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Effects of bolt torque tightening on the strength and fatigue life of airframe FRP laminate bolted joints

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Abstract

The experimental study presented herein, investigated the effects of bolt torque tightening on the strength and fatigue design of bolted AS7/8552 fibre reinforced polymer laminates. Damage initiation and final failure manifestation on the joints was investigated and presented using optical microscopy. Subsequent experimental result analysis explored the application domain of bolted joints within the airframe design sector, bound by the current airworthiness certification requirements and expected airframe design life. The reasons for the static strength of the joint laminates or the fatigue failure of the bolt being the main design drivers for the tested joints were highlighted. The study concluded with comments and suggestions on the application of bolt torque tightening in relation to the strength, fatigue life and damage tolerance characteristics of joints on similar fibre reinforced polymer laminate composite material systems.

Keywords: fatigue; fracture; strength; mechanical testing; optical microscopy;

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1. Introduction

The aim of the experimental study presented, was to investigate the effects of bolt torque pre-tightening on the strength and fatigue life of fastened FRP laminates in the specific context of airframe design and certification.

The aerospace vehicle design sector has embraced the application of fibre reinforced polymers (FRPs) for some decades now. These materials provided the FRP airframe structural designs with enhanced strength and stiffness regarding the most traditional designs made of aluminium alloys. For most designs, a reduction in the structural weight was achieved especially for the structures with defined load paths, benefiting from the directional property tailoring of the unidirectional laminate FRP materials.

The production method for classic aluminium alloy airframe structures is to assemble forged, machine formed and thin sheet of aluminium alloy components together, in forming larger structural assemblies fastened by bolts and rivets. It has been recognized that the fewer the joints in such structures, the stiffer and the lighter the design is, the longer the life of the structure and the fewer the problems encountered in service [1]. There were nevertheless limitations to the size of the structural components that could be produced as single structural items prior to assembly for avoiding excessive fastening and riveting.

With the introduction of FRPs, new manufacturing concepts have emerged. The FRP material is generated while the structural component is manufactured by curing of the composite matrix, within or outside oven/autoclave chambers. The idea of generating complete airframes during a single manufacturing stage started to be quite tempting since the conception in the application of the FRPs in airframe manufacturing. Generally, larger structural parts are generated from FRPs but there are limitations to this single stage production process as well. The current status for FRP airframe components, in the aviation industry for most of the cases that have not been cured or co-cured with their mating part is to assemble them by the use of bolts. Riveting is not a preferred method for FRP laminate assembly mainly due to the high transversal loading incurred during the fastening process, loading which most of the FRP laminates are relatively intolerant [1]. Adhesive bonding can be regarded as another means of mating, but currently poses a lot of certifications issues especially to the certification of civil aircraft.

Bolted joints on FPRs have been criticised as not being very efficient means of structural assembly. Joint efficiency is judged by the ratio of the actual loading transferred though the joined structure versus the load transferred had the structure been uninterrupted without the presence of any joining means. In that respect, FRP structures can reach a ratio of 0.4 while similar arrangement in aluminium structures can reach the level of 0.65 [1]. But when comparing the weight per unit length of assembled structures for carrying the same amount of loading, FRP bolted structures as a complete assembly weight less than a supposed substitute made of aluminium alloys.

Amongst the possible bolted joint failure modes [2], airframe design favours bearing failure [1]. Design recommendations regarding edge distances, fastener spacing, thickness and layup of the laminate, will safe guard the bolted structure from failing under different failure modes than bearing failure. The experimental study herein, made use of specimens were bearing failure was promoted. The material for specimen manufacture was unidirectional HexPly pre-preg AS7/8552 carbon fibre /epoxy matrix tape. This material is currently used on some civil aircraft fuselage structures.

The experimental study presented herein, apart from correlating the published results from other researches and other FRP material systems with AS7/8552 laminate, places the bolt bearing fatigue of FRP laminate problem within the context of airframe design, certification and current design airframe lifespan. Experimental findings of the effects of bolt tightening preload on different FRP material systems and various joint design parameters were investigated and presented in the following section.

2. Literature review

The effects of the pre-tightening toque on the static and fatigue strength of FRP bolted joints reported in the literature are presented below. Some important definitions:

- Bearing stress is a reference stress level, defined as the load carried by the joint, divided by the bolt-hole diameter and the specimen thickness.

According to ASTM 5961 [1] testing method, under static loading conditions:

- Bearing strength is defined as the value of bearing stress occurring at a significant event on the bearing stress / bearing strain curve. The 2% offset strength is prescribed in the standard [1] while the term "significant" has been subjected to interpretation by Camanho and Lambert [3], where the 5% in stiffness drop has been proposed. The actual definition of the bearing strength is not going to influence the output of this study.
- Ultimate bearing strength is the value of bearing stress at the maximum force capability of a bearing specimen.

According to ASTM 6873 [4] testing method and under fatigue loading:

- Failure in a bolted specimen under fatigue loading can be regarded as the catastrophic failure in the laminate or the bolt, or in terms of a percentage of bolt-hole elongation which is the permanent change in the bolt-hole diameter in a bearing coupon caused by accumulated damage formation.

2.1 Bolt torque tightening effects on static testing

Various aspects of the effects of pre-tightened bolts on the strength of FRP laminates under static loading conditions have been studied [5-7]. Crews [8] conducted static bearing tests using specimens made from graphite/epoxy (T300/5208) laminates. The clamp up effect significantly increased the ultimate bearing strength of the specimens. Worth noting was that maximum hole elongation prior to failure occurred in the case of zero bolt preload. Also observed was the effect of clamp up on the failure mode of the specimen. For the specimens with torqued bolts, failures were normally beyond the washer, as opposed to the non-preload cases where bearing failure in the vicinity of the contact area was exhibited. Khashaba et al [9] noted complimentary results with increases in ultimate bearing strength with increased clamp up torque. Specimens were manufactured from glass fibre reinforced epoxy. The effect of increases in washer size was found to have limited effects on the ultimate bearing strength but had a significant impact on hole elongation prior to failure. Sen et al [10] investigated the effect of various layup combinations. Using single lap joint configurations, Sen achieved somewhat similar results to the previous authors, with noticeable increase in ultimate bearing strength with increased clamp up torque. The specimens were tested at three torque levels of 0 Nm, 3 Nm and 6 Nm. Ramkumar and Tossavainen [11] conducted an extensive static and fatigue program testing the effect of various parameters on the static and fatigue strength of both single and double lap configurations. It was found that a 30% increase in bearing strength under static loading conditions was achievable with increasing the torque from finger tight to 22.6 Nm. Poon and Gould [12] conducted a series of static and fatigue tests on a several specimens with variations on the clamp up torque. Specimens were manufactured from IM6/5245C composite material. These specimens were tested in a double lap configuration. Clamp up torques of 0 Nm, 5.6 Nm and 16.9 Nm were applied to the bolts. It was evident that a significant improvement in the ultimate bearing strength is achieved with increased in clamp up torque.

2.2 Bolt torque tightening effects on fatigue testing

The effects of pre-tightened bolts on the life of bolted FRP laminates under fatigue loading conditions have been studied as well [13-16]. Smith and Pascoe [17] conducted fatigue tests on XAS/914 laminate specimens using two different torque values 2.3 Nm and 5.6 Nm as well as simple finger tight clamping. The data showed that the finger tight clamp up torque specimen appeared to fail 1 - 2 decades lower at a given stress level. Additionally, through microscopy, Smith confirmed the reduction in damage of specimens with a higher clamp up torque at a given cycle count. Continuing the research and testing conducted by Ramkumar and Tossavainen [11], various parameters were tested under fatigue such as stress ratios, layup and geometry. It was found that at low torque levels bolt-hole elongation increased relatively gradually, whereas at high torque levels, bolt-hole elongation change was very abrupt. Crews [8] conducted several fatigue tests with variation on testing environments (air and water) and clamp up torque. Graphite/epoxy (T300/5208) laminates were used. Crews noted the variation of bolt-hole elongation with each clamp up condition. Lim et al [18] conducted a series of static and fatigue tests on Glass–epoxy composites in double lap configurations and a series of layups. These were then tested at various clamping pressures. The study results showed that the percentage of stress applied to the specimen, compared to its maximum static strength, yielded a similar fatigue life regardless of the clamping pressure. Lim also found that the fatigue life decreases linearly with respect to the applied stress and that the fatigue life of 1 million cycles corresponded to an applied fatigue stress of approximately 50% of the maximum static strength. Lim conducted limited fatigue tests with other layup combinations incorporating an additional clamp up pressure of 70 MPa, relating to an approximate bolt torque of 5 Nm. While the orthotropic properties of these particular layups had a significant impact on the fatigue life of the specimens, the increase in fatigue life due to increased clamp pressure was evident in the results. Poon and Gould [12] tested IM6/5245C specimens under constant amplitude tension-compression cycles in a double lap joint configuration. His findings were in terms of bolt hole elongation against number of cycles were it was noted, unlike the results produced by Crews, there was relatively little to no hole elongation until bearing failure onset. Saunders et al [19] fatigue tested AS4/3501-6 graphite/epoxy specimens, under tension-compression loading sequences. Specimens were tested in a single-lap configuration with two in-line titanium fasteners. It was concluded in the study that under the conditions of low secondary bending the dominant structural failure mode of mechanically fastened joints in thick laminates was fatigue failure of the fastener.

Concluding to the above literature research, bolt torque pre-tightening has been reported as having a positive effect on the static strength and fatigue life of bolted joints on FRP laminates. In some cases, different response has been noted in the failure mechanism and failure response measured by bolt-hole elongation. Different composite material systems respond differently to bearing fatigue loading. Nevertheless bolt pre-torque tightening enhanced the static and fatigue life of the specimens in the above mentioned cases. The experimental testing survey presented on the following section, was performed on AS7/8552 material and was aimed at benchmarking the above mentioned experimental findings with this aerospace grade FRP material system.

3. Experimental methods

3.1 Hardware

Specimen design

A double lap joint configuration was chosen for testing the effects of the bolt torque pre-tightening on the static strength and fatigue life as shown in figure 1. The double lap joint design was selected in order to isolate the in-plane behaviour of the laminates from the secondary effects caused in a single lap joint.

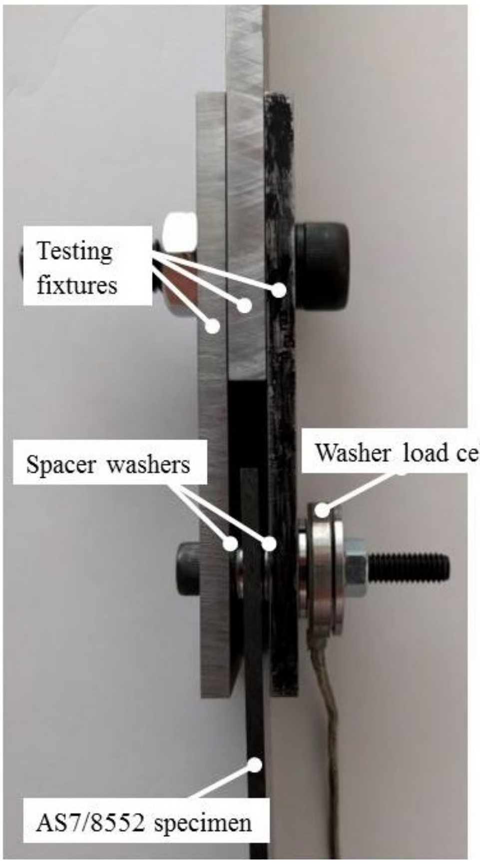

Figure 1: Double lap configuration test set up assembly with washer type load cell

The specimens were manufactured from AS7/8552 HexPly® prepreg unidirectional tape in a quasi-isotropic layup. The tape roll had a nominal laminate thickness of 0.145mm. Twenty four layers layup configuration, $[45\ 90\ {-45}\ 0]_{3s}$, was decided upon to achieve the specified applicable specimen thickness of approximately 3.5 mm. The specimen geometry was based on the applicable standards. ASTM D5961 [1] was followed for the bearing response under static loading. ASTM D6873 [4] testing standard dictated the practice for the bearing fatigue response under constant amplitude cyclic load. This standard is utilizing the same testing provisions as in ASTM D5961 and provided procedural guidelines to determine the number of cycles until failure or for the measurement of bolt-hole elongation throughout the testing.

Washer Load Cell

An Omega™ 20 kN washer load cell, shown in figure 1, was placed between the nut and washer insert to measure the clamp force. This was connected to a 5V DC exciter and provided an output of 0-8 mV/V to a digital voltmeter.

Fasteners

Quenched and tempered steel (Grade 12.9) M6 socket head cap screws were used to fasten the specimen to the fixture. Titanium alloy fasteners were not selected as previous testing has shown titanium bolts to fail due to fatigue under cyclic testing [19]. Failure of the bolt was not a desirable event in the testing survey. Steel bolts have also been used in similar experimental works, as in references [9, 18 and 20].

Application of pre-tightening torque

Smith and Pascoe [17] reported some slippage effects where the load was initially taken up by the friction between the washer and specimen. It was noted that under testing there was a sudden jump in displacement at the point where the frictional load is exceeded and the bolt was contacting the full bearing area. Consequently the specimens were loaded statically to 10% bearing strength prior to torque tightening the bolts.

3.2 Testing

Static and fatigue tests were performed on an Instron servo-hydraulic dynamic testing machine. During static testing, load, cross head displacement and bolt pre-torque clamp force data were recorded. The testing loading direction was aligned with the zero degree layers of the quasi-isotropic specimen as per the applicable ASTM D5961. Variation in the load application with respect to the major laminate axis can have a significant effect upon the static bearing strength of the specimen [21, 22] but such an investigation was beyond the scope of the current study.

Static testing

A series of static tests were conducted to determine the ultimate bearing strength of each pre-torqued specimen. During this process the force, strain and clamp force was recorded. Static testing was displacement controlled with a fixed rate of 2 mm/min and ceased once failure occurred in the specimen. Testing of the specimen under static loading took place at the three pre-torque value levels, namely finger tight, 5 N/m and 10 N/m.

Fatigue testing

Fatigue testing was not performed for generating design data. It was mainly used for verification of the general trends observed by other researchers in the field, mentioned in the literature review section. In order to generate S-N data scatter at the respective bolt torque pre-tightening levels as shown in figure 7, a total of 24 specimens were tested under Constant Amplitude fatigue Loading (CAL). The fatigue stress levels selection and the number of specimens per level are described in the following section. During testing, the number of cycles and the cross head displacement were recorded for analysis.

The cyclic frequency for fatigue testing was increased as much as possible for minimising the duration of the test. The limitations on the frequency were mainly associated with test equipment capabilities, time-dependant processes and hysteric heating [23]. The latter being a significant influence in particular with high cyclic rates, as increases in temperature are able to change the properties of the laminate. ASTM 6873 noted that for some material systems a temperature change of 10ºC has demonstrated measurable degradation of material properties. Sun at al [23] conducted a series of fatigue tests at various frequencies to determine the hysteretic heating occurring within the specimens. These specimens were similar in geometry and under similar test conditions to the ones presented herein. It was found that for test frequencies less than 20 Hz under these test conditions should not noticeable degrade material properties through hysteretic heating. During the experimental study presented herein, a frequency of 10 Hz was chosen for testing, since this frequency is often used for similar fatigue experiments. Testing was conducted under a stress ratio R equal to 0.1.

Due resources limitations, specimen run-out was marked at 600,000 cycles, the effect of which was taken into consideration during result analysis and discussion. The damage metric in the fatigue experiments was selected as the 4% bolt-hole elongation. ASTM 6783 [4] suggested stopping the testing and resume after the measurement of the hole deformation but in this study the machine head displacement was measured instead since it was regarded as a process generating more consistent results. The final overall percentage in bolt-hole elongation was measured and verified on the specimen at the end of the test.

4. Experimental results and analysis

4.1 Effects of bolt pre-tightening torque on the joint static strength

Static bearing tests three different bolt pre-torque settings are shown in figure 2. A matching linear region that spans from about 250 MPa up to 400 MPa approximately can be observed for the three cases, which signifies the portion of the testing were damage has not occurred on any of the specimens.

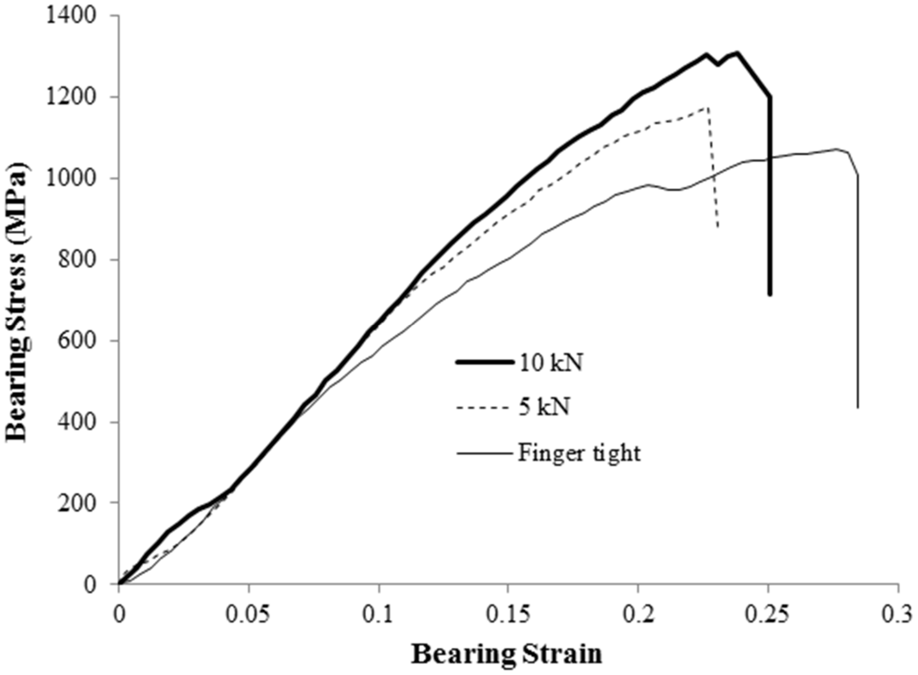

Figure 2: Static bearing tests at different bolt pre-torque tightening settings

Beyond the common to the three curves linear region, deviation from the linear response is the indication of damage initiation and accumulation. Bearing strength can be measured either from offsetting the linear component by a certain percent to the right of the chart or by a percentage change in the curve tangency as described previously. The bearing strength calculated per ASTM D5961 was approximately 770 MPa for the finger tight case, while for the 5 kN and 10 kN bolt torque tightening levels was found 1050 MPa and 1230MPa respectively. The different approaches to deducting the bearing strength as outlined in section two, will result in different bearing strength levels. The effect of bolt torque pre-tightening under static loading measured was approximately a 35% increase in the bearing and ultimate bearing strength of the joint at pre-tightening torque levels of 10 Nm. Authors of similar investigations [8, 9 and 12] have reported slightly smaller to similar percentages of strength increase for different FRP materials, layup arrangements and bolt pre-tightening levels. Without any clamp up force, the majority of the applied load was transferred from the fixture to the specimen through the bolt coming into contact with the FRP laminate bearing area. When clamp up torque was applied to the joint, a portion of the load was transferred by the friction between the specimen and washers.

Using optical microscopy and having examined the bearing plane of the failed specimen, it was evident that clamp up torque helped resisting bearing failure and prevent bunching and expanding of fibres around the bolt hole. The crosshatched region in figure 3 shows the bearing plane section through the specimens used for observing damage. In figure 4, the comparison of representative fracture patterns is displayed between the un-torqued and 10 Nm pre-torqued specimens. The washers were effectively compressing the laminate in the vicinity of the bolt hole and failure was manifested mainly at a distance further from the bearing area in contact with the bolt.

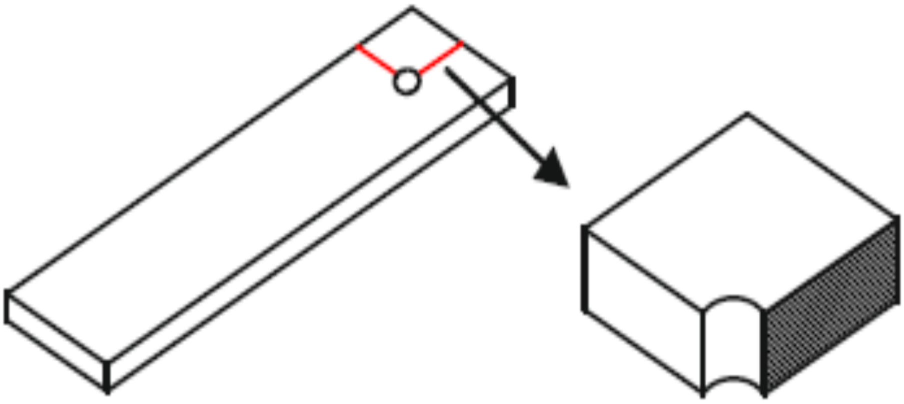

Figure 3: Bearing plane definition and location of the optical microscopy pictures on the samples

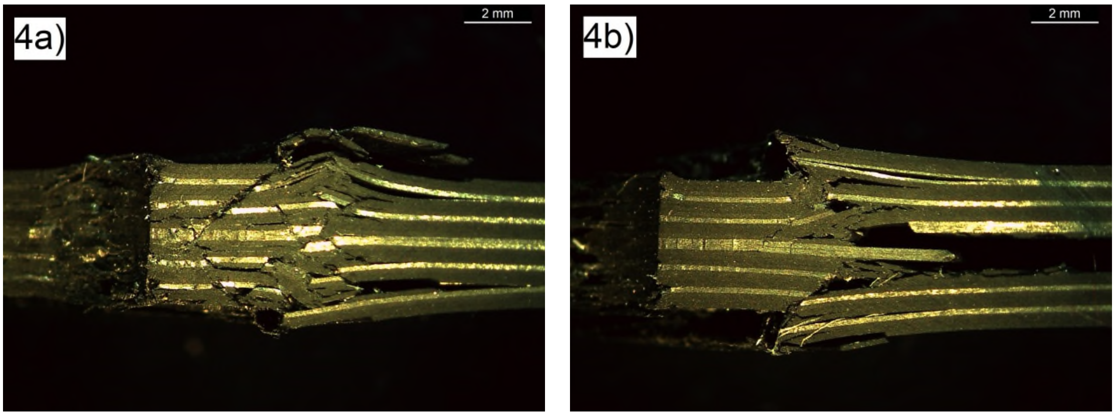

Figure 4: Characteristic images of failure under static loading, a) without bolt pre-tightening, b) with 10Nm bolt torque pre-tightening.

The compression force transmitted through the washers on the specimen, shielded a part of the annular area against fibre bunching and helped in the spreading of the loading to a greater portion of the laminate as if a bolt of a wider shank was used. This torque tightening effect could be hypothesised and visualized as a larger *"effective bolt diameter",* evident in figure 4b. The bearing failure occurred at a distance from the actual bearing area in contact with the bolt shank dependents on the washer size and the pre-torque tightening levels.

4.2 Effects of bolt pre-torque on the joint fatigue life

Initial trials under CAL fatigue, showed that damage was insignificant for the in-service loading the joint was supposed to be designed for. Out of the 24 specimens fatigue tested overall, a total of nine specimens were tested at loads below their respective bearing strength. Three finger tight specimens at 400 MPa maximum load, three specimens torqued at 5 Nm and loaded at 650 MPa and three torqued at 10 Nm, loaded up to 900 MPa. These nine specimens can be traced at the far end of the chart in figure 7. The bearing stress values were selected following the static bearing strength tests, ensuring that these stress levels were not causing any form of static failure in the specimens, while the load magnitude was in the region of the expected service loading or higher. When failure did occurred at these loading levels, it happened after the cut off limit set at 600,000 cycles and was related more to bolt failure rather than failure in the bearing area of the FRP laminate. In figure 5, specimen cross sections undergone constant amplitude cyclic loading are exposed.

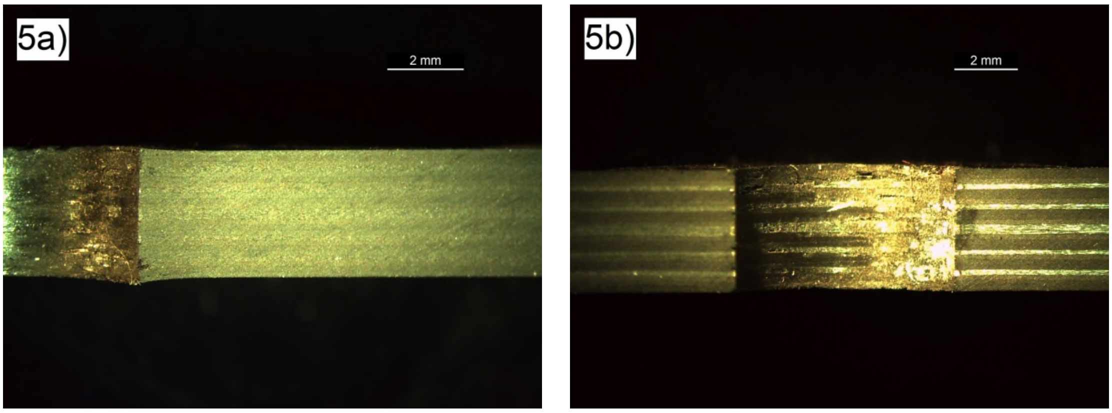

Figure 5: Characteristic image of failure under fatigue loading at loading levels before the static bearing capability, a) without bolt pre-tightening, b) with bolt pre-tightening.

It could be argued that signs of material degradation have appeared but there was no significant percentage in bolt-hole elongation. Residual static strength was not measured since the specimens were dissected for optical microscopy inspection. Whitworth [24], Grant et al [25] reported the same or larger residual strength after testing in bearing fatigue experiments.

It was recognized that in order to generate failure under cyclic loading within the aerospace design life specifications, the specimens had to be loaded at cyclic loading levels past their static bearing load capability. The remaining 15 specimens were tested at alternating stress levels between their bearing and ultimate bearing stress. The results from these tests are occupying the main central part of the chart in figure 7. In figure 6, the characteristic patterns of failure exposed at the bearing area cross sections are shown. For these specimens, test ceased after reaching a value of 4% bolt-hole elongation. Similarly to the static case, for the specimen with no pre-torque, damage emanated from the bearing area in contact with the bolt shank. Apart from this location, in the torqued specimen cases, damage sites are generated at the area under the washer as well.

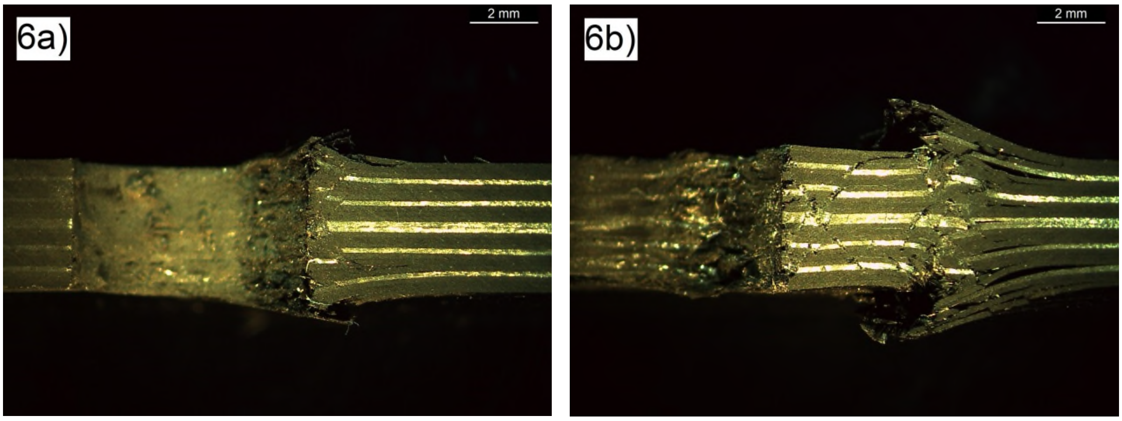

Figure 6: Characteristic image of failure under fatigue loading at loading levels past the specimen static load bearing capability, a) without bolt pre-tightening, b) with bolt pre-tightening. Specimens failed under excessive (4%) bolt-hole elongation.

In both cases, fracture shear planes were present similar to the static fracture patters, result which was expected since the specimen were loaded past their static bearing capability. This fatigue cycle loading approach resembled more the low cycle fatigue regime in metallic structures, where the alternating stresses in the material are high enough to plastically deform the highly stressed areas in every loading cycle. Observations related to the bolt-hole elongation rate showed that at low clamp up configurations, bolt-hole elongation increased relatively gradually, whereas for the high clamp up torqued ones, a very abrupt bolt-hole elongation increase was evidenced.

Bearing stress versus fatigue life for the specimen tested under fatigue is presented in figure 7. The data on the S-N diagram revealed that below a certain stress level and for the testing time frame, specimens did not fail under cyclic loading, while for a certain range above this level and close to the bearing failure stress, there was a large scatter in the life expectancy. Three specimens were used for verifying the run-out cases at each pre-tightening level. The rest of the points on the chart represent a single specimen failure.

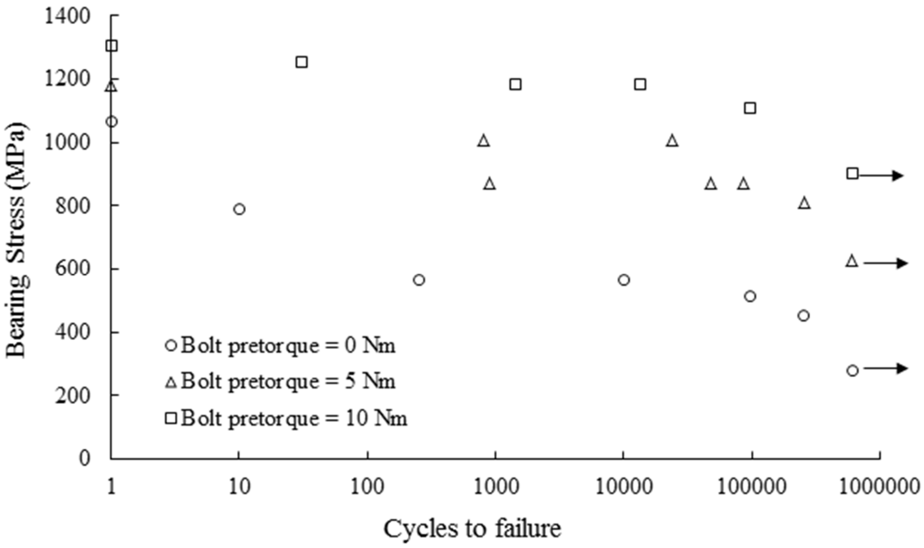

Figure 7: S-N data at various bolt torque pre-tightening levels

The small changes in the bearing load that resulted in significant changes in fatigue life can be attributed to more than one factor. Bearing failure under cyclic loading will be initiated under in-plane failure conditions and propagated under various in-plane and out-of-plane damage mechanisms. Harris [26] described the intrinsic large scatter in the in-plane fatigue behaviour of FRP materials, stochastic process which can be further augmented from unpredictable damage caused during drilling process [27] and dimensional tolerances between the bolt shank and the bolt-hole [28, 29].

For the material tested, bolt torque pre-tightening had increased the static bearing strength. In terms of fatigue, as long as the loading was kept below the bearing strength which was a function of the bolt pre-tightening load, specimen life was not influenced up to 600,000 cycles. At higher pre-torque values, larger loads were sustained without failure, only because the specimen static bearing strength was increased and static bearing failure was not initiated. This well-known fact in the airframe industry is the reason why structural testing for certification purposes in composite structures, start with the application of static ultimate loading followed by the application of the in service variable loading. In metallic structures, the opposite procedure is followed, allowing fatigue loading to initiate/propagate cracks on the structure and then proceed with the ultimate static loading testing.

5. Discussion

The discussion of the results presented in this section is in relation to the airframe design and certification processes as opposed to other important studies in the field [30]. Civil and military aircraft airworthiness certification specifications form a part in the means of controlling and ensuring the safety of flight. Within such specifications, as for example shown in references [31, 32], the expected performance criteria for the airframe structures are listed. According to the specifications clauses relevant to our investigation [31] and employing simple wording, airframe structures must (*):

- Function properly under the application of service loading applied quasi-statically without exhibiting signs of detrimental permanent deformation or deformation levels that interfere with the proper operation of the aircraft. This loading level is defined as Limit Loading (LL)
- Not fail under the application of the service loading applied quasi-statically, multiplied by a safety factor which in the majority of the cases equals to 1.5. This loading level is defined as Ultimate Loading (UL) and UL= LL x 1.5
- Not fail catastrophically under the application of the actual service variable loading spectrum throughout the operational life of the aircraft

(*) The above statements are simplified expressions employed for providing with a simple translation to the actual certification specifications and should not be regarded as substitutes to the actual airworthiness certification specification clauses. Joint fitting factors or other material/design factors that are also employed for joint sizing are not discussed herein to avoid masking the essence of the study with additional complications

Airworthiness certification specifications require proof of structural performance for the different loading types and loading levels as shown above. The proper interpretation of the airworthiness certification specifications applied on airframe design depends on the actual structural component and is provided on a case by case scenario.

In the case of bolted joints on FRP laminates, the specifications interpretation is demonstrated in figure 8. In figure 8, a representative bearing load-displacement is displayed for the specimen design specifications and material stated in the experimental methods section, subjected to quasi-static tensile loading. This chart can be easily modified in terms of bearing stress versus bearing strain. On the loading axis, ultimate loading (UL) is marked as the region of the specimen's bearing strength, which can slightly vary depending on the standard or the interpretation given to the bearing strength as discussed previously.

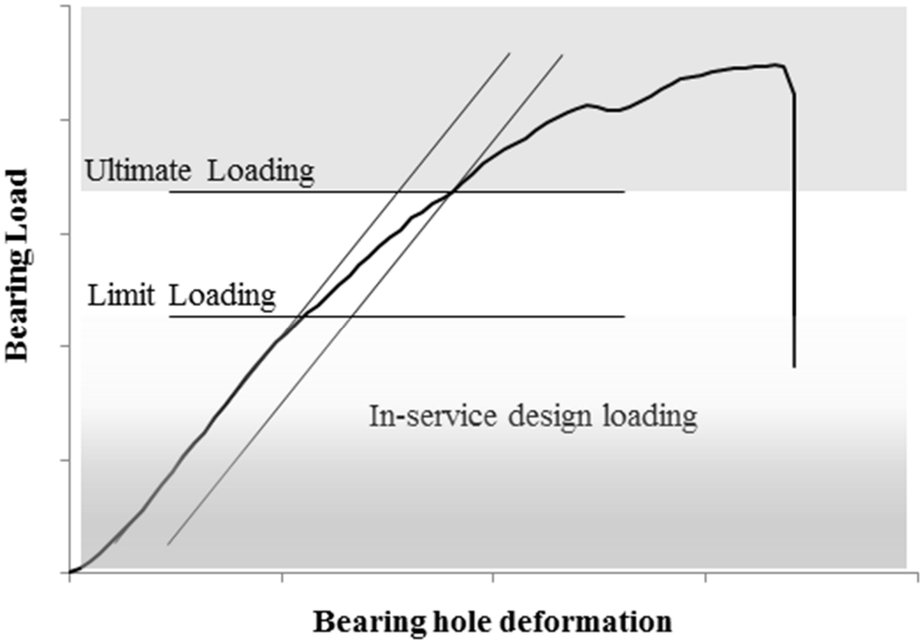

Figure 8: Typical bearing load to bearing bolt hole deformation curve for the quasi-isotropic, AS7/8552 specimens at finger tight pre-tightening toque

The maximum loading to be met in service, which is the limit loading (LL), when multiplied by the safety factor of 1.5, has to be less or equal to the specimen's bearing strength as suggested in the certification specifications.

Actual aircraft component loading to be encountered in service is expected to lie at, or underneath the LL line. In service loading, in most of the cases, is variable in magnitude. Statistical distributions of the probability of the loading level occurrence in terms of number of cycles are generated based on experience and in-service flight test measurements. Although in service expected loading is variable in nature, it is a certification requirement to provide proof that the structure is able to endure loading applied in a quasi-static format, according to the first and second bullet points in this section. Proof is also needed for the structure that it can endure the actual in-service variable loading spectrum according to the third bullet point. In most of the cases, these loading sequences and distributions contain only a minor amount of loading cycles close to LL [33], with the majority of the loading levels to non-damaging by being much less than the LL level [34]. The experimental results of fatigue loading presented in the previous section, for the material and specimen design tested, has shown no signs of fatigue failure while being tested under constant amplitude loading at levels close to LL, within the time frame of 600,000 cycles. It has been noted [35] that actual variable amplitude fatigue loading spectra at various R ratios can be more damaging since the alternating compression-tension cycles help transporting the wear particles out of the bolt hole. For the study presented herein, in order to promote simplicity in the experimental equipment, fixtures and testing procedures, made use of a simple constant amplitude loading sequence at severe amplitude levels, assumed capable of providing the necessary proof to the points made in the study.

It is anticipated that if running fatigue tests past a few millions of cycles, some deterioration could appear even for loading levels before the specimen static capability [36]. But it is not practical to generate such results for the common airframe component type of loading and lifespan [33, 34].

The effect of applying the certification requirements to bolted joints on FRP laminates of the study was to limit the loading application levels for meeting the static strength requirements, to regions where fatigue was not affecting the joint significantly. This is one of the major differences with the bolted joints on aluminium alloy structures, were fatigue initiation and propagation takes place at loading levels below the allowable static loading.

Unidirectional fibre reinforced polymer laminate response to static and fatigue bearing loading is expected to show variations in the mechanical response in relation to the studied AS7/8552 FRP laminate. The conclusions drawn within this study are specific to the material and specimen design parameters and testing. Nevertheless, there is a class of aerospace grade FRP materials exhibiting similar static mechanical response to loading as the on presented in figure 8 and have similar response to fatigue loading. Bolted joints on such materials do not suffer from fatigue failure since their static limit cut-off will prevent them from failing. Depending on the bolt used though, the joint could effectively be prone to fatigue failure through failure in the bolt. In the experimental study presented herein, steel bolts were used with relatively high resistance to fatigue, but using other fastener materials [37], the bolts might fail. Non proper designs might require fatigue sizing of the bolts rather than of the bolt-holes. In such cases, the effect of the pre-torque would be to decrease the life of the bolt, hence decrease the life of the joint.

Regarding this problem from a different perspective, during current inspection practices and procedures on aluminium airframes, inspectors are looking for cracks emanating on the structure around the bolt periphery. Hence inspection procedures are are focused around bolt-holes. In the case of FRP airframe structures, the bolts have to be inspected instead which is not very practical. Yet another thing to be considered is that bolt failure is not a favourable joint failure mode in the airframe design since the structure may experience the so called “zipper effect”, were the structure disintegrates after the sequential failure of the bolts in a bolt pattern.

At low clamp up torque, bolt-hole elongation increased relatively gradually, where high clamp up torque showed a very abrupt bolt-hole elongation increase. The gradual bolt-hole elongation in the case of smaller pre-torque and hence smaller clamp-up force contains a fail safety characteristic by the means of gradually relaxing the loading concentration at a specific area and distributing that to the neighbouring structural components.

Fatigue loading during service, will diminish the levels of pre-torque, either through wear or creep hence the allowable bearing strength will deteriorate. Some levels of pre-torque are always going to be advantageous in that sense but its additive effect should not be factor in when deriving structural strength allowables [35].

6. Conclusions

For the static bearing loading cases and for the bolted joints on the FRP material tested herein, with increasing pre-tightening torque the joint static strength increased. This result has been reported in the literature on many other material systems and laminate configurations. Pre-tightening levels cannot exceed the transverse compression strength of the laminate. For the relatively heavily torqued pre-tightened joints, failure took place mainly on the specimen part after the washer. An effectively increased bearing area was observed. Pre-tightening levels and washer diameter affected the location of the damage pattern. Pre-torque levels cannot be guaranteed throughout the life of the joint hence structural strength allowables have to be derived from lightly torqued specimens. The lower pre-tightened torqued specimens had a longer displacement to failure. This feature is advantageous to damage tolerant designs.

For the fatigue bearing loading cases, static strength certification requirements safeguard against laminate fatigue failure the currently used aerospace grade carbon FRP materials under the current airframe operational life expectancy. Fatigue design of bolted joints on FRP structures should address fatigue at the bolts. Within the cyclic loading time frame and type of loading set in this study, the structure was not affected by fatigue. Increasing the bolt pre-tightening, the static strength allowable increased which provided with an apparent increase in the fatigue life. During fatigue testing and at low clamp up torque, hole elongation increased relatively gradually, where high clamp up torque showed a very abrupt hole elongation increase. Hence low torqued specimen provided with warning, feature which could potentially be utilized by structural health monitoring systems.

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