NUMERICAL MODELING OF HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE SHEAR PANEL

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High-performance fiber-reinforced concrete (HPFRC) made from engineered cementitious composite can significantly enhance structural performance. The ductility of the structure and the shear load resistance can be enhanced, especially for short-span elements. Improved structural performance can reduce the risk of structural failure during an extreme event of an earthquake. This paper presents numerical modeling of the HPFRC shear panel structure using a multi-surface plasticity model embedded inside an in-house 3D-NLFEA finite element package. The model's parameters were calibrated with the existing test of the HPFRC shear panel. For HPFRC under compression, the peak strain, elastic modulus, and the softening function related to the compressive fracture energy were adjusted. For HPFRC under tension, the strain hardening and crack localization when the HPFRC softens were also proposed. The comparisons were made between the numerical model and the existing test of the HPFRC shear panel. Some conclusions were drawn on the accuracy of the model and its possible application at the structural level.

Keywords: HPFRC, Engineered cementitious composite (ECC), Reinforced bars, Displacement.

1 INTRODUCTION

Concrete is a widely used construction material due to its high compressive strength and durability. However, it is susceptible to cracking and failure under tension, making it vulnerable to failure in shear. Researchers have developed various techniques to enhance concrete's tensile strength and ductility to address this issue. One such technique is using Polyvinyl Alcohol Engineered Cementitious Composite (PVA-ECC) fibers. PVA-ECC fibers are high-performance fibers (HPF) that can significantly improve concrete tensile strength, toughness, and ductility. PVA-ECC fibers can enhance shear stress resistance and prevent premature failure when used in a concrete shear panel. However, modeling the nonlinear behavior of a concrete shear panel made of PVA-ECC fibers can be challenging, as it involves accounting for the complex interactions between the concrete matrix and the fibers.

Several researchers have attempted to model reinforced concrete shear panels. Susetyo et al. (2013), Suryanto et al. (2010), and Zhang et al. (2022) used a single element and applied force to produce pure shear behavior. However, the simplified model did not allow for deformation between the nodes, which may not accurately reflect the actual behavior of the RC shear panel.
This study aims to gain insight into the behavior of PVA-ECC reinforced concrete panels, which will replace the conventional shear key in a high-speed train slab track. Before conducting experimental tests on the shear key, which may require complex loading states and heavy specimens, it is more convenient to model the shear key of this high-speed train by understanding the fundamental behavior of PVA-ECC reinforced concrete in general. Therefore, this study proposes a numerical and constitutive model extension to predict the behavior of PVA-ECC reinforced concrete shear panels.

2 METHODOLOGY

2.1 Model Geometry, Material Properties, and Boundary Conditions

The modeled specimen was obtained from the experimental work carried out by Xoxa (2003). This study only examines one specimen PK1 from Xoxa (2003) out of the six specimens tested. Figure 1a shows the geometry of specimen PK1. The shear panel width is 890 mm, and the thickness is 70 mm. The reinforcement is one layer. The concrete strength is 48.9 MPa. The concrete uniaxial peak strain is 0.00492. The elastic modulus of the concrete shear panel is 14,828 MPa. The steel reinforcement has a diameter of 6 mm. The steel reinforcement D6-SD295 has a yield strength of 361.4 MPa and an ultimate strength of 493.1 MPa. Young's modulus of the steel reinforcement is 189,800 MPa. Figure 1b shows the 3D model of shear panel PK1 which includes the reinforcing bar configuration, applied displacement control, and boundary conditions. Figure 1b shows that the applied displacement was enforced on each side of the panel, resulting in pure shear conditions that caused distortion. The shear panel comprised 60,207 hexahedral elements and 70,560 nodes. The steel reinforcing bar was meshed into 1,840 truss elements and further subdivided into smaller elements using embedded meshes in the 3D-NLFEA package. The rationale for using smaller elements, rather than a single membrane element, was to enable detection and tracking of crack localization and propagation in the shear panel.

![Figure 1. Shear panel PK1 (a) specimen geometry (Xoxa 2003), (b) 3D-model.](image-url)
2.2 Material Constitutive Models

The shear panel in this study was composed of concrete, PVA-ECC fibers, reinforcing bars, and steel plates. To accurately capture the behavior of the reinforcing bars, they were treated as embedded elements, following the approach proposed by Ranjbaran (1996). This method enabled control of the strain in the reinforcing bars by the deformation of the parent elements. The constitutive model for the reinforcing bars utilized an elastic-perfectly plastic model without hardening, as described by Chen and Han (2007). In addition, a perfect bond assumption was made for the reinforcing bars.

For the concrete material, a multi-surface plasticity model proposed by Piscesa et al. (2019), which incorporates different failure surfaces for concrete under compression and tension. For concrete under compression, the Menetrey and Willam (1995) failure surface was used, which falls into three parameter failure surface. Although it is possible to have the compression failure surface to handle tensile stress in concrete, the non-associative flow rule of the potential plastic function would not be suitable for concrete under tension. Hence, a tension cut-off failure surface (Rankine criterion) was utilized to appropriately model concrete under tension. In Piscesa et al. (2016) and Piscesa et al. (2017), the failure surface of Menetrey and Willam (1995) was modified to explicitly control the concrete material's peak and residual stress under a confined state. In addition, the flow rule was non-constant and varied as a function of the confining device stiffness and the confining pressure (Piscesa et al. 2018). For concrete under tension, an associative flow rule was employed.

Two methods can utilize the contribution from the fiber into the concrete constitutive model. The first method is by assuming the fiber contribution is treated as micro-smeared reinforcement such that the overall behavior of the stress-strain model for the FRC is captured only by adjusting the stress-strain model for concrete under tension and compression. The second method uses a discrete element for the fiber, including the shape of the fiber, into the parent element. Bond slip between the fiber and the concrete can also be modeled by considering the normal stress acting on the concrete or neglecting it. For sufficiently large fibers, it is possible to model the fiber as a discrete-embedded element into the parent element. This way, the overall behavior of the FRC can be affected by the dispersion of the fiber. Bad fiber dispersion can lead to lower strength of FRC and vice versa.

On the other hand, for a very tiny fiber, such as PVA-ECC fiber, the use of discrete-embedded elements would be computationally expensive. For each fiber, the stiffness should be included in the stiffness of the parent elements similar to that of embedded formulation of reinforcing bar (Ranjbaran 1996). A much smaller element is necessary to ensure the cracks can propagate and pass the fiber such that the fiber is activated. Large element size may cause the fiber inside the element to be constantly strained along its length, which is not preferred. Therefore, for PVA-ECC fiber, it is wise to model the behavior of the FRC embedded into the constitutive model by adjusting the material properties and the stress-strain model under tension and compression.

2.3 Proposed Load-Crack Hardening and Softening

Figure 2 shows the relationship between the load-crack hardening and softening when modeling the PVA-ECC fiber concrete under tension. During the hardening stage, as the concrete cracks and fiber initiation occurs, the crack saturation takes place, and the crack band widens. In the softening stage, as the fibers begin to break one by one, localization occurs. In Figure 2, the tensile stress at the first crack is 1.924 MPa and at peak, when the concrete hardens, is 2.886 MPa. The tensile stress at the first crack is assumed to be 0.33\(\sqrt{f_c}\) as suggested by Ayoub and Filippou (1998). The PVA-ECC concrete tensile stress at the first crack and the peak was determined by ensuring the response of the numerical model was somewhat close to the shear panel test result. The tensile
stresses obtained in this study were higher than the used tensile stress in the numerical study of Suryanto et al. (2010) but lower than the average tensile coupon test of the PVA-ECC material.

Figure 2. Tensile stress as a function of the crack opening displacement.

3 ANALYSIS RESULTS AND DISCUSSIONS

Figure 3 shows the plot of shear stress as a function of shear strain for all the modeled shear panels including one specimen PK1 from the available test result (Xoxa 2003). Figure 3a was intended to show the effect of shear reinforcement in resisting the pure shear forces. As illustrated in Figure 3a, for the shear panel made from plain concrete only, once the concrete crack, the shear load capacity drops significantly from 1.928 MPa to 0.781 MPa and only restore a very small portion of its capacity. On the other hand, for RC shear panel, once the first crack is formed, the shear load carrying capacity drops from 1.928 MPa to 1.574 MPa and gradually increases to 2.184 MPa. After the second peak, the shear load carrying capacity also reduces gradually.

Figure 3b showed the result from the experimental test and numerical simulation of PVA-ECC RC shear panel PK1 alongside the numerical result of RC and plain shear panels PK1. As shown in Figure 3b, the shear load level for the PVA-ECC RC shear panel at the first crack is almost similar to the conventional RC shear panel. Unlike the conventional RC shear panel, the shear load
The carrying capacity of the PVA-ECC RC shear panel gradually increased once the first crack was formed from 1.934 MPa to 4.048 MPa for the numerical simulation and from 1.930 MPa to 3.930 MPa for the test result. The predicted shear load carrying capacity using the 3D-NLFEA package was 3.00% higher than the test result.

Figure 4 shows the shear panels cracking pattern displayed as the crack opening displacement (COD). As shown in Figure 4a, the RC shear panel has crack localization symmetrically located due to the perfect symmetry of the model. There is a slight localized crack at the mid-diagonal panel with a smaller crack opening displacement. On the other hand, the PVA-ECC RC shear panel is shown to have crack saturation with almost similar crack opening displacement for each of the small, localized crack locations. The reinforcing bars for both the observed shear panels were shown to be yield. The only differences are that for RC shear panel, the band that the rebar yield was narrower compared to the PVA-ECC RC shear panel.

4 CONCLUSIONS

This paper has presented a numerical simulation of the shear panel with high-performance fiber-reinforced concrete using PVA-ECC material. The numerical simulation was carried out using an in-house 3D-NLFEA package which has a built-in plasticity-fracture model for concrete. Only the behavior for concrete under tension was adjusted. A custom stress-strain model which includes the hardening phase where crack saturation in the PVA-ECC takes place and softening phase where localized cracking occurred was proposed. The stress level at the first crack and peak was adjusted to get a reasonable prediction of the response compared to the test result. The failure pattern of the PVA-ECC shear panel showed that the crack saturation did occur followed by a series of localized cracking in the middle of the diagonal direction. The crack opening displacement at these localized cracks was almost similar. On the other hand, the simulated RC shear panel was shown to have symmetric localized cracks. Further study to evaluate the accuracy of the proposed stress-strain model should be carried out by investigating different shear panel models and examining both the result from the model and the test result. In addition, the effect of random material properties should be carried out to initiate the non-symmetric localized cracking pattern. It is also worth investigating the behavior of RC shear wall made of SFRC in the future.
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