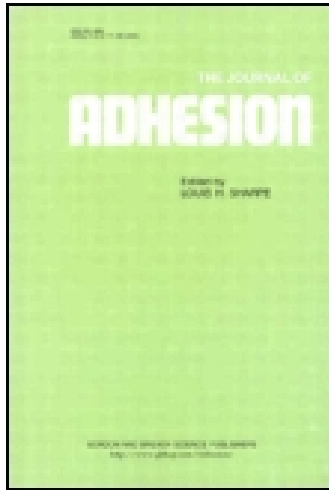


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# Effects of Temperature and Hole Drilling on Adhesively Bonded Single-Lap Joints

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*In this study, the load-carrying capacity of a single-lap joint bonded by an adhesive was determined experimentally. Glass fiber-epoxy composite material was chosen as adherends and Loctite<sup>®</sup> 9466 A&B2 was used as adhesive. The vacuum assisted resin infusion method (VARIM) was used to manufacture composites. In this experimental study, the effects of hole drilling and temperature were investigated. Five hole configurations and three temperatures (room temperature, 50°C, and 80°C) were considered. The results show that hole drilling elevate the failure load and when the temperature increases the load-carrying capacity decreases.*

**KEYWORDS** Hole drilling; Lap-shear; Stress analysis; Surface modification; Temperature

## 1. INTRODUCTION

Composite materials have been greatly used in engineering applications thanks to their high strength-to-weight ratio. Composite materials often require assembling their components together by using bonded or mechanically fastened joints and these joints are subjected to a wide range of environmental effects such as temperature and moisture. Adhesively

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bonded joints are increasing alternatives to mechanical joints in engineering applications and provide many advantages over conventional mechanical fasteners [1].

The thermal effects are important in adhesively bonded joints because these generally lead to reduce the joint strength. For example, Banea and da Silva [2] studied the temperature effect on the performance of two different adhesive types. They found that the lap-shear strength of adhesives was affected by temperature. Wang and Kelly [3] investigated the temperature effect on adhesive bonded double-lap joints. The environmental conditions were chosen as room temperature-dry and hot-wet. The tests were made with different speeds, and strength of the joints and failure patterns were presented. Grant et al. [4] investigated single-lap joints behaviors in tension and three point bending at  $-40^{\circ}\text{C}$ ,  $+20^{\circ}\text{C}$ , and  $+90^{\circ}\text{C}$  experimentally and numerically. They showed that the failure load of lap joints under tension at both  $+90^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$  are less strong than joints tested at  $+20^{\circ}\text{C}$ . Banea and da Silva [5] performed an experimental study to determine the effects of temperature, adhesive thicknesses, and the overlap length on the lap-shear strength. They found that the lap-shear strength of the RTV (room temperature vulcanizing) silicone adhesives was affected by the temperature. On the other hand, the adhesive RTV106 (high temperature acetoxo adhesive sealant) showed a better behavior at high temperatures than the adhesive AS1805 (high temperature thixotropic adhesive sealant). They also showed that the failure load decreased when the bondline thickness increased. Deb et al. [6] studied the mechanical behavior of adhesively bonded joints with the help of double-lap-shear (DLS) coupon tests conducted at different extension rates and temperatures. They found that the effect of increasing extension rate at a given temperature is generally to increase the failure load while simultaneously decreasing the joint ductility. Sayman et al. [7] investigated adhesively bonded single-lap joints under different temperatures and transverse impact energies. They observed that when the temperature increase the strength of joints decreases.

Another important effect on the joint strength is adherend modification. Researchers focused on the adherend modification to increase the strength of the joint. Hai and Mutsuyoshi [8] studied the structural behavior of double-lap joints steel plates bolted and bonded to hybrid CFRP/GFRP (carbon fiber reinforced plastics/glass fiber reinforced plastics) laminates. They investigated two types of joints, namely bolted joints and hybrid joints (bonded and bolted). Pinto et al. [9] analyzed the effect of hole drilling in the adherends on the strength of single-lap joints, experimentally. They used two different adhesives with varying adherend thickness, layout, and diameter of hole. They found that the joints strength never increases from the un-modified condition, showing a varying degree of weakening, depending on the selected adhesive and hole drilling configuration. Tong [10] and Cheuk and Tong [11], studied the failure modes of bonded laminated

composites, containing cracks, under tensile loading, experimentally and numerically. It was shown that the embedded crack can significantly reduce the failure load of the joints.

In this study, adhesively bonded composite single-lap joints were investigated experimentally at different temperatures (room temperature, 50°C, and 80°C) and holes were drilled in the overlap area with four different orientations in order to investigate the effect of hole drilling. Failure modes were also investigated. Glass fiber reinforced epoxy composite materials were used as adherends and Loctite<sup>®</sup> 9466 A&B was used as adhesive.

## 2. EXPERIMENTAL STUDY

### 2.1. Materials

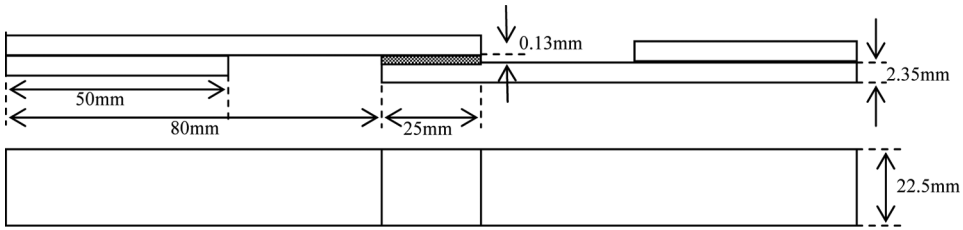
Loctite<sup>®</sup> 9466 A&B epoxy based adhesive manufactured by Henkel Ltd (Hertfordshire, UK). was used as the adhesive. The adhesive was cured at room temperature for 24 hours. The mechanical properties of the adhesive, retrieved from datasheets, are shown in Table 1. The adherend composite material used in the experiments was manufactured with the vacuum assisted resin infusion method (VARIM). The adherend was manufactured using six layers of plain weave glass fabric. Glass fiber of which density was 500 g/m<sup>2</sup> and an epoxy were used in the manufacturing. Araldite LY 564/Aradur 3487 BD hot curing epoxy system which manufactured by Huntsman (Basel, Switzerland) were used. Curing was performed on a specially designed heating table at 80°C for 8 hours. A peel ply was used on the upper surface to obtain a rough surface, to provide a good adhesion. In this study, the adhesive was applied on the rough surfaces. A series of tests according to ASTM D3039, ASTM D5641, and ASTM D7078 were conducted to find the mechanical properties of the composite adherend. The properties

**TABLE 1** Properties of the Adhesive

Tensile strength	Peel strength	Service temperature range	Glass transition temperature	Maximum tensile strain
32 MPa	8 MPa	-55°C to +120°C	62°C	% 3

**TABLE 2** Properties of the Adherend

Elastic modulus in fiber direction	Elastic modulus in transverse direction	Tensile strength in fiber direction	Tensile strength in transverse direction	Compressive strength in fiber direction	Compressive strength in transverse direction	Poisson ratio	Shear modulus	Shear strength
$E_1$ 22.3 GPa	$E_2$ 21.3 GPa	$X_t$ 406 MPa	$Y_t$ 346 MPa	$X_c$ 233 MPa	$Y_c$ 210 MPa	$\nu_{12}$ 0.16	$G_{12}$ 3080 MPa	$S$ 65 MPa

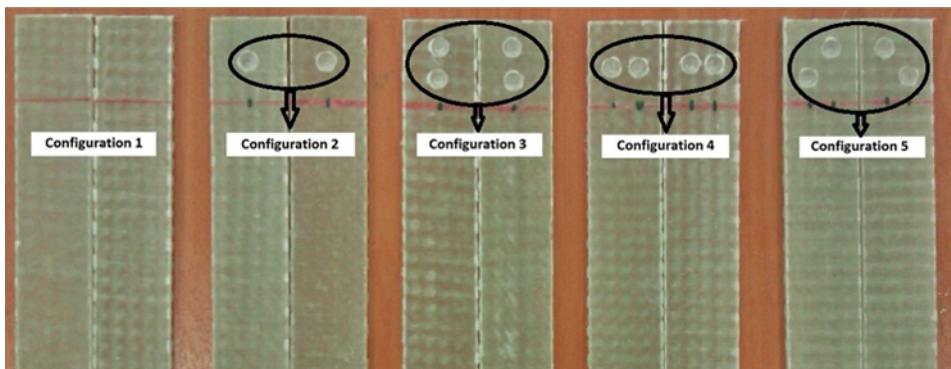


**FIGURE 1** Schematic view of the specimen.

of adherends and dimensions of single-lap joints are given in Table 2 and Fig. 1, respectively.

## 2.2. Joint Manufacture and Tensile Test Process

The composite adherends were drilled at varied orientations, in order to determine the effect of hole drilling on the adhesive bonded joint. Five different types of hole configurations were chosen, as shown in Fig. 2. The hole diameter was chosen as 5 mm and the depth of the holes was half of the adherends thicknesses. The holes were opened by a Quantum upright drilling machine (Qingdao, China). The thicknesses of the adhesive and the adherend were 0.13 and 2.35 mm, respectively. The adherends were cleaned with acetone after drilling to obtain a good adhesion. After bonding, there was an 8-day waiting period before testing. The tensile tests were performed using five samples for all temperatures by using Shimadzu AG-X (Kyoto, Japan) with a loading capacity of 100 kN and the test speed was chosen as 2 mm/min. The elongations of the specimens were measured by an extensometer connected to the test machine. Tensile tests were carried out at room temperature, 50°C, and 80°C. The test machine allows making a test between  $-180^{\circ}\text{C}$  and  $320^{\circ}\text{C}$  with its Shimadzu TCLN 382T thermostatic chamber.



**FIGURE 2** Hole orientations.

## 3. RESULT AND DISCUSSION

Single-lap adhesively bonded joints with composite laminates were tested at different temperature and different hole configurations, as shown in Fig. 2. The load–displacement curves of the bonded joints tested at different temperatures are given in Figs. 3–7. These figures show a linear behavior up to failure for adhesive Loctite<sup>®</sup> 9466 A&B, because of its brittleness. In these figures, the maximum slope is obtained in the joint tested at room temperature and the minimum is observed at 80°C. This implies that when the temperature increases, the bonded lap joints failure strength decreases. The failure displacement also decreases with temperature in configuration 1 in

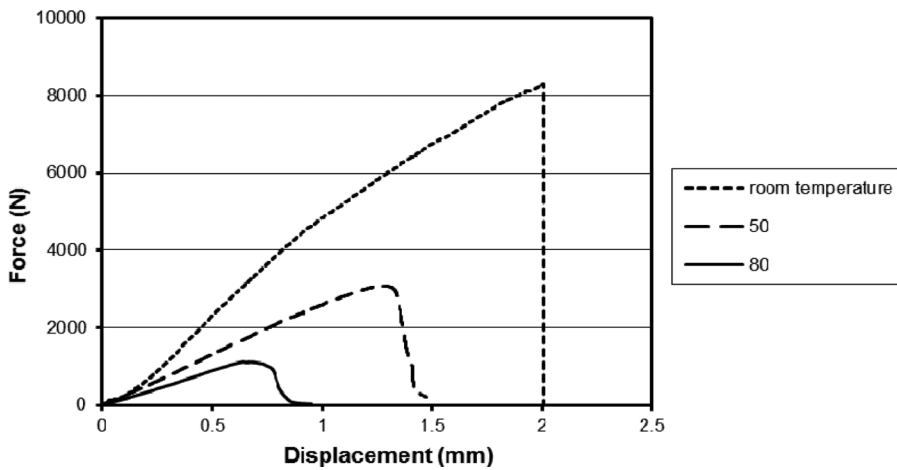


FIGURE 3 Load–displacement curves at different temperatures for configuration 1.

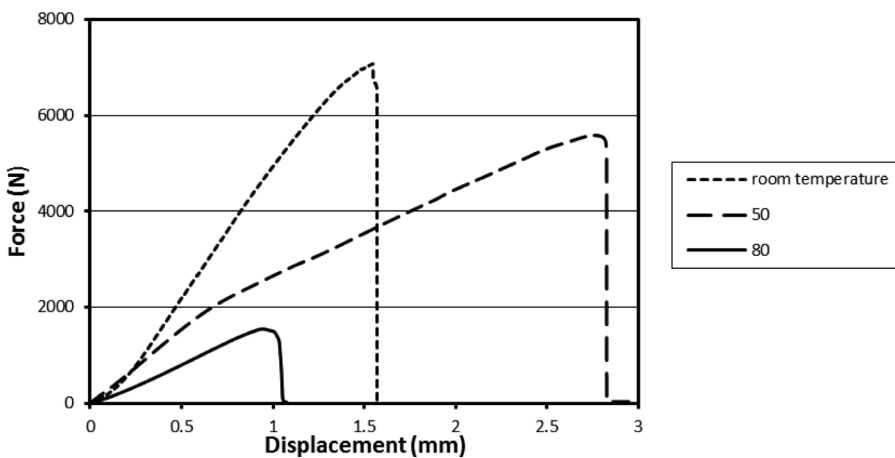
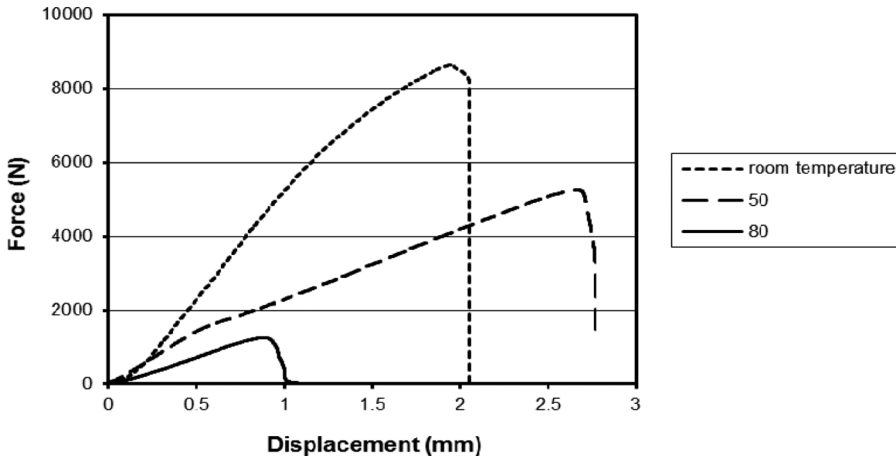


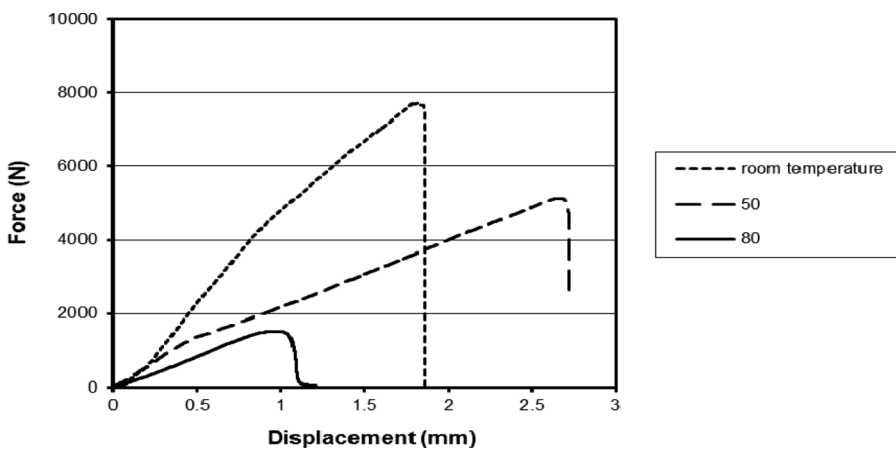
FIGURE 4 Load–displacement curves at different temperatures for configuration 2.



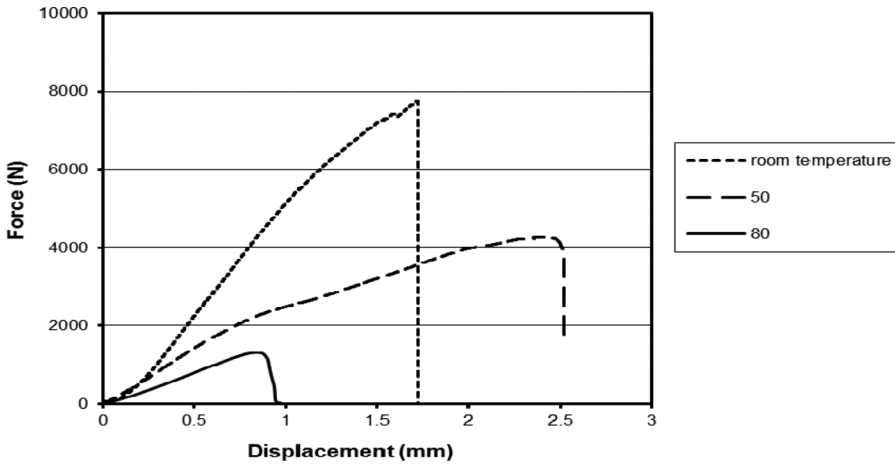
**FIGURE 5** Load–displacement curves at different temperatures for configuration 3.

Fig. 3, but in other configurations the maximum failure displacement was observed at 50°C and the minimum failure displacement was observed at 80°C. The maximum elongation is approximately 2 mm at room temperature for all configurations. However, when the temperature rises to 50°C, the elongation is over 2.5 mm for configurations 2, 3, 4, and 5. A sharp decline is observed in the failure displacement and failure load when the temperature rises to 80°C.

The lap-shear strengths as a function of temperature and holes configurations are shown in Fig. 8. This figure represents the average and standard deviation result of the average shear stress for the different configurations at different temperatures. The lap-shear stress decreased in configurations



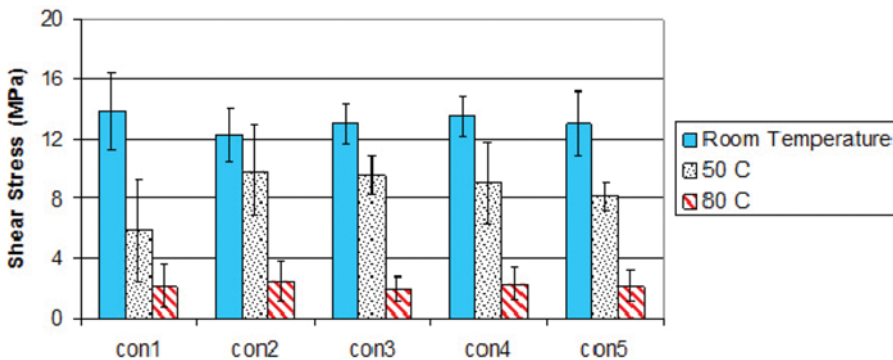
**FIGURE 6** Load–displacement curves at different temperatures for configuration 4.



**FIGURE 7** Load–displacement curves at different temperatures for configuration 5.

2, 3, 4, and 5 with respect to configuration 1 at room temperature. The maximum shear stress in configurations 2, 3, 4, and 5 increased with respect to configuration 1 at 50°C. The minimum value of the shear stress was observed in configuration 1 and the maximum shear stress was observed in configuration 2. The maximum shear stress was obtained at room temperature and the minimum shear stress was observed at 80°C for all configurations. As a result of experimental study, hole drilling little affects the failure load at room temperature, however, there is a positive contribution at 50°C. A sharp decrease was observed when the temperature was over glass transition temperature.

It is known that at room temperature the failure takes place at the end of the overlap [1]. Because of their location, the holes had little effect on the lap-shear strength at room temperature, while at 50°C, as the

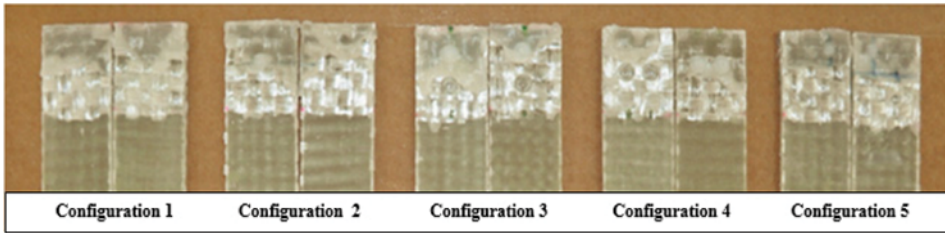


**FIGURE 8** Lap-shear strengths as a function of temperature and configurations of holes.

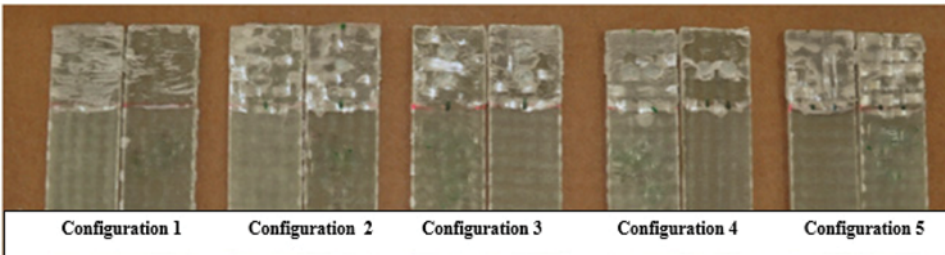


adhesive becomes more ductile, the overlap contributes more to the strength as the adhesive yields and the holes can increase the lap-shear strength. At 80°C, as the test temperature overpassed the adhesive glass transition temperature, the holes had no effect because of the adhesive degradation.

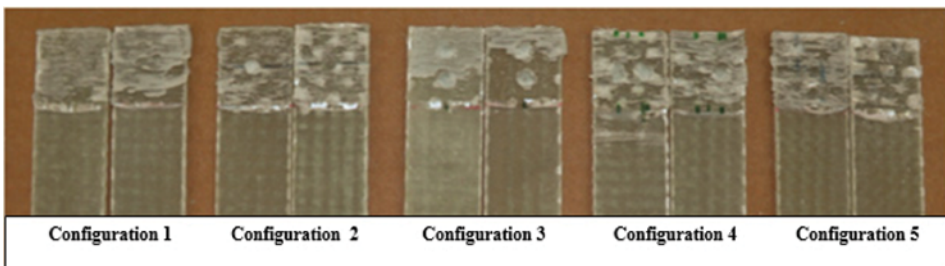
Heslehurst and Hart-Smith [12] identified failure modes of adhesively bonded joints. The failure modes after tensile tests are given in Figs. 9, 10, and 11. The failure mode of specimens which tested at room temperature is observed as light-fiber-tear failure (Fig. 9). When the temperature increases to 50°C and 80°C, the failure modes become cohesive failure in the adhesive (Figs. 10 and 11) because adhesive lost its strength and adhesive becomes more ductile when the temperature increases to 50°C and 80°C.



**FIGURE 9** Specimen failure modes after room temperature tests.



**FIGURE 10** Specimen failure mode after 50°C temperature tests.



**FIGURE 11** Specimen failure mode after 80°C temperature tests.

#### 4. CONCLUSION

In this work, the effects of temperature and hole drilling on the strength of adhesively bonded single-lap joints were studied experimentally. As a result of this experimental study:

- a. The hole drilling never benefits the shear strength at room temperature.
- b. The strength of adhesive joints decline when the temperature increases.
- c. The maximum shear strength is found at room temperature.
- d. The failure occurs in the adherend at room temperature, but when the temperature increases to 50°C and 80°C the failure is cohesive.
- e. At room temperature, brittle failure was observed, while ductile failure occurred at 50°C and 80°C.

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