Research of hail impact on aircraft wheel door with lattice hybrid structure

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Abstract. Aimed at a long lasting issue of hail impact on aircraft structures and aviation safety due to its high speed, the resistance performance of hail impact on the wheel door of aircraft with lattice hybrid structure is investigated. The proper anti-hail structure can be designed both efficiency and precision based on this work. The dynamic responses of 8 different sandwich plates in diverse impact speed are measured. Smoothed Particle Hydrodynamic (SPH) method is introduced to mimic the speciality of solid-liquid mixture trait of hailstone during the impact process. The deformation and damage degree of upper and lower panel of sandwich plate are analysed. The application range and failure mode for the relevant structure, as well as the energy absorbing ratio between lattice structure and aluminium foam are summarized. Results show that the tetrahedral sandwich plate with aluminium foam core is confirmed the best for absorbing energy. Furthermore, the high absorption characteristics of foam material enhance the capability of the impact resistance for the composition with lattice structure without increasing the structure surface density. The results of study are of worth to provide a reliable basis for reduced weight aircraft wheel door.

1. Introduction

Severe convection weather such as hail has long been the potential threat to the safety of aircraft [1, 2]. Even a short while passing through the hailstone regions, it is sufficient to cause damage to aircraft structure such as depression, cracking and even piercing if crushed with hailstone at a high speed.

The exposed parts such as wheel door, leading edge, radome and engine, will be easily damaged during this condition, which severely impact both flight performance and mechanism operating. According to statistics, depot repair expenses of airliners caused by collisions of foreign matters are up to $3-4 billion each year all over the world, leading to flight delay and aviation accidents which further create immeasurable economic losses. Through the observation of damaged aircraft and the experimental tests, it has been recognised that the extent of the mentioned damage depends on the features of both hailstone(mass, impact angle and velocity), and the impacted structure(geometric and material).

The research of weather conditions has been possible to predict some extreme weather conditions which lead to avoid the flight routes passing through the hail regions. However, it is not always to make an accurate prediction for a great many circumstances beyond our reach.
Therefore, the structures of modern aircraft are called by specific requirements to guarantee a certain level of functionality after being impacted by a number of hailstones. Porous metal structure of random (metal foam) or periodic topology has attracted much attention from the aircraft industry, dependent on its characteristics such as lightweight, high strength, impact resistance and sky-high designability, etc [3–5]. However, as the experiment is difficult for reproducing the whole process of hail impacts, also time consuming, numerical simulation becomes particularly important. Actually, after being properly validated by experimental evidences of hail impacts, also setting reasonable material parameters and geometrical features are able to provide rational references for hail impact resistance structure design [6].

In recent years, the issue of hail impacting of aircraft has been returned to the sight of researchers due to the frequently severe convection weather and hence prompt more researchers to carry out relevant experimental studies [7] and numerical simulations [8] successively. Kim [9,10] conducted experiments and finite element modeling of hail impacts with different speeds to carbon fiber composite laminated plates and obtained the failure mode of laminated composite plates in various conditions. Regarding Meo [11], the numerical simulation was performed for the damage mode of composite honeycomb sandwich panels subjected to low velocity impacts. While through experiments, Yungwirth [12] indicated that the impact resistance performance of structures could be improved significantly by filling epoxy resin into the lattice structure. Based on experiments, Thomas [13] found that the composite advanced grid stiffened structure had a favorable continuous hail impact resistance ability. By means of numerical simulation, Han [14] compared hail impact resistance properties of sandwich plates with four different types and then found that pyramid sandwich structure had a good impact resistance capacity.

As predecessors only adopted metal or composite plates to solve the hail impact problem and lattice configurations with fillers had been less studied, explicit finite element analysis tool of LS-DYNA was employed in this paper. Initially, the model has been validated referring to the results of experimental tests carried out by the British Royal Aircraft Establishment (RAE), also cited in NASA technical notes [15, 16]. Through designing a variety of lattice structures, the validated models have been used to reproduce the damages caused by hailstone, and study their hail impact resistance performances under different circumstances.

2. Numerical model
2.1. Numerical model of hailstone
As a mixed substance constituted by water drop, ice crystal and snowflake, large deformation and solid-liquid conversion happen to hailstone when hitting the object surface with a high speed. In order to describe the entire physical process, currently feasible methods mainly include the traditional Lagrange Finite Element Method, the Arbitrary Lagrangian Eulerian (ALE) Method and the Smooth Particle Hydrodynamics (SPH) Method, among which, the SPH model is able to provide more accurate result with less time consuming [17].

Therefore, the SPH model of hailstone is adopted in this paper. Moreover, by referring to the hailstone data provided by relevant scientific research institutes (table 1), the diameter of hailstone is finally chosen to be 50mm and it is deemed that such hails vertically impact the center of a sandwich plate with the impact speeds being $100 \text{m} \cdot \text{s}^{-1}$ and $200 \text{m} \cdot \text{s}^{-1}$ respectively.

At the same time, the elastic plastic hydrodynamic material model (*MAT 10 of LS-DYNA [18]) is utilized to describe the mechanical behaviour of hailstone, and its properties are shown in table 2. This model shows the characteristic that in the early contact period, it exhibits a high stiffness, and in the later period, it behaves like fluid. This model is defined by a failure criterion relative to the tensile stress, once the tensile failure stress reached, the deviatoric stress is set to zero and the material only can sustain compressive, in addition, the Equation of State (EOS) of water (table 3) is adopted as the material model required. There are 9678 particles
which the model consisted of.

| Impacting Mass(g) | Velocity(m·s$^{-1}$) | Energy(J) | Working condition |
|-------------------|------------------------|-----------|------------------|
| Hail 161.6        | 119-155 222            | 1154-1944 | Ground           |
|                   |                        | 3990      | Take off, landing |

Table 2. Mechanical properties of hailstone used in *MAT 10 of LS-DYNA [17]

| Properties                  | Values |
|-----------------------------|--------|
| Density(kg·m$^{-3}$)        | 846.00 |
| Shear modulus(GPa)          | 3.46   |
| Yield stress(MPa)           | 10.30  |
| Plastic hardening modulus(GPa) | 6.89  |
| Pressure cutoff(MPa)        | −4.00  |

Table 3. Parameters of Mie-Grüneisen EOS of water

| Model | $C_0$(m·s$^{-1}$) | $S_1$ | $S_2$ | $S_3$ | $\gamma_0$ | a |
|-------|-------------------|-------|-------|-------|------------|---|
| SNL   | 1647              | 1.92  | 0     | 0     | 0          | 0 |

2.2. Numerical model of wheel door

The guard board model of wheel door is given in figure 1. Considering that the physical dimension of the plate is rather large (1000mm×194mm), in order to be simplified, a length of structure equipped with the inside protective plate (125mm×125mm) is only taken into consideration (split part of figure 1). As the inner curved plate with a radius which is small, it will be treated as a slab. Thickness of the outer panel is 1.5mm and the inner panel 2.4mm. Then, a model of simplified protection plate is established as figure 2 combining the dimension of reinforcing rib shown in figure 1 (half H-shaped rib), with an overall thickness of 23.9mm.

In line with the dimension of simplified guard board model, 8 sandwich structure models are constructed (figure 3). With regard to those plates, their upper and lower panels as well as the internal trusses are LY12 aluminium alloy with the kinematic hardening plastic constitutive model (*MAT 3 of LS-DYNA [18]). The mechanical parameters are given in table 4. Actually, the energy absorbing of the aluminium alloy is mainly through the crack of inner lattice truss with plastic deformation, it is not easy to keep structural integrity during the impact process. In contrast, the lattice structure with foam core can efficiently avoid the tearing and penetration of...
Figure 1. The guard board model of wheel door

Figure 2. Dimension of guard board with hailstone impacting

(a) Corrugated core  (b) Pyramidal lattice core  (c) Tetrahedral lattice core
(d) Double pyramidal lattice core  (e) Kagome core  (f) Y-shaped lattice core
(g) Foam core  (h) Lattice-foam hybrid core

Figure 3. Model of sandwich structure

the face sheets and inner truss. Hence, two AlSi7Mg0.5 foams with densities of 150kg·m⁻³ and 300kg·m⁻³ are taken into account for the simulation. The Deshpande-Fleck foam constitutive model (*MAT 154 of LS-DYNA [18]) is adopted and corresponding mechanical properties are given in table 5.
Table 4. Mechanical properties of aluminium alloy used in *MAT 3 of LS-DYNA

| Properties                         | Values  |
|------------------------------------|---------|
| Density (kg · m⁻³)                 | 2785    |
| Young’s modulus (GPa)              | 70      |
| Poisson’s ratio                    | 0.269   |
| Yield stress (MPa)                 | 290     |
| Tangent modulus (GPa)              | 7       |
| Hardening parameter                | 1       |

Table 5. Mechanical properties of aluminium foam used in *MAT 154 of LS-DYNA [19]

| Properties                        | FoamA | FoamB |
|-----------------------------------|-------|-------|
| Density (kg · m⁻³)                | 150   | 300   |
| Young’s modulus (MPa)             | 300   | 1500  |
| Plastic Poisson’s ratio           | 0.05  | 0.05  |
| Foam yield surface shape factor (α)| 2.10  | 2.10  |
| Hardening coefficients (γ, MPa)   | 1.19  | 6.10  |
| Compaction strain                 | 2.89  | 2.20  |
| Hardening coefficients (α₂, MPa)  | 52.1  | 38.1  |
| Hardening coefficients (β)        | 3.26  | 3.10  |
| Plastic failure stress (MPa)      | 0.93  | 4.41  |
| Foam hydrostatic failure strain   | 0.10  | 0.10  |

2.3. Contact and boundary conditions
In case that the hail impacts sandwich plate at a specified speed, in order to guarantee that each component can continue to contact with each other after some failure deformation appears, the upper and lower panels of the sandwich structure as well as the lattice structure should be tied each other. The eroding contact is used for hailstone and sandwich plate, and automatic contact affected between aluminium foam and lattice structure respectively. Simulation boundary conditions are set that one of the opposite sides of plate is fixed, and the other is non-reflection which follows the actual conditions.

2.4. Model validation
The experimental test was carried out by British RAE, which considered the impact of a 25.4mm diameter hailstone against an aluminium alloy plate with an initial impact velocity of 192 m · s⁻¹. The plate was a square 0.91mm thick panel of 305mm side-edge, which was fixed at the boundaries with blind rivets so that eventually the free target surface consisted of a square region of 200mm side-edge. The previous hailstone and aluminium alloy models are used for the validation, with 4831 particles of hailstone and 1681 quadrilateral shell element of aluminium alloy plate.

The plastic deformation (figure 5) observed after the impact (measured with regard to Section A-A in figure 4) was used in the following as reference. The result obtained after the simulations
carried out using the previous models are compared with the experiment test data (figure 6). In particular, the maximum displacement (measured in the centre of the panel) was 12.04 mm. The comparison is made for the deformation in the velocity direction with the experiment data. It is noticed that the SPH model give errors within 4.7%. The error is mostly derived from the difference of the parameters of aluminium alloy, as it’s hard to get the original data for simulation. Therefore, the parameter settings and grid distribution of the hailstone and aluminium alloy model are reasonable.

Figure 4. Size of the experimental plate

Figure 5. Plate deformation with hail impact

Figure 6. Result comparison between numerical simulation and experiment of the deformation through A-A Section

3. Results and analysis of numerical simulation

Numerical simulation of hail impacting sandwich structure is performed by LS-DYNA, with the consistent unit of cm – g – μs. In addition, the surface density is treated as the only standard which is always used in mechanical properties comparisons, and each of the sandwich plate is set to the same surface density of 13.0kg · m⁻².

Relevant data of all constructions at a speed of 100m · s⁻¹ are given in table 6. Result shows that foamed, pyramid, tetrahedral and double pyramid structures are able to play a role of protection for the upper panel. Hence, high-speed impact simulation is continuously conducted based on those four structures mentioned above.
Table 6. Results of single core panels with impact velocity 100 m·s⁻¹ of hailstone

| Core                | Maximum deformation(mm) | Tearing diameter(mm) |
|---------------------|--------------------------|----------------------|
|                     | Top          | Bottom             |                      |
| Guard board         | 6.93         | 0.15               | 11.33               |
| Corrugated          | 3.01         | 0.37               | 21.52               |
| Pyramidal lattice   | 0.82         | 0.73               | —                   |
| Tetrahedral lattice | 0.47         | 0.22               | —                   |
| Double pyramidal lattice | 0.54     | 0.41               | —                   |
| Kagome              | 4.36         | 0.65               | 22.41               |
| Y-shaped lattice    | 5.82         | 2.21               | 19.35               |
| FoamA               | 5.35         | 2.96               | —                   |
| FoamB               | 5.71         | 2.48               | —                   |

__: no damage

By contrast, relevant data of those four constructions at a speed of 200 m·s⁻¹ is given in table 7. Result shows that only pyramid, tetrahedral and double pyramid ones are able to keep the structure with no tearing. According to results given in table 7, pyramid, tetrahedral and double pyramid structures with better protective performance are selected to be embedded aluminium foam core with two different densities. Through simulation, under the condition of the same surface density (dimensions of the internal lattice structure are reduced appropriately), the composite lattice structure of tetrahedron-foamA has the best impact resistance performance (see table 8).

If the surface density is reduced to 12.0 kg·m⁻² by adjusting the thickness of the bottom panel, the structure still remains a rather favorable impact resistance performance (see table 9).

Table 7. Results of single core panels with impact velocity 200 m·s⁻¹ of hailstone

| Core                | Maximum deformation(mm) | Tearing diameter(mm) |
|---------------------|--------------------------|----------------------|
|                     | Top          | Bottom             |                      |
| Pyramidal lattice   | 4.55         | 1.75               | —                   |
| Tetrahedral lattice | 1.32         | 0.52               | —                   |
| Double pyramidal lattice | 1.26    | 0.71               | —                   |
| FoamA               | 9.52         | 4.11               | 24.2                |
| FoamB               | 13.58        | 3.63               | 21.9                |

Based on above data, some remarks could be drawn. 1)According to table 6, corrugated sandwich plate has a better rigidity with strong deformation resistant capability, but less with concentrated force. 2)From to table 6 and table 7, as aluminium foam relies on cellular deformation to absorb energies, its resistance to bending is insufficient and hence inappropriate to serve as a pure force-bearing component. 3)According to table 8 and 9, lattice structures depend on plastic deformation and fracture between structures to absorb energies which are converted into heat energy for dissipation later (figure 7). Their deformed regions are only limited to parts under impact so that continuous carrying capacity could be ensured. 4)As figure 8 shows, if foamed materials are filled into gap of the structure, energy can be absorbed effectively to resist
impacts, meanwhile, aluminium foam is able to absorb large amounts of energies after being impacted. It also should be noticed that the total energy of lattice core is smaller than internal energy after 30µs, due to some negative external work caused by the structure rebound. The peak impact energy absorption ratio between lattice structure and aluminium foam is about 3:2.

5) According to table 9, thickness decreasing of the lower panel leads to stiffness degradation of the integral structure and a slight increase of deformation in the bottom panel.

**Table 8.** Results of hybrid sandwich panels with impact velocity 200m·s⁻¹ of hailstone

| Core                          | Maximum deformation (mm) |
|-------------------------------|--------------------------|
|                               | Top          | Bottom     |
| Pyramidal lattice+FoamA       | 2.14         | 1.66       |
| Tetrahedral lattice+FoamA     | 0.91         | 0.72       |
| Double pyramidal lattice+FoamA| 1.15         | 1.10       |
| Pyramidal lattice+FoamB       | 2.58         | 1.88       |
| Tetrahedral lattice+FoamB     | 1.63         | 0.94       |
| Double pyramidal lattice+FoamB| 1.44         | 1.20       |

**Table 9.** Results of adjusted hybrid sandwich panels with impact velocity 200m·s⁻¹ of hailstone

| Core                          | Maximum deformation (mm) |
|-------------------------------|--------------------------|
|                               | Top          | Bottom     |
| Tetrahedral lattice+FoamA     | 1.53         | 0.88       |
| Tetrahedral lattice+FoamB     | 1.84         | 1.11       |

**Figure 7.** History of internal energy of tetrahedral lattice-foam A hybrid structure

**Figure 8.** History of total energy of tetrahedral lattice-foam A hybrid structure
4. Conclusions
By simulation and analysis of hail impacting lattice-foam hybrid sandwich plate, it could be concluded as follows. 1) Numerical values of hail and material model given in this paper can be used to effectively simulate the mechanical behaviour of hail impacting process and validly reveal the overall trend of impact protection abilities of all structures. 2) Comparing with the ordinary H-shaped rib and foam metal structure, the lattice structure has a stronger impact protection performance. Sandwich configurations which are designed rationally play a decisive role in protection from hail impacts. 3) Filling foamed materials are able to improve the protective performance effectively and the utility rate of structure space to make structure weight reduction possible. 4) Tetrahedral lattice core with low density foam structure has the advantages of both so that its favourable rigidity and strength can be ensured. Besides, it is also equipped with extraordinary energy absorption effects.

Analysis results acquired in this paper can be used as references for the impact resistance design of aircraft wheel door.

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