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High velocity impact on NCF reinforced composites

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ABSTRACT

In the current paper, a series of high velocity impact tests using $\varnothing 50$ and $\varnothing 25$ mm ice spheres and 0.32 g granite stones on non-crimp fabric (NCF) composite plates are reported. The impact tests were performed using an air gun and velocities between 100 m/s and 199 m/s. The impact events were monitored using a high-speed camera, with a 20 million frames per second capacity, as well as by a displacement transducer for out-of-plane displacement measurements of the impacted plates. NCF composite plates of two different thicknesses were impacted. The composites were manufactured from carbon fibre and epoxy resin by vacuum infusion.

Engineering type models were employed to predict impact response and impact damage formation. Comparison between predicted and resulting damage for the impact test validates the application of a semi-empirical model for predicting impact velocity thresholds for damage formation. Analytical models relying on the assumption of solid impact bodies cannot be employed for these types of impact.

1. INTRODUCTION

Foreign object impact is considered one of the main threats to composite material structures performance. This is due to the materials sensitivity to out-of-plane loads. Damage caused by impact is known to substantially lower the strength of the part, e.g. compression after impact strengths half of that of the pristine structure are commonly reported. Furthermore, impact damage is very subtle and hence is usually not detected at a visual inspection. For these reasons, for any composite structure, effects of damage caused by foreign object impact on the structural performance must be considered already at the design stage. In this context, high velocity impact from ice and stones present particular threats to aircraft structures.

To allow consideration of impact damage in the design models for impact response and damage formation, i.e. impact damage resistance must be at hand. A number of impact damage resistance models and modelling techniques are available for solid impact bodies [1-4]. The applicability of these models for analysis of ice and stone impact is not fully assessed. Kim and co-workers [5,6] have addressed the ice impact event and developed a semi-empirical approach to the problem. These types of simple and easily accessible engineering models [1-6] are required in the design phase as a complement to the more detailed and cumbersome analyses using numerical approaches. The most promising numerical procedures employ soft particle hydrodynamics (SPH) to model the behaviour of the ice at impact [7].

The objective of this study was to monitor ice and stone impact on non-crimp fabrics (NCF) composite laminates and to investigate the validity of engineering impact resistance models for analysis of ice and stone composite impact.

2. EXPERIMENTS

Two material configurations using different thickness, 4 and 6 mm, were investigated. The laminates were made from biaxial carbon fibre NCF and epoxy. The laminates consisted of biaxial NCF fabrics of direction $0^\circ/90^\circ$ and $\pm 45^\circ$ stacked into a quasi-isotropic lay-up. The laminate lay-ups were $[0/90/45/-45]_{2S}$ and $[0/90/45/-45]_{3S}$ for the 4 and 6 mm thickness plates respectively. The plates were manufactured by vacuum infusion and the resulting fibre volume fraction was approximately 50%. The panels were cured according to the supplier's recommendations. Specimens were saw cut from panels to a final dimension of approximately $150 \times 100 \text{ mm}^2$. Eight plates of each configuration were impact tested.

The cut plates were mounted in a window fixture according to the EN standard prEN6038 and the knots were finger tightened. The inner dimensions of the window frame used in the impact test were $125 \times 75 \text{ mm}^2$. The impacting object was launched in an air gun by the release of compressed air (see Figure 1). The impact velocity was controlled by altering the compressor pressure. The plates with thickness 4 mm were impacted using $\phi 25 \text{ mm}$ ice (velocity 115-192 m/s) and 0.32 g stones (velocity 139-191 m/s). The plates with thickness 6 mm were impacted using $\phi 25 \text{ mm}$ ice (velocity 103-114 m/s) and $\phi 50 \text{ mm}$ ice (velocity 103-165 m/s). The ice spheres were frozen in plastic balls after filling thorough a drilled hole and degassing. In a first freezing step the filled plastic balls were kept at -2°C for 24 hours. After this the temperature was lowered to -10°C at which the ice was kept until testing. In the test lab the ice was kept in an insulated box and continuously cooled using a container partially filled with fluid nitrogen placed in the box. The temperature in the box was in the range -10 to -40°C .

The mid-point deflection of the composite plate was measured using a laser displacement transducer (MEL M7L/20mm) placed behind the plate. The displacement

transducer sampled at 10 kHz (can be used up to 17 kHz) with a resolution of 0.009 mm. The displacement range for the transducer was 20 mm with ± 0.04 mm accuracy. The behaviour of the impacting body (ice and stone) was monitored using a high-speed video camera (IMCO Ultramac FS 501 Astromed system frame grab and IMCO Ultramac ICS 20 CCD) with a maximum capacity of 20 million frames per second. The video camera was set-up for a 100 μ s delay between the frames and a 5 μ s exposure time.

After impact the plates were dismantled and subject to visual inspection. Any damage detected at the ocular inspection was recorded. Following impact testing all plates were analysed by ultrasonic C-scan. Finally, some plates were cross-sectioned and polished to establish detailed damage maps from the impact.

3. ENGINEERING IMPACT MODELS

Two engineering models for analysis of foreign object impact on monolithic composite laminates have been developed by Olsson [2,3], the small mass and large mass impact models. They constitute simple tools for evaluating the severity of a solid object to composite plate impact. The models by Olsson have been evaluated in this work to assess whether they are suited also for the case of an ice or stone impact onto a composite plate. Note that it is not expected that the ice will behave as a solid body, as assumed by the models, during impact.

The models [2,3] are divided according to type of behaviour at impact; short impact times (through-the-thickness waves), intermediate impact times (flexural and shear waves), and long impact times (lowest vibration mode, quasi-static). The following discussion will focus on the intermediate (small mass impact) and long impact times

(large mass impact). The type of behaviour at impact is governed by the impactor/plate mass ratio according to:

$$\text{Small mass impact:} \quad M < M_p^*/4 \quad (1)$$

$$\text{Large mass impact:} \quad M \geq 2M_p \quad (2)$$

where M is the impactor mass, M_p^* is the mass of affected plate area and M_p is the mass of the plate. The aspect ratio of the mass of affected plate area is given by the ratio of flexural wave speeds $(D_x/D_y)^{1/4}$. The load and displacement responses during an elastic large mass impact are in phase, the basic shape of the response curves is similar and peak values appear at the same time, in short, a quasi-static response. This is in contrast to the small mass impact case where the peak load appears very shortly after first point of contact. At the time of peak load, the displacement is often just a fraction of the peak displacement during the small mass impact. The stone and $\phi 25$ mm ice impact cases studied here belong to the small mass impact category, whereas the $\phi 50$ mm ice impact is an intermediate case to those described by Eqs. (1) and (2).

The damage threshold levels evaluated by the Olsson models refer to damage due to high contact forces (i.e. splitting, delamination and fibre fracture). These are representative for laminates where the major deformation mechanisms are bending and shear deflection. Full expressions of the Olsson small and large mass models are found in references [2] and [3].

Kim, Welch and Kedward [5] evaluated the severity of a composite plate ice impact using a different approach, a semi-empirical method. In their approach they impacted a number of composite plates using ice spheres with different diameter onto composite plates with different thickness. They discovered a rather simple relation between the ratio of the diameter of the ice sphere, D , and the thickness of the plate, H , to a failure

threshold energy, FTE . An energy-balance study of the impact event gives the following relationship between the FTE and the ice sphere diameter, density of the ice, ρ_{ice} , the composite panel interlaminar shear strength, τ_{ILS} and the shear modulus G_{ILS} :

$$\alpha = \frac{\rho_{ice} V_{FTE}^2}{(\tau_{ILS}^2 / G_{ILS})} \quad (3)$$

where α is a non-dimensional parameter and V_{FTE} is the ice projectile velocity corresponding to the FTE . The threshold level, which relates to delamination formation, will have to be experimentally confirmed for different material systems but has the potential, according to Kim, Welch and Kedward [5], to reduce the amount of experimental work otherwise necessary to quantify the damage resistance of a composite material system to ice impact.

4. EXPERIMENTAL RESULTS

4.1 Impact response

The behaviour at impact for these objects showed to be rather different compared to a solid body impact. The difference between a solid object impact and an ice sphere impact are related to the energy transfer between the parts:

- Firstly, part of the initial kinetic energy of the ice sphere is transferred into creating new surfaces by crack initiation and crack propagation, which are not present for solid body impact.
- Secondly, the second part of an ice impact is an impact with a material which is much more compliant than the originally solid ice.
- Thirdly, the yielded ice, now basically in fragments, hits the plate and flows very similar to a fluid.

Figure 2 shows high-speed camera pictures from an ice impact illustrating the described behaviour. The sequence of the pictures in the figure is from the top left going downwards, next column going upwards and so on. The figure depicts the basic behaviour, the local crushing and the subsequent fluid-like flow. The typical response of a 6 mm thick plate to small and large diameter ice impact is plotted in Figure 3. The out-of-plane displacement is measured in the centre of the plate.

The behaviour of the stone is more difficult to assess, but seems to be very similar to that of the ice. The stone crushes at impact as illustrated in Figure 4. Based on this observation, an engineering solid body impact modelling approach may not be relevant to capture critical forces during a stone impact event.

4.2 Fractography

The $\phi 25$ mm ice impacts did not cause any visible damage to the thick plates. The ultrasonic C-scans confirm this. For the $\phi 50$ mm ice impacts the situation was different. Impacts occurring at speeds below 110 m/s did not cause any visible damage to the plate surfaces or edges. At increased speeds (110-136 m/s) visible damage on the surface was detected. The damage was not located at the impact site, it was found in the clamping regions (at the window frame position) in the form of matrix splits and fibre fractures. The ultrasonic C-scan pictures depicted in Figure 5 and the polished cross section shown in Figure 6 indicate that the delamination velocity threshold for the thick plates is between 103 and 107 m/s. The matrix cracks visible in Figure 6 are solely contained in the $\pm 45^\circ$ and 90° layers closest to the impacted surface. No damage was found in or below the uppermost 0° layer (fourth layer from the impacted side). For higher impact velocities matrix cracks develop deeper into the material. Increasing the impact velocity to 107 m/s these matrix cracks evolve into delaminations.

For $\phi 25$ mm ice impact on the 4 mm thick laminates at high velocities (>190 m/s) conspicuous surface damage (surface splits and edge delaminations) occurred at the clamped regions. Ultrasonic C-scan show massive delaminations. For lower impact speeds, no delaminations due to ice impact could be detected. Under no ice impact condition was fibre failure at the impact site identified.

The plates impacted by 0.32 g stones featured conspicuous damage at the impact site. Figure 7 shows the impact site on a 4 mm thick plate impacted at 153 m/s. The impact site has suffered severe fibre failure as well as matrix splitting and delamination extending only a few millimetres away from the impact centre. Thus, the stone represented a more aggressive threat to the composite than did the ice, in that surface

damage appeared at the contact point. It should be noted that the granite stones used in the impact tests were not spherical in shape. They had rather sharp edges, see example in Figure 8. These sharp edges may have played an important role in the fracture of fibres at the impact site.

5. COMPARISON BETWEEN MODEL PREDICTIONS AND EXPERIMENTS

The models according to Olsson [2,3] were applied prior to the experiments to predict matrix cracking, delamination formation and fibre failure due to ice and stone impact. The estimations indicated that both matrix cracks and delaminations would occur in the plates (thickness 4 and 6 mm) when impacted by ice spheres ($\phi 25$ and $\phi 50$ mm) at 100 m/s. The experimental results showed that no damage at all was inflicted on either plate in the $\phi 25$ mm ice impact case. However, matrix cracks were found in the thicker plate after a $\phi 50$ mm ice impact at 103 m/s and delaminations formed at an impact speed of 107 m/s. It is clear that the ice is a lesser threat than predicted and should not be represented by a solid object. The described differences between a solid body impact and an ice impact together with the experimental results indicate the models by Olsson [2,3] are not suitable for predictions of the severity of an ice sphere impact onto a composite plate. The small mass model, due to Olsson [2,3] was also applied to the stone impact at 155 m/s on the 4 mm thick laminate. No damage was predicted as a result of the impact. However, the tested laminates suffered from fibre fracture, matrix cracking and delamination at the impact location. Unexpectedly high contact loads due to the stones having sharp edges in opposite to the assumed spherical shape may have caused this damage.

Incorporating the ice impact results in the present work of the NCF composite material using the graph according to Kim, Welch and Kedward [5], the method shows definite

potential for use in design for ice impact damage resistance. The result is illustrated in Figure 9 together with an assumption of an impact threshold level for onset of delamination. The values used for the interlaminar strength and interlaminar shear modulus were $\tau_{ILS} = 67MPa$ and $G_{ILS} = 5.17GPa$, respectively.

The form of the non-dimensional parameter α is input kinetic energy per unit volume divided by interlaminar strain energy per unit volume, which for laminated composites is a relevant measure of damage. The empirical method developed by Kim, Welch and Kedward [5] has a definite potential for being a simple method for evaluating damage resistance of laminated material systems.

6. CONCLUSIONS

High velocity impact of ice and stone on NCF composite laminates present a challenge to the design engineer of composite structures for aeronautical applications. Impact tests with ice and stone show that these behave differently to solid bodies in an impact event. At impact the ice sphere cracks and flows, imposing a much lesser threat to the composite than would a solid body of the same dimension and weight. As a result, no damage could be detected at the impact site at a visual inspection. Unexpectedly, the granite stone behaved very similar to the ice upon impact with the composite plate. The stone literally went into dust at impact, leaving significant damage (fibre fracture, delamination and splitting) at the impact site.

Analytical models for small mass impact analysis were employed to analyse ice and stone impact at 100 and 155 m/s respectively. The models predicted the ice impact as being critical, whereas the stone impact was predicted not to cause any damage. In both cases the experimental results were the opposite. Assessment of the test data reveals that the analytical models by Olsson [2, 3] are not adequate for predicting the response

of ice impact due to the “soft” and subsequent fluid-like flow behaviour of the ice. Discrepancies between predictions and experiments for the stone impact are believed to be caused by the sharp edges of the employed stones. The model assumes a spherical shape of the impacting body in the contact zone. In contrast, the empirical method developed by Kim et al. [5] has been demonstrated to provide an efficient method for damage resistance analysis of NCF composite laminates forecasted for high velocity ice impact.

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Figure Captions

Figure 1: Experimental set-up. The air gun was loaded with ice or stone using a low-density foam carrier to the left in the picture and shot by release of compressed air.

Figure 2: Typical impact of a $\phi 25$ mm ice sphere (impact velocity 96 m/s).

Figure 3: Response from $\phi 25$ mm (114 m/s) and $\phi 50$ mm (110 m/s) ice impact.

Figure 4: Composite plate impact with 0.32 g stone at 175 m/s.

Figure 5: Ultrasonic C-scan of two 6 mm thick plates impacted by $\phi 50$ mm ice at a) 103 m/s and b) 107 m/s.

Figure 6: Damage in cross-section A-A (weft-direction) of a 6 mm plate impacted at 103 m/s; Matrix cracks in the $\pm 45^\circ$ and 90° layers closest to the impact surface.

Figure 7: Surface damage detected at the impact site on a 4 mm thick plate (stone @ 153 m/s).

Figure 8: Shape of a 0.31 g granite stone used in the study.

Figure 9: Results of ice impact experiments of NCF composite plates plotted according to Kim, Welch and Kedward [5].

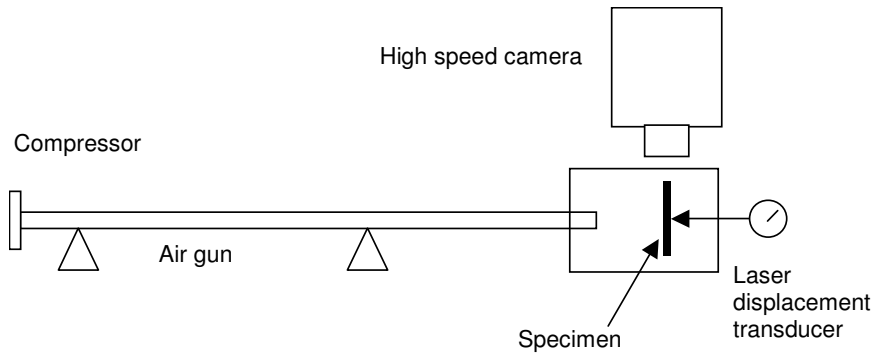


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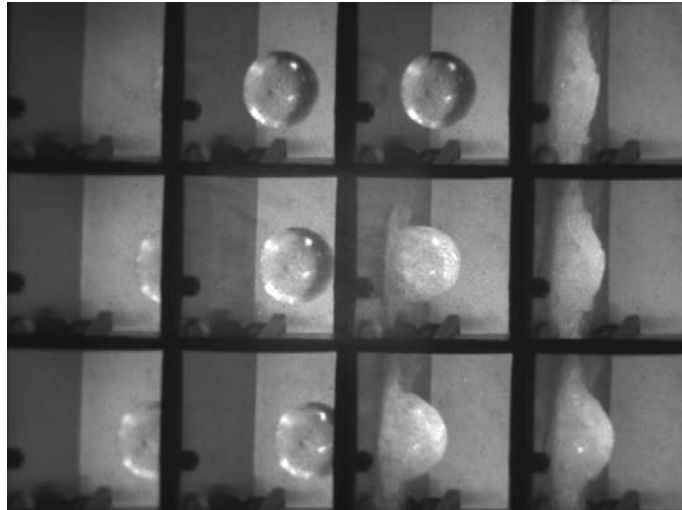


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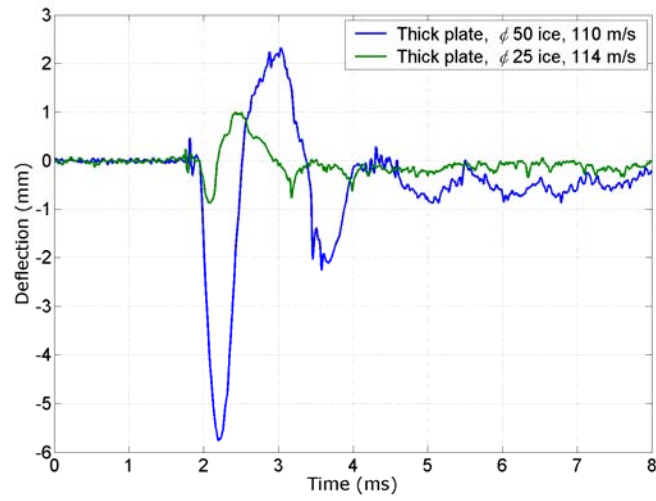


Figure 3: Response from $\phi 25$ mm (114 m/s) and $\phi 50$ mm (110 m/s) ice impact.

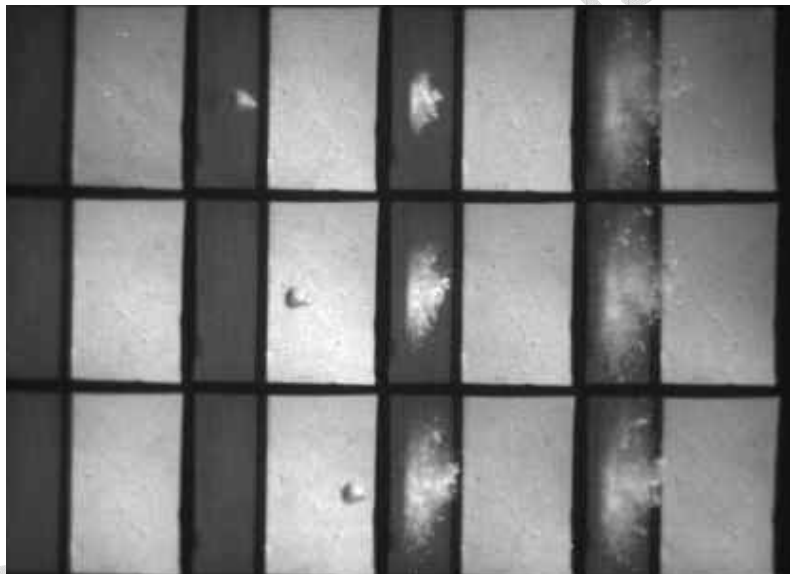


Figure 4: Composite plate impact with 0.32 g stone at 175 m/s.

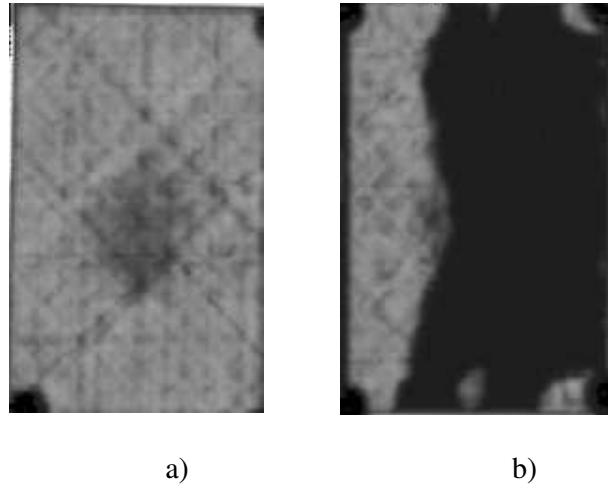


Figure 5: Ultrasonic C-scan of two 6 mm thick plates impacted by $\phi 50$ mm ice at a) 103 m/s and b) 107 m/s.

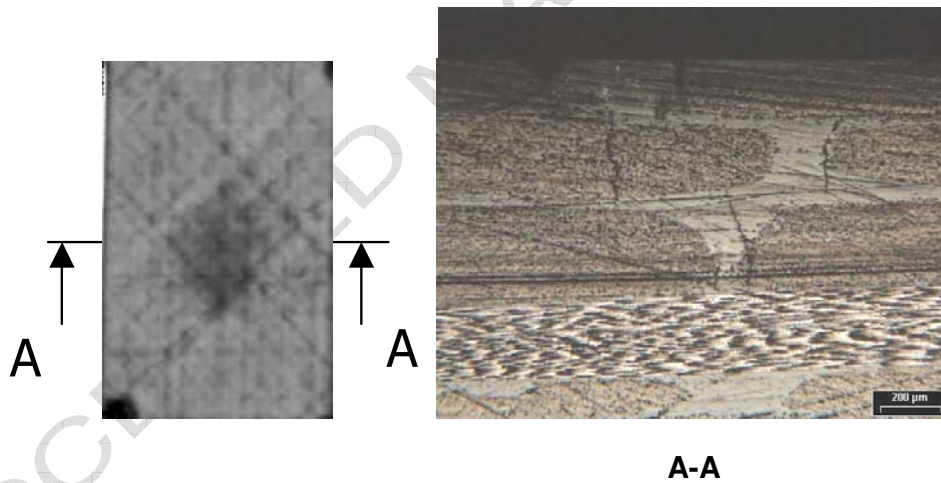


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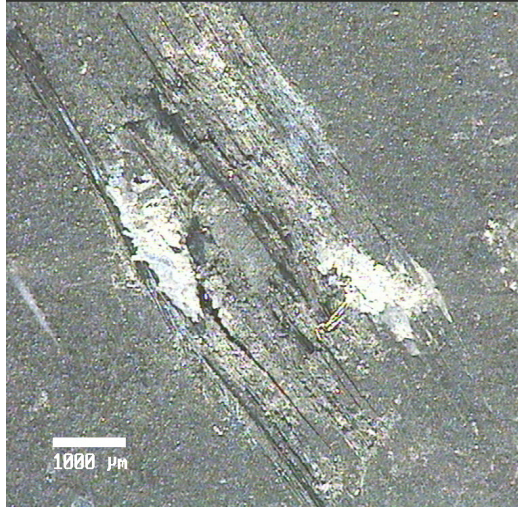


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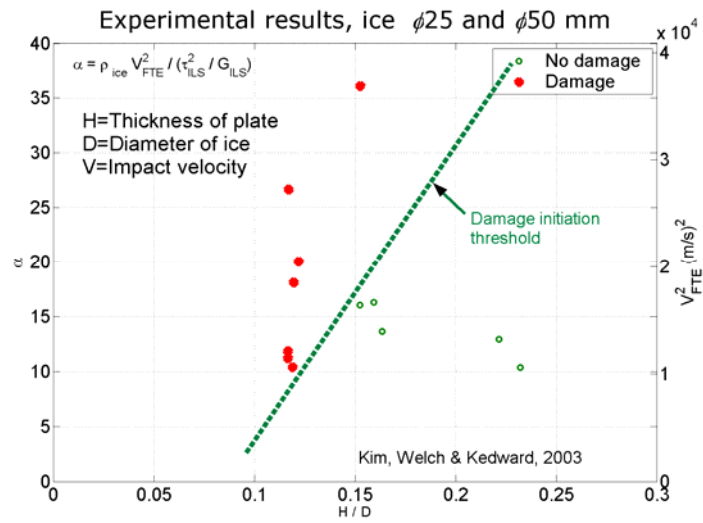


Figure 9: Results of ice impact experiments of NCF composite plates plotted according to Kim, Welch and Kedward [5].