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Numerical analysis of the combined aging and fillet effect of the adhesive on the mechanical behavior of a single lap joint of type Aluminum/Aluminum

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Abstract. Bonded joints have proven their performance against conventional joining processes such as welding, riveting and bolting. The single-lap joint is the most widely used to characterize adhesive joints in tensile-shear loadings. However, the high stress concentrations in the adhesive joint due to the non-linearity of the applied loads generate a bending moment in the joint, resulting in high stresses at the adhesive edges. Geometric optimization of the bonded joint to reduce this high stress concentration prompted various researchers to perform geometric modifications of the adhesive and adherends at their free edges. Modifying both edges of the adhesive (spew) and the adherends (bevel) has proven to be an effective solution to reduce stresses at both edges and improve stress transfer at the inner part of the adhesive layer. The majority of research aimed at improving the geometry of the plate and adhesive edges has not considered the effect of temperature and water absorption in evaluating the strength of the joint. The objective of this work is to analyze, by the finite element method, the stress distribution in an adhesive joint between two 2024-T3 aluminum plates. The effects of the adhesive fillet and adherend bevel on the bonded joint stresses were taken into account. On the other hand, degradation of the mechanical properties of the adhesive following its exposure to moisture and temperature was found. The results clearly showed that the modification of the edges of the adhesive and of the bonding agent have an important role in the durability of the bond. Although the modification of the adhesive and bonding edges significantly improves the joint strength, the simultaneous exposure of the joint to temperature and moisture generates high stress concentrations in the adhesive joint that, in most cases, can easily reach the failure point of the material even at low applied stresses.

Keywords: adherend bevel; fillet of adhesive; humidity; single-lap joint; temperature

1. Introduction

Structures assembled by adhesive bonding are increasingly being used in different fields, namely civil engineering, aeronautics, and automotive. In bonded structures, loads are transmitted from one adherend to another through the adhesive layers in the overlap surface, i.e., the adhesive acts as a load transfer mean. The major difference between bonded and mechanical joints is the contact surface, which in the case of bonding joints is much larger than in the case of mechanical fasteners. Thus, stress concentrations are minimized and stresses become more uniform in the bonded area.

Single-lap joints have been studied for about more than sixty years and many analytical and numerical models have been developed. Volkersen (1938) proposed the first approach to analyze this type of structure, by considering only shear strains in the adhesive and axial deformations in the adherends. Demarkles (1955) improved the model including shear deformation of the adherends. These analyzes do not include the bending moment produced by the eccentric path of the load. The effect of the bending moment results in loads normal to the plane of the adhesive, called peel stresses, which peak at the edges of the joint. Goland and Reissner (1944) were the first to analyze the effect of the eccentric path of the load by applying moments to the joint edges.

The most practical joint configuration is single-lap, which has been extensively studied, and several ideas have been proposed to improve their performance. The eccentricity of the load applied to the joint edges causes a significant stress concentration at the overlap ends, but minimal stresses at the core of the adhesive. Several authors have tried to reduce these stress levels by using several methods. In general, there are two types of methods to reduce stress concentrations, namely changes in the material or in the geometry of the adherends and adhesive. For example, introduction of notches, folding of the bonded surface or the use of corrugations at the covering ends of the adherends can reduce peel stresses at the overlap end.

Different shapes of the adhesive edges have been studied to reduce the various stresses and ensure a better stress distribution in adhesive joints. Harris and Adams

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(1984) proposed the creation of adhesive fillets, while Giovanni *et al.* (2002) modified the edges of the adherends by the presence of a chamfer. On the other hand, it is difficult to manufacture these adherends and to control their shape. Therefore, these methods are rarely relied upon in practice. McLaren and MacInnes (1958) studied a different method. The authors varied the bending moment factor by simply deforming the adherend at the end of the overlap length. Other authors (Lang and Mallick 1998) have used geometric modifications in the adherends at the level of the covering part and have concluded that if the size of the modified zone increases, then the stress concentration at the edges decreases. Avila and Bueno (2004) have shown that the use of corrugated sheets allows for a uniform stress distribution. Sancaktar and Nirantar (2003) have shown that if the bevel angle of the adherends at the overlapping ends is important, the stresses on the joint are minimal and this is well demonstrated by Oterkus *et al.* (2006). The material modifications mainly optimize the properties of the adhesive and the adherends. Pires *et al.* (2003) have shown that the use of a bi-adhesive system is advantageous at the joint: when the adhesive is more flexible, the stress distribution is more uniform in the single-lap joint and the stress concentration becomes minimal. Fitton and Broughton (2005) studied the effect of varying the adhesive modulus of as a method to optimize the performance of the joint. The results from the study of Sancaktar *et al.* (2000) showed that the use of a stiff adherend has made the stress distribution more uniform.

The use of an adhesive fill*et al.*so makes it possible to reduce the concentration of stresses in the joint by increasing the bonding surface. Several authors (da Silva 2006, Bigwood and Crocombe 1990, El Hannani 2016) have extensively studied the influence of an adhesive fillet. These authors showed that it reduced the excess of the peel stresses at the edge of the joint. On the other hand, it was also shown that the adhesive fillet can be the privileged site of fracture of the adhesive layer and of the joint. In the study of Adams and Peppiatt (1973), it is shown that a layer of adhesive with a fillet causes less stress concentrations than an adhesive layer with a straight edge.

The correlation of experimental data with numerical modelling was accomplished by Tsai and Morton (1995). Lang and Mallick (1998) were interested in all possible forms of adhesive fillet. The elliptical shape was determined to be optimal, and it was noted that the presence of the adhesive fillet further reduced peel stress more than the shear stress. More recently, Andreassi *et al.* (2007) were concerned in both the modeling of the formation of the adhesive fillet with fluid mechanics aspects, and the influence of the formed fillet on stress fields. A reduction of the maximum strain by 20% was observed when the fillet is elliptical. The modification of the corners of the adherend has been studied by Zhao *et al.* (2011). In their study, various degrees of rounding were studied, and two different types of adhesives were used: one very brittle and another with a large plastic deformation. Experimental results on the strength of joints with different degrees of rounding were presented. For joints bonded with brittle adhesives, the effect of the rounded adherend corners is more significant than that with ductile adhesives. The influence of the adhesive fillet has shown its effectiveness in the joint strength in the work of Akpinar *et al.* (2013), who have experimentally and numerically studied the mechanical behavior of a single-lap joint with adhesive fillets and under a bending moment. The authors showed that the single-lap joint with the fillet had a significant effect on the stress distribution. In addition, the fillet increased the load capacity of the joint and decreased the stress concentrations in the joint.

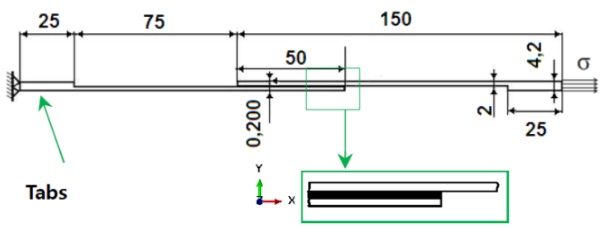
During its service lifetime, a bonded joint will be submitted to environmental loading such as high humidity and/or temperature. Changes in mechanical properties of polymers subjected to environmental conditions (temperature and humidity) coupled with severe mechanical stress are of considerable importance for designers and users of these materials. The reduction of mechanical strength due to the ingress of water may be related to physico-chemical modifications occurring at the interface (or interphase) between the adherend and adhesive and/or due to the degradation of the bulk polymer (Demir *et al.* 2021, Akpinar *et al.* 2021, Zanni-Deffarges and Shanahan 1995, Rezgani *et al.* 2018, 2016). The major disadvantage of using an adhesive joint is its exposure to the environment (temperature and humidity) (De Nève and Shanahan 1992, Wahab *et al.* 2001). Viana *et al.* (2016) have researched the combined effect of degradation by temperature (high and low) and humidity of adhesive joints. They have shown that temperature and humidity influence the behavior of the adhesive by moisture-induced plasticization of the adhesive and reduce its yield strength and stiffness, and increase its tension until failure. Moreover, low temperatures were responsible for creating residual stresses in the adhesive joint, and had an impact on the strength of the adhesive joint.

The present work aims to study the combined influence of the presence of an adhesive fillet and the effect of the environment (temperature and humidity) on the strength of an adhesive joint between two aluminum adherends (2024-T3 alloy). With this purpose, the stress distributions in the adhesive layer are estimated as a function of aging time and temperature. The effect of changing the edges of the two adherends and the adhesive was demonstrated. Three different temperatures of 20, 40 and 60°C were considered, as well as different aging times.

2. Geometric model and mechanical properties

The basic geometric model for a single-lap joint is shown in Fig. 1(a), considering 25 mm of width. Two configurations were chosen, a single-lap joint and a modified joint with a combination of geometric modifications; namely bevel at the edges of the two adherends and adhesive fillet (Fig. 1(b)). This second model is inspired by the work already carried out by El Hannani *et al.* (2016).

The dimensions of the different adherends are shown in Fig. 1. One of the joint edges is clamped, while the other edge is subjected to an applied normal stress of σ=15 MPa.



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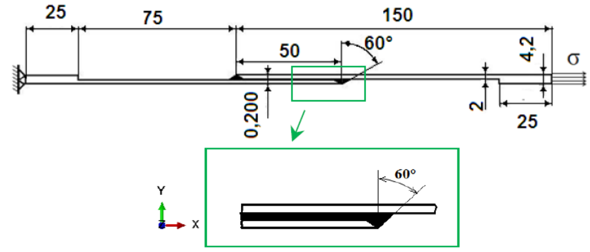
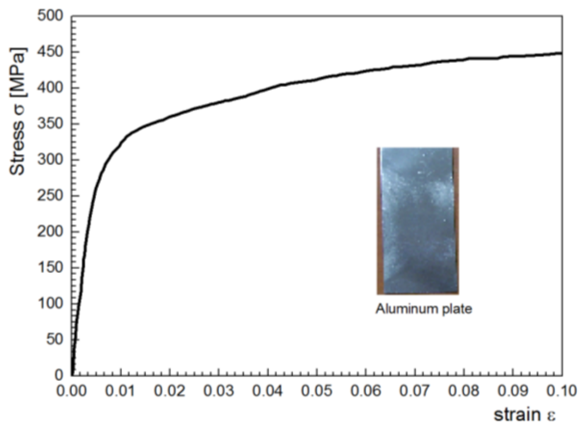


(b)

Fig. 1 Geometrical representation of the joint (a) Single-lap joint, (b) Modified joint (joint with modification at the edges of the adhesive and adherends) (El Hannani *et al.* 2016)



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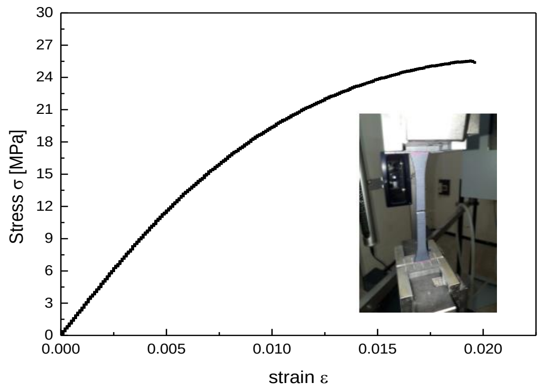


(b)

Fig. 2 Tensile stress-strain curve for: (a) Aluminum plate, (b) Adhesive Adekit A140 (Madani *et al.* 2010)

At the level of the fixed edge, the two faces are blocked, i.e., U1=U2=0. On the other hand, at the level of the faces at the loaded edge the two faces are subjected to U2=0.

El Hannani *et al.* (2016) takes into account the optimization of the single-lap joint by modifying the edges of the adhesive and the adherend. The authors showed that the 60° bevel angle presents a minimum of stresses in the adhesive layer.

In order to model the geometry presented in Fig. 1, the mechanical properties are required. For this purpose, tensile tests were carried out on Aluminum 2024-T3, in the form of a plate, and on the Adekit A-140 adhesive, in the form of standardized specimens. The characteristic curves are shown in Fig. 2. From these two curves, one can determine the mechanical properties of the two materials shown in Table 1.

Table 1 Mechanical properties of the joint materials (Madani *et al.* 2010)

Property	Materials		Description
	Aluminum	Adhesive	
E (MPa)	69000	2690	Young's modulus
G (MPa)	26500	1120	Shear modulus
ν	0.3	0.3	Poisson's Ratio
σ (Pa)	220	14.9	Yield tensile strength
ρ	2,77	1,38	Density

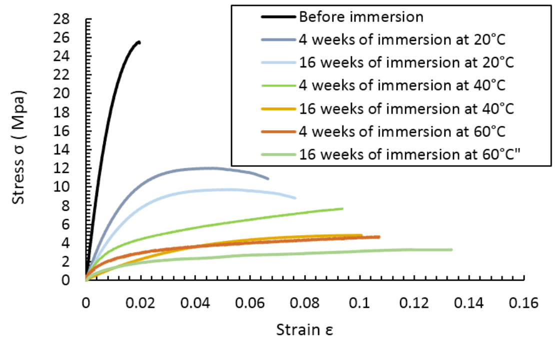
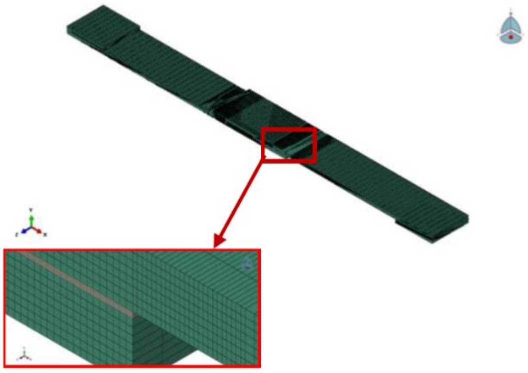


Fig. 3 Stress-strain curves of adhesive for various times of immersion in distilled water at different temperatures (Rezgani *et al.* 2018)

3. Characterization of the aged adhesive

The tensile tests carried out on samples of the adhesive Adekit A140 as a function of temperature and at different aging times were carried out by Rezgani *et al.* (2018). Fig. 3 shows the stress-strain curves for different immersion times in distilled water at 20, 40 and 60°C. When the adhesive test specimens are tensile tested before immersion in distilled water, their behavior is generally brittle, and no plasticity threshold is observed (Fig. 2). This behavior changes with aging time and temperature. Indeed, the absorption of water by the polymer modifies its behavior from a stiff state to a ductile state, which is not beneficial for the adhesive when it works in shear or peel.

Fig. 3 shows that, after hydrothermal exposure of the adhesive, its strength considerably decreases. However, it gives it a gain in ductility with a fairly wide plastic range. The increase in temperature accelerates the process of diffusion of water molecules and therefore its aging. Thus,



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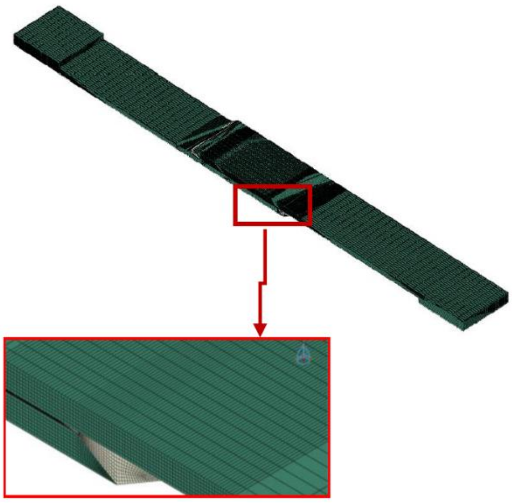

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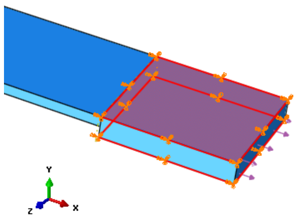

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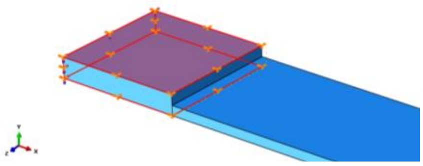

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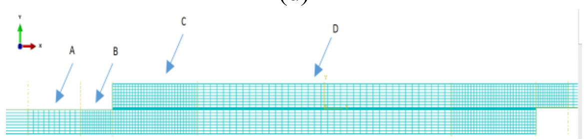
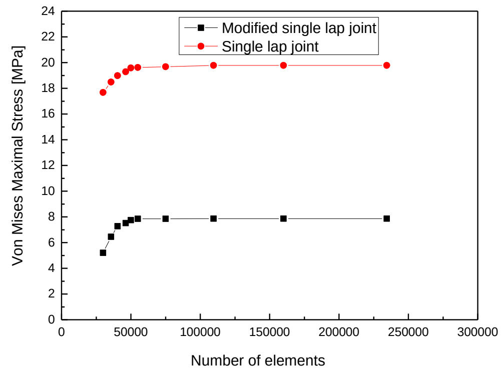


(e)

Fig. 4 Mesh of the assembled structure (a) Single-lap joint, (b) Modified joint, (c) Boundary conditions at loaded side (d) Boundary condition at clamped side and (e) Mesh detail in overlap zone

for short periods of immersion (one week), a considerable drop in the traction curve is observed, which implies a lower elastic part and a greater plasticizing effect of the polymer. The two behaviors vary inversely with the increase in immersion time.



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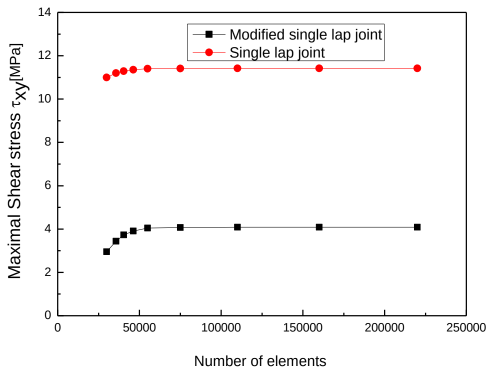

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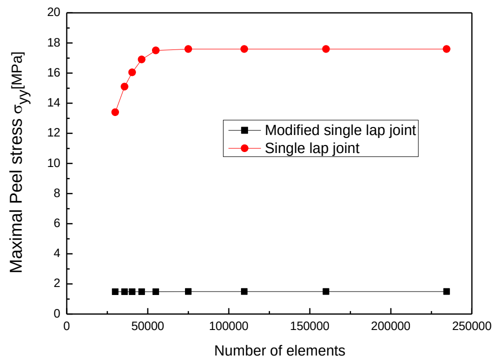


(c)

Fig. 5 Convergence analysis of FEM according to the maximum of (a) von Mises, (b) Shear and (c) Peel stresses

4. Numerical modeling

The numerical analysis was performed by using the Abaqus calculation software (6.14) using a non-linear static analysis, the Green-Lagrange strain formulation and three-dimensional modeling. Three-dimensional finite element modeling of the structure presented in Fig. 1 is a complex task. For this reason, simplifying hypotheses have been proposed:

- Each layer is considered as a three-dimensional structure. The two plates are joined through an adhesive considered to be a third material.

Table 2 Presentation of the effect of mesh type and density on the value of the maximum von Mises stress for the single-lap joint and modified joint

	Element number	C3D8	C3D8H	C3D8R	C3D8I
Modified joint Maximum von Mises stress	40400	10.41	10.41	7.27	7.88
	55000	10.83	10.83	7.85	8.18
	75100	10.83	10.83	7.85	8.18
	110400	10.93	10.93	7.86	8.20
Single-lap joint Maximum von Mises stress	46300	25.47	25.47	19.28	21.93
	50000	25.65	25.65	19.58	22.09
	72700	25.66	25.66	19.68	22.12
	109600	25.67	25.67	19.78	22.14

- The adhesive layer is homogeneous, non-linear and isotropic.
- The adhesive deforms in shear, peel and tensile.
- The contact between adherend/adhesive/adherend is considered to be perfect; no friction between the contact surfaces was considered.
- All stresses are taken at the middle width of the models, after a preliminary study showing small differences between the joint edges and the middle-width.

The structure was meshed with linear hexahedral C3D8R elements (bricks), namely 50.000 elements for single-lap joint (Fig. 4(a)) and 55.000 for the modified joint (Fig. 4(b)). For the adherends, the thickness has been described by 8 elements along the free region between the tabs and overlap, whereas at the level of the tabs a mesh of 16 elements is necessary. On the other hand, the thickness of the adhesive has been described in 8 elements. Regarding the horizontal mesh element size (Fig. 4(d)), the inner overlap region (D) was constructed with 0.76 mm for each element, and at the overlap edges (C) with 0.33 mm per element. Near the overlap length, the mesh has been refined at zone B for a size of 0.27 mm for each element, and at zone A for a size of 0.61 mm for each element. In the adhesive layer thickness, the length of 0.025 mm was considered for each mesh element. At the tabs, the elements' length is 3.25 mm per element and the thickness 0.26 mm. Fifteen elements were equated along the models' width, giving a unit length of 1.66 mm.

A study of convergence of results was carried out to choose the most suitable number of elements for the two models (Fig. 5). The study consisted of determining the different maximum von Mises, peel and shear stresses in the adhesive layer for the unaged adhesive. In the convergence study initially carried out to reach the optimal mesh, a different number of elements was taken into account depending on the thickness of the adhesive, and the result did not show a relevant difference in the stress values. As shown in Fig. 5, the stresses in the adhesive layer at ambient temperature converged for 50.000 elements for the single joint model and 55.000 for the modified model. In this study, a range of elements such as C3D8, C3D8R, C3D8H, C3D8I were tested. These types of elements by their qualities are the most frequently used in the various analyses. A sensitivity study of the type of elements with

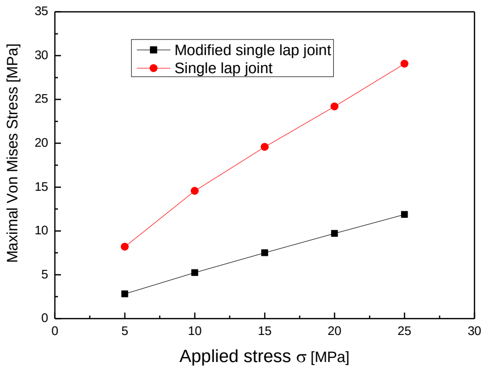


Fig. 6 Variation of the maximum of von Mises stress according to the applied stress σ

respect to the results of the variation of the von Mises stress is presented. It is clearly noticed that C3D8R elements exhibit the lowest von Mises stress values (Table 2).

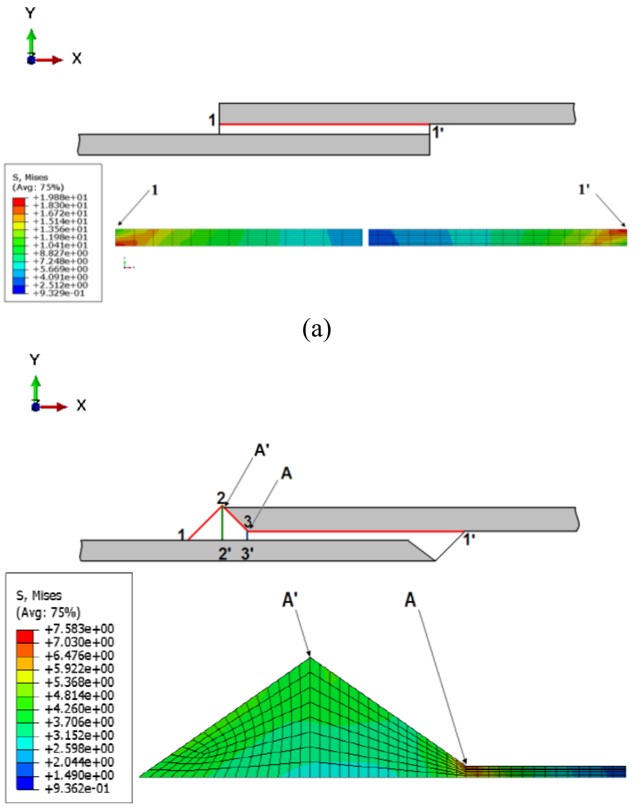
To check the effect of the applied load, different loads were taken on the two models (Fig. 6).

It can be clearly seen that the modified single-lap joint resists better to the applied load, since the effect of the presence of an adhesive fillet and adherend bevel reduces the von Mises stress by almost half. The response of the adhesive in the modified joint is not affected by the value of the applied stress. Even if the applied stress increases, the von Mises stress remains almost below the elastic limit, since the bonding zone is very wide compared to the basic model. However, for the single-lap joint, the increase in the applied stress causes the adhesive to deform considerably, and the maximum von Mises stress slightly exceeds the elastic limit for an applied stress of 15 MPa. In order to avoid being near the failure limit of the adhesive, the stress of 15 MPa was chosen.

5. Analyses and results

Once the joint is exposed to aging, one should be cautious in modeling the mechanical behavior of an adhesive joint taking into account the degraded properties of the adhesive under the effect of temperature and humidity. Adhesives generally become more ductile and weaker and the interface tends to lose toughness, often leading to a gradient in the mechanical properties of the adhesive layer and over the interface. The sides of the adhesive joint always absorb water faster than the center of the adhesive, which will result in a more significant loss of the properties of the joint edges compared to the center if the joint is exposed for a limited time and has not still reached saturation. Consequently, the numerical simulation must be able to simulate the gradient of the properties of the adhesive (Viana *et al.* 2016).

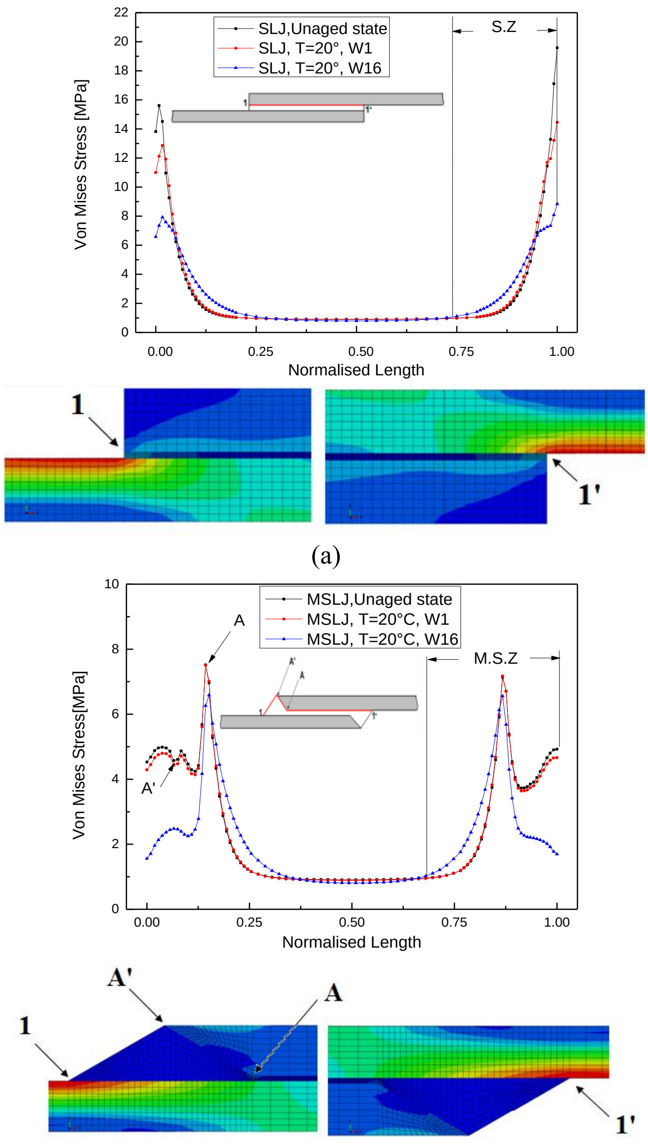
In the present case, and since the edges of the joint are the most stressed in relation to the center of the adhesive, the total surface of the adhesive was considered as being aged, considering that all the elements of the adhesive joint have the same mechanical properties after each aging period. In order to enable estimating the stress distribution



(a)

(b)

Fig. 7 Stress measurement lines in the adhesive joint, (a) Single-lap joint (b) Modified joint



(a)

(b)

S.Z: solicited zone of the single-lap joint.
M.S.Z: solicited zone of the modified joint.

Fig. 8 Variation of the von Mises stress according to the standardized length of the adhesive for the two joint configurations at 20°C for different immersion time, (a) Single-lap joint, (b) Modified joint

in the adhesive layer, the line (1-1') along the overlap length was selected (Fig. 7). The length of the line (1-1') depends on the length of the adhesive for the two joint configurations and, thus, the normalized length was considered.

5.1 Aging at 20°C

Fig. 8(a) represents the von Mises stress distribution according to the standardized overlap length for the two configurations.

Note that the joint with modification of the two edges of the adhesive and the adherend clearly reduces the value of the von Mises stress at the edge of the adhesive to around 75% of the standard single-lap joint. Peak stresses are visible at point A, although smaller when compared to the right edge. The middle of the overlap remains inactive in both cases. The stresses distribution in the adhesive joint is not symmetrical in the single-lap joint since one edge of the adhesive belongs to one adherend (point 1') and the other edge coincides with the edge of the second adherend (point 1). On the other hand, for the modified joint, a symmetry is present at the level of the distribution of the von Mises stress since the two edges are bonded with the adherends.

The exposure of the adhesive to water after one week of aging reduces its Young modulus but increases its ductility. By absorbing water, the adhesive becomes ductile and less stiff, so it becomes less resistant to the applied load, since the von Mises stress drops considerably in both configurations (Fig. 8). By increasing the aging time (16 weeks of immersion), the core of the adhesive becomes more active in the transfer of load, and the stressed area (solicited zone) in the adhesive becomes more important, which reduces the stresses at the edge.

At point A, the stress value is not much affected by immersion time (Fig. 8(b)). On the other hand, by increasing the aging time, the adhesive becomes more ductile with a large plastic area (see Fig. 3), therefore showing a lower resistance to the applied load.

Fig. 9(a) represents the effect of the aging time on the maximum value of the von Mises stress. It is clearly observed that the maximum stress value in the adhesive layer considerably decreases if the aging time increases.

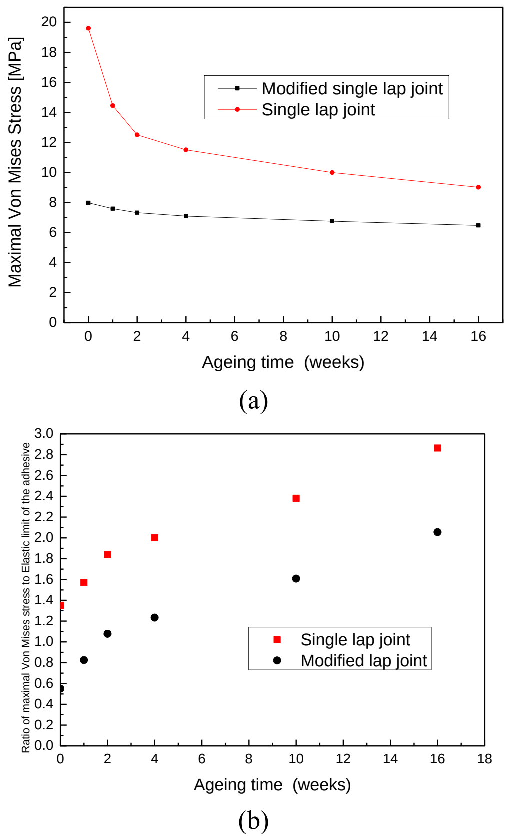


Fig. 9 (a) Variation of the maximum of von Mises stress according to aging times and (b) Variation of ratio maximum von Mises stress to elastic limit of the adhesive to the time of immersion for a temperature 20°C

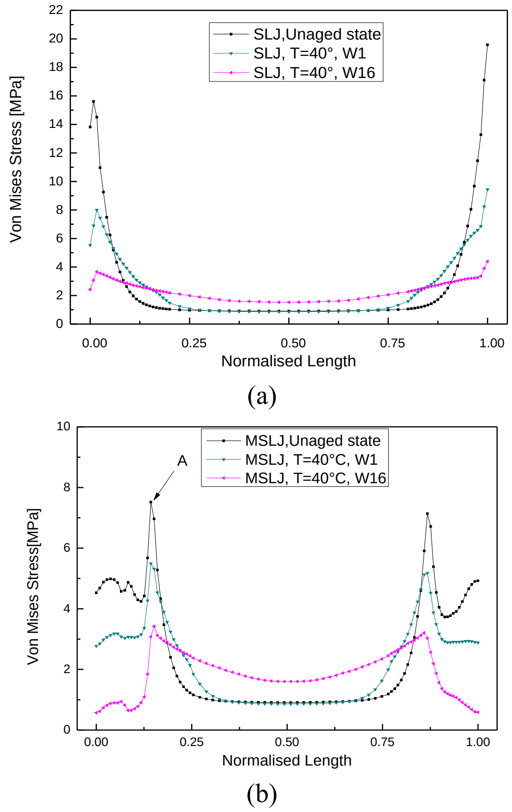


Fig. 10 Variation of the von Mises stress according to the standardized length of the adhesive for the two joint configurations at 40°C for different immersion times, (a) Single-lap joint, (b) Modified joint

Moreover, the modified joint significantly reduces the values of the von Mises stress over the single-lap joint condition. The decrease in von Mises stresses in the adhesive joint as a function of the immersion time does not mean that the adhesive resists the applied stress. If the von Mises stress is compared to the value of the elastic limit of the tensile curve of the adhesive for each immersion time (Fig. 3), one can have an idea that the adhesive becomes less strong. Note that if the immersion time is short, the value of the von Mises stress in the adhesive joint is lower than the elastic limit of the material at ambient temperature. If the immersion time increases, the value of the von Mises stress suddenly increases to exceed the elastic limit of the adhesive and can be close to the failure limit (Fig. 9(b)).

The stress value becomes lower in the two joint configurations. At the overlap edges, the stress value in the joint with adhesive fillet and adherend bevel is reduced by 19% compared to the non-aged case. However, in the case of a single-lap joint, the reduction in stress is 55% after 16 weeks of aging. The reduction of the stresses following the aging of the adhesive in the two models does not mean that it presents a good resistance with respect to the applied load. After a long aging period, the behavior of the adhesive in the two assemblies becomes similar in terms of the value of the von Mises stress. The adhesive becomes less resistant in both joint configurations. The percentile reduction in von Mises stresses between the single-lap joint and the modified joint drops considerably from the unaged state (almost 59%) to 28% if the aging time is increased.

5.2 Aging at 40°C

By increasing the aging temperature to 40°C, the adhesive behaves in the same way to 20°C (Fig. 8) but with weaker mechanical properties. von Mises stresses are lower for the modified joint with fillet and bevel. Likewise, the stresses are always concentrated at the edge and the middle of the adhesive is almost inactive.

After a week of aging (Fig. 10), the adhesive loses its strength against normal and peel stresses and becomes too ductile. However, lower von Mises stress values are obtained. The inner portion of the adhesive becomes active and a large part of the overlap zone becomes solicited if the aging time increases (Fig. 10). The adhesive becomes more ductile compared to the case at 20°C, and its capacity to resist the applied load becomes weaker if the values of the maximum von Mises stresses are compared to the elastic limit of the adhesive (Fig. 3). The maximum von Mises stress values exceed in most cases of aging time the elastic limit of the adhesive. The value of the stress becomes lower with a significant drop in around 57% for the modified joint, and 78% for the single-lap joint, when compared to the case of ambient temperature. The difference in the stress value varies depending on the duration of aging in the dry state, being 60% between the two joint configurations. On

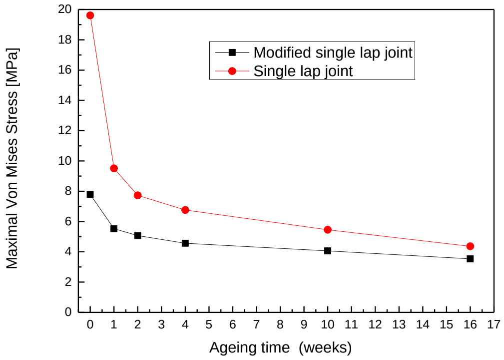
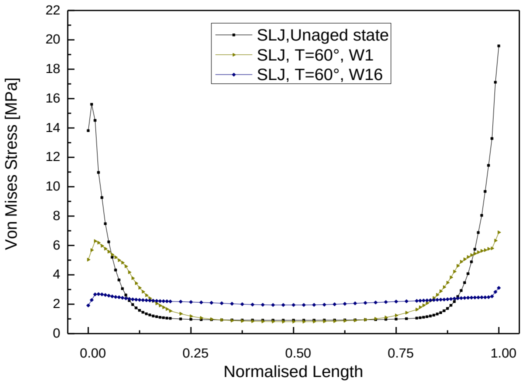
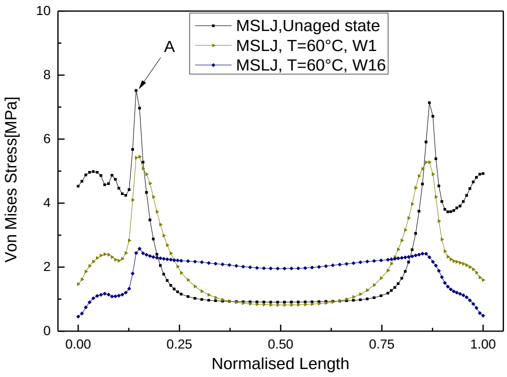


Fig. 11 Comparison of the maximum value of the von Mises stress between the single-lap joint and modified joint at 40°C



(a)



(b)

Fig. 12 Variation of the von Mises stress according to the standardized length of the adhesive for the two joint configurations at 60°C for different immersion times, (a) Single-lap joint, (b) Modified joint

the other hand, after 16 weeks of aging, this difference lowers to 26% (Fig. 11).

5.3 Aging at 60°C

When the aging temperature is 60°C, the adhesive loses more its strength properties (Fig. 3) and becomes rubbery with weak mechanical properties. After one week of aging at *T*=60°C (Fig. 12), it was noticed that the two joints have almost identical stress values, with a negligible difference. As the size of the solicited area is the same, almost the entire section of the adhesive is solicited. At this temperature, the adhesive loses much of its stiffness. During this time, there will be a gain in ductility with a larger plastic area, which will allow the adhesive to absorb a large part of the applied load. As the aging time increases, the stresses in the adhesive layer become less significant. It was also found that, at this temperature and after 16 weeks of aging, the two joint configurations behave similarly (Fig. 12).

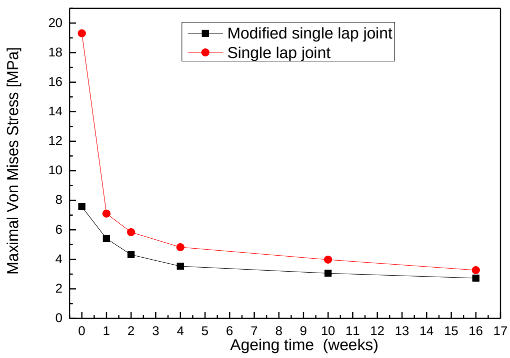


Fig. 13 Comparison of the maximum value of von Mises stress between the single-lap joint and modified joint at 60°C

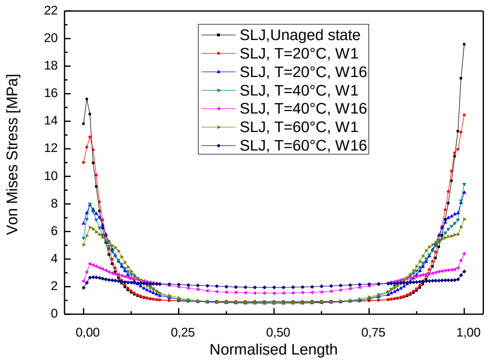
Fig. 13 represents the variation of the maximum von Mises stress as a function of the aging time, for the two joint configurations: single-lap joint and modified joint. It is clearly noted that the adhesive fillet clearly reduces the value of the stresses at the bevel edge and leads the adhesive to be solicited in a larger area, which is beneficial for the durability of the joint. In the dry state, the stress reduction is 65%. On the other hand, after 16 weeks of aging at *T*=60°C, there is a reduction of 65%.

In the same way as the other two temperatures, von Mises stresses largely exceed the elastic limit stress of the adhesive (see Fig. 3). The modification made to the edges of the adhesive and the adherend does not have a major influence on the reduction of the different stresses compared to the case at ambient temperature. It was also noticed that, after 16 weeks of aging at 60°C, the edge of the adhesive at the level of the fillet becomes inactive while its core remains a little stressed.

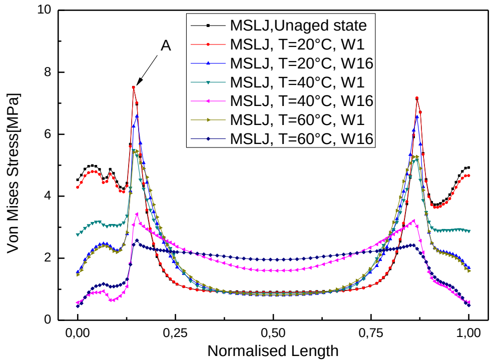
The beneficial effect of the presence of geometric modification at both edges of the adhesive and of the adherends on the reduction of the stresses in the joint disappears as the temperature and the duration of aging increase. The percentile reduction in the von Mises stress, which was 59% before aging, becomes too low for a temperature of 60°C with a duration of 16 weeks of exposure to immersion.

5.4 Comparison of results

Fig. 14 shows a comparison of the von Mises stress distribution in the two joint configurations for different aging temperatures. As the aging temperature increases, the adhesive joint in the two joint configurations behaves in the same manner apart from the different values obtained. A considerable decrease in the stress value at the edges of the

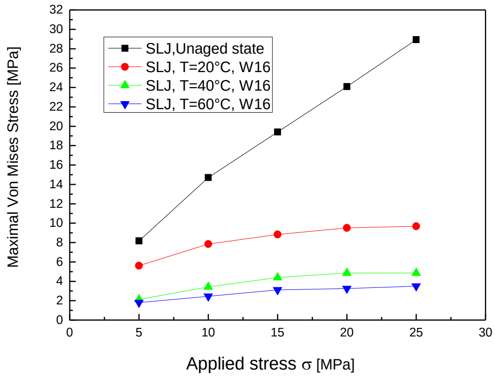


(a)

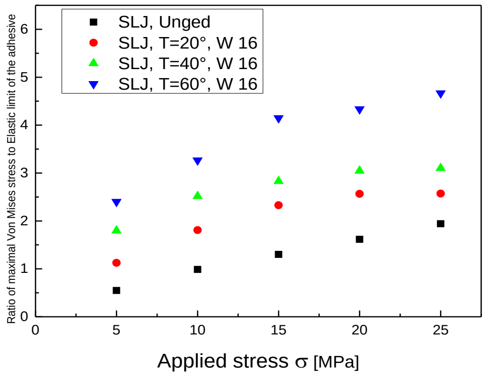


(b)

Fig. 14 Distribution of von Mises stresses in the length of the cover joint (1-1) for different temperatures and aging times, (a) Single-lap joint, (b) Modified joint. (W: weeks of aging, T: temperature)



(a)



(b)

Fig. 15 (a) Variation of the maximum of von Mises stress according to the applied stress σ for the single-lap joint for different temperatures and (b) Variation of ratio maximum von Mises stress to elastic limit of the adhesive to the applied stress σ for different temperatures at 16 weeks of aging

adhesive with an increase in the size of the stressed area is observed, meaning that the inner overlap becomes more active, which reduces the concentration of stresses at the edge bevel.

In the combined presence of an adhesive fillet and edge bevel of the adherend, a stress peak is noted (point A), which causes a distribution of different stresses than that in the case of a single-lap joint. Stresses in the case of the modified joint symmetric, unlike the case of the single-lap joint where the value of the stress differs on both sides of the adhesive layer. The section of the adhesive becomes more active in the case of the modified joint, which shows low values of the von Mises stress. On the other hand, at the free edge (1) the von Mises stress decreases when the temperature increases. At point A (the peak over-stress), the stress value increases and becomes more important compared to the values of von Mises at the edge, and then it decreases by a considerable value once reaching 60°C.

The analysis of the maximum von Mises stress as a function of the applied load for the two joint configurations, as a function of temperature for 16 weeks of aging, is presented in Figs. 15 and 16, respectively.

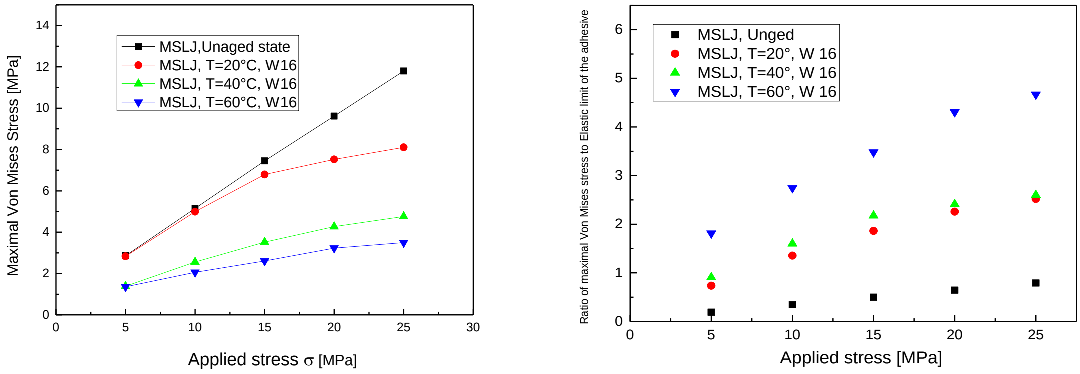
It can be clearly seen that the increase in the applied stress leads to an increase in the von Mises stress in the two joint configurations and the highest values are found for the single-lap joint. The increase in temperature leads to a reduction in the mechanical properties of the adhesive, which causes a reduction of von Mises stresses for the two configurations. Once the 16 weeks of aging have been reached, the von Mises stress becomes almost equal in the adhesive joint for the two joint configurations.

At this aging time the adhesive loses a large part of its strength and the value of the von Mises stress largely exceeds the elastic limit of the adhesive.

The decrease in the von Mises stress following the aging of the adhesive, and therefore in the strength of the single-lap joint with and without fillet, is in good agreement with the work of Zheng *et al.* (2020), who analyzed the load-displacement response of the two models and showed that the presence of a fillet significantly increases the joint strength. This difference in the value of the maximum load disappears so that the two joint configurations have practically the same value after a long period of aging.

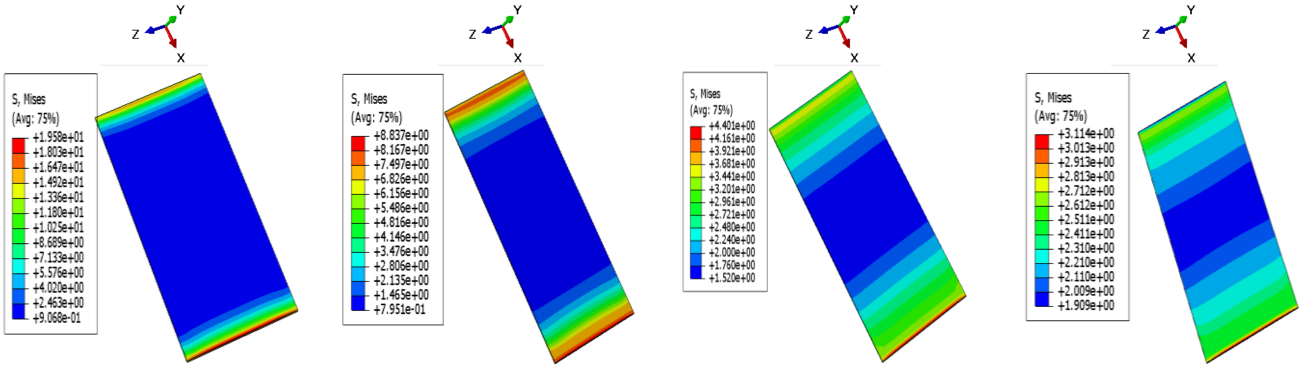
The von Mises stress level in the adhesive joint is shown in Fig. 17, where it is clearly seen that the size of the high stress area increases in the adhesive surface, thus relieving the high stresses at the edges. On the other hand, the core of the adhesive becomes more active. The maximum value of the von Mises stress decreases as a function of the immersion time and temperature in the two joint configurations so that the difference in the von Mises stress value between the two joint models becomes minimal.

Compared to the case of the unaged adhesive, the



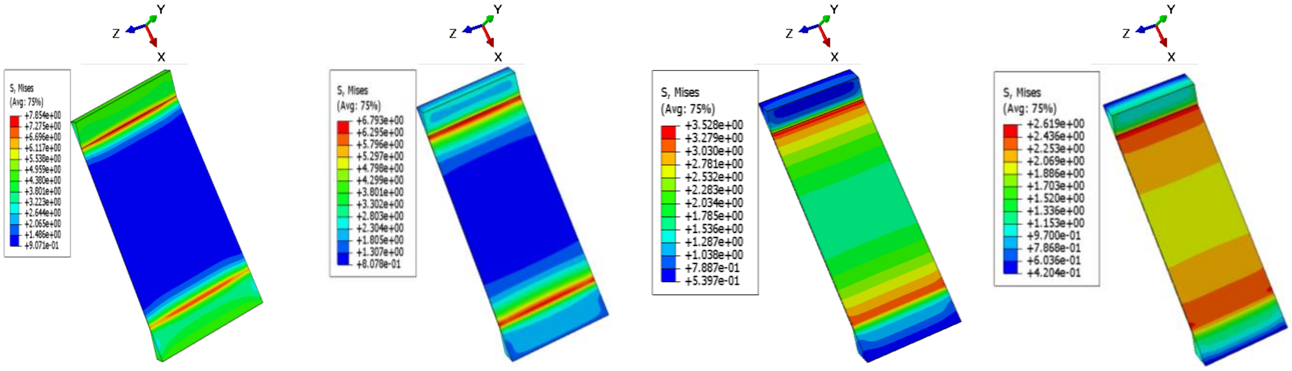
(a) (b)

Fig. 16 Variation of the maximum of von Mises stress according to the applied stress *σ* on the modified joint for different temperatures and (b) Variation of ratio maximum von Mises stress to elastic limit of the adhesive to the applied stress *σ* for different temperatures at 16 weeks of aging



Unaged state | *T*=20°C, 16 weeks of aging | *T*=40°C, 16 weeks of aging | *T*=60°C, 16 weeks of aging

(a)



Unaged state | *T*=20°C, 16 weeks of aging | *T*=40°C, 16 weeks of aging | *T*=60°C, 16 weeks of aging

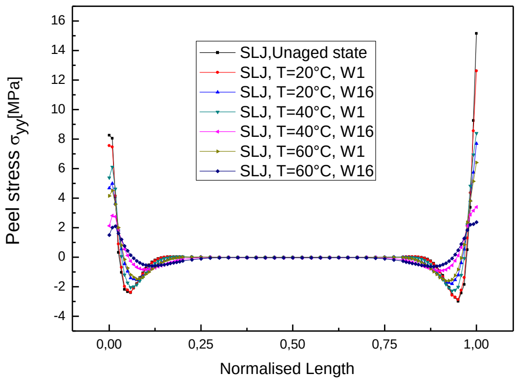
(b)

Fig. 17 von Mises stress level in the adhesive joint after 16 weeks of aging at different temperatures (a) Single-lap joint (b) Modified joint

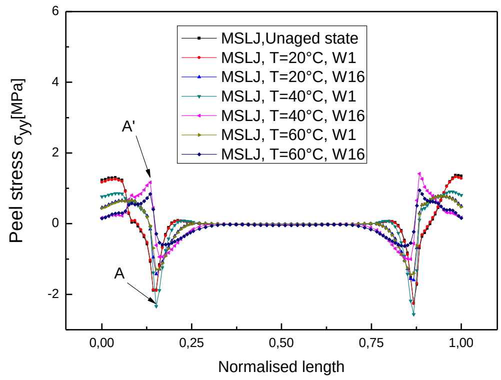
decrease of the von Mises stress value in the adhesive layer following its aging clearly shows that, for an applied stress of 15 MPa, failure of the adhesive joint can take place. If the maximum von Mises stresses (Fig. 17) are compared with the failure limit of the adhesive at 60°C for a period of 16 weeks of immersion (Fig. 3), it is noted that the adhesive reaches the breaking point easily. The value of the von Mises stress at this temperature in the two configurations is almost identical.

5.5 Peel stress

Taking into account the load path eccentricity in the joints, a bending moment will be created. For this purpose, the distribution of the σ_{yy} peel stresses has been determined according to the overlap length (Fig. 18) for the two joint configurations. It is clearly noted that the stress distribution is not symmetrical along the two edges of the adhesive and that the value of the peel stress remains low in the case of

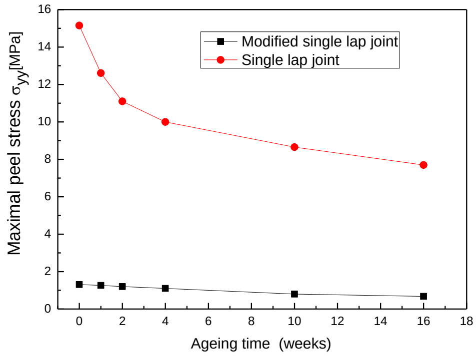


(a)

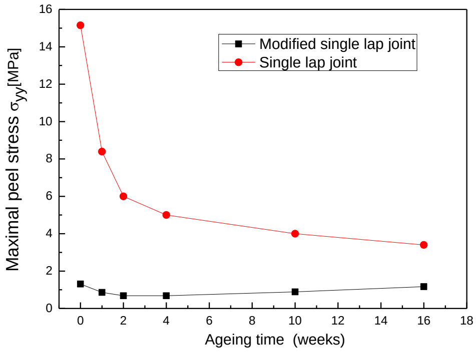


(b)

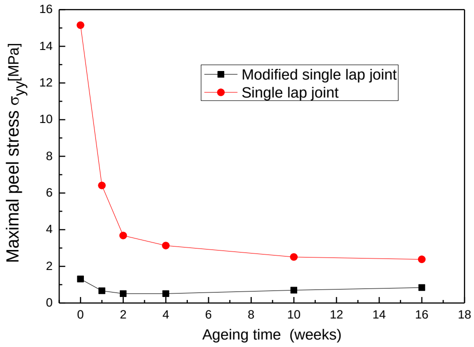
Fig. 18 Distribution of peel stresses in the length of the cover joint (1-1') for different temperatures and aging times, (a) Single-lap joint, (b) Modified joint. (W: weeks of aging, T: temperature)



(a)



(b)



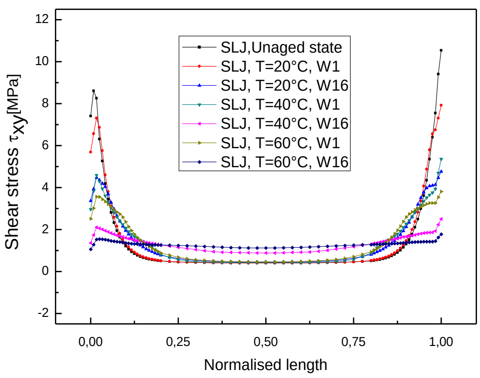
(c)

Fig. 19 Variation of maximal peel stress according to aging times for the single-lap joint and modified joint, (a) T=20°C, (b) T=40°C, (c) T=60°C

the modified joint, which represents more contact surface than single-lap joint. σ_{yy} peel stresses decrease with the increase in temperature and the aging time (Fig. 19), therefore a small solicited area appears at the two edges, while a large part of the adhesive becomes inactive. For the modified joint, the point "A" has high compression values compared to point "A' " and the edge, but it remains low compared to the case of single-lap joint.

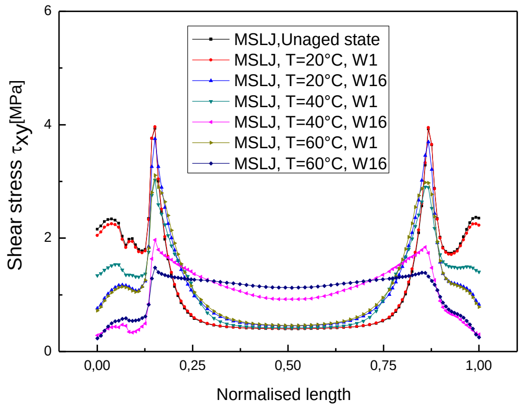
5.6 Shear stress

The shear stress distributions are presented in Fig. 20. It is clearly noted that the values of τ_{xy} shear stresses for the modified joint are lower than those of the single-lap joint. This is due to the presence of the adhesive fillet, which provides more contact surface than that of the single-lap joint. τ_{xy} shear stresses are symmetric for the modified joint, unlike happens for the single-lap joint. The highest values are found at the free edge of the adhesive in both joint configurations. For the modified joint, there is a stress peak at point "*A*", which has higher values than at the free edge of the corner of the adhesive. The stressed area for the modified joint is larger than that of the single-lap joint. The maximal value of the τ_{xy} shear stresses decreases by increasing the temperature and the duration of aging (Fig. 21). The core of the adhesive becomes more active as the temperature increases.



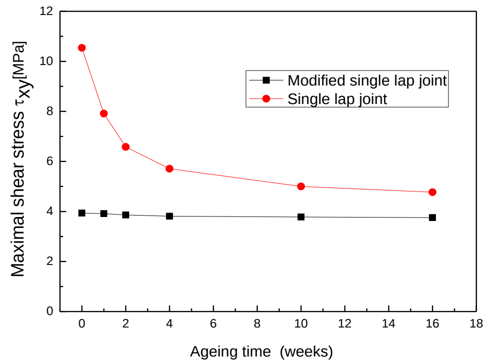
(a)

Fig. 20 Distribution of shear stress in the length of the cover joint (1-1') for different temperatures and aging times, (a) Single-lap joint, (b) Modified joint. (W: weeks of aging, T: temperature)

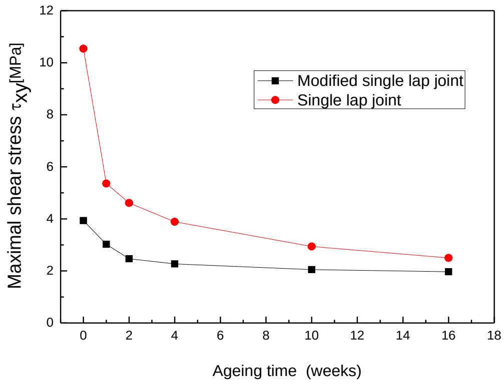


(b)

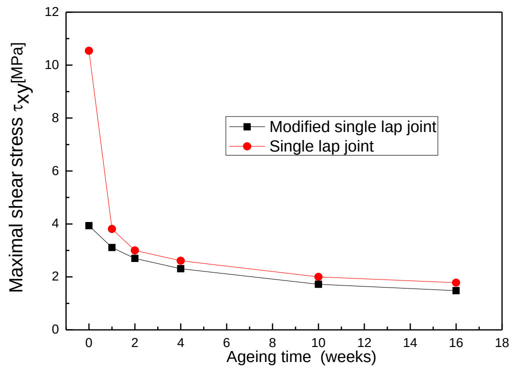
Fig. 20 Continued



(a)



(b)



(c)

Fig. 21 Variation of maximal shear stress according to aging times for the single-lap joint and modified joint, (a) *T*=20°C, (b) T=40°C, (c) *T*=60°C

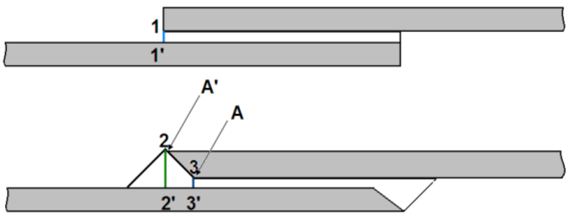


Fig. 22 Stress measurement lines in the adhesive joint, (a) Single-lap joint (b) Modified joint

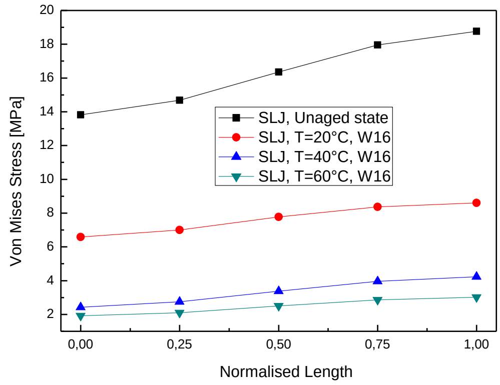


Fig. 23 Distribution of von Mises stresses at line 1-1' after aging (W: weeks of aging, T: temperature)

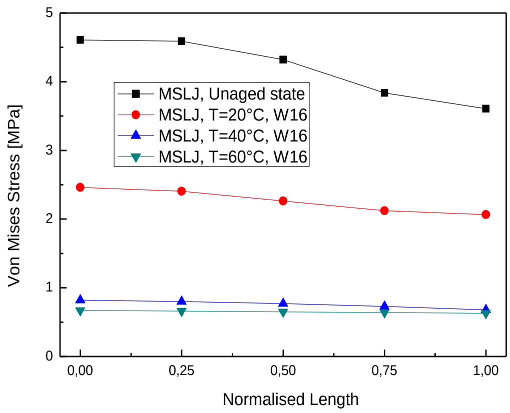


Fig. 24 Distribution of von Mises stresses at line 2-2' after aging (W: weeks of aging, T: temperature)

5.7 Stress analysis at the adhesive edge

To assess the effect of the modification of the adhesive edge and of the adherend on the von Mises stresses in the layer of adhesive, virtual lines were considered (Fig. 22):

- 1.1 ': depending on the thickness of the adhesive edge for the single-lap joint;

- 2.2 ': depending on the thickness of the adhesive at the extreme point which contains the sharp angle of contact between the adhesive fillet/adherend bevel;

- 3.3 ': depending on the thickness of the adhesive at the adherend bevel/adhesive point of contact.

For the single-lap joint, the distribution of the maximum von Mises stress varies on both sides of the thickness of the adhesive in a non-symmetrical way, from point 1 in contact with the free edge of the adherend, which presents the highest value of the von Mises stress compared to point 1'.

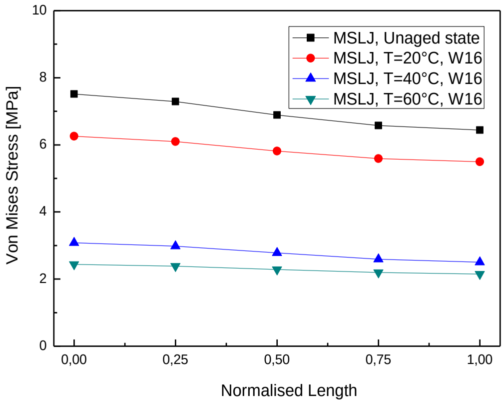


Fig. 25 Distribution of von Mises stresses at line 3-3' after aging (W: weeks of aging, T: temperature)

By increasing the temperature, the value of the von Mises stress considerably decreases in the same way at the level of the two points of the adhesive edges (Fig. 23).

However, for the modified joint (adhesive fillet and adherend bevel), the value of the von Mises stress is almost identical at line 2-2'. By comparing it to the single-lap joint, the values of the von Mises stresses are clearly lower. By increasing the temperature and the aging time, the value of the von Mises stress decreases slightly to become almost stable after 16 weeks of aging (Fig. 24).

In the line (3-3'), which contains the point of adherend bevel/adhesive contact, the values of the von Mises stress are clearly higher than those in the line (2-2') but they remain lower than in the case of a single-lap joint. By increasing the aging time and the temperature, the value of the von Mises stress considerably decreases (Fig. 25).

6. Conclusions

The numerical finite element analysis undertaken in this study aimed to estimate the stress distributions in an adhesive joint. Two types of bonded joints were addressed, a basic joint (single-lap joint) and another with modifications at the edges of the adhesive and the two adhrends (modified joint). The analysis took into account the combined effect of the modification of the two edges of the adhesive and the adherends as well as the impact of aging of the adhesive at different temperatures and immersion times. The mechanical properties of the adhesive are taken from tensile tests carried out on the Adekit A140 adhesive after various periods of hydrothermal aging (temperature from 20 to 60°C and immersion times from 1 to 16 weeks). The main conclusions of this work are as follows:

- The free edge of the adherend influences the value of the various stresses (von Mises, peel or shear) in the joint, which requires a geometric modification (bevel) to reduce this stress gradient and avoid debonding.
- the geometrical modifications made to the edges of the adhesive and the two adherends (adherend bevel and adhesive fillet) have made it possible to reduce the various stress components in the adhesive joint, while the single-lap joint presents significant stresses compared to the modified joint.
- At 20°C, before aging, the modification of the edges of the adhesive and the adherend bevel reduce the von Mises stress by almost 59%, 91% for the peel stress and 62% for the shear stress. However, these rates of stress reduction decrease with increasing aging time and temperature.
- The modified joint has the lowest values of the various stress components in the adhesive joint before and after aging, which is advantageous for the service life of the structure.
- The mechanical properties of the adhesive considerably decrease with increasing temperature and aging time.
- If the adhesive is exposed to temperature and humidity, the value of the various stress components is reduced compared to the unaged case, but this does not mean that the aging of the adhesive is beneficial for the strength of the joint. By comparing the different values of von Mises stresses with respect to the elastic limit of the adhesive for each temperature and duration of aging, it is noticed that the adhesive becomes too weak and does not resist the applied stress.
- For a high temperature and duration of aging (60°C and 16 weeks of aging), the adhesive presents the same behavior in the two joint configurations, its strength is reduced low, and the value of von Mises stresses reaches the limit of failure easily.
- The increase in the aging time significantly decreases the values of the various stress components in both joint configurations.
- The modified area at the edges of the adhesive becomes inactive and has low values of the various stress components if the temperature and aging time are high.

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CC

Appendix

Plastic properties of (a) Adhesive

σ	ε
14.9	0
17.07	0.00018889
19.044	0.00038889
21.018	0.0006
23.072	0.00086666
25.01	0.001155
27.023	0.001511
29.039	0.001977
31.01	0.002733
31.41	0.00388889

Plastic properties of (b) Aluminium 2024-T3

σ	ε
220.246	0
226.692	0.000149474
234.212	0.000348736
238.977	0.000498157
248.477	0.000747143
257.365	0.001045843
267.643	0.001443972
277.209	0.001891678
293.001	0.002885862
308.944	0.004176825
326.255	0.006407254
337.724	0.008039746
358.021	0.013904576
362.638	0.015868249
368.886	0.018708743
373.295	0.02056539
377.73	0.022759603
384.167	0.02611474
389.396	0.029893998
398.818	0.033659026
402.868	0.036785757
405.727	0.036833784
414.177	0.044488592
418.219	0.046440741
430.458	0.05849734
432.977	0.061125709
437.046	0.067014402
439.829	0.069899332
445	0.077674989
446.415	0.080851129