Current Science
CS 6 (1), 5614-5622 (2026)
Received 14 December 2025 | **Accepted** 08 January 2026 | **Online Available** 09 January 2026
https://doi.org/10.52845/CS/2026-6-1-1

Current Science

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OPEN ACCESS

ISSN(O) 2795-8639

Original Article

Experimental Study on Scarf Repair of Composite Laminates under Different Loading Conditions

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Abstract:
Scarf repair can not only restore the strength and stiffness of the structure, but also maintain the smoothness of the aerodynamic profile. It's an important permanent repair method for composite structures. In this paper, the mechanical properties of scarf repair composites under different loading conditions were investigated through experiments. Tensile and tensile-shear tests under different environments were conducted, and different repair parameters as well as the influence of the environment on the repair strength, stiffness and failure modes were investigated through experiments. Key issues requiring attention in the scarf repair of aircraft composite structures were proposed.

Key Words: Composite laminates; Scarf repair; Experimental study; Failure mode

1. Introduction

Composite materials have become one of the main structural materials for military and civil aircraft. As the amount of composite materials used in aircraft increases, their repair problems become more critical[1-5]. The scarf repair can not only ensure the smooth aerodynamic surface, but also transfer load efficiently by closely aligning the neutral axis of the parent and the patch, thus becoming the most important repair method for aircraft composite structures[6]. The bonded area of the scarf repair is the weakest part of the repaired structure and also the focus of the design research[7]. Samaneh Tashi et al[8] analyzed the scarf repair 2D and 3D FEM of simulation results discrepancies considering the effect of stacking sequences of laminate. They showed that the laminate lay-up angles and stacking sequence substantially affect the 2D and 3D simulations agreement. The scarf repaired composite laminate with a scarf angle ranging from 10° to 18° were examined under low velocity impact by Punita Kumari et al[9]. It was shown that when the scarf angle was large, it performed best with less absorbed energy and less damage. R.D.F. Moreira et al.[10] have tested the scarf repairs under static and fatigue loading in three-point bending considering a scarf angle of 10°. The high-cycle fatigue model was based on the modified Paris law to simulate material softening as a function of time, considering quasi-static and fatigue degradation. Haibao Liu et al.[11] found the patch thickness had larger effects on the impact behavior of repaired composites, and a plug can provide added structural integrity and reduce damage in the adhesive bond. D V Srinivasan et al.[12] studied different repair based on 8.6° scarf, thin CFRP strap and Ti-6Al-4V straps were used in bonding CFRP composites. Results showed that delamination due to the inner edge peel stresses was a critical failure mode of the strap repaired joints. The post repair high velocity impact behaviour of carbon-glass hybrid composite was investigated by Chinmaya K.S et al.[13]. They found that the number of glass plies in the patch governed the damage development in the specimen and residual velocity of projectile. Z.E.C. Hall et al.[14] studied the low-velocity impact testing of carbon-fibre reinforced-plastic pristine and patch-repair CFRP panels. The results showed a plug gave an interlaminar damage area that was smaller than the pristine panels. The effect of patch-parent stacking sequence and patch stiffness on the tensile behaviour of the patch repaired carbon-glass hybrid composite was investigated by Chinmaya Kumar Sahoo et al[15]. It was shown that the patches with glass ply facing the parent laminate showed better recovery.

This paper will contribute to the work of revealing the stacking sequences, environment and scarf angle on the failure strength and damage mechanisms of composites scarf repair.

2. Experimental methodology

2.1 Specimen Design

The actual repair area is generally in a complex stress state, for which two types of specimens were investigated: (1)Tensile specimen, the loading direction was perpendicular to the repair boundary, as shown in Fig 1; (2)Tensile-shear specimen, the loading direction and repair boundary at an angle of 45 °, as shown in Fig 2. In the figure, d_1 is the scarf bonding width, d_2 is the width of additional plies, t_1 is the thickness of parent laminates, and t_2 is the thickness of the patch. The scarf angle is defined using:

$$\alpha = \arctan\frac{d_1}{t_1} \quad (1)$$

Fig. 1 Tensile specimen

Fig. 2 Tensile-shear specimen

The specimens were designed with different layups, different thicknesses, and different scarf angles, as summarized in Table 1. The test environments included the cold temperature dry environment CTD (-55°C), the room temperature dry environment RTD, and the elevated temperature wet environment ETW (71°C water bath).

Table 1 Test items and configuration of repaired specimens

Stacking sequence	**α**	No. Tensile specimens			No. Tensile-shear specimens
		CTD	**RTD**	**ETW**	**ETW**
A	6°	6	6	6	6
B	6°	6	6	6	6
C	6°	6	6	6	6
	8°	/	6	/	6
E	6°	6	6	6	6

2.2 Specimen Preparation

Repair patches are generally available in two forms: prepreg patches and pre-cured patches. The prepreg patch is cut into the required shape and then directly laid-up and cured in the repair area, which is limited by the heating and pressure conditions. It is difficult to guarantee the quality of the patch itself, thus affecting the repair strength. The pre-cured patch is made by cutting and laying the prepreg into the required patch shape, then pre-curing it. The pre-cured patch is completed cured with bonding it to the parent laminates (which may include honeycomb and other core materials) by adhesive film. Compared to prepreg patch, the quality of the pre-cured patch is better controlled in terms of forming and bonding quality. Therefore, to ensure consistency with the actual repair process, the specimens simulated the repair of pre-cured patches.

The material of both the parent laminates and the patch of the specimen was HF10A/NY9200GA high-temperature cured carbon fiber/epoxy composite material, and the adhesive was J-116B high-temperature adhesive film. As shown in Fig 3, the specimen preparation process was as follows: after the A plate (parent laminates) was completely cured, the scarf surface was polished at the end according to the specified scarf angle; after the B plate (patch) was laid in the specified layers, it was pre-cured according to the process conditions; the adhesive film was laid on the combined surface of the A plate and B plate, the vacuum bag was pumped and vacuumed, and then cured by hot bonder.

Fig. 3 Schematic of the specimen

2.3 Experimental Procedure

The specimens for ETW test were first subjected to 14 days of aging treatment in a constant temperature water bath at 71°C, the water bath device was shown in Fig 4, and then these specimens were tested at 71°C. The low temperature was -55°C. The test setup is shown in Fig 5. The RTD test was performed on an INSTRON8801 universal test machine, and the high and low temperature tests were performed on a WDW-50C universal test machine. The test loading rate was 0.5 mm/min, and the specimen deformation was measured continuously using an extensometer and strain gauges, where the extensometer was clamped on the bonded section to accurately measure the repair stiffness.

Fig 4 Water bath device

Fig 5 Experimental set-up for CTD testing

3. Results and Discussion

3.1 Failure Mode

The fracture specimens showed that the main failure modes included cracking of the adhesive layer and fracture of the additional plies (Fig 6). For the tensile specimens, the adhesive surface was under shear and out-of-plane peeling stresses, the failure began to appear on the side without additional plies, followed by the rapid propagation of the adhesive cracks. Eventually, the entire adhesive surface was debonded and the additional layers were damaged in shear. For the tensile-shear specimen, the failure process was similar, but because the additional plies were (± 45 °) layers, the failure of the additional plies was tensile failure.

Fig 6 Failure modes in repaired specimens

Compared with RTD and ETW environments, low temperature increased the brittleness of the adhesive and additional plies, and they were quickly pulled apart, resulting in a sudden destruction of the specimen. For the specimens treated by ETW environment, debonding appeared between the fiber and matrix in additional plies. It can be explained that the additional plies were thin and the higher moisture absorption rate of the adhesive layer.

It can also be seen that the additional plies reduced the peeling stress on its side, making cracks appear first on the other side. For actual repair, the side without additional plies usually corresponds to the inner surface of the structure, and during long-term use, the cracks on the inner surface cannot be visually inspected, and the rapid expansion of the cracks may result in a latent risk. Therefore, the durability and damage tolerance of the repaired structure must be carefully analyzed and verified in order to establish a reasonable repair life and inspection interval. For the case where the repair structure is a honeycomb sandwich structure, the presence of honeycomb support on the inner surface can reduce the peeling stress of the adhesive layer, which is more beneficial for the durability of the repair structure.

3.2 Repair Stiffness

The stiffness of the repair zone was measured by means of an extensometer clamped in the middle of the specimen. The modulus of the parent laminates was also measured. The stiffness recovery of different specimens is given in Fig 7. The stiffness recovery rate is defined as the ratio of the equivalent modulus of the repair zone to the modulus of the parent laminates.

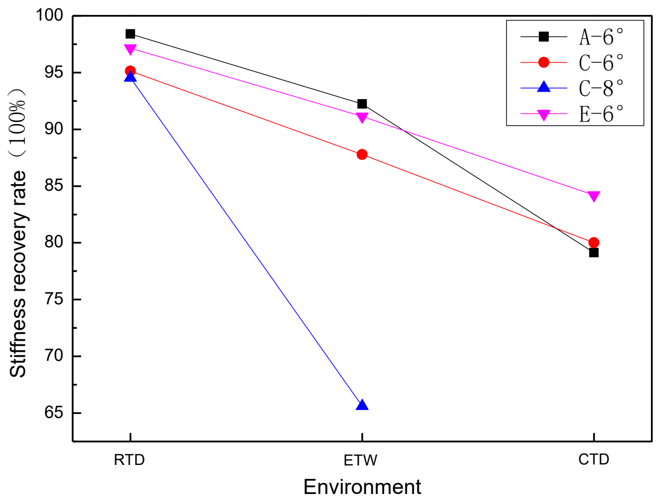

Fig 7 Stiffness recovery rate for different specimens

The stiffness recovery rate has a significant relationship with the stiffness of the parent laminates itself. In general, the higher the proportion of 0° ply of the parent laminates, the lower the repair stiffness recovery rate. The highest proportion of 0° ply of the B-specimen (0° ply proportion of 45%), the stiffness recovery rate in RTD was only 82.5%, while the stiffness recovery rate of the A-specimen (0° ply proportion of 25%) and E- specimen (0° ply proportion of 16.7%) reached 98.4% and 97.1%, respectively.

The test results showed that the stiffness recovery rate also had a certain relationship with the scarf angle. The smaller the scarf angle, the larger the stiffness recovery rate. For C-specimen, the stiffness recovery rate of 6° scarf angle in ETW was 87.8%, which was much higher than that of 65.6% for 8° scarf angle.

Environment treatment also had a large effect on the stiffness recovery rate. The test results showed that the stiffness recovery rate of the specimen in RTD was the highest, followed by a specimen in ETW, and specimen in CTD had the lowest stiffness recovery rate. Under the test conditions described in this paper, there was basically a linear decrease among the three.

3.3 Scarf Angle

From Fig 8, it can be seen that even if the difference in scarf angle is only 2°, its influence on repair strength was relatively significant. Although the average RTD tensile strength of the 6° scarf angle was slightly higher than that of the 8° scarf angle, the ETW tensile-shear strength was 25% lower than that of the 8° scarf angle. This result was slightly different from common sense.

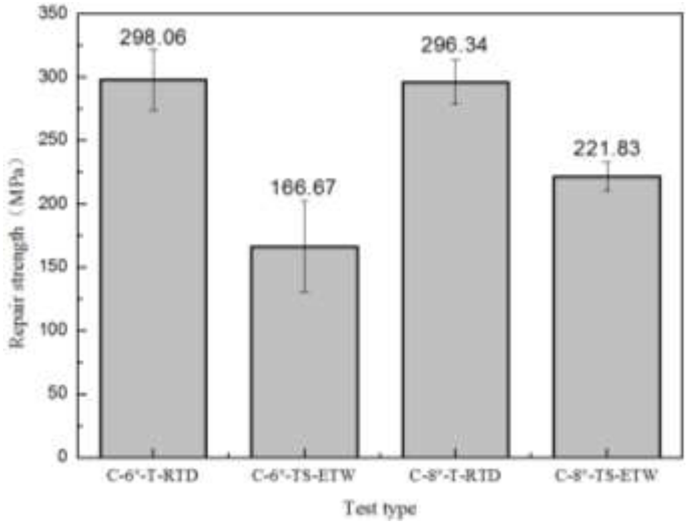

Fig 8 Repair strength at different scarf angles

The smaller the scarf angle, the longer the adhesive surface, the lower the average stress of the adhesive layer. If other factors are not taken into account, the repair strength should be proportional to the length of the adhesive joint, i.e., the smaller the scarf angle, the higher the repair strength. In practice, due to the existence of stress concentration on the adhesive end face, the increase in repair strength is not a trigonometric function relationship with the scarf angle. The problem is further complicated when the effects of actual repair operations, hot and humid environments, and other factors are considered. The smaller the scarf angle, the larger the range of parent laminate materials to be removed, and the higher the possibility of defects such as damage to the parent laminates, the deviation of the scarf angle, and porosity of the adhesive layer that may be caused by the operation. It can also be seen from the results that the dispersion of 6° scarf angle was greater than 8° scarf angle, both the test in RTD and ETW. On the other hand, a larger adhesive surface also implies a higher moisture absorption, especially when the parent laminates is thin, and the long-term effect of the hot and humid environments may lead to a greater proportion of strength loss in the repair structure. Therefore, for actual scarf repair, the quality of repair should be ensured through the application of specialized repair tools and the strengthening of operational skills, etc. At the same time, the appropriate scarf angle should be determined according to the actual loading conditions and the service environment.

3.4 Stacking Sequence

In order to reduce stress concentration, the layup and 0° direction of the patch are generally the same as that of the parent laminates, while the additional plies are mainly ±45° layup to improve the repair strength of the complex stress state. The test results showed that since the failure modes were dominated by the debonding of the adhesive surface and fracture of the additional plies, the influence of the stacking sequence on the average repair strength was not significant, and all deviations were within 10% (Fig 9).

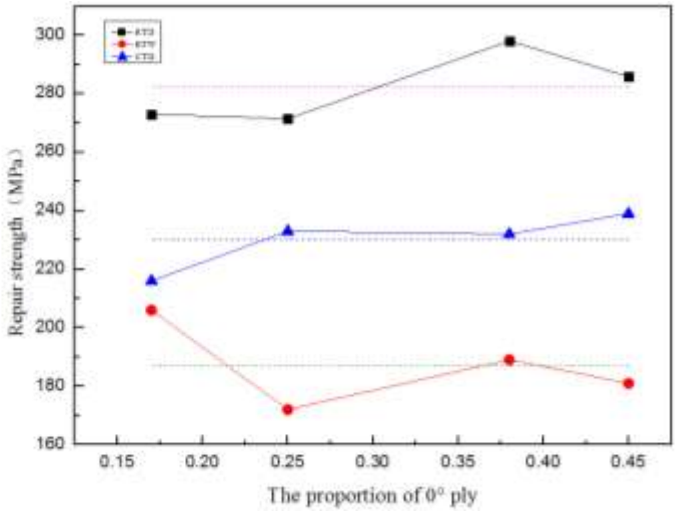

Fig 9 The Influence of Stacking Sequence

Therefore, in order to improve the strength of scarf repair, under the premise of meeting the requirements of aerodynamics, weight, etc., the number of additional ply can be increased or the scarf angle can be reduced, but the quality of polishing scarf and the adhesive joint should be strictly controlled.

3.5 Environment

Regardless of the type of specimen, the influence of the environment on the repair strength was significant, as shown in Fig 10. Both CTD and ETW environments reduced the failure strain of the repair structure, and the influence of ETW environment was greater than that of CTD environment.

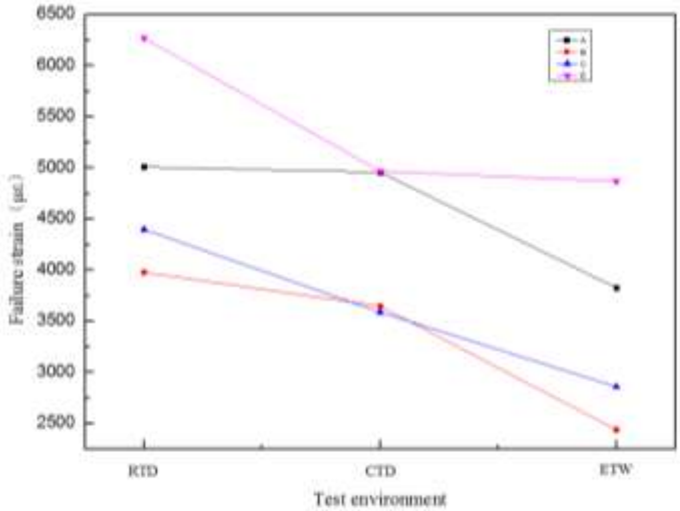

Fig 10. Influence of environment on repair strength

Compared to the failure strain in the RTD environment, the failure strain in the CTD environment decreased within about 20%, while the failure strain in the ETW environment decreased up to 38.7%, which was attributed to different mechanisms. The CTD environment made the resin and adhesive layer brittle and weakened the plastic deformation ability, thus reducing the failure strain. In ETW environment, moisture diffused in the resin matrix and adhesive layer, leading to expansion effect, lowering the glass transition temperature, and at the same time acting as a plasticizing and softening effect, reducing the modulus and strength of the adhesive layer and matrix.

Generally, the moisture absorption rate of the adhesive layer is higher than that of the resin matrix. The moisture diffuses inward through the periphery of the adhesive surface as well as the surface of the matrix, and the gradient of moisture absorption leads to microcracks in the adhesive and matrix. When the adhesive and the resin matrix are saturated with moisture absorption, the residual thermal stresses generated during the repair process are released to a certain extent, but their mechanical properties will also be reduced. This results in a significant reduction in the ETW strength of the repair structure. For this reason, in the actual repair of aircraft structure, the repair surfaces and edges should be well sealed to enhance the durability of the repair structure.

4. Conclusions

A series of tests in different environments were used to investigate the mechanical properties of scarf repair composite laminates, and the influence of stacking sequence, scarf angle, and environment on the strength, stiffness, and failure mode were obtained. Moisture enters the adhesive through the edge and the thin additional plies, which reduced the repair strength in ETW environments, while CTD environments reduced the repair strength due to the reduced toughness of the adhesive. The smaller the scarf angle, the greater the repair stiffness, but the influence of the scarf angle on the repair strength was more complicated. The repair strength of 6° scarf angle was higher than that of 8° scarf angle in RTD environment, but the ETW strength was lower than that of 8° scarf angle. The influence of stacking sequence on repair strength was not significant over the range of layering ratios studied in this paper.

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