HAIL IMPACT ON COMPOSITE PLATES – EXPERIMENTS AND NUMERICAL MODELLING

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Abstract. Aircraft structures may be subjected to various in-service impact threats, such as tool drops, runaway debris, bird strikes etc. With the increasing use of monolithic composite laminates on aircraft primary structures and large external surfaces (i.e. fuselage panels, wing skins, leading edges etc.) hail impact can also be a major threat that could potentially compromise structural integrity and lead to structural failures. For these reasons hail impact has received increasing interest within the research community as well as the latest aircraft composite structures development programmes.

This paper describes the experimental approach for measuring the damage caused to monolithic CFRP and GFRP composite plates subjected to impact by an ice-ball (i.e. simulated hailstone) and the several possibilities for predicting this damage by numerical modelling in Simulia Abaqus™ finite element software. The experimental part of this work is concerned with the development and calibration of air pressure gun, and the evaluation and comparison of different composite materials behaviour under the hail impact conditions. In the numerical modelling part of this work an Abaqus™ explicit modelling approach to simulate damage initiation and growth in both ice and composite materials is presented and the derived results are compared to the experimental measurements.

Keywords: Hail impact, Composite, Aircraft, FEM, Abaqus™ Explicit

1 Introduction

The new generation of aircraft is utilizing composite structures extensively. It is necessary that the use of such material does not reduce the level of safety historically provided by the use of conventional materials such as metals. Laminated composite structures are known to be more susceptible to impact damage than a similar metallic structure. In composite structures, impacts may create internal damage, which is hardly detectable by visual inspection and can cause severe reductions in structural strength. Therefore, the effects of foreign object impacts on composite structures must be well understood.

As the utilization of composite materials grows, also new non-conventional impact threats must be considered. This work is focussed on hail impact.

Hail impact can cause severe damage on aircraft structures both in the air and on the ground. Since impact tests are expensive and difficult to perform, it is straightforward to understand the importance of developing numerical models to reproduce and analyse the consequences of hailstone impacts. Therefore, this study investigates hail ice impact via a combined experimental and numerical approach.

2 Impact testing

2.1 Testing facility

High speed impact tests are usually conducted by a gas gun. This method was also used for the work presented in this paper. Air-guns use a reservoir of pressurized air, which is then released into a barrel and expands to push the projectile up the barrel. Figure 1 shows the configuration of the test facility. A high pressure vessel is charged with compressed air through a regulator. Maximum pressure given by an air supply is 100 psi. A ball valve is utilized to release the compressed air which accelerates the projectile. Although this valve is hand operated, consistent values of projectile velocity were reached during the calibration testing processes thanks to high flow rate and fast pressure release of this valve.

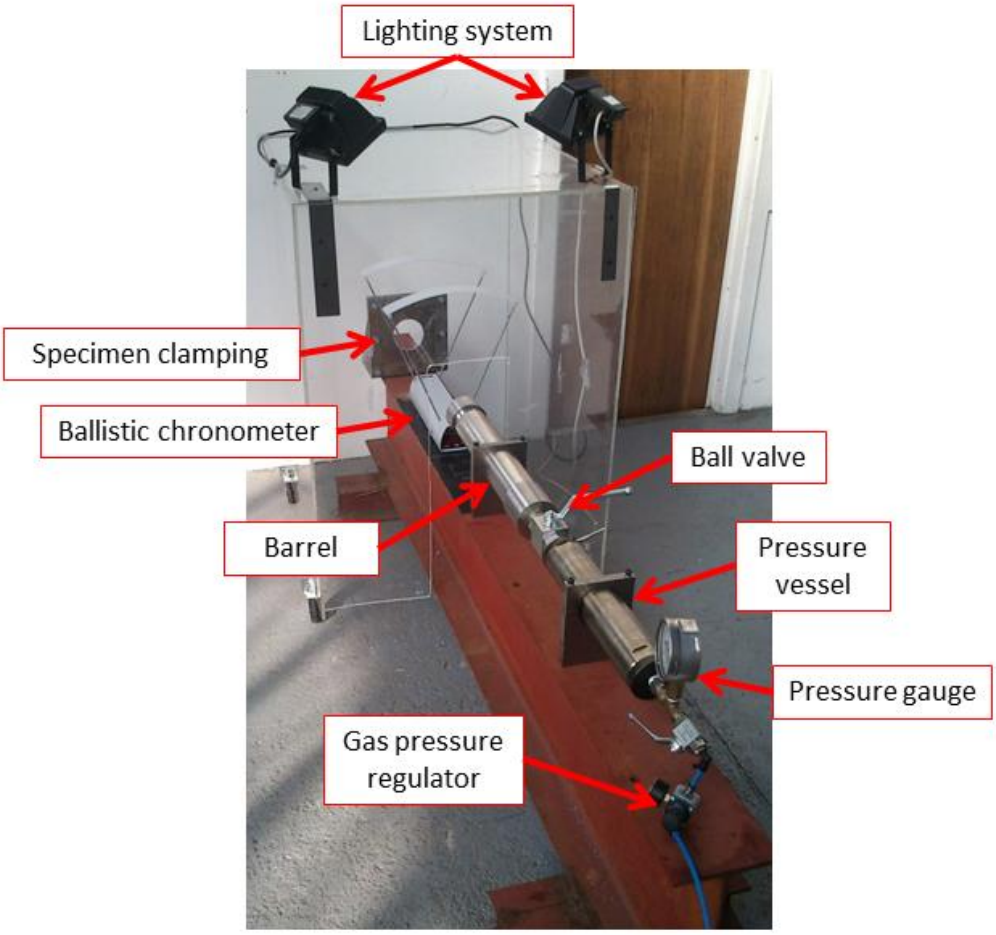

Figure 1 Impact test configuration.

The projectile needs to be protected as it travels down the gun barrel so that it is not damaged prior to impacting the target. PTFE sabot is used due to its low friction coefficient and durability during repeated employment. The sabot is stopped when it reaches the end of barrel by an end-cap with rubber pads and the projectile alone comes out from the sabot and flies into the target. Gun loading is done through the muzzle of the barrel by pushing the projectile positioned in the sabot cup down the barrel.

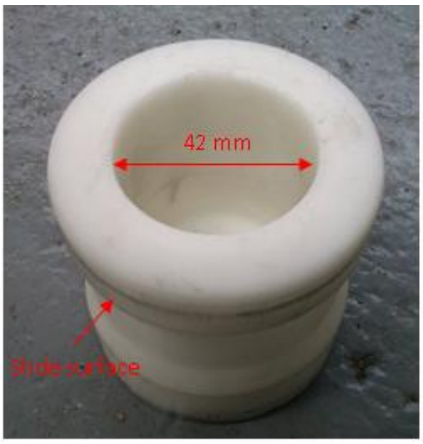

Figure 2 Sabot used for simulated hailstone impact testing.

A ballistic chronometer is used to measure the velocity of projectiles. It operates on the principle of measuring the time it takes for an object to travel from the first projectile sensor to the second projectile sensor. The sensors, mounted internally in the case, gather light through the two rectangular openings in the top of the case. The sensors are photosensitive devices that can detect changes in light intensity that occur when a projectile interrupts light rays when it passes over the opening. The chronometer is capable of measuring velocities 7 - 2150 m/s. To ensure consistent lightning conditions a set of lamps are positioned above the measuring area.

The specimen clamping is designed according to ASTM F 320 [1]. Two modifications were used during the testing. One leaves a squared impact area with 175 mm side; the other has a circular area with 100 mm diameter. Circular clamping was used in the second stage of experimentation to induce larger damage in the tested composite plates.

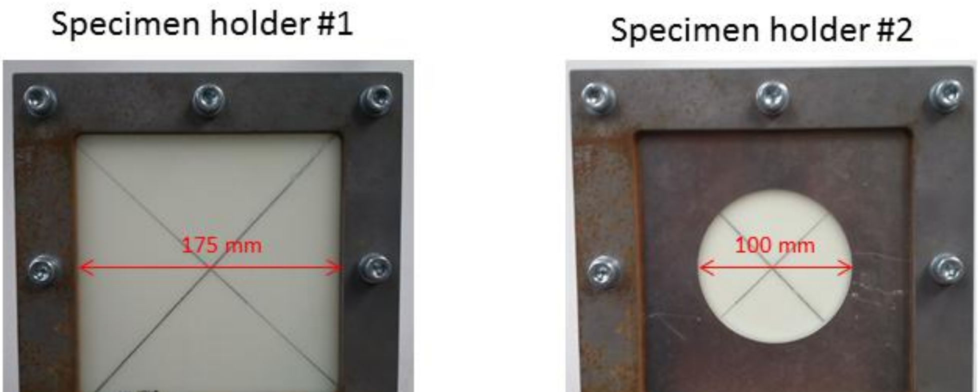

Figure 3 Specimen clamping design.

2.2 Simulated hail ice

Testing using real hailstones in their naturally occurring state is nearly impossible. It has a complex internal structure and shape. Typically is an oblate spheroid that is spherically layered or agglomerated. It also varies in density and might consist from frozen, porous, and liquid regions. Usually the density is from 810 to 920 kg/m^3 [2]. Halpin and Kim [3] reported the distributions of naturally occurring hail sizes. The 90th and 99th percentile hail sizes are 44.7 and 66.8 mm, respectively.

Laboratory manufactured ice balls were used in this study to simulate naturally occurring hailstones. Dimensions were chosen with regards to probability distribution of naturally occurring sizes. Ease of manufacturing played also an important role. A mould for making 10 ice golf balls with nominal diameter of 42.67 mm (1-2/3 inches) was utilized. Resulting ice balls had a diameter of 39.81±0.91 mm.

Two procedures for freezing the water were investigated. Firstly the mould was filled at once, resulting in a monolithic ice ball. Secondly, the mould was filled at approximately 12 steps, resulting in flat-wise layered sphere. Both approaches gave similar results during the composite panel impact testing in terms of caused damage and post-impact behaviour.

The average density of manufactured ice balls was 771±0.03 kg/m^3. This was somewhat lower than expected values. ASTM F320 recommends using cotton filled ice, which may increase the density and overall integrity of simulated hail ice. However, this was not utilized during this study. According to Ref. [3], the cotton reinforced hailstone is significantly more damaging than ordinary simulated hailstone and may be misleading for damage tolerance improvement. Therefore this practise is not recommended as hail threat representation.

Figure 4 Real and simulated hailstone comparison.

2.3 Calibration

Gas gun performance was characterized by evaluating the relationship of the air pressure versus ice ball velocity. Several ice balls were fired at different level of air pressure from 20 to 100 psi and chronograph readings were recorded. The relationship was found to be linear in this pressure range. The projectile velocity range was 64 - 189 m/s. Figure 5 shows this relationship. Actual weight of the projectile doesn't seem to have a significant influence on the resulting velocity, as can be seen from the right part of Figure 5.

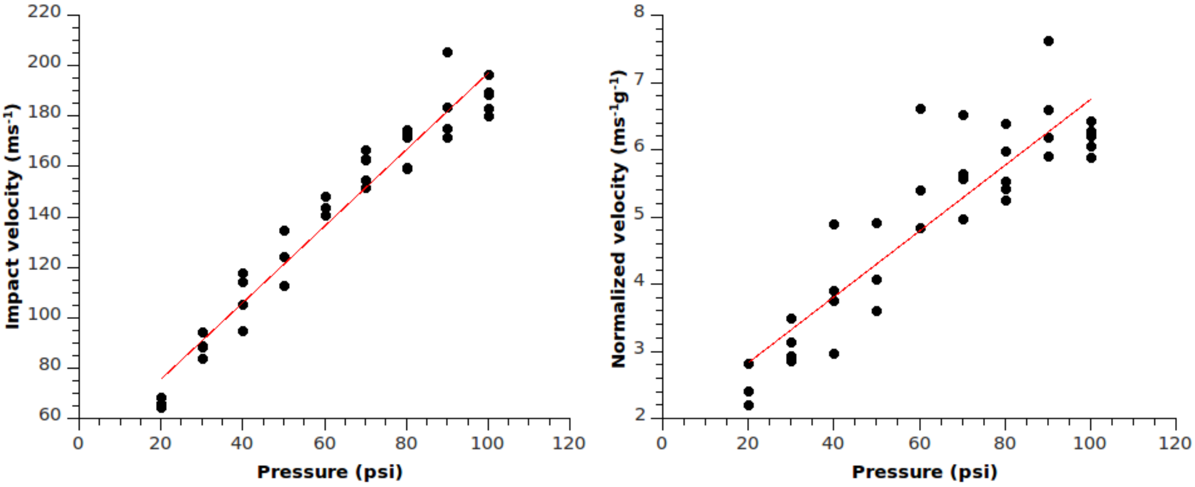

Figure 5 Calibration chart for air-gun chamber pressure vs. resulting impact velocity.

2.4 Tested panels

Five different types of flat panels were tested as they are listed in Table 1. The dimensions of panels were 200 × 200 mm.

#	Type	Description	Layup	Thickness [mm]
1	CRFP	Epoxy/HS-Carbon UD 600gsm	$(+45/-45)_s$	2.6
2	GRFP	Epoxy/E-glass UD 600gsm	$(0/90)_s$	2.0
3	GRFP	Epoxy/E-glass UD 600gsm	$(0/+45/-45)_s$	3.0
4	GRFP	Epoxy/E-glass PW 600gsm	$(0/90)_s$	1.3
5	GRFP	Epoxy/E-glass PW 600gsm	$(0/90/0)_s$	1.95

Table 1 Description of tested panels

2.5 Experiments and results

The ice balls were removed from the mould using warm water, to avoid introducing cracks and fractures by knocking them free from the mould. All mould lines and excess material were removed from the outer surface. The ice balls were then placed back into deep freeze in order to consolidate the outer layer. Prior to loading the ice ball into the sabot, its diameter and mass were measured. Thermally insulated carrying bag and gloves were used when manipulating the ice balls.

All panels were tested at maximum available pressure of propeller gas (100 psi) and velocity of approximately 190 m/s. Two different types of clamping were applied as described in section 2.1.

Panels gripped at the squared clamping had no apparent damage even after several repeated impact events. Ultrasonic C-scan confirmed that no internal damage was caused to the panels by simulated hailstone impact.

The circular type of clamping was introduced in order to reduce the elastic energy absorption (i.e. through elastic bending) of the panels and possibly to cause higher level of damage. This assumption proved to be true, since matrix cracking (i.e. characteristic whitening in GFRP) around fibre tows was observed at the back face of tested panels (Figure 6). Only panels #2 through #5 were tested with this clamping condition with various degrees of damage, although the damage character was very similar for all specimens. Delamination didn't occur in either of tested panels.

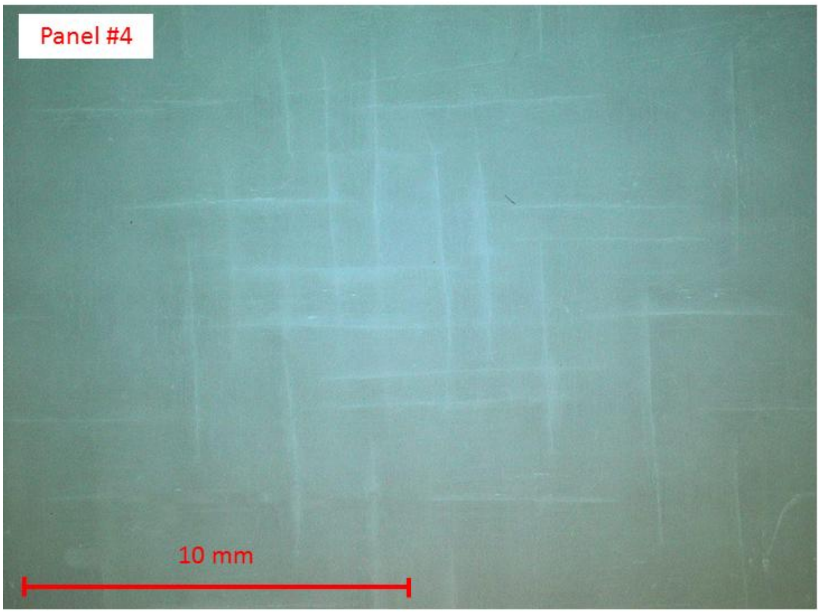

Figure 6 Observed damage in panel #4.

3 Numerical simulation

3.1 Model of composite plate

Due to similar nature of damage in all experimentally tested panels, only panel #4 was chosen to be modelled using Abaqus™ explicit. Each ply is modelled by continuum shell element (SC8R), where thickness is determined from the element nodal geometry. Interaction between plies is defined by surface based cohesive behaviour, which can be used to model delamination propagation via linear elastic fracture mechanics principles.

Damage prediction in composite laminates usually consists from two sections: (a) intra-laminar and (b) inter-laminar. Intra-laminar damage model requires definition of a number of parameters like (a) linear elastic definition of undamaged material, (b) damage initiation criteria and (c) damage evolution response.

Four discrete modes are considered for both initiation and propagation of damage: (a) fibre rupture in tension, (b) fibre buckling and kinking in compression, (c) matrix cracking under transverse tension and shearing, and (d) matrix crushing under transverse compression and shearing. Hashin failure criteria [4] is used for damage onset prediction in Abaqus™.

Damage evolution is characterized by energies dissipated during damage for fibre tension, fibre compression, matrix tension, and matrix compression failure modes. Linear damage evolution as described by line AC in Figure 7 was considered.

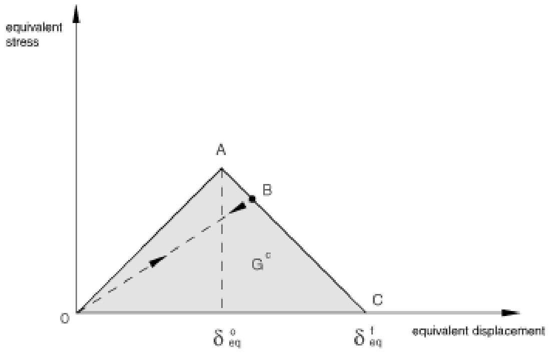

Figure 7 Linear intra-laminar damage evolution.

Inter-laminar damage model is based on surface cohesive behaviour in terms of traction-separation response. Damage is defined within the same general framework used for conventional materials and consists of (a) a damage initiation criterion and (b) a damage evolution law. The initial response is assumed to be linear. A maximum stress criterion is used to evaluate the damage initiation point, while damage evolution is based on fracture energies dissipated as a result of the damage process. The dependence of the fracture energy on the mode mix is described by Benzeggagh-Kenane fracture criterion [5]. Table 2 gives summary of lamina mechanical and damage properties used for analysis.

Epoxy/E-glass PW 600gsm	Elastic	E_1	E_2	v_{12}	G_{12}	G_{13}	G_{23}
		28000	28000	0,15	4000	4000	4000
	Density	ρ					
		1,86E-009					
	Damage initiation (Hashin)	X_t	Y_c	X_t	Y_t	S_L	S_T
		454	473	456	477	62	62
	Damage evolution (Energy)	G_{ft}	G_{fc}	G_{mt}	G_{mc}		
		4,57	4,57	4,57	4,57		
	Cohesive b. (Damage initiation)	N_{max}	T_{max}	S_{max}			
		45	60	60			
	Cohesive b. (Damage evolution)	G_{Ic}	G_{IIc}	G_{IIc}	B-K		
		0,402	3,09	3,09	1		

Table 2 Material and contact properties

3.2 Ice model

Two approaches were used to model ice behaviour in Abaqus™ explicit. First one is a Lagrangian finite elements approach. This approach is extremely efficient when considering nonlinear problems, though it has its weak point in the excessive mesh distortions, which are rather typical in events featuring soft-bodies or fluid-like materials such as the ones considered here [6].

The other method is the smoothed particle hydrodynamics (SPH) approach. Here the FE mesh is replaced with a set of particles with mass properties. This method is effective for applications involving extreme deformation, such as fluid sloshing, gas flow and impact analysis. The method can use any of the materials available in Abaqus™ explicit. The smoothed particles model can be created by simple conversion from Lagrangian finite element formulation [7].

Material for both models was defined as elastic plastic with failure. This material model allows a plastic hardening behaviour that adequately reproduces the effect of the propagation of the micro-cracks inside the ice before it crushes, reaching a fluid-like state. When the plastic failure strain is reached, all shear stress components are relaxed to zero. Furthermore, if the tensile failure pressure is reached, the material carries only hydrostatic compressive stresses as a fluid. The mechanical properties of the ice are summarised in Table 3. Obviously, this is only a simplified representation of a complex material such as the ice. In fact, this model does not consider the complicated nonlinear mutual dependency between pressure and volume and the influence of the strain rate on the failure strength. However, it was showed that this material model makes it possible to reproduce correctly the ice behaviour during a high-velocity impact and therefore it has been adopted [6].

The diameter of simulated hailstone was 40 mm and consisted of 2800 elements (C3D8R - Lagrangian, PC3D - smoothed particles).

Young's modulus	E [MPa]	9000
Poisson's ratio	v[-]	0.3
Density	ρ [tonne/mm^3]	7.72E-010
Yield stress	[MPa]	5.2
Tensile failure pressure	[MPa]	0.5

Table 3 Ice material properties

3.3 Impact results

Boundary conditions applied to the model corresponded to the experimental setup with circular impact area. Steel supports were connected to both sides of composite plate by a tie constraint. All nodes of the ice impactor had prescribed an initial velocity.

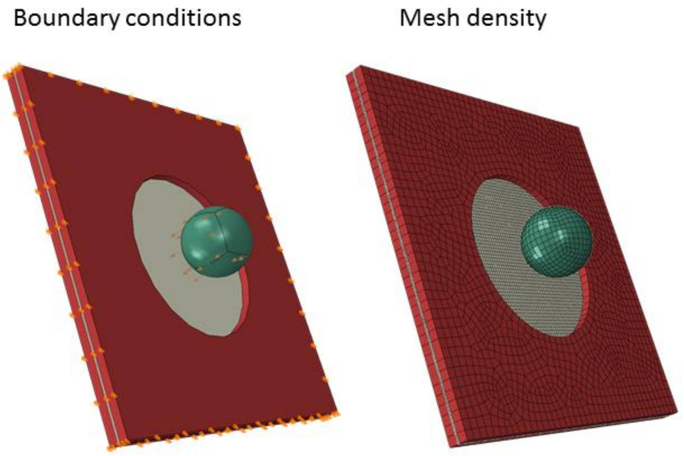

Figure 8 Finite elements model

Lagrangian and SPH models have similar results in terms of deformation of projectile during the impact event, as can be seen in Figure 9. An initial velocity of 180 m/s was applied and both models were compared with images from high speed camera, taken from [8]. It was shown that both models have good capability of realistically imitate real ice impact behaviour.

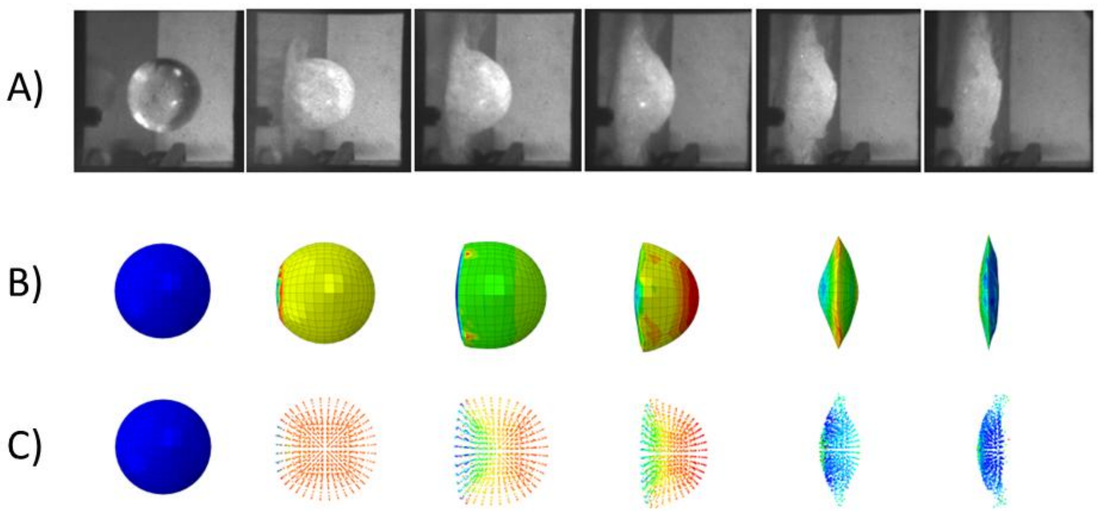

Figure 9 Impactor deformation (A-High speed camera [8], B-Lagrangian model, C-SPH model)

The results of both models are very similar; however SPH model predicts slightly higher level of damage caused to the panel. Figure 10 compares caused damage in terms of delamination after impact (CSDMG variable).

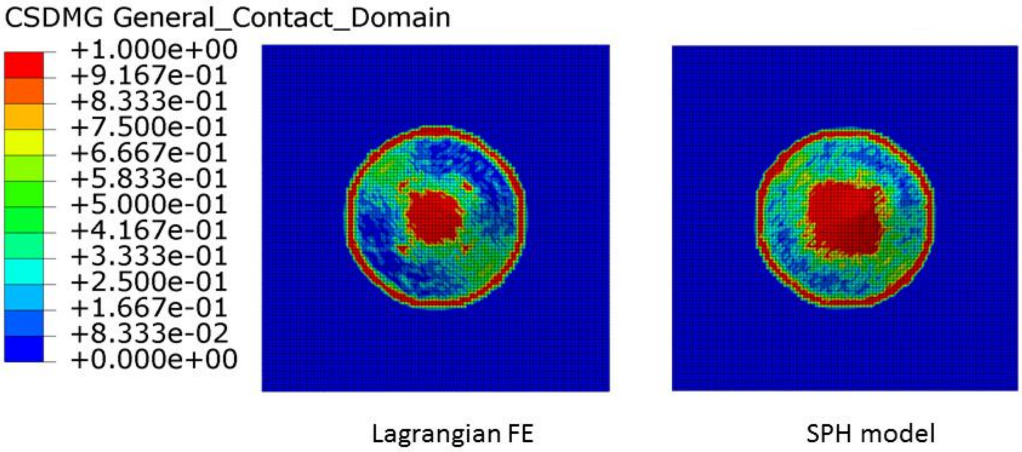

Figure 10 Delamination after impact comparison of Lagrangian and SPH model

Hashin criterion for matrix tension failure (DAMAGEMT) was chosen as a measure of panel damage. Figure 11 shows progress of delamination and matrix tension failure with increasing impactor velocities. Matrix tension failure remains almost constant above 180 m/s, while delamination extent is significantly increasing.

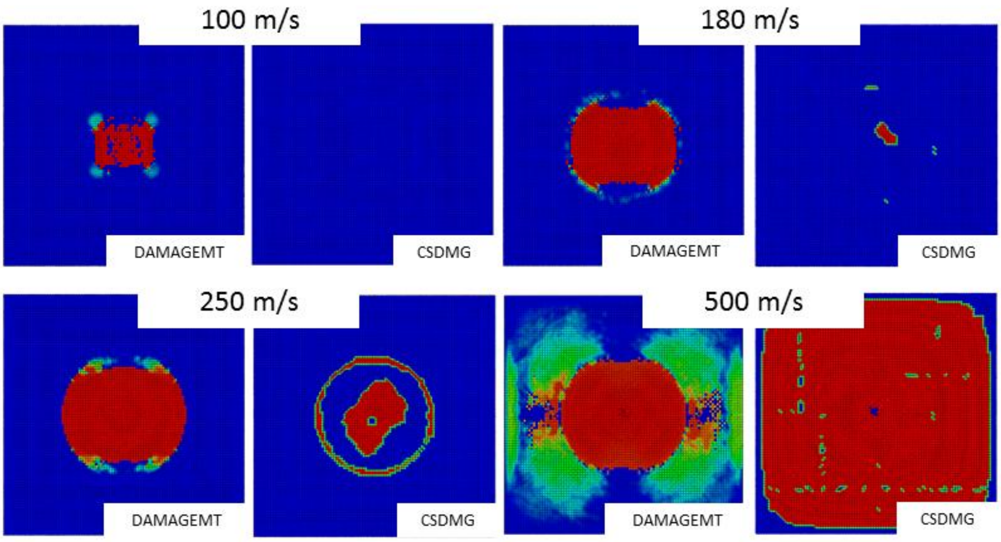

Figure 11 Influence of impactor initial velocity on panel damage

4 Conclusion

A hail impact facility was designed and built with the aim to study damage in composite laminates during and after simulated hailstone impact. This facility is based on air gun principle and is capable of firing ice projectiles up to 40 mm in diameter and in range of velocities 60-190 m/s. The only type of damage detected after impact was in a form of matrix cracking at back face of tested panels. From numerical simulation performed in Abaqus™ Explicit it can be assumed that further increasing of impact energy would cause development of delamination; however more extensive testing is needed in order to better correlate experimental and simulation results.

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