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The impact damage and residual load capacity of composite stepped bonding repairs and joints

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ABSTRACT

Step topology adhesively bonded structure is preferable applied in composite repairs and joints of primary load-bearing structure. The failure mechanism and responses under low velocity impact are still not expressly revealed. A series of experiments for impact are conducted. Responses of impact contact load, deflection, absorbed energy and speed were tested. A critical impact energy of adhesive damage and residual strength was found. Above the energy level, tension capability after impact would drop largely. The stepped adhesive damage occur in the second step to the fifth step. The bondline damage modes include adhesive cohesive failure, composite-adhesive interface failure, matrix crack, interlamina delamination. The failure adhesive, interlamina, and matrix are bear tension-shear combined stress in the bottom-half at thickness direction. To testify the failure mechanism and reveal more, a progressive damage model of FEM based on zero thickness cohesive zone method was built. The constitutive relation is considered linear strain softening. The simulation results show more accurate damage detail of adhesive and composite materials with time varying. Synthesizing experimentation and simulation, the failure mechanism of composite stepped structure with impact load is distinctly known. The experimental results also help the parametric inversion of the simulated model. The cohesive zone element parameters of stiffness, strength and fracture toughness are validated and useful.

1. Introduction

Fiber reinforced polymer composite material has been a preferred material for aircraft structures. As composite materials are used largely, the demands for parting surface jointing and damage material repairing will be arising. Composite stepped bonding structures are applied to composite joints and repairs in aircraft structures. Because it has advantages e.g. dispensing with drilling holes, possessing flush shape, reducing stress concentration, satisfying stiffness and strength design requirements, and so on. Some opening papers state that scarf repair or joints are better than stepped repair or joints because scarf topology has smaller stress concentration. However, in real aircraft jointing and repairing engineering for composite structures, stepped topology is easier implemented than scarf. Hence, studying composite stepped bond structure is of important significance.

Randolph [1] indicated that the approaches which have been suggested in open literature for modelling composite repairs are not entirely adequate. Thus, modelling approach that provides an overall view of bonded repairs for composite structures is needed. Li [2] proposed a three-dimensional semi-analytical model for the composite laminated plates. It bases on the state space methods and meshless method. Wang [3] emphasized the composite repairs are increasingly important in primary load-carrying structures. Composite repairs' two design approaches were reviewed. They are safe-life approach and damage tolerance methodology. It draws conclusions that multi-step repairs exhibit a higher stress concentration than scarf repairs [4] of the same length. However, the FEM modelling method and stress analysis needs to be studied more systematically and deeply. Experimental and computational failure mechanism also need to be investigated in development. The precise stress distribution, load capacity, damage mode and failure mechanism should be known well especially for the increasingly used primary bonding structures in the future.

Impact has strong influence to composite stepped and scarf repairs [5–7]. It is found that out-plane load could cause higher peel stress concentration than in-plane load, and adhesive crack mode is mixture mode then transform to pure mode II [8]. Health monitoring technique was applied to detect scarf adhesive damage [9]. The impact damage tolerance for composite scarf repair structure was compared with laminate plates [10]. CAI (Compression after Impact) mechanical performance for 2 mm thickness stepped repair was experimentally studied [11]. Experiments of multiple low velocity impact and CAI was studied for GFRP bonding lap joints [12]. The patch of GFRP(Glare Fiber

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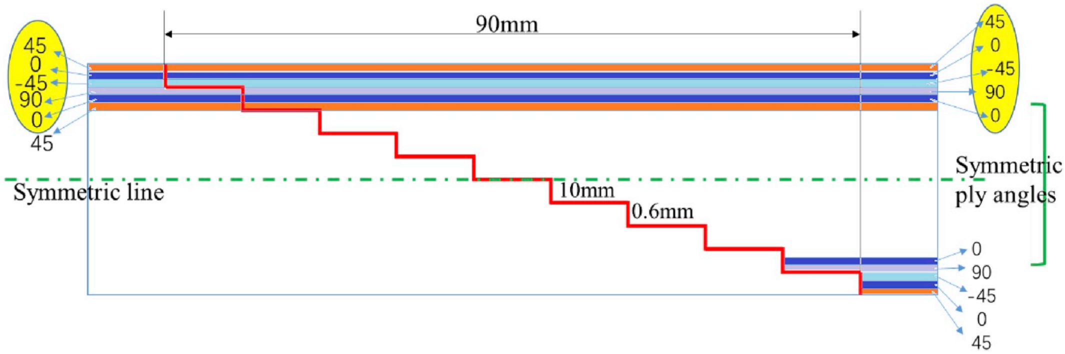

Fig. 1. The schematic of the composite stepped bonding structure.

Reinforced Plastics) stepped repair structures could absorb 50%–80% impact energy [13]. The honey comb GFRP structures repaired by lap joint are damaged on the surface with 3 J, and are penetrated with 8 J impact energy [14]. In summary, composite scarf repairs or joints under impact load were studied by few researchers. The studies for composite stepped structures are mostly GFRP. The CFRP stepped repairs or joints are rarely studied. Moreover, impact response and damage mechanisms are not researched systematically. The conjunction investigation of macroscopic damage phenomenon and microscopic failure cracks also should be conducted.

2. Materials, processing craft, specimens size and test matrix

In order to investigate the stress distribution for composite stepped bonding repairs and joints, the typical composite stepped bonding structure were specially designed. The geometry and plies are schematically shown in Fig. 1. The laminate plies stack sequence is $[45/0/\text{-}45/90/0]_{3S}$. The total plies number is 30. Each three plies make one step and the total steps number is 10. Each ply thickness is 0.2 mm. The whole bonding area length is 10 mm and the thickness is 0.6 mm. The stepped bonding structure size is 250 mm × 25 mm × 6 mm. The adhesive thickness is 0.15 mm. The adhesive material is LOCTITE-EA-120HP. The composite materials are Carbon Fiber Reinforced Plastics (CFRP). The carbon fibers are T300 series. The matrix material is an epoxy resin. The single ply thickness can be controlled by spreading out 128 carbon fiber bundles in 1 m^2 area. The adhesive thickness can be controlled by embedding silicon carbide particles with diameter 0.15 mm. When the two composite adherends are compressed and solidified. The particles play the part of limiting distance of adherends.

The specimen material, geometry and size are same with section 2. Process craft is shown in Fig. 2. For step overlap bonding structure, aluminum mold of steps was milled. Prepreg was then clipped to different length and lie to mold in sequence. The pregreg and mold were put together into autoclave and solidified. Then the adhesive was brushed uniformly on the step surface. Two composite adherends were combine and compressed together for at least 48 h at ambient temperature. Finally, the whole composite bonding structure was cut into 250 mm × 25 mm × 6 mm specimens (see Fig. 3). (see Table 1).

3. Experiments

In the tests, the responses of impact load, absorbed energy, speed and deflection were monitored and saved. Different energy levels of 3 J, 4 J, 5 J, 6 J, 8 J and 10 J were conducted respectively. After impact testing, specimens were cut into two segments along the central line. Specimens can be analyzed under optical microscopic. The details of microscale cracks will be illustrated as follows.

Fig. 2. Composite stepped bonding specimens process craft.

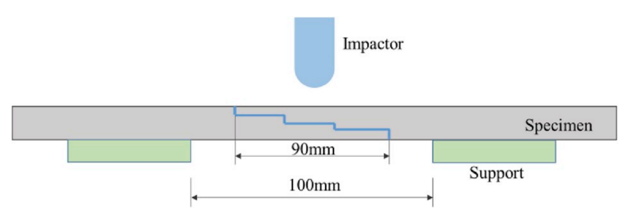

Fig. 3. Schematic of impact test setup.

3.1. Impact load, absorbed energy, speed and deflection

The impact tests in different energy levels were set by giving the impact tip different initial velocities. As are shown in Figs. 4–8, impact load and absorbed energy vs. time could reflect the impact procedure. Fig. 7 shows the relation of deflection and speed vs. time. First, we focusing on the impact load. Impact load of 3 J case tells us that graph looks like a parabola. However, as energy level increases, the impact load curves appear the force peak and the force drop. There are a distinct force drop before the absorbed energy reaches to be stable for the relatively high energy levels. Second, as impact energy increases, absorbed energy of specimen becomes more. The ratio of absorbed energy escalates likewise with impact energy level increasing. The absorbed energy ratios to impact energy 10 J, 8 J, 6 J, 5 J, 4 J and 3 J are 64%,