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An Experimental Method for Measuring Clamping Force in Bolted Connections and Effect of Bolt Threads Lubrication on its Value

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Abstract**—**In this paper, the details of an experimental method to measure the clamping force value at bolted connections due to application of wrenching torque to tighten the nut have been presented. A simplified bolted joint including a holed plate with a single bolt was considered to carry out the experiments. This method was designed based on Hooke's law by measuring compressive axial strain of a steel bush placed between the nut and the plate. In the experimental procedure, the values of clamping force were calculated for seven different levels of applied torque, and this process was repeated three times for each level of the torque. Moreover, the effect of lubrication of threads on the clamping value was studied using the same method. In both conditions (dry and lubricated threads), relation between the torque and the clamping force have been displayed in graphs.

Keywords**—**Clamping force; Bolted joints; Experimental method; Lubrication.

I. INTRODUCTION

JOINING by mechanical fasteners is common practice in the assembly of structural components. However, the most important elements in structures (especially aerospace structures) are bolted joints as we can see they are used in very large numbers on modern aircraft nowadays. It has been experimentally proved that the bolts and nuts clamp joint parts together well and present good resistance to applied loads. According to results of previous researchers, bolted joints have higher tensile and fatigue strengths than welded, riveted and also pinned joints [1, 2]. Comparison between fatigue test results for steel members that have been joined together using rivets and those joined using both rivets and bolts in old railway bridges in Ref. [1] indicates a considerable increase in fatigue life of specimens which had more bolts instead of rivets.

Moreover, bolted joints present the advantage, versus welded joints, of an easier assembly in situ. So they are called nonpermanent joints which continue a built-in option: to disassemble or not. However, drilling holes in members in order to create fastener joints inherently causes a stress concentration near the hole and reduces the load carrying cross sectional area. Also, drilling a hole may cause a rough surface finish which is prone to fatigue crack initiation and propagation under dynamic loads, and there were a lot of attempts to alleviate this defection using cold expansion method and interference fit [3-6].

Consequently, proper design of the joint and selection of the appropriate bolt fasteners with the aim of designing safe and efficient structures are extremely important especially in some usage in industries such as aerospace and automotive industries. Due to this importance, many attempts are conducted to develop and optimise the design of bolted joints. In other words, since the failure of the joints can lead to the catastrophic failure of the structures, an accurate design methodology is essential for the optimal design of the joints.

When a nut and bolt are used to join mechanical members together the nut is tightened by applying torque, thus causing the bolt to axially stretch. As the bolt head and nut (usually with a washer) clamp the joint members together, the bolt is left in tension (called a preload too) and the mechanical members are compressed together [7]. Past research has shown that the bolt clamping effect can decrease the stress concentration at the bolted hole region and thus increase the tensile and fatigue strengths of the joint [7, 8]. As a high initial clamping force is very desirable in important bolted connections, we must consider means of ensuring that the preload is accurately developed when the parts are assembled. In other words, how a bolt torque relates to a bolt tension precisely in different bolt conditions.

If the overall length of the bolt can actually be measured when it is assembled, the bolt elongation due to the preload can be computed using the axial deformation formula. Then the nut is tightened until the bolt elongates through the distance of deformation. This ensures that the desired preload has been attained. But it is impractical in many cases to measure bolt elongation. In such cases the wrench torque required to develop the specified preload is estimated by using some methods such as the turn-of-the-nut, pneumatic-impact wrenching, and torque wrenching. Although the coefficients of friction may vary widely, there is a good estimate of the torque required to produce a given clamping force using an analytical formula presented by Eq. (1):

$$F_{cl} = \frac{T}{K\, d_{bolt}} \tag{1}$$

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In this equation, T is the torque (N.m), F_{cl} is the initial clamping force (kN), d_{bolt} is the bolt nominal diameter (mm), and K is the torque coefficient defined as the term which depends on friction coefficients, lead and thread angles, and mean diameter of the bolt. However, the coefficient of friction depends upon the surface smoothness, accuracy, and degree of lubrication [7]. Therefore, it is needed to find out the precise coefficients to calculate K in order to use this formula for determining the clamping force in bolted connections. However, the torque coefficient of 0.20 is usually used when the bolt condition is not stated [7]. It was also found that the mean coefficient of 0.208 is suitable for both lubricated and unlubricated bolts, according to the result of tests conducted by Blake and Kurtz [9]. Literature surveys show that available methods used to measure the clamping force value may give an approximate answer, whereas, it is usually essential to find out the exact value for design of some important bolted connections subjected to high level loads.

In this research, an experimental method was designed to measure the more accurate values of initial clamping force in bolted connections due to application of wrenching torques. A simplified bolted joint including a holed plate with a single bolt was considered to carry out the experiments. This method was invented based on Hooke's law by measuring compressive axial strain of a steel bush placed between the nut and the plate. Moreover, the effect of lubrication of threads on the clamping value was studied using the same method.

II. EXPERIMENT PROCEDURE

The specimen employed in the tests was made of 4.5-mm-thick aluminium alloy 7075-T6 plate, and had a 5 mm-diameter centre hole drilled and reamed (Fig. 1). To clamp the specimen at its hole area a metric hex head steel bolt (M5x0.8–8.8) was used.

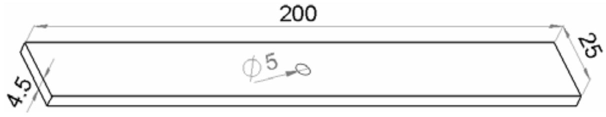

Fig. 1 The dimensions of the holed plate in mm.

In order to use the bolt and nut in elastic region, some primary experimental tests were carried out and the results showed that initial plastic deformations at threads started at approximately 8 N.m wrenching torque [10]. To measure the clamping force (bolt axial tension) at different applied torques, a special experimental method was designed using a steel bush. Fig. 2 shows the bush dimensions. The elastic modulus for the bush material was determined (E_{bush}=204188 MPa) using stress-strain data obtained from simple tensile tests, as shown in Fig. 3, in order to obtain the accurate values for the mean axial clamping force

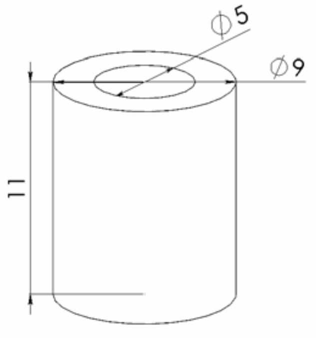

Fig. 2 The dimensions of steel bush in mm

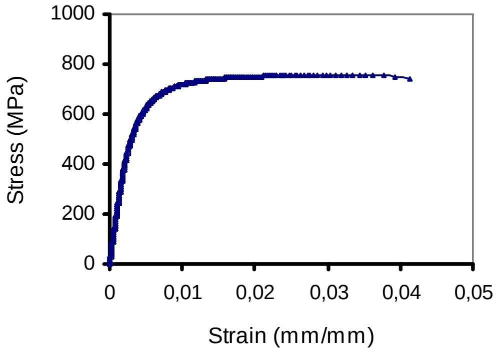

Fig. 3 Stress-strain diagram for bush material

At the bush outer surface, two strain gauges (FLA-2-11) were stuck on axial directions every 180°, as can be observed in Fig. 4, to measure the compressive axial strain due to the clamping force, and so the stress in the bush using Hooke's stress-strain law. Having the bush cross section area in hand and the axial stress, the axial force in the bush and then the clamp force has been determined. Fig. 5 shows the load cell situated in the joint. In the experiment, torques were applied in 1 N.m increments from 1 to 7 N.m to the nut using a torque wrench, and then the axial strains were recorded for each value of the torques. This test was repeated three times for each case to obtain the mean value of compressive strains (ε_m). Using obtained data, the relation between the compressive strains and the applied torques for the specimen was shown in Fig. 6. As the figure shows there is a linear relation between the mean strain and the applied torque. This confirms that the bush material is still in elastic region even under maximum applied value of the torque.

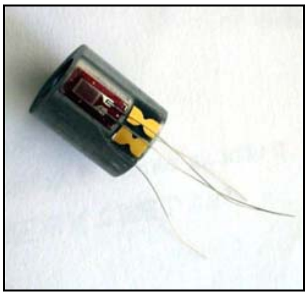

Fig. 4 Strain gauges stuck on the bush

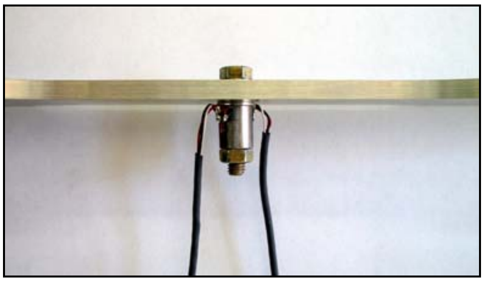

Fig. 5 Position of prepared load cell in the joint

Subsequently, corresponding clamping forces were determined using Eq. (2):

$$F_{cl} = E_{bush}\, A_{bush}\, \varepsilon_m = 204188 \times \frac{\pi}{4}\left(9^2 - 5^2\right)\varepsilon_m = 89.8 \times 10^5 \varepsilon_m \ \ (N) \qquad (2)$$

where A_{bush} is the area of the bush cross section. Fig. 7 displays the relation between the measured clamping forces and the applied torques for the joint. According to the obtained linear equation for fitted curve on the graph and also Eq. (1), the torque coefficient K is obtained experimentally for the joint:

$$\frac{1}{K\,(5 \times 10^{-3})} = 973.95 \ \Rightarrow \ K = 0.205$$

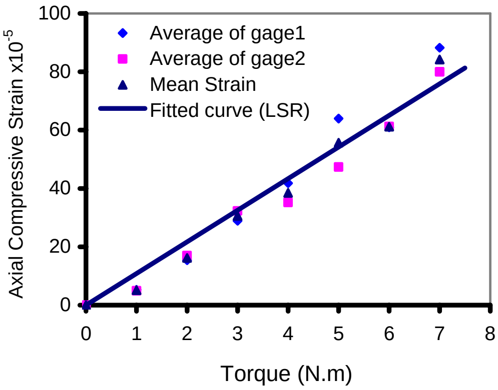

Fig. 6 Experimental relation between the applied torque and the axial strain of the bush

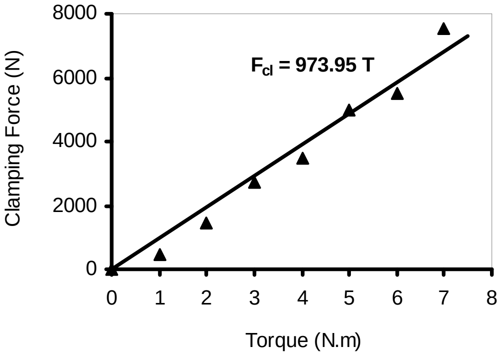

Fig. 7 Experimental relation between the clamping force and the applied torque at the joint

III. EFFECT OF LUBRICATION

Generally, lubrication of bolt threads causes the friction and torque coefficient to decrease and so the clamping to increase, according to Eq. (1). In order to study how the bolt threads lubrication can change the torque coefficient and the clamping value, a same experiment was also conducted for specimen clamped by a greased bolt. In this experiment, some grease was rubbed uniformly on the threads of the bolt and nut. Afterwards, selected torques was applied by using the torque wrench, and obtained data was recorded for each case (similar to previous tests for dry condition). In order to compare the clamping forces due to the same wrenching torques in the dry and lubricated bolted joints, the obtained results for both conditions have been displayed in Fig. 8. One can see that the torque coefficient K is obtained 0.165 in the lubricated condition, according to Eq. (1), and the obtained linear equation on the graph.

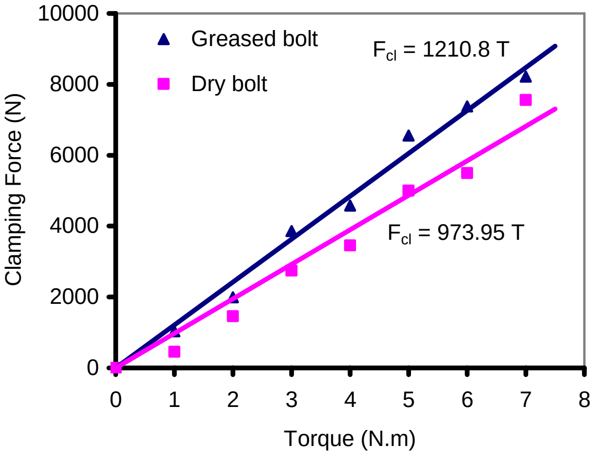

Fig. 8 Effect of threads lubrication on the clamping force; comparison between dry and lubricated conditions

IV. CONCLUSION

As the clamping force created in the joint due to the tightening torque causes the joining members to compress and so the fastener to axially stretch, presented method, which is based on axial deformation, can be correctly used in a variety of bolted connections to measure the design preload (initial clamping force) precisely. It is better to use bolts with longer length to place the load cell between the nut and the members easily.

It is found that the lubrication of bolt threads provides higher preload in the joint comparing with dry condition because of decrease in friction coefficient, and consequently, decrease in torque coefficient from 0.205 to 0.165, for the dry and lubricated conditions, respectively. To conclude, applying torque to the lubricated bolt creates higher preload that is desirable and safer for design of mechanically fastened joints connecting main parts of the structures

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