

## Influence of hygrothermal aging on the mechanical strength of an Aluminum/Aluminum bonded assembly

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**Abstract.** The adhesive bonding technique has become widely prevalent in recent years, especially in fields such as engineering, aerospace, and sports. During operational service, adhesives are subjected to severe environmental conditions, including temperature variations, humidity, and UV radiation, which can impact their performance. In this study, we utilized the mechanical properties of the aged epoxy adhesive Adekit A140 in a finite element model to assess the impact of temperature and water absorption on the degradation of mechanical properties in metal-metal adhesive joints used in aeronautical structures. Our primary objective was to analyze, using the finite element method, the influence of these environmental factors on the joint's strength by evaluating the distribution of Von Mises stresses. The adhesive's mechanical properties, such as Young's modulus (E), were measured at different immersion periods and then integrated into the numerical modeling. The results revealed that water absorption leads to a significant degradation of the adhesive's mechanical properties, primarily manifested as a reduction in Young's modulus. Despite this degradation, an increase in plasticity was observed, which surprisingly improved the overall strength of the bonded assembly under certain conditions. Notably, after 90 days of immersion, the joint's strength demonstrated a 15% reduction in stiffness but exhibited enhanced durability due to plastic deformation, indicating a potential trade-off between stiffness and durability in long-term service. This provides valuable insight into the design of adhesive joints under varying environmental conditions.

**Keywords:** degradation; temperature; metal/metal adhesive joints; Von Mises stress; water absorption

### 1. Introduction

The widespread adoption of adhesive bonding has significantly increased over the years, becoming ubiquitous in a broad range of industries and applications. This surge in popularity can be attributed to its ability to provide reliable and efficient joining solutions without the need for mechanical fasteners or welding, which can compromise the integrity of materials or add unnecessary weight. Adhesive bonding has become particularly valuable in sectors such as

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engineering, aerospace, automotive, construction, and even sports equipment manufacturing, where lightweight and high-strength materials are critical for performance. Its versatility extends to bonding dissimilar materials, offering the advantage of evenly distributing stress across the joint, enhancing durability and overall structural integrity.

Mubashar *et al.* (2009) examined the impact of moisture absorption and desorption on single lap adhesive joints. Experimental investigations were conducted to analyze the moisture absorption behavior of the single-part epoxy adhesive, FM73. The results of the experiments showed a gradual deterioration in the failure strength of the single lap joints with 2024 T3 adherends over time when exposed to water immersion at 50 °C. Fang *et al.* (2019) addressed the structural applications of FRP composites, emphasizing their role as primary load-carrying components. The focus is on their performance in challenging environments, such as elevated temperatures, high humidity, water immersion, and exposure to ultraviolet (UV) radiation. These findings are presented based on firsthand experiences, aiming to showcase their practical suitability and offer examples for individuals or projects facing similar requirements. Heshmati *et al.* (2017) examined the impact of environmental aging on the mechanical behavior of adhesively bonded double-lap shear joints comprising steel and adherents of CFRP or GFRP. A total of 192 specimens, consisting of 84 joints and 108 material coupons, underwent aging for a period of up to three years in diverse environments, including (i) immersion in distilled water at 20 °C and 45 °C, (ii) immersion in de-icing salt solution at 20 °C and 45 °C, and (iii) exposure to 95% relative humidity at 45 °C. Nguyen *et al.* (2012) studied the mechanical behavior of double strap joints with steel and CFRP subjected to challenging environmental conditions. A total of seventy-five joint specimens underwent were exposed to different scenarios, including (1) simulated sea-water at 20 °C and 50 °C for up to 1 year in a temperature-controlled sea-water tank, and (2) constant, as well as (3) cyclic temperatures, with a high level of relative humidity (RH) for up to 1000 hours in an environmental chamber. Li *et al.* (2019) presented the Highlights the latest advancements and accomplishments in the performance of FRP-concrete bond systems under chloride exposure. This review focused on the durability of epoxy resin, FRP composites, and the interface between FRP and concrete in conditions involving immersion exposure and wet-dry cycle exposure. Li *et al.*; (2022) concluded that as the immersion time increased, the tensile strength of CFRP initially rose and then declined, whereas that of BFRP exhibited a nearly continuous decrease. CFRP demonstrated notably superior chloride resistance compared to BFRP, with CFRP's strength retention being approximately 160% higher than that of BFRP after 360 days of exposure. Additionally, epoxy resin with a lower epoxy value showed enhanced corrosion resistance. Tafsirojjaman *et al.* (2022) provided an extensive overview of diverse methods aimed at enhancing the performance and design of steel structures through the utilization of FRP composites. Strength prediction models were provided for a variety of loading and environmental conditions to facilitate the assessment and secure design of FRP-strengthened steel structures, thereby minimizing their susceptibility to failure. Ke *et al.* (2020) examined the impact of elevated temperatures on the mechanical performance of epoxy adhesives and CFRP-steel hybrid joints. Initially, the glass transition behavior and mechanical properties of four different epoxy adhesives were analyzed through dynamic mechanical analysis (DMA) and tensile tests under elevated temperatures. Subsequently, the failure process of CFRP-steel double-lap joints was investigated at various elevated temperatures. Bazli *et al.* (2020) investigated the impact of UV radiation, moisture, and elevated temperature on the mechanical properties of pultruded GFRP profiles. The findings indicated a general decline in the mechanical properties of different GFRP sections with prolonged conditioning. Notably, the rate of decrease remained relatively slight up to 1000 hours, accelerated significantly between 1000 and 2000 hours, and then slowed down again

during the 2000–3000-hour period. Bazli *et al.* (2021) conducted a comprehensive review of over 100 experimental and numerical studies that concentrate on both environmental considerations and the structural performance of hybrid FRP-SWSSC (Steel Wire Strand Reinforced Self-Consolidating Concrete) structures. The short- and long-term structural behaviors of FRP-SWSSC structures was examined under varied loading configurations and environmental conditions. The structural performance of diverse systems was explored, including FRP-reinforced SWSSC beams, SWSSC filled with FRP tubes, FRP-strengthened/wrapped SWSSC members, and composite members comprising glass FRP (GFRP) profiles and SWSSC. Sharifianjazi *et al.* (2022) provided a comprehensive review of more than 100 research studies that investigate the structural responses of various concrete structures reinforced or strengthened with FRP (Fiber-Reinforced Polymer) after exposure to elevated temperatures, spanning from ambient conditions to flames. Various structural systems were examined, encompassing FRP laminate bonded to concrete, FRP-reinforced concrete, FRP-wrapped concrete, and concrete-filled FRP tubes. Bandaru *et al.* (2023) produced quadriaxial non-crimp (NC) glass fabric/Elium based polymer composites were produced through vacuum-assisted resin transfer molding (VaRTM). The static mechanical characteristics of these composites were assessed under tensile and flexural loads. To investigate the impact of aging on the mechanical properties of glass fabric/Elium (GF/E) composites, test samples were subjected to a 60-day aging process in distilled water at a temperature of 60°C. Boulenouar *et al.* (2023) emphasized the impact of mechanical and geometrical properties of both the adhesive layer and the composite patch on the stress intensity factor (SIF) variation at the crack front. The results demonstrated a significant reduction in the SIF at the crack front when employing a double patch, in contrast to facial and lateral repairs. Costa *et al.* (2017) concluded that the trend observed is that hygrothermal aging tends to reduce the number of cycles a joint can endure and decreases the threshold fracture toughness value. This implies that cracks are more likely to initiate sooner. However, it's important to note that there are exceptions to these behaviors as well. Garg *et al.* (2017) studied the impact of hygrothermal aging on the interface between glass fiber and epoxy matrix was examined using both destructive and non-destructive methods. The experimental findings revealed a correlation between the decrease in ultrasonic voltage amplitude and the decline in tensile strength over an increasing immersion time. Consequently, comparing the transmitted guided wave signal between intact specimens and those subjected to various levels of hygrothermal aging enabled the performance assessment of GFRP composites. Huang *et al.* (2023) presented the tensile modulus and strength of flat coupons made from flax-glass hybrid FRP (HFRP) with varying fiber volume fractions and fabric stacking sequences. The specimens were subjected to constant hygrothermal conditions (50 °C and 95% RH) and cyclic weathering (water spray-ultraviolet radiation) for six months. The results indicated that the tensile modulus of HFRP was hardly affected by hygrothermal and weathering exposures, regardless of the matrix type. Following environmental exposure, HFRP with an epoxy (EP) matrix exhibited a lower retention ratio of tensile strength (65.4–88.0%) compared to that with a polyurethane (PUR) matrix (80.7–94.1%), attributed to higher moisture absorption in the EP-based HFRP. Medjdoub *et al.* (2022) clearly indicated that altering the edges of both the adhesive and bonding agent plays a crucial role in determining the durability of the bond. While modifying these elements significantly enhanced joint strength, subjecting the joint to simultaneous exposure to temperature and moisture resulted in elevated stress concentrations within the adhesive joint. In many instances, these stress concentrations were observed to surpass the material's failure point even under low applied stresses. Pitta *et al.* (2022) explored the fatigue resistance of four joint configurations (metal/metal, metal/composite, composite/composite, and composite/metal) employing riveted, adhesive bonded, and hybrid joining techniques is explored through both

experiments and finite element analysis. The experimental results indicated that the fatigue life of hybrid joints surpasses that of adhesive bonded joints, and the latter significantly outperformed conventional riveted joints. Wang *et al.* (2022) concluded that square or hexagonal fiber arrangement models yield comparable results to random fiber arrangements in real-world scenarios. Water absorption curves for GFRP are observed and overestimated in models without and with defects considered, respectively. Ultimately, it was suggested that both simplified and refined finite element models be utilized to quickly estimate the water absorption of GFRP composites. The findings of Xie *et al.* (2022) indicated that an increase in immersion duration and temperature exacerbated the degradation of fatigue performance. Prolonged immersion rendered the fatigue life of the anchorage more sensitive to stress amplitude, leading to a degradation of initial stiffness. Additionally, a decrease in stress ratio accelerated tendon slippage and hastens stiffness degradation during cyclic loading, irrespective of moisture conditions.

Mu *et al.* (2024) both studies explore the effects of hygrothermal aging on adhesive joints under high temperatures, but with different substrates and analysis techniques. The BFRP-Al study investigates basalt FRP-aluminum joints, incorporating accelerated aging at 80°C and 95% RH, and uses Differential Scanning Calorimetry (DSC) to assess shifts in glass transition temperature ( $T_g$ ) and failure mechanisms. In contrast, your study focuses on aluminum-to-aluminum joints and introduces edge modifications to mitigate stress. The BFRP-Al study's predictive modeling of bond performance could complement your analysis by incorporating  $T_g$  variations and durability predictions under similar conditions. Jing Wang *et al.* (2024) in comparison, both studies examine environmental aging on material properties but focus on different materials and aging methods. The glass/epoxy composite study investigates hygrothermal aging effects, assessing mechanical degradation via tensile strength and using machine learning to predict natural aging based on accelerated aging data. In contrast, your work centers on adhesive joints with aluminum, focusing on stress distribution and edge modifications under aging and temperature effects. The machine learning approach for aging predictions in the composite study could enhance your research by offering predictive insights into long-term adhesive joint performance under similar environmental conditions. Zhang *et al.* (2023) examined adhesive debonding in cement-prosthesis interfaces, this study explores the relationship between interfacial stress, slip, and environmental aging in biomedical applications. This research is beneficial for comparing the effects of stress distribution and aging on joint durability and resistance. Wei Tan *et al.* (2021) in comparison, both studies investigate the impact of hygrothermal aging on adhesive joints, focusing on changes in mechanical properties under varying stress states and temperatures. The polyurethane-aluminum study examines butt joints at different angles (0°, 45°, 90°) to simulate normal, combined, and shear stress, while your study centers on edge modifications in aluminum-to-aluminum joints. The polyurethane-aluminum study finds that failure loads are highly sensitive to temperature and stress type, with SEM analysis indicating adhesive hydrolysis as a degradation factor. This study's failure modeling could enhance your work by incorporating stress and temperature variability effects.

The novelty of this study lies in its focused investigation of the mechanical degradation of metal-metal adhesive joints, particularly using the aged epoxy adhesive Adegit A140, under the combined effects of temperature and water absorption. While adhesive joints are widely used in aeronautical structures, the long-term performance and durability under environmental stressors like humidity and temperature variation are less explored. By incorporating finite element modeling to simulate and assess these factors, the study advances the understanding of how environmental degradation impacts joint integrity over time. This work offers valuable insights into the reliability of adhesive bonds in demanding aerospace applications, paving the way for improved design and maintenance strategies.

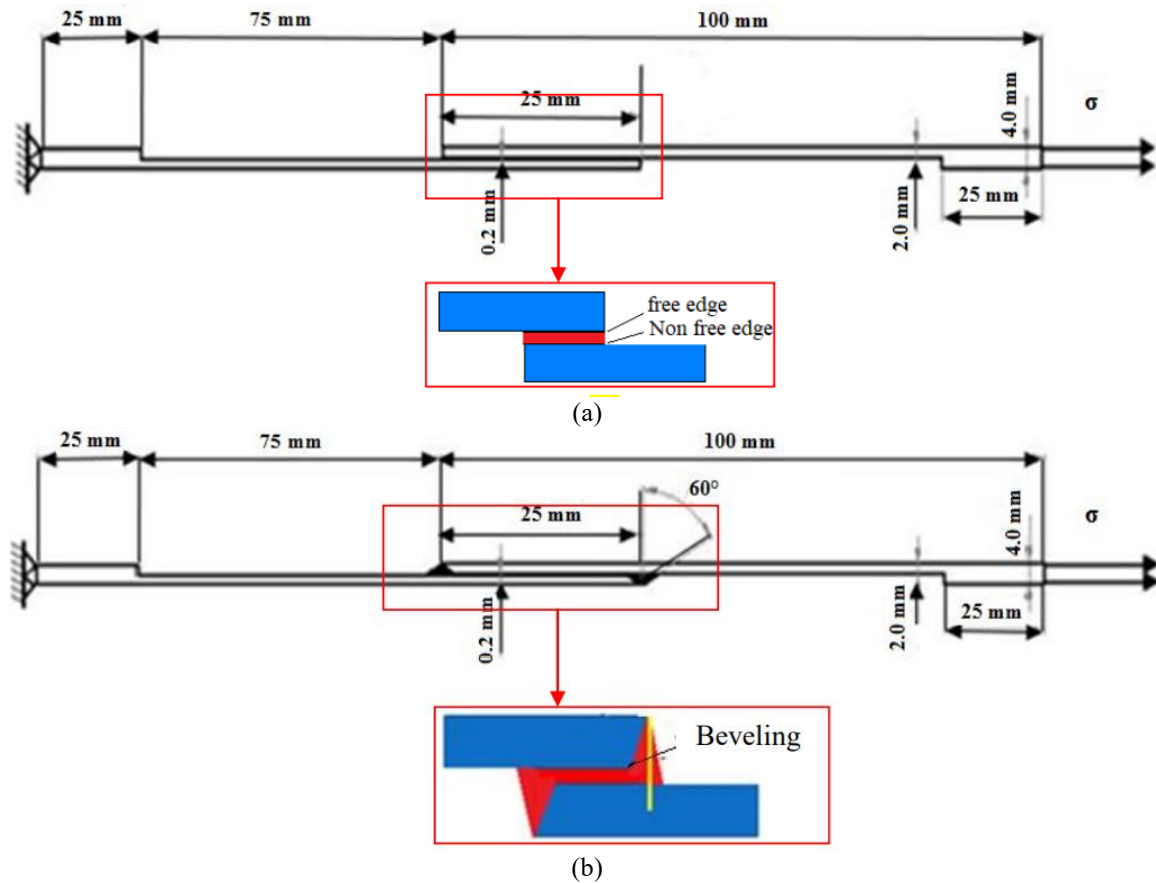


Fig. 1 Finite element geometric model of the plate and the adhesive: a)- without beveling, b)- with beveled

This study focuses on utilizing the mechanical properties of an aged epoxy adhesive, specifically Adekit A140, through a finite element model. The primary objective is to assess the impact of temperature and water absorption on the degradation of the mechanical properties of metal-metal adhesive joints, widely employed in aeronautical structures.

## 2. Finite element model and description of material properties

This study employs a three-dimensional finite element method analysis to assess the stress distribution in the adhesive joint of an Aluminum/Aluminum assembly. The dimensions of the different substrates are depicted in the figure.

This section aims to examine the adhesive's behavior over the aging process, with a specific focus on ductile plate assemblies. This study aims to address the gap in understanding how edge modifications of both the adhesive and the plate influence the overall durability and mechanical performance of adhesive joints under environmental stressors. Unlike previous studies that primarily focused on the bulk adhesive properties or the mechanical response of unmodified joints, this work explores the effects of geometrical alterations at the adhesive-plate interface. These modifications,

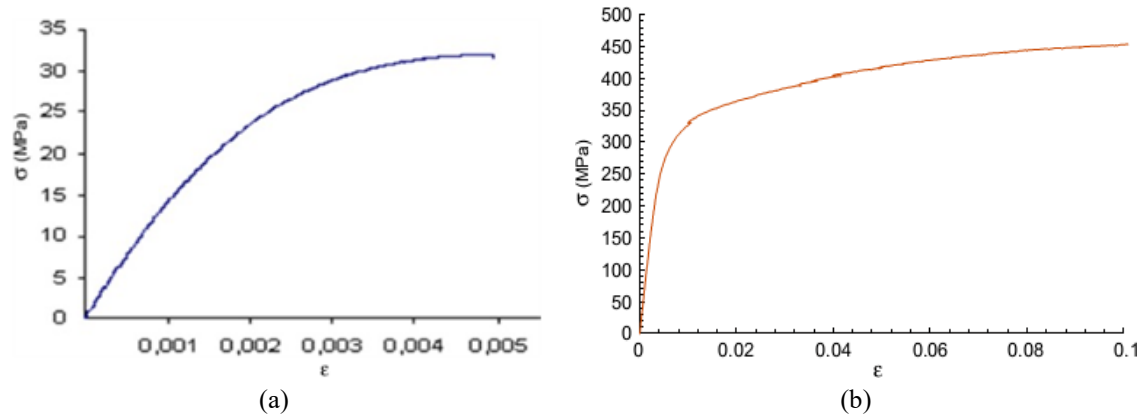


Fig. 2 Tensile stress–strain curve for: a) - adhesive Adekit A140. Madani *et al.* (2007), b)- aluminum plate

Table 1 Mechanical properties of Aluminum 2024-T3 plate and the adhesive Adekit A140

Material	E (Gpa)	G (Gpa)	$\nu$
Adekit A140	2.690	0.99	0.3
Al 2024T3	69	36.92	0.3

which include beveling and bulging of the edges, are expected to have a significant impact on the stress distribution within the adhesive layer, particularly as the assembly undergoes aging.

The geometric model used for this analysis is inspired by the work of Ait Kaci *et al* (2017), as presented in his thesis, which introduced a foundational framework for understanding adhesive joint behavior under mechanical loads. However, our study expands on this framework by incorporating the effects of environmental aging—such as moisture absorption and thermal cycling—on modified joint geometries, providing a more comprehensive view of how these joints behave under real-world conditions. Fig. 1 illustrates the specific geometric changes made to the adhesive and plate, showcasing both with and without edge modifications. By focusing on these edge modifications, this study introduces a novel approach to improving the reliability and longevity of adhesive joints, which is especially critical for applications in aerospace, engineering, and other high-stakes industries. The results are expected to offer new insights into optimizing adhesive joint designs for better performance in harsh environmental conditions.

In this section of the study, we focused on the assembly of Aluminum/Aluminum. Tensile tests conducted on the aluminum 2024-T3 plate and the adhesive ADEKIT A140 provided characteristic curves as shown in Fig. 2. FOULC (2008).

From these two curves, we can extract the mechanical properties of the two materials as presented in Table 1.

### 3. The mesh

Meshing is a crucial process in finite element analysis that involves dividing a complex geometry into smaller units, known as elements or cells, to make the problem more manageable. This discretization allows for the numerical solution of complex problems by breaking them down into

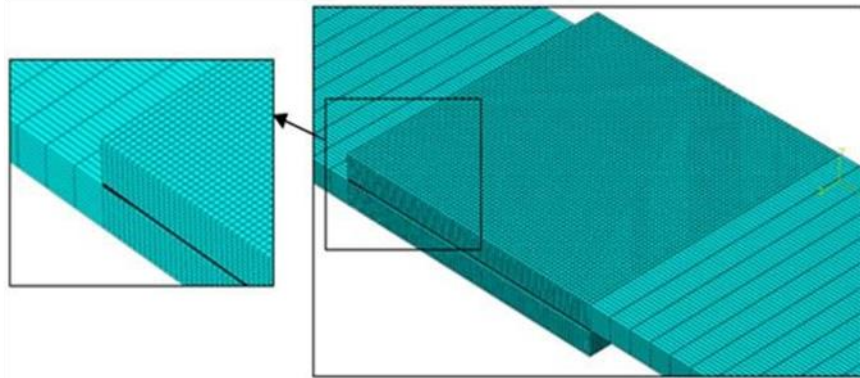


Fig. 3 Mesh refinement in the analysis of a lap joint

simpler components, connected through a system of grids or nodes. During preprocessing, one of the most important tasks is mesh generation, which plays a vital role in defining how accurately the model represents the real-world geometry. Proper meshing requires aligning the domain with elements of specific shapes, such as triangles or quadrilaterals. Triangulation, a well-established method, is commonly used to create meshes with triangular elements, particularly for two-dimensional geometries. This technique is highly automated and available in most preprocessing software, providing a flexible and efficient solution for modeling complex geometries and their boundaries. However, despite the flexibility offered by triangular elements, they come with a disadvantage: simulations using triangular elements often yield lower accuracy compared to those that use quadrilateral elements (Fig. 3).

In this study, the configuration was modeled using C3D10R elements, which are 10-node quadratic tetrahedral elements. These elements provide higher accuracy for capturing stress and strain distributions, particularly in regions with complex geometry or high stress gradients. The aluminum plate model used in this study consisted of a total of 44,764 elements, ensuring comprehensive coverage and detailed resolution of the structural behavior.

A three-dimensional finite element model of such a structure will involve several degrees of complexity. In this study, simplifying assumptions are made, which still allow us to capture the essential features of the response. These assumptions include:

- Each layer considered an individual three-dimensional structure under a state of plane stress,
- Individual layers connected with adhesive bonds,
- The adhesive layer is homogeneous and isotropic,
- The adhesive assumed to deform in shear, tensile, and peel.

#### **4. Comparison between the beveled and normal shape for different temperatures with and without aging of the adhesive**

##### *4.1 Von Mises stress variation*

The analysis of the results by the finite element method of the distribution of Von Mises stresses in the adhesive layer depicted in the figures below:

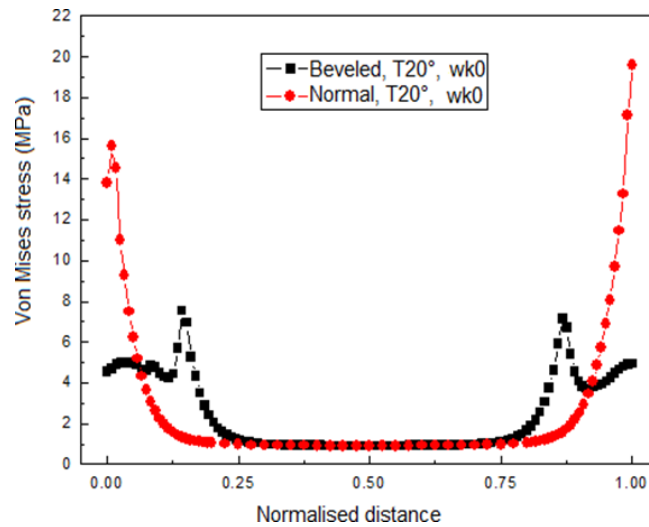


Fig. 4 Comparison between the beveled and normal shape at a temperature of 20°C without aging of the adhesive. (T20: Temperature 20°C, S0: without aging)

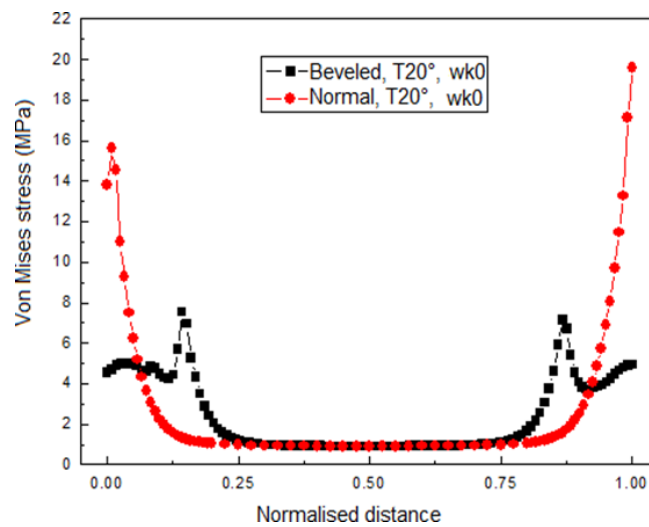


Fig. 5 Comparison between the beveled and normal shape at a temperature of 20°C without aging of the adhesive. (T20: Temperature 20°C, S0: without aging)

#### 4.1.1 Aging at 20°C

Fig. 4 depicts the stress distribution along the overlap length before aging. On observe that the beveled shape of the adhesive significantly reduces the stress value at its edge by almost 50%. A stress peak is noted at point A but remains relatively low compared to the case where the adhesive edge is straight. The core of the adhesive remains inactive in both cases.

In Fig. 5, on note that the stress value is reduced in both cases [normal and beveled]. The exposure of the adhesive to water reduces its strength by decreasing the value of its Young's modulus but increases its ductility. By absorbing water, the adhesive becomes more ductile, and its shear strength

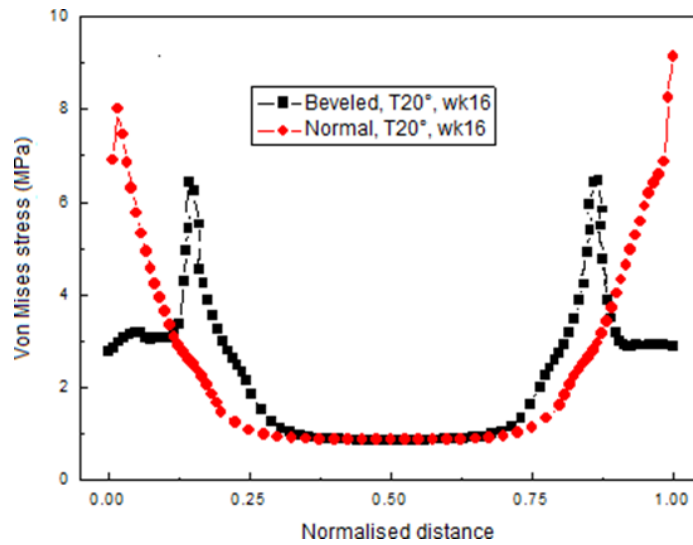


Fig. 6 Comparison between the beveled and normal forms at a temperature of 20°C during the 16th week of aging

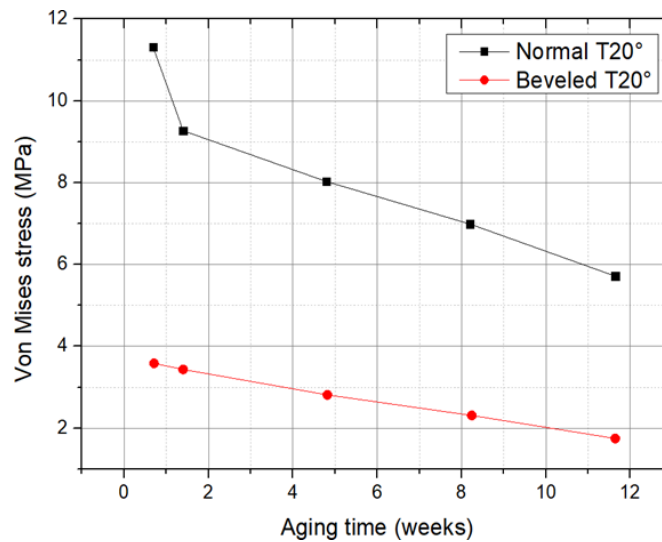


Fig. 7 Variation of the maximum Von Mises stress value as a function of aging duration

improves, providing better resistance to applied loads. Consequently, the Von Mises stress decreases (Fig. 5).

By increasing the aging duration, the core of the adhesive becomes more active. In the case of a non-beveled assembly, the stress value decreases by almost 50% at both the free edge and non-free edge. In contrast, for an assembly with modifications to the edges of the adhesive and the plate, a reduction of 60% is observed at both edges of the adhesive. However, at point A, a slight decrease in the Von Mises stress value is noted. Under the influence of plate bending due to the eccentricity of the two applied forces, stress concentrations will occur at this point.

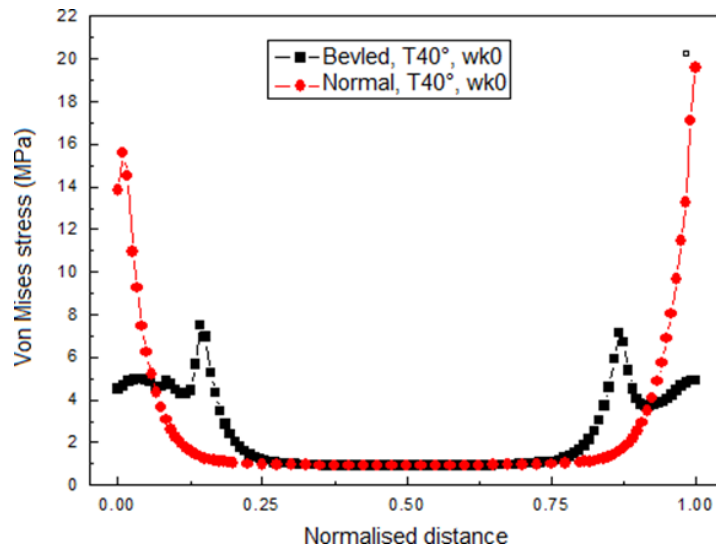


Fig. 8 Comparison between the beveled and normal forms at 40°C without aging of the adhesive

The variation of the maximum Von Mises stress value with aging duration at a temperature of 20°C is depicted in Fig. 6. It is evident that the adhesive's strength improves with increasing aging duration, with a significant drop in stress noted from the early stages of aging. The enhancement of both the edges of the plate and the adhesive results in a reduction in the Von Mises stress, contributing to improved assembly strength and, consequently, an extended service life.

The water absorption by the adhesive makes it more ductile, resulting in higher shear strength compared to tension and consequently lower Von Mises stress values.

At point A, the stress value is not affected by the immersion duration. However, with increasing aging duration, the adhesive becomes increasingly ductile, exhibiting a significant plastic range and improved resistance to applied loads.

The stress value decreases over time for both assembly cases with varying immersion durations. At the edge, the stress value in the assembly with a bead is significantly reduced, albeit by only 2 MPa compared to the non-aged case. In contrast, for the assembly without modification, the stress reduction is 8 MPa after 16 weeks of aging.

#### 4.1.2 Aging at 40°C

Increasing the temperature to 40°C (Fig. 9), the adhesive behaves similarly to the case at 20°C. The stress value is lower in the case of an assembly with a bead and bevel, and stresses are still concentrated at the edge with an inactive core. After one week of aging, the adhesive loses its strength and becomes ductile, offering more resistance to the applied load; however, resulting in low Von Mises stresses.

As the aging duration of the adhesive increases, its internal structure undergoes significant changes, leading to a marked increase in activity within the core. This results in a redistribution of the applied load across a larger portion of the adhesive's overlap area. Consequently, the adhesive becomes progressively more ductile, allowing it to deform more easily under applied stresses. This increased ductility improves its ability to accommodate local stress concentrations, thereby enhancing the overall resistance of the adhesive joint to the external load.

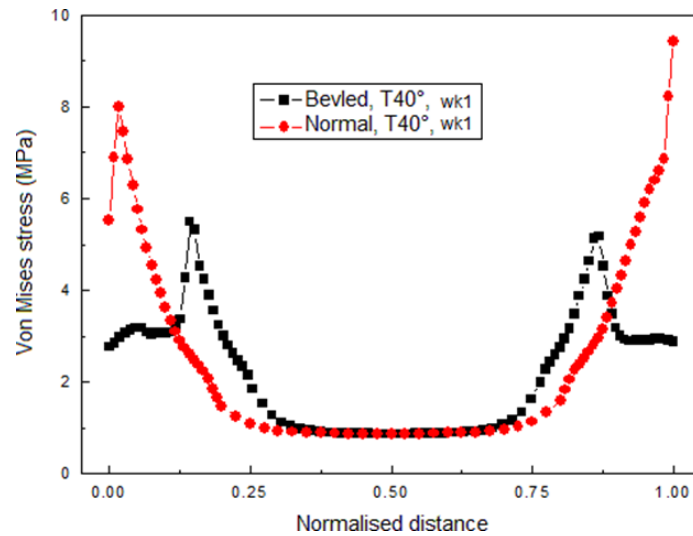


Fig. 9 Comparison between the beveled and normal forms at 40°C during the 1st week of aging

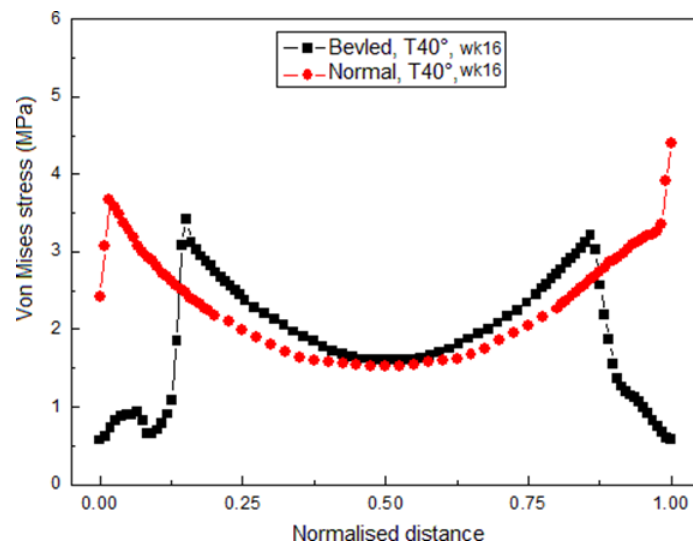


Fig. 10 Comparison between the beveled and normal forms at 40°C during the 16th week of aging

The stress distribution within the adhesive joint reveals that the stress intensity decreases noticeably, especially when comparing joints with beveled edges to those with standard, unmodified edges. Specifically, a substantial stress reduction—nearly 40%—is observed between the beveled and normal configurations of the adhesive and the plate, as shown in Fig. 10. This significant decrease in stress suggests that modifications to the adhesive’s geometry, such as beveling, play a crucial role in mitigating stress concentrations and improving load-bearing capacity.

At this advanced stage of aging, the core region of the adhesive becomes highly active in terms of load-bearing, indicating that the overall stiffness of the adhesive has decreased. This transition to a more ductile state shifts the primary stress-bearing zone from the adhesive’s outer regions to its internal core.

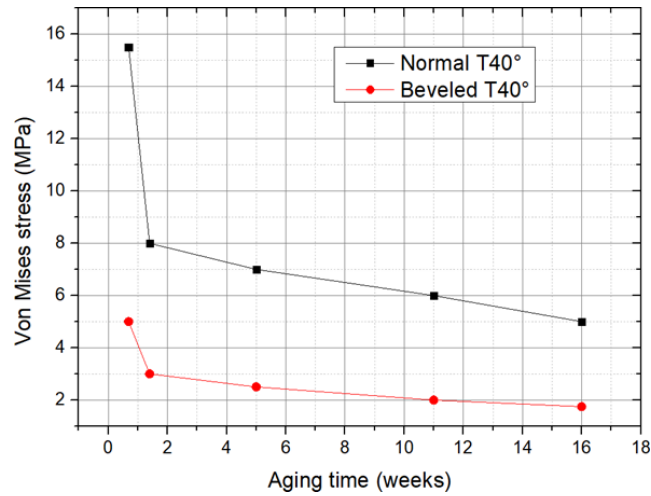


Fig. 11 Comparison between the beveled and normal shapes at a temperature of 40°C

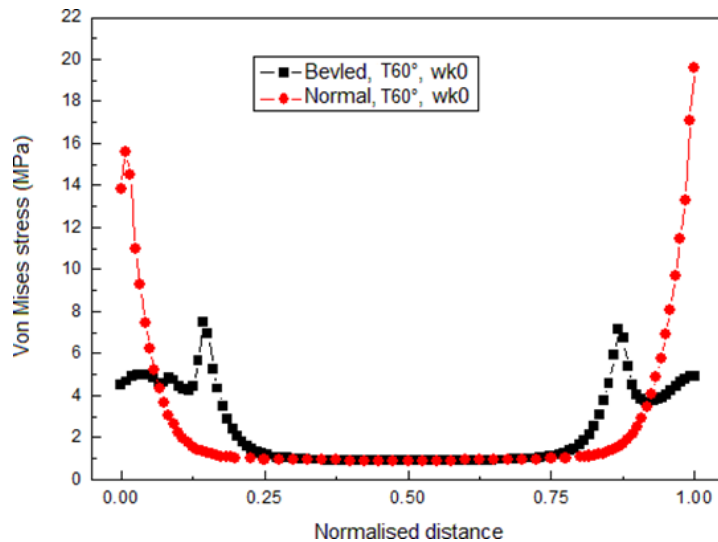


Fig. 12 Comparison between the beveled and normal shapes at a temperature of 60°C without aging

As the aging duration increases, there is a noticeable progressive reduction in the stress values within the adhesive. This decrease in stress is particularly significant when comparing different aging durations under dry conditions. Initially, the stress difference reaches 75%, reflecting a substantial reduction in the adhesive's ability to withstand load. However, as the aging continues, this difference lessens slightly, with the stress reduction stabilizing at 60% after 16 weeks of aging (Fig. 11). This suggests that, over time, the adhesive becomes more ductile, allowing for a redistribution of the load across a larger surface area, which contributes to the overall decrease in stress. These changes highlight the impact of aging on the adhesive's mechanical performance, where prolonged exposure to environmental conditions leads to a more flexible, yet less resistant material. This trend is crucial in understanding how the adhesive's structural integrity evolves over time.

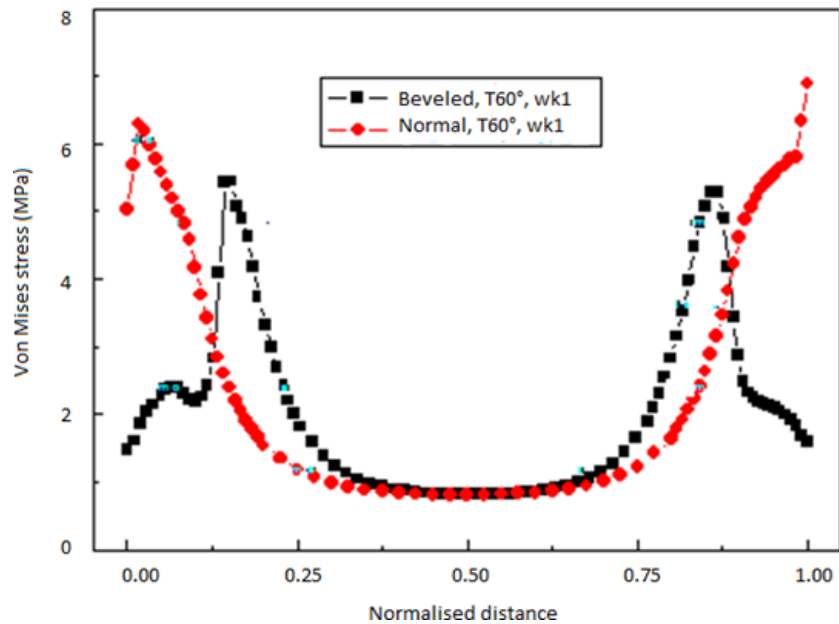


Fig. 13 Comparison between the beveled and normal shape at a temperature of 60°C during the first week of aging

#### 4.1.3 Aging at 60°C

When the temperature rises to 60°C, the adhesive undergoes a significant transformation, losing nearly all of its structural integrity. At this elevated temperature, the adhesive transitions into a rubbery, flexible state, characterized by drastically diminished mechanical properties. Its ability to bear loads or resist deformation is severely compromised, leading to a substantial reduction in strength. This rubbery phase indicates a critical threshold in the adhesive's thermal tolerance, where it can no longer maintain the rigidity required for effective bonding. This temperature-induced degradation is particularly concerning in applications requiring the adhesive to endure high temperatures while preserving its load-bearing capabilities, as it may result in structural failure under operational stresses. Understanding this behavior is essential for predicting the adhesive's performance in environments where temperature fluctuations are a factor.

After one week of aging at a temperature of  $T=60^{\circ}\text{C}$ , it is observed that both assemblies have almost identical stress values with a slight difference. Also, the stressed area is nearly the same along the adhesive section.

The adhesive effectively absorbs a significant portion of the stresses in both assembly cases, and the values are very low at this temperature. At the edges, the stresses in the case of the straight assembly are higher than for the assembly with modifications to both the adhesive and the plate.

At point A, the peak stress exceeds a value of over 100% compared to the free edge. At this location, the adhesive's resistance to peeling is low. The flexibility of the adhesive provides good resistance to the imposed stress.

Fig. 14 shows the stress distribution along the overlap length for both standard (normal) and beveled adhesive joint assemblies. The beveled configuration, with its adhesive fillet, significantly reduces stress at the edges but is more exposed to environmental factors. After 16 weeks of water immersion, the adhesive becomes rubbery, showing high ductility and maintaining good shear

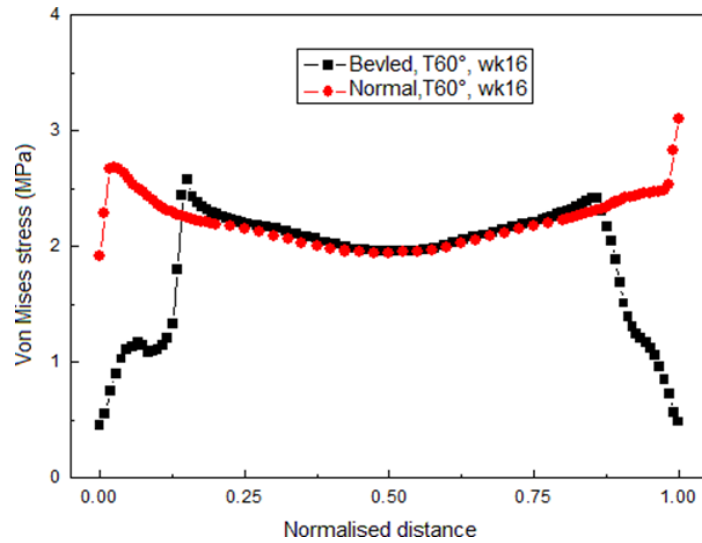


Fig. 14 Comparison between the beveled and normal shapes at a temperature of 60°C during the 16th week of aging

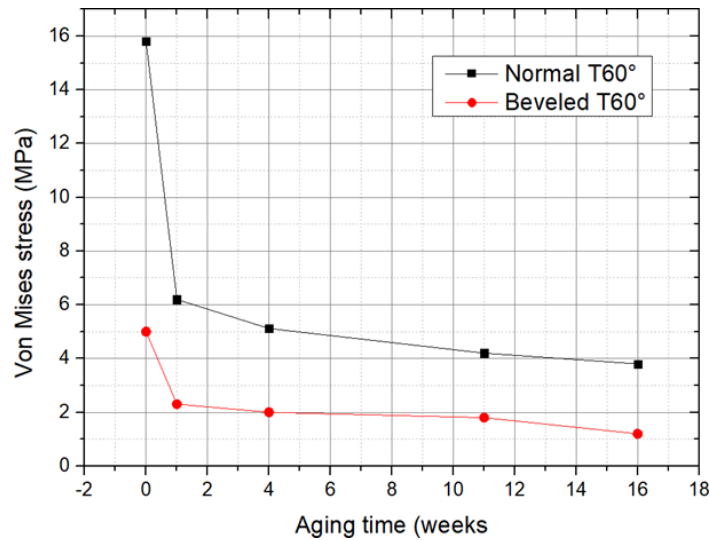


Fig. 15 Comparison between the beveled and normal forms at 60°C temperature

resistance to the applied stresses. This ductility enhances the joint's toughness. Despite the difference in joint shapes, the core of the adhesive experiences similar stress behavior in both configurations. However, the beveled joint consistently exhibits lower stress values across the overlap, making it more effective at managing mechanical loads and reducing stress-induced failures, especially in environments prone to degradation over time.

Fig. 15 displays the maximum Von Mises stress values for both beveled and normal joint configurations as a function of immersion duration at a temperature of 60°C. The results demonstrate that the modified, beveled form of the plate and adhesive consistently exhibits lower Von Mises stress values compared to the normal configuration, irrespective of the aging duration. As the

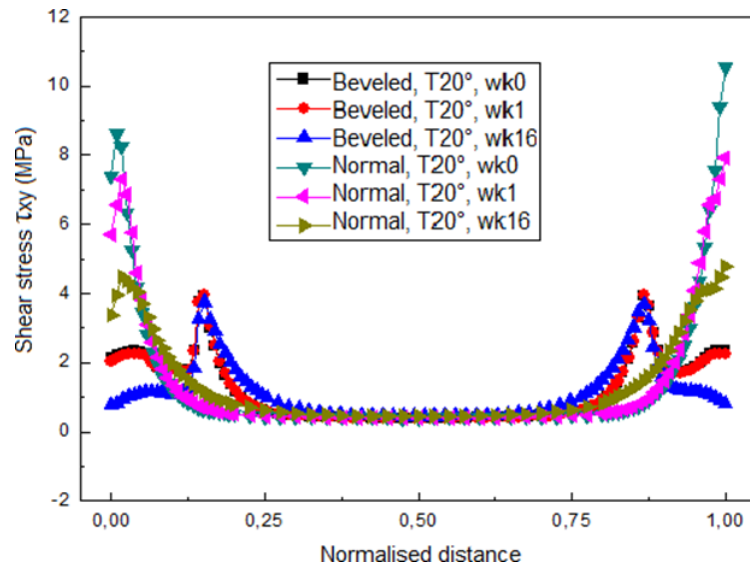


Fig. 16 Comparison of shear stress between the beveled and normal forms at a temperature of 20°C before and after aging

adhesive undergoes prolonged immersion, the stress difference between the two configurations gradually diminishes, indicating that the beveled shape provides superior stress distribution, especially in the early stages of aging. This advantage reduces over time, but the beveled joint remains more resilient in terms of stress management, even after extended exposure to elevated temperatures and water absorption. These findings underscore the effectiveness of edge modifications in enhancing the long-term mechanical performance of adhesive joints under harsh environmental conditions.

#### 4.1.4 Shear stress variation

Fig. 16 illustrates the distribution of shear stress along the overlap length at a temperature of 20°C for different aging durations.

##### a) Aging at 20°C

It is evident that the adhesive in the assembly with beveling and fillet exhibits better resistance compared to the case of the normal assembly (without modification). In this case, the adhesive provides more bonded surface, minimizing stress transfer into the adhesive. The modification of both edges of the adhesive and the plate significantly reduces the bending moment, thereby reducing shear and peel stresses. Shear stress decreases in both assembly cases in the presence of water absorption and aging. This decrease in stress values appears in the first week of adhesive aging. Similarly, for the assembly with modification of the plate and adhesive edges, there is a peak of over-stress at point A, which has higher shear stress values than at the edge.

Fig. 17 highlights the comparison between the normal and beveled configurations, emphasizing the impact of edge modifications in both the plate and adhesive, as well as the effect of aging duration on shear stress values. The results reveal that for the beveled form, the aging process has minimal influence on the shear stress values, maintaining a stable performance even as the adhesive is exposed to extended environmental conditions. In contrast, the normal assembly experiences a

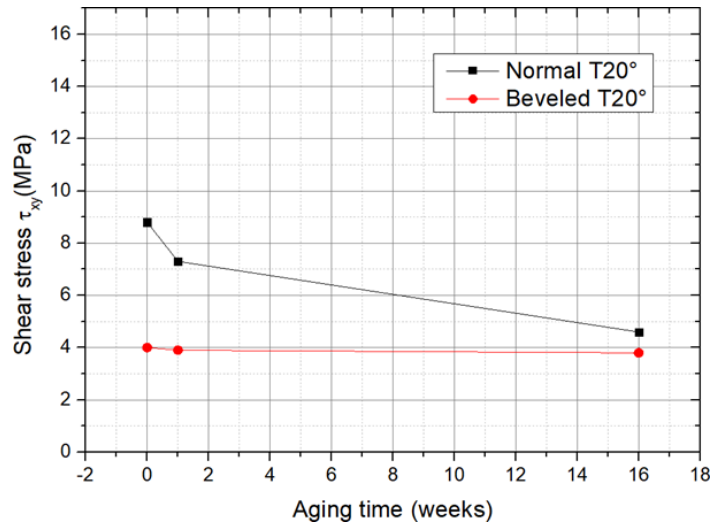


Fig. 17 Comparison of shear stress between the beveled and normal forms at a temperature of 20°C before and after aging

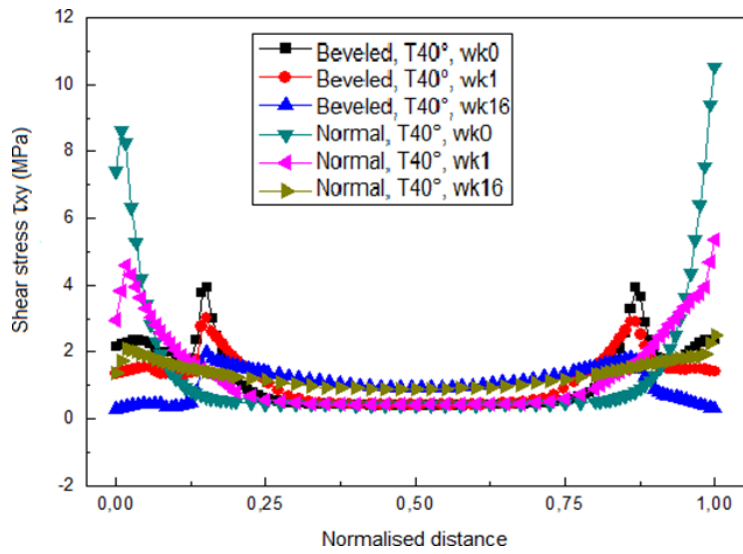


Fig. 18 Shear stress comparison between the beveled and normal forms at a temperature of 40°C before and after aging

significant increase in shear stress as the aging duration extends, indicating a marked sensitivity to environmental degradation. Over time, the difference in shear stress between the normal and beveled forms gradually decreases, but the beveled configuration consistently demonstrates better resistance to stress. This suggests that the beveled joint offers superior durability and performance in resisting shear forces, particularly in aging environments, compared to the normal assembly. The edge modification in the beveled form helps mitigate the adverse effects of aging, preserving the structural integrity of the adhesive joint over time.

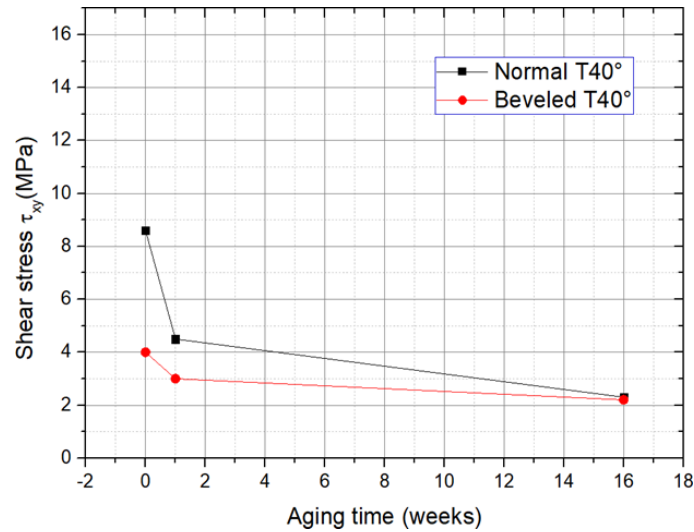


Fig. 19 Comparison of shear stress between the beveled and normal forms at a temperature of 40°C before and after aging

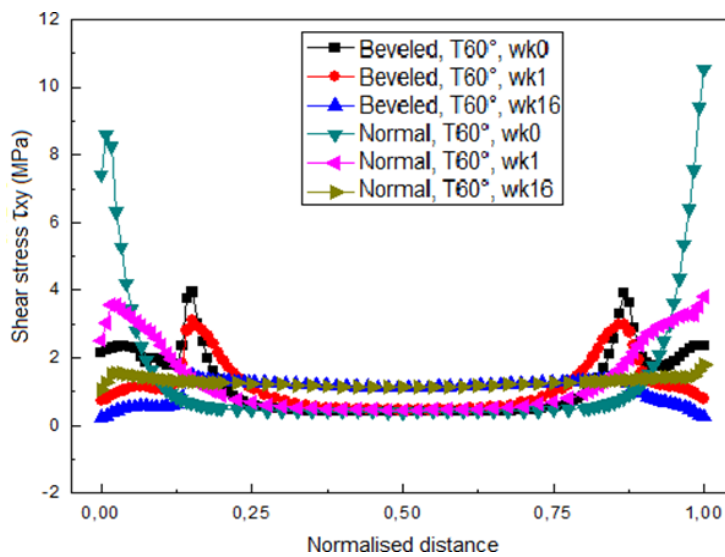


Fig. 20 Comparison of shear stress between the beveled and normal forms at a temperature of 60°C before and after aging

*b) Aging at 40°C*

Fig. 20 present a comparison between the maximum shear stress values for both assembly cases as a function of aging duration and temperature.

*c) Aging at 60°C*

In Figs. 18 and 20, the influence of aging temperature on shear stress is evident for both 40°C and 60°C. As the temperature increases, shear stress values decrease significantly in both the normal

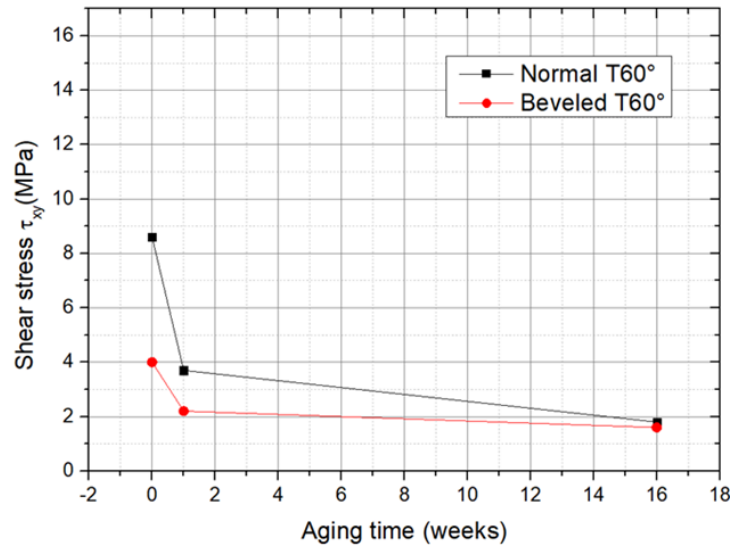


Fig. 21 Comparison of shear stress between the beveled and normal forms at 60°C before and after aging

and beveled assemblies. In the beveled assembly, the shear stress remains nearly constant along the overlap length despite rising temperatures, with only a slight variation at point A, showcasing its resistance to temperature-induced degradation. Conversely, in the normal assembly, the increase in aging temperature and duration leads to a marked reduction in shear stress, reaching very low values, which indicates a significant weakening of the adhesive bond. This contrast demonstrates the beveled assembly's superior ability to maintain consistent adhesive performance under thermal and environmental stresses compared to the normal assembly.

It is noticeable that the shear stress significantly decreases with the aging duration, with the normal assembly exhibiting the highest values of this stress. The difference between the shear stress values of the two assemblies is well observed, and this difference decreases as the aging duration increases, eventually disappearing completely by the 16th week of aging.

## 5. Conclusions

This study focuses on the effect of adhesive aging at various temperatures on the strength in a single lap joint assembly of Aluminum/Aluminum. The results from numerical analysis have led us to the following conclusions:

- The research suggests that altering both the edges of the adhesive and the aluminum plate is an effective strategy for reducing various stresses within the adhesive joint. This modification likely involves changes in geometry or surface treatment to optimize the bonding interface.
- The presence of an adhesive fillet, an additional layer of adhesive material that forms a rounded profile along the edges of the joint, appears to contribute positively to the assembly's strength. The fillet increases the bonding surface, leading to an overall improvement in the strength of the joint.
- The study indicates that a significant portion of the stresses experienced by the joint are initially transferred to the adhesive. However, over each aging period, these stresses are substantially reduced. This reduction in stresses may be attributed to the aging process or other mechanisms that alleviate

the load on the adhesive over time.

- Aging the adhesive in a water immersion environment seems to have specific effects on its mechanical properties. The study notes a decline in mechanical strength after aging in water, accompanied by a substantial increase in ductility. The post-aging mechanical properties, characterized by improved resistance to shear and peel in the single lap joint assembly, suggest that water immersion aging may have a positive impact on the adhesive's overall performance.

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