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Net-tension strength of double-lap joints under bearing-bypass loading conditions using the cohesive zone model

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ABSTRACT

Tensile failure is a primary failure mode in structures with multi-fastener joints specially for large bypass loads. Therefore, the precise prediction of the net-tension strength of these joints is essential for reliable design of many engineering structures. In this paper the analytical model presented by Kabeel et al. (2014) has been extended to predict the net-tension strength of double-lap joints under combined bearing-bypass loading conditions. Due to the ability of the cohesive law to predict the effect of the structure size on its strength, the present model is formulated based on the cohesive zone model. The effect of the bypass stresses on the joint net-tension strength has been studied. The present model is able to predict the optimum geometry of the joints and, consequently, its maximum nominal strength. A comparison of the obtained predictions with those of the available experimental work reveals good agreement. The obtained results can be used as design charts for the double-lap joints that are made of isotropic quasi-brittle materials.

1. Introduction

Mechanical fasteners are used extensively in aerospace and many other engineering structures as load transfer elements. The majority of mechanically fastened joints in these structures are multi-fastener joints. These joints act as weakness spots in the structure because of high stress concentrations due to the presence of holes and fasteners. Therefore, an accurate strength prediction of these joints is essential for a reliable design of the structure.

To determine a multi-fastener joint strength, first the load distribution between joint fasteners must be determined. Then, the critical bolt-hole is analyzed under its bearing and bypass stresses to obtain the joint strength according to the expected failure mode.

Load distribution in multi-bolt joints has been investigated by many authors using different methods. Some of them [1,2] used experimental techniques in their investigations. Others used numerical methods such as the finite element method [3–5] and the boundary element method [6]. Analytical methods such as the complex variable approach [7,8], the boundary collocation method [3,9] and spring-based methods [10,11] are also used to study the load distribution in these joints. Using these analyses it is possible to determine the critical fastener-hole. Accordingly, the ratio between the bearing and the bypass load of this hole can also be determined.

In multi-row joints, fasteners in the same row almost carry equal load portions [5–9] provided that all fasteners are symmetrically positioned in the joint and have the same clearance and friction conditions. In addition, the most loaded row in the joint is one of the most outer rows. Also, in single-column joints the critical fastener-hole is one of the most outer holes [1,3,4,10,11]. Fig. 1 shows the multi-fastener joints in a single-column or in a double-column. In this figure $2W$, R, e and L are the joint width, the hole radius, the edge distance and the total applied load respectively, while L_{bi} is the bearing load of the corresponding fastener and i refers to the fastener number.

Cleavage, shear-out, bearing and net-tension failures are the common failure modes encountered in mechanically fastened joints. Generally, the joints are designed to avoid shear-out and cleavage failures [5]. This can be achieved by using a sufficiently large edge distance and a sufficient number of off-axis plies in case of laminate joints that are made of unidirectional plies. Bearing failure is characterized by a permanent deformation of the hole. It is a gradual, progressive and in-plane failure mode. Being easy to detect and a non-catastrophic failure mode, it is desired in some practical applications [12]. Conversely, net-tension failure is an

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abrupt and catastrophic failure mode. In spite of its dangerousness, it is a primary failure mode in multi-bolt joints specially for large bypass loads [13–15]. Therefore, the net-tension strength prediction of these joints is of great importance for a reliable design of many engineering structures.

In case of a single-fastener, the joint strength can be controlled with the joint geometry for a given material and applied load. A more complex load situation is encountered in multi-fastener joints. This is because of the interaction of the bearing-bypass stress concentrations. Therefore, the bypass stresses play an important role in controlling the failure of these joints [11]. A measure of the bypass ratio (ζ) can be defined as the ratio between bypass (L_B) and bearing (L_b) load as:

$$\zeta = \frac{L_B}{L_b} \tag{1}$$

The joint net-tension strength is the mean stress at failure plane ($\sigma_N = L/(2W - R)t$) just before failure. L is the sum of the bearing and the bypass load; in the most outer row it is the total load transferred by the joint. σ_N can be normalized with respect to the material strength (σ_u) as: $\bar{\sigma}_N = \sigma_N/\sigma_u$. Also, it is related to the normalized total remote stress ($\bar{\sigma}_\infty = \sigma_\infty/\sigma_u = L/(2Wt\sigma_u)$) and the normalized bearing stress ($\bar{\sigma}_b = \sigma_b/\sigma_u = L_b/(2Rt\sigma_u)$) by:

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

where $\theta_W = R/W$ is the ratio of the hole diameter to the joint width.

The net-tension strength of mechanically fastened composite joints occurs between the material elastic and plastic limits [13,16,17]. The existence of a stable fracture process zone (FPZ) before failure in quasi-brittle materials is the reason for this behavior. The size of the FPZ ($\mathcal{L}_{\mathrm{FPZ}}$) depends on the material characteristic length (ℓ_M) which is considered as an inverse measure of the material brittleness [18] and 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.

For constant geometry -constant θ_W – the brittle failure is reached when the relative size of the fracture process zone with respect to the joint size ($\bar{\ell}_{\mathrm{FPZ}} = \ell_{\mathrm{FPZ}}/R$) is very small. This happens in very large joints. On the other extreme, when $\bar{\ell}_{\mathrm{FPZ}}$ is very large, the stress field in the whole joint approaches its material strength and the joint failure is ductile. This occurs in case of very small joints. The elastic and plastic limits are defined with respect to the normalized net-tension stress as:

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

where K_t is the stress concentration factor due to the combined bearing-bypass stresses, as shown in Fig. 2 [19].

As the bypass load tends to zero, the joint response is the same as that of the single-fastener joint. Conversely, when it is near to the total applied load, the joint strength approaches that of the open hole specimen with the same material and geometry. The expected net-tension strength for these joints is shown in Fig. 3, where $\bar{\ell}_M = l_M/R$ is the inverse of the normalized hole radius and $\bar{\sigma}_{Nf} = \sigma_{Nf}/\sigma_u$ is the normalized form of the nominal stress at failure (σ_{Nf}). The expected strengths of this figure are correspond to $\theta_W = 0.128$ [20,21].

The literature shows that the problem of mechanically fastened joints is very important in engineering structures. Also, it shows that the majority of the available models for predicting strength of multi-fastener joints are numerical models. It is well known that the analytical models have the advantage of its ability to predict the behavior of these joints in a few minutes. Thus, the main objective of this paper is to develop an analytical model able to predict the net-tension strength of multi-fastener double-lap joints. The present model is based on the cohesive zone model which is able to predict the effect of the structure size on its strength. Moreover, it takes into account the material softening that occurs before fracture which is neglected in most of other models. The present model is restricted to the joints that are made of isotropic quasi-brittle materials.

This paper is arranged as follows: in Section 2, a numerical model for net-tension failure of multi-fastener joints is presented. The obtained predictions are presented in Section 3. A general discussion is introduced in Section 4, where a simple analytical model for calculating the bypass to the bearing load ratio of the critical bolt in the joint is described. Also, it is explained how to find the optimum design of the joint. Finally, at the end of the paper conclusions are summarized.

2. Numerical model for net-tension failure of multi-fastener joints

Multi-fastener joints can be modeled as a single-fastener joint under combined bearing-bypass loading conditions as shown in Fig. 4(a). As mentioned before, L_b represents the load supported by the critical fastener, whilst L_B represents the corresponding bypass load. The present formulation is based on the cohesive zone

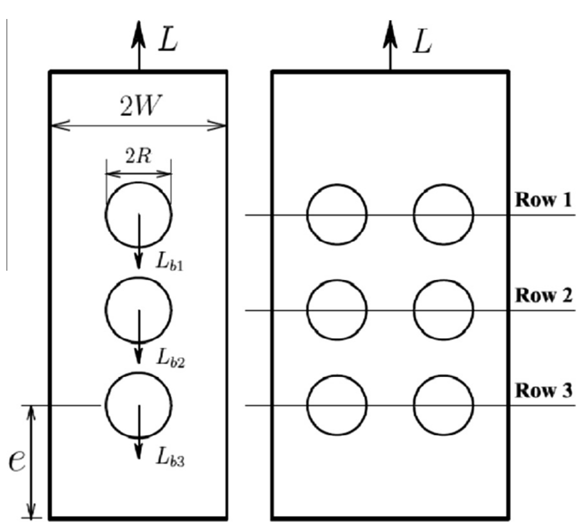

Fig. 1. Single-column and double-column of multi-row joints.

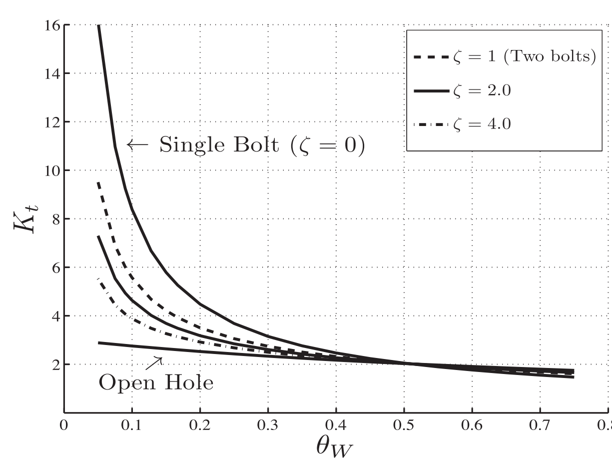

Fig. 2. Stress concentration factors for multi-fastener joints.