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A coupled damage-plasticity model for the cyclic behavior of shear-loaded interfaces

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ABSTRACT

The present work proposes a novel thermodynamically consistent model for the behavior of interfaces under shear (i.e. mode-II) cyclic loading conditions. The interface behavior is defined coupling damage and plasticity. The admissible states' domain is formulated restricting the tangential interface stress to non-negative values, which makes the model suitable e.g. for interfaces with thin adherends. Linear softening is assumed so as to reproduce, under monotonic conditions, a bilinear mode-II interface law. Two damage variables govern respectively the loss of strength and of stiffness of the interface. The proposed model needs the evaluation of only four independent parameters, i.e. three defining the monotonic mode-II interface law, and one ruling the fatigue behavior. This limited number of parameters and their clear physical meaning facilitate experimental calibration. Model predictions are compared with experimental results on fiber reinforced polymer sheets externally bonded to concrete involving different load histories, and an excellent agreement is obtained.

1. Introduction

Interfacial strength deterioration due to cyclic actions is still a major open issue relevant for a broad range of applications (Roe and Siegmund, 2003; Nguyen et al., 2001), such as delamination of composite materials in aerospace engineering (Turon et al., 2006) or more generally fatigue life prediction in bonded joints (Kinloch and Osiyemi, 1993). In this case, the dissipative and damage processes responsible for failure of the system are usually localized in small regions where two body portions are joined together and where high stress concentrations are present, whereas the remaining portions of the physical domain are in linear elastic conditions. In particular, fatigue may induce the accumulation of plastic dislocations and damage at the interface level which, in turn, may lead to the nucleation of micro-cracks. Their gradual coalescence may result in a macro-crack, whose propagation is responsible for interface failure (Turon et al., 2006; Andersons et al., 2004) even for applied stresses smaller than the maximum attained in monotonic quasi-static conditions (Carloni and Subramaniam, 2013).

The resistance against fatigue is generally quantified in terms of number of cycles or time (days/years) prior to failure, for which reason it is usually named fatigue life. To date, three categories of methods have been available to quantify the fatigue life: statistical methods, fracture mechanics approaches, and numerical simulations of the interface crack propagation through ad hoc constitutive laws. Statistical methods are based on the analysis of a large number of experimental tests

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reproducing the specific situation at hand (such as in Ko and Sato, 2007) and, for this reason, do not allow for any generalization. Fracture mechanics based approaches typically adopt the Paris theory, relating the variation during the cycles of the energy release rate ΔG (or of any another related quantity, e.g. Roe and Siegmund, 2003; Nguyen et al., 2001) with the growing rate of the fatigue crack by means of experimentally calibrated parameters. This approach is valid only when the so-called Paris regime is predominant (Robinson et al., 2005), i.e. in low-cycle fatigue and away from the transient phases of fatigue crack propagation (crack nucleation and right before failure). Moreover, the parameters are again estimated case by case preventing the generalization of the evolution law.

Numerical models based on the definition of suitable constitutive interface laws lump all the deterioration processes taking place in the thin region connecting two bodies, namely the interface, in a zero-thickness layer. Cohesive zone theory is widely used to define such constitutive laws. While some authors adopted analytical approaches (e.g., De Lorenzis and Zavarise, 2009; Rabinovitch, 2008), most of the studies in the literature deal with numerical methods because of the complex non-linear behavior associated to the interface degradation. In the field of bonded joints, Alfano and Crisfield (2001) proposed a finite element framework including damage that has then been extended and generalized by Alfano and Sacco (2006) and Serpieri et al. (2015). Freddi and Frémond (2006) and Marfia et al. (2011) coupled the damage in interfaces and neighboring domain, while Freddi and Sacco (2014) included also the confinement effects of the stresses parallel to the interface plane. Considering the modeling of cyclic behavior, some models available in the literature are formulated considering experimentally calibrated parameters (see Turon et al., 2006; Martinelli and Caggiano, 2014, among others), opening some questions on the accuracy outside the range of variables used to define the parameters. Other authors used coupled or uncoupled fracture, damage or plasticity theories to describe the behavior of the interface (see for example Roe and Siegmund, 2003; Nguyen et al., 2001; Yang et al., 2001). In this case, the local response is ruled by a set of internal state parameters that sometimes do not have a straightforward physical meaning (e.g. Turon et al., 2006). On the other hand, the simplest models may not fulfill thermodynamic laws (e.g. Martinelli and Caggiano, 2014).

When two bodies, namely adherends, are mainly subjected to pure axial actions and the interface plane is parallel to them pure shear behavior (i.e. mode-II) can be usually assumed (Matsubara et al., 2006). In these cases, the relative displacement of the two adherends occurs primarily parallel to the crack plane, resulting in a mainly shear stressed interface that can exhibit damage even after few cycles (Trethewey et al., 1988; Matsubara et al., 2006; Tumino and Zuccarello, 2011). The present work proposes a new model for the fatigue behavior of interfaces undergoing pure shear (i.e. mode II) loading conditions. The primary motivation is the simulation of the cyclic response of interfaces with no possible sign reversal of the interfacial tangential stresses (e.g. interfaces with thin adherends). Among the possible applications, the case of fiber reinforced polymer (FRP) laminates bonded to quasi-brittle (e.g. concrete) substrates is considered here. For this specific application, Ko and Sato (2007) proposed a purely empirical interface law based on a modified Popovic relationship and used for calibration a set of experimental results from variable-amplitude high-cycle FRP-concrete pure shear tests. Carloni and Subramaniam (2013) introduced a modified Paris relationship, where the variation of the energy release rate ΔG was substituted by the more easily measurable applied load F. Martinelli and Caggiano (2014) formulated a phenomenological damage model to simulate high cycle fatigue. In the same field, Turon et al. (2006) adopted a mixed-mode cohesive-zone model involving a damage parameter experimentally calibrated using the Paris law.

In our proposed model, the interface constitutive relationship is formulated in a thermodynamic framework, coupling damage and plasticity and neglecting friction or interlocking at the interface level. One of the most important features of this new model is that the cyclic deterioration of the interface integrity is described through the definition of only one additional parameter, beside the classical ones used to describe the monotonic behavior. Moreover, each parameter used has a sound physical meaning, condition that facilitates their experimental evaluation.

The paper is structured as follows. In Section 2 the thermodynamic framework is set together with the variables involved and the potentials used. In Section 3 the model is derived after stating some basic assumptions. Results of the numerical analyses and comparisons with experimental data from the literature are presented in Section 4, while some conclusive remarks are reported in Section 5.

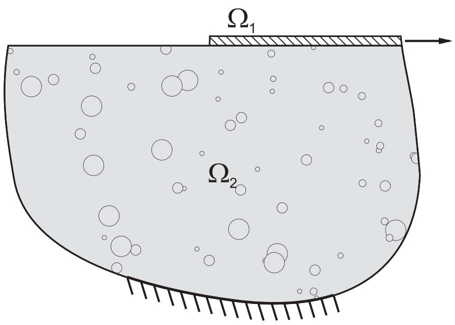

Fig. 1. Scheme of the interface problem studied.