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Modelling the performance of ECC repair systems under differential volume changes

Jian Zhou
Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Mo Li
Advanced Civil Engineering Materials Research Laboratory (ACE-MRL),
Department of Civil and Environmental Engineering, University of Michigan, USA

Guang Ye, Erik Schlangen & Klaas van Breugel
Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Victor C. Li
Advanced Civil Engineering Materials Research Laboratory (ACE-MRL),
Department of Civil and Environmental Engineering, University of Michigan, USA

ABSTRACT: An ultra ductile material, known as Engineered Cementitious Composite (ECC), has been proposed to be one of most promising repair materials. An analytical model was developed to calculate the stresses in ECC repair system under differential volume changes. With this model, the performance of ECC repair system was investigated. In an ECC repair system, although the shrinkage of ECC increases dramatically after the first cracking of ECC, the stress increases only by a small amount. It can be expected that the use of ECC can reduce the potential of repair material failure in tension and interface delamination and therefore enhance the durability of repair systems.

1 INTRODUCTION

Most materials used in concrete repairs have a tendency to deform due to shrinkage, heat release at early age and ambient temperature change. The restraint of these deformations by substrate concrete induces stresses in repair systems. The stresses can lead to vertical cracking through the thickness of the repair material, peeling of the repair material from the substrate concrete and/or delamination of the interface. Moreover, the repair material cracking and the interface delamination accelerate the penetration of water, oxygen, chlorides, alkalis or sulphates into repair system. This can cause reinforcement corrosion or concrete deterioration. Finally, the concrete repair fails and the repair of concrete repair must be carried out.

ECC has been proposed to be one of the most promising repair materials (Li 2004). It is a micromechanically designed cement-based material reinforced with short random fibres. Unlike common cement-based materials ECC shows tensile strain-hardening behaviour with strain capacity in the range of 3–7%, which is hundreds of times of the strain capacity of common cement-based materials. The high ductility of ECC is achieved by multiple cracking with crack width self-limited to about 60 μm. Figure 1 shows a typical tensile stress-strain curve of ECC. When ECC is used as repair material, the multiple cracking can release stresses in repair systems induced by differential volume changes. In other words, the large differential volume change in ECC results in only a

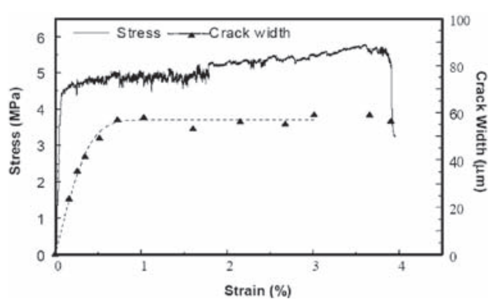

Figure 1. The tensile stress-strain curve of ECC (Li 2003).

small increase in stresses. The risk of repair material in tension and interface delamination is therefore reduced. Meanwhile, the crack width in ECC under service condition is typically less than 80 μm, which is much smaller than the crack width in normal concrete under tensile load (Lepech & Li 2005). It can be expect that the use of ECC can enhance the durability of concrete repairs. This phenomenon has been demonstrated both in the laboratory (Li & Li 2005) and in the field (Lepech & Li 2006).

An analytical model (Zhou et al. 2007, 2008) was developed based on the classical plate theory and the assumption of the linear relation of shear stress and slip at interface. This model was successfully used to calculate the stresses and strains in repair systems subject to differential volume changes. In this paper, this model will be further developed to estimate the performance of ECC repair systems under differential volume changes. The modelling results, with comparisons to experimental observations, are reported here.

2 MODEL DEVELOPMENT

An analytical model was developed based on the classical plate theory and the assumption of the linear relation between shear stress and slip at the interface (Zhou et al. 2007, 2008). This model can be used to calculate the stress and strain in the concrete repairs subjected to differential volume changes. The procedure of model development can be divided into four stages. Take the case of the differential shrinkage as an example, which is shown in Figure 2. Firstly, the repair material was assumed to be separated from the substrate concrete. The shrinkage of the repair material was restrained at the ends, and a tensile stress $\sigma_{sh}(y) = E_r \times \varepsilon_{sh}(y)$ was thus induced in the repair material, where $\varepsilon_{sh}(y)$ is the shrinkage of repair material and E_r is the elastic modulus of repair material. Secondly, the repair material was bonded on the substrate concrete. For the equilibrium of the repair system, a compressive stress $-\sigma_{sh}(y)$ was then applied at the ends of the repair material. This stress was simplified to

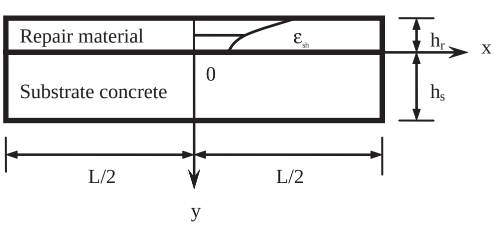

Figure 2. Concrete repair subjected to differential shrinkage.

be constant through the depth of the repair material, which can be written as $\sigma_{eq} = -\frac{1}{h_r}\int_{h_r}^{0} E_r\varepsilon_{sh}(y)dy$, where h_r is the thickness of repair material. Thirdly, the stresses and strains in the repair system subjected to the external stress σ_{eq} were calculated based on the plate theory and the assumption of the linear relation between shear stress and slip at the interface. Last, the restrained shrinkage stress $\sigma_{sh}(y)$ was superimposed to the stress in the repair material calculated in the third stage. According to this model, the highest tensile stress σ_{xx} in the repair material is situated at the middle of the bottom, and the highest peeling stress σ_{yy} and shear stress σ_{xy} at the interface are situated at the two ends. The maximum values of the stresses can be calculated by the following equations:

$$\sigma_{xx} = \frac{E_r\varepsilon_{sh}}{1+\frac{E_r h_r}{E_s h_s}}\left(1-\frac{2}{e^{\lambda\frac{L}{2}}+e^{-\lambda\frac{L}{2}}}\right) \quad (1a)$$

$$\sigma_{yy} = \frac{E_r\varepsilon_{sh}}{\frac{1}{\lambda h_r}-\frac{E_r}{E_s}}\left(1-\frac{e^{\lambda L}-1}{e^{\lambda L}+1}\frac{2}{\lambda L}\right) \quad (1b)$$

$$\sigma_{xy} = \frac{E_r\varepsilon_{sh}\lambda h_r}{1+\frac{E_r h_r}{E_s h_s}}\frac{e^{\lambda L}-1}{e^{\lambda L}+1} \quad (1c)$$

where, $\lambda = \sqrt{\frac{K}{E_r h_r}+\frac{K}{E_s h_s}}$, E_s = the elastic modulus of substrate concrete, h_s = the thickness of substrate concrete, K = the shear stiffness of interface and L = the length of repair system.

In essence, the stresses induced by temperature change can be treated similarly as those induced by the differential shrinkage. The stresses induced by temperature change can be calculated with Equations 1 by replacing ε_{sh} with $(\alpha_r - \alpha_s) \times \Delta T$, where α_r is the thermal expansion coefficient of the repair material, α_s is the thermal expansion coefficient of the substrate concrete and ΔT is the temperature change.

As shown in Figure 1, ECC, under tensile load, behaves differently before and after the first cracking which corresponds to the bend-over point in the tensile stress-strain curve. Accordingly, the tensile stress-strain curve of ECC can be divided into two parts. When the stress is lower than the first cracking strength σ_{fc}, ECC behaves like common cement-based materials. When the stress is between the first cracking strength σ_{fc} and the ultimate strength σ_{cu}, ECC shows strain-hardening behaviour. In terms of structural response, the unique behaviour of ECC can be reflected by using the different elastic moduli

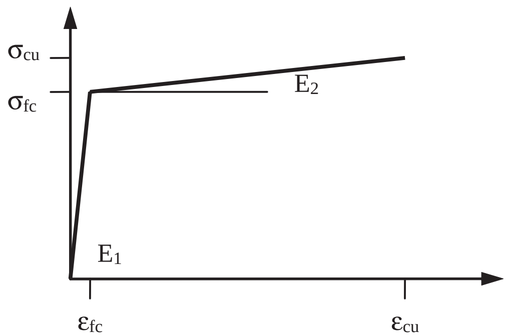

Figure 3. The simplified stress-strain curve of ECC.

before and after first cracking. The stress-strain curve can be simplified as shown in Figure 3.

The calculation of stresses in the ECC repair system was divided into two stages. In the first stage, i.e. when the tensile stress in ECC is smaller than the first cracking strength of ECC, as the differential volume change increases, the stresses in ECC repair system increase. The stresses can be calculated by using Equations 1 with the elastic modulus of ECC of E_1. The critical value of the differential volume change ε_{fc} corresponding to the stresses leading to the first cracking of ECC can be calculated with the following equation:

$$\sigma_{xx}^1 = \frac{E_1\varepsilon_{fc}}{1+\frac{E_1h_r}{E_sh_s}}\left(1-\frac{2}{e^{\lambda_1\frac{L}{2}}+e^{-\lambda_1\frac{L}{2}}}\right)=\sigma_{fc} \tag{2a}$$

where $\lambda_1=\sqrt{\frac{K}{E_1h_r}+\frac{K}{E_sh_s}}$ With the calculated value of differential volume change ε_{fc}, the maximums of stresses at interface can be calculated by:

$$\sigma_{yy}^1 = \frac{E_1\varepsilon_{fc}}{\frac{1}{\lambda_1h_r}-\frac{E_1}{E_s}}\left(1-\frac{e^{\lambda_1L}-1}{e^{\lambda_1L}+1}\frac{2}{\lambda_1L}\right) \tag{2b}$$

$$\sigma_{xy}^1 = \frac{E_1\varepsilon_{fc}\lambda_1h_r}{1+\frac{E_1h_r}{E_sh_s}}\frac{e^{\lambda_1L}-1}{e^{\lambda_1L}+1} \tag{2c}$$

Once the tensile stress in ECC is higher than the first cracking strength of ECC, ECC cracks and the calculation enters the second stage. It was assumed that the whole ECC layer goes into the strain-hardening stage after the first cracking, and the stress-strain gradient is E_2. The stresses induced by the increase in the differential volume change from ε_{fc} to ε_{sh} can be calculated by:

$$\sigma_{xx}^2 = \frac{E_2(\varepsilon_{sh}-\varepsilon_{fc})}{1+\frac{E_2h_r}{E_sh_s}}\left(1-\frac{2}{e^{\lambda_2\frac{L}{2}}+e^{-\lambda_2\frac{L}{2}}}\right) \tag{3a}$$

$$\sigma_{yy}^2 = \frac{E_2(\varepsilon_{sh}-\varepsilon_{fc})}{\frac{1}{\lambda_2h_r}-\frac{E_2}{E_s}}\left(1-\frac{e^{\lambda_2L}-1}{e^{\lambda_2L}+1}\frac{2}{\lambda_2L}\right) \tag{3b}$$

$$\sigma_{xy}^2 = \frac{E_2(\varepsilon_{sh}-\varepsilon_{fc})\lambda_2h_r}{1+\frac{E_2h_r}{E_sh_s}}\frac{e^{\lambda_2L}-1}{e^{\lambda_2L}+1} \tag{3c}$$

where $\lambda_2=\sqrt{\frac{K}{E_2h_r}+\frac{K}{E_sh_s}}$.

By superimposing the stresses calculated in these two stages, the stresses in ECC repair system induced by the differential volume change can be determined by the following equations:

$$\sigma_{xx}=\sigma_{xx}^1+\sigma_{xx}^2 \tag{4a}$$

$$\sigma_{yy}=\sigma_{yy}^1+\sigma_{yy}^2 \tag{4b}$$

$$\sigma_{xy}=\sigma_{xy}^1+\sigma_{xy}^2 \tag{4c}$$

3 SIMULATION

Layered ECC repair systems were experimentally investigated (Li & Li 2005). In the layered repair systems, a layer of ECC repair material with the thickness of 50 mm was bonded on the top concrete substrate with the thickness of 100 mm as shown in Figure 4. The length of repair system was 1560 mm, and the width of repair system was 100 mm. The concrete substrates were moisture-cured until the age of 28 days, and then left to dry in ambient condition for another 60 days before the repair materials were placed. The additional 60-day curing was for the purpose of allowing most potential shrinkage in the substrates to occur before placing the repair materials. The contact surfaces of the concrete substrates were roughened to 7~8 mm. The substrate surfaces were roughened in fresh state using a chisel to remove slurry cement from external surfaces of coarse aggregates. Before

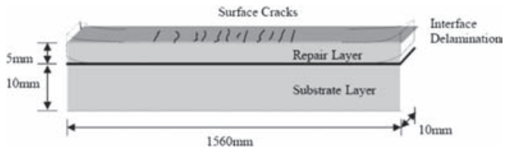

Figure 4. The layered repair system.

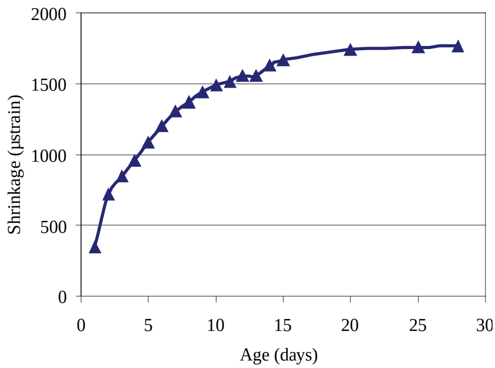

Figure 5. Free shrinkage of ECC in the ambient condition of 15–21°C and 25–55% RH.

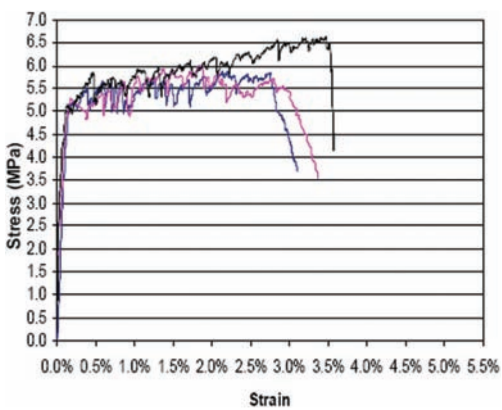

Figure 6. The tensile stress-strain curve of ECC at 28 days.

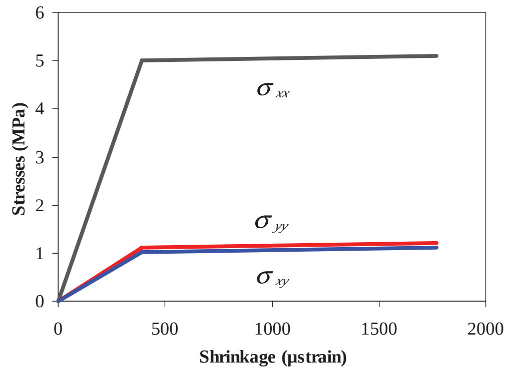

Figure 7. The stresses in ECC repair system at 28 days calculated with Equations 4.

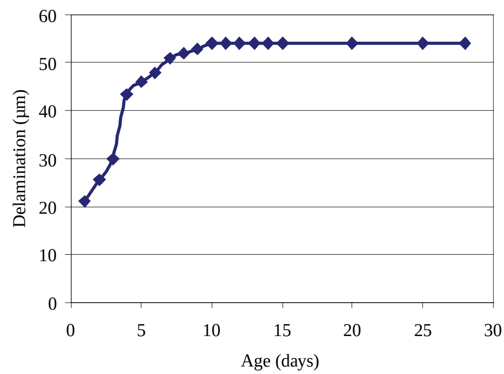

Figure 8. Interface delamination opening at the ends of ECC repair system.

placing the repair layers, the substrate surfaces were cleaned with a brush and high-pressure air to ensure a clean bonding surface, and then they were damped to an adequate moisture level. The repair materials were moisture cured for 24 hours and then demoulded. After demoulding, the specimens were moved into a room with the ambient condition of 15–21°C and 25–55% RH. Two dial gauges were used to measure the opening of interface delamination at the ends of specimens. The modulus of elasticity of concrete substrate was measured under compression at 28 days, and the value was 26,000 MPa. Free shrinkage tests on ECC were carried out according to ASTM C157/C157-99 and ASTM C596-01 standards, except that the storing and testing condition of the specimens was set to be exactly the same as the layered specimens. Figure 5 shows the free shrinkage of ECC in the first 28 days. The uniaxial tensile tests of ECC were also carried out at 28 days as shown in Figure 6. The tensile strain capacity of ECC was higher than 2.5%. The measured first cracking of ECC was averaged to be 5.0 MPa, and the measured ultimate strength was averaged to be 6.0 MPa. The modulus of elasticity before the first cracking was 20,000 MPa and the stress-strain gradient after the first cracking was 40.4 MPa.

The material properties measured from experiments were used as input in the calculation of stresses in ECC repair systems by using Equations 2–4. The shear stiffness of interface K was assumed to be 10 N/(mm$^2 \times$ mm) (Ackermann 1993). Figure 7 shows the calculated results. When the shrinkage of ECC

Figure 9. Experimentally observed surface cracking of ECC repair layer. This picture shows a half of ECC repair system. The blue marks indicate the cracks with the width between 40 μm and 60 μm, and the black marks indicate the cracks with the width smaller than 40 μm.

increases to 392 μstrain, the tensile stress in ECC reaches the first cracking stress of 5.0 MPa. After the first cracking, although the shrinkage increases around 3.5 times, the stresses in ECC repair system only increases a little bit. This is because of the low stress-strain gradient in strain-hardening stage. The experiments show the same phenomena. As the shrinkage increases 85% after 4 days as shown in Figure 5, the interface delamination opening increases 24% as shown in Figure 8. The final tensile strain of ECC was calculated to be 0.18%, which is much smaller than the tensile strain capacity of ECC of 2.5%. It means that ECC cracks but does not fail in tension under the relatively high differential shrinkage. In the experiment, many cracks were also observed with the crack width in the range of 10–60 μm as shown in Figure 9.

4 CONCLUSIONS

An analytical model was developed to calculate the stresses in ECC repair systems according to the bilinear behaviour of ECC under uniaxial tensile load. With this model, the performance of ECC repair systems was investigated. In ECC repair systems, the increase in the shrinkage after the cracking of ECC results in only a small increase in stresses. Although ECC has relatively high drying shrinkage compare to normal concrete, the tensile strain remains much smaller than its tensile strain capacity. It can be expect that the use of ECC can reduce the potential of the repair material failure in tension and interface delamination and therefore enhance the durability of repair systems.

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