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Numerical modelling on degradation of mechanical behaviour for engineered cementitious composites under fatigue tensile loading

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A B S T R A C T

A multiscale modelling framework is developed in this paper for analysing the degradation of mechanical behaviour of Engineered Cementitious Composites (ECCs) under fatigue tensile loading. Degradation models for calibrating fatigue-induced deterioration of the fibre-matrix interface and fibre fatigue rupture are proposed at the microscale. Based on these, the cycle-dependent crack bridging relation is derived at the mesoscale. At the macroscale, the degradation behaviour of the bridging stress in ECC with presence of multiple cracks is modelled using extended finite element method. This multiscale characterisation method is validated by comparing the computed degradation relation of the bridging stress to that obtained from the experiment. Good agreement is obtained, which demonstrates the effectiveness of the developed multiscale modelling framework for the analysis of fatigue behaviour of ECCs. In addition, the deterioration of the fibre-matrix interface is found to be responsible for a steady decreasing bridging stress, while the fibre fatigue rupture is found to contribute to an accelerated loss of bridging stress.

1. Introduction

Engineered Cementitious Composites (ECCs), featuring superior tensile strain-hardening capacity with a moderate fibre content, are a relatively new and unique member of the High Performance Fibre Reinforced Cementitious Composites (HPFRCCs). For instance, ECCs reinforced with no more than 2% by volume fraction of polyethylene (PE) fibres or polyvinyl alcohol (PVA) fibres can attain a tensile strain capacity up to 3–6% [1,2]. In addition, ECCs develop multiple closely-spaced microcracking in tension and the crack width is normally self-controlled below 100 μm. Ultra-tight crack widths as narrow as 20 μm have been observed in ECCs containing high volume fly ash [3]. ECCs demonstrate remarkable energy absorption capability and damage tolerance, and the tight crack width also implies an exceptional durability [4]. Therefore, ECCs are very promising construction and building materials for a broad range of applications. In particular, ECCs are finding applications in structures which are subjected to fatigue loading, such as the link slab on the bridge deck [5,6] and the overlay for the deteriorated concrete pavement [7,8]. Thus a thorough understanding of the mechanical behaviour of ECCs under fatigue loading is indispensable.

The mechanical behaviour as well as the structural performance of ECCs under static loading conditions have been investigated extensively. However, few studies on their mechanical behaviour and the failure mechanisms under fatigue loading

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Nomenclature

β_1	slip-hardening coefficient at the 1st cycle
β_N	slip-hardening coefficient at the Nth cycle
d_f	fibre diameter
E_f	Young's modulus of fibre
E_m	Young's modulus of matrix
f_1	fibre snubbing coefficient at the 1st cycle
f_N	fibre snubbing coefficient at the Nth cycle
f'	fibre strength reduction coefficient applicable to inclined fibres
G_f	Shear modulus of fibre
θ	inclination angle of fibre
k_{fr}	degradation coefficient of the frictional bond
k_{fu}	degradation coefficient of the fibre strength
L_f	fibre length
l_e	fibre embedment length
N	number of loading cycles
V_f	fibre volume fraction
δ	crack opening displacement
δ_{AC}	accumulated change of the crack opening displacement
δ_{max}	the maximum crack opening displacement during a cyclic loading
δ_{min}	the minimum crack opening displacement during a cyclic loading
δ_N^*	crack opening displacement at full debonding
τ_1	interfacial frictional bond strength at the 1st cycle
τ_N	interfacial frictional bond strength at the Nth cycle
σ_{bN}	single-fibre bridge stress at the Nth cycle
$(\sigma_{fu})_1$	fibre strength at the 1st cycle
$(\sigma_{fu})_N$	fibre strength at the Nth cycle
σ_N	integrated fibre bridging stress at the Nth cycle
z	distance from the fibre centroid to the crack plane

conditions were reported. Suthiwarapirak et al. [9,10] studied the flexural fatigue behaviour of ECCs. Four-point fatigue flexure tests were conducted on the PE-ECC, PVA-ECC and an ordinary steel fibre reinforced cementitious composite (S-FRC) for comparison. It was found that ECCs demonstrated significantly prolonged fatigue life at higher stress levels compared to the S-FRC. The fatigue life of the ordinary S-FRC was merely equal to the number of cycles taken to first cracking, as the failure took place immediately after the first cracking. However, the fatigue life of ECCs amounted to the total number of cycles spent on initiating and developing a number of cracks until one of them leaded to failure. As a result, the number of cracks that can be formed under fatigue loading is an important factor affecting the fatigue behaviour of ECCs. The studies also showed that the fatigue behaviour of ECCs could be influenced by the fibre failure mode as well. As the PVA fibre has lower tensile strength but much stronger bonding to the cementitious matrix than the PE fibre, the PVA fibre tended to fail by rupture rather than pullout. Therefore, while the PE-ECC exhibited fibre pullout-dominant failure under both static and fatigue loadings, the PVA-ECC exhibited fibre rupture-dominant failure with poorer fatigue resistance at lower stress levels [10]. Tension and tension-compression fatigue behaviour of ECCs were investigated by Matsumoto et al. [11,12]. Instead of a constant stress amplitude, uniaxial fatigue tension/tension-compression tests were conducted under a constant strain amplitude. The tensile stress at the maximum strain level against the number of cycles was obtained. The tensile stress was found to decrease continuously with the increase of loading cycles. As the tensile stress across the crack is carried by the bridging fibre, the decrease of the tensile stress indicates the degradation of the fibre bridging ability.

The fatigue-induced deterioration of the fibre bridging mainly due to the persistent fibre-matrix interface damage and fibre fatigue rupture [13]. Under fatigue loading, the fibre slides back and forth along the tunnel and as a result the interface is progressively smoothed and worn out, leading to a decay of the interfacial friction. Under fatigue loading the fibre may also break even when the tensile stress of the fibre has not reached the tensile strength of the fibre. Consequently, the crack bridging stress decreases with the increase of loading cycles. The fatigue-induced degradation of the bridging stress is an important feature for materials that exhibit crack bridging. The overall degradation rate of the bridging stress with multiple cracks is defined as the degradation relation of the bridging stress of an ECC [13]. As mentioned, the microscopic changes have eventually caused the changes in mechanical properties at the macroscope.

A few studies on the fatigue behaviour of fibre reinforced cementitious composites based on the microscopic changes have been conducted. Zhang et al. [14] studied the cyclic crack bridging behaviour of steel fibre reinforced concrete and