Rigid-body-spring model numerical analysis of joint performance of engineered cementitious composites and concrete

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Abstract. This paper presents a numerical investigation of effectiveness of using engineered cementitious composites with polyvinyl alcohol fibers for concrete cover layer repair. A numerical model of a monolithic concaved L-shaped concrete structural detail which is strengthened with an engineered cementitious composite layer with polyvinyl alcohol fibers is created and loaded with bending moment. The numerical analysis employs nonlinear 3-D Rigid-Body-Spring Model. The proposed material model shows reliable results and can be used in further studies. The engineered cementitious composite shows extremely good performance in tension due to the strain-hardening effect. Since durability of the bond can be decreased significantly by its degradation due to the thermal loading, this effect should be also taken into account in the future work, as well as the experimental investigation, which should be performed for validation of the proposed numerical model.

1. Introduction

Cover layer delamination and spalling due to concrete degradation or corrosion of reinforcement is one of the common causes of concrete structures repairing (see figure 1). An aggressive environment affect concrete significantly because of water and chemically aggressive particles (alkalis, chlorides etc.) penetration. Engineered cementitious composites (ECC) with polyvinyl alcohol (PVA) fibers can be used as repair material to reduce the negative environment effect due to its tensile ductility in the form of pseudo strain hardening, that is achieved by cement matrix multiple cracking (see figure 2) and differ from observed in metal “real” strain hardening [1, 2]. The research of tensile behavior of PVA-ECC has shown the formation of a large number of tiny cracks with a width of less than 60 μm. The presence of microcracks only, provides high durability of this material because the transport of environmental products into the concrete takes place through the cracks with a width above 0.1 mm [3].

Adhesion properties of the repair material play the crucial role in concrete cover repairing process. New material layer should provide reasonably high bond strength with old concrete layer and bars of reinforcement to ensure the joint operation of the composite structure. According to available research [4], PVA-ECC allows for much stronger bond compared to ordinary mortar, this makes PVA-ECC suitable for the described purposes. Thus, this study deals with concrete to PVA-ECC bond only.
Figure 1. Type of concrete cover damage

Figure 2. Tensile stress-stain behaviour of (A) brittle, (B) quasi-brittle, (C) strain softening, (D) strain hardening materials [6, 7]

A zone of special interest is represented by monolithic concrete joint of beam and column due to the concave corners presence. They may produce serious problems because of non-uniform stiffness distribution and restriction of deformation [5]. Plane concrete L-shape structure detail, strengthened by PVA-ECC layer is considered in this study to investigate PVA-ECC-concrete composite behavior.

To simplify numerical analysis and to control mechanical properties of materials and bond between them in a simple way, 3D Rigid-Body-Spring Model (RBSM) is used to simulate possible delamination and crack propagation in composite PVA-ECC-concrete L-shape structure detail.

2. Material models

RBSM is type of discrete method model, that is invented by Kawai [8]. The main benefit of RBSM is the ability to model difficult three-dimensional behavior of material, by using simple constitute model, that can be vitrificated easily by providing classical benchmark tests. The using of random geometry of particles [9] in order to simulate crack pattern and its propagation, to compute deformations and stresses of concrete and reinforced concrete structures shows reliable results.

Material is modeled as undeformable rigid-bodies interconnected by sets of springs on their surfaces. Voronoi cell shape rigid particles are generated to reduce mesh bias on cracks initiation and propagation by obtaining of random geometry.

In this model, each rigid-body has six degrees of freedom (three translational and three rotational) defined at the nuclei of Voronoi diagram. Center of gravity and vertices of the boundary surface of two neighboring particles create triangles (see figure 3). One normal and two shear springs are set at the center of these triangles to take into consideration bending and torsion without rotational springs setting [10].

Figure 3. Rigid-Body-Spring model
2.1. Concrete material model

3D RBSM concrete material model in tension compression and shear are shown in figure 4. The tensile stress-strain relation for normal springs is linearly elastic with the slope of elastic modulus $E$ up to tensile strength $f_t$ with bilinear softening behavior after cracking. Tensile fracture energy is also taken into account [10-12].

The compression model for normal springs is modeled as combination of two quadratic functions with the resultant S-shape curve. Compressive failure is not considered in this model [10-12].

The shear stress-strain relation is represented as a combination of stresses and strains of two shear springs. The shear stress is increasing elastically with the slope of shear modulus $G(E, \nu)$ up to the shear strength $\tau(f_t)$, then the softening behavior is assumed. Slope of softening $K(\beta, G)$ is depended on normal spring stresses through the softening ratio $\beta(\sigma)$, that is increasing up to the maximum value with increasing of tension stresses [10-12].

The Mohr-Coulomb type criterion is assumed as the shear spring failure criteria [10-12].

![Figure 4. Concrete material model](image)

All necessary parameters and constants can be found in [10-12].

2.2. PVA-ECC material model

3D RBSM PVA-ECC tension stress-strain relation was taken from the experimental investigation of PVA-ECC with 2% fibers content [13], and simplify reasonably as shown in figure 5. The normal spring in tension is modeled as linear elastic up to the tensile strength $f_t$ with a linear hardening branch after cracking up to the spring failure.

![Figure 5. Tension model of normal spring of PVA-ECC](image)

![Figure 6. Tension model of normal spring of PVA-ECC to concrete bond](image)
Since, the numerical analysis presented in this study has no compression in PVA-ECC layer, the compression model is assumed to be the same as in concrete material model.

The shear material model is constructed in the way similar to concrete shear material model from mechanical material properties (elastic modulus $E$, Poisson’s ratio $\nu$, etc) and material properties in tension (tensile strength $f_t$).

### 2.3. Bond material model

The tensile bond behavior is presented in previous numerical and experimental study [4] and shown in figure 6. The stress-strain tensile relation takes form of cubic parabola up to the failure without any softening branch (see equation (1)). The trend of stress-strain curve of bond is similar to stress-strain curve of PVA fibers in tension [14], that means, that bond is provided by PVA fibers mostly.

$$\sigma = \sigma_{ult} (a \cdot \varepsilon_{norm} + b \cdot \varepsilon_{norm}^2 + c \cdot \varepsilon_{norm}^3),$$

where: $\sigma_{ult}$ - ultimate stresses occurring in element; $\varepsilon_{norm}=\Delta u/\Delta u_{ult}$ - normalized strain, expressed by the ratio of the relative displacement of the nodes to the ultimate relative displacement; $a$, $b$, $c$ - shape coefficients, $a+b+c=1$.

The bond is not affected by any compression in this study example, thus the using of the concrete compression model is justified.

The bond material model in shear is created by using of tensile stress-strain curve parameters (elastic modulus $E$, tensile strength $f$) with the same procedure, as in concrete shear model. The corresponding mechanical parameters of bonded layers (Poisson’s ratio $\nu$) are averaged to find the unknown parameters of the bond.

### 3. Numerical analysis

To investigate bond properties of PVA-ECC strengthening layer on concaved concrete structure detail the L-shaped concrete sample with the layer of PVA-ECC on outer surface (see figure 7) is modeled in Matlab using non-linear 3D RBSM. Concrete with the modulus of elasticity, $E_{con}$, of 35 GPa, Poisson’s ratio, $\nu_{con}$, of 0.18, tensile strength, $f_{t,con}$, of 3.5 MPa, compression strength $f_{c,con}$, of 40 MPa PVA-ECC with the modulus of elasticity, $E_{ecc}$, of 20 GPa, Poisson’s ratio, $\nu_{ecc}$, of 0.22, tensile strength, $f_{t,ecc}$, of 5 MPa, compression strength $f_{c,ecc}$, of 50 MPa and the bond between materials with initial modulus of elasticity, $E_{bond}$, of 0.1 GPa, Poisson’s ratio, $\nu_{bond}$, of 0 (for shear modulus calculation the value of 0.2 is used), tensile strength, $f_{t,bond}$, of 1.5 MPa, compression strength $f_{c,bond}$, of 15 MPa are considered in numerical model.

![Figure 7. Modelled sample](image)

The modeled sample is subjected to the bending moment as shown in figure 7. Displacement-controlled modified Newton-Raphson method is used as the convergence algorithm. In the convergence process, displacements that cancel the unbalanced force of elements are added to the elements. The displacements are calculated using the stiffness matrix. Convergence of the model is judged when the $\Sigma$(Reaction of elements in the model)$^2$ becomes less than $10^{-6}$. When the model does not converge at a given maximum iterations (maximum number of iterations is 400 in this model), the analysis proceeds to the next step [15].
4. Results and discussion
The crack pattern of concrete part (see figure 8) and the crack pattern of PVA-ECC layer (see figure 9) are represented as the results of numerical analysis. Analysis of results shows that the sample destruction starts in concrete part, PVA-ECC layer is not delaminated and create the cohesion zone instead. This phenomenon is associated with compliant ductile properties of PVA fibers, that play a major role in creation of bond and providing its load-bearing capacity, while the adhesion chemical bond is destroyed in much lower deformations [4]. PVA-ECC layer is not broken due its high performance and strain hardening in tension, the microcracks are spread of all the volume of PVA-ECC layer, which corresponds to the available experimental studies [13]. Thus, the proposed numerical model shows reliable results and can be used in further studies.

![Figure 8. Crack pattern of concrete part of modelled sample (magnification=300)](image)

![Figure 9. Crack pattern of PVA-ECC layer (magnification=300)](image)

According to the results of numerical analysis the microcracks in PVA-ECC are too thin to provide intensive chemical particles transfer, which is approved by experimental investigation [16]. PVA-ECC provides strong bond with concrete. That properties make PVA-ECC suitable material for concrete cover repair.

The durability of PVA-ECC to concrete bond causes concern due to the degradation of mechanical properties of PVA fibers under influence of high temperature [14]. The behavior with similar trend of degradation shows PVA-ECC to concrete bond [4] under the cyclic thermal load. This type of load is one of the critical for concrete cover layer. Thus, this effect should be investigated more carefully.

5. Conclusions and future work
Based on the obtained results the following conclusion can be done:

The proposed numerical material model shows similar to experimental results and can be used in future numerical modeling.

PVA-ECC shows extremely good performance and has necessary for repair material properties, such as high mechanical properties, good hardening and setting properties, high durability and high bond strength, low permeability even after cracking. Thus, it can be used for concrete cover repairing.

Degradation of PVA fibers and PVA-ECC to concrete bond under exposure of high temperatures or thermal cyclic load can cause premature concrete cover delamination. Thus, this issue should be investigated in future work.

The proposed material model should be validated with experimental investigation.

The numerical model should be expanded and allow for PVA-ECC to reinforcement bond modeling. The experimental analysis should be provided for these purposes.

The effect of bonded surface roughness should be considered in future work.

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