain, \( \varepsilon_{tu} \) and ultimate compressive strain, \( \varepsilon_{cu} \) was determined as a function of mesh size dependency as described by Hung and El-Tawil [14]. The nonlinear behavior of reinforcing steel is defined by the “Hysteretic Material” model [15]. This model is composed of trilinear backbone curve, and its associated hysteretic parameters provide the flexibility in capturing the cyclic behavior. An important aspect is the ability to capture the cyclic degradation in terms strength and stiffness (unloading and reloading).

The calibration of the beam-column element model was conducted in a systematic manner. Initially, the specimen with a reinforcement ratio of 0.95% was chosen and analyzed under the FEMA loading protocol. The initial analysis results showed that the component level response was governed by hysteretic behavior of steel. Adjusting properties of the ECC showed limited impact on overall structural response. The unloading and reloading stiffness degradation factor of the hysteretic steel model was adjusted to closely match the analysis results with the experimental data. To illustrate the difference of the hysteretic steel model with and without stiffness degradation, the analytical results are compared to the experimental data. As shown in Fig. 4, it is observed that both models can capture the peak strength close to experimentally observed strength. The model without stiffness degradation (Uncalibrated) tends to over predict the unloading stiffness and under predict the reloading stiffness of the specimen (Fig. 4a). This causes underestimation of the energy dissipation capacity of the R/ECC specimen by 14%. Upon adjusting the hysteretic properties of the steel, the model with stiffness degradation (Calibrated) was able to capture the energy dissipation observed in the experiment within 1% error (Fig. 4b). This steel material model was considered as a degraded material model, and was used for all subsequent simulations. The properties and parameters for modeling ECC and reinforcing steel can be seen in Tables 1 and 2 and the selected constitutive cyclic behavior of both the materials can be seen in Fig. 5.

Figure 4. Comparison of two different models with experimental data.
Table 1. ECC material parameters adopted for numerical model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>E</td>
<td>Young's Modulus</td>
<td>16</td>
<td>GPa</td>
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<td>$f_{c'}$</td>
<td>Compressive Strength</td>
<td>45</td>
<td>MPa</td>
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<tr>
<td>$f_t$</td>
<td>Tensile Strength</td>
<td>3</td>
<td>MPa</td>
</tr>
<tr>
<td>$\varepsilon_{cu}$</td>
<td>Maximum Compressive Strain</td>
<td>6</td>
<td>%</td>
</tr>
<tr>
<td>$\varepsilon_{tu}$</td>
<td>Maximum Tensile Strain</td>
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<td>%</td>
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Table 2. Steel material parameters adopted for numerical model.

<table>
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<th>Variable</th>
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<th>Units</th>
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<td>Young's Modulus</td>
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<td>$f_y$</td>
<td>Yield Strength</td>
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<td>$f_u$</td>
<td>Ultimate Strength</td>
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<table>
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<th>Hysteretic Parameters</th>
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<th>CF**</th>
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<td>Pinch-x</td>
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</tr>
<tr>
<td>Pinch-y</td>
<td>1.0</td>
<td>0.60</td>
</tr>
<tr>
<td>beta</td>
<td>0.0</td>
<td>0.55</td>
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</tbody>
</table>

UCF*: Uncalibrated Factor, CF**: Calibrated Factor

Figure 5. Constitutive material models (a) ECC and (b) steel.
Numerical Simulation

The simulated and experiments hysteresis are compared in Fig. 6. The plots on the left side show the results of the specimen with 0.95% reinforcement ratio, while the right pertains to the case with 1.0% reinforcement ratio. In both cases, the models were subjected to the three deformation histories (FEMA, Small Pulse (SP), and Large Pulse (LP)). It is observed that numerical responses capture the global force-deformation relationship from experimentation.

Measures of Accuracy

To quantify the efficiency of the calibrated model, experimental results and calibrated numerical simulations are compared in terms of lateral strength ratio, energy dissipation ratio, and unloading stiffness ratio (see Fig. 7).

1. Lateral strength ratio \( \frac{F_{\text{num}}}{F_{\text{exp}}} \): The ratio between maximum numerical and experimental strength is shown in Fig. 8a. It is observed that the numerical model reproduce accurately the experimental response with a standard deviation of 2.5%. The numerical model underestimated and overestimated the lateral strength by a maximum of 2% and 5%

2. Energy ratio \( \frac{E_{\text{num}}}{E_{\text{exp}}} \): The ratio of numerical and experimental total energy dissipation is shown in Fig. 8b. The satisfactory results are obtained with a standard deviation of 9.4%. At most, the numerical simulations overestimated and underestimated the energy dissipation by 22% and 1%

3. Stiffness ratio \( \frac{K_{\text{num}}}{K_{\text{exp}}} \): The stiffness degradation of numerical model was also evaluated by comparing unloading stiffness at each drift levels to the experimental results. The average stiffness ratios are plotted in Fig. 8c from each unloading cycle. The standard deviation is also plotted for reference. The results showed good agreement with the experimentally observed unloading stiffness.

Limitations and Opportunities for Expanding the Calibrated Model

The calibrated numerical model provides an accurate means of estimating the global response across various deformation histories for specimens having constant material properties and shear span-to-effective depth ratios. Recent numerical studies have been conducted using a continuum modeling approach to understand the performance of reinforced HPFRCC members by varying tensile properties of HPFRCCs, shear-span-to-effective depth ratios, and longitudinal reinforcement ratios [16] [17]. The results show that tensile strength has the pronounced impact in terms of influencing the global force–deformation response, followed by reinforcement ratio and shear span-to-effective depth ratios. It is expected that further experimental and numerical studies are needed by varying material properties and structural characteristics to further validate the proposed fiber-modeling approach. Future experiments may reveal more information about the seismic performance of reinforced HPFRCC members.
Figure 6. Simulation of numerical model to the experimental data.
Figure 7. Illustration of measures of accuracy.

Figure 8. Measures of accuracy.
Conclusions

The main objective of this study was to develop a fiber hinge model calibration procedure to simulate the nonlinear response of R/ECC beams under cyclic deformation histories. The fiber modeling was based on force-based beam-column element with distributed plasticity. The hysteretic parameters of steel material models were calibrated to match the component level response. Globally, the numerical results showed strong agreement with experimental data. In terms of lateral strength, the model accurately captured the experimental results. Moreover, it is observed that fiber model captures various features such as stiffness degradation and energy dissipation. The sensitivity of fiber based model to a large number of reinforcement ratios under different deformation histories is under investigation, including predicting deformation capacity. This work will support the application of R/ECC components in practice.

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References


