Composites Science and Technology 87 (2013) 42–49

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Nominal strength of quasi-brittle open hole specimens under biaxial loading conditions

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ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 9 July 2013
Accepted 21 July 2013
Available online 6 August 2013

Keywords:
B. Failure criterion
B. Strength
C. Notch
C. Stress concentrations

ABSTRACT

One of the main purposes for an accurate strength prediction is to get a reliable design tool of a given structure. Since most of aircraft and aerospace structures contain many holes and are subject to multidirectional loading conditions, due to stress concentration, cracks will necessarily emanate from these holes before failure. Therefore, the nominal strength prediction of open hole specimens under biaxial loading conditions is very necessary for the safe design of these structures. The main goal of this work is to develop an analytical model able to predict the nominal strength and the failure envelope of isotropic quasi-brittle open hole specimens under biaxial loading conditions. In this model, the nominal strength is analyzed taking into account the hole radius and the biaxiality load ratio. The model is formulated based on the cohesive zone model considering various shapes of the cohesive law. Other approaches such as the different methods of the critical distance theories are also presented and compared with the results of the cohesive crack model.

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1. Introduction

Concrete, composites and toughened ceramics among others are examples for quasi-brittle materials. Due to the industrial importance of these materials, the development of stress concentrations arising from notches or holes has been always of great concern. The prediction of the ultimate strength remains the main challenge in the simulation of their mechanical response [1].

Quasi-brittle materials develop a stable Failure Process Zone (FPZ) before failure, whose size (ℓ_{FPZ}) depends on the material characteristic length (ℓ_M):

$$\ell_M = \frac{EG_C}{\sigma_u^2} \tag{1}$$

where E,G_C and $\sigma_u$are the material Young's modulus, the critical fracture energy and the material strength, respectively.

The reason of the influence of the size effect on the structure's strength (Fig. 1(b)) is linked to the development of this FPZ [2]. Due to the importance of this effect, it must be considered in the predictions of the nominal strength of quasi-brittle structures [3–8].

When dealing with failure prediction of open hole specimens two extreme situations can be expected: brittle or ductile failure [2]. Specimens with small holes are notch insensitive: the perturbation of the stress field caused by the hole is enclosed in a region smaller than the length of the FPZ and the specimen fails according to the plastic limit (line P Fig. 1(a)). On the other extreme, specimens with large holes are notch sensitive and the relative size of the FPZ is negligible with respect to the specimen size; herein brittle failure is expected (line E Fig. 1(a)). The nominal strength for brittle failure is predicted by the elastic limit depending on the value of the stress concentration factor (K_t). For a hole in an infinite plate it depends on the load biaxiality ratio (λ) so that $K_t = 3 - \lambda$. The transition from ductile to brittle failure occurs smoothly by increasing the hole radius.

The Cohesive Zone Model (CZM) was initially proposed by Barenblatt [9,10] and Dugdale [11]. It assumes that the FPZ can be modeled with a localized plane where the dissipation mechanisms take place. The cohesive law defines the constitutive behavior in the FPZ by defining a softening function that relates the stresses and the crack opening displacements. Further, it has been widely recognized that the cohesive law is able to model the size effect on the structural strength [2,-8,12–14]. The cohesive law can be implemented in finite element codes by means of cohesive elements [15–17] or by smearing the cohesive law in the solid element [18–21]. If the bulk response is assumed as linear and small displacements are considered, the equilibrium equations can be applied by imposing Dugdale's finite stress condition. This condition state that the stress intensity factor due to the remote stresses is in equilibrium with the stress intensity factor due to the cohesive stresses [22–24].

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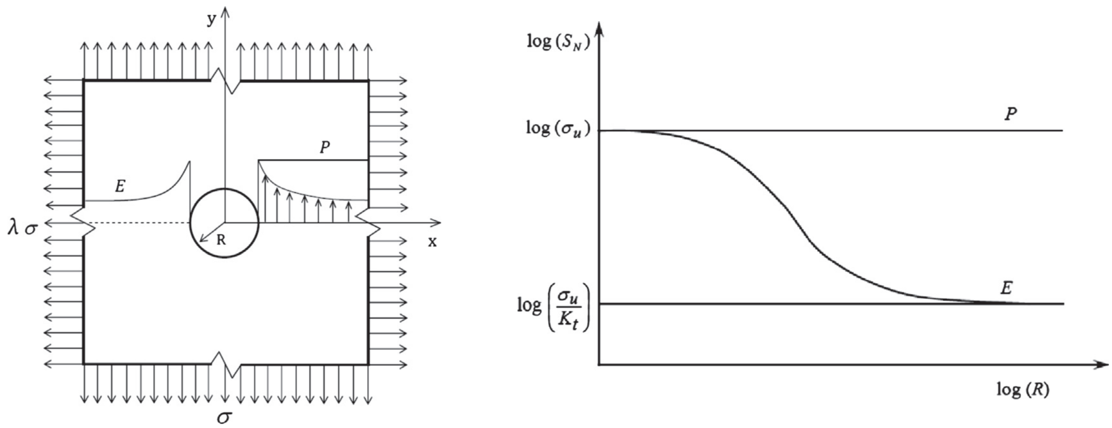
http://dx.doi.org/10.1016/j.compscitech.2013.07.022



(a) Open hole specimen under biaxial loading (b) Size effect law on the structural strength

Fig. 1. Loading condition and size effect law.

Other models based on what have been recently named critical distance theories (CDTs) [25,26] are also used in studying the failure behavior of quasi-brittle structures. These methods are a set of empirical methodologies for quick structural design. They share the common feature of using an elastic analysis together with a material characteristic length that defines the transition from ductile to brittle failure. The CDTs can be divided into three main categories: one based on the elastic stress field of the undamaged specimen as in the Point Stress Method (PSM) and the Average Stress Method (ASM) [27–29], another one based on linear elastic fracture mechanics in which a flaw of some characteristic length exists at the hole boundary, as in the Inherent Flaw Model (IFM) and the Finite Fracture Mechanics (FFM) [29–31] and, finally, a third category obtained by imposing the simultaneous fulfilment of an stress and a fracture criteria [24,32–34].

The aforementioned references consider only uniaxial loading conditions, while most aircraft and aerospace structures are exposed to multidirectional loading conditions. Therefore, there was a need for some studies considering specimens under biaxial loading. Unfortunately, multi-axial strength data is scarce because of the limited number of testing equipments and facilities available for these tests and the enormous cost involved [35–37].

Nevertheless, some experimental studies have considered laminated composite open hole specimens under biaxial loading [37–39]. In these studies, the nominal strength under different loading schemes is predicted [37], the influence of a hole diameter on the nominal strength and on failure is evaluated [38] and the mechanisms involved in the compressive failure are studied [39].

On the other hand, using numerical simulations, Shah et al. [40] predicted failure envelopes of open hole specimens made of quasi-isotropic composite laminates. Based on PSM and ASM, Camanho and Lambert [41] presented a methodology to predict the final failure in mechanically fastened joints of composite laminates.

As shown in the literature, there is a shortage in analytical models and numerical simulations that investigate the nominal strength of quasi-brittle structures subjected to multidirectional loading conditions. So, the objective of the present work is to find the normalized nominal strength of open hole specimens made of isotropic quasi-brittle materials and subjected to biaxial loading conditions.

The present paper is organized as follows: in Sections 2 and 3 a formulation based on CZM and its results are presented; a formulation based on CDTs is introduced in Section 4; in Section 5 the obtained results of the CDT models are showed as well as a general discussion; and finally the conclusions of the presented work are listed.

2. Formulation based on the cohesive zone model (CZM)

In this section the nominal strength of infinite quasi-brittle open hole specimens under biaxial loading conditions, as shown in Fig. 1(a), is analyzed. The model presented is based on the Dugdale/Barenblatt CZM. The complete solution of this problem under the hypothesis of linear elastic analysis can be obtained by summation of two solutions as shown in Fig. 2. The first one is the solution of an open hole with a crack of length ℓ_{FPZ} and an applied biaxial remote stress. The second is the solution of a specimen with cohesive stress at FPZ.

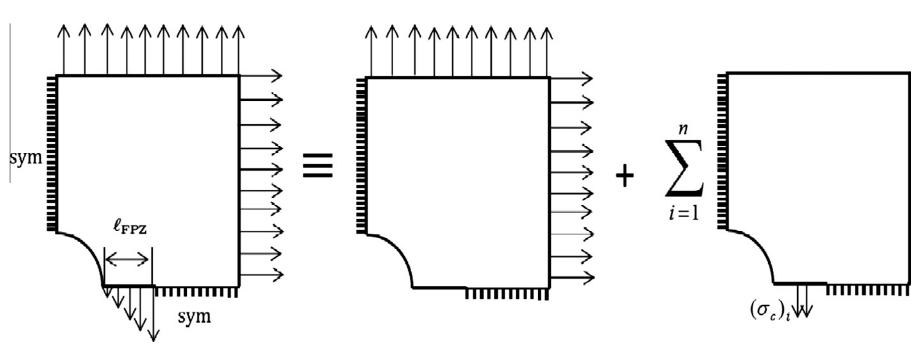


Fig. 2. Open hole specimen with a failure process zone modeled as a superposition of two linear problems.

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