Tribology International 103 (2016) 440–448

Contents lists available at ScienceDirect

Tribology International

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

Experimental and numerical investigation of fretting fatigue behavior in bolted joints

Janne Juoksukangas [a,*], Arto Lehtovaara [a], Antti Mäntylä [b]

[a] Group of Tribology and Machine Elements, Department of Materials Science, Tampere University of Technology, P.O. Box 589, 33101 Tampere, Finland
[b] Research & Development, Wärtsilä Finland Oy, P.O. Box 244, 65101 Vaasa, Finland

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form
25 July 2016
Accepted 26 July 2016
Available online 27 July 2016

Keywords:
Fretting
Contact
Fatigue
Finite-element method

ABSTRACT

Bolted joints may suffer from fretting damage which can significantly decrease fatigue life. A testing arrangement was developed to study the effect of different operating and design parameters of a single bolted joint on fretting fatigue life. Fretting fatigue stress-life (S-N) tests were conducted to investigate in particular the effect of bolt preload and cyclic bulk loading on fatigue life. Fretting fatigue life decreased when increasing the preload and also when increasing the bulk stress. The Digital Image Correlation method was applied to measure tangential displacements close to the contact. A corresponding finite element model of the test setup was used to analyze contact variables in greater detail. The numerical results corresponded well to the experimental results.

1. Introduction

In mechanical engineering, bolted joints are often used in assemblies to clamp parts together and to transfer loads. However, bolted joints may suffer from fretting damage, which is one of their major failure mechanisms [1]. Fretting refers to small oscillatory relative movement between connected parts under normal loading. Fretting can lead to high local stresses, surface damage and wear that can further lead to fatigue crack nucleation.

The main operating parameters in bolted joints are bolt preload (creating normal load in the contact) and external cyclic bulk loading of bolted parts. The purposes of the bolt preload are to clamp parts together and to create frictional forces between the bolted parts to carry shear loading. Preload affects the sizes of the stick (adhesion) and slip zones of contacts during fretting loading [2]. Typically, at low or negligible preload, the point of fatigue cracking is at the bolt hole where the hole induced stress concentration exists [2,3]. A preloading with compressive stress can decrease the stress concentration effect at the bolt hole and thus increase fatigue life [1,3–6], which has also been shown in riveted joints [7]. An increase in preload can move the point of cracking away from the area of the hole and produce a further increase in fatigue life [1]. However, even when the cracking point is moved outside the stress concentration area, fatigue life can be decreased due to fretting [2,3]. In addition, the value of coefficient of friction (COF) has an effect on the point of cracking. In an experimental study [3], the COF was reduced by lubricating the contact and the point of cracking moved to the hole edge area, resulting in reduced fatigue life. The predominant wear mechanism has been observed to change from adhesive wear to abrasive wear when increasing preload [2]. A hybrid joint (e.g. an adhesive layer between bolted plates) can notably decrease stress concentration at the bolt's hole [8,9] and it can have longer fatigue life compared to pure bolted joints [8]. An interference-fitted bolt may also increase the fatigue life of a joint [10].

Typically, experimental testing relating to bolted joints is carried out using commercial material fatigue testing machines with axial loading of the specimens [1–3,8,11–16]. Considering practical bolted connections, bending loading may commonly exist. However, bending loading has been used less frequently, e.g. [17]. Ultrasound technique has been used to study contact pressure distribution [18] and cracking [5,11]. Numerical studies, based mainly on the finite element method (FEM), have been carried out to study the contact behavior of bolted joints [2,6,9,19–24], to predict fretting fatigue life [6,14,19,25–27] and to apply fracture mechanics [6,8]. Analytical solutions have been developed to study contact quantities [28], and to control the preload [29]. The bolt loosening has practical importance and has been studied, for example, in Ref. [29,30].

Relative tangential movement, slip, between contacting parts is an important variable in fretting. Tangential displacements in the contact are typically measured using a linear variable differential

* Corresponding author.
E-mail addresses: janne.juoksukangas@tut.fi (J. Juoksukangas), arto.lehtovaara@tut.fi (A. Lehtovaara), antti.mantyla@wartsila.com (A. Mäntylä).

http://dx.doi.org/10.1016/j.triboint.2016.07.021
0301-679X/

transformer (LVDT) or an extensometer, but such measurements also include compliances of the test device. Moreover, displacement of only one point can be measured. Alternatively, a Digital Image Correlation ('DIC') can be used to measure the displacement field of a fretting contact and, in turn, the relative tangential displacements (slip). DIC is an optical method that uses captured digital images of loaded structures to resolve displacements [31]. DIC has previously been applied to fretting contacts, e.g., [32,33]. In bolted joints, numerical results have been compared to DIC measurements with good accuracy and the coefficient of friction has been identified as a function of loading cycles using the FEM and DIC [15]. The materials in contact were aluminum alloy and carbon/epoxy. DIC has been used to analyze a bolted joint under vibration loading [34].

Although there are several studies relating to fretting fatigue in bolted joints, there is still a need for further research to gain a more complete understanding of fretting behavior in bolted connections. Though quenched and tempered steels are commonly used materials in heavy load conditions, relatively little attention has been given to their fretting fatigue behavior. For example, in medium speed combustion engines, parts are under heavy loading conditions where the contact surfaces need to transfer high contact tractions. In bolted lap joint studies, the focus is on aluminium and titanium alloys in the literature. Therefore, there is a need for fretting research in bolted joints made of quenched and tempered steels. Here, a single bolted joint was studied both experimentally and numerically. A test setup was developed to study, mainly, the effect of joint preload and bulk loading on fretting fatigue life using bending loading. Several fretting fatigue tests were carried out with different operating and design parameters. The Digital Image Correlation method was applied to measure tangential displacements close to the contact which were used further together with a corresponding finite element model to evaluate the coefficient of friction of the contact. The model was used to study contact variables in greater detail.

2. Experiments

2.1. Test device

A previously developed complete contact fretting test device was used here [35]. Only minor modifications were needed to study bolted joints. Two flat test specimens, shown schematically in Fig. 1, are clamped together at one end (main clamping). The test contact (single bolt joint) is 30 mm away from the main clamping. The cyclic bulk loading in the specimens is established by the transverse loading (displacement) applied at the specimens' free tips by an eccentric mechanism. This loading also induces the shear load to the joint under examination. Relative slip between the specimens is created as a result of the different strains in the

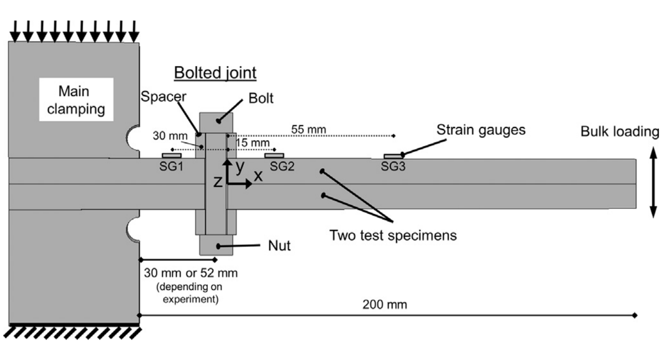

Fig. 1. Schematics of the bolted joint testing arrangement.

specimens (i.e., the contact surface of one specimen is in tension at the same time as the contact surface of the other specimen is in compression). The specimens are clamped together from the free end to apply the bulk loading. Though clamping obviously induces fretting at this point, it is supposed that it would have no significant effect on the actual test contact.

The specimen had a length of 250 mm, width of 40 mm and thickness of 10 mm. The material was EN 10083-1-34CrNiMo6+QT. Grinding direction was longitudinal and the grinding produced a *Sa* value of 0.25 μm, measured with a Wyko NT1100 optical profilometer. The normal load created by the bolt was transferred to the fretted contact via spacers. The spacers were made of steel with a height of 10 mm and the outer and inner diameters were 16 mm and 8.5 mm, respectively. The diameter of the bolt hole in the specimen was 9 mm. M8 12.9 hex socket bolt was used with a corresponding nut. FEM analysis showed that the bolt shank and the specimens do not touch under cyclic loading and this was further confirmed in the experiments.

Strain gauges were attached to the bolt to continuously measure the preload during testing. A device was built to calibrate the preload measuring arrangement against an external force sensor. Three strain gauges were attached to the upper test specimen having *x*-positions of −30 mm, 15 mm and 55 mm (Fig. 1). The bulk loading frequency was 20 Hz but during DIC measurements the loading frequency was decreased to 0.6 Hz. The tests were conducted under normal laboratory conditions with relative humidity under 45 RH and temperature between 24 and 29 °C. The tests were carried out in dry (unlubricated) conditions. Before testing, the specimens were wiped with acetone.

The experimental test matrix is shown in Table 1. Parameters were the bolt preload, bulk (bending) stress, spacer outer diameter and bolted joint position in the specimen. Three bolt preloads were used (20 kN, 25 kN and 30 kN). The preload was either close to the design value or markedly below practical loading conditions (56%, 70% and 85% of the bolt's proof strength). In series 1 and 2, the three bulk stress amplitudes at the location of the center point of the hole were approximately 130 MPa, 170 MPa and 205 MPa and were linearly scaled from the strain gauge measurements (SG2 and SG3, Fig. 1). The contact contributes to the measured stress values which can be seen in the measurements. The reported values are selected after about 80,000 loading cycles, after which the bulk stress values have somewhat stabilized. These stresses correspond to specimen tip displacement amplitudes of about 1.4, 1.8 and 2.3 mm, respectively. In series 3 and 4, the bulk stress amplitudes were 180–200 MPa. In all tests, the bulk loading was fully reversed, i.e., the desired value for stress ratio *R* was −1. Fatigue tests were run until one or both of the specimens cracked completely or the cut-off limit of three million cycles was reached.

In series 1, three preloads and three bulk stresses were used. Series 2 was a repeat series, where two tests with 25 kN preload were conducted with all three bulk loadings. In series 3, the active contact area was increased by using a larger spacer, having an outer diameter of 24 mm. The slip was increased in series 4 by moving the bolt position towards the free end. In series 5, four interrupted tests were performed to study fretting damage development. The number of cycles was approximately 40,000, 200,000, 400,000 and 600,000. The preload was 25 kN and the highest bulk loading amplitude (205 MPa) was used. A new specimen was introduced in every test. A total of 24 experimental tests were carried out.

2.2. Digital image correlation measurements

A five megapixel digital camera with 200 mm lens and an extension tube was positioned behind the test device, and with the aid of a mirror, the lateral surface of the specimens was