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Net-tension strength of double lap joints taking into account the material cohesive law

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ABSTRACT

Bolted/pinned joints are common elements in many engineering structures and their failure can lead to catastrophic failure of these structures. Therefore, their strength prediction is essential for an accurate design of the joints and, consequently, for the reliable design of the structure. The main objective of this paper is to introduce an analytical model to predict the net-tension strength of mechanically fastened joints in isotropic quasi-brittle structures. The model is formulated based on the cohesive zone model. The effect of the material cohesive law, the contact stress distribution due to presence of the bolt, the specimen size and the hole radius to specimen width ratio on the strength of the joint are considered in the present model. The obtained predictions are compared with the available experimental results with good agreement. The present model is capable of introducing simple design charts for the bolted joints in structures made of isotropic quasi-brittle materials.

1. Introduction

Most of aircraft and aerospace structures contain many components joined together. These components should be occasionally disassembled for inspection and, eventually, replacement of the damaged parts. Bolted joints are a preferred option as mechanical fasteners for this purpose because they can be easily assembled and disassembled. Although riveted joints are more difficult to remove than bolted joints, they are widely used in these structures.

Since these joints act as load transfer elements in many engineering structures, the performance of these structures is greatly dependent on their behavior. Reliable design of the mechanically fastened joints requires an accurate prediction of its strength depending on the expected type of failure. Bearing, net-tension, shear-out and cleavage are the most frequent types of failure encountered in bolted joint connections. Net-tension and cleavage failures are abrupt, whereas bearing and shear-out are more ductile.

In bolted joints, there are more than one measure of the stresses applied to the joint. They are defined by the bearing load (L) divided by some characteristic length of the structure. At the same time they can be normalized with respect to the material strength (σ_u). The remote stress (σ_∞) in its normalized form can be given by:

$$\bar{\sigma}_\infty = \frac{\sigma_\infty}{\sigma_u} = \frac{L}{2Wt\sigma_u} \tag{1}$$

where $\bar{\sigma}_\infty$ is the normalized remote stress, $2W$ is the specimen width and t is the specimen thickness. This measure of the joint stress is the one used in the ASTM standards [1,2].

Sometimes, it is more interesting to define the mean stress at failure plane (σ_N), the nominal stress, by the bearing load divided by the net area, $\sigma_N = L/[2(W-R)t]$, where R is the hole radius. This is the usual measure of stress in stress concentration handbooks as Peterson [3]. Another possibility is to use the hole radius as a measure of the applied stress [4], $\sigma_b = L/(2Rt)$, where σ_b is the bearing stress. These measures of stress, in normalized form, can be related by:

$$\bar{\sigma}_\infty = \bar{\sigma}_N(1-\theta_W) = \bar{\sigma}_b\theta_W \tag{2}$$

where $\bar{\sigma}_N = \sigma_N/\sigma_u$ is the normalized nominal stress, $\bar{\sigma}_b = \sigma_b/\sigma_u$ is the normalized bearing stress and $\theta_W = R/W$ is the hole radius to specimen width ratio.

The net-tension strength of bolted joints in composites is neither defined by perfectly elastic nor perfectly plastic analysis [5,6]. This intermediate response is attributable to the stable growth of the Failure Process Zone (FPZ) before failure in

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quasi-brittle materials. The size of the FPZ (ℓ_{FPZ}) depends on the material characteristic length (ℓ_M) which is considered as an inverse measure of the material brittleness [7] given by:

$$\ell_M = \frac{EG_C}{\sigma_u^2} \tag{3}$$

where E is the Young's modulus and G_C is the critical fracture energy of the material. Under bearing load, the plastic and elastic limits are defined with respect to the normalized nominal stress as:

$$(\bar{\sigma}_N)_{\text{Plastic}} = 1 \quad \text{and} \quad (\bar{\sigma}_N)_{\text{Elastic}} = \frac{1}{K_t} \tag{4}$$

where K_t is the stress concentration factor due to the bearing stress. To define the corresponding normalized stresses with respect to the gross area or the hole radius, Eq. (2) can be used.

The joint geometry, loading, strength limits and failure modes when the ratio of the end distance to the hole diameter ($\theta_e = e/(2R)$) is sufficiently large are shown in Fig. 1. In this figure, e refers to the end distance and $(\bar{\sigma}_\infty)_f$ is the remote stress at failure $(\sigma_\infty)_f$ in its normalized form. The factor K_t depends on the contact stress profile due to the bolt and the geometric parameters θ_W and θ_e [3,4]. Therefore, the elastic limit in Fig. 1 is plotted according to Peterson's data [3]. Also, the bearing strength (S_b) depends mainly on the hole radius and the material compressive strength. The bearing limit in Fig. 1 corresponds to a $[90/0/\pm45]_{3s}$ IM7-8552 CFRP laminate [8,9], where $S_b = 737.8$ MPa and $\sigma_u = 845.1$ MPa. It must be noted that, at the bearing limit $\bar{\sigma}_{bf} \equiv \bar{S}_b$, where $\bar{S}_b = S_b/\sigma_u$ is the normalized bearing strength and $\bar{\sigma}_{bf} = \sigma_{bf}/\sigma_u$ is the normalized form of the bearing stress at failure (σ_{bf}).

Bearing failure is non-catastrophic and is characterized by damage accumulation and permanent deformation of the hole [8]. Typically, the bearing strength is defined when the permanent deformation is 4% of the hole diameter [2]. In composite materials this will happen before the other modes of failure when θ_W is less than 1/4 provided that θ_e is sufficiently large [10]. As θ_W increases, the failure mode shifts from bearing to net-tension failure. The maximum strength of the joint is expected around the transition from bearing to net-tension failure, within the range $1/4 \leqslant \theta_W < 2/3$ for many joints [11].

Experimental studies have been extensively used for investigation of failure mode and failure load of several types of joints [8,12–19]. They confirm that the net-tension strength of the joint has a value between the elastic and the plastic limits [8,19]. Experimental work gives very reliable design indications, but it is expensive and time consuming.

Numerical techniques are frequently used for strength prediction of the bolted joints [13,16,18]. These methods require complex continuum damage models implemented in the finite element method. Even though the numerical techniques are accurate and able to simulate complex geometries, they are complicated and still very time consuming.

Also, semi-analytical models have been developed for the strength prediction of bolted joints of composite structures. Most of the available models are stress based [20], in which a failure criterion is applied at a point, or averaged, at some characteristic distance of the maximum stressed point [8,21–24]. Others, are based on the linear elastic fracture mechanics [25] by assuming the presence of a characteristic flaw at hole boundary [22,26]. However, the characteristic lengths of both methods are dependent on size and geometry [27]. Finally, a combination of stress and fracture method [28,29] is used in [19]. All these methods result in predictions able to detect the notch sensitivity so that the resulting joint strength is defined between the elastic and plastic limits.

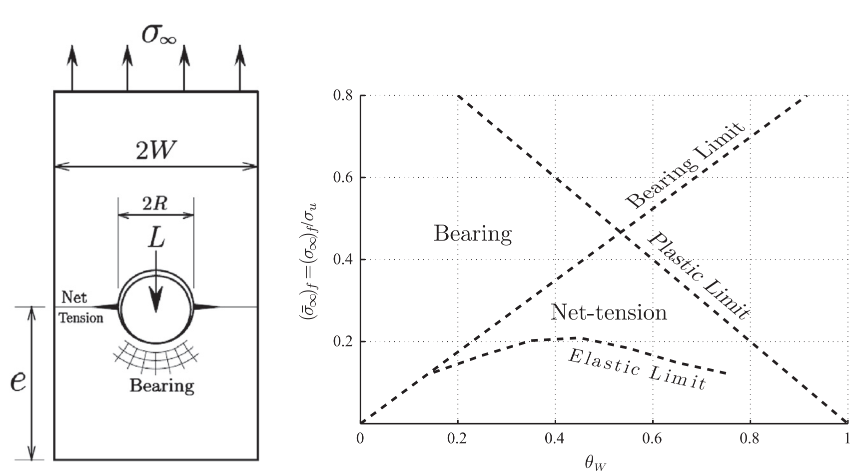
More sophisticated methods are obtained by considering the failure process zone explicitly. These models assume that the dissipation mechanisms are localized in the failure plane and described by means of a cohesive law. Usually, these models are implemented in finite elements [30] or solved by means of the application of the Dugdale condition [31,32]. Hollmann [33] applied the cohesive zone model for simultaneous net-tension and shear-out failure analysis of composite laminates containing a bolt-loaded hole. These models offer a link between a material cohesive law and the structural strength.

From the literature, it is clear that there is a shortage in analytical models that predict the net-tension strength of the bolted joints. So, the objective of the present work is to develop an analytical model to predict the net-tension strength of the bolted joints of isotropic quasi-brittle structures. The presented model is based on the cohesive zone model and concerned with double-lap joints of a single bolt. By-pass stresses are not considered in this work.

The paper is organized as follows: In the next section a mathematical formulation of the problem based on the cohesive zone model is presented. The obtained results as well as a general discussion are presented in Section 3. Finally, conclusions are summarized at the end of the paper.

2. Numerical model for net-tension failure

A numerical model for the net-tension failure of mechanically fastened joints of isotropic quasi-brittle structures is introduced



(a) Geometry and Loading (b) Strength limits and failure modes for large θ_e

Fig. 1. Geometry, loading and failure modes of bolted joints when θ_e is large enough.