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# An experimental study on crack propagation at rock-concrete interface using digital image correlation technique

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ABSTRACT

The digital image correlation (DIC) technique is employed to investigate the fracture process at rock-concrete interfaces under three-point bending (TPB), and four-point shearing (FPS) of rock-concrete composite beams with various pre-crack positions. According to the displacement fields obtained from experiment, the crack width, and propagation length during the fracture process can be derived, providing information on the evolution of the fracture process zone (FPZ) at the interface. The results indicated that under TPB, the fracture of the rock-concrete interface is mode I dominated fracture although slight sliding displacement was also observed. Under FPS, the mode II component may increase in the case of a small notched crack length-to-depth ratio, resulting in the crack kinking into the rock. It was also observed that the FPZ length at the peak load is far longer for a specimen under FPS than under TPB.



## 1. Introduction

For concrete structures built on a rock foundation, e.g. concrete dams, the interface between concrete and rock is usually considered as the weakest structural zone, enabling cracks to initiate and propagate along the interface under the hydrostatic loading. Similar to cement-based materials, a rock-concrete interface exhibits a typical quasi-brittle behavior, i.e. there is a fracture process zone (FPZ) ahead of the interfacial crack, which features strain softening and strain localization behavior. Both the FPZ length and the crack opening displacement in the FPZ are essential parameters for characterizing the nonlinear behavior of concrete. Considering the small size of the FPZ compared with the large size of structures, some researchers [1,2] have employed linear elastic fracture mechanics to analyze the fracture behavior of rock-concrete interfaces, in which the FPZ length was ignored. However, based on the linear elastic fracture mechanics, once a crack initiates, it will immediately enter the unstable propagation stage, i.e. the nonlinear response of a structure cannot be reflected without an FPZ. Meanwhile, it is well known that fracture energy plays an important role in the fracture analysis of cementitious materials [3] and is significantly affected by the size of the FPZ [4]. By comparing the linear and nonlinear fracture methods (with/without FPZ), Červenka et al. [5] demonstrated that performing a nonlinear analysis of a cementitious material interface could increase the critical fracture energy by approximately 20% compared to a linear analysis. Therefore, with regards to the safety assessment of rock-concrete structures such as concrete dams built on a rock foundation, nonlinear fracture mechanics is more reliable for fracture analysis of a rock-concrete interface in the field.

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**Nomenclature**

| | |
|---|---|
| $a_0$ | initial crack length |
| $\Delta a$ | crack propagation length |
| $a$ | crack length |
| $B$ | width of specimen |
| $C_1$ | distance from pre-notch to geometric centre of specimen |
| $D$ | depth of specimen |
| $E_t$ | Young's modulus of concrete |
| $f_c$ | uniaxial compressive strength of concrete |
| $f_t$ | uniaxial tensile strength of concrete |
| $G_f$ | fracture energy of concrete |
| $K_{\mathrm{i}}$ | stress intensity factors |
| $l_{\mathrm{FPZ}}$ | FPZ length |
| $L$ | length of specimen |
| $L_1$ | distance from loading point $P_1$ to geometric centre of specimen |
| $L_2$ | distance from loading point $P_2$ to geometric centre of specimen |
| $P$ | applied load |
| $u$ | opening displacement along the X direction |
| $v$ | sliding displacement along the Y direction |
| $n_u$ | Poisson's ratio of concrete |
| $\sigma$ | cohesive force |
| $w$ | crack opening displacement |
| $w_0$ | stress-free crack opening displacement |
| $CMOD$ | crack mouth opening displacement |
| $CMSD$ | crack mouth sliding displacement |

So far, both experimental and numerical methods have been utilized to study FPZ evolution in quasi-brittle materials. Some studies have shown that the FPZ length of concrete decreases rapidly when a crack approaches the top surface of a specimen [6–8]. This is often called the boundary effect and has been successfully explained through the concept of local fracture energy [6,9,10]. Based on the experimental results of mode I fracture, it was found that the maximum FPZ length of concrete increases with the increase of the specimen height, and decreases with the increase of the notched crack length-to-depth ratio ($a_0/D$) [11]. Dong et al. arrived to the same conclusion [12] by introducing the initial fracture toughness criterion in the analysis of concrete fracture. It has also been found in this study, that the FPZ length may continue increasing even after the FPZ has fully developed. Meanwhile, taking sandstone as an example, the FPZ evolution under mixed mode fracture was studied through experiment [13]. It should be noted that the aforementioned studies aimed at investigating the FPZ evolution in single materials, such as concrete and sandstone. In the case of a composite material such as a rock-concrete interface, to the best of the authors' knowledge, no study regarding its FPZ evolution has been reported. In the few studies which have been made on crack propagation along a rock-concrete interface [14–16], the main objective was to develop a numerical method to effectively simulate the fracture process at the interface rather than to investigate crack evolution. In those studies, usually the curves of load vs. crack mouth opening and sliding displacements (P-CMOD, P-CMSD) obtained from experiment were compared with the ones from simulation to verify the proposed numerical methods. In fact, for the purpose of an in-depth insight into a fracture mechanism, the verification of a numerical method using the FPZ evolution in various fracture stages is more significant and convincing. Therefore, together with the fracture behavior, it is important to investigate the FPZ evolution at the rock-concrete interface.

Digital image correlation (DIC) is an optical technique that is used to visualize the surface displacements of a specimen. Through a comparison of digital images of specimen surfaces before/after deformation, the displacements of the regular grid points on the specimen surface can be obtained, so that the FPZ evolution during fracture process can be derived if combined with a softening constitutive law for crack opening displacement and cohesive force. Due to its convenience, high responsiveness, accuracy and non-destructive nature, the DIC technique has been widely used for investigating a number of processes, including the fracture and fatigue behavior of strengthened reinforced concrete beams [17], the mode I fracture in cementitious materials [11,18–20], the mixed mode fracture in sandstone [13], the fracture properties at concrete-concrete interfaces [21], and the interfacial debonding properties in concrete [22]. The results of the above research have demonstrated that the DIC technique can be used to carry out the fracture analysis of concrete with reasonable accuracy.

In this study, the DIC technique is employed to investigate the fracture properties and characterize the FPZ length under three-point bending (TPB) for the rock-concrete interface. Also, in the case of four-point shearing (FPS), the crack opening and sliding displacements at various stages before the peak loads are obtained using the DIC technique with respect to different mode mixity ratios. Based on the experimental results, the FPZ evolution during crack propagation and the effects of the mode mixity ratio on fracture properties are discussed. It is expected that the experimental results presented here can