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Nonlocal criterion of bridged cracks growth: Weak interface

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Abstract

A nonlocal fracture criterion with accounting of the work during bonds deformation at a fracture process zone has been implemented analytically for analysis of quasistatic cracks growth along a weak interface. The criterion consists of two clauses: (1) the necessary energy condition of the crack tip limit equilibrium which takes into account the energy release rate to the crack tip and the rate of the deformation energy consumed by bonds in the crack process zone; (2) the sufficient condition is the equality of the crack opening at the process zone trailing edge to the bond limit stretching. Subcritical and quasi-statical regimes of cracks growth are analyzed for the case of a homogeneous plate with internal straight bridged crack and bonds traction which is constant and independent of the external loading. The critical fracture stress and the crack bridged zone size in the limit equilibrium state have been determined and analyzed. The limit case of a crack which is filled with bonds is considered as a weak interface model.

Keywords: Bridged cracks; Fracture criterion; Quasi-statical crack growth; Weak interface

1. Introduction

The Griffith–Irwin fracture criteria are used if fracture processes in materials are localized in small domains close to tips of cracks (fracture process zones) and interaction of newly formed surfaces of cracks can be neglected. In this case the crack limit equilibrium state is completely defined by the material cohesion modulus or by the critical stress intensity factor.[1–3] In inhomogeneous materials (adhesive joints, ceramics) traditional one-parametric fracture criteria do not work well. Fracture conditions in such cases are considered not only at cracks tips but also in some zones in the vicinity of flaws, with considering distributions of stresses in these zones. Non-local fracture criteria, which can be used in these cases, have been intensively developed recently.[4–9] These criteria are based, as a rule, on two fracture conditions for the crack tip advancing (the stress and energy conditions,[4,5] the critical stress intensity and the *T*-stress,[6] the finite fracture mechanics conditions[7–9]) but they were implemented for cracks without consideration of large scale process zone effects.

In analysis of adhesion joints fracture there are two main approaches: (a) consideration cracks between identical or different materials with the process zone which can be comparable to the whole crack length[10–14]; (b) assumption that the process zone exists along the whole interface between adhesion junction of materials without crack[15,16] or with crack.[17–19] In the both cases the definitions ‘weak interface’ or ‘imperfect interface’ are used. We will follow the first approach and consider a crack with the process zone of large scale below in this paper.

The fracture process zone of a large scale can be considered for mechanical modeling purposes as a certain layer of finite length which is adjacent to the crack tip and contains material with weakened bonds between its individual structural elements. One of the computational modeling way of such layer includes the treating of the process zone as a part of the crack with the explicit application of bridging forces, which restrain the crack opening, to the crack surfaces in this zone. The tip (front) of such modified crack coincides with the leading edge of the process zone. Similar models are classified as the cohesive or bridged models depending on the stress singularity condition at the crack tip.[20] The magnitude of the bridging forces depends, as a rule, on the opening of the crack in this zone and the environmental conditions (the presence of physical fields, aggressive media, etc.). Within of the crack model with bridged forces in the pro-

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cess zone, it is necessary to use special criteria for cracks growth analysis which enables us to consider the process zone length changing during cracks growth and to determine the advancing conditions for the process zone trailing edge as well as for the crack tip. Since the length of the process zone can be changing during cracks growth then these criteria should also account the energy consumed by deformed bonds during cracks growth. Criteria of this type are fundamentally nonlocal and are based, at least, on two fracture conditions. For bridged crack models when the singularity at the crack tip is considered, a force equation for the crack tip advancing is conventionally used as the first condition of the crack growth criterion in the form[20]

$$K_\infty - K_b = K_{Ic} \tag{1}$$

where K_∞ is the stress intensity factor due to the action of the external loads, K_b is the stress intensity factor due to the reinforcing by bonds within the crack bridged zone and K_{Ic} is the fracture toughness of the material, which corresponds with the bonds deformation in a small region ahead of the bridged zone, close to the crack tip (for example, the material intrinsic fracture toughness).

Another condition at the crack tip is used for the cohesive type models if the requirement of stresses finiteness at the crack tip is imposed. For example, instead of (1) can be used the condition of the attaining the stress $\sigma(\sigma_*, u, L, d)$ at the crack tip to the critical value σ_{th}[21,22]

$$\sigma(\sigma_*, u, L, d) = \sigma_{th} \tag{2}$$

The choice of the condition for the crack critical opening (or the critical strain condition) at the trailing edge of the cohesive or bridged zone is possible as the second condition of the crack growth criterion in both cases.

Another type of the fracture condition which can be used instead of (1) or (2) is based on consideration of average stresses ahead of the crack tip. In this case the stress σ in (2) is the average value of stresses on a certain characteristic segment close to the crack tip.[23–25]

Note that, if the stresses-based conditions as (1) or (2) are used non self-similar crack growth can be accounted, but the energy consumption due bonds deformation within the crack process zone does not consider in these fracture criteria. The energy flux into the crack tip together with the process zone energy flux were considered and used for the deriving of the material R-curves.[26] This approach was also successfully used to analyze fracture toughness of fiberboard.[27]

The nonlocal fracture criterion for the analysis of quasistatic growth of interfacial bridged cracks with accounting of the energy consumed by bonds has been initially proposed for two-dimensional problem[12] and next it was formulated for three-dimensional interfacial bridged cracks.[13] This criterion is based on two fracture conditions: (a) the energy condition for the crack tip advancing, which takes into account the work done in deforming of the bonds within the crack bridged zone (the stress intensity factors are non-zero at the crack tip); (b) the kinematic condition is used to determine the advancing of the trailing edge of the crack bridged zone. Application of this criterion for a weak interface is considered below analytically in the case of homogeneous plate with a straight crack.

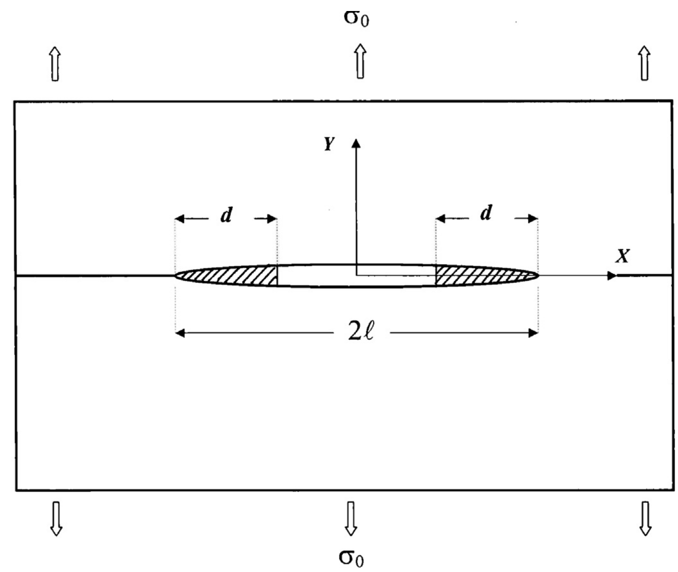

Fig. 1. Bridged crack under the tension loading.

2. Nonlocal fracture criterion for bridged cracks growth

The nonlocal fracture criterion for a straight crack at the segment $|x| \le \ell, \quad y = 0$ and with bridged zones of size d (Fig. 1) in two-dimensional homogeneous plate consists of two conditions[12,13]:

(a) the necessary energy condition of the crack tip limit equilibrium (Π is the total potential energy of the elastic body, U is the bonds deformation energy in the crack bridged zone, b is the thickness of the body, G_m is the material or adhesion layer intrinsic toughness)

$$-\frac{\partial \Pi}{\partial \ell} = \frac{\partial U}{b \partial \ell} + G_m \tag{3}$$

(b) the sufficient condition – this is the equality the crack opening $u(\ell - d)$ at the trailing edge of the bridge zone and the bond limit stretching δ_{cr}

$$u(\ell - d) = \delta_{cr} \tag{4}$$

Conditions (3) and (4) represent the nonlocal criterion of bridged cracks quasistatic growth. The jointed solution of these equations enables, when the crack length and the bonds characteristics are specified, to determine two basic parameters of fracture, the critical external load (the fracture stress) and the bridged zone size in the crack limit equilibrium state. Note, that the approximated equation for a small scale bridged zone (obtained by J-integral approach) similar to (3) was used by Budiansky et al.[28]

Let's introduce the following notation[13]

$$G_{tip}(d, \ell) = -\frac{\partial \Pi}{\partial \ell}, \qquad G_{bond}(d, \ell) = \frac{\partial U}{b \partial \ell} + G_m \tag{5}$$