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Investigations on the fretting fatigue failure mechanism of bolted joints in high strength steel subjected to different levels of pre-tension

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ABSTRACT

Bolted connections are widely used as an effective joining method with higher fatigue strength than equivalent welded and riveted joints. The fretting fatigue problem caused by components in contact subjected simultaneously to fluctuating loads and relative small movements is of special importance in the vicinity of bolted joints. In the present paper, a series of fatigue tests on bolted connections using moderately thick plates made of high strength steel S500MC carried out using different pre-tension levels is described. It was shown that fretting fatigue decreased when a higher pre-tension force is used. In addition, a 3D finite element model was built to assess the stress gradient in the connection and several multiaxial criteria were used to determine the location of the initial crack. These numerical results were correlated to the experimental results and showed acceptable predictions.

1. Introduction

Reducing the weight of the structural components has always been a target in structural design, to allow for a decrease of materials consumptions provided that proper mechanical strength is maintained. This has a particular importance in vehicles and heavy duty machinery, such as trucks, excavators and agricultural machinery, where lighter structures result in higher load carrying capacity and less fuel consumption. It has hence become a current trend to employ high strength steels (HSS) in the components of these structures, leading to a reduction of their weight [1,2].

HSS are an increasingly used generation of steels exhibiting improved properties compared to conventional steel grades. Their enhanced mechanical properties (e.g. yield strength varying from 460 N/mm^2 to 700 N/mm^2 and higher) originate from their complex microstructure obtained thanks to specific thermo-mechanical treatments (e.g. quenched and tempered). The use of HSS with yield strength up to 460 MPa in construction and mechanical applications has increased during the last decades thanks to its structural advantages [3–10]. On the contrary, the use of very high strength grades, with yield strengths above 690 MPa, in civil and mechanical engineering structures is relatively uncommon especially because of restrictive design rules and welding problems [11,12]. The susceptibility of HSS to weld defects – which is critical in mobile structures subjected to alternating stresses – indeed requires special post weld treatments to be carried out [13]. In order to avoid this problem, bolted connections are seen as a good alternative to welded equivalents. The fatigue strength of HSS bolted connections and especially their fretting fatigue behaviour remains however scarcely investigated in the scientific literature.

Bolted connections are used as an effective and versatile joining technique in a variety of engineering applications. Design rules for bolted connections are widely available in European standards [14,15] together with extensions to include higher steel grades [16]. The fatigue strength curves and detail categories in [17] are mainly based on fatigue tests carried out on bolted and welded carbon steels details with nominal yield stress ranging from 235 to 400 MPa i.e. mainly S235 and S355. And, even if the part 1–9 may cover higher structural steel grades given in EN 1993-1-12 (S235–S700), the phenomena governing the fatigue resistance of HSS welded joints are currently not perfectly known. In [18], Puthi el at. investigated the effect of bolt spacings and edge distances in bolted connections made of S460 and underlined that the current guidelines may lead to overly conservative design dimensions. Moze et al. [19,20] came up to similar results for S690 double shear plane bolted connections. Shi et al. [21] tested bolted connections made of Q460 and concluded that the design guidelines from [17]

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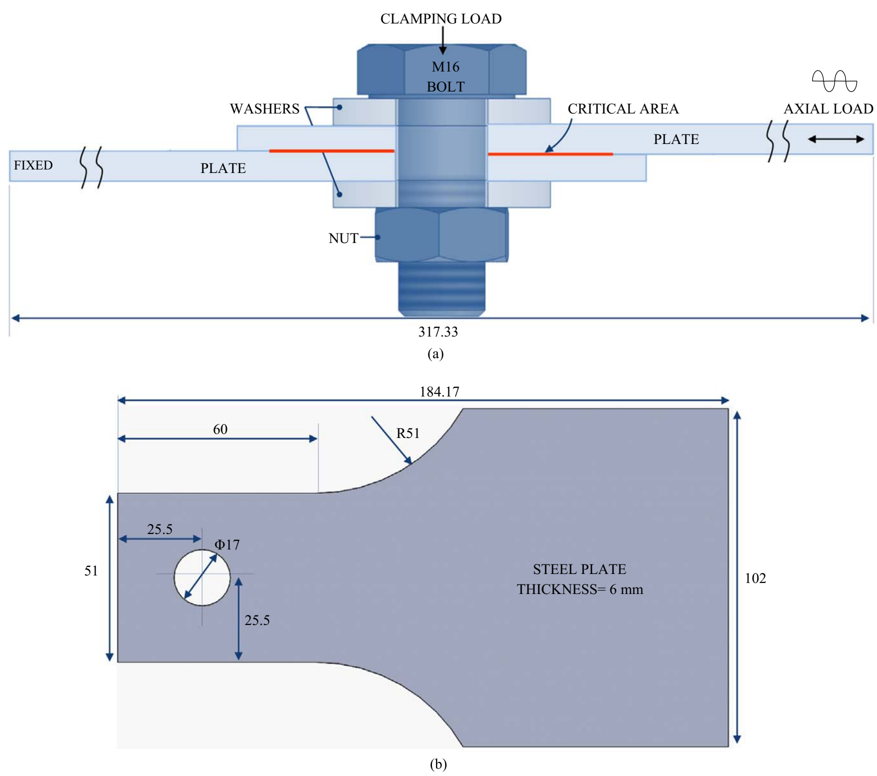

Fig. 1. (a) Assembly view of the SLBJ specimen (b) Geometry of the dog-bone HSS specimen.

provide unsafe bearing capacity and cannot appropriately predict the failure modes. Despite the fact that the existing literature on fatigue of bolted connections in HSS is currently limited, Hämäläinen [22] has reported the susceptibility to fretting fatigue of bolted connections made of S960QC and the possible challenges linked to it. Fretting fatigue damage is reported as one of the principal failure mechanisms in bolted connections [23]. In slip-resistant joints, small oscillatory relative movements cause fretting between surfaces in contact. This phenomenon leads to very high local stresses and wear, which can lead to premature crack nucleation.

Several factors affect the behaviour of the bolted joint and its resistance to fatigue. The pre-tension force (also known as preload or clamping force), which is applied to the bolt and compresses the joined components against each other, is one of the most significant parameters. It creates frictional forces among the mated surfaces to carry shear loads. Many reference studies [24–28] were achieved on the effect of the preload on the fatigue life of bolted connections, for a broad range of materials and joint configurations. However, contradictory results have been reported. For example, Valtinat et al. [27] concluded that the pre-tension of the bolt has a major positive influence, as the subsequent high pressure produces a more favourable stress state around the hole in carbon steel members. As for Minguez in [28], he indicates that the increase of the preload force in single lap joints made of aluminium alloys had no significant repercussion on the fatigue life, whereas in double lap joints, the higher the preload the higher the fatigue resistance. Moreover, Benhamena [29] reported the negative effect of the preload force on the fatigue life of bolted connections made of steel and aluminium. The great majority of these investigations focus on aluminium and titanium alloys due to their importance in the aerospace industry, whereas little research has, so far, been addressed to the effect of the preload force in connections made of HSS. Overall, there exists currently a lack of knowledge on the fatigue strength of bolted connection made of HSS and a confusion on the effect of the preload force on the fatigue strength of bolted connections.

As the contact interface in a bolted joint is concealed between the plates, Finite Element Analysis (FEA) allows to study many more topics, such as the distribution of slip and frictional shear stress under different loading conditions, than tests performed in a laboratory. It has been shown that the FEA modelling approach is a suitable methodology to investigate the behaviour of bolted connections under different contact conditions [30–33]. Several authors have used this approach to carry out numerical studies including a thorough representation of the contact problems in bolted connections [24–26]. In [34], Esmaeili used the data extracted from FEA to evaluate the suitability of different multiaxial criteria for the prediction of fatigue strength in bolted connections. Although their research did not focus on fretting fatigue, they demonstrated that some of the studied multiaxial criteria were appropriate for estimating the fatigue life.

This research aims to extend the existing knowledge about the failure mechanisms of HSS bolted connections submitted to fretting fatigue and to evaluate the effect of the preload force on fretting fatigue primarily variables, such as the slip amplitude or damage at the contact interface, among others. For this purpose, this paper is organised as follows: Preceded by a description of the experimental set-up and of the materials under investigation in Section 2, the Finite element model (FEM) of one single bolted lap joint is thoroughly described in Section 3. The results of the study are presented in Section 4 where the experimental observations are shown along with the results from the numerical model. In Section 5, the results are analysed and conclusions for this study are provided.

2. Experimental study

2.1. Material, geometry of the specimens and preload forces

The experimental specimen is a single-lap bolted joint (SLBJ) consisting of two identical plates made of S500MC, a 10.9 M16 bolt and its respective nut (EN 14399-4) [35] and two washers (EN 14399-6) [36] placed on both sides. The geometry of the plates is depicted in Fig. 1. The end of the plates has a dog bone like shape in order to ensure a smooth stress flow. The edge distances have been chosen in