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Fracture characterization of Carbon fiber-reinforced polymer-concrete bonded interfaces under four-point bending

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ABSTRACT

A combined analytical and experimental approach is presented to characterize both mode-II and mixed mode fracture of Carbon fiber-reinforced polymer-concrete bonded interfaces under four-point bending load, and closed-form solutions of compliance and energy release rate of the mode-II (four-point symmetric end-notched flexure) and mixed (four-point asymmetric end-notched flexure) mode fracture specimens are provided. The transverse shear deformation in each sub-layer of bi-material bonded beams is included by modeling each sub-layer as an individual first order shear deformable beam, and the effect of interface crack tip deformation on the compliance and energy release rate are taken into account by applying the interface deformable bi-layer beam theory (i.e., the flexible joint model). The improved accuracy of the present analytical solutions for both the compliance and energy release rate is illustrated by comparing with the solutions predicted by the conventional rigid joint model and finite element analysis. The fracture of Carbon fiber-reinforced polymer-concrete bonded interface is experimentally evaluated using both the four-point symmetric and asymmetric end-notched flexure specimens, and the corresponding values of critical energy release rates are obtained. Comparisons of the compliance rate-changes and resulting critical energy release rates based on the rigid joint model, the present theoretical model, and numerical finite element analysis demonstrate that the crack tip deformation plays an important role in accurately characterizing the mixed mode fracture toughness of hybrid material bonded interfaces under four-point bending load. The improved solution of energy release rates for the four-point symmetric and asymmetric end-notched flexure specimens by the flexible joint model can be used to effectively characterize hybrid material interface, and the fracture toughness values obtained for the Carbon fiber-reinforced polymer-concrete interface under mode-II and mixed mode loading can be employed to predict the interface fracture load of concrete structures strengthened with composites.

1. Introduction

Fiber-reinforced plastic (FRP) composites are commonly used for hardening of structures made of conventional materials, like concrete and wood. They usually in the form of fabrics or laminates are externally bonded to the concrete or wood

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Nomenclature

Principal symbols

a	crack length
A_i	axial stiffness of sub-layer i
b	width of specimen
B_i	transverse shear stiffness of sub-layer i
C	compliance of the specimen
C_C	compliance based on the rigid joint model
C_F	compliance based on the flexible joint model
C_j	contribution of the crack tip deformation to the total compliance of the specimen
c_i	integral constants
d	distance between the loading point and its corresponding support
D_i	bending stiffness of sub-layer i
E_i	Young's modulus of sub-layer i
G	energy release rate
G_c	critical energy release rate
G_i	transverse shear modulus of sub-layer i
${G_c}^a$	critical energy release rate or fracture toughness at crack arrest
${G_c}^i$	critical energy release rate or fracture toughness at crack initiation
h_i	thickness of sub-layer i
I	brittleness index
I_i	moment of inertial of sub-layer i
K	stress intensity factor
K_c	critical stress intensity factor
L	length of bi-layer beam
M	loading parameter at the crack tip due to bending moment
M_i	bending moment in sub-layer i
M_{i0}	externally-applied bending moments in sub-layer i
M_T	total resulting bending moment
N_i	axial force in sub-layer i
N_{i0}	externally-applied axial force in sub-layer i
N_T	total resulting axial force
Q_i	transverse shear force in sub-layer i
Q_{i0}	externally-applied transverse shear force in sub-layer i
Q_T	total resulting transverse shear force
P	applied load
${P_c}^a$	critical load at crack arrest
${P_c}^i$	critical load at crack initiation
u_i	longitudinal displacement of sub-layers i
w_i	vertical displacement of sub-layers i
α, β, φ	parameters based on classical beam theory
ϕ_i	rotation of sub-layers i
$\Delta\phi$	difference of rotation between the rigid joint and flexible joint models
$\Delta\omega$	difference of transverse displacement between the rigid joint and flexible joint models

Principal abbreviation

AL	aluminum
CBT	conventional beam theory
CFRP	Carbon fiber-reinforced polymer/plastics
ENF	end-notched flexure
3-ENF	three-point symmetric end-notched flexure
4-ENF	four-point symmetric end-notched flexure
4-AENF	four-point asymmetric end-notched flexure
ERR	energy release rate
TENF	tapered end-notched flexure
FEA	finite element analysis

structures. As one of the most common failure modes, interface debonding along the bonded interface often happens in this type of structural hardening schemes due to pre-existing cracks or flaws introduced during the bonding process. To assess this type of failure modes, fracture mechanics has been widely employed, in which the energy release rate (*ERR or G*) or stress