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# Experiment and design methods of composite scarf repair for primary-load bearing structures

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ABSTRACT

A relative thick plate of composite being repaired by scarf bonding was substituted as the scarf joints and studied under tensile load in this paper. The experimental investigation told us the ultimate capability of load and failure mechanism of composite scarf joints. In order to explain failure mechanism for scarf bonding repair of composite structures distinctly, FEM based on continuum damage mechanics (CDM) was carried out. CDM equations were derived by adding the delamination mode and 3D Hashin criteria based on strain into the composite constitutive relation. Furthermore, a modified semi-analytical method (MAM) was developed to obtain shear stress distribution in theory. MAM can improve the accuracy of Harman and Wang method, solve the stress asymmetry, obtain secondary peak of shear stress, and increase the highest peak of stress. In the end, the discussions for the methodologies of MAM, CDM and linear FEM were executed to compare the errors of predicting ultimate load. The discussion revealed that MAM has sufficient accuracy as an analytical methodology which could be utilized to design composite scarf repairs in a short cycle simply.



## 1. Introduction

On account of extensive use of composite materials and the shortcoming of relative low ability of resistance to the impact load, the composite structures face the repair problems. The most popular repair method for fiber reinforced plastic (FRP) is the scarf bonding repair. For this kind of repair, the small scarf angle is usually 2–10°. Nowadays, this kind of scarf bonding repair has been tried to be applied to primary-load bearing structures [1]. The composite structures of primary-load bearing have remarkable characteristics of thicker and more 0° plies. The 0° plies which have the biggest stiffness in the composite laminate plies could lead to the stress concentration phenomenon in the adhesive. However, the traditional average method cannot obtain the stress concentration.

Scarf joint is 2D representation of scarf repair along the most highly loaded direction [2]. Kumar et al. [3] studied the scarf angle effect on the ultimate tensile load without including the investigation into the micromechanics to explain the failure mechanism. Goh et al. [2] adopted the impact damage being substituted by preset bondline flaws to study the damage tolerance of the composite scarf joints. Cheng et al. [4] investigated the insight of damage mechanisms in scarf repair of composite structures under tensile load but lack of detailed plies and adhesive damage sequence and locations. Pinto et al. [5] only used Cohesive Zone Modelling for simulation of the damage and growth in the ductile adhesive layer. Liu and Wang [6] studied the tensile behavior of composite patches by experiments and 3D progressive damage model. In this paper, we adopted the substituted scarf joints instead of complicated scarf repairs.

Understanding the failure mechanisms and their interactions at each length scale is critical for the robust design [7]. Because experiments cannot tell us the materials damage sequences and damage locations of the different materials, we adopted FEM based on continuum damage mechanics (CDM) to help the experiment.

Harman and Wang [8] deduced the improved governing equation to get the shear stress of scarf joint. In this paper, we modified Harman and Wang's analytical method and formed an alleged modified semi-analytical method (MAM) by applying the concept of differential and rule of composite ply stiffness distribution. The objective of MAM is to solve the imperfect of the analytical method by Harman and Wang, such as asymmetry, inexistence of secondary peak of shear stress, and relatively low peak of shear stress.

## 2. Experiments and results

The scarf joint [9] substituted the scarf repair of composite structure in this paper. Because the stress state of scarf joint

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represented the most dangerous location of the scarf repair no matter what kinds of plane loads e.g. biaxial loads. In order to verify if scarf joint (Fig. 1) could replace the maximum stress state in scarf repair (Fig. 2), FEM was connected to these two models, in which the adherends were homogenous materials by comparing the stress distribution. Certainly the anisotropic material analysis also has been operated. From Figs. 3 and 4, when the circle direction $\varphi$ varies, the maximum stress located as $\varphi = 0°$ and the stress state of scarf joint is basically similar to $\varphi = 0°$ of scarf repair. This demonstrates that scarf joint model indeed can substitute scarf repair model as basic research.

### 2.1. Details of the specimens

Considering the scarf repair as the primary-load bearing composite structures, the experimental investigation used 4 mm thickness composite scarf joint made from T700/LT03A unidirectional carbon/epoxy prepreg and FM73M. The composite layup sequence is $[45/0/-45/90/0/45/0/-45/0/0/90/0/-45/0/45/0]_S$. The plies' percentage of 45°, 0° and 90° is [37.5/50/12.5]%. This kind of layup being composed of 0° of 50% is representative for primary-load bearing composite structures. The prepreg material has a nominal ply thickness of 0.125 mm and curing temperature of 120 °C. FM73M of an epoxy-based structural adhesive has a curing temperature of 120 °C and thickness along the scarf of 0.2 mm. The properties of the unidirectional plies is given in Table 1. As is shown in Fig. 5, it is schematic of specimen, in which the gray zone denotes CFRP and others denote GFRP being used to be clamped by the machine. The width of the scarf bonding zone is 45.7 mm. We pasted 5 strain gages, in which 1–3 gages were to monitor if the specimen would be loaded uniformly according to standard test method for tensile properties of polymer matrix composite materials named ASTM. Designation: D3039/D3039M-08 for simple tension of CFRP plate and 4, 5 gages were used to investigate whether the strain of bonding zone agree with the pure CFRP plate.

The scarf joints were loaded under quasi-static tension at the displacement rate of 0.5 mm/min. The failure was determined as no load-bearing capability and the strength was taken as the maximum load recorded by the machine and computer.

### 2.2. Stress and strain

During the experiments, there were no minor cracking sounds until catastrophic fracture of brittle material. The applied tensile loads and displacements at loading ends of specimens are showed in the Fig. 6 which told us that damage mode of scarf bonding joint was brittle failure. The ultimate applied stresses are 349.9 MPa, 322.5 MPa and 383.1 MPa respectively. The failure strains of gage 3 are 5680με, 5413με and 5424με respectively. In addition, by the law of the first ply failure and the principle of stiffness allocation, we could estimate the ultimate tensile stress of virgin composite laminates equaling to 1186 MPa. So the ratio of the tensile strength of the scarf joint to the as-prepared virgin composite laminates is approximately 0.296.

Fig. 7 shows five gages stress–strain in the specimen 2 which has the biggest dispersions of strain values. Strain values of five gages between 0 and 2000με coincided. It illustrates that when

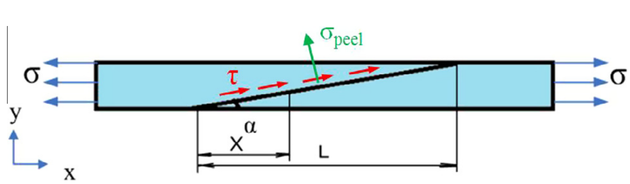


**Fig. 1.** Scarf joint model under tensile load.

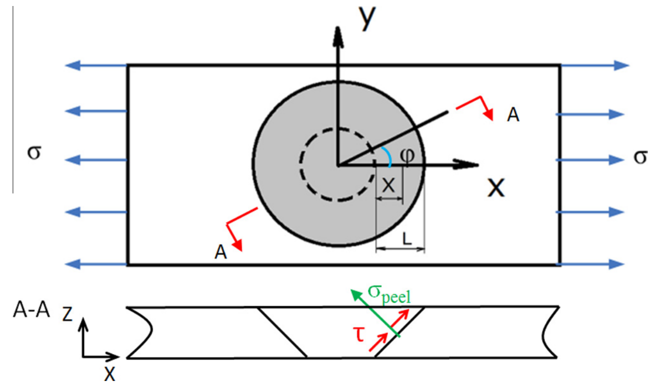


**Fig. 2.** Scarf repair model under tensile load.

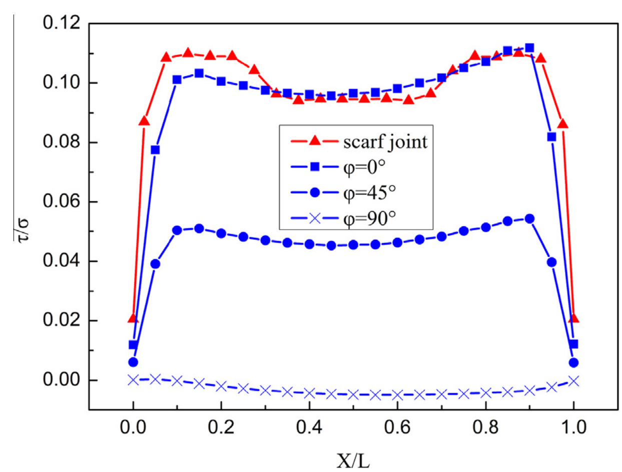


**Fig. 3.** Shear stress in the scarf repair and scarf joint.

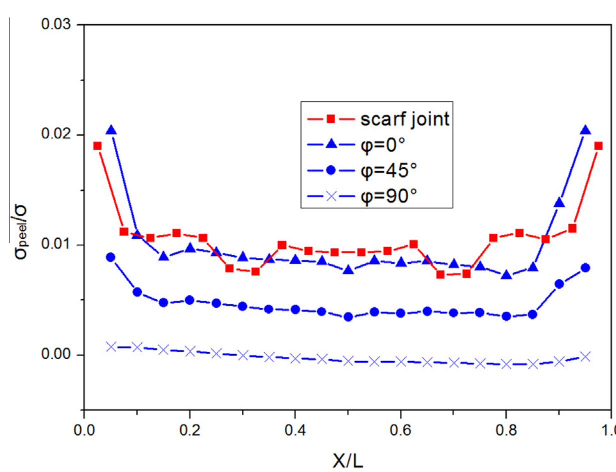


**Fig. 4.** Normal peel stress in two models.

**Table 1**
Mechanical properties of T700/LT03A and FM73M.

| Material | $E_{11}$ (GPa) | $E_{22} = E_{33}$ (GPa) | $\nu$ | $G_{12} = G_{23} = G_{13}$ (GPa) | $\rho$ |
|---|---|---|---|---|---|
| T700/LT03A | 128 | 8.46 | 0.322 | 3.89 | 1560 kg/m$^3$ |
| FM73M | 2.27 | | 0.35 | 0.84 | 1200 kg/m$^3$ |