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NUMERICAL INVESTIGATION OF SHEAR BEHAVIOR SHCC STRUCTURAL ELEMENTS

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Abstract: *Fiber reinforced cement-based composites is a large group of composites with variety of properties. The purpose of adding fibers is to overcome the brittleness of the concrete by improving the post-cracking behavior and enhancing ductility. This paper deals with the group Strain Hardening Cement based Composites (SHCC) which exhibits excellent mechanical behavior showing tensile strain hardening and multiple fine cracks. The primary objective of the presented research is to verify a developed constitutive model. The constitutive model is intended to be utilized for large-scale simulations and thus it must be robust and efficient. Therefore, it is necessary to compare the numerical simulations against the experimental data. The paper summarizes the studies performed on the shear behavior of reinforced SHCC elements tested on beam specimens monotonically loaded by an anti-symmetrical moment.*

Keywords: **Strain Hardening Cement-based Composite (SHCC), Rotating crack model, Damage, Shear behavior.**

1. Introduction

Concrete has been used for many centuries as a safe and durable building material. Two of the main advantages of concrete are its high compressive strength and that it can be cast on the construction site into a variety of shapes and sizes. The most prominent disadvantages of concrete and other cementitious materials are their brittle failure behavior in tension and low tensile strength. The low tensile strength is usually compensated for with steel reinforcement, but wide cracks leading to the corrosion of the steel reinforcement still occur during the normal use of concrete (Otieno et al., 2010). These cracks lead to durability problems and cause structural degradation to occur more rapidly.

Fiber reinforced cement-based composites is a large group of composites with variety of properties. The purpose of adding fibers is to overcome the brittleness of the concrete by improving the post-cracking behavior and enhancing ductility. This paper deals with the group Strain Hardening Cement based Composites (SHCC) which exhibits excellent mechanical behavior showing tensile strain hardening and multiple fine cracks (Li and Wang, 2001; Boshoff and van Zijl, 2007). The primary objective of the presented research is to verify a developed constitutive model described in (Vorel and Boshoff, 2012; Vorel and Boshoff, 2013). The constitutive model is intended to be utilized for large-scale simulations and thus it must be robust and efficient. Therefore, it is necessary to compare the numerical simulations against the experimental data. The paper summarizes the studies performed on the shear behavior of R/ECC elements tested on beam specimens monotonically loaded by an anti-symmetrical moment (so-called Ohno method). Two different specimens, with and without stirrups, are assumed (Kabele and Kanakubo, 2007; Kabele, 2009).

2. Computational Model

In this section the main features of the utilized numerical model are briefly described. The complete description and definition of the model can be found in (Vorel and Boshoff, 2012; Vorel and Boshoff, 2013). The model is implemented in the open source finite element code OOFEM (Patzák and Bittnar,

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2001) for plane stress elements using a coaxial rotating crack method (RCM) with two orthogonal cracks as described in (Han et al., 2003). This numerical approach is classified as the smeared crack model with the softening defined by means of the cohesive crack and overlapping crack model (Carpinteri et al., 2007).

To model the specific behavior of SHCC in tension, the application of classical constitutive material models used for quasi-brittle materials is not straightforward. The employed numerical model is based on a rotating crack assumption to capture the strain hardening and softening, the multiple cracking, the crack localization and multiple orthogonal crack patterns (Suryanto et al., 2008). In heterogeneous materials where micro-cracking occurs prior to the formation of a macro-crack, the rotating crack model may be more realistic than the fixed crack model. Micro-cracks are formed orthogonally to the major principal stress when the tensile strength is first violated. However, upon rotation of the principal stress axes new micro-cracks arise in the “rotated” direction and it is most likely that upon termination of the stress rotation, the latter micro-cracks will grow into macro-cracks. This justifies the choice of a rotating crack model from a physical perspective. A complete description of the rotating crack model can be found, e.g., in (Rots, 1998). Note that the rotating crack model evaluates a given strain state and generates the inelastic strain in the principal directions of the strain and does not automatically include the effect of Poisson's ratio, as the stress is evaluated on the basis of individual principal strains.

To allow the residual deformations and to account for the Poisson ratio effect, a new approach is employed where the effective principal strain is used to determine the equivalent stress from the simplified uniaxial stress-strain diagram. The effective principal strain is based on the principal strain, which is free of inelastic deformations caused during the stress state change. The evolution of inelastic strain is assumed to be linearly dependent on the previously reached maximum strain for the elastic and hardening part and linearly dependent on the crack opening for the softening branch. This simplification corresponds well with experimental results (Vorel and Boshoff, 2012).

3. Numerical Study

The open source finite element program OOFEM is utilized to perform numerical simulations of selected experiments on Ohno beams. The specimens labeled PVA20-00 and PVA20-30 in (Kabele and Kanakubo, 2007) with shear reinforcement ratios of 0.0 and 0.3%, respectively, are exploited. Plane stress idealization of the problem was adopted. The finite element mesh typically consisted of about 3300 isoparametric four-node quadrilateral plane-stress finite elements of size around 25 mm. The SHCC material is represented by the constitutive model briefly described in the previous section. The material parameters summarized in Tab. 1 are obtained by fitting the uniaxial stress-strain diagrams presented in (Kanakubo, 2006; Kabele and Kanakubo, 2007; Kanakubo et al., 2007). The main steel bars and stirrups are represented by two-node truss elements with the cross-sectional area and position presented in (Kanakubo et al., 2007). The Mises plasticity condition with no hardening is assumed for the steel (Kanakubo et al., 2007) and an isotropic damage model with exponential softening is assumed for the

Tab. 1: SHCC model parameters.

General		**Tension**		**Compression**	
Param.	***Value***	***Param.***	***Value***	***Param.***	***Value***
E	18.41 GPa	σ_{t0}	3.4 MPa	$\lvert\sigma_{c0}\rvert$	1.0 MPa
ν	0.35	ε_{tp}	0.0167	$\lvert\varepsilon_{cp}\rvert$	0.0035
		σ_{tp}	4.1	$\lvert\sigma_{cp}\rvert$	39.3 MPa
		$w_{t,cr}$	4.37 mm	$\lvert w_{c,cr}\rvert$	0.23
		a_t	3.0	a_c	3.0
		b_t	0.8	b_c	0.8
		b_t^{cl}	0.9	b_c^{cl}	0.98
				β_c	2.2

steel-concrete contact, see (Patzák, 2013) for more details. The strength limit for the interface elements is setup to approx. 5 MPa.

Fig. 1 depicts the overall response of the beams, i.e., the shear load (one third of applied force) vs. translational angle (rotation of the side stubs about support pins). The peak load and the pre-peak loading part is captured satisfactorily for the beam without shear reinforcement (PVA20-00). However, the beam with the shear reinforcement shows a softer response and underpredicts the peak load by 15% when compared to the experimental data. This deficiency is attributed to the insufficient description of the steel-concrete interface due to the utilized interface model.

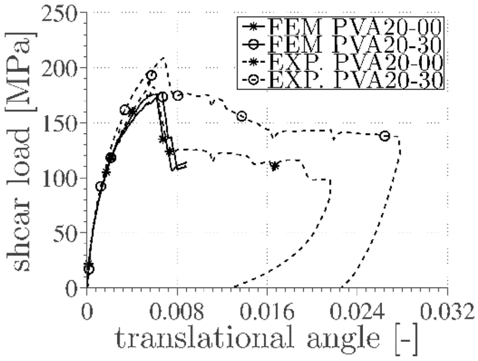

Fig. 1: Comparison of numerical simulations and experimental data.

To demonstrate the behavior of the beams at the peak load, Fig. 2 shows the damage magnitude of the individual beams.

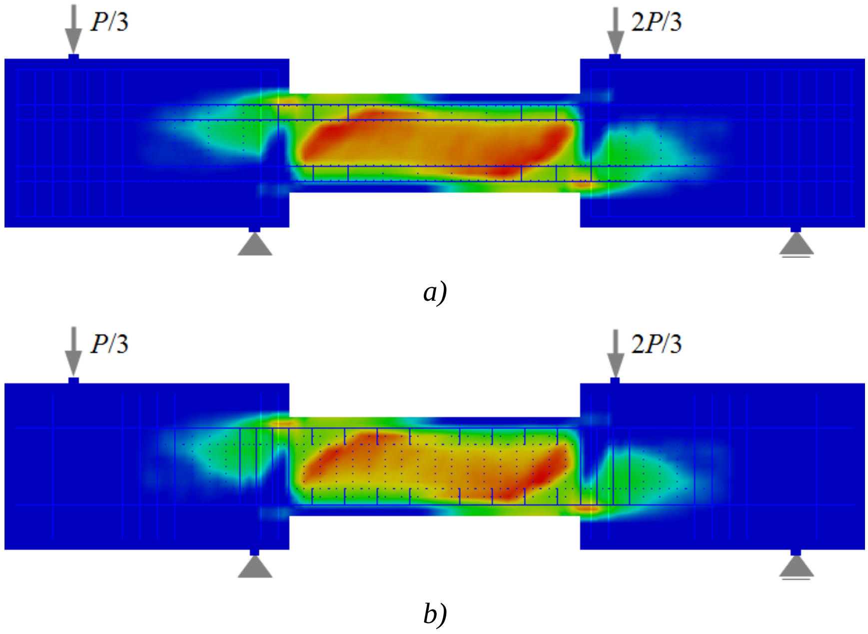

Fig. 2: Damage at the peak load for beams: a) PVA20-00, b) PVA20-30.

4. Conclusions

Based on the comparison of experiments and numerical analyses, the following conclusions related to the shear behavior of utilized numerical model can be drawn. The material model based on the rotating cracks appears to be sufficient for the simulation of the shear loaded structural members, as can be seen in Fig. 1. However, if the higher shear reinforcement ratio is assumed, the outlined numerical approach underpredicts the peak load. This behavior is attributed to the utilized interface model and will be the subject of future research.

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