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Fatigue crack propagation at concrete–concrete bi-material interfaces

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ABSTRACT

This paper presents experimental and analytical studies on fatigue crack propagation in concrete–concrete cold jointed interface specimens. Beams of different sizes having jointed interface between two concretes with different elastic properties are tested under fatigue loading. The acoustic emission technique is used for monitoring the fatigue crack growth. It is observed that the interface having a higher moduli mismatch tends to behave in a brittle manner. The CMOD compliances at different loading cycles are measured and the equivalent crack lengths are determined from a finite element analysis. An analytical model for crack growth rate is proposed using the concepts of the dimensional analysis.

1. Introduction

Understanding of the fatigue behavior of cementitious materials has become a major concern for major infrastructures such as long-span bridges, offshore structures, and airport pavements, which are subjected to repetitive loads either through vehicular traffic or wind and wave loadings. Repetitive/cyclic nature of loading induces internal, permanent, micro-structural changes in the material resulting in deterioration of strength and stiffness. Since replacement of an existing structure is not always feasible and cost-effective, a repair is normally done which may involve the application of fresh material over the parent material, thereby, creating an interface. Furthermore, in large concrete structures involving mass concreting, constructions are carried out in many stages leading to the formation of a cold jointed interface between successive lifts of concrete.

An interface is considered to be one of the weakest zone in comparison with the parent and newly applied material and is more prone to crack propagation due to the mismatch in modulus of elasticity between two different materials on either sides of it. The performance of the repaired system under loading is strongly dependent on the performance of the interface. To ensure that such repaired systems have adequate service life, care should be taken to achieve good compatibility between the materials involved to resist to mechanical and chemical loading [1].

Interfacial crack propagation has been studied by Slowik et al. [2] through experimental investigations wherein the mixed mode response of rock–concrete bimaterial specimens simulating a dam-foundation interface is evaluated. The tests were carried out by subjecting the specimens to a complex stress field similar to the ones observed in a gravity dam. One of the important conclusions drawn was that an interface crack has a tendency to kink into the adjoining material when subjected to mixed mode type of loading.

To extract the fracture properties, Cervenka et al. [3] have performed a numerical study on the same bi-material specimen using both linear and non-linear fracture mechanics concepts. Puntel et al. [4] developed a model by modifying the one proposed by Cervenka et al. [3], to account for cyclic loading in combination with an asperity based frictional model. This model can be implemented in finite element codes which are based on either discrete or smeared crack approaches. Kunieda et al. [5] have applied tension softening diagrams to evaluate the bond properties at the interface between old and new concrete. Chandra Kishen and Rao [6] have experimentally investigated the fracture behavior of concrete–concrete transverse jointed interface specimens under monotonic loading.

Most of the work related to cementitious interfaces that are available in the literature are based on understanding the mechanical behavior under static loading. Research works on experimental and analytical studies on concrete–concrete bimaterial interface under fatigue loading are scarce in the literature. Hence, in this work, an extensive experimental investigation is carried out on various types of bimaterial interface specimens subjected to

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fatigue loading, and crack propagation is monitored along the interface using the acoustic emission (AE) technique. An analytical model is developed to compute the fatigue crack growth rate at such interfaces by using the concepts of dimensional analysis in conjunction with the theory of fracture mechanics. The crack growth law would be useful in evaluating the fatigue life of structures having jointed interfaces.

2. Interface crack propagation

Unlike the use of conventional stress intensity factor K_I in an homogeneous material, the state of stress at the tip of an interface crack is inherently mixed mode. Due to mismatch in the elastic properties of the two materials on either sides of the interface, symmetry is disrupted even though the geometry of the body is symmetric. An interface crack tip is subjected to both in-plane normal and shearing tractions although pure Mode I loading is applied. The observed mode I and mode II stress fields at the interfacial crack tip cannot be decoupled to represent normal and shear stresses respectively, since the ratio of stress fields is dependent both on the distance ahead of the crack tip and the elastic mismatch factor of the interface [7,8].

Under linear elastic conditions, unlike the homogeneous case wherein the stresses near the crack tip show an inverse square root singularity ($\sigma \sim r^{-\frac{1}{2}}$), the stresses near an open interface crack behave in an oscillatory manner. The oscillatory singularity at a distance r from the crack tip is characterized by $r^{-\frac{1}{2}+\epsilon}$, where ϵ is referred to as oscillation index defined as a function of material constants [9]. The nature of stresses leads to inter-penetrating crack surfaces in a small zone behind the crack tip, and the analytical solutions near the crack tip are found to be inadmissible [10,11].

Considering a crack along an interface of two dissimilar linear elastic isotropic materials shown in Fig. 1, the near tip normal and shear stresses can be expressed as follows [7]:

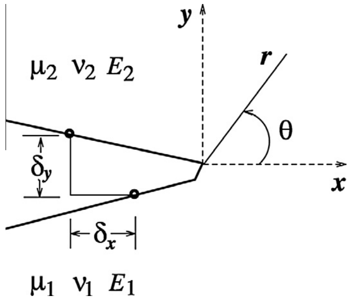

Fig. 1. Geometry of an interface crack.

$$\sigma_{yy} + i\sigma_{xx} = \frac{K}{\sqrt{2\pi r}} r^{i\epsilon} \tag{1}$$

where $K = K_1 + iK_2$ is the stress intensity factor at the interface crack tip and $i = \sqrt{-1}$. The expressions for the bi-material stress intensity factors K_1 and K_2 are given in Ref. [10]:

$$K_1 = \frac{\sigma[\cos(\epsilon \log 2a) + 2\epsilon \sin(\epsilon \log 2a)] + \tau[\sin(\epsilon \log 2a) - 2\epsilon \cos(\epsilon \log 2a)]}{\cosh \pi\epsilon} \sqrt{a} \tag{2}$$

$$K_2 = \frac{\tau[\cos(\epsilon \log 2a) + 2\epsilon \sin(\epsilon \log 2a)] - \sigma[\sin(\epsilon \log 2a) - 2\epsilon \cos(\epsilon \log 2a)]}{\cosh \pi\epsilon} \sqrt{a} \tag{3}$$

where σ and τ are the normal and shear stresses acting along the interface. The oscillation index ϵ has been defined in terms of Dunders' elastic mismatch parameter β [12]:

$$\epsilon = \frac{1}{2\pi} ln \left[\frac{1-\beta}{1+\beta}\right] \tag{4}$$

Dunders [12] has defined two elastic mismatch parameters β and α depending on the material properties:

$$\beta = \frac{\mu_1(1-2\nu_2) - \mu_2(1-2\nu_1)}{2[\mu_1(1-\nu_2) + \mu_2(1-\nu_1)]} \tag{5}$$

where μ and ν are the shear modulus and Poisson's ratio, respectively, and 1 and 2 denote material 1 and material 2, respectively (as is shown in Fig. 1):

$$\alpha = \frac{\overline{E_1} - \overline{E_2}}{\overline{E_1} + \overline{E_2}} \tag{6}$$

α provides the measure of relative stiffness of the two materials, and $\overline{E}$ denotes the modulus of elasticity for plain strain case.

3. Experimental program

The beam specimens are prepared using standard Portland cement (specific gravity of 3.15), river sand (passing through 4.75 mm sieve, specific gravity of 2.67 and fineness modulus of 2.37) and crushed granite aggregates (having maximum size of 12 mm and specific gravity of 2.78). Four different types of concrete mixes are designed and designated as mix A, B, C and D. The details of mix proportions are shown in Table 1.

Geometrically similar notched beams of three different sizes having span to depth ratio (S/D) of 2.5, notch to depth ratio (a_0/D) of 0.2 and notch width of 2 mm are casted. The details of beam geometry are reported in Table 2. The following procedure is adopted for preparation of interface specimens: on day one, the first-half of the beam is casted with mix A. On day two, the interface is cleaned with a water jet and is kept exposed for 24 h. A notch is introduced at the interface during the casting process itself by inserting a wooden strip of 2 mm thickness. On day three, the

Table 1
Details of mix proportion.

Sl. no.	Mix designation	Cement quantity (kg/m^3)	Mix proportion C:FA:CA:w/c	Compressive strength (N/mm^2)	Poissons' ratio	Elastic modulus N/mm^2
1	A	385.19	1:1.86:2.61:0.54	34	0.20	30,000
2	B	495.24	1:1.22:2.03:0.42	45	0.19	32,000
3	C	547.37	1:1.01:1.83:0.38	54	0.18	34,000
4	D	650.00	1:0.69:1.54:0.32	66	0.17	35,000

Table 2
Geometry details of beam specimens [24].

Specimen type	Depth D (mm)	Span S (mm)	Thickness B (mm)	Notch Size$a$ (mm)
Small	76	190	50	15.2
Medium	152	380	50	30.4
Large	304	760	50	60.8