IMPACTS OF PRINCIPAL STRESS ROTATION ON THE NONLINEARITY OF STRAIN-HARDENING CEMENTITIOUS COMPOSITES WITH FIBERS

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Abstract

An experimental program was conducted to investigate the effects of simultaneous opening-sliding of multiple cracks on the behaviour of strain-hardening cementitious composite plates. Newly proposed testing method was developed to reproduce possible rotating principal axis during the material strain-hardening. The experimental results showed the change in principal stress direction has a substantial impact on the macroscopic plate behaviours including multi-directional cracking pattern, and reductions in strength, ductility, and initial stiffness. A space-averaged constitutive model for this type of material was developed and further incorporated into FE analysis program. The model simulated reasonably various responses observed in the experiment and demonstrated the reductions observed were attributed to the lack of shear transfer across the multiple cracks. Further analyses of shear-critical R/SHCC panels and beams were carried out and confirmed the applicability of the model to simulate the behaviours at structural levels. Finally, this paper briefly presents our recent attempt to improve the structural performance with robust SHCC material under stress field rotation.

1. INTRODUCTION

Strain Hardening Cementitious Composite (SHCC) is a group of cement-based composites that exhibits multiple-fine cracks and pseudo-strain hardening behaviour in tension. To fully use the strain-hardening property of SHCC, it is desirable to allow multiple cracks to develop under service loading condition [1]. Allowing cracks to form must, however, be accompanied with a capability of transmitting not only tensile stresses, but also shear stresses across their surfaces. Shear tractions can particularly develop on cracks surfaces when the principal stress directions at subsequent loadings no longer align to the first principal stress direction, which determines the orientation of the first set of multiple cracks.

Example of an application, where continuous rotation of principal stress axes occurs in today practice, is a bridge deck-type structure. Consider, for instance, a bridge deck made of SHCC. Due to the random movement of wheels over the deck, multi-directional cracks first
occur at different locations on the deck. On subsequent wheel running, these preexisting cracks may alternately open and close, and simultaneously slip, transmitting both tensile and shear stresses across their crack surfaces. It is therefore of importance to clarify the effects of this aspect of behaviour on the post-cracking performance of SHCC.

Since the first introduction of SHCC in the early of 1990s, considerably less attempts has, however, been made to quantify the ability of multiple cracks in SHCC to transmit shear. Such quantification on a single crack can pose a significant challenge as a very precise testing device would be required to deal with numerous closely spaced microcracks during the material strain-hardening when subjected to shear. A new testing technique was, therefore, developed by the authors [2]. Instead of quantifying the ability of one microcrack to transmit shear, it was attempted to quantify the average shear provided by a group of microcracks. This idea was realized by testing and investigating the response of pre-cracked ECC plates subjected to principal stress rotation. Important findings of the test are summarized herein.

To provide a mechanistic basis on the plates test result, this paper describes recently developed constitutive models in the context of a smeared, fixed crack approach for analysis of ECC and R/ECC [3,4,5]. At material levels, the models were used to simulate the behaviour of pre-cracked ECC plates subjected to principal stress rotation tested by the authors [2]. At structural levels, the accuracy of the proposed models were tested against the response of five R/ECC panels subjected to monotonic and cyclic pure shear and two shear-critical R/ECC beams, with and without web reinforcement, subjected to reversed cyclic shear [3,4,5]. The capability of the models to simulate the damage states of cracked ECC and R/ECC subjected to complex loading are focused in addition to the importance of having sufficient interface shear transfer during the material strain-hardening. Finally, the result of a test program to improve shear transfer property of SHCC with coarse aggregate is presented.

2. EXPERIMENTAL PROGRAM

2.1 Description of the Test Plates and Test Parameters

The SHCC investigated in the study is ECC that contains 12-mm long PVA fibers and in the proportion 2% by volume [1]. Eighteen plates were made. The dimensions of the plates are shown in Fig. 1(a). There were two plate types. The first type corresponds to the control plates (S1, S2, S9, and S10) with dimensions of 400×250×20 mm, while the second one corresponds to the main plates (S3 to S8, S11, and S14) with dimensions of 550×420×20 mm.

Two experimental parameters were considered. The first was the orientation of the initial crack (20°, 45°, and 70°), while the second was the degree of initial damage (40% and 70% of the average ultimate tensile strains of the reference plates measured from the bottom surface of each plate, $\varepsilon_{tu}$). Plates S13 to S18 were additionally fabricated with a crack orientation of 90° to examine the effects of transverse cracking under various initial damage degrees.

2.2 Testing Procedure and Measurement Devices

The experimental testing procedure is shown in Fig. 1(b). For the reference plates, a four-point bending test was conducted (Stage 2). For the main plates, the testing procedure was divided into two stages. In the first stage, cracks were first introduced in bending (Step A). When the initial tensile strain on the bottom plate surface reached 40% or 70% $\varepsilon_{tu}$, the plate
was unloaded and then flipped upside-down (Step B). The plate was again loaded in bending to flatten the plate (Steps C and D). The plate was then cut (Step E) to alter the angle of the initial crack to a certain angle. Finally, the cut part was re-tested in bending (Step G, Stage 2).

Two types of transducers were used: Cable Position Transducer (CPT) and Linear Variable Differential Transducer (LVDT). Six CPTs were used to measure average strains at the bottom surface of each plate as illustrated in Fig. 1(c). Two LVDTs were mounted to the frame of the loading machine to obtain average mid-span deflection of each plate.

2.3 Test Results

Figure 2(a) shows the load-midspan deflection response for Plates S1-S12. Compared to the response of the control plates, Plates S3 to S8 indicated significant influence of predamage on the strength and the initial stiffness. Figure 2(b) summarizes the observed and predicted reduction ratio of initial stiffness and strength [2,5]. The reduction in strength tends to increase with increasing precrack angle until the angle approaches 70°, and then begins to decrease. The initial stiffness rises with increasing precrack angle up to 90°.

Figure 3 shows the typical cracking pattern of control and main plates after failure. The control plates showed multiple cracks across the plate width as the applied principal tensile stress direction remained along the plate longitudinal direction during the whole course of the test. The main plates subjected to principal stress rotation showed a nearly orthogonal crack pattern, consisting of pre- and secondary-cracks. Unlike the pre-cracks, the secondary cracks did not form orthogonal to the second principal stress direction, but formed somewhat orthogonal to the pre-cracks (<15° deviation). This nearly orthogonal crack pattern suggests
the occurrence of strong anisotropy due to limited stress transfer along the pre-cracks and hence no secondary cracks formed across the plate width.

3. NUMERICAL MODELING

3.1 Modelling of ECC and R/ECC in a Space-averaged Approach

Cracked ECC is treated as an anisotropic material that the behaviour can be represented by their fundamental responses under compression, tension, and shear. The RC models described in Maekawa et al [6] were used as the base models. All formulations describing monotonic response were modified, while those describing cyclic response were directly adopted. The summary is given herein, with more details described in [3].

A simple elastic-plastic model is adopted to represent the behaviour of reinforcement embedded in ECC. The hysteretic response of the reinforcement is modelled after Kato [7]. The modelling of cracked ECC in compression is based on the elasto-plastic model for cracked concrete, with the strain corresponding to the compressive strength $\varepsilon_R$ shifted from a
typical value of about 0.2% to 0.5% for concrete and ECC, respectively [see Fig. 4(a)]. The weakening effects of transverse cracking are accounted by a reduction factor \( \omega \) [Fig. 4(d)].

The modelling of cracked ECC in tension adopts a tri-linear model [see Fig. 4(b)]. The weakening effects of transverse cracking are accounted by a reduction factor \( \omega \) shown in Fig. 4(e), which was approximated from the bending strengths of Plates S13 to S18.

The modelling of shear transfer adopts the shear transfer model for concrete (see Fig. 4(c), [6]). A reduction coefficient \( A = 0.25 \) is introduced to the model to reflect weaker shear transfer resistance of ECC than aggregate interlock. Two components considered to contribute for shear transfer: shear friction and fibre bridging. It is postulated that the contribution of shear friction gradually diminishes from ultimate shear strain \( \gamma_u \), while that of the fibre bridging remains. This is treated as a shear softening phenomenon and is represented with a decay function in which the steepness is controlled with a softening parameter \( c \). For PVA-ECC with \( V_f = 2\% \), \( \gamma_u = 1 \) and \( 4 \, K_u \), for ECC and R/ECC, respectively, and \( c = 0.4 \). Figure 4(f) illustrates the proposed shear transfer response for various values of \( \epsilon_c \).

![Figure 4](image.png)

**Figure 4:** Material models for ECC in the context of space-average, fixed crack approach

**3.2 ECC under reversed loading (no rotation of principal stress axis) [3]**

Figure 5(a) presents the computed response of an element subjected to reverse cyclic loading, plotted against the response of 50 mm-dia cylinder tested by Kesner et al [9]. Figure 5(b) compares the predicted and observed response of a 21-mm-thick ECC plate that was tested in a four-point bending, with clear and constant moment spans of 340 and 170 mm, respectively. As seen, the correlation of both predicted and observed responses is good.
3.3 Pre-cracked ECC Plates subjected to Principal Stress Rotation [3,5]

Figure 6(b) and (c) shows the load-displacement relation during Loading Stages 1 and 2, respectively with pre-loading done as that in the experiment [see Fig. 1(b)], while Figure 6(e) compares the predicted and observed average strains from the plate soffit. The x-dir in the x-y coordinates is set along the direction of pre-crack opening. As can be seen, the analysis fairly simulates the load-displacement curve (including initial stiffness, shape, and strength) and replicates the average strains representing the kinematics of bi-directional multiple cracks.
well. This verifies the applicability of the models to account for previous loading history and pre-existing damage to the remaining responses.

3.4 R/ECC Panels subjected to Pure Shear [4]

Figure 7 compares the predicted and observed response of five R/ECC panels tested by Xoxa [10]. As shown, the proposed models are capable of replicating various responses of the panels, provided that tensile property of the ECC is calibrated against those obtained from the panel tests [see Fig. 7(a) and (b)]. Successful replications of the responses of Panels 1 to 3 verify the accuracy of the proposed ECC compression and tension models, while those of Panels 4 to 6 confirm the applicability of the proposed shear models. In regard to the latter, it demonstrates that an explicit representation of shear transfer of PVA-ECC is achievable.

Figure 7: Comparison of the predicted and observed responses of selected pre-cracked plates

Figure 8: Predicted and observed response of PVA-ECC Beams without and with web rebars
3.5 R/ECC Shear-critical Beams [3]

Figure 8 compares the predicted and observed response of two shear-critical R/ECC beams tested by Kanda et al [11], without and with web reinforcement. Two tensile properties were considered: model 1 resembled that of coupon tests, and model 2 was a reduced property. The prediction with the former property overestimate strength and stiffness, while that with the latter gives a better estimate and confirms the applicability of the proposed models.

4. IMPROVEMENT OF CRACK-SHEAR TRANSFER

An attempt to improve shear-transfer property of ECC is presented in a companion paper [12]. Figure 9 shows the cracking pattern for plates pre-cracked at 45° containing no and 10% of coarse aggregate by volume. The addition of aggregate shows a potential to control the orientation of secondary, multiple cracks to form orthogonal to the new stress direction.

5. CONCLUSIONS

- Cracked SHCC is an anisotropic material that exhibits behavioral changes depending on the orientation of precracks and the extent of predamage. This anisotropic behavior was observed from orthogonal crack pattern regardless of the rotation of principal stress axes.
- Smeared crack models for PVA-ECC with an explicit shear-transfer model were proposed. Their applicability to account for previous loading history and existing damage and to account them for the remaining response is presented at material and structural levels. Accurate predictions of load and deformation responses were obtained.
- The addition of coarse aggregate in PVA-ECC shows a potential to control new multiple cracks to form nearly orthogonal to the latest principal stress angle.

REFERENCES