Study on the Dynamic Behavior and Impact of Tire Fragments on Aviation Aluminum Alloy Plates

Ke Zhang1,a*, Qing Chen2,b, Xiaoyang Wu3,c, Peiyan Wang4,d, Zhufeng Yue5,e
Northwestern Polytechnical University, Xi’an, China.
a*cemail: calecheung@nwpu.edu.cn

ABSTRACT: This paper presented the dynamic behavior of tire fragments and their impact on aluminum alloy plates by the methods of experiment and numerical simulation. In the experiment, the impacts of tire fragments on aluminum alloy plates under quadrilateral constraint, bilateral constraint and four-corner constraint were studied. According to the experimental results and based on Ogden model and Johnson-Cook model, a simulation calculation model for fragment impact was proposed. Analysis of plastic deformation area, failure mode, etc. verified that the proposed model could stimulate the impact of tire fragments on aluminum alloy plates. By comparing different constraint conditions, it is found that within the impact range, the plate under quadrilateral constraint can resist the strongest impact.

1. Introduction

As a key component of aircraft, aviation tires are of great significance for ensuring the take-off and landing of aircrafts [1]. With the rapid development of the aviation industry today, more and more aircrafts have been put into use. However, the frequency of air crashes is also getting higher. Among them, tire burst has been attached great attention by experts for causing air crashes with a high accident risk. At present, some mainstream countries in the world have included tire burst in the assessment of civil plane airworthiness verification. The main purpose of airworthiness verification is to ensure that the planes can fly normally even after the tires burst. Foreign airworthiness certification guidance in terms of tire burst mainly include FAA's Airworthiness standards, transport category airplanes (14 CFR, Part25), EASA's Notice of Proposed Amendment, JAA's TGM/25/8 JAA Temporary Guidance Material, TGM/25/8 (issue 2) Wheel and Tire Failure Model. CAAC issued the Airworthiness Standards for Transport Aircraft in 2011 and stipulated two requirements for preventing burst tire fragments causing damage. Clause 25.729(f) defines that key equipment in the cabin should be protected; Clause 25.963(e) defines that the fuel tank flap should be protected to avoid tire fragments breaking fuel tank and causing aircraft fire[2].

At present, scholars at home and abroad have carried out researches on the impact of fragments on aircraft body. McKown S et al. conducted static tests on fragments and aluminum alloy materials, and conducted experiments and simulations on the impact of fragments on aluminum alloy plates, verifying the reliability of the model [3, 4]. Yao et al. used simulation method to calculate the impact of tire fragments on different aviation aluminum alloy sheets, and believed that the aluminum alloy sheets could resist the impact of tire fragments at an angle of 90° and a speed of 135m/s [5].

In the experiment of this paper, the impact effects of fragments on 7075-T6 aluminum alloy plates under quadrilateral constraint, bilateral constraint and four-corner constraint are studied. Based on Ogden model and Johnson-Cook model, a simulation calculation method for fragment impact is proposed.
2. Fragment Impact Experiment

In the experiment, tire fragments are launched by an air cannon, and the whole test equipment consists of four parts, namely an air cannon system, a velocimeter system, a shield and a support platform. The air cannon system is shown in Figure 1. The air cannon consists of four parts, that is, an air compressor, an air storage tank, a bore, and a dejector. The equipment is based on air compression theory and works like this: the stored compressed air is instantly released and shoots out the bullets installed in the bore, and the ejection speed of the bullets is controlled with the pressure of the stored air. In this experiment, the fragments hit the specimen at a predetermined speed of 100 m/s. A laser velocimeter is used to measure the speed, the principle of which is to measure the time the laser ray takes within an area of one meter which is blocked by two objects, and thereby calculate the flight speed of the object within the area. The shield uses a soft metal mesh to block objects that fly out to avoid damage to other people, buildings, equipment, etc. The support platform is composed of square steel with a dimension of 100 mm * 100 mm, on which there are specimen fixtures to install different sizes of specimen.

In this paper, small fragments of nose landing gear tires are used in the impact experiment. The tires of the landing gear are Michelin Air X, radial tires. Through conversion, the small fragment is with a dimension of 61 mm * 61 mm * 20 mm and a mass of 0.114 kg.

The aluminum alloy plate is the same as the aircraft skin material, the material grade is 7075-T6, with a dimension of 700 mm * 700 mm. Three constraint conditions are considered in the experiment, namely, quadrilateral constraint, bilateral constraint and four-corner constraint. Under quadrilateral constraint condition, four aluminum alloy plates with a width of 100 mm are pressed on the four sides of the plates and the plate is connected to the supporting fixture with 68 bolts. Under bilateral constraint condition, two aluminum alloy plates with a width of 100 mm are pressed on the left and right sides of the plate and the plate is fixed with 28 bolts. Under four corner constraint condition, the four corners of the plate are fixed with 16 bolts. The three constraint conditions are shown in Figure 2.
3. Simulation Experiment of Fragment Impact

ANSYS/ls-dyna software is used in the simulation experiment. The material parameters are measured by the Hopkinson dynamic performance experiment, and the parameter settings are shown in Table 1 and Table 2.

Table 1 Parameters of fragments in mechanical model

| $\rho$ (tonne/mm$^3$) | A (MPa) | B (MPa) | n | c   |
|------------------------|---------|---------|---|-----|
| 2.72e-9                | 473.0   | 210.0   | 0.3813 | 0.033 |

Table 2 Parameters of aluminum alloy plates in Johnson-Cook model

| $\rho$     | $\mu_1$ | $\alpha_1$ | $\mu_2$ | $\alpha_2$ | $\mu_3$ | $\alpha_3$ | C | m |
|------------|---------|-------------|---------|-------------|---------|-------------|---|---|
| 1.4e-9     | 24.9    | 0.4656      | 24.9    | 0.48        | 24.9    | 0.78        | 1 | 0.22 |

The numerical simulation model is shown in Figure 3. The aluminum alloy plate uses shell 163 and has 19,600 unit grids. The fragment uses 3D solid 164 and has 700 unit grids. There is a normal contact between the fragment and the plate, and the contact is defined by the keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE, which can effectively solve the problem of surface-to-surface contact. By solving the algorithm, the time is 0.005s.

4. Result Analysis and Discussion

Figure 4 shows the simulation of the impact of fragment on aluminum alloy plate under bilateral constraint. The numerical simulation shows that in the tire fragment impact experiment, when the fragment is in contact with the aluminum alloy plate, ripples like water waves are produced on the plate and are transferred outward. The simulation result shows at 0.8ms, the central ripple presents an X-shaped wave, which indicates the wave is reflected when it passes to the constrained boundary, and the propagation time in the horizontal direction is shorter than that in the vertical direction.

Figure 5 shows the warpage and deformation of the plate in impact experiment and simulation experiment respectively. The plate shows a symmetrical distribution. Since the left and right sides of the test piece are fixed, and the upper and lower sides are not fixed, the upper and lower sides of the specimen warp, and the left and right sides are flat. The specimen does not completely fail at 100m/s, plastic deformation only occurs at the central impact position and the fixed boundary area. Figure 8 shows the plastic deformation area after impact. The middle pit is caused by the impact of fragment. The plastic deformation on the boundary area is caused by the fixture during the impact. The results of the simulation experiment and impact experiment are quite consistent.
4.1. Energy conversion

In the process of tire fragment impacting the plate, the initial energy is the kinetic energy of the fragment, then most of the kinetic energy are transferred to the plate as the fragment impacts the plate, and the energy is then converted into elastic energy if only elastic deformation occurs on the plate. When the displacement of the plate is the maximum, the fragment will rebound and most of the energy will be released. At this moment, it is necessary to prevent the fragment from rebounding and causing secondary damage. If the impact load is greater than the critical value, the elastic deformation energy converted from kinetic energy is irreversible. Irreversible energy mainly includes plastic deformation energy, viscous deformation energy, friction energy, fracture energy and so on. Since the impact process is extremely short, but the energy conversion time of the plate structure is long, the energy absorbed by the plate can be reversed by the remaining amount of kinetic energy of the fragment.

4.1.1. Quadrilateral constraint

Figure 7 shows the curve of energy change when small fragment of nose landing gear tire impacts the plate under quadrilateral constraint condition. It can be seen from the Figure that the kinetic energy of the fragment drops rapidly before 0.52 ms, and then rises. The energy change process of the fragment can be roughly divided into 3 stages. The first stage is the impact stage (0-0.52ms). In this stage, the kinetic energy of the fragment decreases, while the kinetic energy and internal energy of the plate increase. The minimum kinetic energy is at 0.52ms, 267.1J of internal energy is transferred to the plate, and the internal energy is 250.2J. Therefore, 517.3J of energy is absorbed by the plate at 0.52ms. The second stage is the viscous stage (0.52-2.23ms). In this stage, the fragment is in close contact with the plate, and the energy conversion is complicated. There is energy exchange between the plate and the fragment, as well as internal and kinetic energy conversion between them. In this stage, the internal energy and kinetic energy of the plate basically present a symmetrical distribution about 250J, and the energy fluctuates sharply. At 2-2.23ms, the kinetic energy of the plate drops by 145.1J, the internal energy rises by 113.63J, and the kinetic energy of the fragment rises by 30.1J, indicating that 31.47J of energy is transferred back to the fragment, wherein 95.6% of the energy is converted into the kinetic energy of the fragment, and the rest is converted into the internal energy. The third stage is the separation stage (2.23-5ms). At 2.23ms, the fragment detaches from the plate, the plate oscillates, and there is exchange between the internal energy and kinetic energy of the plate. In this stage, the sum of the internal energy and kinetic energy of the plate is 450.7J, which basically remains unchanged. During the impact, the plate obtains 89% of the energy.

4.1.2. Bilateral constraint

Figure 8 shows the curve of energy change when small fragment of nose landing gear tires impacts the plate under bilateral constraint condition. Similar to the quadrilateral constraint condition, the impact process can be divided into 3 stages. The first stage is the impact stage (0-0.56ms). In this stage, energy conversion is the same as the quadrilateral constraint, the minimum kinetic energy is 0.04ms later than
that under quadrilateral constraint. It is because the constraining effect of two sides is weaker than that of four sides. At 0.56ms, the kinetic energy and internal energy of the plate are 259.0J and 260.8J respectively, which is 6.3J lower than the kinetic energy of the plate under quadrilateral constraint, and the internal energy increases by 9.0J. This indicates that the energy transfer amount of the fragment is more when the plate is constrained on two sides. The second stage is the viscous stage (0.56-2.34ms). At 2.34ms, the kinetic energy and internal energy of the plate are 168.6J and 324.7J respectively, and the kinetic energy of the fragment is 27.4J. According to the calculation of the curve, the total energy of the plate decreases by 16.77J and the kinetic energy of the fragment increases by 15.53J during the period of 2-2.34ms. The energy exchange between the plate and the fragment is less than that under quadrilateral constraint, indicating that energy exchange becomes more stable when the boundary constraining is reduced. At 2.34ms, the fragment detaches from the plate, which is 0.11ms later than that under quadrilateral constraint. This indicates that energy exchange becomes slower under bilateral constraint condition. The third stage is the separation stage (2.34-5ms). In this stage, the kinetic energy of the fragment remains almost unchanged, and the total energy of the plate is 489J, which is an increase of 30J compared to that under quadrilateral constraint.

4.1.3. Four-corner constraint

Figure 9 shows the energy curve when small fragment of the nose landing gear tires impacts the plate under four-corner constraint condition. Different from quadrilateral constraint and bilateral constraint, the impact process can be divided into two stages. The first stage is impact stage (0-0.59ms). compared with the other two conditions, the minimum kinetic energy is the latest, 0.04ms later than that under bilateral constraint condition and 0.07ms later than that under quadrilateral constraint condition. This indicates constraint conditions have different effects on energy transfer. When the constraint effect on the boundary of the plate is strong, the kinetic energy of the fragment is transferred to the plate earlier. When the initial kinetic energy is 569J, the minimum kinetic energy under quadrilateral condition is 6.61J, the minimum kinetic energy under bilateral constraint condition is 3.75J, the minimum kinetic energy under four-corner constraint condition is 2.95J. This indicates the fragment will lose more energy when the constraint effect on the boundary of the plate is reduced. It is worth noting that the minimum kinetic energy is not 0, which indicates the shape of the fragment changes during the impact, causing the parts of the fragment move at different speeds. The second stage is the viscous stage (0.58-5ms). At the beginning of this stage, the kinetic energy and internal energy of the plate maintain relatively stable. The weaker is the constraint effect, the longer the stable period is. According to the simulation experiment and high-speed camera data, it is because the fragment is closely in contact to the plate. Under quadrilateral constraint condition, the contact time between the fragment and the plate is the longest, so there is more energy exchange compared with that under other two conditions.

### Table 3 Rebound speed and energy conversion

| Constraint       | Rebound speed | Kp (J) | Ip (J) | Kf (J) | Conversion |
|------------------|---------------|--------|--------|--------|------------|
| Quadilateral     | TEST 34 | 33.28 | 141.9 | 310.1 | 63.1 | 89.0% |
| Bilateral        | FEA 23.6 | 22.89 | 140.8 | 350.7 | 27.78 | 94.4% |
| Four-corner      | 14.0 | 11.6 | 152.3 | 364.2 | 7.4 | 98.6% |

Table 3 shows the rebound speed of the fragment and the energy values at 5ms. The rebound speed error between the impact experiment and the simulation experiment is less than 3m/s, which indicates the two experiments are consistent and the energy absorbed by the plate can be calculated based on the simulation results. Table 4 shows the kinetic energy and internal energy of the plate at 5ms. Since energy conversion of the plate is slow, the energy absorbed by the plate can be estimated by the remaining kinetic energy of the fragment. Under the quadrilateral constraint condition, 505.9J of energy is transferred from the fragment to the plate, and the energy conversion rate is 89%. Under bilateral...
constraint condition, 541.2J of energy is transferred from the fragment to the plate, and the energy conversion rate is 94.4%. Under four-corner constraint condition, 561.6J of energy is transferred from the fragment to the plate, and the energy conversion rate is 98.6%. This indicates that within the tolerable range, more energy will be absorbed by the plate from the fragment when the constraint effect is reduced. This can provide reference for energy absorbing design of some aircraft components.

5. Conclusion
(1) The impact effects of tire fragment on aluminum alloy plates under quadrilateral constraint, bilateral constraint and four-corner constraint were studied through experiment. According to material performance and test results and based on Ogden model and Johnson-Cook model, a simulation calculation model for fragment impact was proposed in this paper. The plastic deformation and strain data obtained from the impact experiment and simulation experiment show that the proposed simulation method can effectively simulate the impact process.

(2) Constraint conditions have different effects on impact force, energy conversion and displacement. The impact force under quadrilateral constrain is about twice that under bilateral constraint and four-corner constraint, and the energy conversion rate under quadrilateral constraint is 9.6% lower than that under four-corner constraint.

References:
[1] Mariusz WO, Krzysztof B, Pawe P, Pawe I. Analysis of the Actual Contact Surface of Selected Aircraft Tires with the Airport Pavement as a Function of Pressure and Vertical Load. Coatings 2020; 10.
[2] Yao SL, Yue ZF, Geng XL, et al. Study on selection of aviation aluminum alloy based on impact analysis of large size tire fragment. Hot Work Technol 2017; 46(18): 104–107 (in Chinese).
[3] McKown S, Mines RAW, Birch RS. Impact of aircraft rubber tyre fragments on aluminium alloy plates: I-Experimental. Int J Impact Eng 2007; 34:627-46.
[4] Karagiozova D, Mines RAW. Impact of aircraft rubber tyre fragments on aluminium alloy plates: II-Numerical simulation using LS-DYNA. Int J Impact Eng 2007; 34:647-67.
[5] Yao SL, Wang AQ, Fang X, et al. Study on plane strain fracture toughness KIC of two new styles of aero aluminum alloys. Mater Heat Treat 2011; 40(10): 20–22 (in Chinese).