

## Statistical evaluation and regression modeling of strength recovery in scarf-repaired composite laminates

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### ABSTRACT

Scarf repair is one of the most effective bonded repair techniques for damaged composite laminates because it can achieve high strength recovery while minimizing stress concentration. In this study, the influence of scarf geometry on the tensile behavior and strength recovery rate (SRR) of scarf-repaired composite laminates was investigated using a statistically supported approach. Experimental tensile-test data corresponding to scarf ratios of 1/10, 1/20, and 1/30, together with defect sizes of 6 mm and 12 mm, were analyzed using two-way analysis of variance (ANOVA) to evaluate the significance of geometric parameters on SRR. The results showed that scarf ratio is the dominant factor affecting repair performance ( $p < 0.001$ ), whereas defect size and interaction effects are statistically insignificant within the investigated range. The SRR increased significantly from approximately 51.0–52.9% at a scarf ratio of 1/10 to approximately 79.2–82.0% at scarf ratios of 1/20 and 1/30. An exponential decay relationship between SRR and scarf angle was established using nonlinear regression analysis ( $R^2 = 0.898$ ). Additional experimental results at a scarf ratio of 1/5 exhibited a noticeable deviation from the model prediction, indicating a transition in the dominant failure mechanism at relatively large scarf angles. The findings provide a statistically supported framework for evaluating scarf repair configurations and balancing mechanical efficiency with repair manufacturability.

**Keywords:** Scarf repair; Analysis of variance (ANOVA); Composite laminates; Strength recovery rate; Scarf angle; Regression modeling; Failure mechanism.

### 1. INTRODUCTION

Composite materials are increasingly used in aerospace, automotive, wind energy, marine, and defense applications because of their high specific strength, low weight, and excellent environmental resistance. During service, composite structures may suffer damage that requires repair or replacement. Among the available repair techniques, scarf repair is widely regarded as one of the most effective bonded repair methods because it can achieve high strength recovery while minimizing stress concentration along the bonded interface [1-4].

The performance of scarf repairs is strongly influenced by geometric and manufacturing parameters, particularly scarf angle, adhesive properties, surface preparation, and overlap configuration [1-3]. Among these factors, scarf geometry plays a dominant role in load transfer and failure behavior. Yoo et al. [2] investigated scarf ratios ranging from 1/5 to 1/30 and reported that the strength recovery rate (SRR) increased from approximately 18% for a scarf ratio of 1/5 to more than 80% for a scarf ratio of 1/30. Similar observations were reported by Sonat et al. [4], who showed that tensile strength decreases with increasing scarf angle and that failure mode is highly dependent on scarf geometry. Other studies have further examined the effects of patch dimensions, adhesive thickness, overlap plies, surface roughness, and environmental conditions on repair efficiency [5, 10-12].

Analytical and numerical approaches have also been widely employed to predict the mechanical performance of scarf repairs. Bing Yan et al. [6] proposed an improved semi-analytical

method for predicting the strength of scarf repairs, while Tashi [7] and Breitzman et al. [8] used three-dimensional finite element analyses to investigate the influence of laminate configuration and repair geometry. Harman et al. [9] explored optimized taper configurations to reduce stress concentration, whereas recent studies have focused on patch-shape optimization and numerical–experimental design approaches to improve repair efficiency and load-carrying capacity [15, 16].

Failure characterization remains an important topic in scarf repair research. Marques et al. [13] performed fractographic analyses and identified several dominant failure mechanisms, including fiber pull-out and intralaminar fracture. Sonat et al. [4] demonstrated that scarf angle significantly influences the transition between cohesive, fiber-dominated, and mixed failure modes. These studies provide valuable insight into the mechanics of scarf repair; however, they primarily rely on experimental observations, analytical modeling, or numerical simulations.

Despite extensive research efforts, most previous studies have focused on experimental characterization, analytical modeling, and numerical simulations [1, 2, 10, 15-20]. Consequently, the relative contributions and interaction effects of geometric parameters governing SRR remain insufficiently quantified. Analysis of variance (ANOVA) provides an effective framework for identifying statistically significant factors affecting mechanical performance [21, 22], yet its application to scarf-repaired composite structures remains limited.

Existing studies consistently demonstrate that decreasing scarf angle improves SRR by reducing peel-stress concentration and enhancing load transfer along the bonded interface. However, smaller scarf angles also require larger repair areas and increased material removal, leading to a trade-off between mechanical performance and repair manufacturability. Therefore, this study aims to quantitatively evaluate the influence of scarf geometry on the strength recovery behavior of scarf-repaired composite laminates using a statistically supported approach. Two-way ANOVA was employed to assess the significance and interaction effects of geometric parameters on SRR, while regression modeling was used to establish the relationship between scarf angle and SRR. The findings provide useful guidance for the design and optimization of scarf repair configurations.

## 2. MATERIAL AND METHOD

### 2.1. Specimen configuration and experimental data

The scarf-repaired composite laminate configuration investigated in this study is illustrated in Figure 1. The laminate thickness was fixed at 2.4 mm, and the repair geometry was characterized by the scarf ratio, defined as the ratio between the laminate thickness ( $t$ ) and the scarf length ( $L$ ). Four scarf ratios (1/5, 1/10, 1/20, and 1/30) were considered, corresponding to different scarf angles and bonding lengths. The scarf angle ( $\theta$ ) was determined from the repair geometry according to:

$$\theta = \text{atan}\left(\frac{t}{L}\right) \cdot \frac{180}{\pi} \quad (1)$$

The investigated specimens consisted of scarf-repaired CFRP laminates bonded using structural adhesive systems, as reported in Refs. [1, 2]. Two defect sizes (6 mm and 12 mm) were considered, while the external-ply overlap length was fixed at 5 mm.

The experimental data used in this study were obtained from previously published tensile-test investigations on scarf-repaired composite laminates [1, 2]. For each repair configuration, five specimens were tested under quasi-static tensile loading conditions. The strength recovery rate (SRR), adopted as the primary response parameter, was defined as:

$$SRR = \frac{P_{\text{repair}}}{P_{\text{intact}}} \quad (2)$$

where  $P_{\text{repair}}$  is the failure load of the repaired specimen and  $P_{\text{intact}}$  is the failure load of the intact laminate. The experimental data summarized in Table 1 were subsequently used for statistical analysis, regression modeling, and interpretation of the failure behavior associated with scarf geometry.

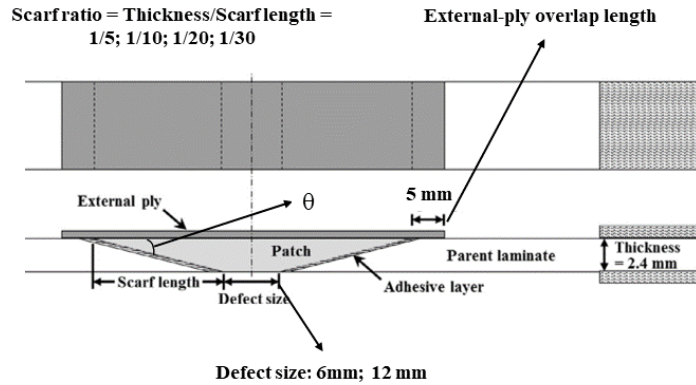


Figure 1. Schematic of scarf repair configuration with definition of scarf angle ( $\theta$ ) and ratio ( $t/L$ ).

## 2.2. Statistical analysis (two-way ANOVA)

A two-way analysis of variance (ANOVA) was performed to evaluate the effects of scarf ratio and defect size on the strength recovery rate (SRR). Scarf ratio (1/10, 1/20, and 1/30) and defect size (6 mm and 12 mm) were treated as the two independent factors, while SRR was considered the response variable. Five repeated measurements were available for each factor combination, resulting in a balanced experimental dataset.

The ANOVA was conducted to assess the statistical significance of the main effects of scarf ratio and defect size, as well as their interaction effect on SRR. Statistical significance was evaluated using the F-test at a significance level of  $p < 0.05$ . Main-effect and interaction plots were additionally employed to visualize the influence of the investigated factors. All statistical analyses were performed using Origin software.

## 2.3. Regression modeling and data processing

An exponential decay model was used to describe the relationship between the strength recovery rate (SRR, %) and scarf angle:

$$SRR = 100 \cdot \exp(-k \cdot \theta) \quad (3)$$

where,  $\theta$  is the scarf angle (degree), and  $k$  is the decay constant. Model parameters were obtained by nonlinear least-squares fitting using the experimental data for scarf ratios of 1/10, 1/20, and 1/30. The goodness of fit was evaluated by the coefficient of determination ( $R^2$ ). Additional data at a scarf ratio of 1/5 were employed to examine the applicability of the model at relatively large scarf angles. All analyses were performed using Origin software.

## 3. RESULTS AND DISCUSSION

### 3.1. Effect of scarf ratio and defect size on strength recovery rate

Table 1 presents the experimental results of the strength recovery rate (SRR) for different combinations of scarf ratio and defect size. For each condition, five repeated measurements were conducted to ensure the reliability of the data.

The mean values of the strength recovery rate (SRR) for each factor combination are presented in Figure 2. As shown in Figure 2(a), the SRR increases significantly with decreasing scarf ratio (i.e., increasing scarf length). For the scarf ratio of 1/10, the mean SRR values are 51.0% and 52.9% for defect sizes of 6 mm and 12 mm, respectively, indicating relatively limited load-transfer

efficiency across the repaired interface. When the scarf ratio decreases to 1/20, the mean SRR increases markedly to 79.2% and 79.4%, respectively. A further decrease in scarf ratio to 1/30 results in mean SRR values of 82.0% and 79.3% for defect sizes of 6 mm and 12 mm, respectively.

In contrast, the effect of defect size is comparatively weak. As illustrated in Figure 2(a), the variation in SRR between defect sizes of 6 mm and 12 mm is relatively small for all investigated scarf ratios. This observation is further confirmed by the main effect plot in Figure 2(b), where the SRR exhibits a strong dependence on scarf ratio, whereas only minor differences are observed between the two defect sizes.

Table 1. Experimental data of strength recovery rate for different scarf ratios and defect sizes.

Strength recovery rate, %		
Scarf ratio (Factor A)	Defect size, mm (Factor B)	
	6	12
1/10	55.29	50.20
	49.69	56.97
	51.71	55.84
	49.77	55.60
	48.50	45.80
1/20	79.54	77.67
	78.80	81.53
	77.61	79.48
	80.73	80.49
	79.29	78.00
1/30	86.47	80.23
	82.07	78.50
	75.26	78.75
	83.14	80.00
	82.89	79.23

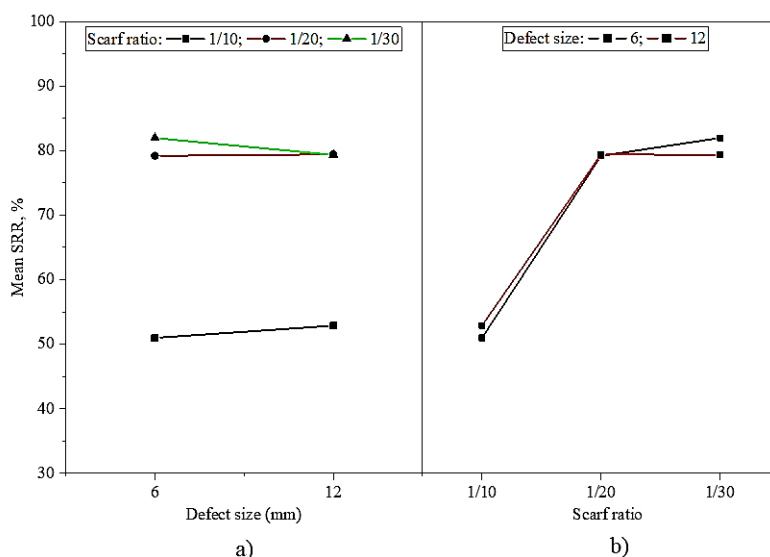


Figure 2. ANOVA plots for strength recovery rate: (a) Interaction plot; (b) Main effect plot.

Moreover, the nearly parallel trends of the curves in Figure 2(a) suggest the absence of a strong interaction effect between scarf ratio and defect size within the investigated range. This indicates that the influence of scarf ratio on SRR is essentially independent of defect size.

To quantitatively confirm these observations, the results of the two-way ANOVA are summarized in Table 2. As shown, the effect of scarf ratio is highly significant, with a very large F-value ( $F = 308.69$ ) and an extremely low p-value ( $p < 0.001$ ), indicating that scarf geometry is the dominant factor governing the strength recovery rate. In contrast, the effect of defect size is statistically insignificant ( $p = 0.878$ ), suggesting that variations in defect size within the investigated range have a negligible influence on SRR. Similarly, the interaction effect between scarf ratio and defect size is also insignificant ( $p = 0.236$ ), which is consistent with the nearly parallel trends observed in Figure 2(a).

Table 2. Two-way ANOVA results for strength recovery rate (SRR).

	DF	Sum of squares	Mean square	f value	P value
Scarf ratio	2	5253.1212	2626.5606	308.6857	$7.53737 \times 10^{-18}$
Defect size	1	0.20386	0.20386	0.02396	0.87828
Interaction	2	26.10067	13.05034	1.53374	0.23614
Model	5	5279.42573	1055.88515	124.0926	$2.44832 \times 10^{-16}$
Error	24	204.21242	8.50885	--	--
Corrected Total	29	5483.63816	--	--	--

These statistical results further confirm that the strength recovery rate is primarily controlled by scarf geometry, whereas the influence of defect size is negligible under the present experimental conditions. Therefore, the subsequent analysis focuses on the effect of scarf angle, which serves as the basis for the regression modeling presented in the following section.

### 3.2. Regression modeling of strength recovery rate

Based on the ANOVA results presented in Section 3.1, scarf geometry was identified as the dominant factor governing the strength recovery rate (SRR). Therefore, regression modeling was performed using the scarf angle as the governing independent variable. Compared with the scarf ratio, the scarf angle provides a continuous geometric parameter more directly associated with the stress transfer mechanism along the bonded interface.

The regression analysis was conducted using the experimental SRR data corresponding to scarf ratios of 1/10, 1/20, and 1/30. An exponential decay relationship was adopted to describe the variation of SRR with scarf angle. The model assumes an idealized condition in which the SRR approaches 100% as the scarf angle tends toward zero, corresponding to nearly ideal load transfer along the bonded interface.

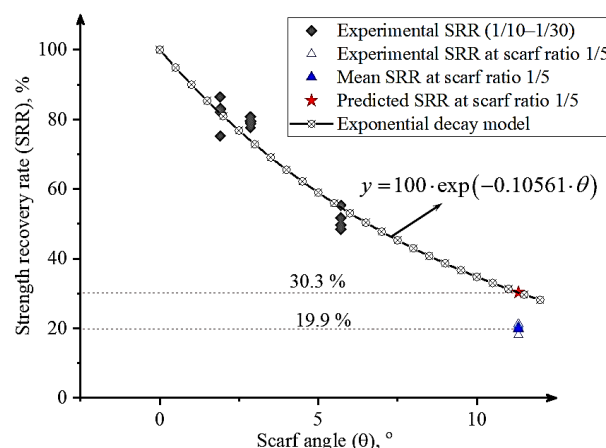


Figure 3. Exponential relationship between SRR and scarf angle.

The fitted exponential model is presented in Figure 3. Nonlinear least-squares regression yielded a decay constant of  $k = 0.10561$ , indicating a strong sensitivity of SRR to scarf angle. The

model provides good agreement with the experimental data within the investigated scarf-angle range, with a coefficient of determination of  $R^2 = 0.898$ .

To further evaluate the applicability of the proposed exponential model at relatively large scarf angles, additional experiments were performed at a scarf ratio of 1/5 under fixed conditions, namely a defect size of 6 mm and an overlap length of 5 mm. The corresponding experimental strength recovery rate (SRR) values are summarized in Table 3. The results yielded an average SRR of 19.91%, accompanied by a relatively small standard deviation ( $SD = 1.19$ ) and a narrow 95% confidence interval ( $\pm 1.47\%$ ), indicating good repeatability and consistency of the experimental measurements.

**Table 3.** Experimental strength recovery rate (SRR) results at scarf ratio 1/5.

No.	Strength recovery rate, %	Mean	Standard deviation	95% Confidence Interval
1	18.06	19.91	1.19	1.47
2	19.70			
3	21.26			
4	20.50			
5	20.02			

As illustrated in Figure 3, the exponential decay model provides good agreement with the experimental SRR data within the investigated low-angle scarf regime. However, the additional experimental result obtained at the scarf ratio of 1/5 exhibits a significant deviation from the model prediction. The experimentally measured average SRR ( $\sim 19.9\%$ ) is substantially lower than the predicted value ( $\sim 30.3\%$ ), corresponding to a relative deviation of approximately 52% with respect to the experimental result. This observation suggests that the exponential relationship established from the low-angle scarf regime may no longer adequately describe the SRR behavior at relatively large scarf angles. A more detailed discussion of the underlying failure mechanism is presented in the following section.

### 3.3. Physical interpretation and comparison with literature

The observed dependence of SRR on scarf geometry can be explained using the classical shear–peel stress model for scarf joints reported in bonded composite repair studies [2]. According to this model, the shear stress  $\tau_p$  and normal (peel) stress  $\sigma_T$  in the adhesive layer are expressed as:

$$\tau_p = \frac{P \sin \theta \cos \theta}{t}, \quad \sigma_T = \frac{P \sin^2 \theta}{t} \tag{4}$$

where  $P$  is the applied load,  $t$  is the laminate thickness, and  $\theta$  is the scarf angle. As shown, the peel stress component  $\sigma_T$  increases proportionally to  $\sin^2 \theta$ , indicating a strong sensitivity to the scarf angle.

At small scarf angles, the peel stress is negligible and the load transfer is dominated by shear stress along the bonded interface. This results in efficient load distribution and high strength recovery rates, as observed in Figure 3. However, as the scarf angle increases, the peel stress becomes significant and promotes interfacial debonding, leading to a rapid reduction in SRR.

The noticeable deviation observed at the scarf ratio of 1/5 suggests a transition in the dominant failure mechanism at relatively large scarf angles. As the scarf angle increases, the effective bonding area decreases while the peel-stress component rises substantially, promoting stress concentration and interfacial debonding. Consequently, the load-transfer mechanism gradually shifts from shear-dominated behavior to peel-dominated failure. Similar observations have been reported in previous studies. Yan et al. [6] identified scarf angle as a key parameter governing repair strength, whereas Yoo et al. [1] and Truong et al. [2] observed increased interfacial damage and mixed failure modes at relatively large scarf angles. Therefore, the significant deviation at the scarf ratio of 1/5 should not be interpreted merely as a regression error, but rather as evidence of a

change in the governing failure mechanism. This finding also suggests that the exponential relationship established for the low-angle scarf regime should not be extrapolated directly to larger scarf angles without additional experimental validation.

From a manufacturing perspective, relatively large scarf angles increase the sensitivity of the repair process to geometric and bonding imperfections because the bonded interface becomes shorter and steeper. Consequently, local variations in adhesive thickness, incomplete wetting, or alignment errors may significantly reduce load-transfer efficiency. Therefore, although large scarf angles reduce repair area and machining effort, they also decrease repair reliability. Based on the present experimental and modeling results, scarf ratios between 1/20 and 1/30 are recommended as a favorable compromise between structural performance and repair feasibility.

## 5. CONCLUSIONS

This study investigated the influence of scarf geometry and defect size on the strength recovery rate (SRR) of scarf-repaired composite laminates using statistical analysis and regression modeling. The main conclusions are as follows:

1. Two-way ANOVA demonstrated that scarf geometry is the dominant factor governing SRR, whereas defect size and the interaction effect between the two factors are statistically insignificant within the investigated range. The SRR increases significantly as the scarf angle decreases.

2. An exponential relationship between SRR and scarf angle was established for the investigated low-angle scarf regime, providing good agreement with the experimental data ( $R^2 = 0.898$ ). However, additional experimental results at a scarf ratio of 1/5 exhibited a significant deviation from the model prediction, indicating that the proposed relationship should not be extrapolated directly to relatively large scarf angles.

3. The observed deviation at large scarf angles is associated with a transition in the dominant failure mechanism from shear-dominated load transfer to peel-dominated interfacial failure. Based on the experimental and modeling results, scarf ratios between 1/20 and 1/30 are recommended as a favorable compromise between structural performance and repair feasibility.

The findings provide a statistically supported basis for the design and performance assessment of scarf-repaired composite structures.

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### TÓM TẮT

#### **Đánh giá thống kê và mô hình hồi quy đối với khả năng phục hồi độ bền của vật liệu composite nhiều lớp được sửa chữa kiểu liên kết vát**

Sửa chữa kiểu liên kết vát (*scarf repair*) là một trong những kỹ thuật sửa chữa liên kết hiệu quả nhất đối với vật liệu composite nhiều lớp bị hư hỏng, do có khả năng đạt được mức phục hồi độ bền cao đồng thời giảm thiểu sự tập trung ứng suất. Trong nghiên cứu này, ảnh hưởng của hình học vùng liên kết vát đến ứng xử kéo và tỷ lệ phục hồi độ bền (*Strength Recovery Rate – SRR*) của composite nhiều lớp được sửa chữa kiểu liên kết vát đã được khảo sát bằng phương pháp có hỗ trợ thống kê. Dữ liệu thực nghiệm thử kéo tương ứng với các tỷ lệ góc vát 1/10, 1/20 và 1/30, cùng với kích thước khuyết tật 6 mm và 12 mm, được phân tích bằng phương pháp phân tích phương sai hai nhân tố (*two-way ANOVA*) nhằm đánh giá mức độ ảnh hưởng của các thông số hình học đến SRR. Kết quả cho thấy tỷ lệ góc vát là yếu tố chi phối chính ảnh hưởng đến hiệu quả sửa chữa ( $p < 0,001$ ), trong khi kích thước khuyết tật và ảnh hưởng tương tác không có ý nghĩa thống kê trong phạm vi khảo sát. Giá trị SRR tăng đáng kể từ khoảng 51,0 - 52,9% tại tỷ lệ góc vát 1/10 lên khoảng 79,2–82,0% tại các tỷ lệ góc vát 1/20 và 1/30. Mối quan hệ hàm mũ suy giảm giữa SRR và góc vát liên kết đã được thiết lập thông qua phân tích hồi quy phi tuyến ( $R^2 = 0,898$ ). Các kết quả thực nghiệm bổ sung tại tỷ lệ góc vát 1/5 thể hiện sự sai lệch đáng kể so với dự đoán của mô hình, được giải thích do sự chuyển tiếp của cơ chế phá hủy chi phối tại các góc vát liên kết tương đối lớn. Các kết quả nghiên cứu cung cấp một cơ sở có hỗ trợ thống kê cho việc đánh giá cấu hình sửa chữa kiểu liên kết vát và cân bằng giữa hiệu quả cơ học với khả năng chế tạo sửa chữa.

**Từ khóa:** Sửa chữa kiểu liên kết vát; Phân tích phương sai (ANOVA); Composite nhiều lớp; Tỷ lệ phục hồi độ bền; Góc vát liên kết; Mô hình hồi quy; Cơ chế phá hủy.