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Numerical and experimental investigation on hail impact on composite panels

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A B S T R A C T

Hailstone impact on composite structures may result in severe damages while aircrafts are flying. Therefore, it is necessary to investigate the damages due to high-velocity hailstone impact on composite laminates. In the present work, a three-dimensional digital image correlation (3D-DIC) method was employed to measure the deformation field of the aluminum alloy plate under hailstone impact. By comparing the results of experiments and simulations, the hailstone constitutive parameters were validated. With the validated hailstone constitutive model, the influences of composite layup, type of reinforced fiber and matrix, impact velocity as well as initial angle of impact on the damage evolution of composite laminates were numerically investigated.

1. Introduction

The extensive application of composites can be seen in a variety of aircraft structures. Flying through a hailstorm is extremely dangerous for aircrafts' safety, especially for exposed composite structures, such as aircraft fuselage, wing skins, leading-edge, control surfaces, engine nacelles, and fan blades. Hailstone impact on the structures is a transient and localized process, characterized with high loading amplitude and high strain rate. The impact of hailstones on aircraft with cruise velocity is probable to cause damage or delamination in composite structures. Since delamination of composite structures is hard to be detected and could lead to significant drop in compressive strength of composite structures, it is essential to investigate the influence of hail impact on the composite laminates.

Most previous studies focused on the investigations of low-velocity metal projectiles' impact on composite structures. A comprehensive review of these works can be found in a review article by Abrate [1]. Jackson and Poe [2] investigated the responses of low and high velocity impact events and highlighted the remarkable distinctions between them. The results indicated that the peak force was a key parameter for evaluating delamination, and structural deformation was found to occur in the local contact area of projectile and target during high velocity impact process. Meanwhile, in case composites are loaded at high strain rates, their mechanical properties, such as stiffness, strength, energy absorption and failure modes, will change more or less. Kim et al. [3] conducted the experiments of spherical-shaped hailstones' impact on woven composite panels. A linear relationship between the peak force and the projectile kinetic energy was observed, while the velocity did not significantly affect the time to peak force. High speed photography showed that the failure of composite panels occurred almost immediately after the first contact between the projectile and the plate, with only a small amount of localized deformation at the time of failure. Because of the localized deformation at the damage initiation, the boundary conditions do not strongly affect the damage modes. Zhu et al. [4,5] pointed out that the localized deformation and fiber crack were the major energy absorption mechanisms of the composite panels during high velocity impact. Furthermore, the compressive wave induced by the impact would reflect at the backside of the composite panel and turn into tensile wave, thus leading to delamination between layers.

Ply design of composite laminates is also believed to play an important role in impact damage resistance of composite laminates. Kim and Sham [6] investigated the interlaminar performance of woven-fabric and unidirectional laminates. In general, the woven-fabric laminates displays better interlaminar performance than their unidirectional counterparts, with a lower maximum load as well

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as a smaller damage area, etc. The high velocity impact response of composite and FML-reinforced sandwich structures was also investigated by Reyes Villanueva and Cantwell [7]. It was shown that the delamination and longitudinal splitting of the composite skins occurred in the unidirectional fiber laminates. On the contrary, the woven fiber/polypropylene-based sandwich structures exhibited higher impact resistance under high velocity impact, with a smaller amount of delamination. Moreover, ply orientations contributed to the anisotropy of composite laminates. The damage area of the composite laminates is not symmetrically circular but approximately elliptical [8,9].

In the aspect of numerical simulation, Kim and Kedward [10] simulated the impact of high-velocity spherical ice projectile on the composite plates with the explicit finite element code DYNA3D. The hailstone was simulated as Lagrangian FE model, and a good agreement with experimental results was achieved. The efficiency of three different numerical models of hail, the Lagrangian FE model, the Arbitrary Lagrangian–Eulerian (ALE) model and the smoothed particle hydrodynamics (SPH) model, in simulating the hailstone impact responses, was investigated by Anghileri et al. [11]. By comparing the numerical results with the experimental data, it was proved that the SPH model was the most effective one and it could reproduce the dynamic behavior of hailstone in case of high velocity impact. The CPU-time of SPH model was found to be much smaller than that of two other models.

In the present work, the SPH model was used to simulate the spherical hailstone which was projected onto the composite laminates with the explicit FE code LS-DYNA. Meanwhile, the three-dimensional digital image correlation (3D-DIC) method was employed to measure the deformation field of the aluminum alloy plate under hailstone impact. The experimental results were compared with the simulation results to validate the hailstone parameters in numerical simulation. Finally, the validated numerical model was employed to investigate the influence of composite layup, type of reinforced fiber and matrix, impact conditions, such as impact velocity and initial angle of hailstone, on the damage evolution of composite laminates.

2. Experiment and simulation details

2.1. Experimental details

For validating the hailstone constitutive parameters as well as the numerical model, three 2024 aluminum alloy plates with the thickness of 1 mm were experimentally impacted by artificial hailstone at the velocities of 174, 216 and 252 m/s respectively. The plates were fixed in a steel frame type fixture to ensure the edges of targets were constrained firmly during impact. Since it is difficult to collect the natural hailstones, the hailstones were made of pure water which was injected into an aluminum mould and frozen at a temperature of −15 °C. One thing worth mentioning is that the reason −15 °C is selected for freezing artificial hailstone is limited by refrigerating capacity of the freezer in the lab. The diameter of the spherical artificial hailstone was 42.7 mm. In experiments, polyurethane sabots were employed to support the hailstones while traveling in the air gun. When the sabot arrives at the end of the air gun, it is separated with the hailstone by a separation device, enabling the artificial hailstone to impact the target alone. Since the mechanical properties of ice depend on temperature [12], to prevent the increase of temperature or even the melting of hailstone, before the sabot and artificial hailstone were installed into the air gun, they were frozen in a refrigerator for over one day at a temperature of −15 °C. In the experiments, they were loaded into the air gun immediately after removal from the refrigerator so that change of the surrounding temperature would not affect the mechanical properties of hailstone remarkably.

The schematic illustration of experimental setup is shown in Fig. 1. The velocity of hailstone was controlled by the pressure in the air chamber, and then measured by laser velocimeter. To record the entire process of the target deformation, there were two high-speed video cameras standing on the back of the target. The 3D-DIC method, an effective, without strain gauges but only painted speckles on the surface of target, non-contact full-field measurement approach was adapted to analyze the three dimensional deformation fields. During the tests, a 250 mm × 250 mm square

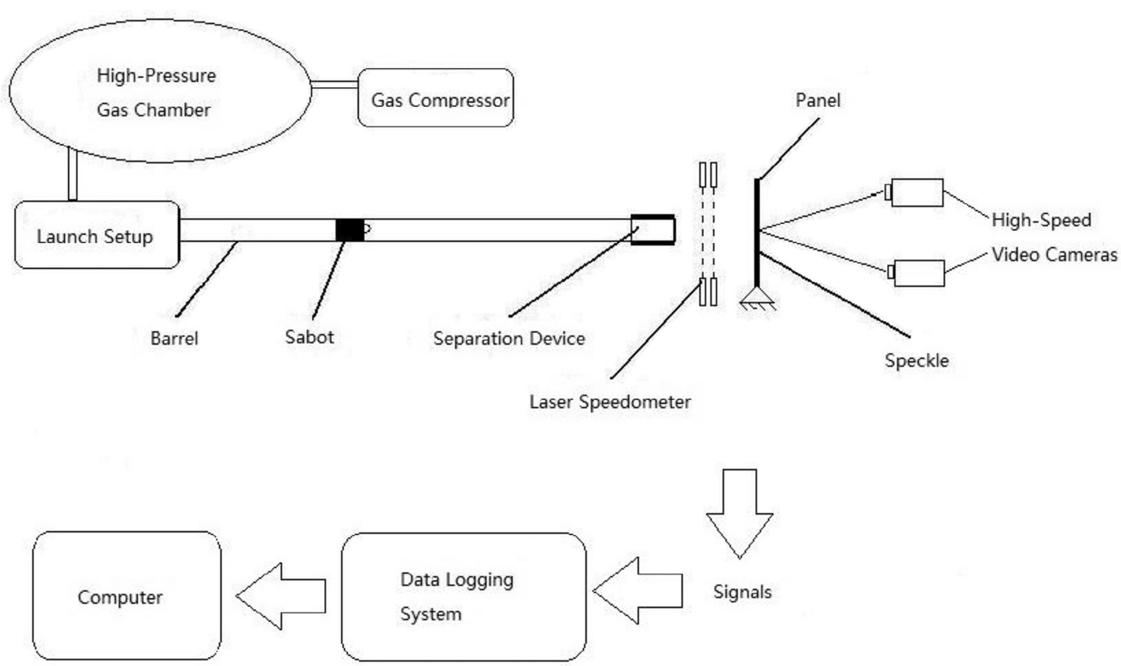

Fig. 1. The schematic illustration of experimental setup.

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