CYIENT

White Paper

2014

COMPREHENSIVE BIRD STRIKE SIMULATION APPROACH FOR AIRCRAFT STRUCTURE CERTIFICATION

Contents

Overview

Bird Strike Simulation Index (BSSI) based on comparison of alternative methods, provides holistic guidance to an industrial user.

In the year 2012, there were 10,726 bird strikes worldwide, as per a Federation for Aviation Administration (FAA) report. This indicates the need for certifying aircraft structures for bird strike using accurate simulation and testing. There are multiple approaches available to model the physics of bird strike such as Coupled Eulerian Lagrangian (CEL), Smooth Particle Hydrodynamics (SPH) and pure Lagrangian methods. However, in a business scenario marked by time and resource constraints, it is often challenging to determine the right approach for a defined purpose in various design phases. Through a comparison of alternative methods, we propose a first of its kind Bird Strike Simulation Index (BSSI) based on key parameters like FEM setup time, run time, and accuracy of pressure and deflection. BSSI provides holistic guidance for industrial users.

Most bird-strike simulation use idealized fastener modeling of metallic riveted panels. This affects the prediction of failure behavior of components attached in an assembly due to micro level embrittlement around fastener hole.

This whitepaper attempts to compare the bird strike methods, and propose a simple and easy to implement approach to efficiently model fasteners. Simulation results are successfully validated by experimental tests, and prove the potential of certification by analysis approach of aircraft structures against bird strikes.

Introduction

Bird strike incidents caused an economic loss of about USD 350 million in 2012.

Aircraft bird strikes have been prevalent since the early days of flight, 100 years ago. The number of strikes reported to the FAA annually has increased 5.8 fold from 1,851 in 1990 to a record 10,726 in 2012. During this 23 year period (1990–2012), 131,096 strikes were reported to the FAA. Birds were involved in 97% of the reported strikes. Every bird strike incident results in a loss of 121.7 flying hours, and costs $32,495 per incident. This amounted to an economic loss of about USD350 million in 2012[1], excluding other monetary losses such as lost revenue, the cost of putting passengers in hotels, re-scheduling aircrafts, and flight cancellations. The total economic loss per year is thus estimated to be around $1.28 billion[2].

Based on the bird strike cases reported, most damages occur on the wing and engines, as illustrated in Fig. 1[3]. Globally, wildlife strikes including bird strikes have killed more than 250 people and destroyed over 229 aircraft since 1988. Bird strike statistics indicate that 74% of all collisions occur at 500ft. above ground level (AGL) and 97% under 3500ft. This indicates that the take-off and landing phases are especially critical[4]. Therefore, the physics of bird strike needs to be accurately modeled in order to make the aircraft structure safe after a bird strike.

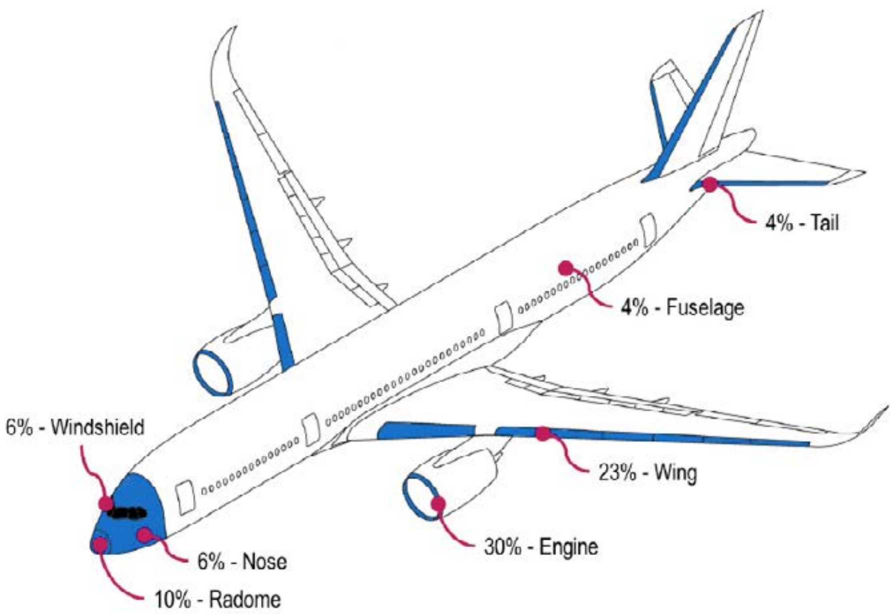

Fig. 1 | The wings and engine of an aircraft bear maximum damage due to a bird strike

Technical Challenges in Bird Strike Modeling

BSSI guides the industrial user in choosing the right approach for the right purpose through analysis.

- **Fastener modeling in Riveted Airframe Bird Strike Analysis:** Fastener failure against high velocity impact loads needs a material damage model that addresses failure modes under impact loads and fastener hole embrittlement. Currently, there is lack of accurate finite element approach for predicting bird impact against riveted frames.

  Bird impact modeling in metallic riveted panels requires accurate modeling of fastener, which is often very complex or time consuming. Hence, idealized models are used for airframe structures like wing, flap, trailing edge and leading edge in aircraft bird strike simulation studies. In a high-velocity bird strike scenario, the fastener will experience both shear and tensile loads. Fastener failure modes also govern the failure of aircraft structure. Aircraft components typically contain large number of fastener holes which significantly affect the failure behavior of components in an assembly. This is due to the micro level embrittlement around the fastener hole.

- **Determining the Right Method for the Right Purpose:** Many explicit analysis approaches are available to accurately model the physics of bird-strike, such as Coupled Eulerian Lagrangian (CEL), Smooth Particle Hydrodynamics (SPH) and Lagrangian methods. However, the challenge is to choose the right method that suits the right purpose given the constraints of resource, time and the need for accuracy.

  A comparative assessment of alternative approaches of analysis helps in design decisions. Results are compared with published literature based on the standard experimental data. Critical parameters like Hugnoniot pressure and Stagnation pressure from each study are compared. Merits in all the three methods and bird models are presented to guide the user in choosing an appropriate method depending on time and resource availability. Bird Strike Simulation Index guides the industrial user in choosing the right approach for the right purpose through the process of analysis. This helps reduce cost and effort for airframe design both for metals and composites.

- **Aircraft Certification against Bird Strike through Analysis:** Full scale dynamic certification testing of an aircraft structure against bird strike is very complex, expensive and time consuming. In addition, loss of bird life is also a significant concern. In recent times The FAA issued a circular on certification by analysis for interiors[7]. The latest trend is in substantiating certification based on FE simulation based approach[8]. In line with this trend, this document reports an experimental validation of bird strike on the wing flap to demonstrate the applicability of certification through analysis for future new aircraft programs.

FAR Requirements

Certification of aircraft components needs to adhere to different requirements. Depending upon criticality and functions like wing, engine, and flap, specific Federal Aviation Regulations (FAR) have been laid out, as summarized in the table below.

FAR	Components	Bird Mass	Aircraft Speed	
25.571(e)(1)	General Structure	4lb	Vc @sea Level .85 Vc	Successful completion of flight
25.631	Empennage	8lb		Continued safe flight and landing
25.775 (b)	Windshield	4lb		Bird does not penetrate windshield
25.775 (c)	Windshield	Not specified	Not specified	Minimize danger to pilots from flying windshield fragments
25.1323(j)	Duplicate Pitot Tubes	Not specified	Not specified	Bird does not damage both tubes
29.631	General Structure	2.2lb	Lesser of Vh or V Ne to 8000 ft	Continued safe flight and landing (Category A) Safe Landing (Category B)
25.775(h)(1)	Windshield	2lb	Maximum flap approach speed	Bird does not penetrate windshield
23.1323(f)	Duplicate Pitot Tubes			Bird does not damage both tubes

Bird Behaviour and Bird Shape Modelling

Bird shape analyses have been performed using the below bird model with a bird mass of 1.8 kg, modeled to strike a rigid target. The bird material takes into account 10% bird material porosity due to trapped air in the lungs and bones. Bird finite element model have been idealized with Lagrangian solid elements for pure Lagrangian method, particle element for SPH and Eulerian element for CEL. The 1.8 kg bird finite element mesh is shown in Fig. 2. Bird geometry has been idealized by a cylinder with hemispherical ends, and a length to diameter ratio equal to two, since this geometry of bird models showed the best correlation with real birds in experimental tests.

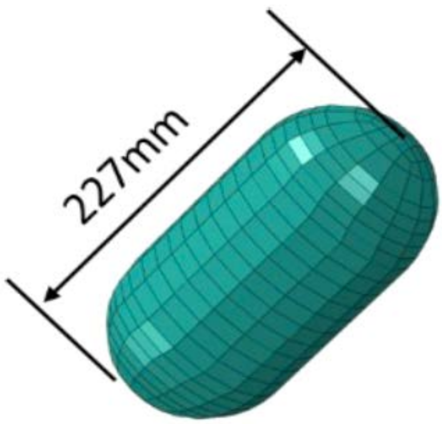

Fig. 2 | Bird material and shape

Analytical Methods Used for Bird Strike Simulation: A Description

A coupled Eulerian-Langragian approach is used to address fluid structure interaction problem.

Pure Lagrangian formulation

In the Lagrangian formulation, the nodes of the mesh are associated with particles in the material under examination. Therefore, each node of the mesh follows an individual particle in motion. This formulation is used to describe solid materials. The imposition of boundary conditions is simplified, since the boundary nodes remain on the material boundary. Another advantage of the Lagrangian method is the ability to track history dependent materials easily. However, a Lagrangian description of this problem may result in loss of bird mass due to the fluid behavior of the bird, which causes large distortions in the bird. In an explicit finite element analysis, the time step is determined by the smallest element. The severe mesh distortion causes the time step to decrease to an unacceptably low value for the calculations to continue. This excessive distortion condition renders the analysis with an unacceptable time step. Furthermore, these excessive distortions also produce a negative elemental volume. Researchers have developed a numerical procedure to solve the problem related to large deformations. Simulation results are depicted in Fig. 3.

Coupled Eulerian Lagrangian formulation (CEL)

In the Eulerian modeling technique, the mesh remains fixed in space and the material flows through the mesh. As the mesh does not move, mesh deformations do not occur, and the explicit time step is not influenced. Stability problems due to excessive element deformation do not occur. In a bird strike simulation, typically only the impactor is modeled as a fluid-like body with Eulerian elements, while the target is modeled as a solid structure with Lagrangian elements. Hence, a coupled Eulerian- Lagrangian approach is used for this fluid structure interaction problem. The mesh in the classical Eulerian technique is fixed in space, and therefore the computational domain should cover not only the region where the material currently exists, but also additional void space to represent the region where material may exist at a later time of interest. Thus, the computational domain for structural analyses with the classical Eulerian technique is relatively large, and leads to high computational cost due to the large number of elements and the cost-intensive calculation of element volume fractions and interactions. Typically, the element size of the Eulerian mesh has to be very small in order to achieve accurate results. Simulation results are shown in Fig. 4.

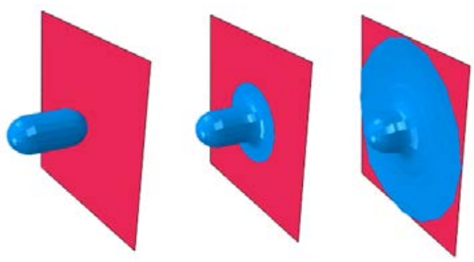

Fig. 3 | Soft body impactor modeling using pure lagrangian

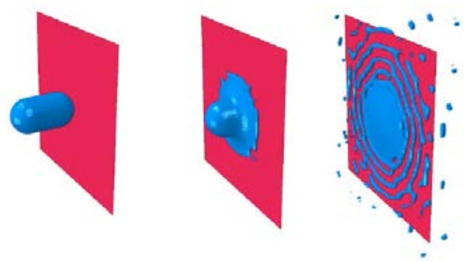

Fig. 4 | Pressure variation during Impact using CEL

In Eulerian mesh motion method, the Eulerian domain changes and adapts itself to encompass the bird during the bird impact on the plate. The initial number of elements for the Eulerian domain can significantly be reduced, leading to computational time savings. But during the analysis, when Eulerian domain expands to capture bird material, the accuracy of the method just before the end time of the analysis drops. At this point of time, bird fluid particles get scattered over larger areas surrounding the point of impact (centre of plate). So, just before the end of the analysis, most of the elements will have volume fraction of fluid zero. In other words, the Eulerian volume fraction (EVF) would go to zero, which is not expected.

Smooth Particle Hydrodynamics formulation (SPH)

SPH method is a gridless Lagrangian technique in which the solid FE mesh is replaced by a set of discrete interacting particles. The method is appealing for impact problems such as bird strikes as it has variable connectivity, which allows for severe distortions. Being a Lagrangian technique, it can be directly linked to standard finite element formulations, avoiding some of the material interface problems associated with Eulerian codes. The method was first introduced and applied to astrophysical problems. In the SPH analysis, it is important to know which particle will interact with its neighbors, because the interpolation depends on these interactions. The bucket sort algorithm is used to search for neighbors in the domain covered by the particles - which is split into several boxes of a given size. Initially, the algorithm searches for neighbors for each particle inside the main box, and the neighbor boxes contained in the domain of influence particle. Based on this, it computes the smoothing length at the beginning of the analysis such that the average number of particles associated with an element is roughly between 30 and 50. The smoothing length is kept constant during the analysis. By default, the maximum number of allowed particles associated with one element is 140. Simulation results are shown in Fig. 5.

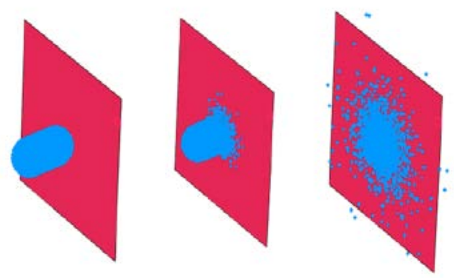

Fig. 5 | Soft body impactor modeling using pure lagrangian

Pressure Distribution During Soft Body Impact

The validity of numerical bird strike simulations critically depends on correct modeling of forces and pressures imposed to the impacted structure. Bird strikes always occur at relatively high speeds, resulting in local stresses in bird material, which are significantly higher than the material strength. This leads to a ‘flow’ of bird material that spreads the impact forces over a wider area. When a soft body impacts a target, a complex pressure field is formed behind the impact region. The pressure time response shows three distinct stages as shown in Fig. 6. The first stage (region A) is characterized by the peak Hugoniot pressure, the maximum pressure phase is followed by a pressure release stage (region B). The final stage (region C) is characterized by the formation of a steady flow pressure, having a much lower and constant value. At high pressures, the hydrodynamic pressure-volume behavior of the bird can be modeled using the Mie-Greisen form of the equations of state with the linear Hugoniot relation between the shock wave in the bird and equation of state (EOS). This provides greater flexibility in modeling the hydrodynamic response of materials. Therefore in the present analysis, a tabulated EOS has been used for defining EOS.

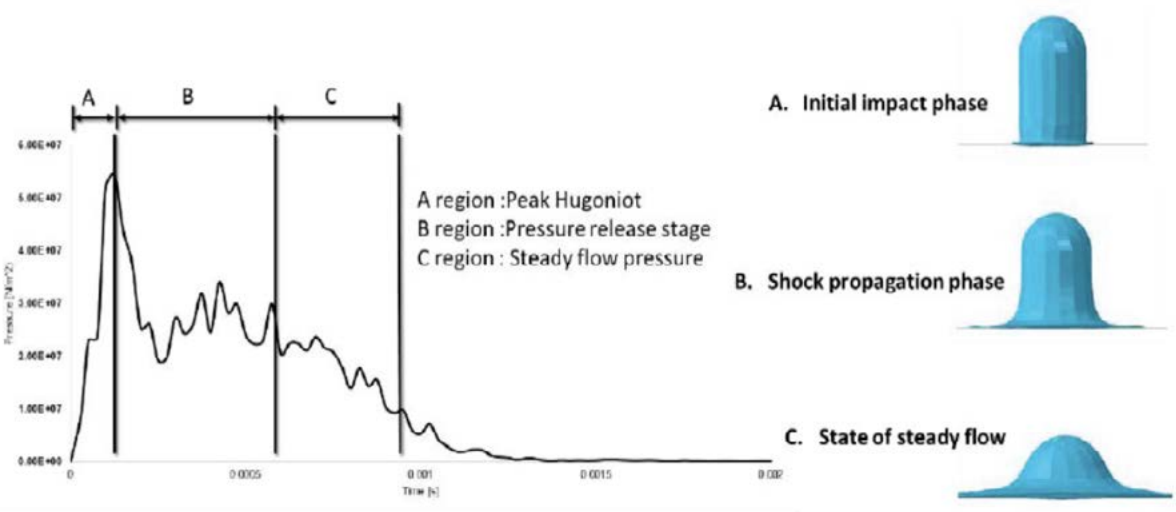

Fig. 6 | Pressure variation in a Soft Body impact

Validation

The EOS bird material model has been validated by comparing Hugoniot and stagnation pressures developed in an impact on a rigid target at the velocity of 116 m/s and 225 m/s normal to the plate. Bird strike techniques such as SPH, CEL fixed space, CEL mesh motion, and pure Lagrangian techniques with experimental and theoretical values have been used.

The obtained results and experimental results[5], 6 are synthesized in Fig. 7 and 8 in terms of Hugoniot pressure, and Stagnation pressure, vs. impact velocity. While the results using pure Lagrangian technique, SPH technique, CEL fixed space and mesh motion techniques are close enough, only SPH technique was able to provide accurate results against experimental Hugoniot pressure and slight difference from theoretical Hugoniot pressure. Though porosity is taken into account for the evaluation of Hugoniot pressure, the theory does not take into account the real shape of the bird and the true nature of the bird impacting the target.

FE results from a pure Lagrangian bird model assigned a hydrodynamic viscous fluid that does not co-relate well with theoretical and experimental peak pressure. This shows that the technique does not adequately capture localized deformation due to high pressure applied on a very small area of impact. At the same time, investigations of bird strike on deformable metallic plate (correlation of FEM and experiment) show that this technique (pure Lagrangian) is more accurate in predicting deflections on deformable plate when compared to other methods, but issues with sever mesh distortion cannot be ignored.

Results from the CEL method do not co-relate well with theoretical and experimental peak pressure, due to its strong dependency on fine mesh. Therefore, the accuracy of the model with CEL mesh motion may be reduced for severe impact or deformations.

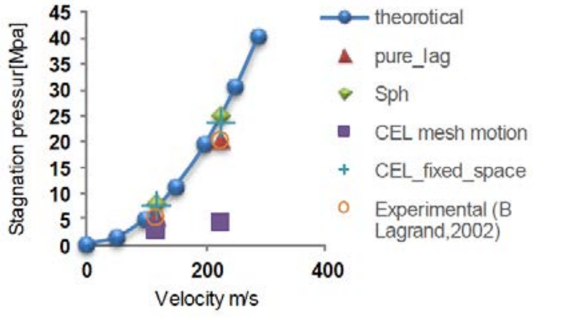

Fig. 7 | Stagnation pressure variation with velocity

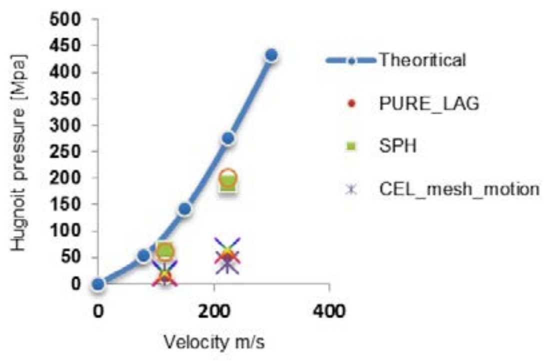

Fig. 8 | Hugnoit pressure variation with velocity

How the alternate approaches stack up

Pure Lagrangian Formulation

Best used in:
Preliminary checks for FEM formulation

Advantages
- Less time required for FEM formulation
- Energy conservation
- Lower computation time. The deformation on plate using Lagrangian method was very close to experimental. But it could not capture localized deformation as it happens in reality when birds strike flat plate . The impact force imparted to a small area by the bird during shock stage would be lesser than the force imparted by the Eulerian methods. The major problem of Lagrangian bird impact or models is the severe mesh deformation.

Disadvantages
- Lower accuracy
- Excessive element distortion leading to instability. Large distortions in the elements may lead to inaccurate results, severe hour glassing, reduced time steps and even error termination, which have to be prevented with adequate element erosion criteria. Although this modeling method is still used today, it is widely accepted that the Lagrangian approach remains an impractical way to model fluid splashing phenomena like bird strikes.

Coupled Eulerian Lagrangian Formulation

Best used in:
Where detailed Fluid Response is required

Advantages
- Actual fluid like behavior resulting in localized deformation, as expected in the experiment
- Better accuracy
- Less time required for FEM formulation
- No excessive material distortion for the bird material. The pressure/force response using the CEL technique would correlate well with the experiment. Deformation is localized at the point of impact as expected in reality. Computation time is very high when compared to other methods.

Disadvantages
- Computation time is very high when compared to other methods. Accuracy of method is relatively high, but this comes at the cost of computation time.

Smooth Particle Hydrodynamic Formulation

Best used in:
Cases where severe deformations are expected

Advantages
- Difficulties associated with fluid flow, and structural problems involving large deformations and free surfaces are resolved
- Computation time required is less than that of CEL methods
- Higher accuracy
- The method's Lagrangian nature associated with the absence of a fixed mesh is its main strength

Disadvantages
- Computation time is very high when compared to other methods. Accuracy of method is high, but this comes at the cost of computation time.

Bird Strike Simulation Index (BSSI)

Usually, parameters like time required to set up the problem in FEM, time required to run the problem, and accuracy of results like deflection and peak pressure developed are key decision variables. Choosing a right approach based on three parameters is a key challenge faced by analysts in the industrial environment. To address this, a Bird Strike Simulation Index is proposed, which encompasses all parameters, and guides users irrespective of the tool used, based on a large number of case studies. Typically, before proceeding with the simulation of assembly of components, an idealized geometry like plate, or a curved plate need to be analyzed - for generating the data sets of FEM setup time, run time, and accuracy. These data points are ranked on a user specific 10 point scale. BSSI is a holistic index, which helps the user to choose the right method depending on the design maturity phase. Fig. 9 shows a typical BSSI plot. Typical BSSI parameters are tabulated below:

	Accuracy	FEM Set up Time	Run Time
SPH	8	5	2
Pure Lagrangian	1	2	2
CEL	5	3	8

Fastener Simulation

Modern aero structures are assembled with millions of fasteners such as rivets and bolts. In the event of a high velocity impact like bird strike, the fasteners take both shear and tensile loads of a higher magnitude. Further, the failure of aircraft structures is expected at fastener locations. Therefore connectors (fasteners) were defined with coupled behavior, which means that a fastener can fail due to shear load or tensile load, or both shear and tensile load.

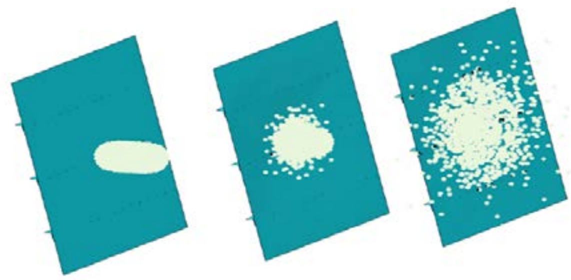

Fig. 9 | Bird Impact on a metallic riveted plate using SPH

Impact Damage Model Set Up

The most challenging aspect of bird strike analysis is solved by a unique methodology of fastener modeling, where the failure modes of fasteners are accounted for shear tensile compressive modes. Aircraft structures involve large number of fasteners, which makes it difficult to model using conventional methods. And fasteners play a critical role in deciding the probable failure location. A proprietary tool 'Smart-Fast' quickly proposes the fasteners as per design iteration during the development cycle. Connectivity of the fasteners decide the failure in addition to structural component spar, ribs, skins and stringers. The fastener decides the failure progression in the component. Both tensile and shear damage definition is specified, along with stiffness for all connectors with respect to their orientation. For example, in the shear plane (if shear plane is X-Y), the software calculates derived component of shear load (resultant of shear FX and FY), and compares it with shear allowable to define whether the connector has been damaged. In this model, this kind of behavior is assigned to all fasteners with the help of connector definition.

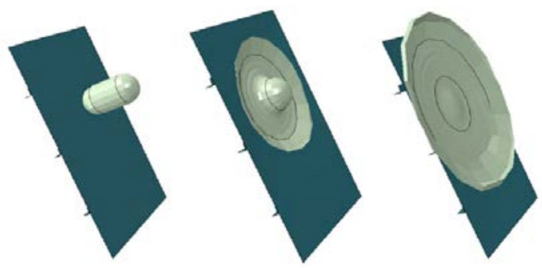

Fig. 10 | Bird impact on a metallic plate using pure lagrangian

The metallic riveted frame is made of aluminum alloy of thickness 3.25mm, with three riveted stiffeners at the two junctions of the frame attachment locations as shown in Fig. 12. The stiffeners are made of the same material, and are impacted with a 1.81kg bird at a normal angle. The geometry of the frame is given in structure is rigidly mounted on steel frames (facing edge clamped with (51*6.35mm) BS4360 Grade 43A steel capping frame bolted through the plate). The bird is set to strike at three different velocities - 94 m/s,111m/s and 131 m/s. The frame and the stiffeners are modeled using shell elements.

Modeling Observations and Assessments

Fastener failure was observed in both the methods – pure Lagrangian and SPH - at impact locations, but both methods did not succeed in predicting the modeling of the structural failure which developed as crack propagation between riveted joints. Further research is being carried out in this area in an attempt to predict both fastener failure as well as crack growth simulation in the event that the plastic strain reaches plastic strain failure value as explained. Experimental results [6] are used for comparing the simulation results.

Impact Velocity (m/s)	Pure Lagrangian Defection (mm)	SPH Residual Deflection (mm)	Experimental Residual Deflection (mm)
94	24.68	21.05	21
111	18.09	29.71	30
131	34.62	39	43

Simulated deformations using pure Lagrangian and SPH method matched very well with published experimental results. Rivet failure was observed in both the methods at impact locations, but both methods could not succeed in predicting the structural damage that occured at fastener hole. A pattern of crack initiation and propagation can be noticed between closely positioned riveted joints for bird- strike at velocity 131m/s as seen in Fig. 11.

To accurately model the phenomenon an attempt was made to achieve penetration by incorporating alternate fastener damage models available in commercial FEA solver. The result of which can be seen in Fig.12.

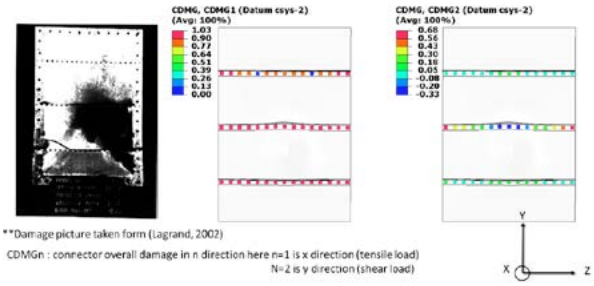

Fig. 11 | Correlation of fastener damage in experiment with connectors

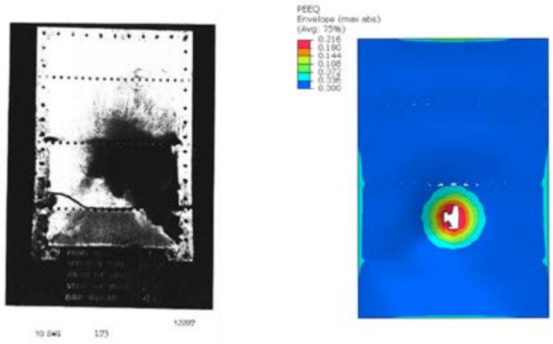

Fig. 12 | Correlation of penetration pattern in experiment with penetration pattern in Abaqus

Enabling Mesh Refinement and Reduction in Fastener Neighboring Element Volume to Obtain Crack Formation

The analysis was further continued in the direction of mesh convergence to obtain a similar crack formation as it occurred in the experiment. A finer mesh was modeled with the intention of observing the crack formation. Two mesh patterns were modeled by reducing the element size. The size was reduced two times and five times the initial value, as shown in Fig.13. Usually, due to the riveting process, stress concentration develops around the fastener hole. To replicate this effect, a weaker region near the fastener location is modeled using an easy to implement approach. The fastener hole equivalent volume was subtracted by reducing the thickness equivalent to the hole volume from one of the neighboring elements of the fastener. For the finer mesh with element edge length 5mm, the penetration was relatively greater than the coarser mesh. For the mesh pattern with element length reduced five times the original size, a crack formation along with penetration was observed, as seen in Fig. 14.

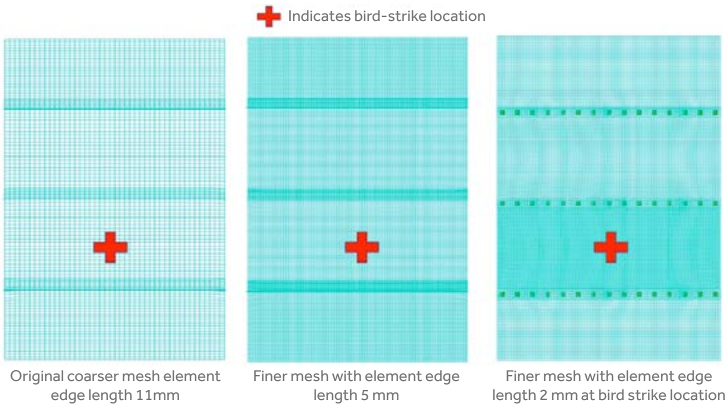

Fig. 13 | Finer mesh pattern to obtain crack formation

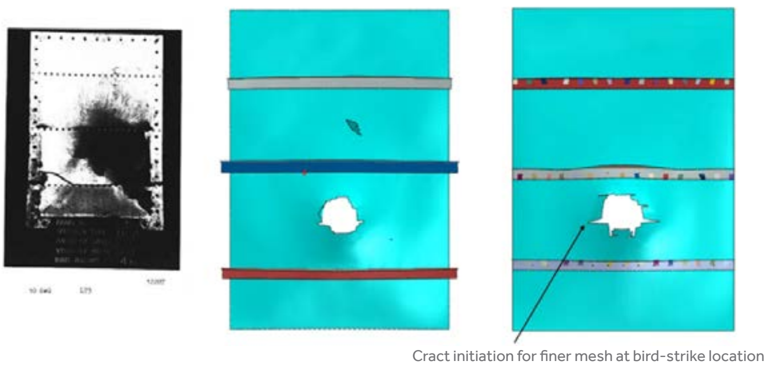

Fig. 14 | Correlation of penetration pattern and crack initiation in experiment with penetration pattern in simulation for riveted airframe with finer mesh and volume reduction at fastener location

Design of experiments studies helped decide the most critical location for bird hit, to avoid the cost of multiple tests, and save the number of birds used in the test.

Cyient was engaged by a leading aerostructure tier-1 supplier to design inboard flap for a next generation business aircraft. As part of the new design process, bird strike simulations were performed. Federal aviation regulation 25.571 requires that the structural members of the aircraft should meet the bird strike impact to be certified for the operation. The test article was designed to replicate the inboard flap of the aircraft. A spectrum of values for velocity, orientation and location were needed for assessing the effect of all these parameters. Design of experiments studies were conducted to decide the most critical location for the bird hit, to avoid the cost of multiple tests, and also save the number of birds used in the test. The results of SPH method of analysis are presented as a representative case.

Correlation of FEM and Experimental Results of Test Article IBF

The inboard flap test article was subjected to the bird-strike tests by the leading aerostructure tier-1 supplier. An FEM model of the same was built using commercial dynamic solver.

The FEM model test article was subjected to bird-strike at a location using explicit solver, with a 4lb bird using smooth particle hydrodynamics technique SPH. The bird was given an initial velocity of 96 m/s, that is 185 knots as per FAA requirement. The model was run for 70ms, and the computation time was around three hours.

FE model simulation videos of bird strike were generated for the same frame rate as the experiment. A comparison of simulated videos and bird strike analysis results showed similar splash pattern of bird and localized damage as seen in the experiment for test article. External damage, internal damage, plastic displacement at damaged regions correlated well with the experiment, and their percentage error was tabulated. The acceleration and strain data plots from accelerometer placed near tracks and strain gauge placed upon actuators in experiment were processed to correlate with acceleration and strain plots at node and elements at same location in FEM. The most important parameters like plastic deformation correlated well with the experiment as shown in the Fig. 15.

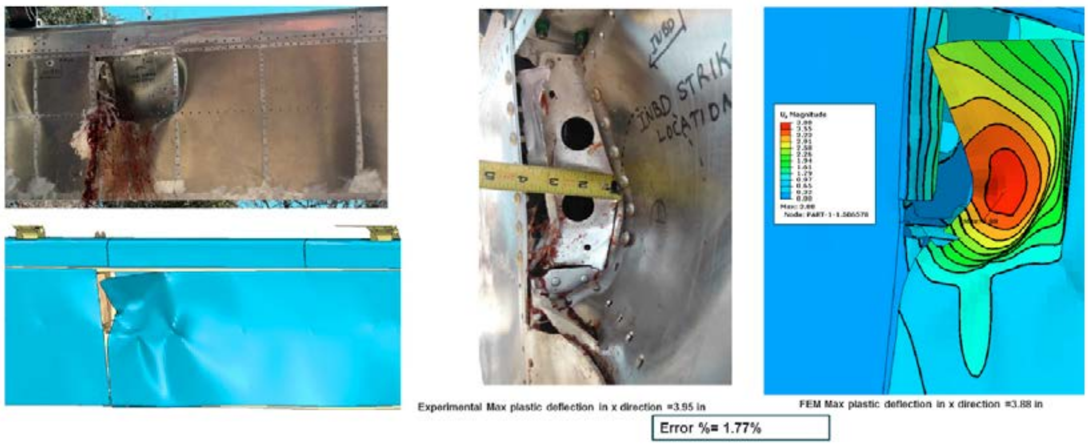

Fig. 15 | Correlation of deformation experiment with simulation

Summary

Bird strike simulation was performed on a new aircraft wing, and the results when compared with test results showed 98% accuracy.

Bird strikes can lead to loss of human life apart from financial loss due to delay and damage of aircraft. To ensure that civil aircraft meet the minimum standards laid out by the FAA, aircraft manufacturers are increasingly resorting to simulation techniques in product development.

Bird Strike Simulation that assures aircraft safety has become a key aspect in the certification of an aircraft. Three methods of simulation were compared namely CEL, SPH, and Lagrangian. A comparative assessment was made in terms of time required to set up the problem, time required to run the problem and accuracy of results. This helped in developing a new methodology for accurate modeling of fasteners and fastener hole embrittlement. Bird strike simulation was performed on a new aircraft wing and the results were compared with test results. There was a close agreement between the two, with an accuracy rate of 98%. The current work demonstrates the adaptability of certification by employing the analysis approach for the certification of aircraft structures against bird strike.

By leveraging this technique, manufacturers can enhance their bird strike analysis process, and reduce the costs involved in multiple tests.

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Our services for the aerospace industry include:
Aero Engines: We help aircraft Engine OEMs to develop innovative technology solutions for improving fuel efficiency, reducing engine emissions and noise. We provide concept to certification engineering solutions along with system level ownership.

Aero Structures: We provide innovative wing and fuselage sub-assembly design solutions from preliminary design through to certification. We offer design & analysis, value engineering, post design release engineering, & manufacturing engineering services.

Aero Systems: We provide subsystem-level engineering solutions for developing their next generation aircraft systems. Our systems knowledge—combined with our expertise in design, structure, thermal and CFD analysis—allows us to provide innovative design solutions optimized for weight and cost.

Avionics: We offer complete product engineering solutions from requirement definition until #SOI3 audit. We provide civil and military avionics solutions compliant to D0-178B and D0-254. Aero Interiors: we help customers to design tomorrow's clean, spacious and efficient cabin interiors. We provide aesthetic and light weight interior designs for commercial and business jets.

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