EFFECT OF CLAMPING FORCE ON FRETTING FATIGUE BEHAVIOUR OF BOLTED ASSEMBLIES: NUMERICAL AND EXPERIMENTAL ANALYSIS

A. Benhamena[1,2,3,4], A. Amrouche[1,2,3,5], R.R. Ambriz[1,2,3], N. Benseddiq[1,2,3], G. Mesmacque [1,2,3] and M. Benguediab [6]

[1] Université Lille Nord de France, F-59000 Lille, France.
[2] USTL, LML, F-59650 Villeneuve d'Ascq, France.
[3] CNRS, UMR 8107, F-59650 Villeneuve d'Ascq.
[4] Laboratoire LPQ3M BP 763, University of Mascara, Algeria
[5] UA, (Université d'Artois), France
e-mails: ali_benhamena@yahoo.fr,
abdelwaheb.amrouche@univ-lille1.fr, ricraf74@gmail.com
noureddine.benseddiq@univ-lille1.fr, gerard.mesmacque@univ-lille1.fr,

[6] Department of Mechanical engineering, University of Sidi Bel Abbes,
BP 89, Cité Ben M'hidi, Sidi Bel Abbes, 22000, Algeria
e-mail: benguediab_m@yahoo.fr

ABSTRACT

One of the principal failures of bolting assemblies is the fretting. The combination of vibration and service load can introduce the damage of fretting fatigue on the contact surfaces of the assembly which trend to evoke a nucleation of crack and then the structure fracture. Contact pressure or clamping force and displacement at the interface or relative slip are two important factors which control the fretting wear and the fretting fatigue. This paper describes the effect of clamping force (tightening torque) on the fretting fatigue behavior of bolted assemblies. Both fretting fatigue experiments and simulation with FEM were carried out. With the increase of contact force, the sites of cracks initiation changed from the edge of the central hole to the free edge of the contact zone and the fretting fatigue life increase dramatically. A good correlation was found between the FEM simulations and the experimental results.

KEY WORDS: Clamping force, torque, fretting fatigue, crack initiation site, adhesive wear and abrasive wear.

1. INTRODUCTION

Bolted joints in mechanical structures transmit a more important effort in various applications. According to Valtinat et al [1] bolted joints have higher tensile and fatigue strengths than welded joints. The prediction of fracture and the reliability of such assembly in various practical applications are primordial given their impact on the economic plan and security. Fretting is caused by the oscillating movement with small amplitude that may occur between contacting surfaces subjected to vibration. The oscillations cause sliding to occur in a small region at the edge of contact, while the center of contact remains stuck together. Fretting causes wear and very high local stresses to occur at or near the edge of contact, which in turn, can result in the nucleation of cracks and the reduction of the fatigue life endurance. In high speed train vehicles, the fretting fatigue can be a serious problem and is one of the costliest sources of in-service damage According to Guo et al [2]. This damage is related to cyclic loading and relative displacement at interface in such assembly. Because of its dramatic impact on structural integrity, the phenomenon of fretting has been extensively studied by various methods [3-4], analytical, numerical and experimental works have been carried out in order to achieve a better understanding the effect of some local mechanical parameters. Such as: The material behaviour, The contact pressure, the friction coefficient, the amplitude of relative displacement and tangential stress at the interface in order to predict the lifetime of assembly under fretting. The effect of contact force on the fretting fatigue life has received considerable attention from many investigations [5-8]. In the same context, an extensive examination of this subject can be found in references [9-11] in order to investigate the effect of relative displacement on the fretting fatigue life. The references cited above show that considerable work has been done to study the problems of fretting fatigue in various industrial applications. However, relatively few studies have focus only the effect of clamping force on the fatigue behaviour of bolted plates by Aragon et al [12]. In service and under cyclic loading, the relative displacement at the interface is inevitable for bolted assemblies, in addition the effect of clamping force on the stress concentration close to the hole, the frictional stresses and the friction coefficient are not fully understood and represent a very active research field. The contact force and the amplitude of relative displacement are two key variables witch to control the fretting fatigue life in bolted assemblies. This fact has lead the authors to the focus of the current study, which involves in first part, on experimental analysis to investigate the effect of contact force on the fretting fatigue life of bolted assembly, the sites of crack initiation, the fretting marks were examined by SEM/EDS. Numerical studies were carried out in order to identify the fields of compressive strain due the clamping force and to valid the FEM model.

2. EXPERIMENTAL AND NUMERICAL MODEL

2.1. Experimental procedure

The experimental part of this work is subdivided in three steps: Tension test, fatigue test and microscopic examination (SEM and EDS).

2. 1 .1 Materials and specimens

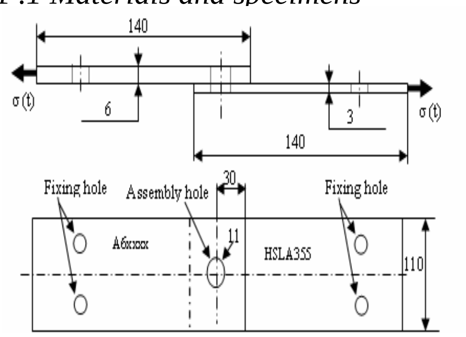

Figure 1. Specimen geometry (all dimensions in mm).

Aluminium alloy A6xxxx from 6.0 mm thickness and high strength low alloy steel (HSLA355) of 3.0 mm thickness were used to produce (6.0 mm A6xxxx + 3.0 mm HSLA355) joints for this investigation. Tensile specimens were machined with the dimensions and geometry as specified by the ASTM B557-06 designation. The quasi-static tension test was performed with a head speed displacement of 0.02 mm s-1. Tensile strain of specimens was measured with an Instron® extensometer model 2620-601. Nominal mechanical properties of the A6xxxx are 196 MPa in yield strength, 315 MPa in tensile strength, and 12% in elongation and of the HSLA355 are 525 MPa in yield strength, 585 MPa in tensile strength, and 15% in elongation, [13].

2. 1.2 Fretting fatigue test

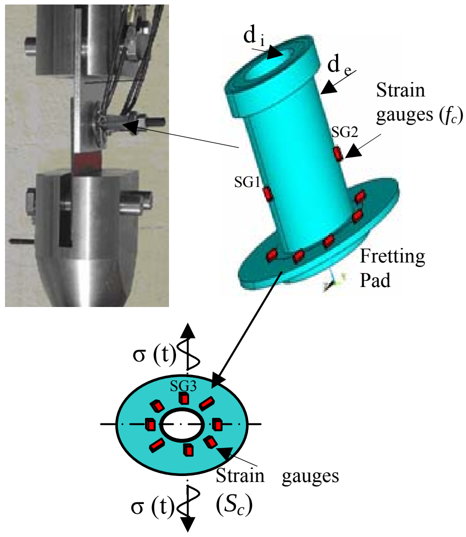

Figure 2. Schematic drawing of central part of the specimen used in fretting fatigue tests and the strain gauges

Fretting fatigue test method is shown in Fig. 1. Fretting fatigue occurs when a component subjected to cyclic loading is in contact with other component under a normal loading. Surface damage is induced by the microscopic motion at the contact surface between these two components which in turn reduces the fatigue life as compared to plain fatigue without fretting. In present work, the fretting pad was used to calibrate the fastening torque (clamping force) in the bolt during the fretting fatigue tests. The fixture, specially designed, includes steel bolts with a nominal diameter of 10 mm (M10x1.5), stainless steel nut, stainless steel washer and a pad, which is used for fixing strain gauges more easily, in order to control the clamping force. The pad was manufactured from steel with circular contact surface at the bottom (Fig.3) were stuck ten strain gauges pasted in different positions; CEA-06-062UW-120 strain gauges (SG) are used to measure the strains. At the pad, two strain gauges (SG1, SG2) have been glued on axial directions every 180o in order to measure the compressive axial strain due to the clamping force (fc) and eight strain gauges (SG3 to SG10) have been glued on perpendicular plan to axial directions every 45o in order to establish a mean value for the strain due to the cyclic loading (Sc) during the fretting fatigue test, The gauge locations (SG) are shown in Fig. 2. The pad was placed between the washer and the aluminum plate in order to control the crack initiation at contact surface (position 1, see Fig. 3). Software was developed in the environment (LabVIEU) to detect indirectly the crack initiation in a hidden area (contact zone) by the treatment of gauge signals.

Fretting-fatigue tests were conducted using constant amplitude loading using a sinusoidal waveform in tension–tension mode. The ratio of the minimum load and the maximum load or R ratio was 0.1 and the test frequency was 20 Hz in all the tests. The level of maximum load is 42.KN, which are approximately 35 percent of the average peak load observed in static tension tests of aluminum plate.

Contact pressure or clamping force and displacement at the interface or relative slip are important factors that control fretting wear and fretting fatigue. Four values of clamping force (tightening torque, T = 2, 4, 6, and 8 daNm) was taken in order to determine the effect of this parameter (tightening torque) and to localize the zone where the fretting mechanism occur in bolted assemblies during the fretting fatigue test. It is known that the strain is proportional to the clamping force. After fretting fatigue test, the strain was measured using a digital data acquisition system (LabVIEU) and the Wheatstone bridge theory. Finally, examination of the wear scars on the joining surfaces between the two plates (aluminum-steel, position 2) and the interfaces between aluminum plate and pad (position 1) were investigated by scanning electron microscopy/energy dispersive X-ray (SEM/EDX) analysis in order to characterize the type of fracture damage in contact surface and to obtain insight into the failure mechanisms.

2.2 Finite element model

Fretting tests may be carried out in the partial slip regime. As highlighted by Hills et al. [14], it is very difficult to achieve a well controlled experiment using an external actuator due to the low displacement amplitudes. Finite element analysis (FEA) is an important tool to design practical mechanical joints, such as the bolted assemblies. According to the dimensions of the structure, a three dimensional model was generated using the commercial software ANSYS® (ANSYS 11, [15]). The bolted assembly shown in Fig. 2 is symmetric in the longitudinal direction (y direction). So, a half model with symmetry conditions was used in the finite element model FEM in order to reduce the calculation time (Fig. 4a). A three-dimensional brick elements (SOLID45) is used for modelling of bolted assembly. In addition, a surface-to-surface contact element, which consists of contact elements (CONTAC173) and target surface elements (TARGE169), is used on the interfaces between all connected parts of bolted assembly in order to simulate numerically the contact problems. Friction between the contact surfaces at the connection is modeled using the classical Coulomb model, where the friction coefficient was set at 0.2. A two-step nonlinear analysis was performed.

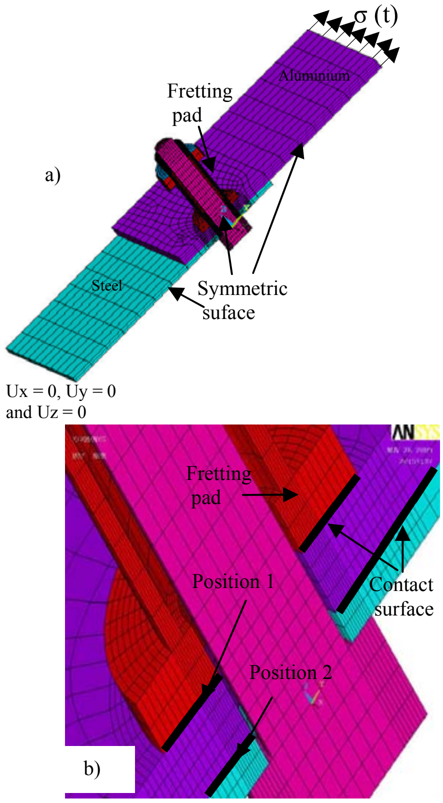

Figure 4. (a) Geometrical and finite-element mesh of assembly and (b) mesh near the contact (damaged surface: Position 1 and Position 2).

In order to simulate the clamping force numerically, in the first step, the preload (clamping force) was modelled as a uniform negative pressure applied on the screw and a positive pressure applied over a ring of 10.mm inner radius and 16.mm outer radius, this ring represents the action of the nut. This phase represent the joining of bolted assembly. After this operation, there is a relaxation of the tensile strain due to the deformability of the pad and the plates under the clamping force action, on attaining equilibrium and in the second step, this assembly was subjected to cyclic loading that generated a multi-axial stress fields at contact zone. The theory of incremental plasticity is introduced to modelling the material nonlinearity. The iterative method of Newton-Raphson is used as an approach to solve nonlinear equations by finite elements.

3. RESULTS AND DISCUSSIONS

3.1. Validation of the finite element model

The amount of tightening torque T required to achieve a set amount of preload fc (clamping force) in a bolt depends upon thread pitch, the friction coefficient in threading, bolt diameter, the friction coefficient between the nut and bolt and the mean collar diameter. For the threaded fasteners according to the ISO normalisation, there is a relationship between the tightening torque and the clamping force expressed by the following:

$$T=\left(0.161p+0.583\mu_t d+\mu_h r_m\right) f_c \qquad (1)$$

where, p: is the pitch, d : is the major diameter, fc : is the clampin force, μ t : is the friction coefficient between the nut and bolt, μ h : is the coefficient of collar friction, dm : is the mean collar diameter (dm=1.25d and dm=2.rm).

Although the torque–preload relationship can be calculated theoretically (eq. 1). But in practice it is not possible to accurately measure the bolt tension in a joint in service. So, it is better to measure both parameters (*T*, *fc*) and hence calibrate the bolt tension experimentally. To ensure that a desired preload (clamping force) has been achieved with a bolt, it is more practical to use a torque wrench to apply the load to the bolt through the nut (see Fig. 1). The axial strain measured by the strain gauges (SG1, SG2) were recorded for each applied torque level. The theoretical expression for the relation between the clamping force and the axial strain is

$$f_c=\pi\ E_p\ \varepsilon_m \frac{d_e^{\,2}-d_i^{\,2}}{4} \qquad (2)$$

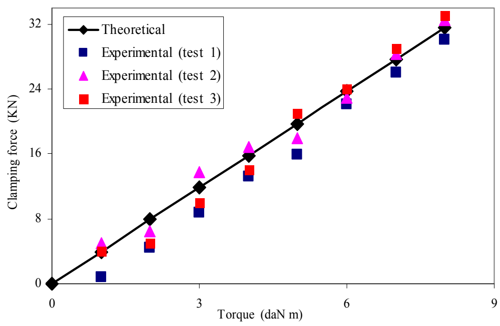

Figure 5. Clamping force versus tightening torque

where, di and de: are the internal and external diameters of the pad, respectively. Ep: is the yuong's modulus of the pad. ε_a : is the compressive axial strain mesuerd by SG1 and SG2. The theoretical (Eq. 1) and experimental results are illustrated in Fig. 5; this presents the clamping force variation according to the tightening torque. We note a fairly good agreement between the theoretical and experimental results.
These results were confirmed by the numerical analysis presented in Fig. 6. This latter shows the compressive strain axial during the simulation of a fretting fatigue test under maximal cyclic loading equal to 70MPa and a tightening torque value of 8daN.m.
We also notice in this case that the compressive strain is strongly concentrated at the interface between the pad and the aluminium plate. This phenomenon can be explained by the fact of strain incompatibility at the interface and the frictional coefficient effect.
Indeed, under this condition and in position at the pad, the compressive strain measured by the strain gauges (SG1, SG2) is 0.001195. At the same position, the compressive strain is calculated numerically and its value equal to 0.001273.

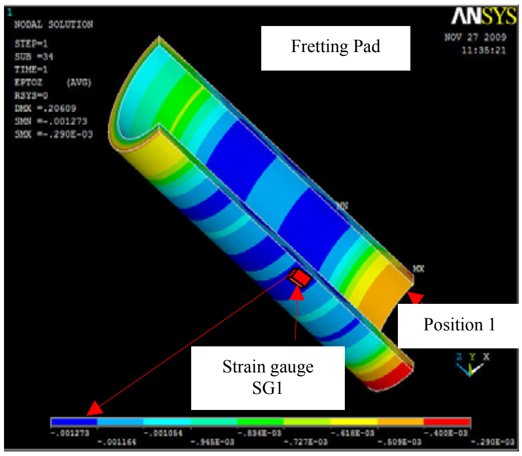

Figure 6. Compressive strain at the pad under maximal cyclic loading 70.MPa and torque 8. daN.m

According to the experimental, theoretical and numerical analysis, it can be seen that the result gave excellent correlation between various methods, thus establishing confidence in the results of the finite element modelling for bolted assemblies.

3.2. Inspection of damage

Many contact problems can be solved with the help of the Hertz theory [16] in order to obtain the surface stress distribution and subsequent bulk stress and strain states. However when a contact does not fulfil the Hertz assumptions, the analytical solution may differ significantly from the real one. This problem has been solved by [17] for the case of the spherical contact submitted to stick-slip behaviour. This situation happens when the tangential load is lower than the product between the normal load and the friction coefficient. Globally the contact is sticking (adhesion), but to respect the Coulomb friction law over the entire contact interface, a slipping annulus appears at the periphery of the contact zone. According to these authors, the contact zone is subdivided in two zones (adhesion and slip zones).

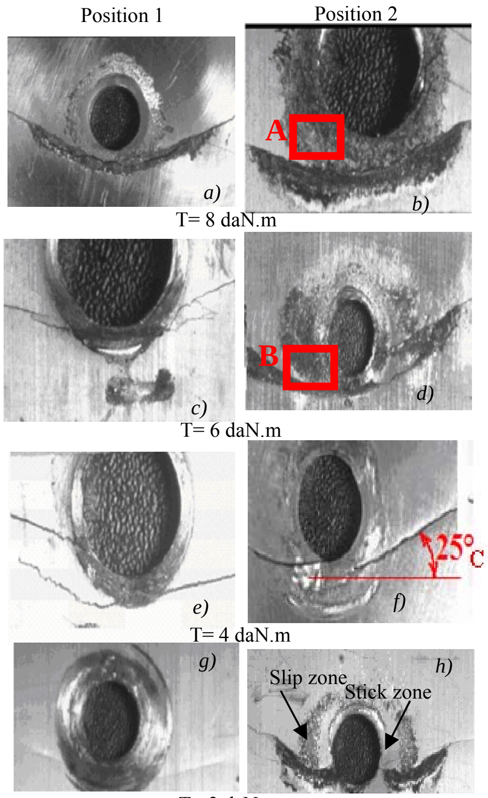

Figure 7. Crack propagation at various tightening torque under maximal cyclic loading 70 MPa.

In this study, we can see the appearance of adhesion and slip zones only at lower values of torque (Fig. 7h) while for higher value; the slip zone is disappeared completely and appears only the adhesion zone. This behaviour can be explained by the fact that the decrease of torque value (clamping force) leads a decreasing of the adhesion zone and therefore an increasing of the slip zone, which favoured the partial sliding at the interface of bolted assemblies. We note that the initiation and cracks propagation taken a position at the interface between the adhesion and slip zones (Fig. 7c-h). One can thus conclude that the position of crack initiation is related directly on the change of adhesion zone size. This latter is varied as function of clamping force level. In other words, for higher torque value, a large zone of adhesion leading to a slip zone very narrow, the initiation and crack propagation occurs at the border contact in the interface or outer edge of the contact region. However, it can be observed that for the range of means value of torque, which lead to reduce the size of adhesion zone and to raise the size of slip zone, consequently, the initiation and crack growth is located within the contact zone at the interface between the adhesion and slip zones. This phenomenon can be explained by the fact of change of net pressure acting on each zone (adhesion and slip zones) in the contact zone. We note also that, whatever the torque value, the frictional marks take an elliptical shape parallel to the cyclic loading direction and its size is more pronounce for higher torque value. This behaviour is in good agreement with experimental observations of Wagle et al. [18].

3.3. Wear mechanisms

To better understand the torque effect on the wear mechanism of such bolted assembly (steel-aluminium) under cyclic loading, a thorough examination of damage surface at the interface between the plates (position 2) using SEM-EDS. Because the degradation and crack initiation was more pronounced in this position for each torque level according to experimental result (Fig. 7) and the experimental observations of Wagle et al. [18]. Fig. 8a showed the overall topography of aluminium alloy, before the fretting fatigue test (in state virgin). The analysis by EDS (Fig. 8b) indicates a strong presence of Al, is a typical in this kind of aluminium alloy. The SEM micrograph of Fig. 8c (from area ‘B’ of Fig. 7d) shows the presence of wear debris of the damaged surface of aluminium for a torque value equal to 6 daN.m. The damaged areas is covered by with narrow grooves (typically in the range of 5–50 µm wide), wear debris and a number of micro cracks, were produced at a position and orientation different relative to sliding direction (cyclic loading direction). According to this figure, we can be noted that the wear mechanism occurred in this case by adhesion. Comparison of EDS analyses of worn surface (Fig. 8d) and that of unworn surface (without fretting, Fig. 8b), shows the loss of aluminium (Al) from damaged surface with increasing of the torque. So, the intensity of Al peak decreased and that of Fe and Si peaks increased with increased in torque value (6 daN.m). It is likely that this loss of Al occurs under the action of harder particles components of Fe and Si of steel specimen under fretting condition. From the above observations, we showed that the torque value is a very important effect on the size of adhesion zone (Fig. 7). At very high torque (8 daN.m), we can be note that the morphology of damaged area (Fig. 8e) is very different compared to a torque value of 6 daN.m (Fig. 8c). This means that the wear mechanism is related to the torque value. In other words, the increasing of torque leads to an increasing of the frictional stresses and to reduce the relative slip at the interface of bolted assembly

4. CONCLUSIONS

The aim of this study is to analyze the effect of tightening torque on bolted assemblies under fretting fatigue condition, from these experimental and numerical results, we can deduce the following conclusions:

- The developed finite element modelling approach to simulate clamping force (tightening torque) in the bolt of such bolted assembly was validated against the experimental results.
- The wear mechanism and contact surfaces degradation depends on the magnitude of tightening torque.
- The adhesive wear dominates at tightening torque and fretting fatigue cyclic number lower while the abrasive wear dominates for tightening torque and fretting fatigue cyclic number higher.
- The size of the adhesion and slip zones on contact zone is related at the magnitude of tightening torque

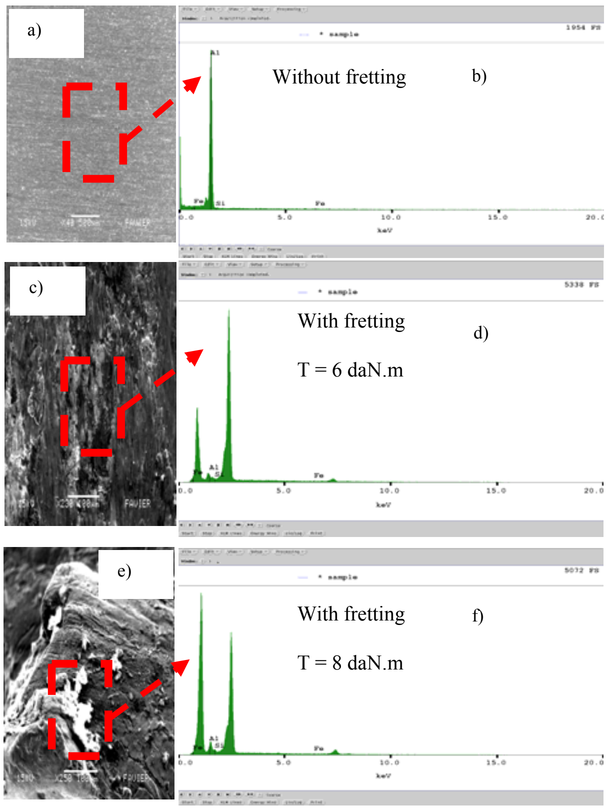

Figure 8. (a–f) SEM micrographs and EDS analysis of aluminium plate under fretting and without fretting at different tightening torques.

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