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Prediction procedure for hail impact

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Abstract. The constant increase of composite materials' performances makes them more and more used in recent aircrafts. Structures, as the wings or the fuselage, may suffer from hail impacts that can make critical damages or even perforate them. In order to guaranty the safety of passengers, aircrafts have to be certified and simulations have to demonstrate good agreements with real behaviour of the structures and the hail projectile. The aim of this work is to propose a procedure to analyse the home made manufacturing of the ice generally performed in laboratories, its mechanical characterization and a mechanical model that can predict the time-space profile of the impact force on a rigid structure. Because of the high strain level of the hail during the impact, the Smooth Particle Hydrodynamics (SPH) method will be used. Indeed, the finite elements method needs heavy remeshing that are time consuming to avoid mesh distortion. The SPH is a numerical meshless method that calculates interactions between particles at every time increment. Models available in the literature have been studied and the model of J.D. Tippmann (Tippmann, Kim, et Jennifer D. Rhymer 2013) is chosen. In this paper, the Tippman model is presented with its solving using the SPH. A parametric study is proposed in order to catch the relevant parts of this model. A simple experimental procedure is then proposed to feed the model and the results of impact simulations at different velocities are compared to experimental measurements realized in the laboratory.

1 Introduction

Most of the time, hailstones of interest are considered perfectly spherical and have diameters from $40\,mm$ to $60\,mm$. Impact speed varies from $40\,m.s^{-1}$ (approximate speed of the free fall of hailstones, in the case of hail precipitation on a parked aircraft on ground) to$150\,m.s^{-1}$ (in the case of an aircraft flying through hail precipitation).

1.1 Types of ice

Studies of hail impact were mostly experimental and tried to understand the constitutive ice material.

Ice can be found in nature with many different microstructures. The one that is most common is the polycrystalline ice [1-2], because found on earth at atmospheric pressure conditions. Among the polycrystalline ice, four types of ice are mainly manufactured in laboratories: accretion ice, compacted snow, perfect moulded ice and moulded ice with defects [3-4]. Laboratories study one type or another depending on their objectives and manufacturing process available.

The ice's behaviour depends on the temperature [1], [5]. It has been chosen to study hailstones impact at -10 °C, a temperature mostly chosen in the literature because near the conditions of the worst case that structures can encounter [6].

1.2 Ice behaviour

Mechanical behaviour of ice was studied and a difference between compression and tension was observed. It strongly depends on the strain rate for the compression [5], [7]. For the quasi-static compression, the behaviour is ductile at low loading speed whereas for high stain rates it is brittle, above $10^{-3}s^{-1}$ [1]. The ultimate stress also varies with the strain rate [1], [7], [8]. In tension, the behaviour of ice mostly depends on its microstructure [1].

For the dynamic loadings, the tests at different strain rates realized in [7] thanks to split Hopkinson pressure bar system shows a strong dependency of the compressive behaviour with respect to the strain rate. Nevertheless, these tests, due to the experimental set up, are not performed at a constant strain rates during the compression. This difficulty still remains an open issue in order to obtain a correct measurement of the mechanical characteristics (compressive Young modulus, maximum stress) evolution regarding the strain rate.

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1.3 Ice modelling

From the beginning of 2000, the improvement of computing capacities has enabled modelling studies of hailstone impacts. Based on characterization tests available in the literature and interpretations of authors, models were developed. These models can be divided in 3 families: the first one tries to simulate the behaviour of ice with an elastic-damageable model [2, 8, 9], the second one with elastic-plastic-failure models [10-12], and the last one with elastic-viscoplastic-damageable model [13]. Most of these models need to be fed by many parameters, whereas some parameters can't be experimentally measured. Also, models don't have convincing results regarding the prediction of the impact force. Some models have good correlation experimental-numeric but are not polyvalent: the results are great for low range of impact speed. To optimise results on wider ranges, parameters have to be tuned every time the test changes.

In the same time, different numerical method were tested to solve the previous models [14]. The classical finite elements method gives great results for the beginning of the impact, before getting high strains [13-14]. After, mesh distortion problems happen and remeshing techniques are needed which dramatically increases the time computation. Arbitrary Lagragian Eulerian (ALE) methods have also been tested [14]. It enables the modelling of very large strain phenomenon. The results are promising but the discretised space has to be larger than the projectile so this method is also time consuming [14]. The last method tested is the Smoothed Hydrodynamics Particles (SPH) method. This mesh free method is also used in studies like the bird impact problem [15]. This method seems to be the most adapted to the simulation of hailstone impact and will be used in the rest of this work.

1.4 Our proposal

It appears that the manufacturing of ice has a major effect on the results of tests. So it is very important to make a precise description of the manufacturing process to enable the repeatability and the pursuit of the study by other laboratories interested in the subject.

The characterisation of ice behaviour is one of the main subjects of research in hailstone impacts. Special considerations have to be taken in order to be sure to correctly extract from tests the parameters needed.

In the modelling part, a few models have been developed, but most of them use parameters that can't be measured experimentally.

For these reasons, the main purpose of this study is to present the first results on the development of a complete detailed procedure to realise simulations of hailstone impact:

- manufacturing of hailstones ;
- measure of the ice parameter of interest for the model ;
- development of the numerical model ;
- validation tests.

2 Material

The material studied is obtained by moulding distilled water in spherical handmade silicone moulds. The moulds and distilled water are vacuumed for 5 minutes. Then the moulds are placed into the freezer at -2 °C in order to solidify the water as slow as possible to limit the number of defects. After solidification, hailstones are coated with grease and placed into the freezer at -20 °C to be stocked until the tests. The result obtained is illustrated **Fig. 1**. The mould joint can be seen in the middle of the hailstone, and defects inside. The hailstone obtained is similar to hailstones obtained in the literature [4]. The characterisation of defects will be necessary to completely describe the hailstone produced, and verify the good repeatability.

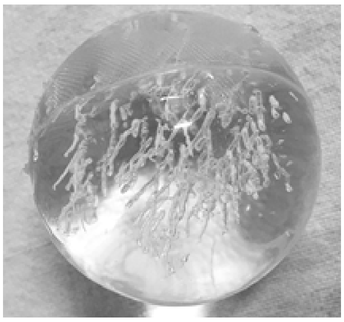

Fig. 1. Picture of hailstones.

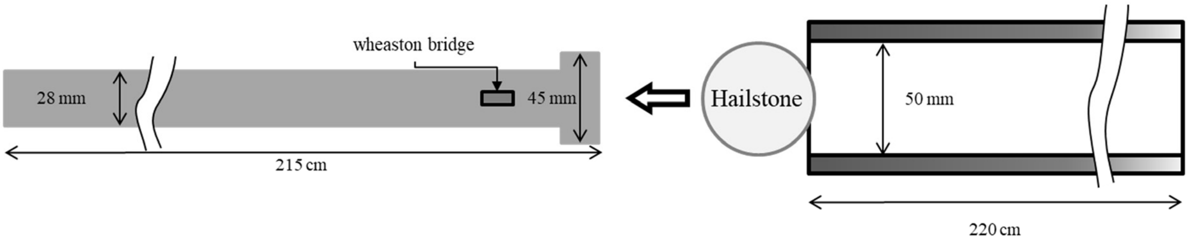

Fig. 2. Sketch of the gas gun installation used for experimental tests.

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3 Impact tests

To realize experimental impact tests, an experimental set up has been developed in the laboratory, cf **Fig. 2**. It is inspired from the one used in [12]. A gas gun accelerates the projectile to the desired speed, and a pressure Hopkinson aluminium bar based sensor enables the measurement of the impact force. The hailstone is directly placed in the gun that is placed into an ice case to maintain its temperature around -10 °C. A Photron SA5 high speed camera is used to measure the velocity of the hailstone (acquisition frequency used of $75000\, frame.second^{-1}$), to validate that the hailstone hasn't been damaged during the travel through the gun, and to observe the degradation of the hailstone during impact.

3.1 Interpretation/Choice of the model

Fig. 3 illustrates the results obtained with the impact force during the impact and 2 pictures taken with the high speed camera of a 50 mm diameter hailstone impacted at $70\, m.s^{-1}$. The tests results presented here is a good representation of the trend of all the 15 tests realised.

Observations of the hailstone under impact solicitations enable us to interpret the damage scenario during the impact. During the first 50 µs, the impact force increases and reaches several kilo-Newtons. When the maximum impact force is reached, the hailstone is multi-cracked and from that time it can be considered as an aggregate of fragments. Thus, the hailstone can't carry shear and tensile stress any more. Its behaviour can be considered as granular.

These observations have lead this study to start the numerical work of the hail impact from the model developed by Tippman [12, 16]. This model is able to take into account the dependence of the strain rate, and the granular behaviour post peak impact force, meaning no shear and tensile resistance is taken into account after fracture.

3.2 Ice's model description

The model is elastic-plastic-failure based. The plasticity and its inelastic flow are used to take into account the strain rate dependency. The failure criterion models the fragmentation.

The elastic part of strains is separated in 2 parts: the volumetric and the deviatoric one. They are calculated from the bulk and shear modulus, K and G respectively:

$$K = \frac{E}{3(1-2\nu)}, \tag{1}$$

$$G = \frac{E}{2(1+\nu)}, \tag{2}$$

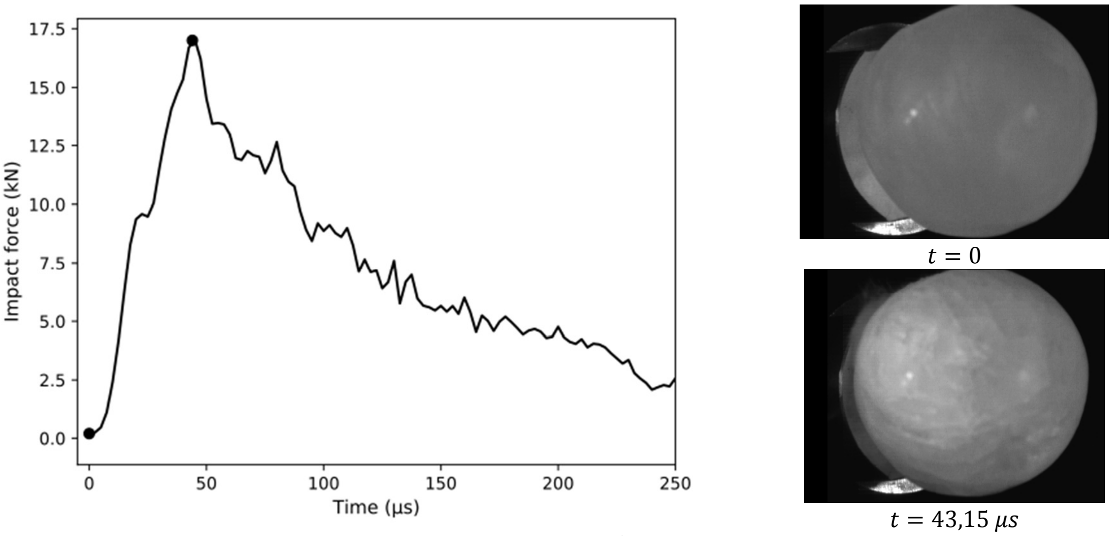
where E and ν are respectively the Young modulus and the Poisson ratio.

The volumetric p and deviatoric $\mathbb{S}$ parts of the stress tensor are then calculated following:

$$p = -K\varepsilon_{vol}, \tag{3}$$

$$\mathbb{S} = 2G\mathbb{e}^{el}, \tag{4}$$

where $\varepsilon_{vol} = tr(\bar{\varepsilon})$ is the volumetric strain, $p = -\frac{1}{3}tr(\bar{\bar{\sigma}})$ is the hydrostatic pressure, , $\mathbb{e}^{el} = \bar{\bar{\varepsilon}} - \frac{1}{3}\varepsilon_{vol}\mathbb{I}$ is the deviatoric strain and $\mathbb{S} = \bar{\bar{\sigma}} + p\mathbb{I}$ is the deviatoric stress.



$t = 0$

$t = 43{,}15\, \mu s$

Fig. 3. Impact force vs time for the impact at $V = 70\, m.s^{-1}$ and 50 mm diameter hailstone with the position of the pictures in the right.

The inelastic flow is described by:

$$d\mathbb{e}^{il} = d\bar{e}^{il}\mathbb{m}, \tag{5}$$

where:

$$\mathbb{m} = \frac{3}{2}\frac{\mathbb{S}}{q}, \tag{6}$$

$$q = \sqrt{\frac{3}{2}\mathbb{S}:\mathbb{S}}, \tag{7}$$

and where $d\mathbb{e}^{il}$ and $d\bar{e}^{il}$ are the inelastic strain rate and the equivalent inelastic strain rate respectively.

The inelastic evolution criterion is the Von-Mises criterion:

$$f = q - \bar{\sigma}(\bar{e}^{il}, d\bar{e}^{il}) \leq 0, \tag{8}$$

where $\bar{\sigma}(\bar{e}^{il}, d\bar{e}^{il}) = \sigma^0 \times R(d\bar{e}^{il})$with σ^0 the static hardening curve entered under a table form in Abaqus; R is the coefficient which depends on the strain rate also entered under the form of a table and $\bar{e}^{il} = \bar{e}_0^{il} + \int_0^t \sqrt{\frac{2}{3} d\mathbb{e}^{il} : d\mathbb{e}^{il}} dt$ where $\bar{e}_0^{il}$ is an initial value taken equal to zero.

The fracture criterion used is based on the hydrostatic pressure. It consists in enabling only compressive loading in the material when the tensile failure criterion is met. When the hydrostatic pressure reaches the criterion p_{max} , the stress becomes:

$$if\ p \geq p_{max} \Rightarrow \begin{cases} p = \max(0, p) \\ q = 0 \end{cases}, \tag{9}$$

This function enables to simulate a granular flow where no shear and traction takes place. The only stress state that is enabled is a volumetric compressions stress state.

Right now, inputs of the model are found in the literature [10], [12]:

Table 1: Parameters of the behaviour model [10, 12].

Young's modulus E	9380 MPa
Poisson's ration ν	0.33
Density ρ	900 kg.m^{-3}
Tensile failure pressure p_{max}	0.517 MPa
Quasi-static yield strength σ^0	5.2 MPa
Rate dependent yield strength $R(d\bar{e}^{il})$	cf **Fig. 4**

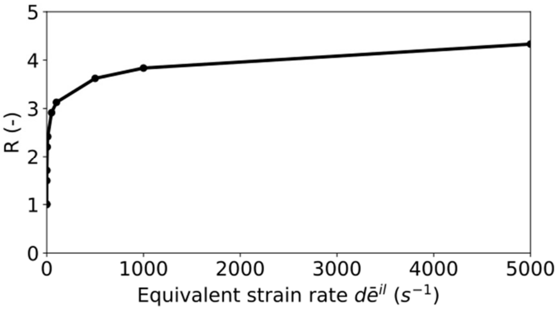


Fig. 4. Strain rate dependency coefficient.

3.3 SPH method

The spatial discretisation of the hailstone is realized thanks to the SPH method. 536184 particles are used. According to [17], kernel functions have major effects on results. Simulation tests have been made and numerical instabilities as negative elastic strain energies can happen. The quintic kernel is chosen because of its best results.

The entire dynamic pressure Hopkinson bar (PHB) sensor is modelled. The numerical measurement of the impact force are thus realised as the experimental ones by outputting the stress at the same position as the strain gauge on the PHB. The sensor is modelled with 18560 C3D8r elements and the material is a classical aluminium elastic linear model with $E_{alu} = 70000\ MPa, \nu = 0.33$ and $\rho = 2700\ kg.m^{-3}$ parameters.

For the rest, all artificial viscosities (of the global model and of each part, projectile and sensor) are set to zero.

4 Results obtained

The different energies of the model have been analysed **Fig. 5**. The results are that the model is conservative, some of the initial kinetic energy is transformed into strain energy, and the rest is conserved as kinetic energy. The percentage of energy dissipated by numerical dumping among deformations energies is equal to 0.96%.

In the **Fig. 6** are illustrated the numerical impact force and, in dotted line, the inferior and superior envelop of the impact forces of the fifteen tests realised with 50 mm diameter hailstones impacted at $70\ m.s^{-1}$. A good trend between the experimental and numerical tests is observed. The slope at the beginning of the impact phenomenon is well reproduced. The peak force is underestimated by 18% to 30%. After the peak force, the shape of the numerical curve represents well the experimental ones, and at the end of the impact the residual force is predicted.

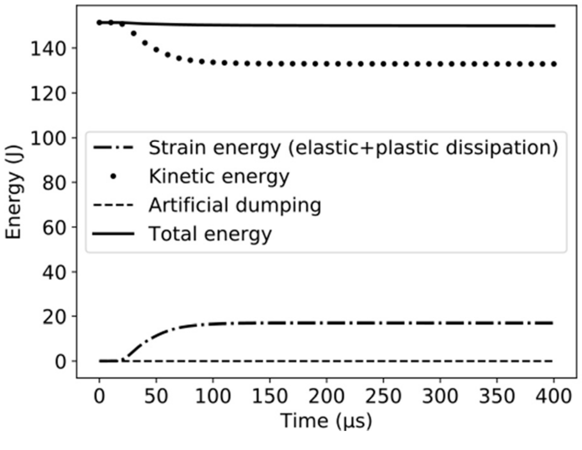


Fig. 5. Energy results of the 50mm diameter projectile for the 70 $m.s^{-1}$ impact.

Fig. 7 shows four pictures of the simulation of the hailstone being impacted. The SPH method is able to represent very high strains without any problem of distortions. Calculations are faster (around 45 minutes of calculation with SPH method, more than 5 hours four finite element method with the same computer) and results are better with the SPH method than with the finite elements method. Thus the utilization of the SPH method is validated.

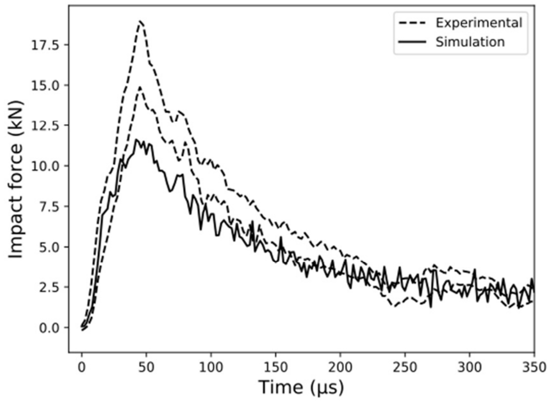
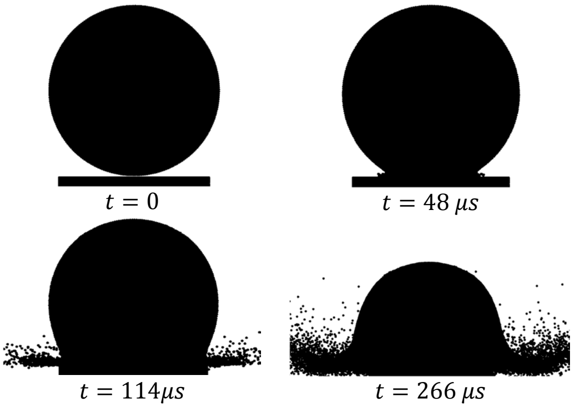


Fig. 6. Numerical – experimental (the min and max envelope of experimental tests are presented) comparison of impact force of a 50mm diameter hailstone at 70 $m.s^{-1}$.


$t = 0$ $t = 48\,\mu s$

$t = 114\mu s$ $t = 266\,\mu s$

Fig. 7. Pictures of the simulation of a 50mm diameter hailstone impact at 70 $m.s^{-1}$.

5 Discussions

A parametric study has been realised on the four main behaviour parameters: E, σ^0 , p_{max} and $R(d\bar{e}^{il})$.

A variation of p_{max} has almost no effect on the model response (maximum force and the post peak force shape). The data available in the literature is used [10, 12]. The three others parameters have major effects.

The young modulus E is dependant of the manufactured ice; the quantity of defects will strongly influence the stiffness of the hailstone such that it needs to be carefully measured.

In the literature, compressive tests on cylindrical specimens are realized, $\sigma_{compressive}^{max}$ is extracted and to feed the model the hypothesis $\sigma_{compressive}^{max} = \sigma^0$ is made. Compression tests realized by [2, 5, 8] show cracks in the direction of the applied load. Yu Fishman [18], for example, has demonstrated that for that kind of test, because of defects, specimens have to be specifically designed to enable the measure of maximum compressive stress, cf **Fig. 8**. Otherwise shear and/or tensile stress state are solicited around defects. So it is primordial to know the size, shape and spatial repartition of defects in specimens to re-evaluate σ^0.

The same phenomenon may happen in tests to measure $R(d\bar{e}^{il})$, the strain rate dependence of the behaviour of ice.

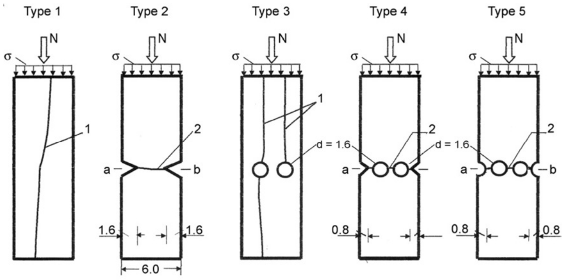


Fig. 8. Different types of geometry specimens tested by Yu Fishman [18].

6 Conclusions

A complete method to realise hailstone impact tests have been developed: manufacturing of hailstones and realisation of experimental tests. Results obtained are similar to results already published in literature, so the experimental process is validated.

A model of ice has been detailed and implemented. SPH method has been validated. The numerical results show good trend compared to experimental ones. Key points to minimise the error have been identified: the determination of parameters to feed the model correctly.

7 Perspectives

Following the conclusions, the determination of E, σ^0 and $R(d\bar{e}^{il})$ will be investigated to correspond to the ice manufactured and the model developed. In parallel, defects in hailstones will be analysed in terms of size and shape.

Currently only one location sensor of force is used to compare experimental and numerical results. To obtain more data to validate the numerical model, the realization of a temporal-space force sensor is under investigation. The goal is to get more information about the spatial distribution of impact pressure on the target.

Finally, hailstone impacts will be performed on composite structures. The present model will be used to predict composite damage after hailstones impacts.

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