Modeling Hailstone Impact onto Composite Material Panel Under a Multi-axial State of Stress

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ABSTRACT

Flying through a hailstorm is dangerous not only for the direct damages but also for the hidden damages which may concur to more serious accidents. In this work, hail impact onto composite structure under a multi-axial state of stress is investigated. Initially, a reliable model of a hailstone is developed referring also to the recent research on ice modelling. In parallel, a numerical model to predict delaminations in pre-stressed composite structures caused by low energy impacts is developed and validated against experimental data. Finally, the impact of the hailstone onto a composite structure is simulated.

Keywords

Hail impact, Carbon Fiber Reinforced Plastic, Delaminations

INTRODUCTION

Flying through a hailstorm is extremely dangerous for aircrafts. The impact of a number of hailstones (even if small in size) at aircraft cruise velocity is likely to have serious consequence. The aircraft parts most touched by this threat are the leading edges of wings and tail surfaces, the rudders, the engines, the pilots' windscreens and the radome. Even when it is not likely to cause the collapse of the aircraft structures, a hailstone impact is a menace for what is known as *invisible damage.* As a consequence of a hailstone impact, in fact, delaminations in structures made with composite materials may occur. Delaminations are not readily detectable and, therefore, are likely to concur to serious accidents. In effort to avoid concurrent cause accidents, it is important to predict the entity of damages caused by hail impact.

In recent years, the development of explicit codes based on *Finite Element Method* (FEM) and the progresses in computer technology have made possible to simulate complex problems such as the simultaneous impact of a number of hailstones onto a composite structure.

A numerical model validated against experimental data is both a reliable tool to investigate the consequence of a hail impact and a feasible framework to develop high resistance low-weight structures.

In this research, the consequences of a hailstone impact onto composite structure in terms of hidden damages and delaminations are investigated. Hailstone impacts are low energy impacts (low-weights and high-velocities). Low-energy impacts are likely to cause stress concentrations in the inter-ply regions where large differences of stiffness exist.

The research consists of three parts.

In the first part, the model of a hailstone [1, 2] is developed also referring to the most recent research on ice modelling [3-5]. During the impact, the hailstone undergoes finite deformations and its behaviour is strongly characterized by the transition from solid to liquid. In order to accurately evaluate the impact loads (magnitude and time history), it is mandatory to reproduce whole the features of the event. Indeed, the feasibility of two meshless methods, *Smoothed Particle Hydrodynamics* (SPH) and *Element Free Galerkin* (EFG), is investigated referring to the results obtained with the customary finite element approach and to the experimental data in literature [3].

In the second part, a numerical model to predict delaminations in pre-stressed composite structures caused by low energy impacts is developed and validated against experimental data. A reliable model for composite material [6] is further developed to take into account delaminations. The interlaminae are reproduced using parameters from damage mechanics and interface *cohesive* elements [7]. Notch tests on composite coupons under multi-axial stress were carried out and the delaminations in the coupons are detected with x-ray.

In the third part, the impact of the hailstone onto a composite structure is simulated and, in view of the results obtained, findings and guidelines for future investigation are drawn.

HAILSTONE MODEL

Modeling hail impact is an extremely complicate issue. A remarkable scattering exists also in laboratory tests [4]. A hail impact is characterized by large deformations and by the transition of the state from solid to liquid – which is mandatory to reproduce in effort to accurately model the event. Furthermore, the ice itself is not a single specific material but a *class* of materials.

The influence of the material model and the feasibility of two meshless models (i.e. SPH and EFG models) are here investigated referring to experimental tests described in [3].

Experimental tests

Using a nitrogen gas cannon, hailstones (i.e. 42.7 mm diameter ice balls) were shot towards a rigid target with a velocity of 73.5 m/s. The target consisted of a solid cylinder installed on a dynamic force transducer. The impact surface was coated with a Titanium plate.

Numerical model

The impact scenario and the tests facilities were modeled in detail. The target body was modeled with eight-nodes solid elements and the Titanium plate with four-nodes shell elements.

Moving from the results of previous researches [1, 2], three hailstone models were developed: the Finite Element (FE), the Smoothed Particle Hydrodynamics (SPH) and the Element Free Galerkin (EFG) models.

Three different material models were considered for the ice. For the FE and the EFG models, in particular, the material models introduced by Kim and Kedward in [3] and by NASA researchers in [5] were adopted.

Kim and Kedward suggested the use of a material model to reproduce the hardening plastic behavior and the passage of state to fluid of the ice (**MAT_ISOTROPIC_ELASTIC_FAILURE*) – the parameters of which were chosen to fit test data.

Recently, NASA researchers have implemented in LS-Dyna a new material model, namely the **MAT_PLASTICITY_COMPRESSION_TENSION_EOS* – which is characterized by a unique yield stress versus plastic strain. The strain rate effects on yield stress are modeled using two load curves that scale the yield stress values in compression and tension, respectively.

Simulations carried out [2] showed that the material model introduced by Kim and Kedward is not suitable for the SPH hailstone. Indeed, a material model (**MAT_ELASTIC_PLASTIC_HYDRO_SPALL*) using the equation of state of water provided a good numerical-experimental correlation [1, 2]. Accordingly, this material model and the one introduced by NASA researchers were adopted for SPH hailstone.

The interface between the hailstone and the Titanium plate was defined via contact algorithm enforced using penalty method (SOFT = 1).

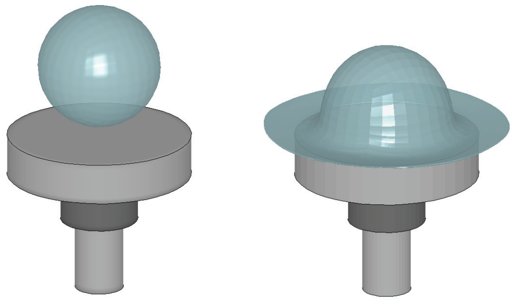
Numerical-experimental correlation

Independently from the model considered, the numerical results when compared with the experimental data provided a good correlations in terms of description of the impact dynamics and in terms of impact forces.

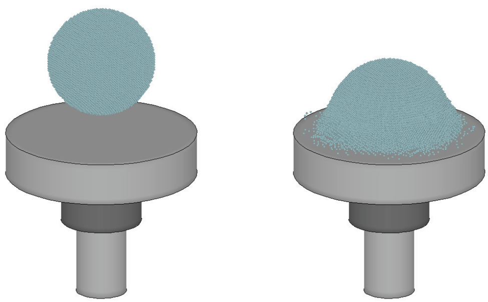
In Fig. 1 the results obtained with the material model proposed by NASA researchers are shown. The numerical-experimental correlation is good for all the FE, the SPH and the EFG models. The latter, in particular, was the model that required the smaller CPU time.

COMPOSITE MATERIAL PANEL MODEL

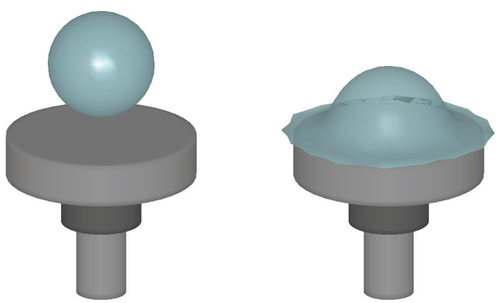
Composite material is widely used because of their excellent mechanical properties (high resistance to density and high stress to weight ratios) and may be used to build high efficiency laminated structures.



FE hailstone model



SPH hailstone model



EFG hailstone model

Figure 1. Results of simulations reproducing the tests described in [3].

Composite materials have an elastic-damage brittle behavior, exhibit complex failure mechanisms and suffer hidden damages caused by low-energy impacts.

Composite material model

Delaminations in composite materials occurs when the external loads generate high stresses though thickness shears (mode II) and the normal stress perpendicular to the laminate (mode III).

The approach adopted to model the inter-laminae (through-thickness) failure is based on *Fracture Mechanics* [8].

Cohesive elements were used to simulate the interface between adjacent laminas [8] which allow to reproduce both initiation of delamination and non-self-similar growth of delamination cracks [7]. The bilinear softening behavior of the interface was modeled (**MAT_COHESIVE_GENERAL*). Thanks to the mixed mode not only the pure separation mode and the pure shear mode, but also the total mixed-mode is taken in a count.

Experimental tests

Aircraft structures work under multi-axial state of stress. In effort to investigate the crash behavior of a composite panel impacted by a hailstone, along with the usual static and dynamic tests carried out to characterized a composite material [6], notched tests with coupon under a multi-axial stress state were also carried out (Fig. 2, LHS).

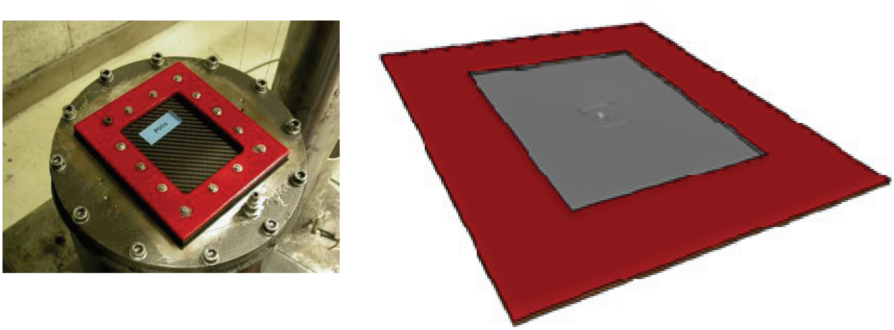
Composite material 160 x 140 mm panels were used. A stacking sequence typical for aircraft skin panels, [0°, 45°, 90°, -45°, 0°], was chosen. A specific test device, a sort of pressure chamber, was used to achieve a multi-axial stress state. The specimens were installed on the device and pre-loaded with a prescribed pressure – varying from 0.5 bars to 2.0 bars. Test with an impact energy of 6 J and 8 J were carried out.

Impact forces were measured and delaminations investigated using an x-ray camera.

Numerical-experimental correlation

The experimental test scenarios were numerically reproduced and the results obtained in the simulations compared with the data collected during the tests.

The tests showed that the damages on the coupon are localized: the upper plies had no though-thickness fractures, but finite displacements; the lower plies on the contrary had though-thickness fractures. The x-ray analysis evidenced that the delaminations were more extended than the visible damages.



Test Simulation

Figure 2. Notcher test with coupon under a multi-axial stress state (LHS) and simulation result (RHS)

The numerical-experimental correlation was good in terms of impact forces and the delaminations were, for extension and depth, similar to the one observed in the tests.

HAILSTONE IMPACT MODEL

Once the hailstone model and the composite laminated model were validated, the impact of a hailstone onto a composite coupon under a multi-axial state of stress was simulated.

In this phase of the research, the EFG hailstone and the material model developed by NASA researchers were used – because of the accuracy in the results and the small CPU time required.

In Fig. 3, the results of the simulation are shown.

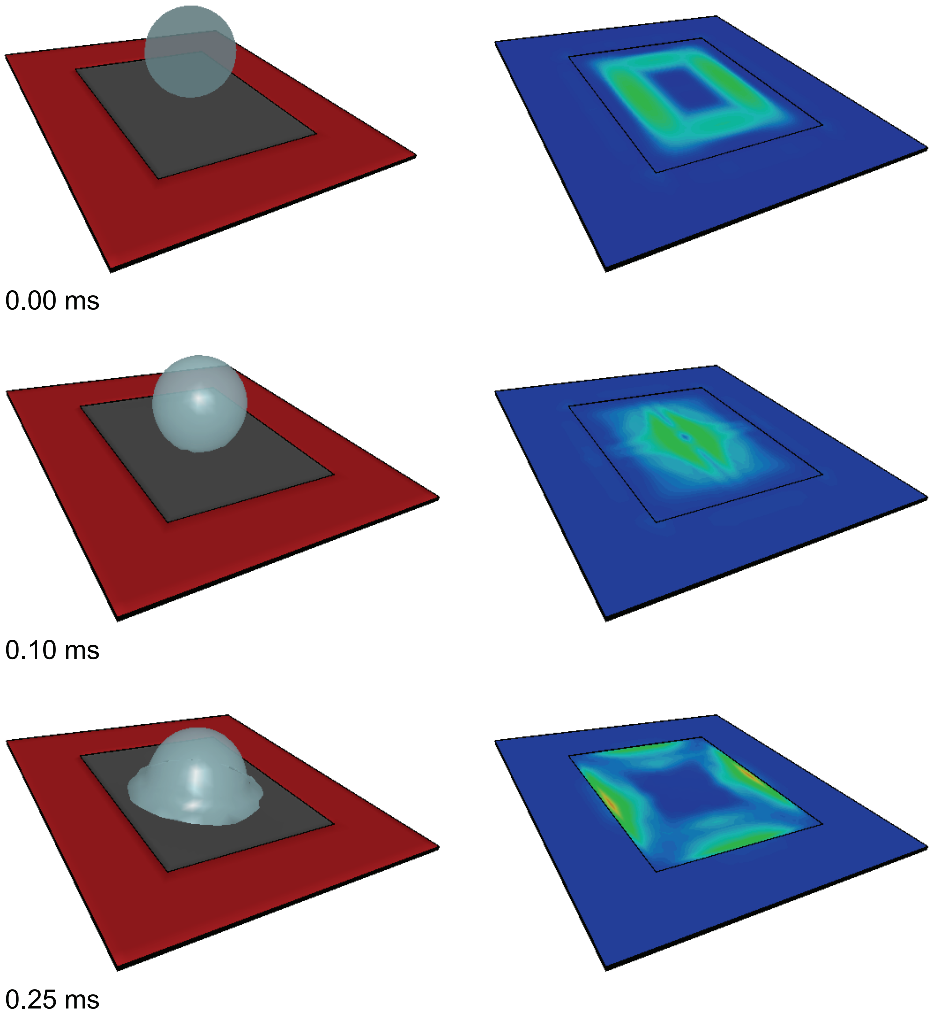


Figure 3. Hailstone impact onto composite panel using EFG hailstone. Frame from the simulation (LHS) and first principal stress (RHS)

In Fig 4, a comparison between the delaminations caused by a notch impact and the delaminations caused by a hailstone impact is presented.

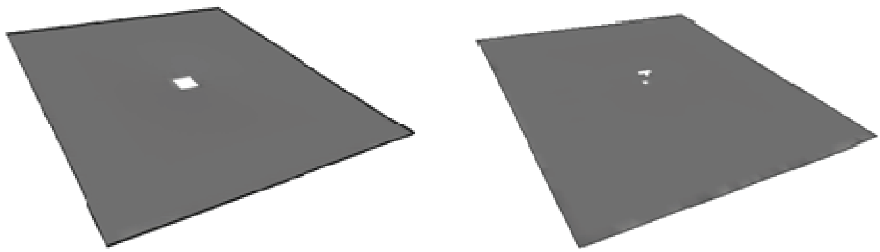


Figure 4. Delaminations caused by a notch impact (LHS) and by a hail impact (RHS).

CONCLUSIONS

Flying through a hailstorm is dangerous not only for the direct damages but also for the hidden damages which may concur to more serious accidents.

Numerical model developed and validated against experimental data may represent a tool to evaluate the consequence of a hail impact and, at the same time, provide the necessary framework to design safer (hail-proof) structure.

In this work, hail impact onto composite structure under a multi-axial stress state is investigated. Initially, a reliable model of a hailstone is developed referring also to the recent research on ice modelling. Meshless approaches to hail modelling, SPH and EFG, were investigated and, eventually, the benefits coming from the use of these approaches were recognized.

In parallel, reference tests were carried out and a numerical model (based on Fracture Mechanic) to predict delaminations in composite structures caused by low energy impacts is developed and validated.

Finally, the impact of the hailstone onto a composite structure is simulated. In view of the results obtained, findings and guidelines for future investigation are drawn.

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