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Tribological Analysis of Bolted Joints Submitted to Vibrations

Komla Apélété Kounoudji^{1)*}, Guilhem Mollon¹⁾, Mathieu Renouf²⁾ and Yves Berthier¹⁾

¹⁾University of Lyon, CNRS LaMCoS, INSA Lyon, UMR 5259
1-1 F-69621 Villeurbanne Cedex, France

²⁾University of Montpellier, CNRS LMGC, UMR 5508
2-2 34095 Montpellier, France

*Corresponding author: Komla-Apelete.Kounoudji@insa-lyon.fr

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An experimental approach was adopted to understand service damages such as crack initiation and surface degradation of bolted joints used in the junction technology of aircraft air bleed valve systems. A vibratory testing stage combined to Digital Image Correlation (DIC) focus on an experimental model device of valve body/actuator body junction. DIC coupled with in situ tribological observations and a Finite Element Model (FEM) has been used to identify more clearly local contact conditions. This approach has enlightened peeling-off and micro-slips instabilities under vibratory loadings, leading to third body formation in bolted joints contacts. The morphology of such third body is placed at the focus of damages observed in involved air bleed valve systems.

Keywords: peeling-off, micro-slip, third body, DIC, FEM, bolted joints

1. Introduction

Bolted connections are ubiquitous in all domains of mechanics. In transport especially, they are found in aerospace, railways, automotive and in aeronautic engineering. In this last field, they can be counted from engines to the smallest equipments such as air bleed valve systems for example.

In mechanical engineering, the behavior of structural parts such as beams and plates is usually well understood. But when it comes to assemble these structural parts using bolts, the reality appears to be more complex. Indeed, from a kinematic point of view, components of bolted joints do not present any relative mobility between them (i. e. any degree of freedom). However, at the scale of contact surfaces inside the joints, micro-slip and/or peeling-off instabilities often occur [1,2] and may be very harmful for mechanical systems. These interfacial movements, often related to vibrations, cause wear of the surfaces or nucleation and propagation of cracks [3,4], which reduce the lifetime of joints. These damages are real problems for aircraft manufacturers as well as for airline companies such as lengthening of delivery times, aircraft crashes in extreme cases, etc. [5-7].

Behavior of bolted joints under dynamics loading may therefore depend in a critical way on the local

contact conditions between their various components. Thus, this study aims to well understand the service damage of bolted joints used in aircraft air bleed valve systems for their control. Indeed, the main role of air bleed valve is to ensure the pressurization of aircraft cabins. As shown on pictures of the Fig. 1, they are located in engines and are globally composed of actuator body and valve body assembled by bolts. Different designs of bolted joints are used in the junction technology of actuator body/valve body (cf. Fig. 1(c)). In service (i. e. operating on an aircraft), damages appear in bolted joints interfaces such as crack and surface degradation (cf. Fig. 2), which can limit lifetime of bleed valve systems. In extreme cases this can cause the depressurization of aircraft cabins leading to crashes. So it's crucial to well understand the causes of these damages. At this end, an experimental approach is adopted to identify local contact conditions of bolted joints loaded surfaces. The experimental stage is focused on a vibratory testing with DIC technique. Numerical processing of DIC measurements coupled with tribological observations of loaded surfaces after test has led to a numerical analysis by FEM.

2. Vibratory testing stage

Vibratory testing stage is performed at first using two-dimensional DIC technique. It is a non-contact

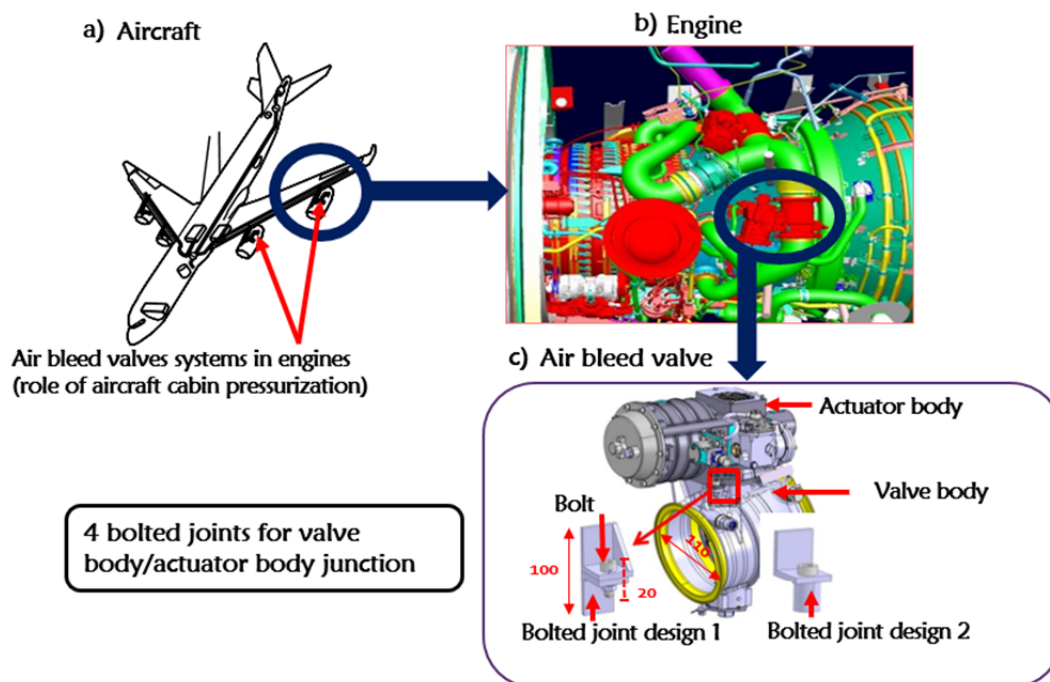


Fig. 1 Air bleed valve systems in aircraft engine

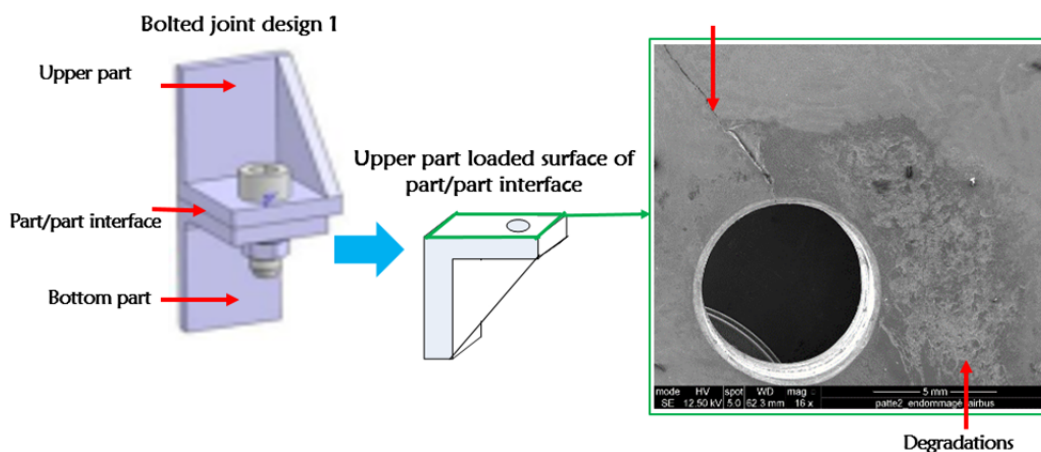


Fig. 2 Different damages on an air bleed valve having operated on an aircraft

technique for displacement and/or strain field measurements in macro, micro and nano-scale mechanical testing applications [8-10].

The principle is based on the fact that displacement and strain measurements are realized by direct inter-correlation of digitized images of speckle pattern, which is a set of small stains disposed randomly on the surface of the specimen to be studied. In our case it was projected on the bolted area and allows for black and white spots. Afterwards, tests were filmed with cameras. An image processing software scans the speckle pattern and establishes for each recorded image (after treatment) planar mapping points. Comparing each image successively recorded and processed by scanning the reference image (unsolicited specimen), it is measured for each point identified, the distance covered between two instants t_0 and t_1 ($t_1 > t_0$). If this operation is repeated

for all of the recorded images, it is then possible to obtain the total displacement of all points of the early study area until the end of the test. Actual displacement of the specimen can be then obtained. From this displacement field, the strain one of the study area is obtained by calculation.

In order to test many designs of actuator body/valve body junction, the performing test is not on a real bleed valve but on a model experimental device (cf. Fig. 3). It's representative of actuator body/valve body junction and is composed of a masses support adjustable in position, a central tube, four specimens and two pedestals (cf. Fig. 3(b)). The combination of the central tube and the masses support resembles geometrically to actuator body; but not the pedestals to the valve body. Indeed, they are designed like this to be able to fasten it on the test bench. Different combinations of different designs of specimens

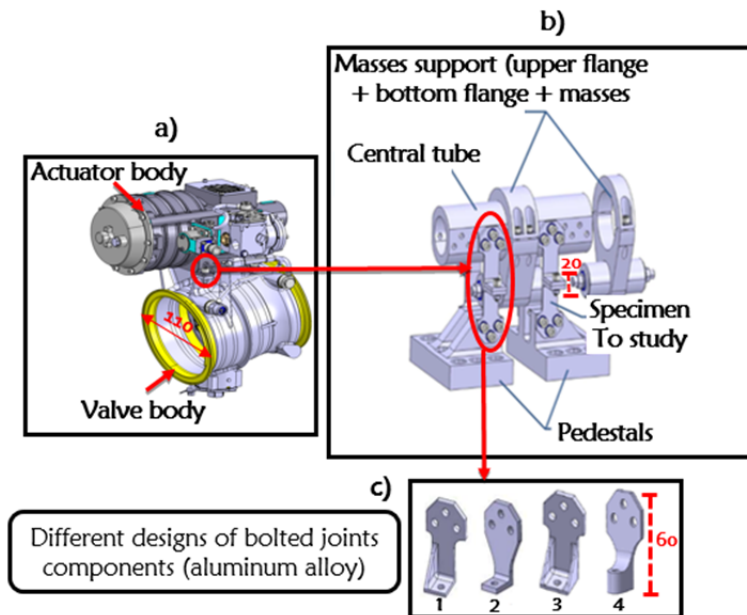


Fig. 3 (a) Real assembly of bleed valve, (b) Model experimental device, (c) Different designs of bolted joints components

in aluminum alloy (2618A) are tested according to two vibration modes that characterize the failure modes of the studied bleed valves:

- (i) an axial swaying mode (in this case the masses support keeps the position shown on Fig. 3(b));
- (ii) a torsional mode (masses support is rotated to 90 degrees).

Among these parameters (designs, vibration modes), only the results of the combination of bolted joint design 1 (cf. Fig. 3(c)), the commonly used in the junction technology of air bleed valves, with axial swaying mode is presented in the remainder of this study. The tests begin after assembling the central tube and the socles with four specimens (Fig. 3(b)). Testing conditions at room temperature on the vibratory test bench (cf. Fig. 4) are:

- (i) a sinusoidal excitation in the X-direction, referring to reference system of the test bench;
- (ii) a scanning frequency, ranging from 200 to 400 Hz

to select the first vibration natural frequency;

- (iii) test performing duration of 20 min with 8g of acceleration level and 236 Hz of first natural frequency.

Two cameras of high acquisition rate type “FASTCAM ultima APX-RS” are used for DIC measurements. The first one is located in X-Y plane and the second one in Y-Z plane. Note that the range of frequency vibration corresponds to the one occurring on bleed valves on an aircraft.

3. Identification of local contact conditions

Local contact conditions are identified by means of numerical processing of DIC measurements, tribological experimental analysis and contacts numerical analysis by FEM.

3.1. Numerical processing of DIC measurements

DIC measurements analyses are realized using Ncorr

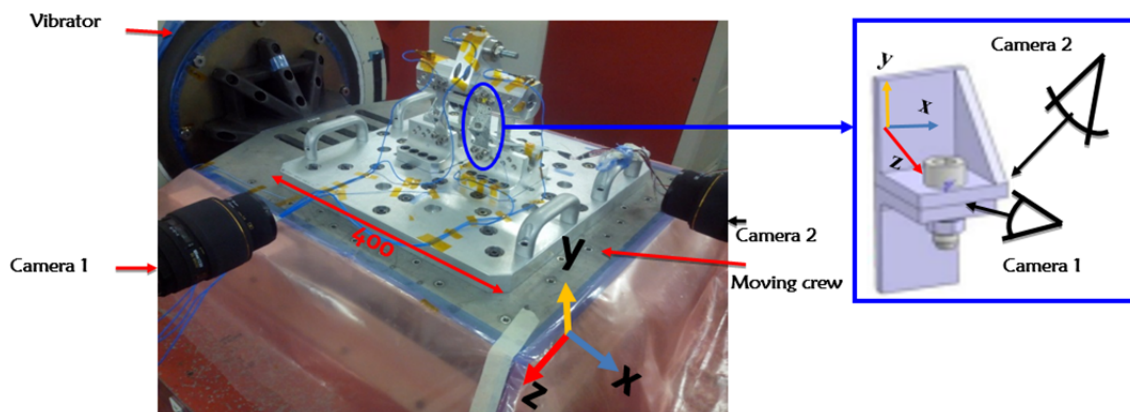


Fig. 4 Vibratory test bench with DIC technique

[11], an open source 2D DIC Matlab program. This open source requires the definition of a region of interest, from the reference image or from one of the speckle images of the assembly at the loaded state according to applications. This region of interest should be colored in white and the other part of the image in black. In our study, the area of interest is defined from the reference speckle images as shown on the images of Fig. 5(a,b). Thus, the images of Fig. 6(b) and Fig. 7(b) are referred to the deformation field measurements in *Y*-direction measurements respectively on the camera 1 and camera 2. These results suggest that there is a local kinematic of the assembly at part/part interface, for example. In order to explore the local contact instabilities that would generate the involved deformation field, average relative displacements are measured at the interface. From the measurements, the interfacial displacements graphs were plotted by means of the scanned images (512 pixels by 256 pixels of definition) of the two cameras and multiblocks regions of interest. Indeed, the regions of interest have been defined separately for each component (block) of the studied assembly (bolt, upper part, bottom part) from the reference speckle images. All the blocks are then assembled as shown on the images in Figs. (8,9). Through a Matlab routine, each block is meshed in order to track down the mesh nodes at the interface (cf. Fig. 6(c) and Fig. 7(c)). From images of Fig. 6(d) and Fig. 7(d), one can observe that, at the local scale the instabilities are micro-slips and peeling-off type at the interface (part/part interface), where the relative displacements in the *X* and *Z*-directions are assigned to

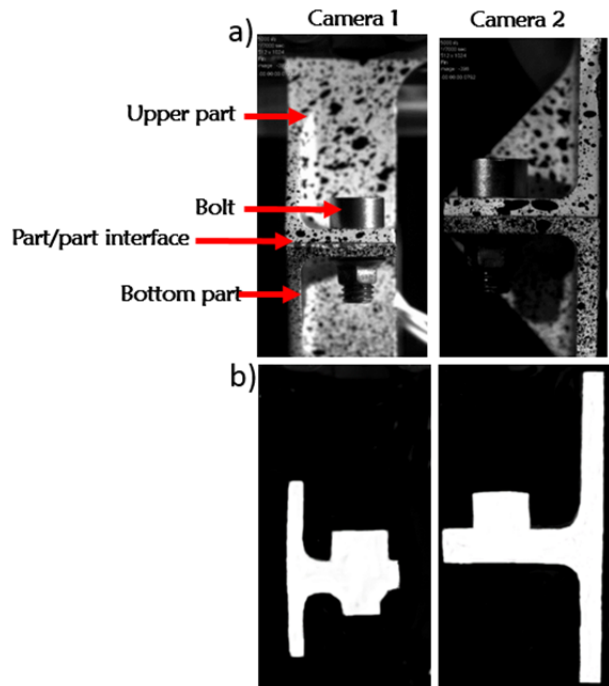


Fig. 5 (a) Reference speckle images for each camera, (b) Regions of interest defined from the reference images for each camera

the blue plots while ones in the *Y*-direction to red plots. These displacements plots are in fact the average displacements of the mesh nodes at the interface. It should be clarified that all the degrees of freedom of the

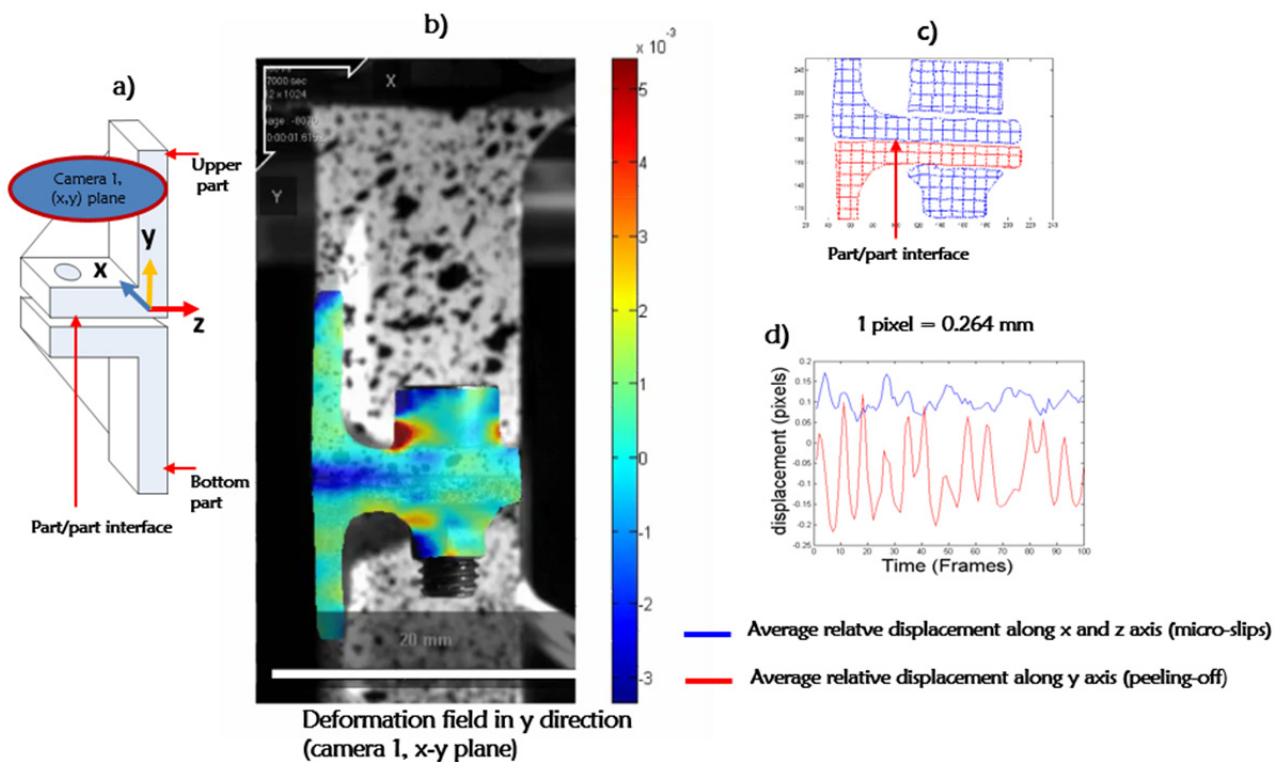


Fig. 6 (a) Bolted joint design 1 with camera 1 position, (b) Deformation field with camera 1 position, (c) Mesh of region of interest with camera 1, (d) Average relative displacements with camera 1

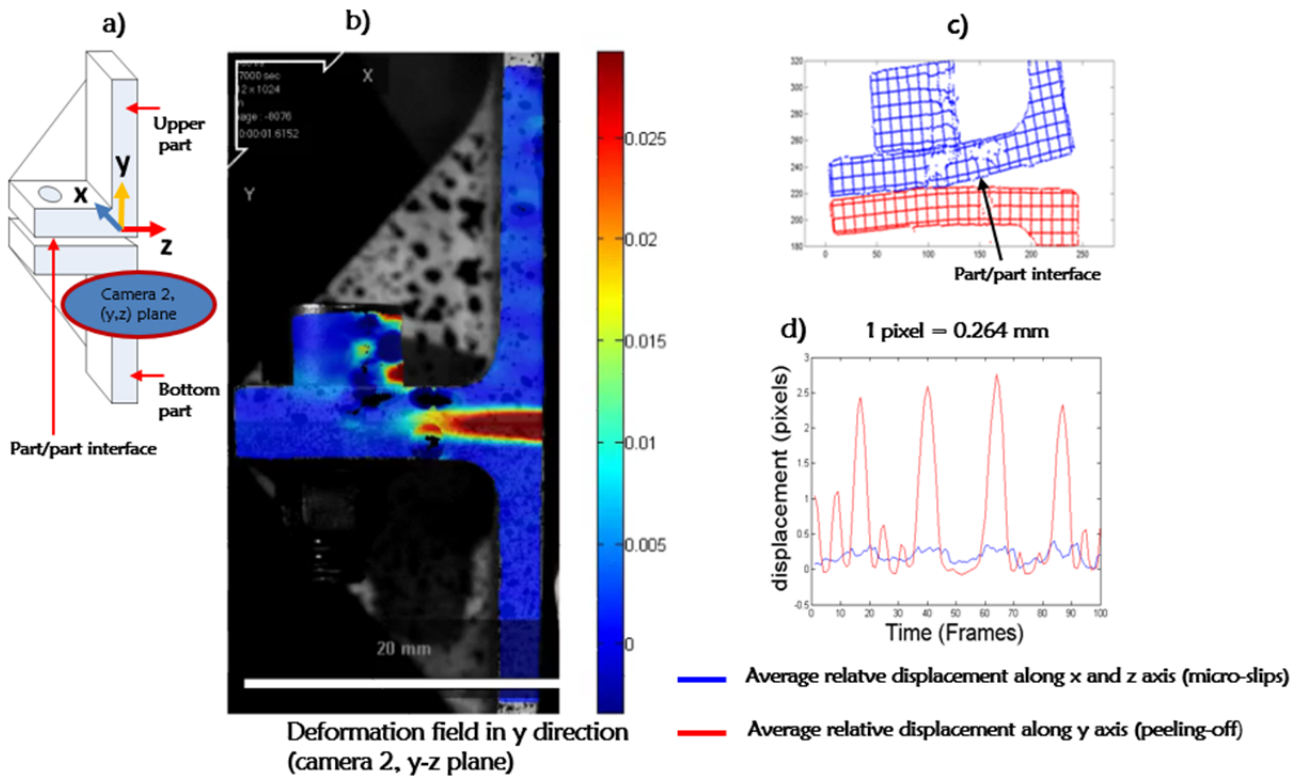


Fig. 7 (a) Bolted joint design 1 with camera 2 position, (b) Deformation field with camera 2 position, (c) Mesh of region of interest with camera 2, (d) Average relative displacements with camera 2

nodes of bottom part are blocked at contrary to those of the upper part which nodes are left free; this allow to note the relative displacements of the interfacial nodes of the free part (upper part) compared to the blocked one. It is clear from this analysis that the interfacial relative displacements are cyclical and peeling-off instabilities are more pronounced than micro-sleeps ones (camera 2, Fig. 7) and are around 2.5 pixels of displacement (the scanned images are defined in pixels), the equivalent of 700 microns. The conclusion is that the assembly is solicited both globally and locally.

Whereas, the components of bolted joints are

supposed not to have any relative mobility. Indeed, according to previous observations, it appears that local contact instabilities such as peeling-off and micro-slip phenomena are omnipresent in bolted joints interfaces.

3.2. Tribological experimental analyses

Previous observed phenomena are not without consequences on the structural integrity of joints partly relative to the tribological behavior of the involved interfaces. Tribological experimental analyses are then need to determine the consequences of identified contact instabilities.

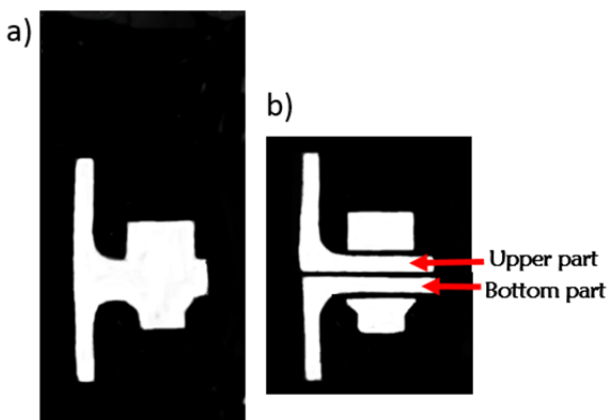


Fig. 8 (a) Monoblock region of interest (camera 1), (b) Multi-block region of interest (camera 1)

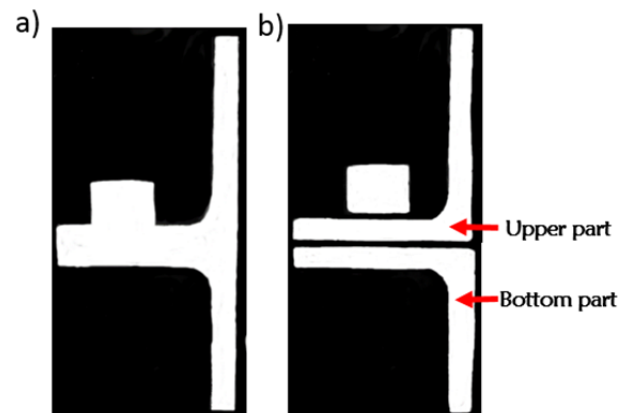


Fig. 9 (a) Monoblock region of interest (camera 2), (b) Multi-block region of interest (camera 2)

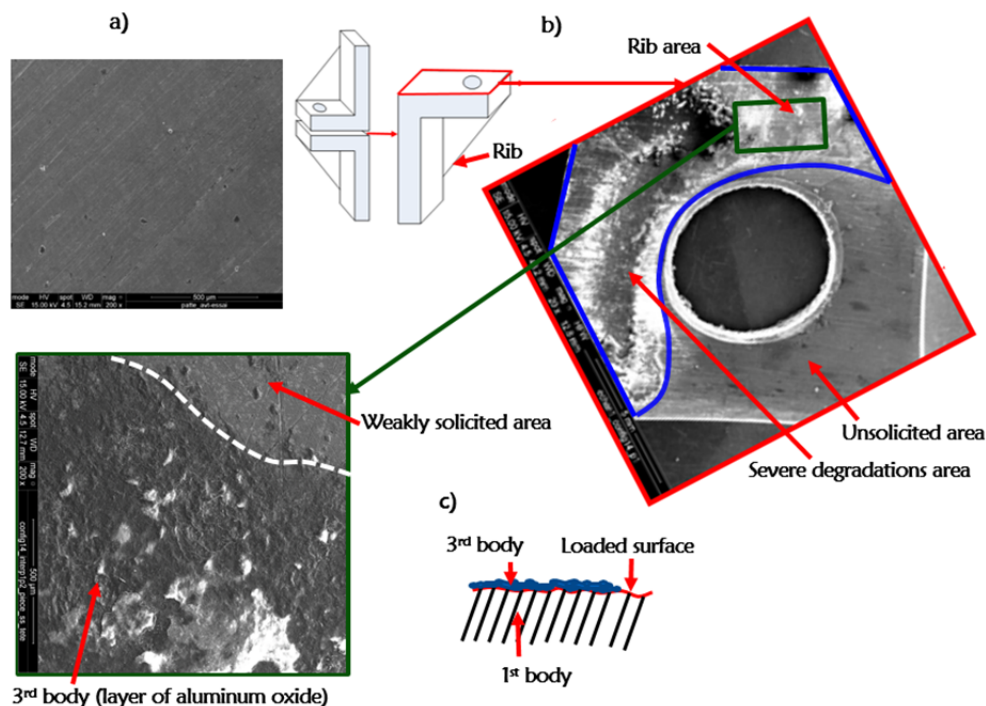


Fig. 10 (a) Surface before testing stage, (b) Surface after testing stage, (c) Sectional view

These last ones consist in looking the interfaces at the local scale using Scanning Electron Microscopy (SEM). The concepts of third body and tribological triplet [12,13] are adopted to organize the different observations and analyses.

After test, the four specimens are disassembled and one of them is devoted to analyses. The involved surfaces are compared before and after testing stage in Fig. 10(a,b). In Fig. 10(b), the hole of the specimen used in the experiment seems to locate at the center of the surfaces; this is due to the cutting conditions for SEM analysis. In actual fact, the hole is not at the center (cf. Figs. 6,7). It appears on the surface post-testing, three areas according to the severity of local sollicitations (cf. Fig. 10(b)):

- (i) a severe degradations area showing a formed third body, which corresponds to the area of great

peeling-off instabilities (cf. Fig. 7(c));

- (ii) a weakly solicited area (without third body) and a third body zone, both in the rib area of the structures (the two parts of the assembly);
- (iii) an unsolicited area which conserves the morphology of the surface before the tests.

Therefore, the involved interface is solicited according to its own dynamic. Looking for the morphology of the degraded region at the local scale, a thin layer of third body appears on the surface as shown on the sectional view (cf. Fig. 10(c)). This third body layer is composed for the main part of an alumina (aluminum oxide). This is explained by the fact that during sollicitations, aluminum particles are detached at the surface. Then, in contact with the oxygen of surrounding air, they are oxidized and form the alumina third body layer.

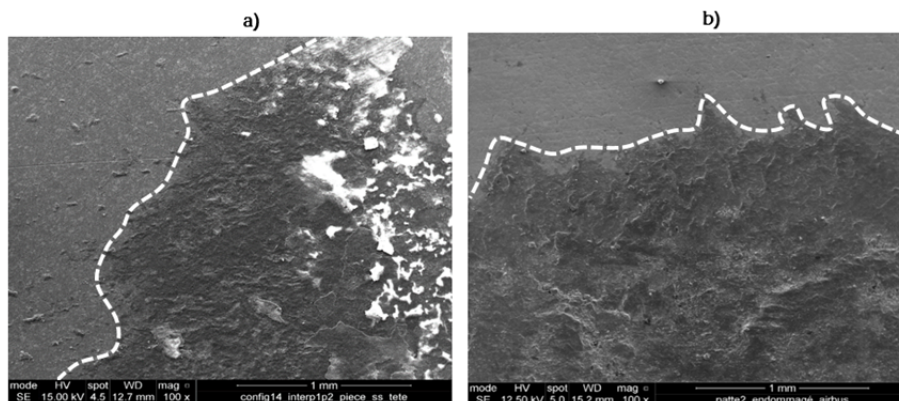


Fig. 11 (a) Degradations of the involved surface during testing stage, (b) Degradations of the involved surface during service stage

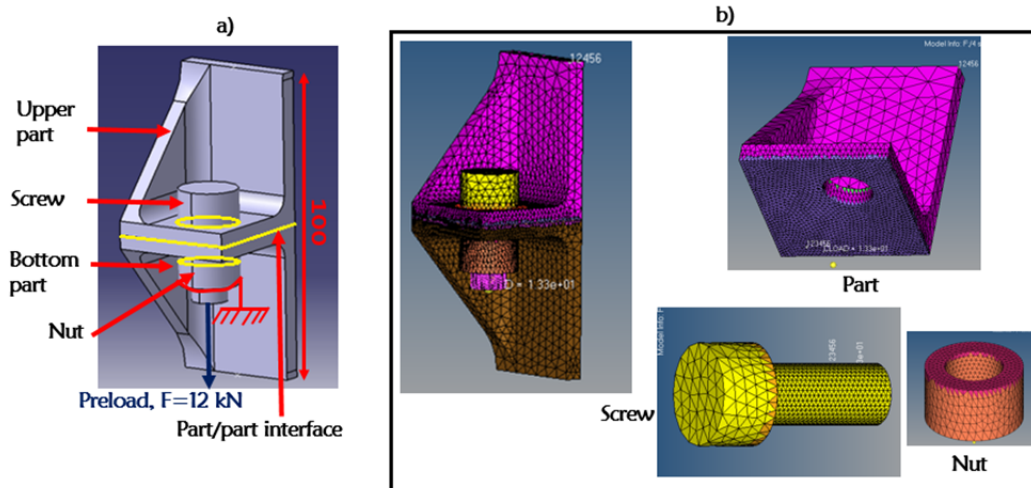


Fig. 12 (a) Simplified bolted joint model, (b) Mesh of different parts of bolted joint model

The degraded surface observed after the testing stage is compared to the same one of a bleed valve having operated on an aircraft (cf. Fig. 11). It can be found that the degradations are similar; the testing stage is allowed to reproduce the same tribological behavior that in service, although the pedestals don't resemble the valve body.

3.3. Numerical analysis

The solicitations undergone by the surfaces during the testing are due both to the tightening loadings and the vibrations. In order to know the contribution of the tightening loading in the surface degradation, it is important to uncouple the two mechanisms.

For this purpose, a finite element model is realized. Only the part/part interface is considered in the present study. Hence the bolt (screw and nut) is simplified (i. e. the threads are not represent). The bolted joint model and its mesh are shown at Fig. 12(a,b). The model is

composed of a total of 64130 elements. This step being dedicated to the simulation of tightening stage, as boundary conditions, the preload, an experimental value of 12 kN (from torque-preload test) is applied by pulling on the screw while blocking the bottom surface of the nut (cf. Fig. 12(a)). The bolt is in steel, and the interactions between surfaces are managed by a Coulomb friction law. The used values (cf. Table 1) are derived from

Table 1 Friction coefficients in different contacts of the numerical model

Surface	Surface	Experimental friction coefficient
Screw	Upper part	0.15
Upper part	Bottom part	0.3
Nut	Bottom part	0.15
Screw	Nut	0.12

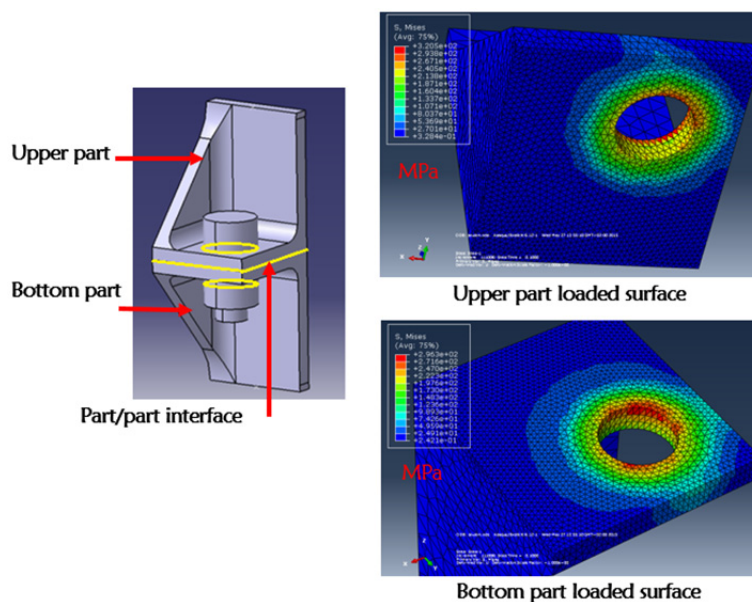


Fig. 13 Von Mises stress field in the involved interface

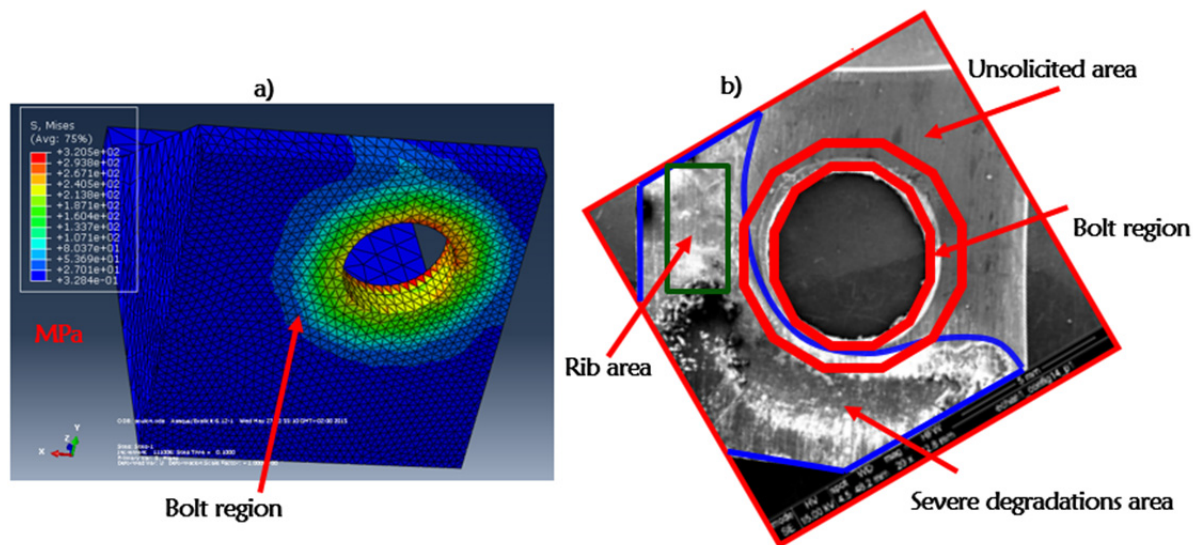


Fig. 14 (a) Numerical model, (b) Experimental model

torque-preload tests.

Von Mises stresses fields corresponding to the involved contact surfaces (part/part interface) are evaluated at the end of the calculation as represented in Fig. 13. According to these numerical results, only the region of the bolt is the most loaded during tightening stage, and not all the contact area (cf. Fig. 14(a)). Moreover, this loading is not so high to damage the region of the bolt if referring to the experimental model (cf. Fig. 14(b)). This means that degraded area is referred to peeling-off and micro-slip phenomena due to vibrations. The only contribution of the tightening stage would be the activation (increasing the reactivity) of surfaces.

4. Conclusions

The experimental approach adopted to analyze bolted joint submitted to vibrations has allowed concluding that a thin layer of third body is formed in contacts due to peeling-off and micro-slip phenomena. Regarding our study, it can be trapped or ejected out of the contact and this can be harmful for mechanical systems. In the first case, the trapped third body constitutes an excess of material. This can increase mechanical stresses in bolted joints leading to fatigue life and crack initiation. Otherwise, the ejected third body constitutes a loss of material of contact. This can beget self-loosening phenomena leading to breakage of bolted joints components.

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