The static and fatigue responses of aged metal laminate doublers joints under tension loading

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Abstract

Experimental studies have been undertaken to investigate the static and fatigue response of metal laminate doublers (MLD) joints under tension loading after ageing in deionised water at a temperature of 50°C up to 2 years. It was found that absorbed water did not have a significant effect on the static and fatigue degradation of the MLD; however corrosion pits located on the aluminium surfaces caused a reduction in fatigue life. Inevitably the laminate contained butts where co-planar aluminium sheets were joined, and it was found that the position of the butt affected the static response of the MLD but, due to a restricted dataset, it has not been possible to assess the effect under fatigue loading. The backface strain technique in conjunction with video microscopy has been utilised to monitor the damage of the adhesive bondlines, the butts and the aluminium layers and successfully identified both the localised and the global damage in the MLD.

Most of fatigue failures initiated at the stringer bondline edge and at the aluminium layers where the butt was located. A careful design should be made to reduce the stress concentration at the stringer edge and to avoid positioning the butts at the upper layer of aluminium close to the stringer edge.

Keywords: laminates; strength; mechanical testing; joints

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1. Introduction

Adhesively bonded aluminium laminates have been used in aircraft structures such as in the lower wing cover, due to the superior resistance to fatigue crack growth than monolithic aluminium.[1,2] When the aluminium laminate is applied in the lower wing cover, it is stiffened using stringers made of monolithic aluminium bonded onto the laminate. During service, both the adhesive layer in the laminate and between the stringer and laminate are exposed to a hostile environment such high humidity or rain and extreme temperatures and such exposure may degrade the performance of the structures.

Water/humidity is ubiquitous and it has deleterious effect on the polymeric adhesive. Water decreases the physical and mechanical properties of adhesives by two mechanisms; plasticization (reversible) and permanent degradation (irreversible).[3] The plasticization reduces the stiffness and tensile strength [4-9] and glass transition temperature [10-12]. The stiffness and the tensile strength continue to decrease with increasing moisture content reaching a plateau as the moisture saturation level is approached.[9,13] The same is true for the glass transition temperature.[12] However, exposing the adhesive for a long period after saturation, when no further plasticization occurs, the moisture causes permanent deterioration such as dissolution of inorganic filler [12], chain scission and leaching of the backbone of the chain structure [14-16] and crazing and cracking [3].

In adhesive joints water can enter into the adhesive through the bulk adhesive, along the adhesive/substrate interface, and in case of permeable substrate, it penetrates through the substrate and then diffuses into the interface and bulk adhesive.[17] Water then decreases the mechanical properties of adhesive (tensile strength and Young's modulus) [4-9], may (depending on surface treatment) cause corrosion in the substrate at the interface [18-20], and hydration of strong metal oxides [21,22]. The consequences of the diffused water in the adhesive joint are reductions in the joint strength, both static [23-28] and fatigue [29-32].

A good aluminium substrate surface preparation such as chromic acid etching (CAE), phosphoric acid anodizing (PAA) and priming gave excellent durability under static [9,22,33] and fatigue [21,29,32,34,] loading, with final failure within the adhesive layer even though the joints had been exposed in a hostile environment for long time. However, a poor surface preparation such as degreasing and grit blasting gave a lower durability to ageing and the failure surfaces were mostly interfacial.[19,35] Furthermore, water can swell the adhesive inducing the residual stress in the joint.[3] Finite element studies have revealed that the residual stresses due to swelling were sufficient to cause damage of the adhesive at the end of overlap.[9]

Previous work carried out by the authors [9,32] showed that when the MLD was statically loaded in shear and in bending the degradation after 2 years exposure was 15.91%, and 20.3%, respectively and in fatigue the reduction in fatigue life was a factor of 2.5-3 and 3.5-4 respectively. These results indicated that the degradation was loading-mode dependent. This paper extends the previous work in shear and bending [36], to include tension, presenting the effect of water on the residual strength and fatigue lifetime of the MLD aged in deionised water up to 2 years. In this study, the joints are subjected to tension loading, applied separately after ageing. The failure behaviour is also included together with backface strain data, which was used in conjunction with video microscopy as a tool to monitor the damage

2. Experimental methods

These test specimens were taken from a metal laminate cut from a developmental lower cover of aircraft wing, supplied by Airbus (Bristol, UK). The metal laminate was manufactured from aluminium alloy 2024-T3 bonded using FM 73M adhesive from Cytec.[37] The laminate consisted of alternating 6 layers of aluminium and 5 layers of adhesive. The thicknesses of each aluminium and adhesive layer were approximately 1.6 mm and 0.15 mm respectively. The stringer was made of aluminium 7055-T77511 bonded to the laminate panel using FM 73M adhesive. This aluminium alloy has an improved performance in compression (and tension) over the alloy 7150 and has been designed for compression-dominated structures such as the upper wing skin.[38] As only the flange of the stiffener has been considered (see Figure 1), the metal laminate with the bonded stringer is referred to as a metal laminate doubler (MLD). The length and the thickness of the stringer were 91 mm and 9.5 mm respectively. The thickness of the stringer adhesive layer was not constant along the length due to the curvature of the laminate. The thickness at the edge and at the centre was around 0.1 mm and 0.2 mm respectively.

Figure 1. The MLD specimens (not to scale).

In the metal laminate (Figure 1(a-b)), there were discontinuities in the form of butts between adjacent co-planar aluminium sheets. The butt region was filled with FM 73M adhesive. This butt is a result of the maximum width of the currently produced aluminium sheets, which is 1.60 m.[39] Therefore, manufacturing a large metal laminate panel involves joining aluminium sheets together in-plane. As seen in Figure 1, there are two butts zone positions in the laminate; under the clamped zone and under the stringer. It is the butt under the stiffener that most limits the joint response. Hence, the grouping of metal laminates was based on the butt position under the stringer. There were two different positions of butts under the stringer (located in different layers); therefore, they were grouped as MLD-1 and MLD-2 according to Figure 1(a) and Figure 1(b) respectively with butts being located in the upper aluminium layer and the 2nd from top layer respectively.

Prior to mechanical testing, the specimens were conditioned in two environments; (i) dry at a room temperature, (ii) immersed in de-ionized water for one year (wet 1 yr) and also for 2 years (wet 2 yrs) at a temperature of 50^{o}C. After the specified time, the specimens were withdrawn from the environmental tank and then mechanically tested under both static and fatigue tension loading. Testing was performed using a servo hydraulic Instron 1341 test machine with a load cell capacity of 50 kN. Strain gauges were attached onto the laminate at both ends. 2 mm inside the stringer edge to measure the damage process of specimen (see Figure 1). A data logger was used to measure the strain history during the test. The grip length was kept at 40 mm at both ends. The static test was carried out at a displacement rate of 0.1 mm/min. This allowed the observation of the damage in the adhesive layers, the butts and the aluminium layers. Fatigue testing was performed at a load ratio, $R = P_{min}/P_{max}$ of 0.1 and a frequency of 5 Hz. During the test the failure process was monitored visually and using a video microscope connected to a computer.

3. Results

3.1 Static response

Table 1 shows the static strength of the MLDs. Due to the limited number of specimens, for the MLD-1, there were no available specimens for dry condition while for the MLD-2 only one dry and one wet 2 yrs were tested. The limited number of specimens means that results presented may be indicative rather than definitive. However, previous experimental programmes [9,32,36] with these same joints showed that repeatability was good. The degradation of the MLD-2 specimen aged for 2 yrs, seemed very small, approximately 1%. However because only one specimen was tested, this value may not indicate the variation. Nevertheless, the standard deviation was very small for the MLD-1 specimens tested after 1 yr and 2 yrs ageing. It is likely that this small level of variation may also be applicable to the MLD-2 specimens. In this case the degradation of the MLD-2 specimens after aging 2 years (1%) is likely to be a reasonable value. Moreover, for the MLD-1 specimens, the degradation between aging from 1 yr to 2 yrs, is also very small. Unfortunately, there are no data available for the MLD-1 joints in the dry condition; however based on the degradation of the MLD-1 from wet 1 yr to wet 2 yrs and of the MLD-2 aged up to 2 yrs, the static strength of the dry MLD-1 may also not differ much from those of the wet 1 yr and wet 2 yrs (approximately 1% higher than that of wet 1 yr and wet 2 yrs).

Table 1. Static strength of MLD in dry, wet 1 yr and wet 2 yrs.

Figure 2. (a) The typical load-displacement curves of two types of MLD after ageing for 2 yrs. The damage process of (b) MLD-1 (wet 2 yrs) [36] and (c) MLD-2 (wet 2 yrs).

Figure 2(a) shows a typical load-displacement curve for MLD-1 and MLD-2 both aged for 2 yrs. It is seen that the static strength of the MLD-2 is higher by 6% than that of MLD-1. It seems that the MLD-2 is a better configuration than MLD-1. The MLD-2 after ageing for 2 yrs failed in the same way as MLD-2 in dry condition. Similarly, the failure processes of MLD-1 after ageing and in a dry condition are likely to be the same. Therefore the load-displacement curves shown in Figure 2(a) are taken to be representative of MLD-1 (the dashed black curve) in all conditions and MLD-2 (the red curve).

In the MLD-1, early plastic deformation of the aluminium was observed, because the butt under the clamping region was nearer to the outside of the grip, thus it was more loaded. The plasticity occurred in the aluminium layer adjacent to the butt in the clamped region. In both cases, the peak load corresponds with the failure of the butt under the stringer (refer to Figure 1 for the butt positions). A 2^{nd} peak load (lower) in the MLD-2 is the failure of the aluminium layer adjacent to the failed butt under the stringer. While in the MLD-1 the failure of butt inside the stringer was quickly followed by the failure of aluminium layer adjacent to the butt outside the stringer. This is why only one peak load was observed. To gain more understanding about the load-displacement curve, the failure of each MLD is presented in more detail below.

Figure 2b shows the schematic failure process of the MLD-1 with the images again taken at the selected points shown in load-displacement curve (see Figure 2(a) for the MLD-1). The detailed failure process of this specimen and the comparison with the finite element result can be found elsewhere in [36]. The summary of the failure process is presented here. The butt just inside the grip started to fail (point ***a'***) when the load reached 34 kN. This is lower than in MDL-2 as the butt is further inside the grip and hence the loads experienced by the aluminium are lower for a given applied load. When this butt failed, the load was transferred to the surrounding layers, increasing the stresses in this region. The load increased until point ***b'***, at load of 41 kN, and then the load-displacement becomes flatter. This was due to the growing damage in the stringer bondline and yielding of the aluminium layers. As the stringer bondline damage reached a certain distance from the butt inside the stringer region, at point ***c***', the butt under the stringer failed completely, followed by a sudden drop in the load. After this failure, the aluminium in the bottom layer failed, because in this region it was highly loaded due to lack of load transfer through the butt, shown by point ***d'*** and the load quickly dropped further. The failure of this aluminium was then followed by the fast damage in the adhesive layer in the laminate. The plateau in the curve, where point ***e'*** is located, was attributed to the delamination process and the yielding of the remaining aluminium layers.

Figure 2(c) shows a schematic representation of the failure process of the MLD-2 and the images relate to the selected points indicated on the load-displacement curve, shown in Figure 2(a) accordingly. The loading curve started to change from linear at a load around 35 kN, where the butt (which is external to the stringer) started to damage. At point ***a***, at a load around 39 kN, the butt was seen to be damaged at the four corners, delamination was also observed around the butt (shown by the arrow). As the load increased to point ***b***, at a load of 42 kN, the stringer adhesive layer started to damage in the fillet, this damage then grew along the adhesive layer to the centre of stringer. After the stringer bondline damage reached a certain point from the butt internal to the stringer, the butt started to fail (at a load of 44.15 kN), followed by an abrupt dropping of the load (point ***c***). This indicates that the peak load is affected by the failure of butt inside the stringer. Delamination was also observed after the failure of butt. The increase in the load after the 1st drop was due to the further yielding and strain hardening of the rest of the aluminium until the point of failure at a load of approximately 41 kN. At this point, the first aluminium layer near the internal butt failed (point ***d***). This failure load corresponded to the static strength of MLD-1; where there are 4 aluminium layers effectively transferring the load. After the load dropping at this point, delamination of aluminium layers around the butt failure continued to propagate, shown by the flatting load-displacement curve.

3.2 Fatigue response

Figure 3. Fatigue load-life time curves of MLD specimens.

Figure 3 shows the fatigue load-life of the MLD specimens in dry and wet conditions. For all cases, the normalised load level was calculated based on the static strength of the MLD-1 in the dry condition. For dry joints, two specimens (one MLD-1 and one MLD-

2) and one specimen (MLD-2) were tested at 64% and 43% load level respectively. While for wet aged joints only the MLD-1 specimens were available to be tested. It seems that the fatigue life trend of wet aged joints was slightly below the fatigue life trend of the dry specimens although the adhesive has nearly been saturated.[9] The specimens aged wet for 1 yr at 60% and 50% load level both failed early respectively due to manufacturing flaws and corrosion pits in the aluminium close to the stringer bondline edge. The specimens that were aged for 2 yrs experienced various degrees of corrosion pits at various locations. The fatigue failure process both in dry and in wet joints is presented in more detail below.

Figure 4. Photograph and the schematic of fatigue failure process of a dry specimen of (a) MLD-1, and (b) MLD-2.[36] Both joints were tested at the same P_{max}.

The schematic of fatigue failure of the MLD specimen in dry condition, where no corrosion took place in the aluminium, are shown in Figure 4. Figure 4(a) and Figure 4(b) show the photograph and the schematic of fatigue failure of the MLD-1 and the MLD-2 respectively. In both types of configurations, the adhesive at the bonded stringer and the butt outside the stringer region were the weakest region as they damaged early in the fatigue process. The damage was initiated at the fillet region and the outside butt, and then propagated to the centre of the joint. The propagation of adhesive damage at the stringer bondline accelerated, particularly at the side where the butts existed (outside and inner butts). In the MLD-1 (Figure 4(a)), when the damage of the stringer bondline reached some distance from the edge (**a**), the damage propagation increased rapidly. This then increased the load on the butt inside the stringer, causing it to fail (**b**). After the butt failure, delamination of the aluminium layer adjacent to it propagated toward the both directions. Redistribution of the stress after the butt failure and delamination increased the stresses in the other lamina, in particular the aluminium layer at the bottom of the specimen close to the outside butt. This then caused the failure of aluminium adjacent to the outside butt where high stress concentration existed due to the butt (**c**). This failure caused further redistribution of the stresses to the remaining aluminium layers and increased plastic deformation, which led to final fracture. The final failure occurred at ≈89,800 cycles.

In the MLD-2 (Figure 4(b)), the damage of the stringer bondline (**a**) stopped growing, but the damage around the outside butt grew further and delaminated the aluminium layers toward the centre of the joint (**b**). The butt failure and the delamination reduced the load carrying cross section area and increased the stresses in the aluminium in the vicinity of the butt. This initiated fatigue damage in the aluminium above the butt. Further fatigue loading propagated the damage in the aluminium toward the failure of the top aluminium layer (**c**). After this failure the delamination of aluminium layers at **b** accelerated, leading to the final fracture that occurred in the final two aluminium layers at the number of cycles of ≈97,000, at **d**.

Most of the wet specimens that have been tested were the MLD-1 type; therefore the failure process described here is representative of these configurations. Due to corrosion pits on the aluminium surfaces of some wet specimens, there are two types of failure process, shown schematically in Figure 5(a) (Type 1) and Figure 5(b) (Type 2). It is worth noting that the failure process is not the case with the early failed specimens due either the manufacturing flaw or heavily corroded pits just under the stringer edge (shown by the circles in Figure 3). The testing was carried out at the higher load level (60%). In Figure 5(a), for the specimen aged wet for 2 yrs, initial failure occurred in the stringer bondline at around 3,000 cycles. The image **a** shows the failure in the fillet and the adhesive layer at both sides at 15,000 cycles, but this did not grow further toward the centre of the joint. The first aluminium failure occurred at 86,000 cycles close to the stringer edge (image **b**), unlike the dry specimens where aluminium failure first occurred around the external butt. At this site, corrosion pits occurred that created a high stress concentration. Furthermore, this region experienced secondary bending due to the tension loading of the MLD increasing the tensile stress. After this failure, the crack propagated through the adhesive layer. At 112,000 cycles, the second aluminium layer failed (image **c**) and then crack propagated along the laminate adhesive layer (delamination). The aluminium layer at ***d*** failed at 124,000 cycles due to pitting corrosion that created a stress concentration superimposed with the secondary bending effect. This was soon followed by the final fracture of the specimen.

In the Type 1 failure just described, the butt did not contribute to the failure, however in the Type 2 failure, the butt did contribute to the failure, as seen in Figure 5(b). The first damage occurred in the stringer bondline at around 100 cycles (**a**). After 50,000 cycles, aluminium layers at **b** failed. At this point, there was a superimposed effect; localised corrosion pits and also high tensile stress because of the secondary bending. At **a,** the damage in the stringer bondline continued to grow to a certain distance from the butt inside the stringer. This then exposed the butt to increased load levels (by removing the load transfer path to the stringer). The butt inside the stringer failed at

100,000 cycles (**c**) and was then followed by the failure of aluminium layer close to it (at **d**) at 137,000 cycles. It seems that the failure of aluminium at point **b** (Type 2) is probably less critical than the failure of aluminium close to the stringer edge (Type 1) indicated by the longer fatigue life of Type 2 failure. However, because only one set of data for each type of failure was available (at a load level of 60%), it is hard to be definitive. Of those two types of failure, the Type 1 failure was more often encountered in tension fatigue, about 67%.

Figure 5. Two types of fatigue failure in wet the MLD-1 specimens tested at load level of 60%. (a) Type 1, (b) Type 2.

In monitoring the failure process of the MLDs under tension fatigue, the backface strain (BFS) method was utilised as it had previously successfully indicated damage in the adhesive in a single lap joint under shear fatigue in a SLJ [40,41,42] and in a MLD under bending fatigue [32]. In the MLD under tension fatigue reported here, the BFS history indicates the damage in the stringer bondline, the butt and the aluminium layers. Figure 6(a) and Figure 6(b) respectively show the BFS history during fatigue loading at 60% load level of the MLD-1 after 1 year ageing and the schematic of damage process. It can be seen that the damage of the stringer bondline occurred at around 3000 cycles (point **a**) indicated by increasing BFS in both gauges. The damage progressing at this site continued until 40,000 cycles and then stopped growing when the damage of aluminium just inside the stringer initiated and propagated. At this site there was a semi circular manufacturing flaw that might produce the early failure. This was indicated by much lowering decreasing BFS at SG2 after these cycles due to the bending of the laminate, which induced the compressive stress on the backface of the laminate at this location. The decrease of the strain continued and reached a minimum after the two aluminium layers just under the stringer edge failed at approximately 54,000 cycles (point **b**).

On the other hand, the damage at the two aluminium layers caused redistribution of the stress and increased the stress in the rest of aluminium. This increased the BFS in SG1 after 40,000 cycles and it continued to increase at 54,000 cycles. After this number of cycles, the BFS at SG2 increased again because the delamination between aluminium layers was propagating (indicated by **c**). This delamination relieved the bending at SG2 and further reduced the stress transfer area between the adjacent aluminium layers. Increasing BFS at SG2 stopped at 67,000 cycles when the damage of the bottom aluminium layer close to the outside butt initiated. The damage initiation and propagation of aluminium decreased the BFS at SG2 and at SG1. The decrease in strain was reversed at 70,500 cycles when the aluminium fractured (point **d**) and this was then immediately followed by the complete fracture of the specimen, indicated by the abrupt increase and decrease of BFS at SG2 and at SG1 respectively.

Figure 6. Failure process of the MLD-1 (aged wet 1 yr) under tension fatigue at 60% load level, (a) BFS history, (b) The photograph of failed specimen and its schematic damage process.

Figure 7. Failure process of the MLD-1 (aged wet 2 yrs) in tension fatigue at 50% load level, (a) BFS history, (b) Schematic of damage process.

At a lower load level (50%) the BFS history and the failure process of the MLD-1 at 2 years exposure is shown in Figure 7. In Figure 7(a), at the early stage of fatigue loading, the backface strain at both strain gauges increased gradually due to both the damage initiation of the stringer bondline and the upper aluminium layer close to the stringer edge. The careful examination showed that there was a corrosion pit at the upper aluminium surface. At around 50,000 cycles the strain of SG1 started to increase more rapidly until point ***a*** (62,000 cycles)**,** meanwhile the strain of SG2 grew more stably. This increase of strain is related to the initiation and propagation of damage in the aluminium (image ***a***) as shown in Figure 7(b). After the failure of the aluminium at that site, the backface strain became more stable. This is related to the propagation of crack in the laminate adhesive layer toward the stringer edge. As the crack approached the edge of stringer, more bending in the laminate occurred which affected the backface strain at SG1, causing it to decrease because of the bending. The backface strain increased again abruptly to point ***b*** when the second aluminium layer failed, close to the first failure, at around 131,000 cycles**.** As the load carrying cross section area decreased after the failure of the two aluminium layers, the stress in the rest of aluminium increased leading to increasing backface strain at SG2. At the same time, the backface strain of SG1 decreased abruptly and increased again rapidly until complete failure. The decrease and increase of backface strain of SG1 after point ***b*** is due to high bending after failure at that location, which causes more compressive stress and then recovers to become more tensile when the damage grows along the laminate adhesive layer.

In Figure 7(a), the relative displacement during fatigue loading is also shown for comparison with the BFS. The relative displacement was calculated by subtracting the displacement at P_{max} with the displacement at P_{min}. It is seen that the history of displacement has the similar pattern with the BFS at SG2, where there was no local damage as occurred at the SG1 side. Hence the measured strain at this side was mostly the elongation of the specimen. This fact indicates that although the displacement history is able to monitor the damage in a specimen it is not sufficiently sensitive to indicate a localised damage in the specimen. Meanwhile, the BFS method is a very useful tool to monitor the localised as well as the global damage.

4. Discussion

Previous studies [9] on the same joints indicated that ageing MLDs up to 2 years and were then loading to failure in bending decreased the static strength about 20.3%. However, when the same joints were loaded in tension the decrease of static strength was only around 1%. This indicated that the effect of moisture on the static strength of the doublers loaded in tension is negligible, although the adhesive has nearly been saturated. This is because the adhesive layer both in the stringer bondline and in the laminate contributes less to the load carrying of the specimen as most of loads are carried out by the aluminium layers, which do not significantly degrade due to water. Nevertheless, ageing in a wet environment may have an effect on the rate of failure, for example the rate damage propagation in the bonded stringer after wet ageing is more rapid than in dry joints.

Basically, in fatigue, the failure responses and fatigue live in dry and wet MLD were also essentially the same. Where differences were found they were due to either manufacturing flaws or corrosion in the aluminium that created pits on the surface. In static loading, the corrosion pits on the aluminium surface seems not to be critical as the failure was preceded by the damage in the adhesive in the stringer bondline and delamination between the aluminium layers followed by damage in the butts before the aluminium layers failed. In fatigue, however, the corrosion pits are critical. These pits acted as stress raisers where fatigue initiation took place. The effect of the corrosion pits was even worse when they occurred at the region close to the stringer edge as this region experienced higher stresses than other regions due to the secondary bending. The corrosion pits were observed in most wet specimens and inevitably caused some variation in the fatigue life and failure process.

The response of the MLD loaded in tension is significantly affected by the position of the butt. Of the butt positions studied, the position outside the stringer is the weakest region in the laminate (as it is not reinforced by the stringer), and it is more severe when butt's position is just under the stringer edge [43] (where there will be stress raising due to secondary bending). When loaded in bending the butt does not have a significant effect as long as the butt’s position is inside the stringer (non-critical position), however when it is located in the outer aluminium layer and adjacent to the fillet (critical position), it would have a significant effect.[44] In the MLD-2, the butt's position was inner in the laminate, relative to the position of butt in the MLD-1, and the outside butt was just under of the grips. In static loading, however, the failure process of both configurations show similarity. In both configurations, the outside butts failed early.

The peak load occurred just before the failure of the inside butt and was then followed by the failure of aluminium in the outer layer close to the failed butt caused by increased load transfer in this layer. In the MLD-1 type joints, the failure of aluminium closest to the failed outside butt is more rapid than in the MLD-2. This is because the butt is nearer to the edge of the grips and hence when it failed, little load could be carried by the adjacent aluminium layers. Thus the stress in the adjacent aluminium layers increased and caused early failure. A butt created a stress concentration around it and the failure when the laminate is loaded in tension occurred in the outer layer adjacent to the butt. Whereas in the MLD-2 the aluminium (just under the stringer) close to the failed inside butt is still supported by the stringer before failure. Thus the stress concentration in this aluminium layer is lower than in the MLD-1. Thus it delayed the failure of this aluminium.

In a dry condition, the MLD-1 and the MLD-2 were subjected to the same applied fatigue load and the difference of fatigue life was around 7%. But because only one specimen was tested for each, the effect of experimental scatter cannot be quantified. Thus the effect of position of the butt on the fatigue life remains undetermined, due to lack of data and further, there is no comparison data either with no butts or with different butt positions. Nevertheless, our previous study [36] on the effect of butt's position in the fibre metal laminate showed that the trend of static strength was in agreement with the trend of the fatigue life. The effect of the position of the butt under the stringer is less severe than that at the critical position (just under the stringer edge). Therefore the effect of the butt's position studied here is likely to be similar with the trend in the static response where the inner butt would have given the better fatigue life.

5. Conclusions

The MLD specimens aged in deionised water at a temperature of 50^{o}C for one year and two years have been tested under both static and fatigue tension loading. The keys finding are summarised below:

a. The effect of moisture on the MLD response was negligible compared to when they were loaded in bending even though the adhesive was saturated. This is because most of loads were carried equally by the aluminium layers.

b. In static loading, the corrosion pits that occurred on the aluminium surfaces does not significantly affect the MLD static strength, however in fatigue they do have a significant detrimental effect (critical), becoming severe when they are located close to the stringer edge. These pits become a place for the initiation of fatigue failure.

c. The backface strain technique has successfully indicated the localised fatigue damage in the adhesive, the butt and in the aluminium layers of the MLD.

d. The position of the butt affects the static response of the MLD, but in fatigue the effects is not clearly determined due to lack of data. This will be an interesting area for future work, involving both experimental and numerical studies.

Acknowledgements

Author gratefully thanks Airbus who provided the metal laminate specimens. Also thanks Dr. Katnam for the data of dry specimens.

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LIST OF TABLES

Table 1. Static strength of MLD in dry, wet 1 yr and wet 2 yrs.

Condition	Static strength (kN)	
	MLD-1	**MLD-2**
Dry	-	44.6
Wet 1 yr	41.57 ± 0.06[a]	-
Wet 2 yrs	41.56 ± 0.14[b]	44.15

[a] two specimens tested
[b] three specimens tested

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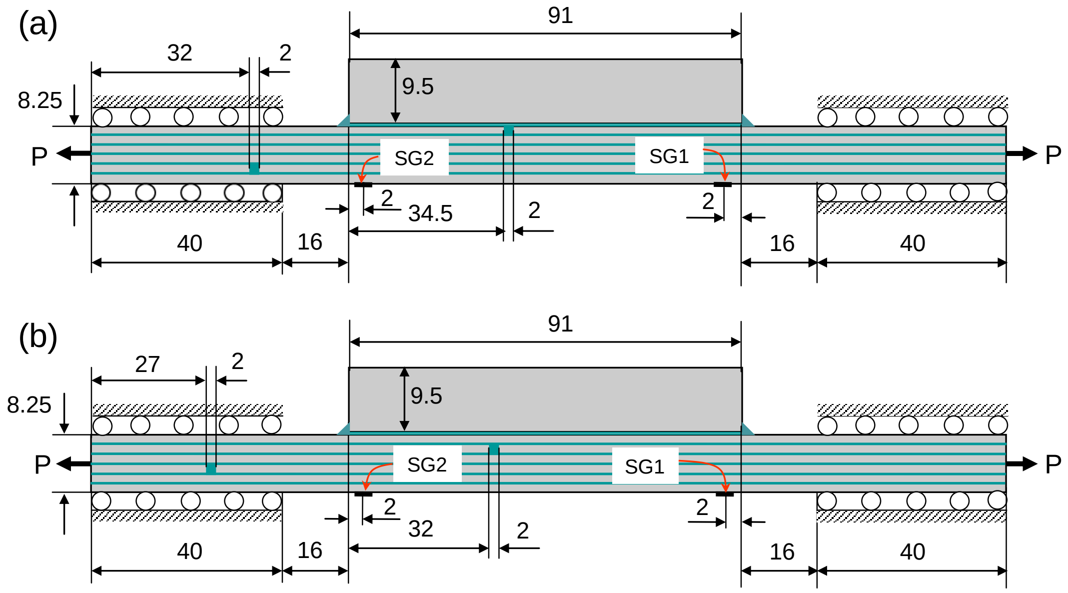

Figure 1. The MLD specimens (not to scale).

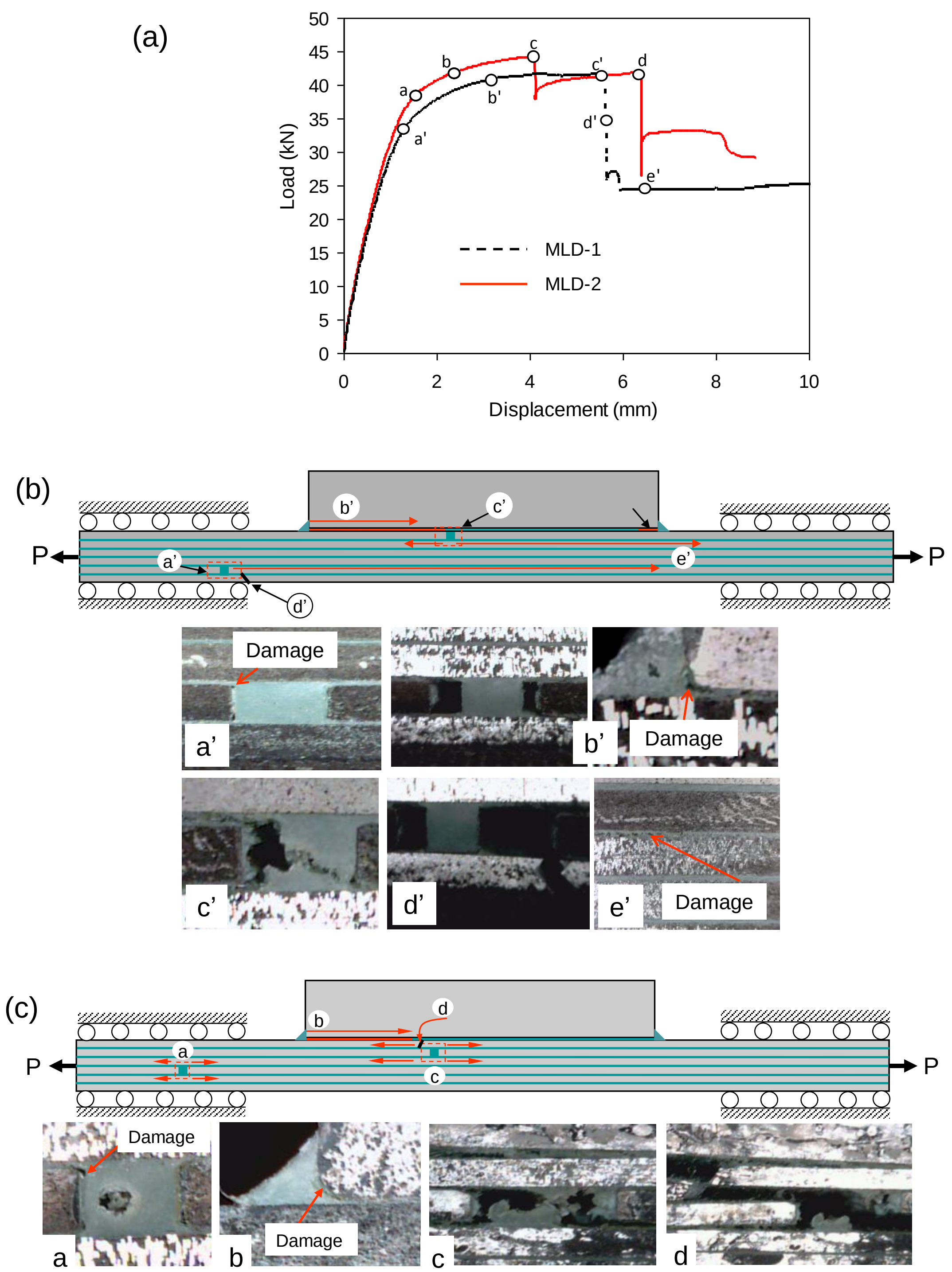

Figure 2. (a) The typical load-displacement curves of two types of MLD after ageing for 2 yrs. The damage process of (b) MLD-1 (wet 2 yrs) [36] and (c) MLD-2 (wet 2 yrs).

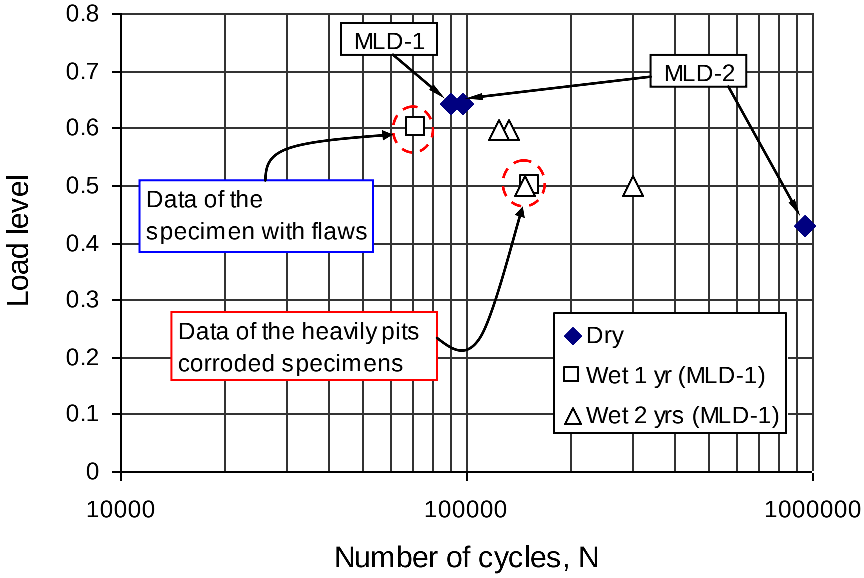

Figure 3. Fatigue load-life time curves of MLD specimens.

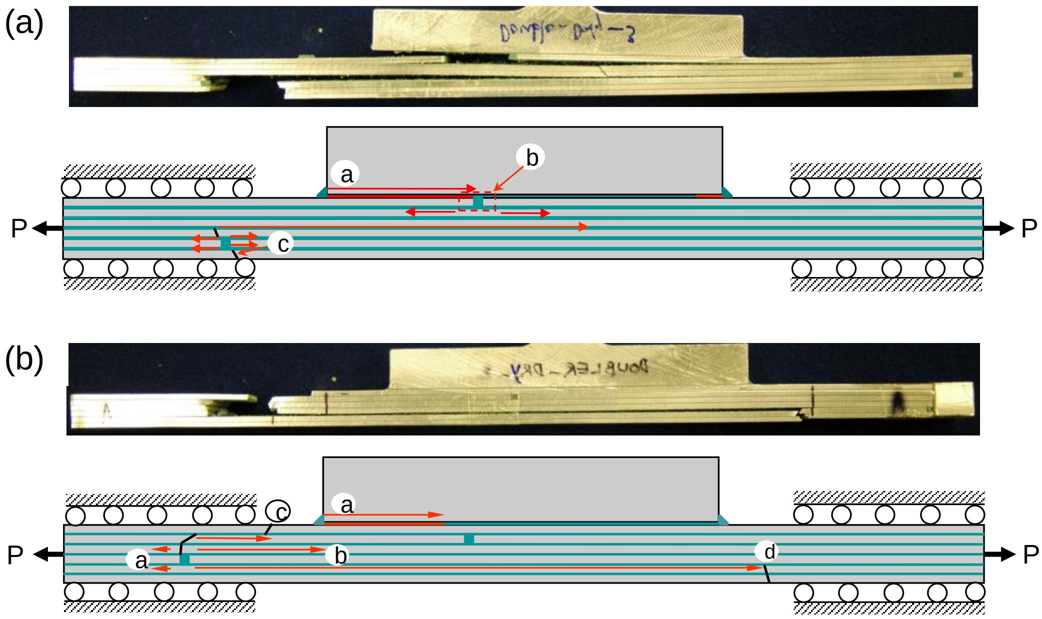

Figure 4. Photograph and the schematic of fatigue failure process of a dry specimen of (a) MLD-1, and (b) MLD-2.[36] Both joints were tested at the same P_{max}.

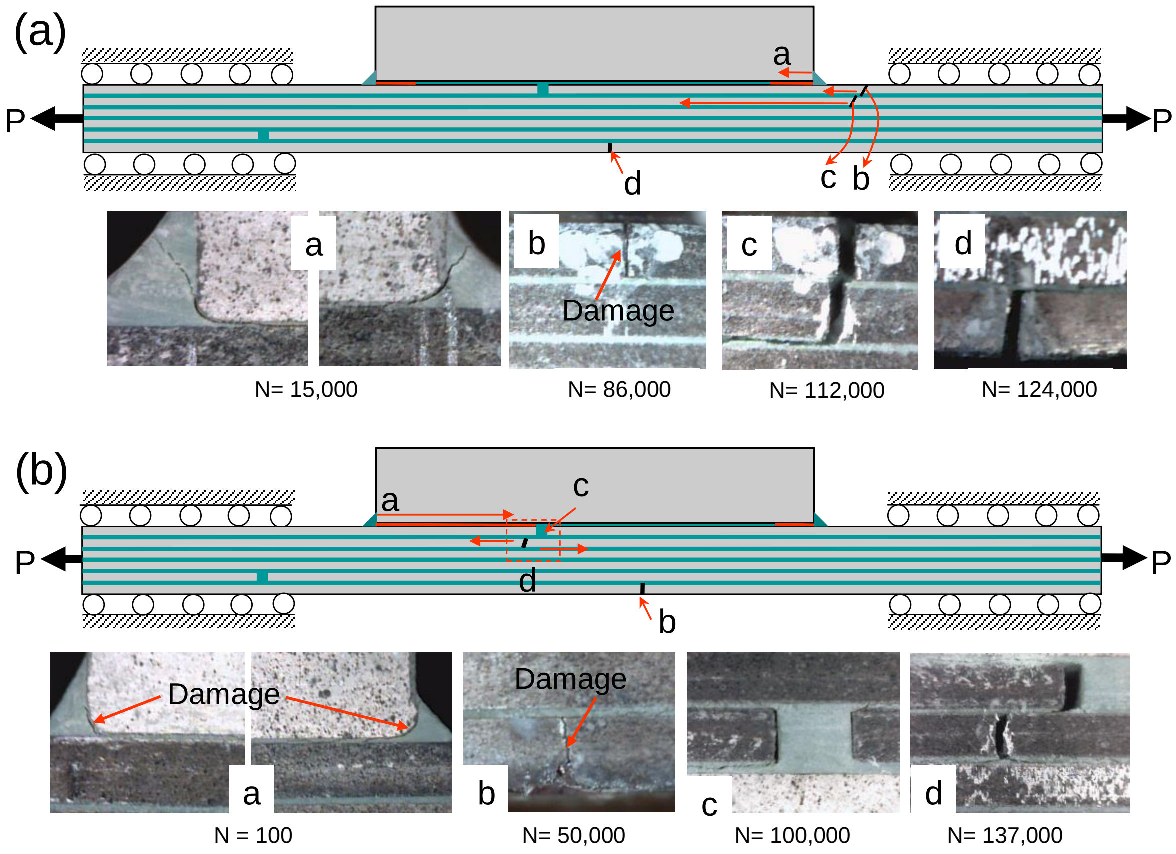

Figure 5. Two types of fatigue failure in wet the MLD-1 specimens tested at load level of 60%. (a) Type 1, (b) Type 2.

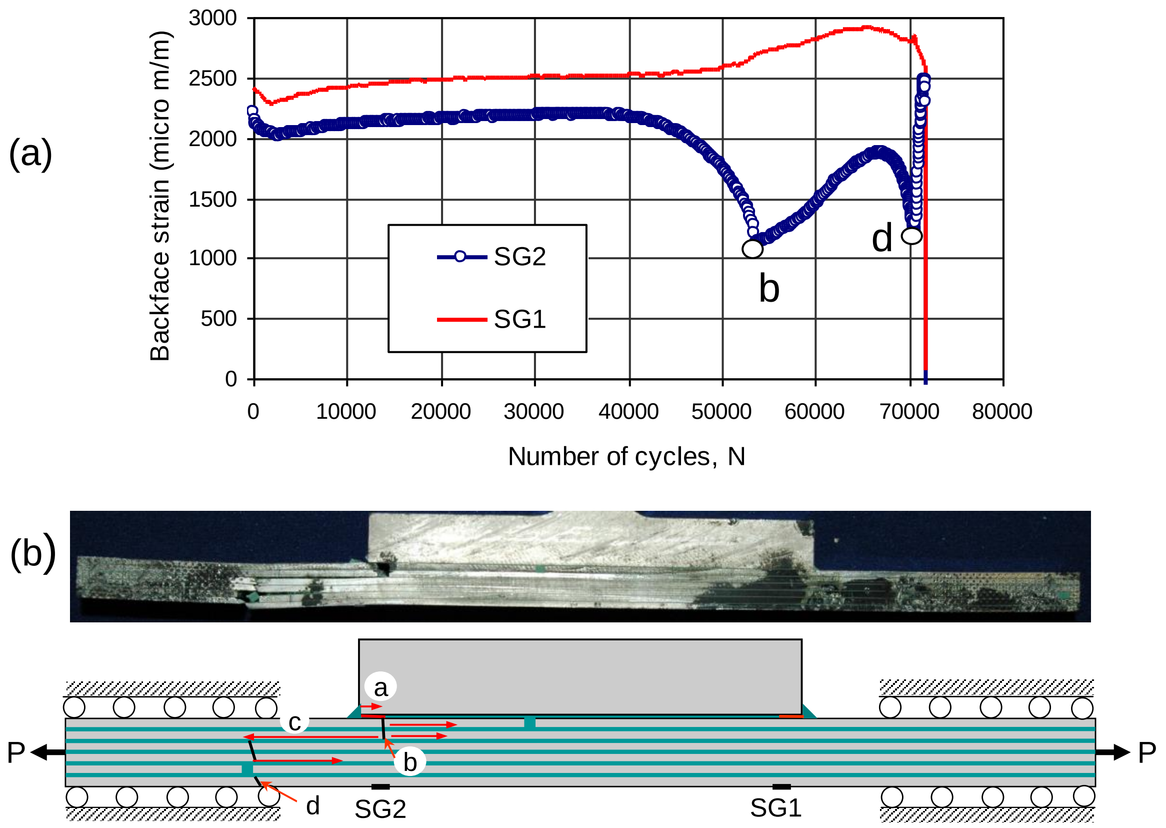

Figure 6. Failure process of the MLD-1 (aged wet 1 yr) under tension fatigue at 60% load level, (a) BFS history, (b) The photograph of failed specimen and its schematic damage process.

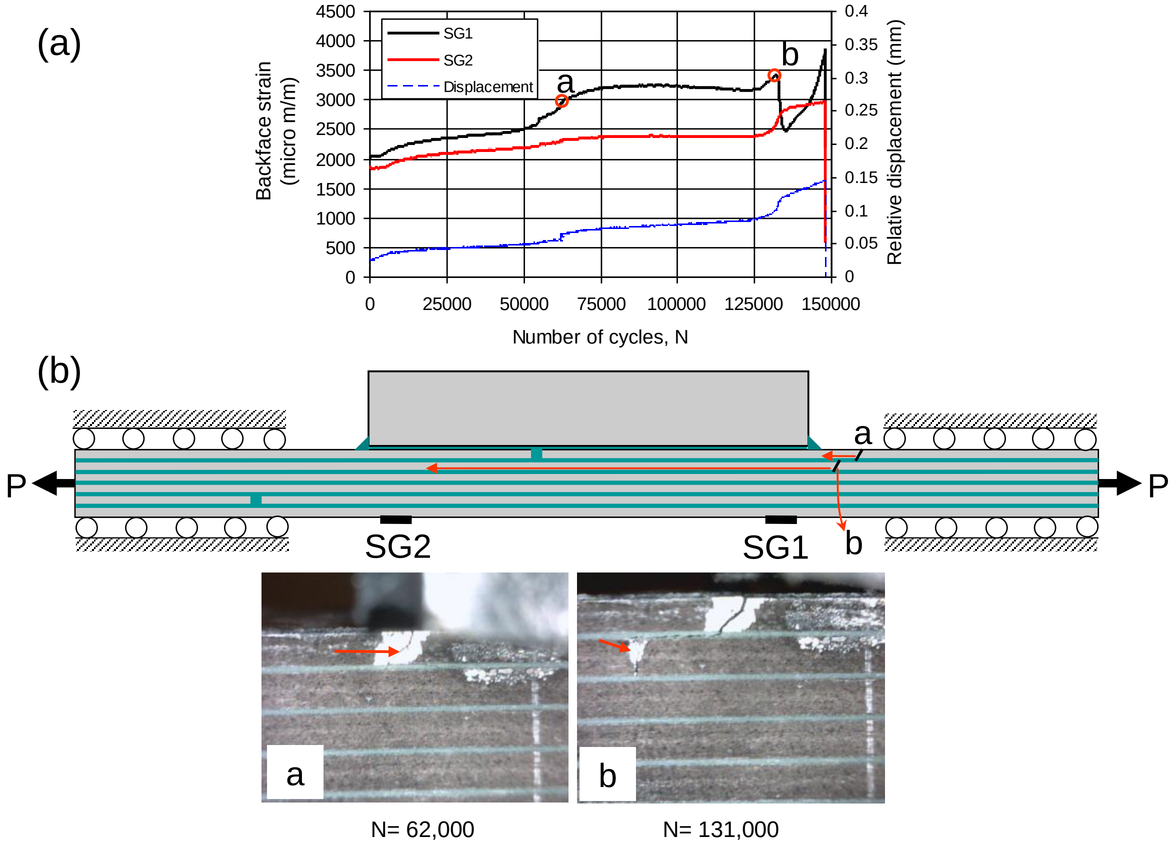

Figure 7. Failure process of the MLD-1 (aged wet 2 yrs) in tension fatigue at 50% load level, (a) BFS history, (b) Schematic of damage process.