Development Of Hail Material Model For High Speed Impacts On Aircraft Engine

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Abstract

Hail impacts represent a threat for aircrafts and their engines. As experimental tests on aircraft engines are expensive and they can not be done in early stages of the development, numerical simulations to predict hailstone impacts on engine blades have to be developed. The purpose of this work is to present a new material model for simulating hailstone impacts on engine blades.

Aeronautical industry has already developed numerical models for similar problems of bird impacts using LS-DYNA®. They simulate the bird using SPH particles to predict projectile failure and Lagrangian solid elements for the blade.. In order to simulate hail impact, numerical model for bird strike is used and projectile material is replaced by a new material model.

Experimental results show hail has a brittle behavior which is similar to concrete's, so mechanical behavior may be simulated by an elastic damage model based on Mazars' law used for concrete. Damage Mazars' model is improved by adding traction and compression damage and a delay effect is added in order to reduce mesh dependence. This hail law is developed in LS-DYNA code through a user defined material (UMAT), tested on simple cases of plate impact and used for impacts on the aircraft engine blade.

This paper presents the existing LS-DYNA models simulating hail impact and their limits and describes hail tests used to study the material law and to develop the numerical model. Validation tests are presented to show out the behavior of hail, effects of model parameters, and the role of delay effect. Hailstone impact tests on an aluminum plate carried out by British Royal Aircraft Establishment (RAE) and Office national d'études et de recherches aérospatiales (ONERA) are used in order to identify the model. An impact on a blade is then simulated with the identified model and is compared with Snecma's test.

Keywords **:** *hailstone material model, high speed impact, SPH, brittle material, elastic law with damage*

Introduction

Foreign Object Damage (FOD) is an important issue in aeronautics. Every year, dozens of thousands collisions between a plane and a foreign object are reported. Most of them do not cause important damage on the plane structure or engines. But they may cause minor changes on the structure that reduce aircraft performance. Just to have an idea, one should remind that FOD has a direct cost of $1 billion a year, which could rise up to $10 billion depending on the case.

Exposed parts of the aircrafts are the front of the structure, tyres, and engines. Engines are particularly vulnerable to FOD. Impact speed is very high as the aircraft speed is added to the rotational speed of the blades. Moreover, even if the impact does not cause major damages, deformed blades will be less efficient and the engine will lose some power. As a result, engines maintenance is responsible for almost 80% of FOD direct cost.

FOD risk is taken into account during the design of both aircraft and engines. For this purpose, certification requirements integrate ingestion tests [7] : birds and hailstones of different sizes and weights are thrown into the engine and the engine is required to react properly. Light birds (1.5 lbs) must not cause more than 25% power loss, whereas heavy birds (4.5 lbs) must not cause an hazardous engine effect. Number and size of the hailstones must be determined with respect to the inlet throat area and must not cause unacceptable mechanical damage or unacceptable power loss.

Prior to the final certification test, some expensive spin tests are usually performed to validate the initial design choices. A failure during an ingestion certification test will have a huge impact in term of cost and delay because of the necessary re-design of the blade. To reduce the number of these tests and to avoid any delay during the certification tests, manufacturers perform analyses with non-linear transient dynamic codes.

In order to do this, Snecma develops a model able to accurately simulate impact of birds and hailstones on engine blade. The simulation must predict blade failure and the residual shape of the blade in order to verify residual power.

The bird impact models are currently simulated at Snecma with a suited methodology and are currently used for the engine design. Hail impact models are less advanced and not used yet for the engine design.

Some material models developed in LS-DYNA® are used for modeling hail material. *MAT_ELASTIC_PLASTIC_HYDRO (MAT_10) combined with the equation of state of water and *MAT_ISOTROPIC_ELASTIC_FAILURE (MAT_13) is used to describe normal impact on panel and applied to engine intake [3].

However, Snecma's impact test on blade cannot be accurately simulated with these existing models. Blade shape introduces a new cutting failure mechanism which is not represented by the existing LS-DYNA material model.

That is why Snecma decided to develop a new material model to use in blade impact applications. Using the experience acquired on bird strike modeled using Smoothed Particle Hydrodynamics (SPH) method and an adapted material law [5, 6], hailstone is modeled using SPH and a new material law developed by Y. Chuzel [2].

This article proposes a new material law to describe hail behavior in order to simulate hail impact, the new law is implemented as a user defined material (UMAT) in ls971R27600-1224 version of LS-DYNA code.

Hail model

Hail properties are very dependent on hail type. Experimental analyses done by Y. Chuzel on hail under high speed impact load focus on mono and poly-crystalline hail and allow to identify mechanical properties, failure behavior, temperature and strain rate influence.
The first ONERA experimental test on mono crystalline cylinder hail (height 30 mm, diameter 25 mm) allowed identifying Young Modulus and failure stress for strain rate up to 10^2 s^{-1} . This test showed a brittle behavior and a failure mode of cleavage (Fig. 1) . It didn't allow identifying a fragmentation failure mode. Ultimate stress at failure is constant for strain rate lower than 10^{-1} s^{-1} (Fig. 2).

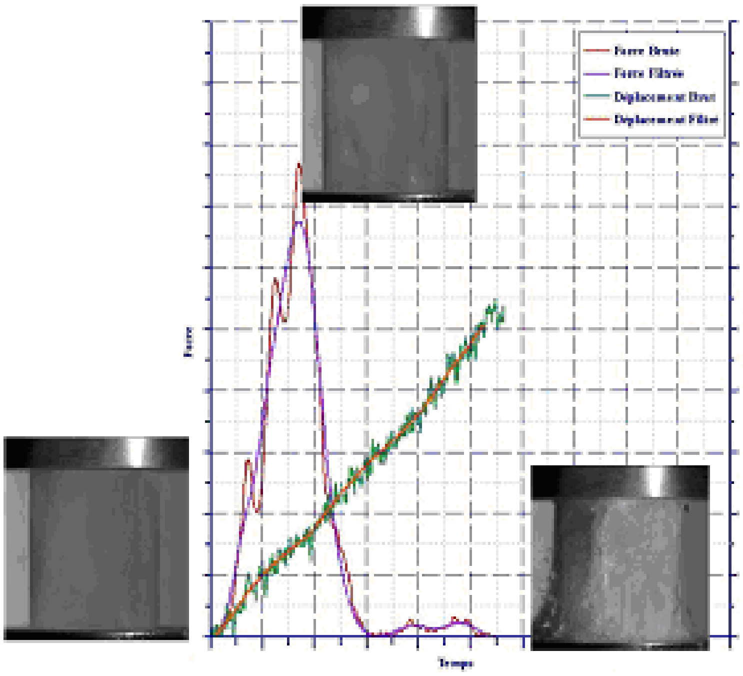


Figure 1 : Force and displacement for a for mono crystalline hail cylinder impact test. *

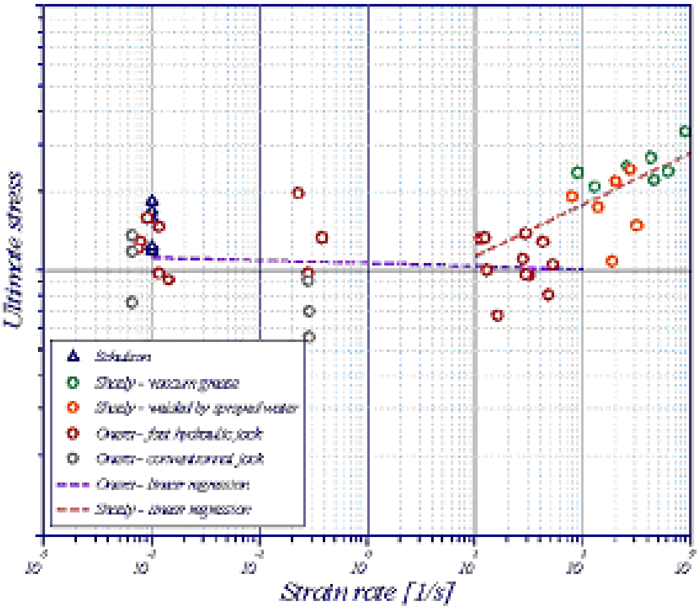


Figure 2 : Ultimate stress versus strain rate for mono crystalline hail cylinder impact test.

The force opposed by the material, at first, linearly depends on the deformation, but beyond a certain deformation, it suddenly drops. This behavior is quite similar to concrete's and it is going to be modeled using a modified Mazar's law [10] based on the following hypotheses:

- Elastic behavior coupled with isotropic damage
- Damage is only caused by tensile strength
- Damage in tension et compression have different evolution

Mazar's law is modified in order to take into account hail behavior and transient dynamic application. The main idea is to consider that the material behavior is driven by the creation of cavities in the sections. Material with cavities caused by damage can be simulated by a numerical non damaged material with a lower Young modulus. The new Young modulus can be written as a function of the damage D and the Young modulus of the non-damaged material:
Damage in the model is activated if equivalent strain is up to a criterion,

$$\tilde{\varepsilon} = \sqrt{\sum \left(\langle \varepsilon_i \rangle_+\right)^2} + \nu\sqrt{2}\sqrt{\sum \left(\langle \varepsilon_i \rangle_-\right)^2} > \varepsilon_{crit}$$

damage in traction and compression is calculated as :

$$D_{t/c} = 1 - \frac{\varepsilon_{D0}(1 - A_{t/c})}{\tilde{\varepsilon}} - \frac{A_{t/c}}{e^{B_{t/c}(\tilde{\varepsilon} - \varepsilon_{D0})}}$$

Damage evolution is described by initial strain ε_{D0} and four parameters A_t, B_t, A_c, B_c whose influence on damage is shown in Fig. 3. For traction and compression parameters *A* is the asymptotic value, and *B* defines the behavior after damage. High value of B means a sudden drop in the force, which corresponds to a brittle material.

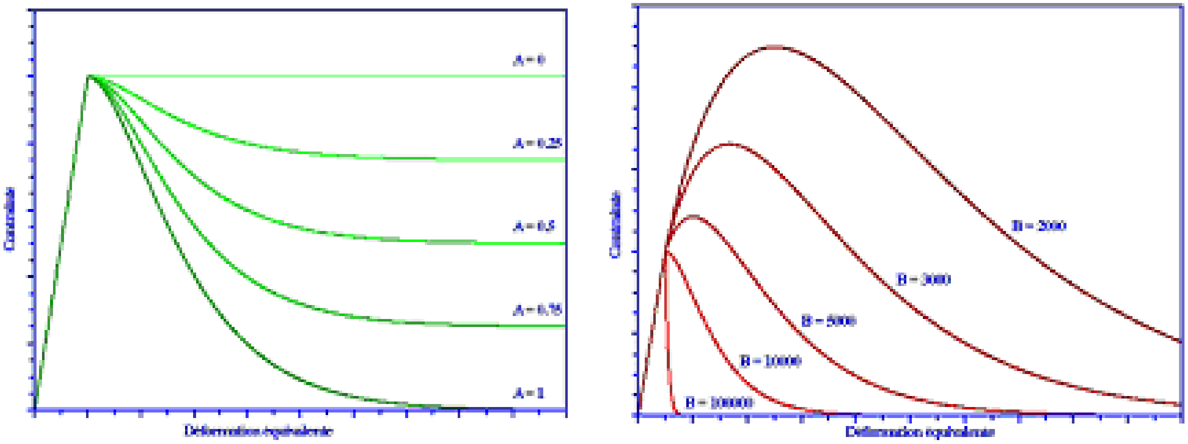


Figure 3 : Force versus displacement, influence of the parameters and B

Damage calculated in traction and compression is updated using delay effect in order to reduce damage rate and mesh dependence [11].

$$\dot{D}_{t/c} = \frac{1}{\tau}(1 - e^{-(D_{t/c}^{nc} - D_{t/c})})$$

As shown in Fig. 4 damage without delay effect is concentrated in the last two SPH planes for every mesh size in a test of beam traction. The damaged area is meshed dependent and converges towards zero. With delay effect, the damaged area is less mesh dependent and it converges for finer mesh.

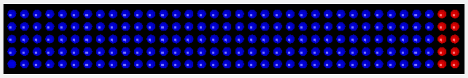
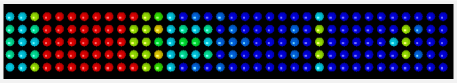
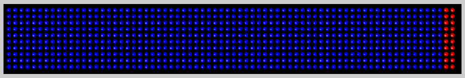
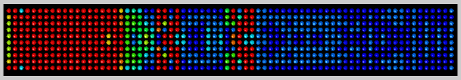
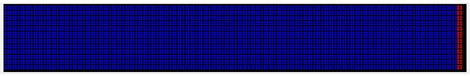
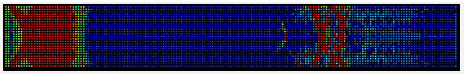
Damage at 30 µs	Without delay effect	With delay effect
Coarse Mesh		
Medium Mesh		
Fine Mesh		

Figure 4 : Influence of the delay effect in a test of beam traction.

Global damage is calculated as a combination of damage in traction and compression:

$$D = \alpha D_t + (1-\alpha) D_c$$

The implementation of the model uses a user defined material (UMAT) where following characteristics are defined:

- Young Modulus for the non damaged material
- density
- Poisson ratio
- ε_{D0}, initial strain
- A_t, B_t, A_c, B_c parameter of damage calculation
- characteristic time of delay effect (τ)
- flag for delay effect activation

Model validation

The material model implemented using UMAT has been validated using various experimental tests. An experimental test carried out by the British RAE [4] and by ONERA [2] is presented to validate plate deformation after impact.

The test consisted in an impact of 25.40 mm diameter spherical hailstone onto a 0.91 mm thick aluminum alloy 2014-T4 panel of 305 mm side-edge (Fig. 5) fixed with blind rivets which presents a free surface of 200 x 200 mm. Several impact speeds were used: 192 m/s for the RAE test, 120, 262 and 405 m/s for ONERA ones. As reference residual deflection is measured for each test and panel residual shape for 192 m/s test (continuous curve in Fig. 6).

The simulation is done with the methodology validated for bird impact process. The hailstone is represented by SPH elements. The panel is represented by solid hexahedral elements using 1 Gauss point elements with Hourglass treatment. The contacts between the hail and the panel are represented by a CONTACT_AUTOMATIC_NODES_TO_SURFACE.

Hail behavior is described by UMAT developed and panel is modeled using a MAT_PIECEWISE_LINEAR_PLASTICITY.

Features of numerical model are described in table below:

LS-DYNA	Panel	Hail	Total
Element type	SOLID	SPH	
Element number	39 000		39 000
Node number	50 000	14 000	64 000

Table 1 : Numerical feature of plate impact

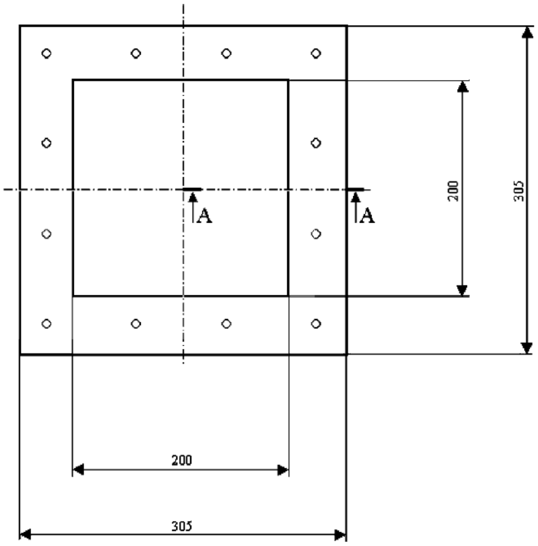


Figure 5 : Experimental test panel

Experimental data are compared to numerical results in term of final displacement in the center of the plate in Table 2 for all impact tests and of final displacement of central plate section only for RAE test (Fig. 7)

Velocity (m/s)	Experimental (mm)	Numerical (mm)
120	5,35	5,89
192	11,20	11,64
262	17,73	18,62
405	32,79	31,9

Table 2 : Comparison on max displacements in plate

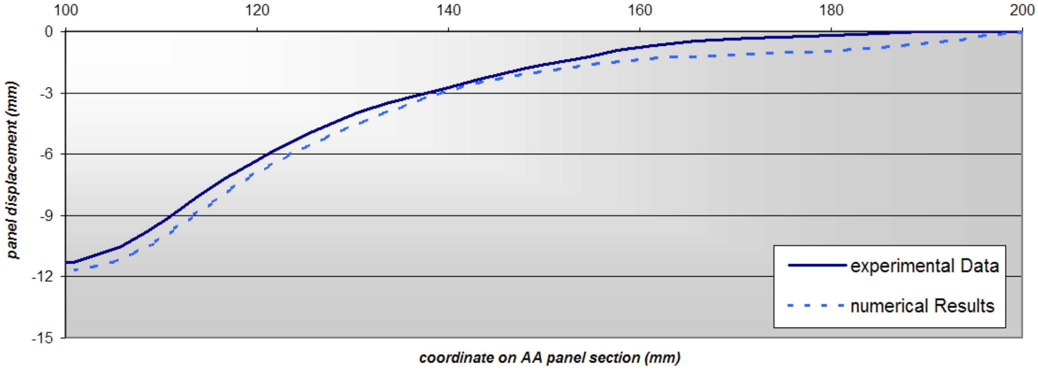


Figure 6 : Comparison of the residual shapes, RAE test at 192 m/s

Another experimental test carried out by ONERA [2] is presented in order to show damage evolution during impact. The test consists in an impact of mono-crystalline cylinder hail (height 30 mm, diameter 25 mm) at 62.5 m/s on an aluminum AU4G panel of 200 x 80 mm and 1.2 mm thickness in three point flexion. Different hail impact angles are tested in order to show two failure modes: fragmentation for an angle equal to 0° and cleavage for impact angle of 20°. Experimental data and simulation results are shown in Fig. 7.

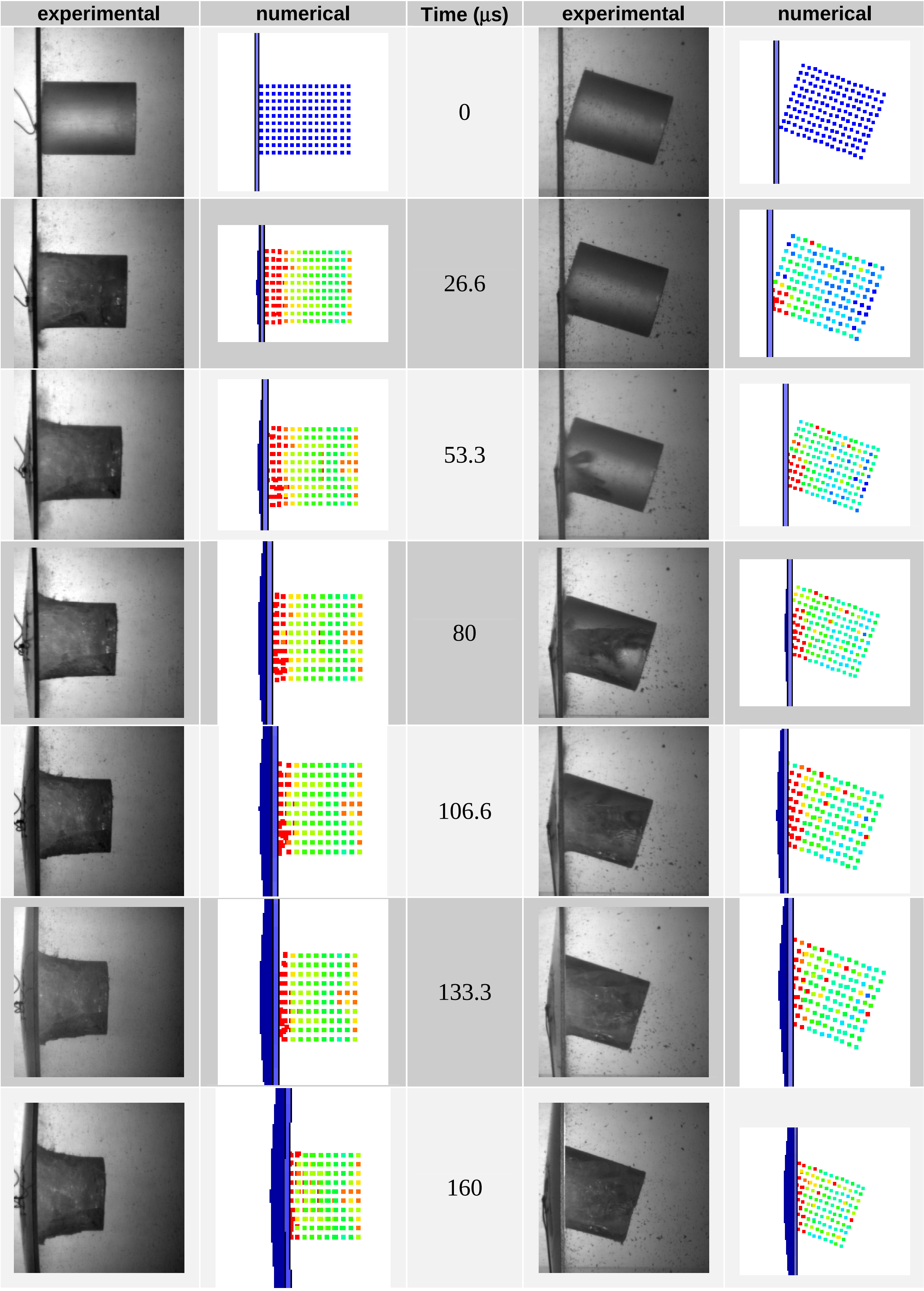


Figure 7 : Cylindrical hailstone impacting on a panel at 0° and 20°

In conclusion the hail model developed shows good results on simple tests in term of residual plate shape, maximum final displacement and damage evolution during simulation. Model developed should be applied on Snecma test case of impact on engine blade.

Blade impact application

Event though the final use of material model developed will be on hail impact on rotating blades, a more simple application to test model result is a hail impact on a static blade where impact velocity is modified in order to take into account hail impact velocity and blade rotation velocity. In the test a 150g cylindrical hailstone impacts a static compressor blade at 304 m/s at 80% high. Final displacements of three nodes on blade tip: leading edge (LE), middle chord (MC) and trailing edge (TE) in the direction of hail velocity are measured and compared to numerical results.

The same simulation method used for plate impact is used as shown in Fig. 8: panel is modeled using a MAT_PIECEWISE_LINEAR_PLASTICITY and hail behavior is described by UMAT developed.

Features of numerical model are described in table below:

LS-DYNA	Blade	Hail	Total
Element type	SOLID	SPH	
Element number	15 000		15 000
Node number	27 000	105 000	132 000

Table 3 : Numerical feature of blade impact

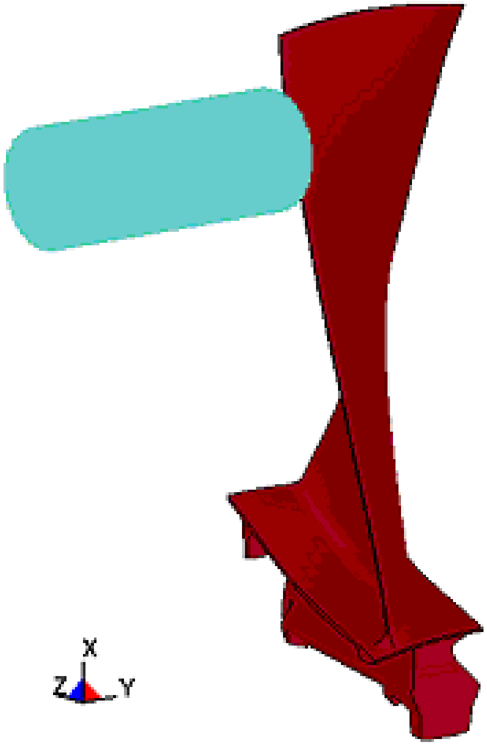


Figure 8 : Blade impact model

SPH model allow hail cutting at impact on blade. Blade flexion could be reproduced along the simulation and numerical results are quite good in term of final displacement at leading edge and trailing edge at tip, only displacement in mid chord at tip is over predicted by numerical simulation. Blade shape is correctly defined all along trailing edge.

Position	Experimental (mm)	Numerical (mm)
LE	55	56
MC	20	43
TE	16	16

Table 4 : Comparison of tip blade displacements

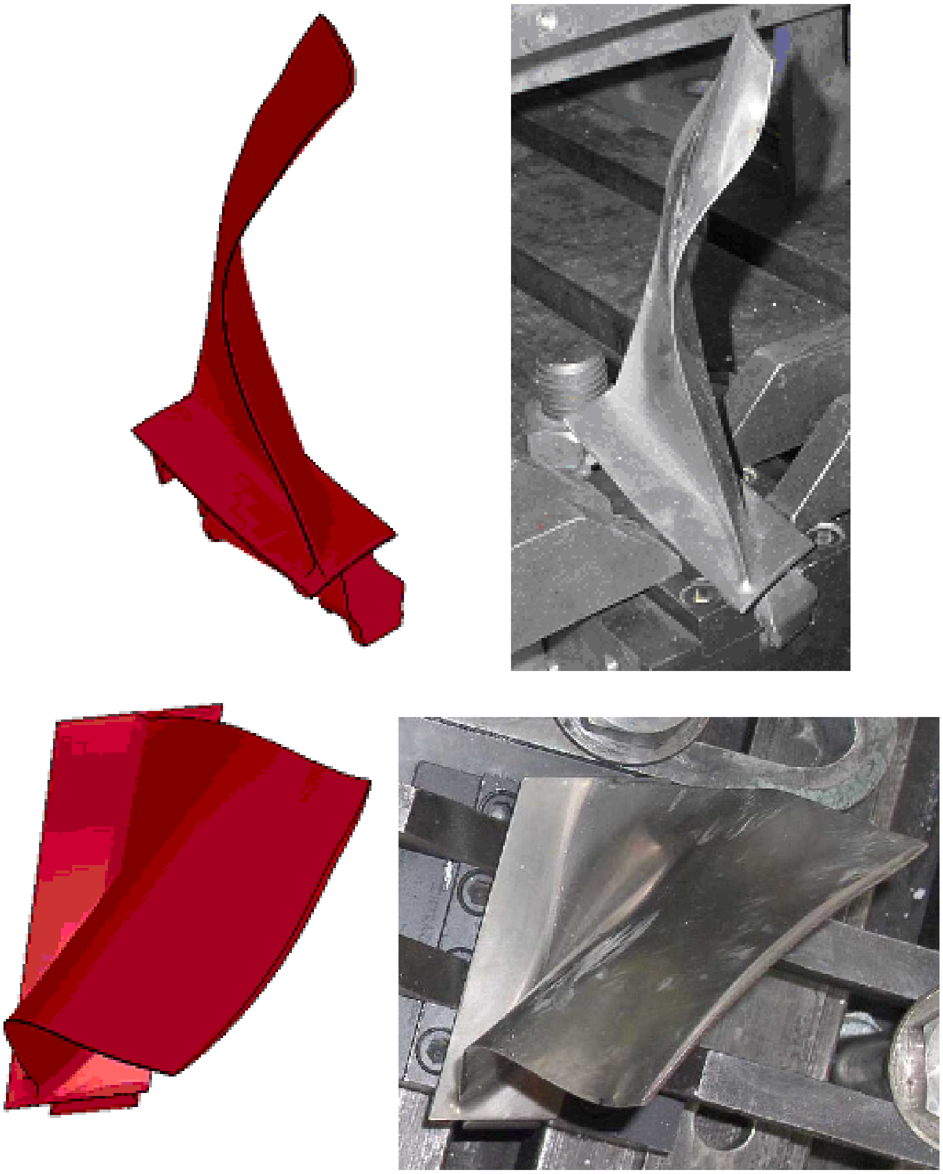


Figure 9 : Comparison on the residual shape, impact on blade

Conclusion

Due to the hailstone impact risk, numerical models for ice are necessary. In particular, engine manufacturers need to simulate accurately the impact on blade and cutting behavior.

The elastic with damage hail law developed using a modified Mazars' law can reproduce hail fragmentation and damage evolution for mono and poly crystalline hail formation.

A close correlation data was found on simple impact plate test so it was possible to analyze hail impact on a static engine blade. Blade impact shape at the end of simulation and hail fragmentation can be reproduced by numerical model.

In order to confirm results obtained on static blade, further tests have to be done on a rotating system for a complete validation of this model for Snecma activities.

In reason of differences in impact behavior shown by hail type, accretion ice which is formed in cold hailstorms will be another point to be studied in order to have more physical description of hail impact on engine

Concluding, hail law developed represents a first promising model for study hail impact on engine blade with introduction cutting behavior.

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