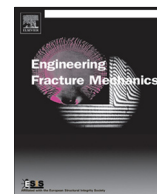




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Theoretical analysis of fracture in double overlap bonded joints with FRP composites and thin steel plates

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ABSTRACT

The effective stress transfer between the fiber reinforced polymers (FRP) and the steel substrate is crucial for the successful retrofit of existing steel structures with FRP composites. However, there are no standard tests for FRP-to-steel interfaces, wherefore different test configurations have been used in recent years to assess the bond behaviour in these interfaces. The present study shows that the choice of test configuration is highly important and leads to different transfer stresses between the FRP and steel composites and consequently, has a direct influence on the strength of the bonded joint. Therefore, it is important to understand the debonding process that occurs in each test and avoid misinterpretations, erroneous analyses and dangerous characterizations of the interfacial behaviour of these interfaces. The current study presents a new analytical approach for the prediction of the debonding of FRP-to-steel interfaces when double-lap pull or double-strap tests are used.

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1. Introduction

The appearance and application of Fiber Reinforced Polymers (FRP) in several engineering areas such as civil, mechanical, aeronautical and other fields, justifies the large number of studies devoted to the adhesion using these composite materials, e.g. [1–7]. Different joints with FRP composites have been studied so far and FRP-to-FRP, FRP-to-steel, FRP-to-concrete, FRP-to-masonry or FRP-to-timber bonded joints are some examples. The bond failure associated to Mode II debonding phenomenon is the most studied case due to its more practical relevance when compared to the other two fracture Modes, i.e. Mode I and III. Researchers have focussed mainly on the strength of the joints when subjected to a mechanical loading (e.g. [8–12]) but most recently the influence of the temperature on the strength of the interface has received some attention (e.g. [13–18]). Additionally, the long-term behaviour of these bonded joints with FRP composites has been worrying some researchers (e.g. [19–24]), who have studied the durability of these joints when exposed to aggressive environments such as salt fog, alkaline solutions, water immersion and temperature cycles.

In general, researchers have been evaluating the bond between an FRP composite and a steel substrate based on nonlinear fracture mechanics (NLFM) and local adhesion bond-slip relationships have been used to help better comprehension of the debonding phenomenon of these interfaces. In the case of interfaces between an FRP composite and a steel substrate, several researchers [24–26] have found that bi-linear bond-slip relationships are adequate to represent the real local behaviour of

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Nomenclature

A_f	cross sectional area of the FRP composite
A_s	cross sectional area of the steel substrate
b_f	width of the FRP composite
b_s	width of the steel substrate
D	debonded stage of the local bond-slip relationship
E	elastic stage of the local bond-slip relationship
E_f	Young modulus of the FRP composite
E_s	Young modulus of the steel substrate
$F_{E,max}$	maximum elastic load transmitted to the FRP composite
F_f	load transmitted to the FRP composite
F_s	load transmitted to the steel substrate
$F_{S-E,max}$	maximum load reached in the softening-elastic stage
G_F	pure Mode II fracture energy
$G_{F,E}$	pure Mode II fracture energy corresponding to the elastic stage of the local bond-slip relationship
L_b	bond length of the interface
L_d	debonded length of the interface
$L_{E,max}$	maximum elastic length
L_{eff}	effective bond length
L_S	length that limits the softening stage
L_S^L	length that limits the softening stage at the left side of the interface
L_S^R	length that limits the softening stage at the right side of the interface
$L_{S,max}^L$	maximum length that limits the softening stage on the left side of the interface
$L_{S,max}^R$	maximum length that limits the softening stage on the right side of the interface
r	ratio between the axial stiffness of the FRP composite and the axial stiffness of the steel substrate
s	relative displacement between the FRP composite and the steel substrate (or slip)
S	softening stage of the local bond-slip relationship
$s(x_i)$	slip at point x_i
$s(x_{i+1})$	slip at point x_{i+1}
$s(x_{i+1/2})$	slip at point $x_{i+1/2}$
$s_E(x)$	elastic slip distribution developed along the bond length
s_{max}	slip corresponding to maximum bond stress
s_S	slip corresponding to the softening stage of the local bond-slip relationship
s_S^L	corresponds to the solution for the left softened side of the interface
s_S^R	corresponds to the solution for the right softened side of the interface
s_{ult}	ultimate slip beyond which the interface debonds
t_f	thickness of the FRP composite
t_s	thickness of the steel substrate
u_f	displacement of the FRP composite
u_s	displacement of the steel substrate
ε_f	strain in the FRP composite
ε_{si+1}	strain in the steel substrate at point $i + 1$
ε_{si}	strain in the steel substrate at point i
ε_s	strain in the steel substrate
σ_f	axial stress in the FRP composite
σ_s	axial stress in the steel substrate
$\tau_b(x)$	bond stress distribution developed along the bond length
$\tau_b(x_{i+1/2})$	bond stress at point $x_{i+1/2}$
$\tau_{b,s}$	local bond-slip relationship
$\tau_{b,E}(x)$	bond stress distribution in the elastic region of the interface
$\tau_{b,S}^L(x)$	bond stress distribution in the softening region developed at the left side of the interface
$\tau_{b,S}^R(x)$	bond stress distribution in the softening region developed at the right side of the interface
$\tau_{b,max}$	maximum bond stress

these interfaces. Unlike FRP-to-concrete interfaces, where the bond-slip relationship can be approximated to an exponential function, the elastic behaviour of steel until yielding may explain why bi-linear bond-slip relationships are more appropriate to represent the local adhesion behaviour of FRP-to-steel interfaces [26].

Other researchers [27–29] found that the type of resin used as the adhesive agent for the bonding between the FRP composite and the steel plate has an influence on the local adhesive behaviour of these interfaces. For instance, Yu et al. [27] used

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