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Experimental and numerical study of the dependency of interface fracture in concrete–rock specimens on mode mixity

Hong Zhong [a], Ean Tat Ooi [b,*], Chongmin Song [c], Tao Ding [a], Gao Lin [a], Hongjun Li [d]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China
[b] School of Science, Information Technology and Engineering, Federation University, Ballarat, VIC 3353, Australia
[c] School of Civil and Environmental Engineering, The University of New South Wales, NSW 2031, Australia
[d] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Institute of Water Resources and Hydropower Research, Beijing 100048, China

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ABSTRACT

The interface between the concrete and the rock is usually considered the weakest link in concrete structures built on rock foundations. The fracture behaviour at the concrete–rock interface is influenced by many factors e.g. the material properties of the individual constituents, the fracture process zone at the interface and the mode mixity ratio. This paper investigates the dependency of the fracture behaviour of concrete–rock interfaces on the mode mixity ratio using experimental and numerical methods. The experimental program involves four-point-shearing of concrete–rock composite beams. It is designed to test a wide range of mode mixity ratio. Using linear elastic fracture mechanics theory, the fracture toughness and the fracture energy are first quantified in terms of the mode mixity ratio. The scaled boundary finite element method, which is known for its accuracy in modelling fracture, is used to compute the fracture toughness and fracture energy. Next, the crack propagation process of the concrete–rock composite beam is modelled using nonlinear fracture mechanics theory. The scaled boundary finite element method is coupled with interface elements to model the fracture process zone, which is a characteristic of fracture in quasi-brittle materials such as concrete and rock. A revised scaled boundary finite element method formulation using generalized coordinates is used to model the cohesive tractions. The cohesive crack at the interface is assumed to propagate when either the Mode 1 or the Mode 2 stress intensity factors change sign. A simple remeshing algorithm is used to propagate the crack at the interface. The numerical simulations are validated by the experimental measurements. The simulated crack propagation processes are described in terms of the mode mixity ratio.

1. Introduction

Many concrete structures such as concrete dams, wharfs and underground geological repositories for nuclear waste storage are built on rock foundations. The physical properties of concrete and rock are well documented in the literature e.g. [1,2]. The behaviour of the interface between the concrete and the rock, which is generally considered as the weak link of

* Corresponding author. Tel.: +61 0470345660.
E-mail address: ooi.ean.tat@gmail.com (E.T. Ooi).

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Nomenclature

A	area
E	Young's modulus
G	energy release rate
G_c	critical energy release rate
G_{f_i}	fracture energy of interface
k_i	secant stiffness of traction-softening curve
K_i	stress intensity factors
K_{ic}	critical fracture toughness
L_{rock}	length of rock span
P	load
$t_n^{(u)}$	ultimate tensile strength
t_n	normal cohesive traction
$t_s^{(u)}$	ultimate shear strength
t_s	shear cohesive traction
w_n	crack mouth opening displacement
w_s	crack mouth sliding displacement
$\mathbf{B}_i$	strain displacement matrix
$\mathbf{c}$	integration constants
$\mathbf{D}$	elastic constitutive matrix
$\mathbf{E}_i$	coefficient matrix
$\mathbf{F}$	force vector
$\mathbf{F}_t$	load vector due to side face tractions
$\mathbf{I}$	identity matrix
$\mathbf{K}$	stiffness matrix
$\mathbf{K}_{IE}$	stiffness matrix of interface element
$\mathbf{N}$	shape function matrix
$\mathbf{q}$	internal nodal force vector
$\mathbf{R}_F$	nodal load vector due to side face tractions
$\mathbf{S}$	Schur matrix
$\mathbf{u}$	displacement vector
$\mathbf{W}$	generalized coordinates
$\mathbf{Z}$	Hamiltonian matrix
ε	oscillatory index
Γ	fracture energy
η	local element coordinate
μ	shear modulus
ν	Poisson's ratio
$\boldsymbol{\sigma}$	stress vector
ξ	radial coordinate
ψ	mode mixity angle
$\boldsymbol{\Psi}$	transformation matrix
$\boldsymbol{\Psi}_{\sigma_i}$	stress mode

the structure-rock foundation system, however, is not a well understood phenomenon. In the stability analysis of such structures, the assumption of perfect bonding at the concrete–rock interface is usually employed, e.g., [3]. More realistic analyses reported in the literature include the use of friction models to quantify the relative movements between the dam foundation and the dam [4] and spring elements that model the water uplift pressure at the concrete–rock interface [5]. These analyses, however, do not account for the fracture behaviour at the interface. A comprehensive analysis of the stability at the concrete–rock interface requires an in-depth understanding of the fracture behaviour of the interfaces between the mortar and the aggregates, which is intrinsic to the concrete and the rock.

Unlike homogeneous materials, the fracture behaviour of a bimaterial interface crack depends on the mode mixity ratio [6]. This has been observed in many experimental studies e.g. [7–13]. Lee and Buyukozturk [7] reported the fracture toughness curves of the mortar–aggregate interfaces in concrete using sandwiched specimens subjected to four-point-bending and Brazilian disk tests. They observed a remarkable increase of interface fracture toughness with shear loading relative to tensile loading. The same authors also observed a similar behaviour in their experimental tests on high strength concrete [8]. In the three-point bending tests on concrete–composite specimens reported by Buyukozturk and Hearing [9], the magnitude of the interface toughness was observed to depend on the mismatch of the elastic moduli and fracture toughness of the aggregate and mortar. Tippur and Rosakis [10] and Tippur and Ramaswamy [11] reported the dependence of the interfacial crack initiation toughness and the dynamic fracture behaviour on the crack tip mode mixity parameter for a