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ISSN 1333-1124
eISSN 1849-1391

AN EXPERIMENTAL METHOD FOR MEASURING THE CLAMPING FORCE IN DOUBLE LAP SIMPLE BOLTED AND HYBRID (BOLTED-BONDED) JOINTS

Summary

In this research, an experimental method for measuring the clamping force as a result of tightening torque in double lap simple bolted and hybrid (bolted-bonded) joints is proposed. Two types of joints, i.e. double lap simple and hybrid (bolted-bonded) joints were prepared for testing. In order to measure the clamping force or pretension resulting from the tightening torque at different applied torques, for both types of joints, a special experimental method was designed using a steel bush that was placed between the nut and the plate. Two strain gauges were stuck to the outer surface of the bush to measure the compressive axial strain and also the stress in the bush using Hooke's law. Finally, the axial force in the bush and subsequently the clamping force were determined. The test was repeated three times for each case to obtain the mean value of compressive strains and to determine the corresponding clamping forces. The relationship between the applied tightening torques and the mean value of compressive strains for both types of joints are shown in graphs.

Key words: *Clamping force; Bolted joint; Hybrid joint; Tightening torque*

1. Introduction

Most machines and structures have various types of joints (such as mechanically fastened, welded, and bonded joints) for the effective productivity and maintainability. Detachable joints such as bolts, rivets or pins are frequently used to create assemblies or structures from detailed parts or structural elements. Among the mentioned detachable joints, bolted joints are widely used in mechanical structures. A key advantage of threaded fasteners over the majority of other joining methods is that they can easily be disassembled and re-used. This feature is often the reason why the threaded fasteners are used in preference to other joining methods. Nevertheless, mechanically fastened connections do have several attributes that are a cause for concern. For example, the geometric discontinuity as a consequence of hole drilling operation in bolted joints results in stress concentration which in turn increases the tendency of fatigue crack to initiate and grow under cyclic loading [1-4].

In order to overcome this problem, the structure frequently needs to be thickened locally. This added thickness, together with a large number of metallic fasteners, increases the weight of structure, and thus decreases the strength-to-weight efficiency ratio.

An alternative method to mechanical fastening is adhesive bonding. In principle, adhesive bonding is a preferable method for Al-alloy sheet material in a lap joint. In order to see the advantages of adhesive bonding with respect to fatigue, two fundamental differences between the two types of lap joints, i.e. mechanically fastened joints and bonded joints, should be pointed out. Primarily, in a mechanical joint, the overlapping areas are attached to one another at discreet points only, i.e. by fasteners. Clearly, severe stress concentrations should occur. However, if the connection is made continuously in the full overlapping area by adhesive bonding, these stress concentrations do not occur because the bonded joints do not require fasteners and holes. Therefore, the stress distributions in the joint are relatively uniform in comparison with those in the mechanical joint. Secondly, the metallic contact between the two sheets does not exist in the adhesive joints, and thus the fretting between the mating sheets is also eliminated [5].

Adhesive bonding is extensively used for various engineering applications, such as aerospace structures, in automotive and marine industries, etc. Tensile loads on the adhesively bonded joints are usually avoided because of the occurrence of peeling failures. However, the static and the fatigue strength under shear loading are acceptable [5].

Similar to mechanically fastened joints, adhesively bonded connections also have their disadvantages associated with the method and performance.

The adhesively bonded connections, in comparison to mechanically fastened joints, are more difficult to manufacture in instances where the adhesive layer thickness is critical. Furthermore, the adhesive joints are more difficult to inspect than mechanical joints as visual inspection is often not an effective way to detect damage because the damage within the adhesive is not visible from the surface.

In order to reduce the weakness and disadvantages of adhesive and mechanical joints, and thus to obtain high performance joints, combinations of a mechanical joint (riveted, bolted, etc.) with an adhesive one, i.e. hybrid joints, are used [5–8]. Hybrid joints are used in many engineering applications such as aerospace, automotive, and naval industries because of their better performance compared to simple joints (adhesively bonded, welded, or mechanically fastened) [9]. Hybrid joints have also been used for the repair of damage and for the improvement of damage tolerance [10,11]. The hybrid joints may include weld-bonded, clinch-bonded and rivet-bonded connections [5-8]. It is important to emphasize that although some limited research has been done on the analysis of hybrid joints, there are still no data on the static and the fatigue strength of hybrid joints.

The hybrid joint method has been studied by several researchers [11-18]. An analytical investigation was conducted by Hart-Smith [8] on a hybrid joint with stepped lap joints between titanium and carbon fibre reinforced plastic adherends. The strength of hybrid joints was found to be the same as that of well-designed bonded joints. Many researchers proposed different numerical methods and analytical solutions to analyse hybrid joints. Chan and Vedhgiri [12] conducted experiments with composite joints as well as a parametric study using finite element analysis to study the stacking sequence effect on the joint strength. In that study, it was also found that bolts do not take an active role in load transfer before the initiation of failure in bonding, which was also noted by Hart-Smith [8]. Barut and Madenci [14] developed a semi-analytical solution method for the stress analysis of a hybrid joint, and found that most of the load is transferred through the adhesive, even though it has a low modulus of elasticity as compared to the bolt. Kweon et al. [18] observed a similar phenomenon in their experiments, where a double lap hybrid joint was considered using composite and aluminium adherends.

One of the most important factors that influence the strength of a bolted joint is the amount of pre-tension or the clamping force resulting from the tightening torque that is applied to the bolt. Preload or clamping force in the bolt is achieved by using a torque wrench. The torque wrench applies torque to the nut or the head of the bolt. This applied torque correlates with induced tension or clamping force [19-22].

Computations indicate that the torque required inducing the clamping force F_{cl} in a bolt with standard threads can be presented approximately by the following equation:

$$T = K F_{\mathrm{cl}} d \tag{1}$$

where T, F_{cl} and d are the applied tightening torque to the bolt head or nut, the clamping force, and the nominal thread diameter, respectively, and K represents the torque coefficient or nut factor which depends on a variety of parameters including, but not limited to, the geometry and friction of the threads [23].

Previous studies revealed that the clamping force can reduce the stress concentration at the bolted hole region, and therefore improve the strength of the joint considerably [19-22, 24,25].

Collings [26] discussed the effects of variables such as laminate thickness and bolt clamping pressure on the strength of bolted joints in carbon fibre reinforced polymer (CFRP) laminates.

Stockdale and Matthews [27] experimentally investigated the effect of clamping pressure on bolt bearing load in glass fibre-reinforced plastics. Deng and Hutchinson [28] investigated the residual clamping stress exerted on the joint by rivets. The relation between the clamping and the applied force was analysed using finite element methods in the small strain framework. Nah et al. [29] proposed a method for estimating the clamping force of bolts subjected to temperature gradient.

In this research, the relationships between the applied torques and the clamping forces in double lap simple bolted and hybrid (bolted-bonded) joints will be investigated experimentally. To do so, two types of joints, i.e. double lap simple and hybrid (bolted/bonded) joints were tested in experiments. In order to measure the clamping force or pretension resulting from the tightening torque at different applied torques, for both types of joints, a special experimental method was designed using a steel bush that was placed between the nut and the plate. Two strain gauges were stuck to the outer surface of the bush to measure the compressive axial strain and thus the stress in the bush using Hooke's stress–strain law. With the cross-sectional area of the bush and the axial stress known, the axial force in the bush and then the clamping force have been determined.

2. Experimental procedures

The specimens employed in this investigation were constructed using 2 mm thick 2024-T3 aluminium alloy. The aluminium alloy 2024-T3 is widely used in the structures of aircraft. Table 1 lists the mechanical properties of the aluminium alloy obtained from tension static tests, while Table 2 presents the chemical composition of used aluminium alloy.

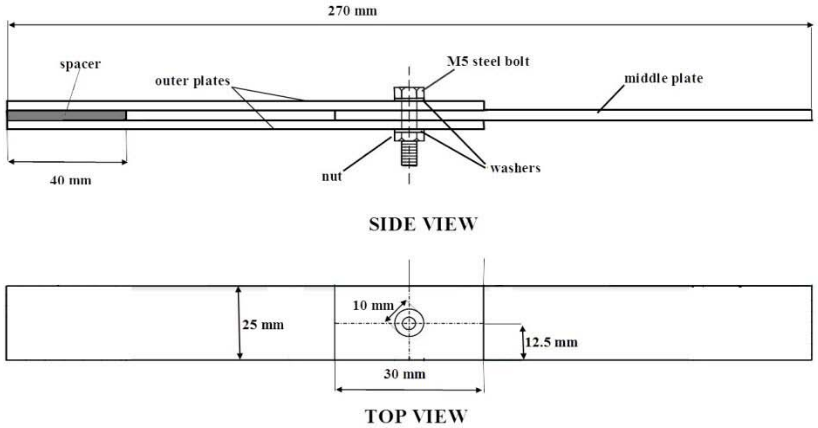
Table 1 Mechanical properties of 2024-T3 aluminium alloy

Elongation, %	Poisson's ratio	Tensile strength, MPa	Yield stress, MPa	Young's modulus, GPa
0.18	0.33	550	315	73.4

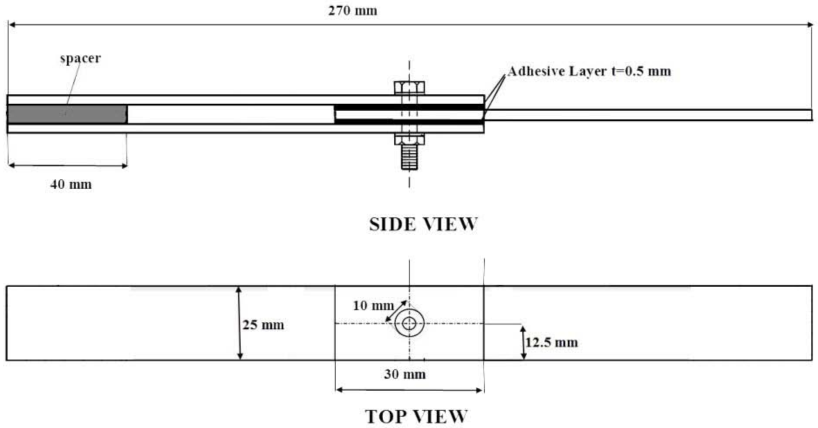
Table 2 Chemical composition of 2024-T3 aluminium alloy (The values are in percentages)

Al	Ti	Zn	Cr	Si	Fe	Mn	Mg	Cu
Bal	0.15	0.06	0.02	0.07	0.18	0.58	1.67	4.82

Two different types of joints, i.e. double lap simple and hybrid (bolted-bonded) joints were prepared. Configurations and dimensions of both tested types of joints are illustrated schematically in Fig. 1.



(a) simple bolted joint



(b) hybrid (bonded- bolted) joint

Fig. 1 Configurations and dimensions of joints. (a) simple bolted joint, (b) hybrid (bonded- bolted) joint.

The hybrid joints were fabricated using the structural two component epoxy adhesive, Loctite 3421 [30], prepared by mechanical mixing of the resin and hardener in equal quantities. The adhesive was selected because of its high strength and long working life. Before the preparation of all specimens, to eliminate any possible surface scratches, the surfaces of the plates were polished mechanically by rubbing with different grinding papers, identified by grit 400 then 600 and finally 1000.

To prepare the specimens, fastener holes of 5 mm in diameter were drilled and reamed in the jointed plates. The bolt used in this experiment had a hexagonal head and a typical 5 mm shank diameter, which was then paired with a hexagonal nut. A circular washer was used under both the hexagonal head and the nut. The optimum length of the un-threaded part of the shank was selected in order to match the thickness of the plates to be joined, so that the contact between the plates and the bolts is along the un-threaded part of the shank. Finally, the nut was tightened by applying torque using a torque wrench up to the required amounts of torque.

As mentioned earlier, 2024-T3 aluminium alloy sheets were used as adherends for the preparation of hybrid joints in this investigation. The preparation of the hybrid joints was done in two steps. Firstly, a double lap bonded joint was manufactured. In order to obtain a high strength joint, the jointed plates were cleaned with acetone and then were let to dry, prior to the application of the adhesive layer. In order to achieve a constant thickness of adhesive layer, 0.5 mm thick sheets were used between adherends.

The prepared bonded joints were left in ambient temperature for 72 hours, in accordance with the instructions of the adhesive manufacturer. Thereafter, to cancel out the effects of fillets, the fillets of bonded joints were removed with a razor.

The second step in the preparation of hybrid joints was made using the same procedures of preparation as in the case of simple bolted joints. In this step, the bolts were tightened using the same amounts of torques as with the simple bolted joints.

2.1 Clamping force measurement

In order to use a bolt and a nut within the elastic region, some primary experimental tests were carried out and the obtained results indicated that initial plastic deformations started at approximately 8 Nm at threads [31]. In order to measure the clamping force or pretension resulting from the tightening torque at different applied torques, for both types of joints, i.e. simple bolted and hybrid joints, a special experimental method was designed using a steel bush that was placed between the nut and the plate. Two strain gauges were stuck to the outer surface of the bush to measure the compressive axial strain and thus the stress in the bush using Hooke's stress–strain law. With the bush cross-sectional area and the axial stress known, the axial force in the bush and then the clamp force have been determined. The used method and the bush dimensions are shown in Fig. 2.

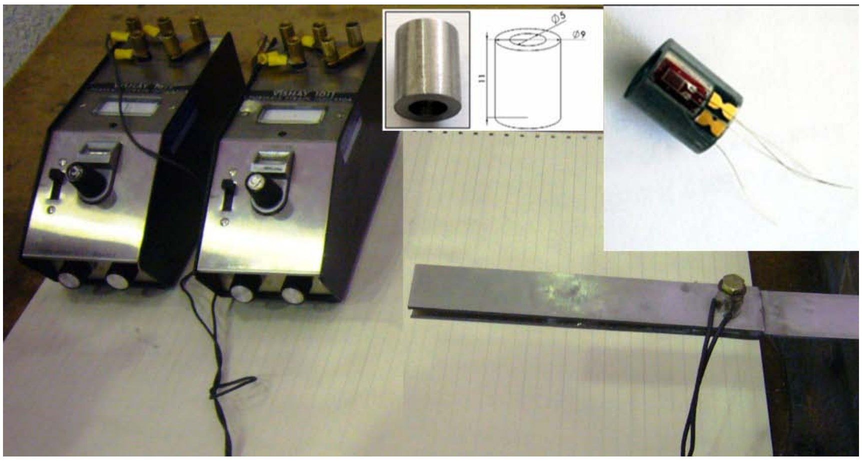


Fig. 2 Measuring the clamping force with load.

In order to obtain the relationship between the applied torque and the clamping force, torques were applied to the nut in 1 Nm increments from 1 to 7 Nm 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), and to determine the corresponding clamping forces using Eq. (1). The relationship between the applied tightening torque and the mean value of compressive strains for both types of joints are given in Fig. 3. The elastic modulus for the bush material (E_{bush}) was also experimentally determined in order to obtain the accurate values of the mean axial clamping force.

$$F_{\mathrm{cl}} = E_{bush} A_{bush} \varepsilon_m = 204188 \cdot \frac{\pi}{4}(9^2 - 5^2)\varepsilon_m = 89.8 \cdot 10^5 \varepsilon_m \text{ (N)} \tag{2}$$

where A_{bush} is the area of the bush cross section. The relation between the calculated clamping forces and the applied torques for the specimen is shown in Fig. 4. As the figure shows, there is a linear relationship between the clamping force and the applied torque. This confirms that the bush material is still in its elastic region, even under the maximum applied torque.

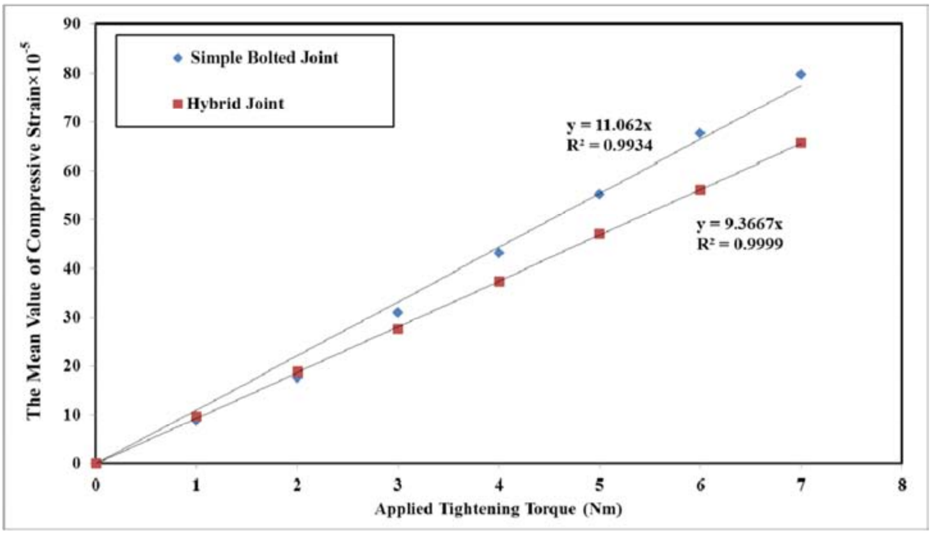


Fig. 3 The relationship between the applied tightening torque and the mean value of compressive strains

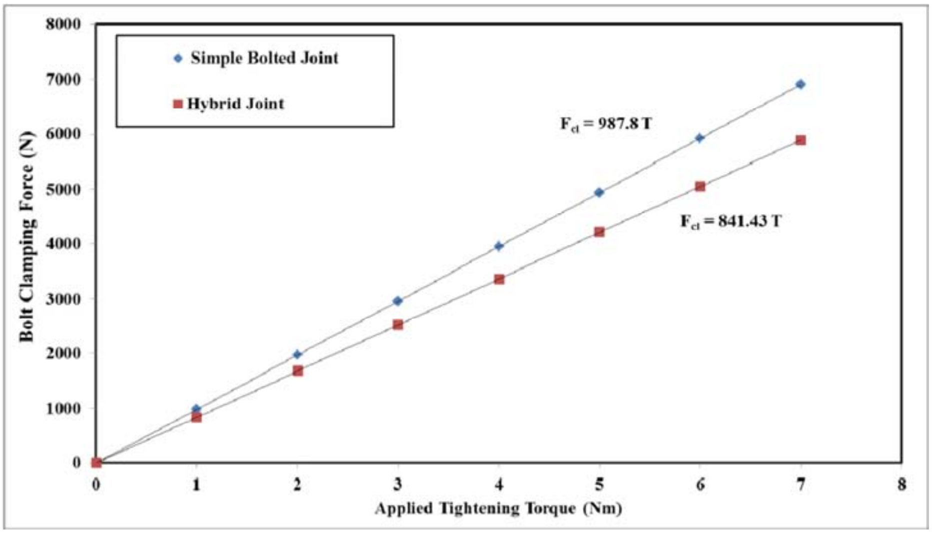


Fig. 4 The Tightening torque-clamping force relationship

According to the obtained linear equation for the fitted curve on the graph and also to Eq. (1), the torque coefficient *K* is obtained experimentally for the double lap simple bolted joint as follows:

$$\frac{1}{K\left(5\cdot 10^{-3}\right)} = 987.8 \rightarrow \quad K = 0.202 \tag{3}$$

In order to obtain the relationship between the applied torque and the clamping force in the case of double lap hybrid joints, the same experiments were conducted with the hybrid specimen. For the purpose of making a comparison between the clamping forces resulting from the same tightening torques in the two types of joints, the obtained results are shown in Figs. 3 and 4.

According to the obtained linear equation on the graph and also to Eq. (1), the torque coefficient K is obtained experimentally for the double lap hybrid bolted joint as follows:

$$\frac{1}{K\left(5\cdot 10^{-3}\right)} = 841.43 \rightarrow \quad K = 0.238 \tag{4}$$

For the case of the double lap hybrid joint, the torque coefficient K obtained according to Eq. (1) and the obtained linear equation on the graph equals to 0.238.

3. Discussion and conclusion

In the present research, an experimental method for measuring the clamping force resulting from the applied tightening torque in double lap simple bolted and hybrid (bolted-bonded) joints has been proposed. Two types of joints, i.e. double lap simple and hybrid (bolted-bonded) joints were prepared to be tested. In order to measure the clamping force or pretension resulting from the tightening torque at different applied torques, for both types of joints, a special experimental method was designed using a steel bush that was placed between the nut and the plate. Two strain gauges were stuck to the outer surface of the bush to measure the compressive axial strain and also the stress in the bush using Hooke's law. Finally, the axial force in the bush and then the clamping force were determined. The relationship between the applied tightening torque and the mean value of compressive strains, and also the clamping force for both types of joints are shown in Figs. 3 and 4 respectively.

The graph in Fig. 4 shows the difference in the torque-clamping force relationship between a bolt tightened in a double lap simple bolted joint and a hybrid (bolted-bonded) joint. As it can be seen from Fig. 4, the torque required to obtain a specific value of clamping force was significantly smaller in the double lap simple bolted joints than in the hybrid joints. In other words, the clamping force which corresponds to a specific value of tightening torque in the hybrid joints is lower than the obtained clamping force at the same value of tightening torque in the simple bolted joints. Also, based upon the torque-clamping force relationship and the dimensions of the bolt, and according to Equation (1), the torque coefficient K was determined for the double lap hybrid bolted joint. It can be seen that the torque coefficient increases from 0.202 for the simple bolted joints to 0.238 for the hybrid joints.

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Submitted: 08.12.2013
Accepted: 10.6.2015

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