Accepted Manuscript

Hydrothermal ageing effect on the mechanical behaviour and fatigue response of aluminium alloy/glass/epoxy hybrid composite single lap joints


PII: S0263-8223(19)30209-0
DOI: https://doi.org/10.1016/j.compstruct.2019.03.078
Reference: COST 10806

To appear in: Composite Structures

Received Date: 18 January 2019
Revised Date: 12 March 2019
Accepted Date: 21 March 2019

Please cite this article as: Mariam, M., Afendi, M., Abdul Majid, M.S., Ridzuan, M.J.M., Sultan, M.T.H., Jawaid, M., Gibson, A.G., Hydrothermal ageing effect on the mechanical behaviour and fatigue response of aluminium alloy/glass/epoxy hybrid composite single lap joints, Composite Structures (2019), doi: https://doi.org/10.1016/j.compstruct.2019.03.078

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Hydrothermal ageing effect on the mechanical behaviour and fatigue response of
aluminium alloy/glass/epoxy hybrid composite single lap joints

M. Mariam a, M. Afendi a, M.S. Abdul Majid a, M.J.M. Ridzuan a, M.T.H. Sultan b,c, M. Jawaid b, A.G. Gibson d

a School of Mechatronic Engineering, Universiti Malaysia Perlis, Pauh Putra Campus, 02600 Arau, Perlis, Malaysia,
b Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
(c)Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor Darul Ehsan, Malaysia
d School of Mechanical and Systems Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

*Corresponding author: afendirojan@unimap.edu.my (M. Afendi); shukry@unimap.edu.my (M.S. Abdul Majid)

Abstract

The effect of hydrothermal ageing on the mechanical behaviour and fatigue response of a hybrid
(bolted/bonded) aluminium alloy (AA7075) and glass fibre reinforced epoxy (GRE) hybrid composite
single lap joints (SLJs) were carried out in this work. This effect was investigated using hybrid joints as a
joint configuration. An adhesive layer of Araldite epoxy and mechanical fasteners of Huck bolt were
attached between the adherends as primary and secondary attachments, respectively. Three types of joint
were exposed to a humid environment at 50 °C for long-term immersion (20, 40, 60, 80, 100, and 120
days) periods. Composite laminates (i.e. glass fibre epoxy GRE) and metal (i.e. aluminium alloy
AA7075) were used as joint adherends. Quasi-static and fatigue tests were carried out to evaluate the
evolution of the mechanical performance and the damage mechanisms of hybrid joints during the ageing
exposition. The dissimilar-AA7075/GRE hybrid SLJ showed the highest joint strength and the longest
failure strain. Moreover, the hybrid joint with dissimilar-AA7075/GRE achieved 83 % and 30.2 % higher
fatigue strength than similar adherends of AA7075 and GRE composites, respectively. As for the damage
mechanisms, shear specimens experienced a typical bearing mode.

Keywords: Glass fibre; Aluminium alloy; Epoxy; Environmental effect; Fatigue strength; Hybrid joint.
1. Introduction

In automotive manufacturing industries, design modifications of vehicles have major impact on customer demand. Compared to the pre-existing method, this will be more challenging when appropriate materials and methods are used. The current trend in the vehicle design is influenced by awareness of environmental issues and less dependence on fossil fuels. Vehicle manufacturers introduced various technologies in terms of the structure in order to reduce the weight, directly achieving low CO$_2$ emissions [1]. One of the convincing methods of emission reduction is the application of lightweight structures. Lightweight materials are increasingly used in automobile and airplane industries to realize energy conservation and emission reduction. In particular, composites as the most promising lightweight materials are widely applied, such as Airbus A380, Boeing 787, and Mercedes-Benz McLaren SLR, because of the advantages of light weight and high specific strength and impact resistance [2-4].

A significant reduction in the structure weight can be achieved by introducing a lap joint combination of light alloys and composite materials as compared to conventional steel materials. However, these dissimilar materials cannot be joined using a conventional welding method. This is due to the difficulties in joining where the mechanical and physical properties are different. This is also difficult owing to high structural dissimilarities and melting temperature, which leads to polymer degradation before the metal is melted. Thus, the use of a hybrid joint is expected to establish a more reliable joint. Previous studies found that hybrid structures performed well under static and high-speed loads [5,6]. To further reduce the material costs and structural weight, the composites were employed with an aluminium alloy, which is universal in automotive and aviation applications [7]. An alternative technique, a hybrid joint, also generated interest owing to its potential advantages over the conventional techniques. In a hybrid joint, adhesive bonding and mechanical fastening are used simultaneously to connect the components of interest (adherends).
This type of joints can be divided into two main categories: (a) those that use bolts/rivets and (b) those that use pins [8]. Meanwhile, it was indicated previously that the use of mechanical fastening and adhesive bonding was simultaneous to join similar and dissimilar structural materials in hybrid joints [9,10]. The benefit was to employ the high-strength and well stress distribution advantage of bolted joints by combining them with adhesives in the same way.

In addition, hybrid joints can be designed where the adhesive and the bolt share the load with the load transfer distribution on the joint design and the operating environment. The temperature and humidity are the main environmental factors significantly affecting the joint strength and durability as reported previously [11-14]. The influences of the factors above on the physical and mechanical properties of composite materials were especially studied [15-17]. Therefore, studying the mechanical response behaviour of such joints in severe environments has a great significance for engineering applications. So far, there have been some discussions about the mechanical behaviour of such dissimilar material structures in harsh environments. Hailin et al. [18] analysed the influence of ageing time on the mechanical behaviour of a dissimilar CFRP/Al single-lap bolted joint in a marine environment. Then, the joining failure mechanism was identified around the fastener hole as pitting damage. The bearing and shear-out failure of the composite was recognised. Fiore et al. [19] found that GFRP/Al hybrid joints showed a higher sensitivity to degradation under a salt-fog environmental condition than CFRP/Al joints, but they all progressively decreased with increasing the ageing time. The damage mechanisms were evaluated and confirmed to be the cleavage/net tension failure mechanism owing to lower resistance of composites. The aforementioned works mainly address mechanical fasteners of bolting and riveting structure under the moisture absorption effect. Lately, Jiang [20] investigated the mechanical performance of CFRP/Al electromagnetically riveted lap joints after exposure to a neutral spray environment. Soykok et al. [21] investigated mechanically fastened joints in glass fibre/epoxy composites
subjected to hot water immersion at 50, 70, and 90 °C for one and two weeks. The mechanical properties of the joints were affected by the water temperature and immersion time.

However, as for the hydrothermal effect during the application, a combination of an adhesive and a mechanical fastener in the bonding of joints was not observed and investigated previously, especially for pneumatic air gun bolting. This combination is known as a hybrid joint. Hybrid joints are employed in automotive industry due to their better performance as compared to bolt and adhesive bonding. In addition, previous works primarily evaluated the joint strength degradation in salt spray, distilled water, etc. at short-term immersion. Moreover, little attention was paid to the mechanical response behaviour of dissimilar hybrid joints, which are the most preferred in the joint technology, exposed to humid environment.

The purpose of this research is to investigate the mechanical properties and degradation behaviour of hybrid SLJs. The degradation of aged specimens was involved into similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE under hydrothermal tap water immersion. For the determination of joint durability, lap joints are commonly used to study the effect of environmental ageing on the joint strength owing to their ease of manufacture and testing [22]. The long-term immersion was studied experimentally. Subsequently, a tensile test was carried out to obtain the failure strength and observe the failure fracture.

2. Experimental part

2.1. Sample preparation

Hybrid SLJ specimens are a combination of an adherend, an adhesive, and a Huck bolt. The adherends were made of AA7075 and GRE composites. The GRE composite adherends were made of unidirectional glass fibre with a thickness of 0.15 mm per layer and fabricated using the vacuum infusion technique [23] with volume fraction of 50.13 %. The fibre composite laminate was prepared with 17 plies with epoxy resin and hardener at a ratio of 3:1. Meanwhile, adhesive epoxy
of Araldite with a thickness of 0.2 mm was used as a primary bonding. The adhesive was mixed into resin and hardener with a ratio of 1:1. Table 1 presents the mechanical properties of the AA7075 and GRE composite adherends [24]. Meanwhile, the properties of Araldite epoxy adhesive under dry and humid conditions are listed in Table 2 [23, 25]. Huck lock bolt C6L is a new technology in fastener structural design that provides strength and decreases weight. A type of Huck bolt was used in the experimental study of the hybrid SLJs as a secondary clamp after the adhesive.

The geometry of the hybrid SLJ specimens is shown in Fig. 1. The geometry of similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE adherend joining was the same. The thicknesses of the AA7075 and GRE composite adherends were 3 mm and 3 ± 0.5 mm, respectively. The tolerance of the GRE composites was followed with the standard, owing to the fabrication technique. The thicknesses of the hybrid joint specimens were calculated to be 6.2 ± 0.5 mm. The length of the overlap area was 64 mm. The diameter and length of the Huck bolt were 6.5 mm and 20 mm, respectively. The hole diameters of the adherends were fixed to be 6.5 mm.

In this experiment, initially, the surface of the AA7075 was proportionally abrasion with 120 grade abrasive paper, an acetone wipe to remove dust particles followed by careful drying with a microfiber cloth [26]. The purpose was to remove residual particles that could significantly influence the joint performance and mechanisms.

2.2. Pneumatic air gun bolting

The types of Huck Lockbolt C6L was used in the joining of hybrid joints as secondary attachment. The mechanical fasteners were supplied by Arconic Fastening Systems and Rings. These types of fasteners are available for use in industrial applications owing to their properties designed to provide permanent, vibration-resistant, and predominant quality joining. The schematic design and equipment of pneumatic air gun bolting are presented in Figs. 2(a) and 2(b). There are two parts of fasteners, which are C6L round head-style pins and 2LC standard head-style collar,
which are made of carbon steel. The Pneudraulic Installation Tool is required for bolt installation with an air pressure of 6.21–6.9 bar (90–100 psi) as depicted in Fig. 2(c). The installation sequence is shown in Fig. 3. At the beginning, the installation was started by inserting the pin into the specimen hole with a collar placed on it. Once the air pressure was set, the installation tool was applied by the jaw and nose anvil pulled on the tail and pushed on the collar, respectively. After that, continued swaging by the nose anvil caused the collar to lengthen and develop a clamp until the pintail completely separated from the pin.

2.3. Moisture absorption through hot water immersion

Prior to tensile testing, the pre-bond moisture exposure of the similar and dissimilar materials (GRE and AA 7075) was realized. The materials were aged for different time periods at a constant temperature in hot water, above the adhesive glass transition \( T_g \) of the Araldite adhesive epoxy \( T_g \), which was reported to be 42 °C. The specimens were immersed in tap water with a temperature of 50 °C for ageing periods of 20, 40, 60, 80, 100, and 120 days. The sample weights were measured before and after the exposure to the hydrothermal condition. The procedures and guidelines for the moisture absorption measurements for all samples followed the ASTM D570 standard test [27]. The samples were practically dry and conditioned at room temperature (RT) for 1 h to eliminate surface moisture. The sample measurement was conducted using a density meter with four decimal place accuracy; the result was recorded as \( M_0 \). All specimens were then immersed in tap water in a sealed bath tub. The ambient temperature was monitored using a digital thermometer in all cases. Subsequently, the specimens were intermittently removed from the hot environment, wiped dry using clean and lint-free micro clothes and weight-recorded as \( M_t \). Weight measurements were carried out using electronic analytical balance measuring to 0.1 mg. The moisture content percentage, \( \Delta M(t) \), was calculated using the following equation:
\[ \Delta M(t) = \frac{M_t - M_0}{M_0} \times 100 \] (1)

2.4. Mechanical testing and fracture observations

The mechanical behaviour and failure mechanism of the adhesively bonded joints (GRE/GRE, AA7075/AA7075, and AA7075/GRE) were experimentally investigated after degradation due to the environmentally hot water exposure. The specimen surfaces were dried and weighed after being removed from the water bath tub at the end of each ageing time. In order to eliminate the moisture penetration to the adhesive and adherend, the specimens were rested for 30 min before testing. The chosen time is reasonable for the specimen to return into the room temperature state.

The tensile tests were conducted using an Instron universal testing machine equipped with a 100 kN load cell. The speed rate was set to 1 mm/min. Three replicates of similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE hybrid SLJ specimens were tested under tensile at 25 °C (RT). The tests were conducted for each ageing time. In addition, the fracture surface of the failure specimens after tensile testing was observed using macro and microscopic analyses. Fatigue tests were performed using a fatigue test machine with a 100 kN load cell at seven different stress levels (30, 40, 50, 60, 70, 80, and 90 %). The tests were conducted in the load control mode with a sinusoidal waveform at a frequency of 5 Hz. The joints were subjected to tension–tension fatigue, with a stress ratio \((R = \sigma_{min}/\sigma_{max})\) of 0.1. The fatigue strength was analysed by drawing S–N curves, and the fatigue fracture surfaces of the tested samples were critically observed under two conditions, dry and wet. For higher accuracy, three replicates were tested at each stress level.

3. Results and discussion

3.1. Moisture absorption behaviour

The moisture content of the similar and dissimilar adherends of the AA7075 and GRE composites was determined, and is presented in Fig. 4, with the joint configuration of hybrid SLJs.
The specimens were aged for 120 days with an interval period of 20 days. From the graph behaviour, as shown in Fig. 4, the saturation was not achieved for any of the adherend combinations. This expectation was confirmed under the ageing condition of the GRE composites: the saturation was not achieved until one year of immersion [28].

Based on Fig. 4, it can be observed that the similar-GRE/GRE specimens exhibit the highest moisture content percentages of 1.48±0.2, 2.38±0.11, 2.99±0.31, 3.21±0.21, 3.39±0.13, and 3.92±0.15 %, for 20, 40, 60, 80, 100, and 120 days of immersion, respectively. The moisture content is reduced by over 100%, in which 0.56 % and 1.12 % for dissimilar-AA7075/GRE with immersion periods of 20 days and 40 days, respectively. However, the water absorption was significantly reduced with a slight change of percentages of 51, 18, 17, and 15 % when the exposure was increased from 60 days to 120 days with 20-day intervals. The moisture content was further reduced when the hybrid joining was investigated with similar-AA7075/AA7075 under wet conditions. From the results, a large percentage reduction was observed with greater than 100 % and 60 % for 20–60 days and 80–120 days, respectively. The comparison of the moisture absorption data reveals that the GRE composites absorbed more moisture than those of AA7075. Similar-AA7075/AA7075 exhibited the smallest and fastest moisture absorption as compared to the joint with the GRE composites. This mechanism is due to the interaction between the metal surface and the adhesive in lap joining, which is weaker. According to Heshmati et al. [29], the metal adherend absorbed more water within the oxide layer as compared to the interphase layer.

On the other hand, a fast degradation occurred on the aged hybrid specimens when the immersion was longer than 60 days for similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE. Furthermore, the moisture content increased with the immersion period, which led to the reduction in the joint failure. This behaviour occurred especially when there was an interface gap between the adhesive and the Huck bolt holes on the adherend surface. Moreover,
with this explanation, it is indicated that the GRE composites experienced some forms of physical damage and/or irreversible chemical degradation.

3.2. Mechanical behaviour of the aged hybrid SLJs under tensile tests

The mechanical properties and behaviour of hybrid SLJs were investigated under tensile test with different joining configurations. Specifically, the joint specimens were immersed for hydrothermal ageing at 50 °C for certain time periods. Figs. 5(a–c) show load-displacement curves of the representative hybrid SLJs of similar aged-AA7075/AA7075, similar aged-GRE/GRE, and dissimilar aged-AA7075/GRE, respectively.

From Figs. 5(a–c), two types of failure were observed from the joint behaviour, which are adhesive and Huck bolt failures at the first and second peaks, respectively. This is due to the fact that hybrid joining is a combination of adhesive and fastening. In hybrid joints, the force reacts primarily by means of contact pressure between the adhesive and the Huck bolt on the adherend surfaces. The first peak failure in the hybrid joint was clarified as the adhesive-bonded strength before the primary failure of the adhesive occurred. However, then the second peak magnitude was observed as an ultimate failure stress after carrying a load of the Huck bolt. Generally, in this case, the first peak was usually of smaller magnitude than the second peak [30].

Fig. 5(a) shows load displacement of similar aged-AA7075/AA7075 for the increasing ageing time (from 20 days to 120 days). The displacement range of the first peak failure of the adhesive was around 0–2.2 mm. In this elastic zone, a linear load curve reduction was observed with increasing the immersion time. However, this is attributed to the increase in the shear displacement. The load drops in the adhesive first peak failure were calculated to be 8.18, 17.3, 15.5, 16.6, and 10.4 % representing the increase time from 20 days to 120 days with an interval of 20 days. The decrease in the slope of the load-displacement curves can be mainly attributed to the reduction in the joint stiffness. A similar agreement was found for the mechanically fastened composite SLJ
On the other hand, a similar behaviour was obtained for a hybrid joint used on similar aged-GRE/GRE, as shown in Fig. 5(b). The load decreased with increasing the immersion time. As can be seen, a failure load of 20 days and 40 days was the same at the first peak failure of the adhesive. A similar behaviour was also obtained over 60 days and 80 days. However, the displacement was not in the same corner. Furthermore, as observed in the elastic region of the hybrid joint, the structural nonlinearity was observed within small initial displacements of 20 days to 80 days as compared to that for similar aged-AA7075/AA7075. A similar indication was found for the behaviour of similar-CFRP/CFRP hybrid joints under hot temperatures [32].

The initial nonlinear behaviour of the load-displacement curves under hydrothermal ageing was observed for the specimen of dissimilar aged-AA7075/GRE with an immersion time of 100 days, as shown in Fig. 5(c). Thus, a linear relationship of that specimen was reached at about 2 kN. However, the rest of the aged specimens performed linearly until the adhesive achieved the full contact between the adherends and the joint slip, which was captured on the bonding area. However, this behaviour was not declared as an ultimate failure load, owing to the presence of the Huck bolt as a bolted joint, once the adhesive failed. The initial loading of the Huck bolt was detected on the lowest load of the adhesive failure until the Huck bolt achieved the full contact with the hole and reached the ultimate maximum failure load. In other words, the hybrid joint strength of the Huck bolt reduced gradually for each increment of the ageing exposure time. This was together with the decrements in the slope on the adhesive failure.

The exposure time of the aged specimens was also one of the parameters that affect the adhesive and Huck bolt behaviours of hybrid joints with the influence of hydrothermal ageing. The contribution of different adherends (AA7075 and GRE composites) to the load transmission of hybrid joints explicitly draws attention to the mechanical properties, in comparison to the unaged specimens. The percentage of stress loss of hybrid joints at 50 °C was compared with that of the
unaged hybrid tested specimens. The comparison between the adhesive bond and the Huck bolt failure stresses for the specimens subjected to ageing is given in Figs. 6(a–c).

As can be seen in Fig. 6(a), the failure stress of hybrid joints in similar-AA7075/AA7075 was evaluated and divided into two stages of the adhesive and Huck bolt failure. The moisture temperature had a significant influence on the failure stress of the first peak of the adhesive failure with a percentage reduction of 14.6, 21.6, 35.2, 45.3, 54.3, and 59.3 %. Meanwhile, the second peak of the Huck bolt failure or the ultimate tensile stress decreased with increasing the exposure time. The Huck bolt failure was reported with a joint strength reduction from 20 days to 120 days as compared to the unaged hybrid specimens in percentages of 9.3, 12.1, 15.6, 27.8, 32.3, and 34.2 %, respectively. An average reduction of 3% and 4% in the adhesive and ultimate tensile stresses of hybrid similar-AA7075/AA7075 was observed at 50 °C.

Furthermore, the percentage reduction of similar-GRE/GRE with the effect of hot temperatures is slightly higher as compared to that of similar-AA7075/AA7075. However, similar-GRE/GRE reached higher ultimate tensile stress than similar-AA7075/AA7075 with 68.8, 60.6, 60.4, 46.8, 45.5, and 47.6 MPa for exposure times of 20, 40, 60, 80, 100, and 120 days, respectively. The reduction in the ultimate tensile stress, as shown in Fig. 6(b), was due to the degradation behaviour of the GRE composites. Compared to similar-AA7075/AA7075 and dissimilar-AA7075/GRE, in this adherend joining combination, a small adhesive failure reduction of the first stage was observed to be 24.9, 24.9, 32.4, 32.4, 43.5, and 49.7 %, which differs from with the properties of the unaged specimens. Moreover, the Huck bolt failure was reported with percentage reductions of 9.8, 20.6, 20.9, 28.7, 37.6, and 40.4 %.

The joint strength of hybrid dissimilar-AA7075/GRE decreased after immersion in hot water for 20–120 days, as can be easily observed in Fig. 6(c). This indicates that there is a hydrothermal influence of the hot moisture absorption on the joint strength of the hybrid SLJ specimens.
However, the performance of the aged specimens eventually reached the highest and utmost ultimate tensile strength as compared to that of similar-AA7075/AA7075 and similar-GRE/GRE. The percentage reduction of the adhesive and Huck bolt failure was reported at 16.2, 29.2, 36, 44, 51, and 52.4 %, and 14.3, 15, 22.2, 28.5, 31.4, and 52.4 %, respectively, from the unaged to aged specimens at varying immersion periods, as shown in Fig. 6(c). From the results, it can be concluded that the use of Huck bolt enhanced the hybrid joint failure stress significantly with the failure of adhesive bonding. A summary of the tensile properties of the adhesively bonded SLJs, at several hydrothermal ageing times at an elevated temperature, is listed in Table 3.

3.3. Failure mechanism evolution of the aged hybrid SLJs under tensile tests

The joint strength of the hybrid SLJs with similar and dissimilar adherends (AA7075 and glass fibre-reinforced epoxy (GRE) composites) was demonstrated with the failure modes at an immersion temperature of 50 °C. The tensile failure appearance and typical failure modes corresponding to the mechanical behaviour are shown in Figs. 7(a–c) with different combinations of adherends and ageing times.

The behaviour and fracture images of the joints demonstrate that the failure of the hybrid SLJs was due to the failure in the adhesive followed by fracturing the Huck bolt until the ultimate failure was reached. The failure occurred over several stages as a hybrid joint is a combination of bonded and bolted joints. Specifically, the adhesive bonded joint initially failed before the final or ultimate failure with the presence of a Huck bolt in the hybrid joint. The fracture mode of the aged specimen for similar-AA7075/AA7075, in Fig. 7(a), shows an adhesion and mixed mode failure in the overlapping area for all ageing cases. Furthermore, the cohesive failure was observed on the GRE composites of similar-GRE/GRE hybrid joints, as shown in Fig. 7(b). Moreover, based on the cohesive failure observation, the fibre matrix on the bottom GRE composites was pulled out.
It could be observed that all aged specimens ultimately failed with the same mode of the second stage of the bolted joint when the AA7075 adherend was bent and the Huck bolts were locked in the adherend. The locking of the Huck bolts ensued with the AA7075 adherend for the cases of both similar-AA7075/AA7075 and dissimilar-AA7075/GRE. Meanwhile, the same occurs in the GRE composites for the case of similar-GRE/GRE. The failure surface of similar-AA7075/AA7075 behaves almost in the same manner at different ageing times. The adherend became bent, causing the Huck bolt to rotate by more than a 40° angle, when the ageing time was increased from 80 days. In addition, it can be seen that a large amount of brown and white rust formed on the AA7075 adherends and Huck bolt fasteners, as shown in Fig. 7(a). This was much more serious when the ageing time was extended to the long-term immersion of up to 120 days. For the case of similar-GRE/GRE, the composite ruptured abruptly on the bottom side of the adherend, near the fastener hole, when immersed for 80 days. The fracture behaviour was characterized as a net-tension mode because of the mechanical degradation of the GRE composites. A small angle of bending was observed on that area, which caused the Huck bolt to rotate and deform. However, a long-term immersion influenced the failure appearance as it absorbed more water inside, which increased the moisture content in the fibre matrix [31]. This phenomenon caused an uneven load distribution and decreased the joint strength of similar-GRE/GRE. Moreover, the effect of temperature and long-term water immersion was attributed to the erosion of the GRE composites around the bolt holes, as shown in Fig. 7(b).

3.4. Mechanical behaviour of the aged hybrid SLJs under fatigue test.

The fatigue failure for hybrid SLJs under hydrothermal effects is proposed, consistent with a load transfer of 30–90%. The results were compared with different adherend combinations of
similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE. The average cycles to failure for each combination are given in Table 4. The resulting $\sigma$ versus $N_f$ data, S–N curves, and common regression lines according to the power law relationships are plotted in Fig. 8. In Fig. 8(a), the hybrid joint with a dissimilar adherend combination of the AA7075 and GRE composites achieves higher fatigue strength than the joint with similar adherends. For instance, the fatigue limit strength at 781k cycles for the dissimilar composites is 83.0 % and 30.2 % higher than that for the similar AA7075 and GRE composites, respectively. It may also be noticed from the curves that the slopes of the Basquin model [24] are different for each adherend, as the similar adherends for both materials exhibit greater slopes than the dissimilar adherends. In the S–N curves, both low-cycle fatigue (LCF) and high-cycle fatigue (HCF) are presented with the long-term ageing of 120 days that influences the fatigue behaviour. Theoretically, LCF occurs when the stresses are greater than the elastic limit, which is in the plastic region of the static behaviour. Meanwhile, HCF is considered when the peak stresses of the material are in the elastic region. As was adopted in the investigation, LCF and HCF were idealized in the S–N curve region as follows [33]:

- $\text{LCF} = 10^0 < N < 10^4$
- $\text{HCF} = N \geq 10^4$

Further, it can be observed that the reduction factor in the fatigue life for similar-GRE/GRE and dissimilar-AA7075/GRE under wet conditions for 120 days is higher than the dry fatigue life at a specified stress amplitude. Meanwhile, similar-AA7075/AA7075 was reported to have a smaller reduction between the wet and dry conditions, as compared to similar-GRE/GRE and dissimilar-AA7075/GRE. A significant consolidation of the data is obtained in the case of the presentations with the narrowest scatter band, as quantified by the correlation coefficients, $R^2$, for the dry and wet specimens. From the regression line graph, similar-GRE/GRE reaches a better correlation data fit.
From Fig. 8(b), it can be seen that at a higher stress level of 90 %, the similar-GRE/GRE specimens show longer fatigue lives followed by dissimilar-AA7075/GRE and similar-AA7075/AA7075. The experimental scatter was relatively large from similar-AA7075/AA7075, about 91 %, as compared to a small scatter of 15 % from dissimilar-AA7075/GRE. However, at a stress level of 60 % and below, similar-GRE/GRE showed a shorter fatigue life as compared to similar-AA7075/AA7075 and dissimilar-AA7075/GRE. At this level, dissimilar-AA7075/GRE performed over the longest fatigue life as it was under the HCF region. The scatter differences were probably due to the material variability. According to Liao et al., the mass fraction of water or the quantity of water absorption did not critically affect the damaged specimens under the fatigue testing, even though it almost reached saturation. However, the time exposure and temperature affected the specimen behaviour [34].

The correlation of the fatigue testing resulted in the $\sigma-N_f$ data and the common regression line according to the power law relationship, which are plotted based on the data fitting conditions for both dry and wet cases for every joint configuration. The trend line is plotted because sometimes the Basquin equation is confirmed to be inadequate when the fatigue life is presented in terms of the applied stress [35]. This is true when the experimental work involves a fastener hole in the specimen. In this study, this was similarly observed in the hybrid joints, which had a combination of an adhesive and a Huck bolt. Referring to Fig. 8, similar-GRE/GRE yielded the narrowest scatter band for both conditions, dry and wet, as quantified by the high correlation coefficient, $R^2$. In the hybrid joints, the crack initiation and propagation occurred on the adhesive and Huck bolts, respectively. The Huck bolt expansion is an appropriate representative of the effect of the hybrid joints as it is directly related to the tangential stress on the bolt hole. However, in this study, this is affected by the error of the adherend types, such as similar-AA7075/AA7075, which contributed to the inferior correlation of the results obtained.
3.5. **Failure mechanism evolution of the aged hybrid SLJs under fatigue test.**

The hybrid SLJ failure modes tested under the effect of hydrothermal ageing at 50 °C for 120 days are shown in Figs. 9, 10, and 11 for similar-AA7075/AA7075, similar-GRE/GRE, and dissimilar-AA7075/GRE, respectively. The failure damage was observed at three different stress levels of 30, 60, and 90 % based on a high-, middle-, and low-cycle fatigue lives, as discussed in the previous section. Tension–tension fatigue tests were conducted on the joint configurations. The fatigue region was found to occur from the edge of the Huck bolt hole, and the fracture region occurred in the centre of the cross section. Fig. 9 shows the failure modes of the hybrid SLJs with the similar adherend of AA7075. As can be seen in the photographs in Fig. 9(a), the failure of the specimen was observed with a pull through the top surface of aluminium. The Huck bolt was rotated 45° to be upside down, which led to adherend yielding. The yielding was noticed for angles smaller than 45°. This behaviour commonly precedes a large neck fracture, as shown before the Huck bolt is pulled out. This occurs with the distraction on the Huck bolt hole on the other side of the adherend. Roughly, the interference is twice the primitive hole diameter. This shows that at certain cycles, the Huck bolts react stronger to cover the adhesive failure. This was a mixed-mode adhesive failure, which was detected on both sides of the adherends. It is believed that the pull-out failure in the joining is due to localised changes in the stress distribution from the clamping action of the bolt tightening. Moreover, at this stress level, the highest fatigue life was recorded, and it can be concluded that severe damage occurred on the joining when the stress amplitude was the lowest.

Figs. 9(b) and 9(c) display photographs of the similar-AA7075/AA7075 fatigue failure/damage around and near the Huck bolt holes. From the figure, the net tension of the Huck bolt was experimentally detected at LCF with stress levels of 60 % and 90 %. Both specimens experienced the same fatigue damage of the bolt hole without exception, on the bottom adherends at the head.
collar of the Huck bolt, which is consistent with stress levels of 60% and 90%. However, the surface quality of both specimens shows a circumferential grooving in the holes. Moreover, an extended hole was not identified in this LCF region as it did not cause severe damage. This is probably due to the effect of the relationship between the fatigue life and the stress level. It may be the result of increasing the stress level, which causes short fatigue life. Concurrently, a characteristic state of damage was observed at the overlap length, which was the adhesive bonding area. It was found that the types of the adhesive failure modes were detected for both specimens. The adhesive failure was found on the interphase layer of the top adherend.

The types of the fatigue failures are presented in Figs. 10(a–c) for similar-GRE/GRE. Several failure modes were observed depending on stress levels of 30, 60, and 90%. From the observations, the failure modes are characterized as a net tension for each stress level. The type of the failures occurred on the top adherends for stress levels of 30% and 60%. Meanwhile, at 90%, the net tension failed on the bottom side of the adherend. The net tension behaviour was detected with a transverse crack starting from the edge of the Huck bolt hole from each side. The cracks allowed the GRE composites to split into two parts. In Fig. 10(a) for low stress level, a light squeeze of the Huck bolt through a large split in the GRE composites allowed the bearing mode mechanism on the adherend bottom side that were located at the collar head. A similar behaviour of the failure modes was obtained by Gay et al., at lower load levels [36]. For the average and higher stress levels, the failure modes are given by the cohesive failure of the GRE composites and adhesives. Moreover, under hydrothermal ageing, a change in the colour of the adhesives was dominantly caused by the chemical degradation.

As the highest and longest fatigue life was for dissimilar-AA7075/GRE in a hybrid joint, the failure modes of the joining were predicted with a combination failure of both adherends. The net tension was observed as the final fatigue failure mechanism for a low stress level of 30%, as shown
in Fig. 11(a). The failure was detected on the collar head of the Huck bolt at the bottom side. Additionally, a small GRE composite deformation was observed. The primary failure of the adhesive was observed as an adhesive failure on the GRE composites. Moreover, the failure of adhesive was initiate at a location with highest stress, which is at the interface corner. The determination was identified when involving the dissimilar joining [37]. A bearing mode/failure is progressive and not a catastrophic mechanism. According to Fiore et al. [19], bearing is the preferred failure mode for highly loaded structural joints in order to avoid catastrophic failures associated with sudden drops in the load capability. In this hydrothermal ageing effect, the bearing failure mechanism was mainly detected on the average and higher stress levels, representing 60% and 90%, respectively.

4. Conclusion

The research objective is to study the influence of moisture in terms of hydrothermal ageing of primary and secondary failures of hybrid SLJs under quasi-static and dynamic testing. The study of the performance of hybrid SLJs under the influence of hydrothermal ageing was found to be the first in the mechanical research field. Based on the experimental results, the following conclusions were drawn:

- Moisture absorption of similar-GRE/GRE hybrid SLJs reach the highest percentage among other adherend combinations, as this type can absorb moisture during immersion at an elevated temperature of 50 °C.

- It can be concluded that the performance of the dissimilar aged-AA7075/GRE hybrid joints in hot water reached the maximum failure load as compared to similar aged-AA7075/AA7075 and similar aged-GRE/GRE. Furthermore, it was found that, dissimilar joints reached highest joint strength. However, the long extension of displacement was obtained on the similar aged-GRE/GRE hybrid joints.
The effect of the adhesive and interference fit between the Huck bolt and the bolt hole joint fatigue life was investigated. Based on the experimental results, the hybrid joint with a dissimilar adherend combination of the AA7075 and GRE composites achieved 83 % and 30.2 % higher fatigue strength than a similar adherend of the AA7075 and GRE composites, respectively.

Additionally, similar-AA7075/AA7075 was reported to have smaller reduction between wet and dry conditions. At a higher stress level of 90 %, the similar-GRE/GRE specimens showed a longer fatigue life followed by dissimilar-AA7075/GRE and similar-AA7075/AA7075.

Similar-GRE/GRE yielded the narrowest scatter band for both conditions, dry and wet, as quantified by the high correlation coefficient, $R^2$. The Huck bolt expansion is an appropriate representative of the effect of hybrid joints as it is directly related to the tangential stress on the bolt hole. However, in this study, this is affected by the error of the adherend types, which similar-AA7075/AA7075 that contributed to the inferior correlation of the results obtained.

The increase in the joint strength of the dissimilar-AA7075/GRE hybrid SLJ was found on the Huck bolt performance, which was identified as a secondary or final failure. However, on the other stage of the primary failure, the similar-GRE/GRE hybrid SLJ was identified to have the longest strain to the failure. In this region, shows that there exists strong bonding between GRE composites and adhesives.

Prolonged immersion periods caused the hybrid SLJs to increase and a more severe secondary failure, especially when the GRE composites were used in the joining. All shear specimens at different ageing times failed with a typical bearing mode.

Data availability statement
The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

References


Figure captions

Fig. 1. Single lap joint geometries for hybrid with dimension of: \( L = \) length 160 mm, \( w = \) width 40 mm, \( H = \) overlap length, \( d = \) bolt hole diameter 6.35 mm.

Fig. 2. (a) Huck C6L Lock bolt dimension, (b) Huck bolts characteristic.

Fig. 3. Huck bolt installation sequences.

Fig. 4. Moisture uptake percentage of hydrothermal ageing of hybrid SLJs at elevated temperature with several of immersion periods.

Fig. 5. Load-displacement curves of hybrid SLJ at varied immersion time: (a) similar-AA7075/AA7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.

Fig. 6. Effect of immersion period on ultimate joint strength of hybrid SLJs with: (a) similar-AA7075/AA7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.

Fig. 7. Typical failure mechanisms of hybrid SLJ under moisture: (a) similar-AA7075/AA7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.

Fig. 8. Fatigue life behaviour under hydrothermal effect of hybrid SLJ: (a) stress amplitude vs number of cycles, and (b) stress level vs number of cycles.

Fig. 9. Failure mechanisms of hybrid similar-AA7075-AA7075 at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.

Fig. 10. Failure mechanisms of hybrid similar-GRE/GRE at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.

Fig. 11. Failure mechanisms of hybrid dissimilar-AA7075/GRE at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.
Fig. 1. Single lap joint geometries for hybrid with dimension of: $L =$ length 160 mm, $w =$ width 40 mm, $H =$ overlap length, $d =$ bolt hole diameter 6.35 mm

Fig. 2. (a) Huck C6L Lock bolt dimension, (b) Huck bolts characteristic
Moisture uptake, $M_t$ (%)

**Fig. 3.** Huck bolt installation sequences.
Fig. 4. Moisture uptake percentage of hydrothermal ageing of hybrid SLJs at elevated temperature with several of immersion periods.

(a) Similar-AA7075/AA7075
Fig. 5. Load-displacement curves of hybrid SLJ at varied immersion time: (a) similar-AA7075/AA7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.
(a) Similar-AA7075/AA7075

(b) Similar-GRE/GRE
Fig. 6. Effect of immersion period on ultimate joint strength of hybrid SLJs with: (a) similar-AA7075/AA7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.

<table>
<thead>
<tr>
<th>Ageing (days)</th>
<th>Similar-AA7075/AA7075</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>![Image of joint failure at 20 days]</td>
</tr>
<tr>
<td>40</td>
<td>![Image of joint failure at 40 days]</td>
</tr>
<tr>
<td>RT</td>
<td>![Image of joint failure at RT]</td>
</tr>
<tr>
<td>20 days</td>
<td>![Image of joint failure at 20 days]</td>
</tr>
<tr>
<td>40 days</td>
<td>![Image of joint failure at 40 days]</td>
</tr>
<tr>
<td>60 days</td>
<td>![Image of joint failure at 60 days]</td>
</tr>
<tr>
<td>80 days</td>
<td>![Image of joint failure at 80 days]</td>
</tr>
<tr>
<td>100 days</td>
<td>![Image of joint failure at 100 days]</td>
</tr>
<tr>
<td>120 days</td>
<td>![Image of joint failure at 120 days]</td>
</tr>
</tbody>
</table>

(a) Dissimilar-AA7075/GRE
<table>
<thead>
<tr>
<th>Ageing (days)</th>
<th>Similar-AA7075/AA7075</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>100</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>120</td>
<td><img src="image3" alt="Image" /></td>
</tr>
</tbody>
</table>

(a) Similar-AA7075/AA7075

<table>
<thead>
<tr>
<th>Ageing (days)</th>
<th>Similar-GRE/GRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td><img src="image4" alt="Image" /></td>
</tr>
</tbody>
</table>

(b) Similar-GRE/GRE
<table>
<thead>
<tr>
<th>Ageing (days)</th>
<th>Dissimilar-AA7075/GRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td><img src="image.png" alt="Image" /></td>
</tr>
</tbody>
</table>

(b) Similar-GRE/GRE
<table>
<thead>
<tr>
<th>40</th>
<th><img src="image1.png" alt="Image" /></th>
<th><img src="image2.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>80</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>100</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>120</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
</tbody>
</table>

(a) Dissimilar-AA7075/GRE

**Fig. 7.** Typical failure mechanisms of hybrid SLJ under moisture: (a) similar-AA7075/A7075, (b) similar-GRE/GRE, and (c) dissimilar-AA7075/GRE.
<table>
<thead>
<tr>
<th>Stress amplitude (Mpa)</th>
<th>Number of cycles (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Wet) similar-AA7075/AA7075</td>
<td>○ (Dry) similar-AA7075/AA7075</td>
</tr>
<tr>
<td>(Wet) similar-GRE/GRE</td>
<td>□ (Dry) similar-GRE/GRE</td>
</tr>
<tr>
<td>(Wet) dissimilar-AA7075/GRE</td>
<td>▲ (Dry) dissimilar-AA7075/GRE</td>
</tr>
</tbody>
</table>

**Low cycle fatigue**

- $y = 193.9N - 0.159$
  - $R^2 = 0.8382$
- $y = 336.38N - 0.159$
  - $R^2 = 0.8382$

**High cycle fatigue**

- $y = 414.69N - 0.187$
  - $R^2 = 0.879$
- $y = 565.55N - 0.211$
  - $R^2 = 0.8937$

(a) Stress amplitude vs number of cycles

(b) Stress level vs. number of cycles
Fig. 8. Fatigue life behaviour under hydrothermal effect of hybrid SLJ: (a) stress amplitude vs number of cycles, and (b) stress level vs number of cycles.

- Specimen pulled through on the top surface of aluminium.
- Mix mode adhesive failure was detected on both sides of adherends.
- Large neck fracture.

(a) 30% stress level

- Huck bolt was rotated into 45° on upside down and this leads to adherend yielding, with less than 45°.
- Large neck fracture.

- Adhesive failure mode at the interphase layer of top adherend
- Fatigue damage near Huck bolt

- Net tension on bottom adherend at head collar
- Circumferential groove inside adherend
(b) 60% stress level

Adhesive failure mode at the interphase layer of top adherend

(c) 90% stress level

• Circumferential groove inside adherend

Fig. 9. Failure mechanisms of hybrid similar-AA7075/AA7075 at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.

• Net tension was failed on the top side of adherend

• Failure modes are characterized as a net tension.

• Crack started from the edge of Huck bolt hole from each side.

• Light squeezed of Huck bolt through a large split in the GRE composites allowing a bearing modes on the adherend bottom side that locating a collar head.
(a) 30% stress level

- Net tension was failed on the top side of adherend
- Cohesive failure mode on the bonding surface

(b) 60% stress level

- Net tension was failed on the bottom side of adherend
Fig. 10. Failure mechanisms of hybrid similar-GRE/GRE at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.

- Net tension was observed.
- Detected on the collar head of Huck bolt at the bottom side.
- Cohesive failure mode on the bonding surface
- Adhesive failure on GRE composites

(a) 30% stress level

(c) 90% stress level
(b) 60% stress level
Fig. 11. Failure mechanisms of hybrid dissimilar-AA7075/GRE at low to high stress levels of: (a) 30%, (b) 60%, and (c) 90%.
Table Captions

Table 1 Material properties of AA7075 and GRE composites adherends.

Table 2 Material properties of Araldite epoxy adhesive under dry and moisture condition

Table 3 Tensile properties of hybrid SLJs at several hydrothermal ageing time at elevated temperature.

Table 4 Fatigue properties of joint configurations of hybrid joints with the effect of hydrothermal ageing at 120 days.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AA7075</td>
<td>220</td>
<td>95</td>
<td>70.0</td>
<td>0.33</td>
</tr>
<tr>
<td>GRE composites</td>
<td>215</td>
<td>79</td>
<td>5.6</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 2 Material properties of Araldite epoxy adhesive under dry and moisture conditions.

<table>
<thead>
<tr>
<th>Environment condition (°C)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry (RT) [23]</td>
<td>1.392</td>
</tr>
<tr>
<td>Saturation (50°C) [25]</td>
<td>0.426</td>
</tr>
</tbody>
</table>
Table 3 Tensile properties of hybrid SLJs at several hydrothermal ageing time at elevated temperature.

<table>
<thead>
<tr>
<th>Adherends</th>
<th>Ageing Time (days)</th>
<th>Average Peak Load (kN)</th>
<th>Joint Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar-AA7075/AA7075</td>
<td>20</td>
<td>11.58±0.4</td>
<td>41.36 ±1.1</td>
<td>1.24 ±0.01</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>11.22± 0.3</td>
<td>40.09 ±1.5</td>
<td>1.14 ±0.06</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>10.77 ±0.2</td>
<td>38.49 ±0.9</td>
<td>0.87 ±0.04</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>9.22 ±0.2</td>
<td>32.95 ±1.3</td>
<td>0.73 ±0.02</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>8.65±0.4</td>
<td>30.89 ±1.4</td>
<td>0.55 ±0.09</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>8.40±0.8</td>
<td>30.00 ± 2.0</td>
<td>0.51 ±0.08</td>
</tr>
<tr>
<td>Similar-GRE/GRE</td>
<td>20</td>
<td>19.27±0.4</td>
<td>68.81 ±2.1</td>
<td>0.39 ±0.04</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>16.97 ±0.4</td>
<td>60.60 ±1.6</td>
<td>0.34 ±0.02</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>16.90 ±0.4</td>
<td>60.36 ±1.7</td>
<td>0.46 ±0.01</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>13.10 ±0.4</td>
<td>46.79 ±2.9</td>
<td>0.46 ±0.03</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>13.33 ±0.3</td>
<td>47.59 ±1.8</td>
<td>0.66 ±0.04</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>12.74 ±0.7</td>
<td>45.50 ± 2.0</td>
<td>0.59 ±0.09</td>
</tr>
<tr>
<td>Dissimilar-AA7075/GRE</td>
<td>20</td>
<td>21.16 ±0.2</td>
<td>75.58 ±2.0</td>
<td>0.97 ±0.01</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>20.99 ±0.3</td>
<td>74.96 ± 1.6</td>
<td>0.78 ±0.02</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>19.20 ±0.3</td>
<td>68.57 ±3.0</td>
<td>0.71 ±0.02</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>17.66 ±0.3</td>
<td>63.06 ±1.5</td>
<td>0.69 ±0.01</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>16.93 ±0.2</td>
<td>60.46 ±2.8</td>
<td>0.55 ±0.01</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>16.93± 1.0</td>
<td>60.46±2.5</td>
<td>0.49 ±0.05</td>
</tr>
</tbody>
</table>
Table 4 Fatigue properties of joint configurations of hybrid joints with the effect of hydrothermal ageing at 120 days.

<table>
<thead>
<tr>
<th>Joint configuration</th>
<th>Joint materials</th>
<th>No. of cycles to failure at stress level with max. fatigue load (Note: Min. fatigue load/ max. fatigue load = 0.1) x 10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Aged Hybrid Joint (120 days)</td>
<td>Similar-AA7075/AA7075</td>
<td>427.02</td>
</tr>
<tr>
<td></td>
<td>Similar-GRE/GRE</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Dissimilar-AA7075/GRE</td>
<td>781</td>
</tr>
</tbody>
</table>