Chinese Journal of Aeronautics, (2014),27(3): 542–549

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A numerical model for bird strike on sidewall structure of an aircraft nose

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Received 11 September 2013; revised 3 December 2013; accepted 6 January 2014
Available online 2 May 2014

KEYWORDS

Bird strike;
Experiment;
Sidewall structure;
Simulation;
Smooth particles hydrodynamic (SPH) method

Abstract In order to examine the potential of using the coupled smooth particles hydrodynamic (SPH) and finite element (FE) method to predict the dynamic responses of aircraft structures in bird strike events, bird-strike tests on the sidewall structure of an aircraft nose are carried out and numerically simulated. The bird is modeled with SPH and described by the Murnaghan equation of state, while the structure is modeled with finite elements. A coupled SPH–FE method is developed to simulate the bird-strike tests and a numerical model is established using a commercial software PAM-CRASH. The bird model shows no signs of instability and correctly modeled the break-up of the bird into particles. Finally the dynamic response such as strains in the skin is simulated and compared with test results, and the simulated deformation and fracture process of the sidewall structure is compared with images recorded by a high speed camera. Good agreement between the simulation results and test data indicates that the coupled SPH–FE method can provide a very powerful tool in predicting the dynamic responses of aircraft structures in events of bird strike.

1. Introduction

Bird strikes are a significant threat to flight safety and have caused a number of accidents with human casualties. According to the web site of the Bird Strike Committee USA,[1] over 250 people have been killed world-wide as a result of bird strikes since 1988 and the damage caused by bird and other wildlife strikes is estimated to cost USA civil aviation alone over $700 million per year. Also from the same web site, about 4800 bird strikes were reported by the US Air Force and about 10900 bird and other wildlife strikes were reported for USA civil aircraft in 2012. Collisions between birds and aircraft during flight can lead to serious damage to the aircraft structure. The point of impact is usually any forward-facing edge of the vehicle such as a wing leading edge, nose cone, jet engine cowling or engine inlet. Therefore, the international certification regulations require all forward facing components to prove a certain level of bird strike resistance before they can be employed in an aircraft.[2–5] Bird-strike tests provide a direct method to examine the bird strike resistance. However, to shorten the design cycle and reduce cost, numerical simulations are often used to examine and assess a structure's response to bird strike.

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2014.04.019

There is a long history of research efforts, especially after the finite element (FE) method was adopted as a tool in the late 1970s, to develop numerical methods for bird strike simulation. An extensive list of references on this subject can be found in Refs. 2–7 Hedayati and Ziaei-Rad[8] introduced a bird model with a geometry similar to a real bird and compared their simulation results with experimental data as well as those using traditional bird models. They found that a bird could strike an aircraft component with its head, tail, bottom or wings and any of these orientations might produce a different effect on the response of the component. Four substitute bird models were introduced and the best substitute model was chosen to capture the pressure and force exerted by the real bird when impacting from different orientations. Smojver and Ivancevic[9] performed bird strike damage analysis of real aeronautical structures using ABAQUS/Explicit and the coupled Eulerian Lagrangian (CEL) approach. Goyal et al.[10–12] performed a bird striking on a flat plate based on the Lagrangian, smooth particles hydrodynamic (SPH), and arbitrary Lagrange Eulerian (ALE) approach respectively in LS-DYNA. Classical test data available in the literature and numerical models were used for basis of comparison. It can be concluded that that SPH simulations best represent the fluid-like response during an impact. A continuum damage mechanics approach was employed to simulate failure initiation and damage evolution in unidirectional composite laminates. The CEL formulation enabled the authors to overcome numerical instabilities caused by extreme material deformation. Wang and Yue[13] developed a finite element model of bird strike on a windshield structure including the windshield, framework, arc-frame, gasket and rivets, in which the adaptive contact relationship and boundary conditions were defined. A contact–impact coupling algorithm and the explicit finite element program LS-DYNA were employed to simulate the damage and failure process of the windshield structure at three bird-strike velocities. Meguid et al.[14,15] showed the mechanical property of a bird changed from the low velocity to the high velocity regimes. At low speeds it was neither uniform nor homogeneous but at progressively higher speeds the bird could be considered as a homogeneous jet of fluid impinging on a structure. Guida et al.[16] studied the bird strike against a composite tail leading edge, where the SPH grid free method was used to describe the bird splashing during the strike. However, none of the above numerical simulation approaches has been verified by real bird strike events since there is very little published information about bird strike experiments on aircraft structures.

In this study, experiments of a real bird striking on the side wall of an aircraft nose are conducted at a desired velocity of 150 m/s. The explicit finite element software PAM-CRASH is used to simulate the bird strike experiments. In order to improve the numerical stability and increase the accuracy of the deformation and damage prediction, a coupled SPH–FE method is adopted in which the bird is modeled using the SPH method with the Murnaghan equation of state and the structure is meshed with finite elements. With the use of SPH, numerical difficulties associated with extreme bird mesh distortion are eliminated. The material parameters are identified and the simulation results are compared with experimental data to verify the numerical model.

2. Test

2.1. Test apparatus

The test work described in the present paper was performed at Jiangsu Anchor Co. Ltd. The objective of the test is to obtain the dynamic response of an aircraft nose sidewall structure under bird strike. The test data will be used by the numerical model presented in Section 3.

Fig. 1 illustrates the arrangement of the test equipment. The gas gun system consists of a compressed air gun with a supporting compressor, instrumentation, and control system. The compressor pumps air into the air storage tank. A valve located between the driving air storage tank and the breech of the gun is designed to drive the high pressure air from the air storage tank into the gun. After the desired air pressure is reached in the pressure chamber, the pressure release valve will open and the gas will expand in the barrel to push the projectile forward. The bird includes the projectile and a sabot with a required mass which must be accelerated to a desired velocity. Before impacting on the specimen, the bird launcher

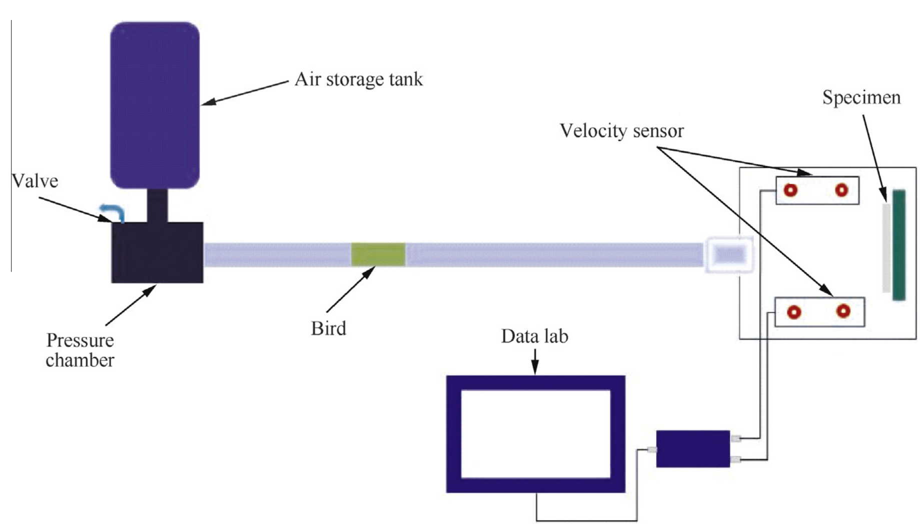


Fig. 1 Arrangement of test equipment.

cannot induce any projectile breakup or severe distortion. In the meantime, the projectile must be launched at the desired orientation.

Fig. 2 shows the gas gun launching the bird. The bird used as the projectile is a killed fowl with a mass of 1.8 kg which is held inside a sabot packed with expanded polystyrene such that it does not experience any position change or damage during the launching process. The sabot has to be as light as possible since it constitutes an unwanted mass and must be separated easily from the projectile just prior to the impact. The tolerance between the sabot and tube is important to ensure that the bird projectile go through the barrel without any friction to slow it down. A sabot stopper shown in Fig. 2 is made of a steel tube. It traps the sabot when the sabot and the projectile reach the end of the barrel. The stopper is designed to allow the projectile to continue its flight without losing its velocity. In this experiment, the bird was fired at a desired velocity of 150 m/s.

Fig. 3 shows the target, the sidewall structure of an aircraft nose. It is fixed on the edges to a clamping fixture by bolts. The clamping fixture is mounted on a vertical steel wall by bolts and the vertical steel wall is attached to the ground. The sidewall structure is composed of ribs, pad plate, skin-1, and skin-2 as shown in Fig. 4, which are assembled by rivets.

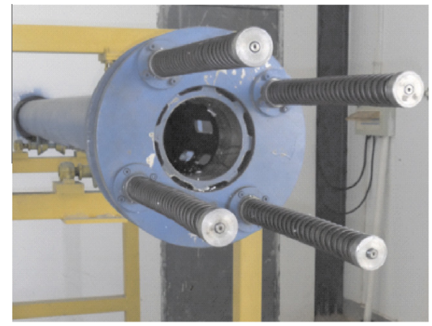


Fig. 2 Gas gun to launching bird.

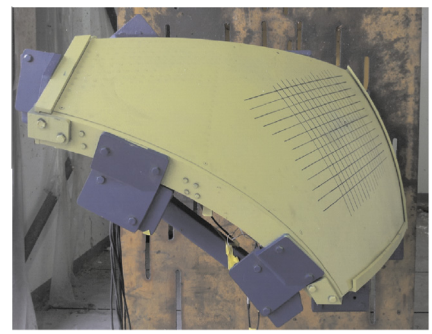


Fig. 3 Target (sidewall structure of an aircraft nose).

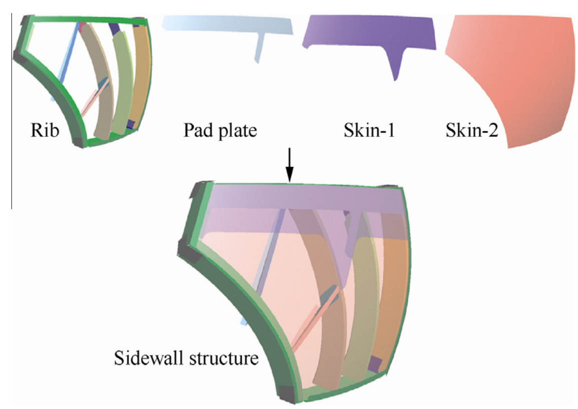


Fig. 4 Components for the sidewall structure of an aircraft nose.

2.2. Data acquisition

The entire bird strike process is very short, lasting only 3–4 ms. Consequently, to record the dynamic responses of the target and capture this process, high speed data collectors must be used. The high speed data acquisition equipment for collecting strain, displacement and force responses usually include strain sensors and super dynamic strain gauges, displacement sensors and amplifier, load cells, an impedance variation device, and a transient recorder. The logical connections among these devices are shown in Fig. 5. In this study, the test data were collected using only strain sensors.

Four strain gauges (S1–S4) are placed on the specimen to measure the local strains and a 4-channel data acquisition system is used to collect the strain measurements at a sample frequency of 10 MHz. Fig. 6(a) shows the layout of measurement locations and Fig. 6(b) shows a photo of the specimen with strain gauges. The velocity of the bird projectile was measured using a laser velocity system before it strikes on the target structure. The entire process of bird strike on the sidewall structure was recorded by a high speed camera.

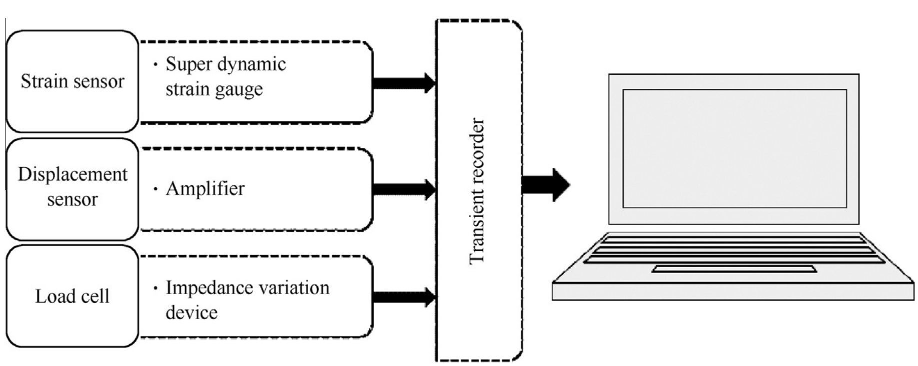
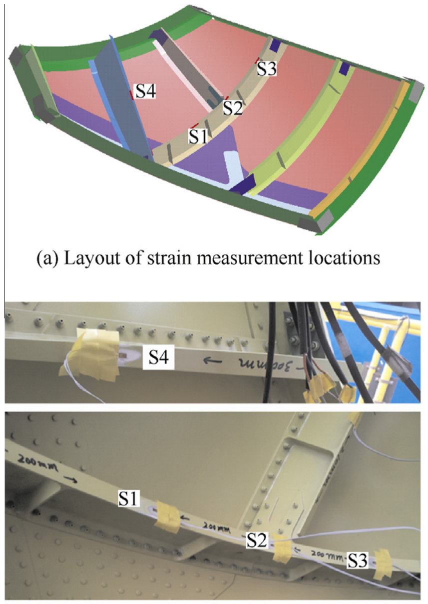


Fig. 5 Logical connections of data acquisition equipment.



(a) Layout of strain measurement locations

(b) Specimen photo showing strain gauges

Fig. 6 Measurement of strains.

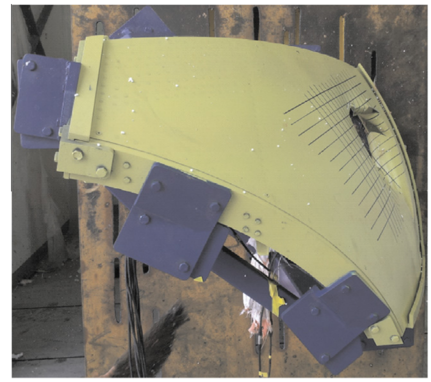


Fig. 7 Deformed and fractured sidewall structure after bird strike.

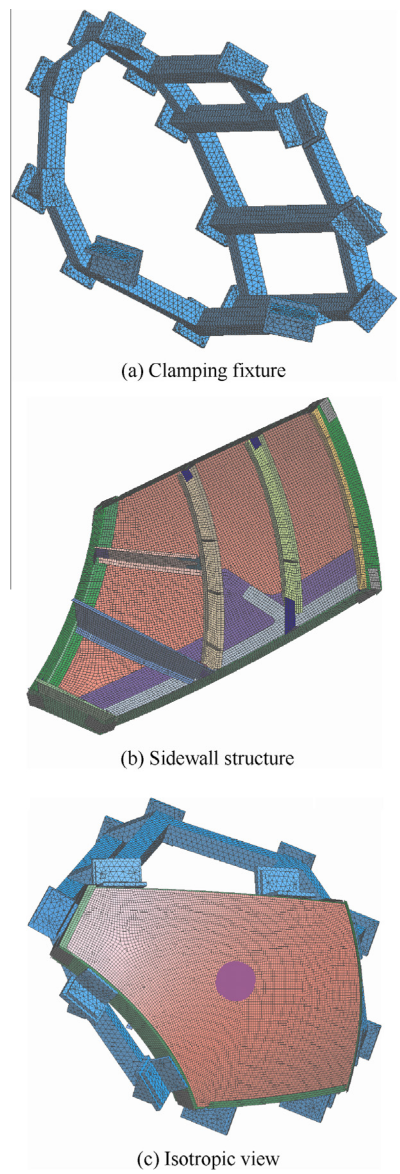
2.3. Test results

The desired impact velocity is 150 m/s and the actual velocity of the bird measured by the laser velocity system as it strikes on the sidewall structure is 152 m/s. These values are very close, suggesting that the gas gun system used in this study is very precise and stable. The direction of the flying bird is along the course of the aircraft. The strain gauges are placed on the inner ribs of the sidewall structure, centering about the impact area to capture the local deformation of the specimen. The dynamic deformation and damage process of the sidewall structure is recorded by a high speed camera system at a time interval of 0.5 ms for comparison with the numerical simulation results presented in Section 4.

Fig. 7 shows the final deformed and fractured sidewall structure. The specimen was penetrated by the bird at the impact area and the skin around the impact area was torn up.

3. Numerical simulation

The numerical simulation of the bird-strike test is carried out using the explicit finite element software PAM-CRASH. Fig. 8 shows the finite element model, which consists of three parts: the bird, the sidewall structure and the clamping fixture. The geometry of the bird is idealized as a right cylinder having a diameter of 106 mm and a length of 212 mm to keep the standard length to diameter ratio of 2:1. The idealized bird is modeled by the SPH method and the Murnaghan equation of state. The sidewall structure consists of ribs, pad plate, skin-1 and skin-2 and these parts are modeled by shell elements. The clamping fixture is modeled by solid elements. The sidewall structure and the clamping fixture are tied together by the



(a) Clamping fixture

(b) Sidewall structure

(c) Isotropic view

Fig. 8 Finite element models of structure and bird.

"tie constraint". Pink elements are used to simulate the actual rivet connections.

3.1. SPH method coupled with FE

According to the photos captured by the high-speed camera, the bird becomes highly distorted and is crushed into debris during the bird strike process. This presents a major challenge for using the finite element method to model the bird. The SPH method is a grid-less Lagrange technique which allows for severe distortion and thus is adopted to simulate the bird in this study.

SPH is a Lagrange particle method introduced by Lucy in the 1970s[17] in order to solve hydrodynamic problems in astrophysical contexts. It has been extensively applied in the study of accretion disc, galaxy dynamics, and star collisions among other problems. This method has been implemented in PAM-CRASH.[18] A smooth particle is input like a 3-DOF (degree-of-freedom) solid element and defined by its center of mass, volume, part number, and domain of influence. It can be used with great advantage to model bulk materials with no cohesion (sand, liquid, gases) or in situations where perforation or mixing is expected. Note however that it can be much more expensive to use than a classical solid element. A smooth particle, similar to a finite element, has its own shape functions, reconstructed at each cycle from its dynamic connectivity. Localization and information transmission from one particle to another are achieved through the notion of an interpolation distance called the smoothing length. A Particle *J* is said to have a contributing neighbor Particle *I*, when Particle *I* lies within the sphere of influence of Particle *J*. In such a case, Particle *I* is said to be connected to the central Particle *J*. The sphere of influence of a particle is a multiple to its smoothing length. The multiplication factor depends on the type of kernel used to construct the smooth particle shape functions. Details of the kernel functions are given in Ref.[19].

Structural nodes and smooth particles must have distinct numbers. Smooth particles can be subjected to constraints or loads as if they were nodes. In particular, finite element to smooth particle coupling is achieved by the use of penalty contacts, where the particles are slave nodes.[20] The interaction of the particles with the finite elements may be modeled by the existing sliding interface algorithms available within PAM-CRASH. The most frequently used sliding interface types to relate smooth particles to finite elements are type 34 in case the materials may be considered as sliding with dynamic contact or as a tied interface when the particles are assumed to stick to the finite element surface. For a finite element mesh, the contact thickness indicates the distance away from a contact face where physical contact is established. For particles interacting with finite elements, the contact thickness should be representative of the particle radius, possibly augmented with the half-thickness of the shell structure. So the node to surface contact is used to model the interaction between the SPH particles and Lagrange elements.

3.2. Constitutive model for bird

It has been shown that at high speed the bird can be considered as a homogeneous jet of fluid impinging upon a structure. Therefore it is adequate to use an equation of state to model the bird material. The SPH method and the Murnaghan equation of state implemented in PAM-CRASH provide a tool to simulate the bird material at high velocity impact. This constitutive model corresponds to a liquid with an artificially increased compressibility used to perform a certain class of hydrodynamic simulations, where the flow velocities remain well below the physical sound speed and the compressibility effects are of minor importance. In such cases, the liquid may be considered more compressible than in reality, which may be achieved using the Murnaghan equation of state model. The artificial fluid must be given a speed of sound still well above the speed of the bulk flow and therefore it creates very small density fluctuations. The pressure for the Murnaghan equation of state is given by

$$p = p_0 + B[(\rho/\rho_0)^{\gamma} - 1] \tag{1}$$

where ρ/ρ_0 is the ratio of current mass density to the initial mass density. This constitutive model may be used to simulate a gravity and inertia driven flow of liquids, i.e., the outflow from reservoirs, mixing of fluids with different densities and sloshing of liquids in partially filled containers. In such phenomena the bulk flow velocities of the liquids can be orders of magnitude smaller than their speed of sound. In the numerical simulations the user can regulate the sound speed and thus greatly reduce the explicit solution time step while preserving

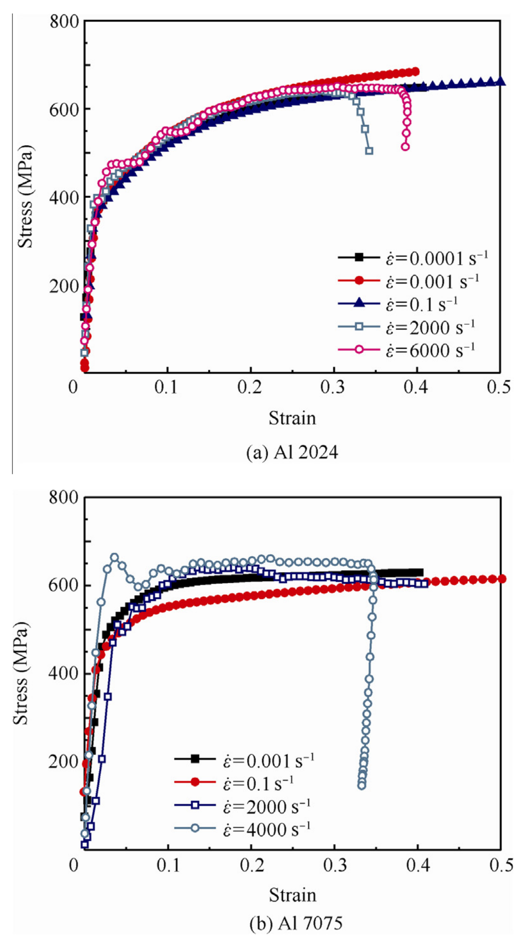


Fig. 9 Dynamic compressive stress–strain curves of Al 2024 and Al 7075.

the essential quality of the results. Details of the Murnaghan equation of state can be found in Ref.[21] The parameters B and γ are obtained by using the optimization method described in Ref.[22] and calibrated parameter values are $B = 9.3$ GPa and $\gamma = 7.14$.

3.3. Material model for sidewall structure

The material model 105 in PAM-CRASH is selected as the constitutive model for the sidewall structure. This is an elastic–plastic material model with isotropic damage for shell elements. The plastic response is described by the strain rate dependent Cowper-Symonds law:

$$\sigma = \left[a + b(\varepsilon_{\rm p})^n\right]\left[1 + (\dot{\varepsilon}/D)^{1/\eta}\right] \tag{2}$$

where $[a + b(\varepsilon_{\rm p})^n]$ represents the static yield stress including strain hardening, $\varepsilon_{\rm p}$ denotes the plastic strain, $\dot{\varepsilon}$ denotes the strain rate, and a, b, n, D and η are material constants. These parameters can be obtained by fitting the test data. The material used for the pad plate and skin is a 2024 aluminum alloy with $a = 350$ MPa, $b = 426$ MPa and $n = 0.34$, and the material used for the ribs is a 7075 aluminum alloy with $a = 400$ MPa, $b = 200$ MPa and $n = 0.45$. Fig. 9 shows the stress–strain curves of these aluminum alloys obtained at different strain rates, suggesting these materials can be considered as strain rate insensitive. Therefore, the rate dependent term in Eq. (2) is ignored. Elastic modulus and Poisson's ratio for Al 2024 are 73GPa and 0.3, for Al 7075 are 71GPa and 0.3. A failure strain criterion is used to model the damage of the structure. Once the equivalent tensile strain in an element reaches the critical failure strain of the material, the element will be deleted. The failure strain is obtained from the tensile test of Al 2024 and Al 7075. In the tensile test, just the failure strain is measured and it is 0.2 for Al 2024 and 0.14 for Al 7075.

4. Results and discussion

In this section, numerical simulation of a bird striking on the sidewall structure at a velocity of 152 m/s is conducted and the simulation results are compared with the test measurements. Fig. 10 compares the computed and measured strains at the four locations. Some factors such as the friction between the bird and skin, the viscosity of the bird, the contact type and stiffness between the bird and skin etc. were difficult to define. This may result in the small difference between the simulation and test for Fig. 10. Although there is some difference between the numerical and simulation curves, the numerical results not only capture the trend of the strain vs time histories at all four locations but also accurately predict the peak strain values.

The process of the bird-strike test is captured by a high-speed camera, which lasts about 3 ms. Pictures of specimen deformation and failure are taken at a time interval of 0.5 ms and compared with the simulation results as shown in Fig. 11. The SPH simulation captures the deformation behavior of the bird, which was broken into debris and flew on the specimen. The deformation and fracture process of

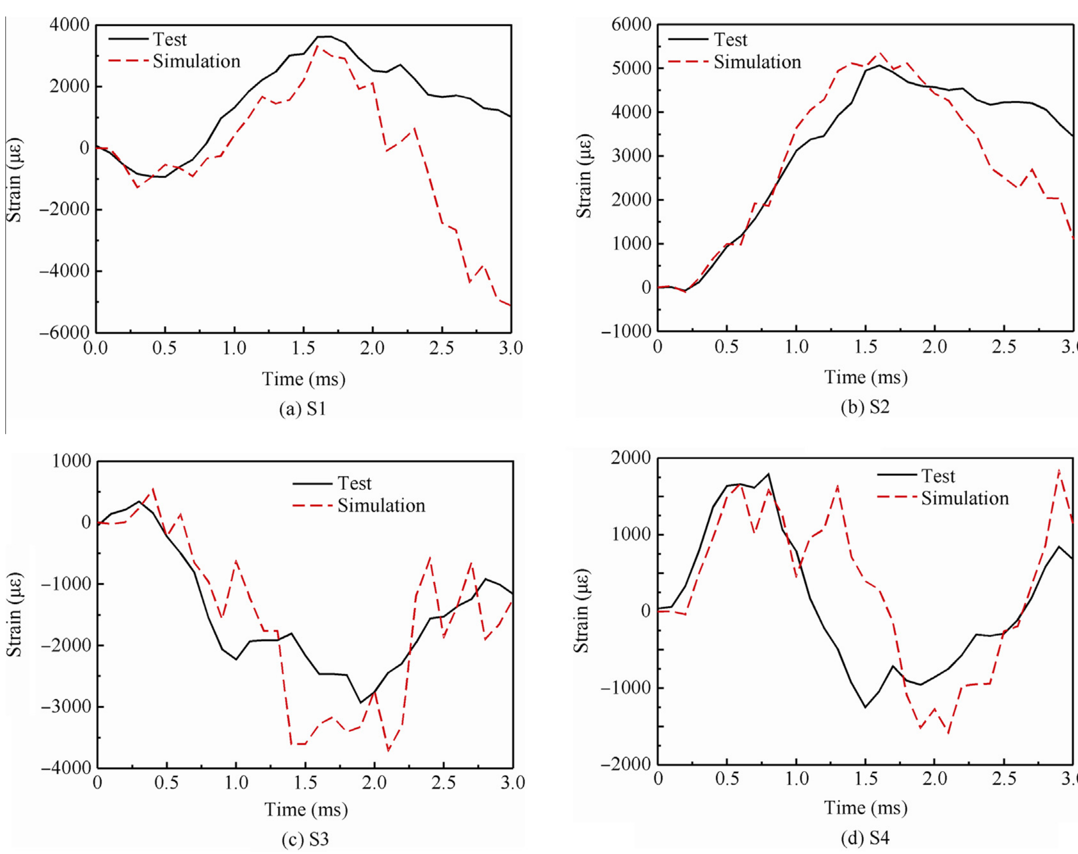


Fig. 10 Comparison of computed and measured strain vs time histories.

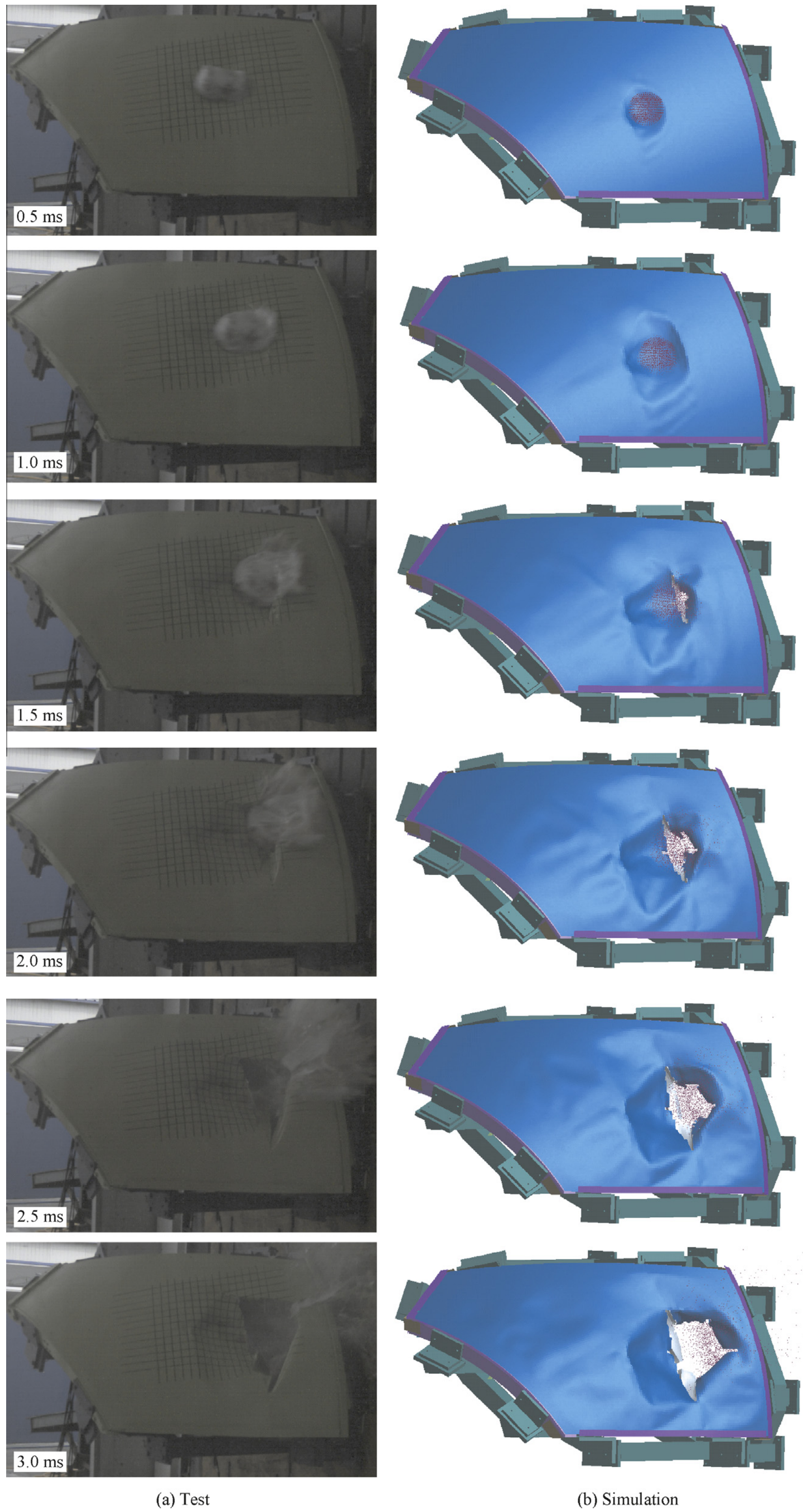


Fig. 11 Comparison of simulated bird strike process with pictures taken by a high-speed camera.

the sidewall structure is accurately predicted by the numerical simulation. The remarkable agreements between the simulation results and the actual video on when the sidewall structure fractures and the shape and size of the hole created by bird strike suggest that the numerical model adopted in this study is capable of predicting bird strike on the sidewall structure and can be used to assist designing bird strike resistant sidewall structures.

5. Conclusions

In this study, tests of a bird striking on the sidewall of an aircraft nose are conducted at an impact velocity of 150 m/s and a numerical model is developed to simulate the bird strike process. The following conclusions can be drawn from this study:

(1) The SPH method can accurately simulate the behavior of a bird at high speed impact. The simulated behavior of the bird breaking into debris and flowing on the target is in good agreement with the high-speed video.
(2) The coupled SPH and FE method is able to simulate the bird strike process and the dynamic response of the target specimen. The computed and measured strains at different locations of the sidewall structure show very good agreement and the predicted deformation and fracture process of the sidewall structure agrees remarkably well with the pictures taken by the high-speed camera.
(3) The coupled SPH and FE method and the numerical model developed in this study provide a tool for simulating the dynamic response of aircraft components under bird strikes, which can be used to assist designing bird-strike proof components.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (No. 11102167) and the Basic Research Foundation of Northwestern Polytechnical University of China (No. JCY20130102).

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