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Characterization of fatigue crack growth of concrete mortar under cyclic indentation loading

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ABSTRACT

This study establishes a computational model for contact fractures in concrete mortar subjected to both monotonic and cyclic contact loadings. We perform experiments using monotonic and cyclic indentation tests with a ball indenter (*i.e.*, cyclic spherical indentation). During the tests, the acoustic emission (AE) method is utilized to detect micro-scale damage in contact fractures. For monotonic contact loading, we determine the critical contact load when the radial crack initiates. It is found that radial cracks occur outside the contact zone (outside of the impression crater). Next, cyclic contact loading is performed, and it is found that the crack propagates with the increasing number of cycles. This fatigue crack growth can be captured by the AE method. In addition, a finite element method (FEM) is used to elucidate the stress distribution of crack initiation and crack propagation during both indentation loadings. FEM computation with a damage-based cohesive zone model (CZM) is carried out to simulate crack growth during cyclic indentation tests. The cohesive model follows a linear damage-dependent traction–separation relationship coupled with a damage evolution equation. It is found that our computation successfully simulates fatigue crack growth. By using the comprehensive experimental/computational framework, the nucleation process (mechanism) of such a complicated crack system is clarified. This methodology may be useful for examining crack propagation of other brittle materials under both monotonic and cyclic contact loadings.

1. Introduction

Concrete mortar and related materials are useful for withstanding compression loads for infrastructure. Significant efforts have been made to improve toughening mechanisms, which will contribute to improving the fracture toughness of concrete mortar [1–4]. These studies found that stable cracks propagate during cyclic loading. Therefore, a simple mechanical model may be required to predict the structural integrity and develop better compositions of microstructures. In fact, sub-critical crack growth associated with cyclic loadings occurs often in concrete structures for a variety of reasons, such as freeze-thaw cycles [3], mechanical loading by traffic, and wind wave loading. Their loading level is below the critical failure load of monotonic loading. Thus, such stable crack propagation is recognized to be fatigue cracking. Fatigue crack propagation results in deterioration of rigidity and strength, leading to substantial failure of entire concrete structures. Thus, if concrete mortar behaves like a brittle solid having low fracture toughness, assessment of fatigue crack initiation and propagation are important.

Since concrete structures have higher compressive resistance, the mechanical conditions of contact and concentric loading may also be important. Indentation loading onto brittle solids generally induces contact fracture, which is similar to impact and foreign

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object damage [5,6]; such damage leads to deterioration of strength and stiffness of entire structures. However, indentation loading induces tri-axial stress states, resulting in complicated damage. Thus, modeling of concentrated loadings onto a concrete mortar may be required from the above engineering aspect, especially when cyclic indentation loading for fatigue crack propagation is a challenge. However, such issues are less well understood in comparison to the fracture issue for monotonic indentation loading.

In this study, cyclic contact loading was applied to concrete mortar in order to investigate fatigue crack propagation. For this purpose, a cyclic indentation test was performed, and fatigue crack propagation was investigated experimentally and numerically. During the experiments, an acoustic emission (AE) method was utilized to monitor micro crack nucleation. In parallel, a finite element method (FEM) was employed to compute stress fields for crack nucleation. With this FEM, crack propagation was simulated using a cohesive zone model (CZM). For cyclic loading, accumulated damage based on the CZM was employed to simulate fatigue crack growth. Therefore, this study will propose a computational model that simulates fatigue crack growth during cyclic indentation tests.

2. Materials

The material used in this study was concrete mortar. The ratio of the concrete mixture was 57% river sand, 29% cement, and 14% water. There was no coarse aggregate. For the fabrication process, concrete placing was conducted for 1 day, water curing for 7 days, and desiccating at room temperature for 14 days. The total fabrication process time was 22 days. The specimen was a cylinder with a diameter of 67 mm and a height of 50 mm. The fabrication company (U-kou Shokai Ltd., Kanagawa, Japan) reported that the porosity is approximately 2% and the uni-axial compressive strength was 24 MPa as measured by a uni-axial compression test.

3. Experimental method

Fig. 1 shows the experimental setup. Ball indentation tests were performed using an electro-hydraulic testing machine (EHF-EB50KN-10 L, Shimadzu Co.) equipped with a ball indenter and two eddy current sensors (EX-201/305, Keyence Co.). The ball indenter with a diameter of 10 mm was made of bearing steel. The indenter impressed on the specimen surface to induce contact fracture. The software for controlling the indentation tests can continuously measure the relationship between indentation force (F) and indentation depth (h) at high resolution under various testing conditions.

This study performed two types of indentation tests: a monotonic indentation test and a cyclic indentation test, as shown in Fig. 2. Fig. 2(a) shows the conventional quasi-static indentation test where the applied loading is controlled linearly with time. Fig. 2(b) shows the conventional cyclic (repeated) indentation test with constant force amplitude (ΔF constant). For both indentation tests, the maximum indentation forces $F_{\max}$ were set to 8.5 kN and 10 kN. For the monotonic indentation test, as illustrated in Fig. 2(a), the indentation force F gradually increased at a rate of $\mathrm{d}F/\mathrm{d}t = 333$ N/s up to the maximum indention force $F_{\max}$, and gradually decreased with the same $\mathrm{d}F/\mathrm{d}t$ to zero. For the cyclic indentation test, as illustrated in Fig. 2(b), a triangular wave with a 0.016 Hz frequency was applied to the specimen. The force range (ΔF) was constant with an indentation force ratio (minimum force/maximum force) of 0.1 (such that the indenter remained in contact with the coating surface). This force history was similar to the results of a conventional fatigue test and is also widely used in studies on indentation testing [7–11].

During the test, AE signals were monitored using two small AE sensors (PAC, Pico sensor), which were mounted on the top surfaces of a specimen (as shown in Fig. 1). Here, AE signals with higher amplitude than the threshold value could be recorded by the hit-count method. Furthermore, to prevent saturation of the detected signal amplitude, CH. 2 and CH. 4 were connected in parallel with CH. 1 and CH. 3, which had large amplitude range. Preamplifiers of 60 dB were used, and output signals were digitized by an A/D converter on a personal computer.

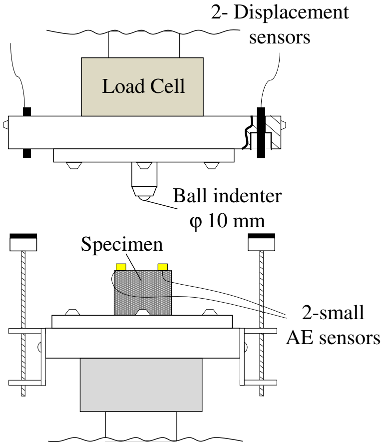

Fig. 1. Experimental setup for ball indentation tests with the AE system.