Aerospace Science and Technology 36 (2014) 36–43

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Pre-tensioning effect on fatigue life of bolted shear joints

Taha Benhaddou [a,b,*], Clement Chirol [b], Alain Daidie [a], Jean Guillot [a], Pierre Stephan [a], Jean-Baptiste Tuery [b]

[a] Institut Clément Ader Impasse Didier Daurat Prolongée, 31400 Toulouse Cedex 04, France
[b] Airbus Operations SAS, 316 Route de Bayonne, 31060 Toulouse Cedex 9, France

ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form 20 February 2014
Accepted 8 March 2014
Available online 17 March 2014

Keywords:
Fatigue joints
Shear joint
Preload
Finite element analysis
Multiaxial criteria

ABSTRACT

A number of experimental studies have demonstrated that pre-tensioning fasteners significantly increases the fatigue life of shear joints. Fatigue life prediction for clamped joints is still a complex and unresolved issue because of the mixed nature of load transfer, which partly occurs by frictional forces. This article presents a calculation method based on a multiaxial-type critical-plane criterion, which determines the fatigue life and fatigue crack initiation site. For this purpose, the values of hydrostatic pressure and amplitude of maximum alternating shear stress on a critical octahedral plane are determined at each point of the structure and for each loading increment, and are used to predict the fatigue life of the joint. A dedicated experimental study was conducted within materials & processes airbus laboratory to validate the numerical results. In addition, a dimensionless parameter *Rs* is introduced to quantify the proportion of load transferred by friction and by bearing of the bolt, and allows the optimal preload to be approximated, above which value more clamping should not give further improvement. This value characterizes the shift of the crack location from the net section to the outside of the compressed area.

1. Introduction

Fatigue failure in aeronautical structures frequently occurs in the joints. Various catastrophic accidents due to fatigue have been reported in the literature [15]. In consequence, joints are a major issue for designing against fatigue. Fastener joining is widely used in the manufacture of structural joints for aeronautical applications as it has a number of advantages: it is a low cost process, it can join hybrid materials, and structural parts can be disassembled and replaced without damaging the remaining parts. In fact, bolted joints have higher strength and fatigue resistance than riveted ones [25]. Good ways to improve the fatigue life of joints are cold expansion of the fastener holes, pre-tensioning of fasteners and installation of interference fit bolts [8,26,16]. The three processes induce compressive stresses and elastic or plastic deformation around the hole and the effect thus depends largely on the joint type. Studies related to the effect of fit tolerance show that interference mounting significantly increases the fatigue life of shear joints and the optimal gain is reached for an interference ratio of 1 to 2% [11]. Some recent studies have investigated the effect of preload for either single lap [16] or double lap shear joints [16,5]. The authors [16] and [7] also show a high benefit of preload for shear joints under constant–amplitude loading with a load ratio $R = 0$. The preload threshold value is then set by the strength of the fastener and the admissible mating pressure under the bolt's head.

Other numerical studies examine the joints installed with preload and interference [6] as reported by Chakherlou and Abazadeh [4], for example. They indicate a good correlation with experimental results concerning the application of criteria for fatigue life prediction but the authors do not generally explain their specific development.

Mastering the process of interference fit mountings is a difficult task compared to preload tightening (Guillot [13]). In fact, these two types of installation can lead to the same benefit in fatigue. The present study focuses on the influence of preload on the fatigue life of shear joints and proposes a prediction method to estimate the fatigue resistance of joints.

Most previous studies [8,7,4] were made on a single plate with a hole at its centre and extrapolated to the fatigue life of complex joints. This approach is applicable only for lightly clamped joints and not for highly preloaded joints. In fact, high preloading modifies the state of stresses in the joint because of the presence of frictional forces between the plates [22]. Depending on the preload

---

[*] Corresponding author at: Institut Clément Ader Impasse Didier Daurat Prolongée, 31400 Toulouse Cedex 04, France. Tel.: +33 58 205 5565.

E-mail addresses: Taha.Benhaddou@insa-toulouse.fr, Taha.Benhaddou@airbus.com (T. Benhaddou), Clement.Chirol@airbus.com (C. Chirol), Alain.Daidie@insa-toulouse.fr (A. Daidie), Pierre.Stephan@univ-tlse2.fr (P. Stephan), Jean-baptiste.Tuery@airbus.com (J.-B. Tuery).

http://dx.doi.org/10.1016/j.ast.2014.03.003

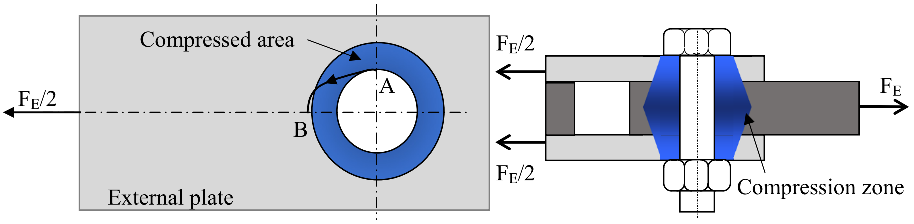

Fig. 1. Location of fatigue crack initiation in relation to preload.

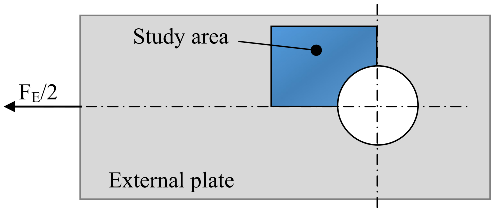

Fig. 2. Definition of study area.

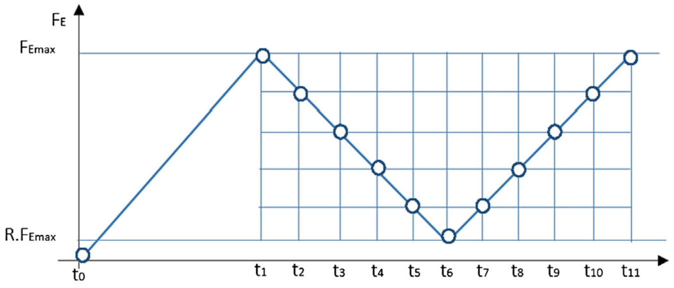

Fig. 3. Definition of loading steps.

value, much of the load, if not all, is transmitted by friction [23]. The state of stress at the compressed area is modified [7] and the fatigue initiation point is no longer located at the notch root (point A, Fig. 1) as reported for bearing type joints but tends to be located outside the compressed zone (point B, Fig. 1) [20,2,3].

This migration of the initiation point makes it necessary to perform complex calculations by applying multiaxial criteria instead of the empirical calculations based on the K_T coefficient for the stress concentration factor that are commonly made for non-preloaded joints.

2. Theoretical approach

The approach presented here concerns double-lap bolted joints characterized by mixed load transfer: the load is transmitted by friction until the bolt comes into bearing. The symmetry of shear planes prevents bending of the plate material (see Fig. 1). Experimental observations show that the sites of crack initiation depend on the level of preload applied: at null or low preload, the coefficient of stress concentration in the notch root is maximal so the fatigue failure usually occurs on the net section while, at high preload, the fatigue crack is initiated on the gross section. The symmetry allows the study area to be defined as in Fig. 2.

The loading cycle is composed of three distinct phases as specified in Fig. 3. The first is related to the introduction of the preload (t_0); in the second, we apply the maximal load $F_{E_{\max}}$ ($t_0 \rightarrow t_1$) and the third is composed of 11 steps that describe an unloading/loading cycle ($t_1 \rightarrow t_{11}$) (Fig. 3). These loading steps are necessary to take account of the hysteresis that occurs due to the dry friction between plates [22,23].

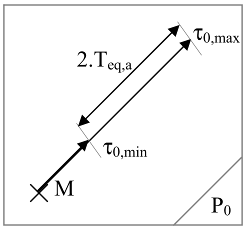

Fig. 4. Calculation of $T_{eq,a}$ for case 1.

2.1. Multiaxial criteria selection

Nowadays, many multiaxial fatigue models and large amounts of data are available in the literature. During the past years, several multiaxial fatigue criteria have been developed and listed in reference books [12]. Recently, studies based on energetic and volumetric formulations [17] or special formulations taking metal or shape defects into account [24] have emerged. However, in spite of the number of criteria proposed, no existing multiaxial fatigue damage model is universally accepted.

On the basis of these qualitative observations accepted by fatigue specialists, different criteria are proposed in the literature [18,1]. In the present study, we develop an approach based on a critical plan criterion which was chosen because it is easy to implement and to apply to a complex joint in an industrial context. The formula proposed is a linear combination of the maximum amplitude of the equivalent shear stress variation and the maximum hydrostatic pressure value within a loading cycle [18], as presented in Eq. (1).

$$T_{eq,a} + B_N P_{H_{\max}} \leqslant A_N \tag{1}$$

where:

A_N and B_N are material-related parameters extracted from experimental tests and defined for a lifecycle N,
$T_{eq,a}$ is the maximum amplitude of equivalent shear stress variation within a loading cycle,
$P_{H_{\max}}$ is the maximum hydrostatic pressure within the loading cycle.

The stress tensor extracted from the output of FE simulation allows these two parameters to be characterized. In fact, considering the principal stresses enables a rapid calculation of the maximal hydrostatic pressure at each point of the loading cycle (Eq. (2)).

$$P_{H_{\max}}(M) = \frac{1}{3}\max(t)\big[\sigma_1(t) + \sigma_2(t) + \sigma_3(t)\big] \tag{2}$$

2.2. Determination of shear stress amplitude

How $T_{eq,a}$ is determined depends on the loading case.

Case 1

Principal axes are fixed during the loading cycle and stress tensor components are proportional to loading (see Fig. 4).