HAIL IMPACT ON COMPOSITE STRUCTURES OF CIVIL AIRCRAFTS

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ABSTRACT

Because of the weakness of composite laminates in the out-of-plane direction, the localized hail impact on composite structures can result into the very dangerous potential failure during the future service life of aircraft. The hail impact on the composite structures was experimentally and numerically investigated to understand the failure process of hailstones during impacting and its resultant damage on composite laminates. A survey has firstly been performed based on the literature review of hailstorm climatological data in order to obtain the hailstone threat extremes for design from meteorological aspect. The hail impact experiments were performed by using the gas guns for composite laminates. Based on the Smoothed Particle Hydrodynamics (SPH), the finite element models were established in LS-DYNA to simulate the failure process of hailstones during high velocity impact and the resultant impact damage in CFRP laminates. By comparing results, the numerical analysis procedure was validated and the influences of the hailstone's diameter and velocity were evaluated.

1 INTRODUCTION

Although the development of weather forecast can make the intersections between flight routes and hailstorm region as few as possible, completely avoiding passing through a hailstorm is not possible for civil aircrafts. When hailstones impact the aircrafts, the exposed structures, such as fuselage and wing skins, leading edge, control surface of empennage etc., can be seriously damaged. Because of the weakness of composite laminates in the out-of-plane direction, the localized hail impact on composite structures can result into the very dangerous potential failure during the future service life of aircraft.

Comparing to the Foreign Object Damage (FOD) caused by the normal threats sources such as the tool drop, runway debris and birdstrike, the hail impact damage may not be visible to visual inspection due to the lack of obvious dent, fiber tear-off, matrix cracking etc. However the delamination inside composite components or disbond between skins and stringers caused by hail impacting can decrease the load carrying capacity of aircraft structures to an unaccepted level, which should be considered as a serious working scenario.

As specified in airworthiness regulations (such as in the JAR from Europe or FAA from United States), the composite structures of modern civil aircraft are required to guarantee a certain level of functionality after having been impacted by hailstones. Therefore, how to accurately estimate the impact damage caused by hailstones is a challenging but urgent request from civil aircraft OEMs in damage tolerance design of composite structures.

Concerning the experimental study of hail impact in laboratory the only widely accepted testing standard was ASTM F320[1] which is designated for aerospace structures instead of for aircrafts. Besides the aforementioned standard much efforts were done to better understand the mechanical behaviour of hailstones and the damage pattern caused by the multi-impact of hail through both experimental and numerical methods. The drop weight facility were employed to introduce the repeat or multiple impacts on composite structures and the impact damage were found accumulating with the repeat impacts [2,3]. However the experimental results indicated that the interference between impacts at different locations were insignificant and can be ignored [4]. By comparing the delamination area, one impact with big energy were noticed producing to more serious damage than several impacts with small energy[5].

In this paper, the hail impact experiments were performed by using the gas guns for composite laminates. Based on the Smoothed Particle Hydrodynamics (SPH), the finite element models were established in LS-DYNA to simulate the failure process of hailstones during high velocity impact and the resultant impact damage in CFRP laminates. By comparing results, the numerical analysis procedure was validated and the influences of the hailstone’s diameter and velocity were evaluated.

2 EXPERIMENT INVESTIGATION OF HAIL IMPACT DAMAGE OF COMPOSITE STRUCTURES

A survey has been performed based on the literature review of hailstorm climatological data in order to obtain the hailstone threat extremes for design from meteorological aspect[6]. The diameter of hailstones are found to be no larger than 50 mm and more than 50% hailstones in a hailstorm have a diameter less than 20 mm. Following the meteorological hail extremes, 2 inch diameter hailstones were employed in the present study to perform the hail impacting tests. Moreover, three different velocities representative to the ground and in-flight hail impact were considered.

The hail impact experiments were performed for the medium modulus, high strength CFRP laminates. The simulated hail ice (SHI) was manufactured following the instruction in [1] to represent the natural hail balls, and fired by the gas guns to produce the hail impact damage. The test matrix was shown in Table 1.The composite laminates were fixed by eight steel bolts to the testing support frame and a layer of rubber cushion was placed between the laminates and support frame in order to avoid unexpected stress concentration and damage at the edge of frame during impacting. The failure procedure of the hailstone is captured by the high speed and after impacting the impact damage of CFRP laminates was recorded using Non-Destructive Inspection (NDI) technologies.

Test	Thickness [mm]	Lay-up code	No. of specimens	Length [mm]	Width [mm]	Velocity [m/s]
1	4.6	A	2	460	460	80
2	3.1	B	2	460	460	160
3	4.6	A	2	460	460	240
Total	-	-	6	-	-	-

Table 1: Hail impact test matrix

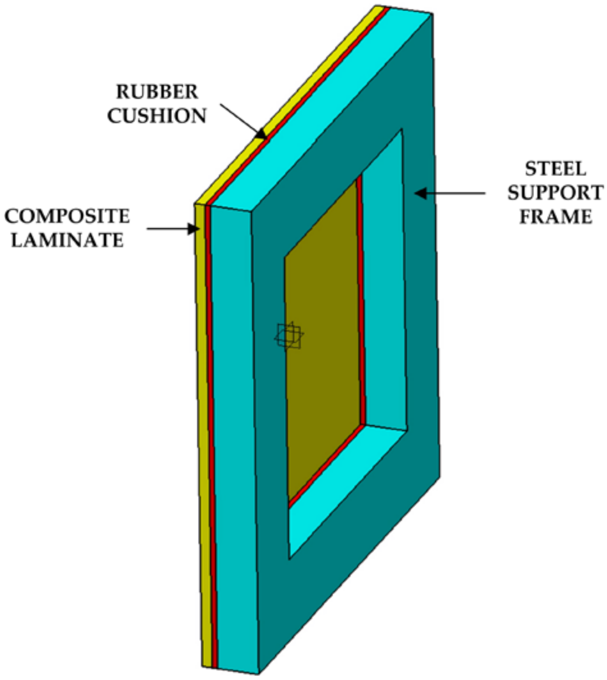

Figure 1: Support frame for composite laminates in hail impact experiments

In total, six hail impact tests were performed for the composite laminates with different impacting velocities. The collapse failure process of hailstones was captured by the high speed camera as shown in Fig. 2. Based on the NDI results, the experimentally obtained damage patterns and locations are shown in Table 2. The main damage pattern was observed as the composite delamination without any sigh of impact dent, which is merely different to the metal structures. The impact damage location was found to be significantly dependent on the impact velocity. For medium velocity hail impact, no obvious delamination of CFRP laminates was noticed in the impacting region. The damage was only found in the clapping areas due to the stress concentration from the bolts fixing the laminate to the support frame. However in high velocity hail impact tests, merely serious delamination occurred in the impacting area and the fiber rupture was found on the back-side surface of laminates. A typical delamination damage in the CFRP laminate resultant from the high velocity hail impact is presented in Fig. 3.

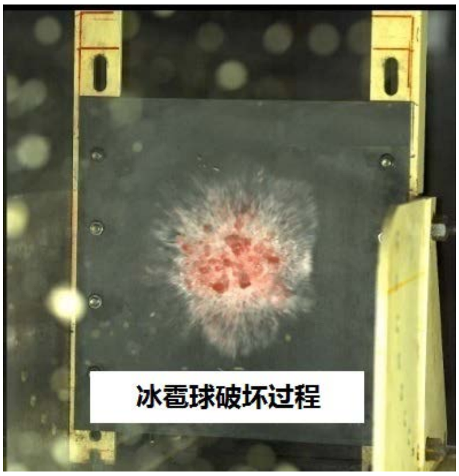

Figure 2: collapse failure process of hailstones during impacting

Specimen NO.	Velocity [m/s]	Damage pattern	Damage location	Damage area [mm^2]
1	80	Delamination	Closed to bolts	180
2	80	Delamination	Closed to bolts	250
3	160	Delamination	Impact region	21,000
4	160	Delamination	Impact region	13,500
5	240	Delamination	Impact region	59,000
6	240	Delamination	Impact region	65,000

Table 2: Damage pattern and location of composite laminates

Figure 3: Imapct damage in the CFRP laminate cause by high velocity hail impact

3 NUMERICAL MODELING OF HAIL IMPACT DAMAGE ON COMPOSITE LAMINATES

The commercial finite element (FE) software LS-DYNA was utilized in present work to simulate the hail impact process in benefit of its extensively advantages in performing explicit dynamic simulations. In the procedure of medium or high velocity impacting, the hailstone exhibits a completely different behavior compared to the rigid impactor which is commonly used in the drop-weight test. When impacting, the hailstone does significantly deform and finally collapses on the surface of structures (see Fig. 4). The large deformation and collapse failure mode may disable the traditional Lagrangian method providing accurate simulations. Thus, the mesh-free smoothed particle hydrodynamics (SPH) method was employed in present work to model the hailstones[7,8]. With the absence of mesh, the hailstone was discretized with a number of regular distributed particles who had certain mass. When the deformation between a pair of mass particles was reaching a threshold their link was separated, in other word the hailstone partially collapsed, and no more load can be transferred.

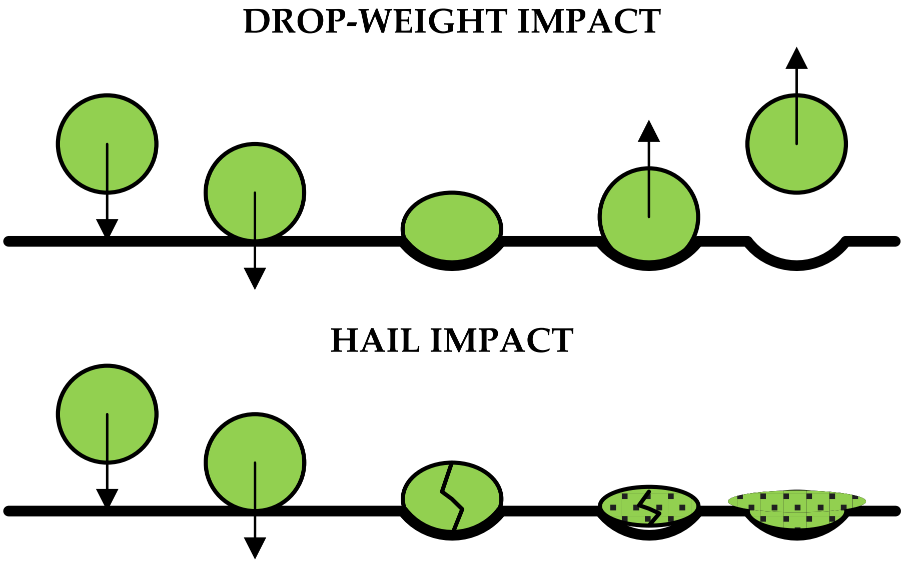

Figure 4: Impact damage in the CFRP laminate cause by high velocity hail impact

In FE models, the hailstone was modeled suing the elastic null material MAT_009 in LS-DYNA and meshed with SPH particles. The Gruneisen equation was taken as the equation of state (EOS), which defines the phase changes of hailstones from solid into liquid. The composite damage MAT_054 was used for composite laminate, which was meshed into two-dimensional shell-like elements. An explicit FE analysis has been performed to model the failure process of hailstones and impact damage of composite laminates. The failure process of hailstones obtained from FEA was shown in Fig.5 which was validated by the video captured by high speed camera in experiments. Moreover Fig.6 shows the typical damage pattern and location produced by the high velocity hail impact, and it was noticed being comparable to the damage region obtained from NDI.

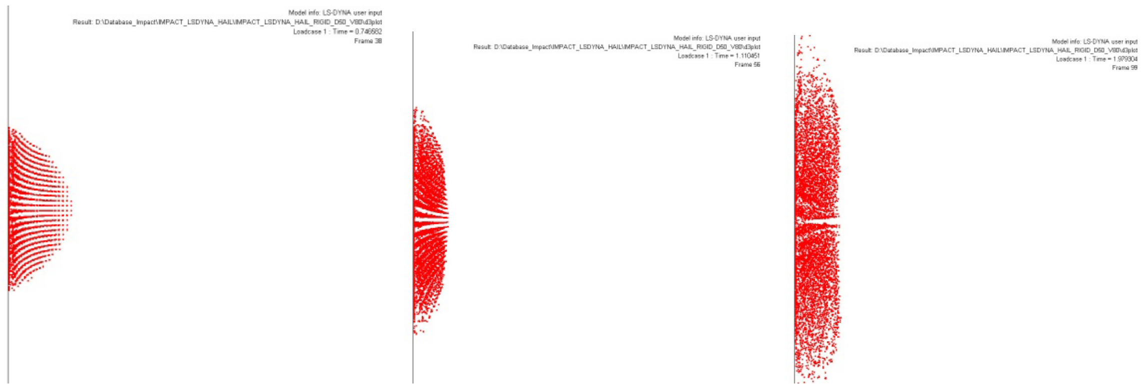

Figure 5: Numerical modeling of failure procedure of hailstone

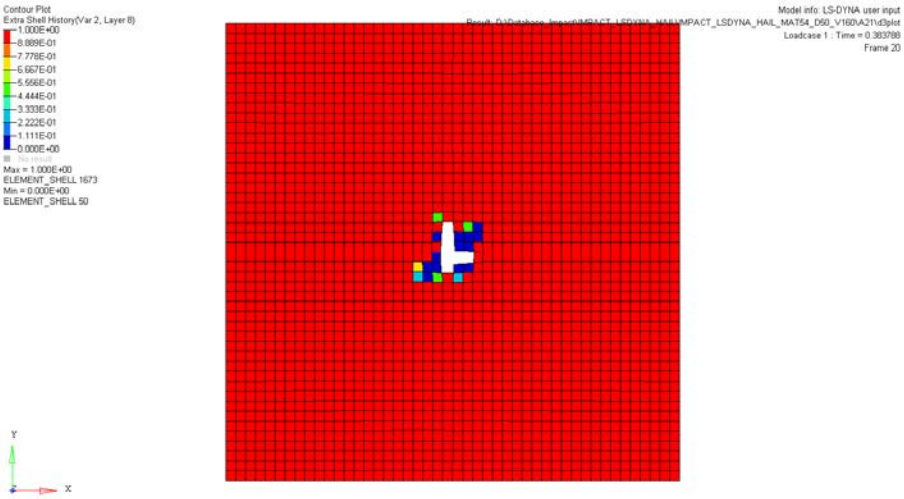

Figure 6: Damage pattern and location of composite laminate in high velocity hail impact

4 CONCLUSIONS

The medium and high velocity hail impact on composite structures of civil aircraft was experimentally and numerically investigations. The following conclusions can be summarized:

1) The experimental results indicate that the high velocity hail impact may produce serious delamination of composite laminate in the impacting area without leaving any sigh of dent or crack on the surface. It indicates that the "invisible from outside" characteristics of hail impact damage may lead to difficulties in daily visual inspections during civil aircraft service life. Certain very dangerous delamination might be ignored due to the lack of VID (Visible Impact Damage). This present work provided a solid evidence encouraging civil aircraft manufactures and airworthiness authorizations to improve current damage tolerance certification design for composite structures;

2) A numerical analysis procedure using explicit FE method was developed and can be used to predict the failure of hailstones during high velocity impacting and the resultant impact damage of composite laminates. Comparing to the very expensive and time consuming hail impact experiments, the numerical analysis may be considered an efficient alternative for the parametric investigations and pre-test calculations of hail impact study.

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