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Effects of stacking sequence and rotation angle of patch on low velocity impact performance of scarf repaired laminates

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ABSTRACT

In this paper, a 3D progressive finite element model was established to simulate scarf repaired laminates subjected to low velocity impact, in which intralaminar damage evolution was captured by user-defined subroutine and interlaminar delamination was simulated via the failure of zero-thickness cohesive elements inserted between plies. By comparison, the numerical results are in good agreement with experimental results. Based on the validated model, the effects of patch stacking sequence and rotation angle on low velocity performances (impact loads and damages) of scarf repaired laminates were investigated respectively. Both of them have effects on the impact performance of scarf repaired laminates, but patch rotation angle has greater effect than patch stacking sequence.

1. Introduction

Composite materials possess some advantages such as high specific strength, high specific stiffness and flexibility in structure design, thus their structure weight can be reduced while the requirements of mechanical properties are met. Based on these advantages, composite materials have been used widely recently, and such a trend is clearly in the aeronautic, astronautic and marine applications especially [1]. The events of low velocity impact of composite structures, e.g. the drop of tools and the collision of other objects, are inevitable during their service. Generally, the damage of composite structures caused by low velocity impact belongs to barely visible impact damage (BVID) and such damage will threaten structure integrity and safety greatly [2]. The structures are generally repaired after damaged, and repaired structures would be also threatened by low velocity impact.

Scarf repair, a main method among adhesive bonding repair of composite structures, is extensively used in aeronautic structures as a permanent repair way because of the advantages such as high recovery rate of strength, smooth aerodynamic surface and low eccentric load [3,4]. Investigating the impact properties of scarf repaired laminates is helpful to learn more about their damage mechanism and to improve the repair design. However, most of the present researchers have focused on either the static properties of scarf repaired laminates or low velocity impact properties of intact laminates, but less about low velocity impact properties of scarf repaired laminates.

As the simplification of 3D scarf repair problem, scarf joint (2D) has been studied by many researchers. Li et al. [5,6] studied the damage of carbon fiber composite scarf joints with pre-strain subjected to low velocity impact. They found that the scarf joints are sensitive to the level of the pre-strain. Hoshi [7] studied the effect of scarf angle on the impact properties of composite scarf joints. The results indicate that the scarf joint with a larger scarf angle has a larger impact damage area. Harman [8,9] investigated damage tolerance and impact resistance of composite scarf joints and obtained that the presence of the scarf joints can reduce the damage tolerance of the base structure by the introduction of a tapered tip which is critical to the overall repair strength and

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vulnerable to delamination when subjected to low velocity impact. But the scarf joints belong to a 2D problem, which is simpler compared with 3D scarf repaired structures.

Chotard et al. [10] experimentally investigated the static, fatigue and low velocity impact properties of scarf repaired U-shaped and box-shaped composite structures. They measured the impact load-time curves and found that the scarf repaired structures have higher dynamic rigidity and strength than the intact ones. This is due to the new local structure created by the patch repair that allows more impact energy to be absorbed and dissipated. Takahashi [11] detected the low velocity impact damage of scarf repaired laminates with Lamb wave and ultrasonic methods and found that the damage area in the adhesive increases with the increase of impact energy. Cheng et al. [12] found that scarf repaired laminates with different impact locations have different CAI strengths. The debonding area between the adherends becomes large while the impact location gets close to the surface edge of the patch. The damage threshold load reaches the minimum when the location is at the patch center. Liu et al. [13] investigated CAI strengths and damage of scarf repaired laminates under different impact locations. The results show that the repaired laminates have higher impact resistance when impacted at patch center, while the lowest impact resistance occurs with impact location at the patch edge. Most investigations have focused on the impact model establishment and some influence factors, including impact location and energy.

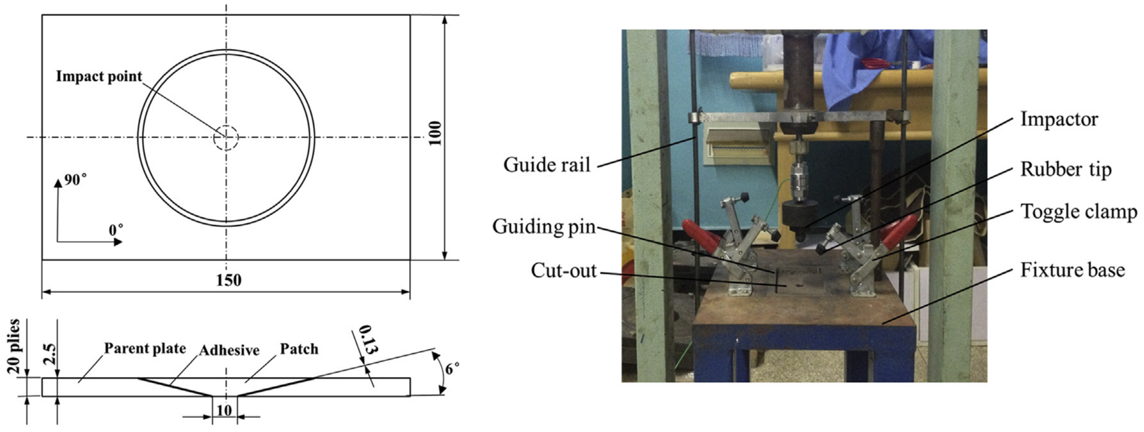
In scarf repair operation process, there is likely mismatch of the stacking sequence and ply angle between the patch and base plate. Ply angle mismatch is generally caused by the patch rotation, and the mismatch angle is called patch rotation angle here. Thus the effects of patch stacking sequence and rotation angle need to be investigated in engineering. The effect of stacking sequence on laminate properties has been investigated a lot [14–16]. Riccio [16] established numerical models to study low velocity impact properties of the laminates with different stacking sequences and found that the stacking sequence has an effect on impact properties of the laminates. However, researches on the effects of patch stacking sequence and rotation angle have been rarely reported.

In this paper, a finite element model based on the user-defined material subroutine (VUMAT) was established to simulate scarf repaired laminate subjected to low velocity impact. The model was verified by experimental results. Then, the model was used to study the effects of patch stacking sequence and rotation angle on low velocity impact performances of scarf repaired laminates. The results can be as a reference for process tolerance in repair design of composite structures.

2. Specimen and experiment

The material used in the specimens is T300/5228A carbon/epoxy unidirectional prepreg with nominal thickness of 0.125 mm. After the laminate was laid in stacking sequence of $[45/0_2/\text{-}45/90/45/0_2/\text{-}45/0]_S$, it was cured in 180 °C and 0.6 MPa conditions in autoclave for 2 h. Then, the laminate was cut into intact specimens of 150 mm × 100 mm with the long side in 0°. The “damaged” material was removed in the center of specimens with scarf angle of 6° and small circular hole diameter of 10 mm by CNC-router. Hard patches were applied to repair the specimens at the center, and SY-14M adhesive film with nominal thickness of 0.13 mm was used to bond the patches and base plates. Then, the specimens were cured in 180 °C and 0.1 MPa conditions in an oven for 2 h. The specimens were detected by ultrasonic C-scan to ensure them without initial damage. The configuration of scarf repaired specimens is shown in Fig. 1 (a), and material properties of the ply are shown in Table 1. The elastic modulus and Poisson's ratio of the adhesive are 3.4 GPa and 0.31 respectively.

Low velocity impact experiment was carried out with dual-rail drop-weight impact test machine according to ASTM D7136 [17], and impact fixture is shown in Fig. 1 (b). The impactor is a steel hemisphere with a radius of 8 mm and weight of 5.5 kg. The specified ratio of impact energy to specimen thickness of 6.67 J/mm was achieved by adjusting the height of the impactor, and the



(a) (b)

Fig. 1. Specimen and impact fixture. (a) configuration of scarf repaired specimen, (b) impact test fixture.

Table 1
Material properties of the ply T300/5228A.

E_1 (GPa)	E_2,E_3 (GPa)	ν_{12}, ν_{13}	ν_{23}	G_{12},G_{13} (GPa)	G_{23} (GPa)	X_t (MPa)	X_c (MPa)
144	9.3	0.312	0.32	4.68	4	1633	1021
Y_t (MPa)	Y_c(MPa)	S_t (MPa)	S (MPa)	G_{ft} (G_{fc}) (N/mm)	G_{mt} (G_{mc}) (N/mm)	G_s (N/mm)	G_{st} (N/mm)
53.8	232	80.4	90	180 (100)	4 (10)	2.5	2.25