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Effects of adhesive layer thickness and adhesive fillet on creep behavior of automotive bonded joints subjected to sustained tensile loads

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Adhesively bonded joints are a highly effective method for achieving lightweight structural designs, yet assessing their long-term durability remains a significant challenge. Creep, a time-dependent effect caused by sustained mechanical loads, can result in viscous strain within adhesive materials, potentially leading to crack formation in bonded structures over extended periods. This study investigates the creep behavior of adhesive joints under sustained tensile loads, focusing on the effects of adhesive layer thickness and the presence of adhesive fillets. Creep tests conducted over 48 hours revealed that higher load levels result in greater strain accumulation, with thicker adhesive layers showing increased susceptibility to deformation. Additionally, joints with adhesive fillets demonstrated lower creep strain, indicating enhanced resistance to sustained loads. These findings emphasize the importance of adhesive layer thickness and fillet design in optimizing the long-term performance and durability of bonded joints, offering valuable insights for applications where creep resistance is critical for joint reliability and service life.

1. Introduction

In recent years, adhesively bonded joints have emerged as a viable alternative to traditional joining techniques like welding, riveting, and bolting, offering numerous advantages [1–6]. For example, the uniform distribution of the adhesive layer across the bonded area reduces stress concentration—a factor present in other joining techniques—resulting in minimal structural damage due to applied loads. Additionally, unlike methods such as welding, adhesive joints enable the joining of a wide range of materials, including both similar and dissimilar ones.

Furthermore, adhesive joints demonstrate higher fatigue life [7] and superior vibration absorption compared to other joining methods. Given these benefits, adhesive joints play an essential role in various industrial sectors, including automotive and aerospace, particularly in vehicle structure construction [8,9].

In the automotive industry, adhesives are crucial for joining vehicle components [10]. Stiff adhesives contribute to high structural rigidity, resisting deformation and ensuring stability in critical areas such as chassis elements. In contrast, flexible adhesives provide elasticity, allowing movement and vibration absorption, making them ideal for components subjected to variable stresses, such as body panels and interior parts.

A critical aspect of adhesive joints is the examination of their durability or long-term behavior [11]. As polymer materials, adhesives exhibit viscoelastic behavior, meaning that over time, under external loads or deformations, the stress-strain distribution within the joint becomes time-dependent, leading to strength degradation. Creep, a time-dependent phenomenon, can occur

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in adhesives under sustained static loads, even at room temperature. This results in a time-dependent increase in strain, which can accelerate at elevated temperatures. Consequently, the gradual increase in strain can lead to premature creep failure in the joint, even at stress levels below the allowable joint stress.

The creep response in adhesive joints is influenced by several factors, including the creep load level and creep duration. The creep load level is defined as a percentage (less than 100%) of the ultimate strength applied to the adhesive joints during a specified time, known as the creep duration. According to past literature, creep as a time-dependent phenomenon can induce structural damage within the adhesive materials of bonded joints over time. This means that during creep loading, the residual mechanical properties of adhesive joints may change, rather than simply reflecting the mechanical strength measured in quasi-static tests. This alteration often appears as a reduction in residual mechanical properties, such as strength and strain.

To date, studies have mainly focused on measuring the residual mechanical properties of single-lap adhesive joints subjected to shear stress. For example, Nguyen et al. [12] measured the ultimate bond strength of CFRP-Steel single-lap adhesive joints under a creep load level equal to 20% of the joint's instantaneous failure load, observing a 30% reduction in ultimate bond strength due to creep damage.

In another study, Agarwal et al. [13] reported that the residual shear strength of CFRP-Steel single-lap adhesive joints initially decreased and then increased as the creep load level rose from 30% to 50% of the instantaneous failure load.

A review of the literature reveals that, to date, no systematic study has investigated the effects of sustained tensile loads on the creep behavior of adhesive joints. Furthermore, prior studies have highlighted the substantial influence of joint geometrical parameters, such as adhesive layer thickness and adhesive fillet, on the mechanical performance of bonded joints. Thus, this study aims to address this gap by examining the tensile creep behavior of adhesive joints, specifically considering variations in adhesive layer thickness and the presence of an adhesive fillet. The results demonstrate that, similar to quasi-static loading conditions, both adhesive layer thickness and adhesive fillet significantly affect the creep behavior of bonded joints.

2. Experiments

To evaluate the bond strength of adhesive joints under tensile creep loading, the butt joint specimen specified in the ASTM D2029 standard [14] has been selected. The geometry and loading setup for this specimen are illustrated in Figure 1. As shown, the specimen consists of two metallic substrates (aluminum in this case) joined by a thin layer of adhesive (Araldite 2015).

The mechanical properties of both the aluminum substrates and adhesive are provided in Table 1. Additionally, the tensile creep load is applied by exerting concentrated loads on either side of the substrate using loading jigs, as depicted schematically in Figure 2. The schematic of the quasi-static and creep tests are also given in Figure 3. The complete schedule of applied creep load levels and corresponding durations is presented in Table 2. It should be noted that the strain was measured by attaching an extensometer to the specimen.

Table 1. Material properties of the adhesive aluminum substrate.

Properties	Aluminum alloy	Adhesive
Young's modulus, *E* (GPa)	70	1.85
Poisson's ratio, ν	0.33	0.33
Tensile failure strength, (MPa)	…	21.63

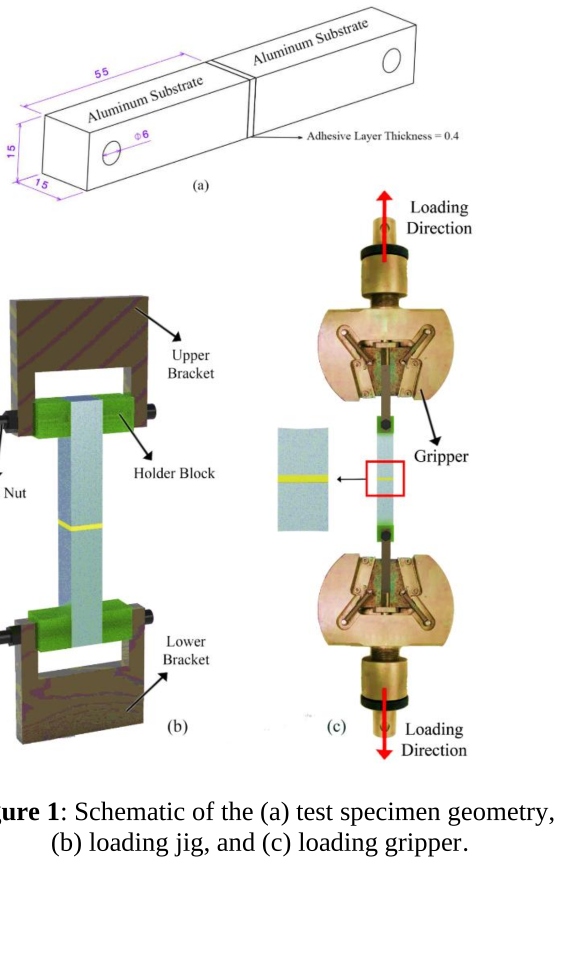

Figure 1: Schematic of the (a) test specimen geometry, (b) loading jig, and (c) loading gripper.

Table 2. Creep tests scenarios.

Creep duration (hour)	48		
Creep load (% static strength)	20%, 40%		
Adhesive layer thickness (mm)	0.4	0.8	1.5

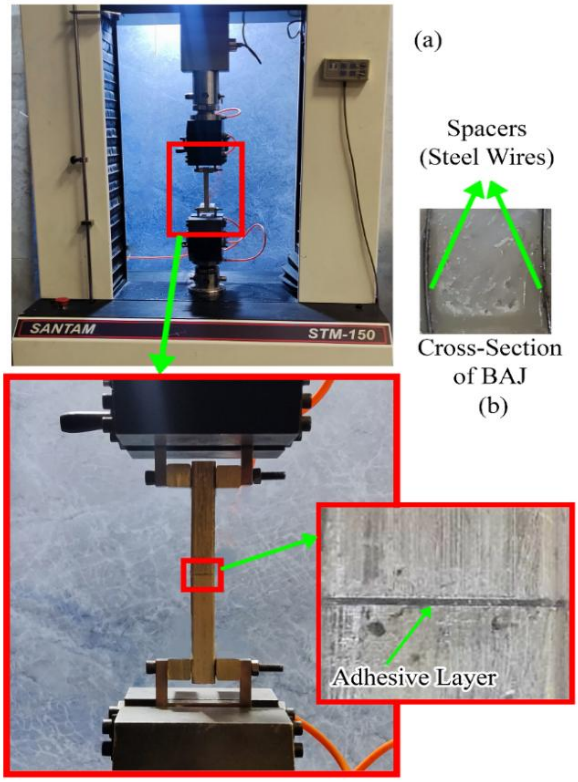

Figure 2: The configuration and loading mechanisms of the universal test machine.

3. Results and discussion

Figure 4 presents the experimental strain-time response of adhesive joints subjected to creep testing. The tests were performed over a constant creep duration (i.e. 48 hours) and under multiple load levels (ranging from 20% to 40% P-max), with adhesive layer thicknesses specified in Table 2. This figure provides insights into how different adhesive thicknesses respond under sustained tensile loads, highlighting trends in strain accumulation over time. As shown in Figure 4, higher creep load levels consistently result in greater strains within the same testing period, regardless of adhesive layer thickness. This indicates a direct correlation between the applied load percentage of P-max and the strain magnitude in the adhesive joints.

For instance, in specimens tested over a 48-hour period, the final strain (which includes elastic, primary, and secondary strain components) ranges from 0.0053 mm/mm to 0.0083 mm/mm, 0.0062 mm/mm to 0.0088 mm/mm, and 0.0079 mm/mm to 0.0126 mm/mm for adhesive layer thicknesses of 0.4 mm, 0.8 mm, and 1.5 mm, respectively, as the creep load level increases from 20% to 40% of P-max. This demonstrates that thicker adhesive layers exhibit varying strain responses under increased load levels, suggesting that both load intensity and adhesive thickness play crucial roles in the creep behavior of bonded joints.

The effects of adhesive layer thickness on the strain-time curves are illustrated in Figure 5. As shown in this figure, adhesive layer thickness significantly influences the creep behavior of bonded joints, with thicker adhesive layers exhibiting greater creep strain at each tested load level. This suggests that the ability of the adhesive layer to resist deformation under sustained loads decreases as its thickness increases.

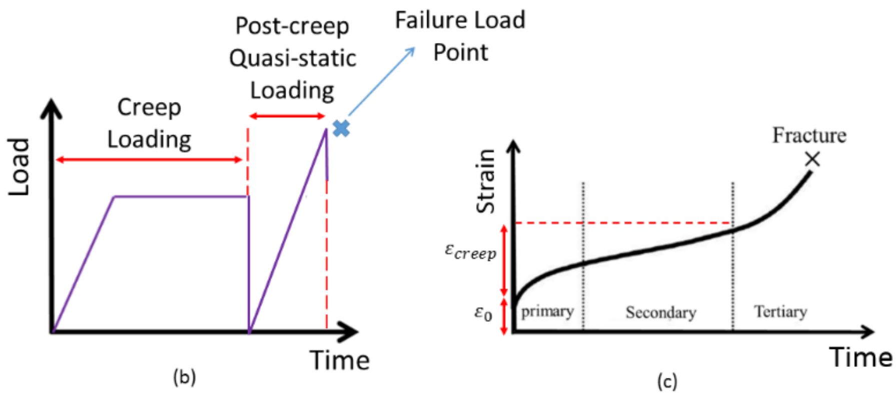

Figure 3: Schematic of the quasi-static and creep tests.

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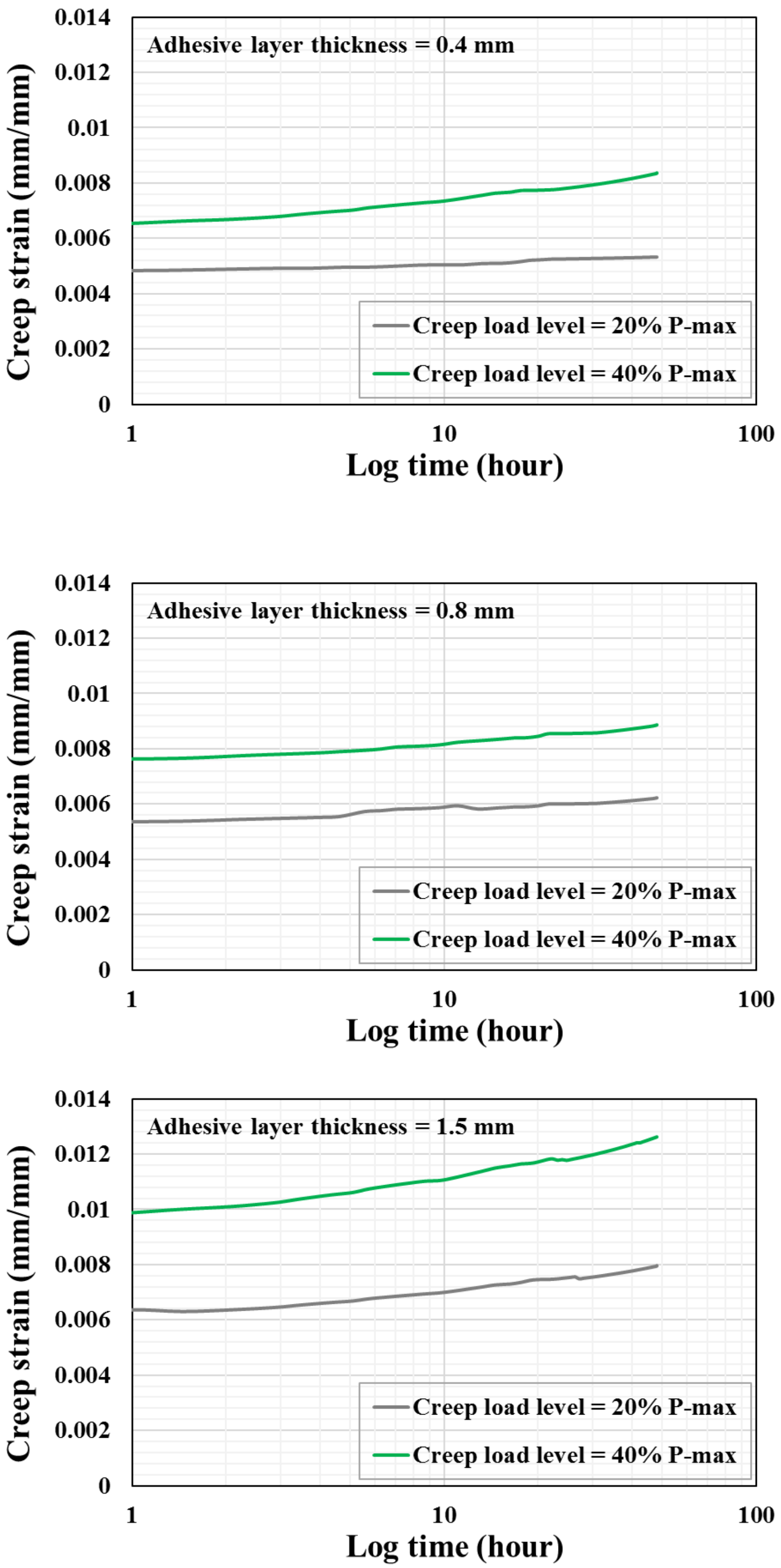

Figure 4: Strain-time curves for each tested adhesive layer thickness.

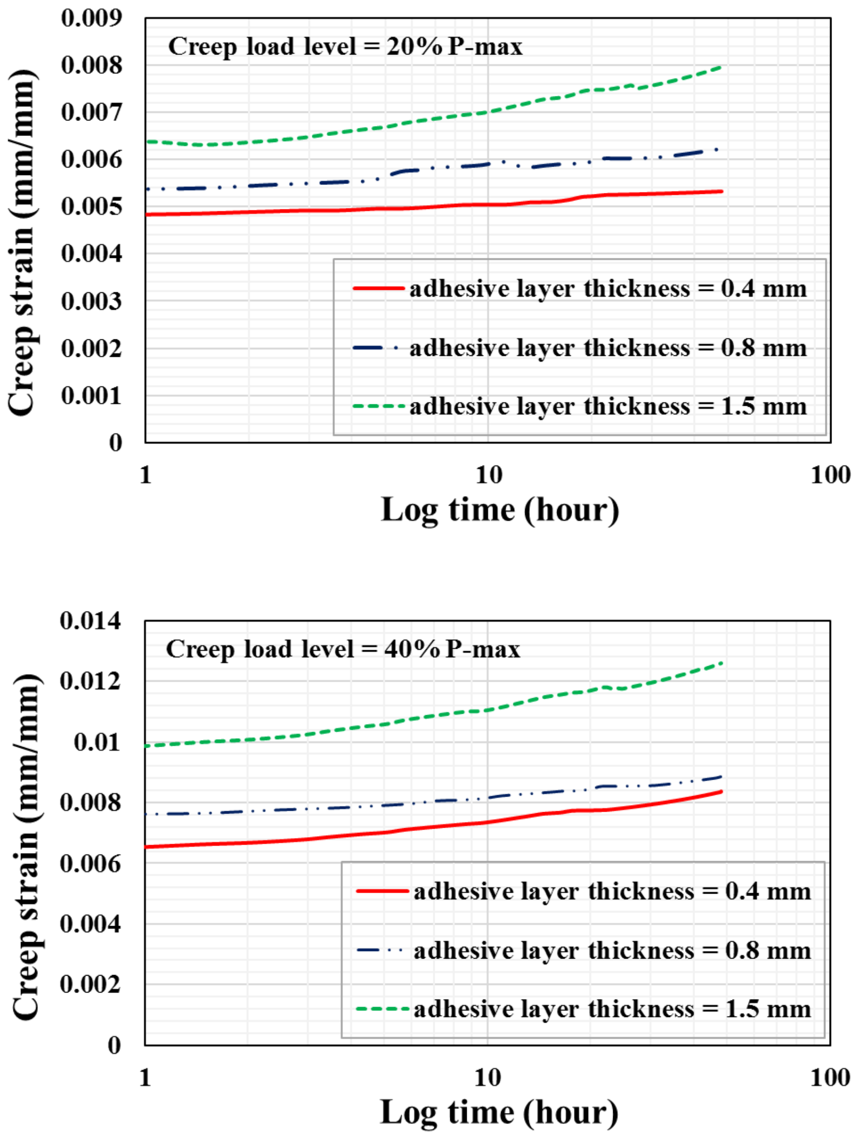

Figure 5: Strain-time curves for each tested creep load level.

For example, in specimens tested over a 48-hour period, the final strain (including elastic, primary, and secondary strain components) varies with both load level and adhesive thickness. Specifically, at a creep load level of 20% P-max, the final strain ranges from 0.0053 mm.mm to 0.0079 mm.mm as the adhesive thickness increases from 0.4 mm to 1.5 mm. Similarly, at a 40% P-max load level, the strain ranges from 0.0083 mm/mm to 0125 mm/mm over the same thickness range. These findings demonstrate that thicker adhesive layers are more susceptible to creep deformation, particularly under higher load levels. This emphasizes the need to carefully select adhesive thicknesses when designing bonded joints for applications involving prolonged tensile loads, as thicker layers may lead to increased creep strain over time, potentially affecting joint durability and performance. This trend was also observed in the research conducted by Zehsaz et al. [15].

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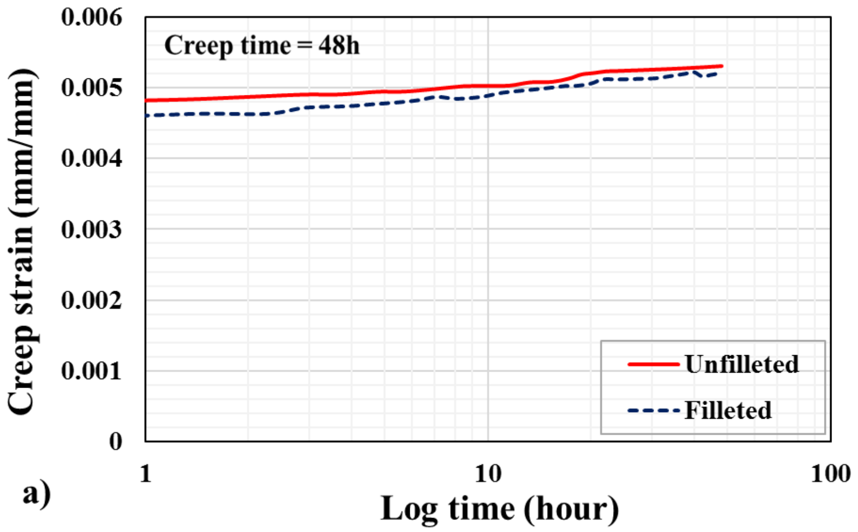

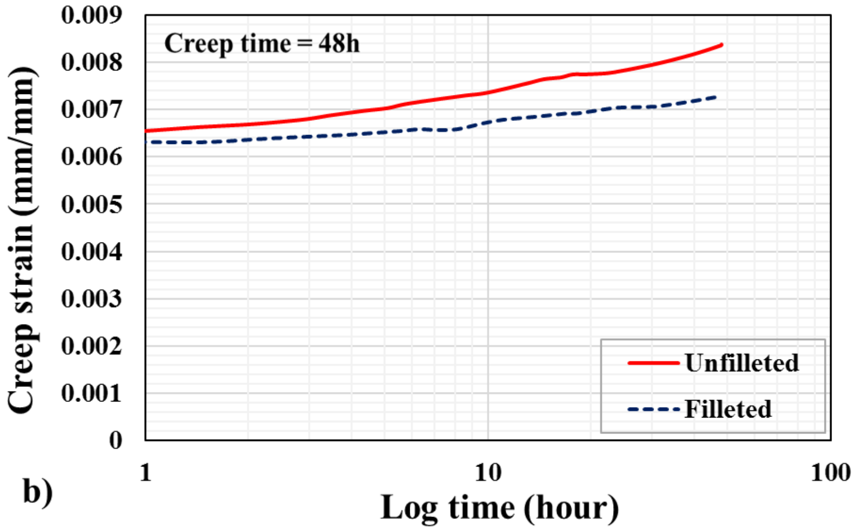

Figure 6: Effect of adhesive fillet on strain-time curves for each tested creep load level: (a) 20% P-max, and (b) 40% P-max

To examine the effect of adhesive fillets on the creep behavior of bonded joints, additional tests were conducted on joints constructed with a 0.4 mm adhesive layer thickness that included an adhesive fillet. As shown in Figure 6, the presence of an adhesive fillet has a substantial impact on the strain-time response of the joints, with filleted joints demonstrating lower creep strain compared to un-filleted joints.

This indicates that adding an adhesive fillet improves the joint's resistance to deformation under sustained loads, suggesting a beneficial effect on the durability of the adhesive layer.

Moreover, it should be noted that this finding aligns with the results of Zehsaz et al. [15], who observed similar trends in their investigation of single-lap adhesive joints subjected to sustained shear loads. In their study, joints with adhesive fillets exhibited reduced creep strain over time, highlighting the reinforcing effect of fillets in adhesive joints under continuous loading conditions.

The results from both studies underscore the importance of adhesive fillet design in applications requiring long-term load-bearing capacity. Incorporating fillets can enhance the overall creep resistance of the joint, offering potential improvements in the structural integrity and service life of bonded assemblies.

It is concluded that the presence of an adhesive fillet reduces creep in the adhesive layer by redistributing stress and minimizing stress concentrations at critical regions, such as edges or corners. Fillets provide a smoother transition of stress across the adhesive joint, reducing peak stresses that can accelerate creep deformation. Additionally, the increased volume of adhesive in the fillet enhances load-bearing capacity, improving the joint's resistance to time-dependent deformation. This geometric modification effectively delays creep-induced failure mechanisms in the adhesive layer.

4. Conclusions

In conclusion, the study highlights the significant effects of adhesive layer thickness and adhesive fillets on the creep behavior of bonded joints under sustained tensile loads. The results indicate that thicker adhesive layers are more prone to creep deformation, especially as load levels increase. This suggests a trade-off between layer thickness and creep resistance, emphasizing the need for optimized adhesive layer selection in joint design. Additionally, the inclusion of adhesive fillets substantially reduces creep strain, improving the joint’s resistance to long-term deformation. The beneficial role of adhesive fillets in enhancing durability was consistent with findings by Zehsaz et al. [15], further supporting their application in load-bearing joints. Together, these results underscore the importance of adhesive geometry in enhancing joint performance and longevity, providing valuable insights for designing bonded joints with improved creep resistance. It should be noted that the type of creep loading (tensile vs. shear) could significantly influence creep failure time due to variations in stress distributions and deformation mechanisms. Therefore, future studies should explore other types of creep loading, such as mixed-mode tensile/shear.

In addition, Creep loading can alter the flexibility and stiffness of joints over time. Prolonged exposure to creep loading can cause time-dependent deformation in joint materials, leading to changes in their mechanical properties. For instance, sustained tensile creep loading may reduce stiffness due to material softening, while shear creep could lead to increased joint flexibility as deformation accumulates. These effects are highly dependent on the material properties, loading conditions, and environmental factors.

The creep tests in this study were conducted at room temperature. It is evident that post-creep effects can influence the creep behavior of adhesive joints, and this phenomenon can be explored in future studies.

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