Bird Strike Simulation in Assuring Aircraft Safety

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Abstract*: Bird strike Simulation helps in assuring aircraft safety, in eliminating cost & effort required for practical tests. There has been significant research done on various ways of doing bird strike simulation, till date Aerospace & defense Industry is concerned with two key issues 1.Comparative assessment of available methods 2. A FE model for fastener failure and fastener hole embrittlement. Current paper addresses relevant issues for today's industry towards a universally accepted method of bird strike analysis Finite element based computational methods. First part of current research aims at bring out comparison between analysis methods along with their pros and cons, the Explicit analysis capabilities of Abaqus were used for modeling the phenomenon using three methods LAGRANGIAN, COUPLED LAGRANGIAN-EULERIAN (CEL) and SMOOTH PARTICLE HYDRODYNAMICS (SPH). Results are compared with published literature based on the standard experimental data. Critical parameters like HUGONIOT pressure and Stagnation pressure are compared from each study. Merits in all the three methods and bird models are presented with a view to guide the user in choosing an appropriate method depending on time and resource availability. A first of its kind Bird Strike Simulation Index (BSSI) proposed with FEM setup time, run time and accuracy as parameters, BSSI will be a holistic guidance for industrial user.*

Second part of the paper deals the most challenging issue of fastener modelling for dynamic loads. Analysis of bird impact modeling onto metallic riveted panels, which are typically idealized models for many practically used airframes structures like wing, flap, trailing edge, leading edge, are done using pure Lagrangian and SPH method. In high velocity bird strike scenario, fasteners will experience both shear and tensile loads and failure of aircraft structures are also governed by fastener failure modes. The fasteners behavior is modeled to simulate the failure due to shear load, tensile load and combined loads. Tensile and shear damage modes are simulated by supplying stiffness values in all connectors. This was possible because large variety of fastener modeling methods available in Abaqus. Results are in good agreement with published experimental results. In reality aircraft components usually contain large number of fastener holes which will significantly define the failure behavior of components of assembly due to micro level embritlement around fastener hole. A first of its kind methodology for fastener hole and fastener damage is implemented which could successfully interlinked to the global impact failure with local micro embritlement.

Keywords*: Bird strike, Fastener damage, Coupled Eulerian Lagrangian analysis (CEL), Pure Lagrangian, Smooth particle hydrodynamics (SPH), Abaqus/Explicit, Hugoniot pressure, Stagnation pressure. Fastener Modeling, Fastener hole embrittlement, micro crack initiation, Damage model for Fastener, Bird strike simulation index (BSSI)*

1. Motivation- Addressing a global air transpiration challenge

Collisions between a bird and aircraft are frequently called as “bird-strike events,” and they are quite common and dangerous. According to the Federal Aviation Administration (FAA), wildlife strikes cost the U.S. civil aviation industry over $300 million and more than 500,000 downtime hours each year (J.Metrism, 2001). Also, people’s lives have been lost or being in risk due to aircraft malfunctions after bird-strikes which make it imperative to design aircraft components capable of withstanding these impacts. To obtain certification from the FAA, an aircraft must be able to land after an impact with a bird weighing 17.79 N (1.81 kg) at any point in the aircraft. These tests take hours of planning to execute and cost millions of dollars to aircraft manufacturing companies. Due to this, it is very important to be able to predict damage caused by a bird-strike impact on aircraft components to save money and time

In 2012, 56% of the remains from reported strikes with civil aircraft in USA were identified to the species level and an additional 7% were identified to species group. The reported costs for civil aircraft in USA totalled $639 million for the 23-year period, 1990 to 2012(FAA Statistic).

Another motivation for this paper is to guide the user on how to solve the issues that he would face during bird-strike analysis on detailed component level assembly and what level of accuracy he would achieve

2. Alternate Approaches for simulation and there comparison

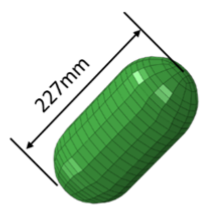

Figure 1 Bird model

Analyses in this work have been performed using bird with mass 1.8 kg modelled to strike on 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 (C3D8R) for pure Lagrangian method, particle element (PC3D) for SPH and Eulerian element (EC3D8R) for CEL. The 1.8 kg bird finite element mesh is shown on Figure 1.

Bird geometry has been idealized by a cylinder with hemispherical ends and a length to diameter ratio equal to 2, due to the fact that this geometry of bird models showed the best correlation with real birds in experimental tests (Airoldi, 2005).A detailed comparison study was done on bird-strike methods based on advantages, disadvantages and accuracy and is described in table 1 on detailed assembly of components. Also an index describing the bird-strike methods based on accuracy, FEM build-up time and run time is shown as 3D representation in figure 2

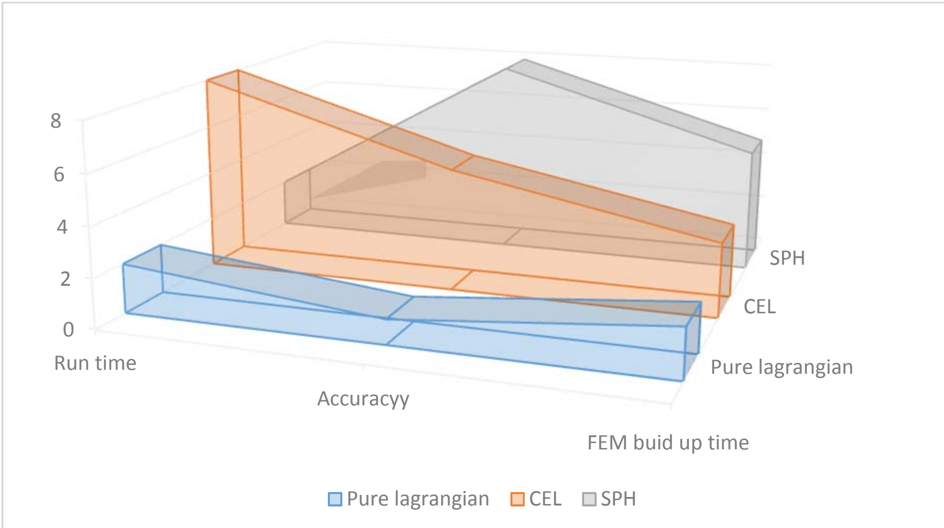

Figure 2 Bird strike method index

Table 1 Comparison of Lagrangian, CEL and SPH approaches its advantages and disadvantages

7.	Advantages and Disadvantages of Bird-strike technique	Accuracy evaluation for Bird strike on a detailed assembly of components
CEL Eulerian fixed space	The pressure/force response using the CEL technique would correlate well with experiment and deformation is localized at point of impact ,which would happen in reality Computation time is very high when compared to other methods. Accuracy of method is good but at cost of computation time	Penetration of Eulerian material through the contact interface can occur in some cases involving Eulerian material contacting Lagrangian shell elements. This type of contact introduces complexity because the sign of the outward normal direction must be determined on the fly as material approaches the Lagrangian element; contact with either side of the element is potentially allowable (Abaqus documentation, 6.12). So if a solid element is used to model the components in an assembly which is tedious, then interior surfaces should also be defined for a solid element in case element deletion is expected. Also if the part is very large then having large volume of Eulerian fixed space is not feasible, as it would increase the computation time.

Smooth particle hydrodynamics	The method's Lagrangian nature, associated with the absence of a fixed mesh, is its main strength. Difficulties associated with fluid flow and structural problems involving large deformations and free surfaces are resolved in a relatively natural way.(Abaqus documentation, 6.12) Computation time is lesser then CEL methods Disadvantage of this method is If the nodes are not placed in a regular cubic arrangement, the mass distribution is somewhat inexact, particularly at the free surface of the body being modeled The SPH technique tends to slightly over-predict the deformation on a simple plate which is more or less acceptable.	The accuracy of SPH method is good, the source that would affect the accuracy of this method is its individual contact definition for every part that is expected to come in contact with another part in the assembly. There is a possibility of interpenetration of particle element on the target but this can be resolved by altering the smoothing length defined
Pure Lagrangian	The deformation on plate using Lagrangian method was very close to actual method but it couldn't capture localized deformation as it would happen in reality when bird strike flat plate ; also the impact force imparted to a small area by the bird during shock stage would be lesser then force imparted by the Eulerian methods(Smojver,2010) The major problem of Lagrangian bird impactor models is the severe mesh deformation. Large distortions of the elements may lead to inaccurate results, severe hourglassing, 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.(Sebastian, 2011)	When pure Lagrangian bird assigned with fluid behavior is made to impact on detailed assembly of component , the Lagrangian element tend to stretch rapidly after their element deletion criteria is met , while doing this the failed elements come in contact with neighboring components far away from point of impact , which is unrealistic. Also at higher velocities there is possibility of sever distortion of element, which could be resolved by activating distortion control but this would add on artificial energy to the system.

2.1 EOS Validation

Validation of the EOS bird material model has been done by comparing Hugoniot and stagnation pressures developed in an impacton a rigid target at the velocity of 116 m/s and 225m/s normal to the plate with bird strike techniques such as SPH, CEL fixed space, CEL mesh motion and Pure Lagrangian techniques available in Abaqus/Explicit with experimental and theoretical values given by (Lagrand, 2002).

The obtained results and experimental arc synthesized in Figures 3 and 4 in terms of Hugoniot pressure P_H, and Stagnation pressure, P_s, vs. impact velocity. FE results using pure Lagrangian technique, SPH technique, CEL fixed space and mesh motion techniques are close enough to experiment and theory in terms of stagnation pressures (Figures 8).But only SPH technique was able to give close results to experimental Hugoniot pressure and slight difference from theoretical Hugoniot pressure.

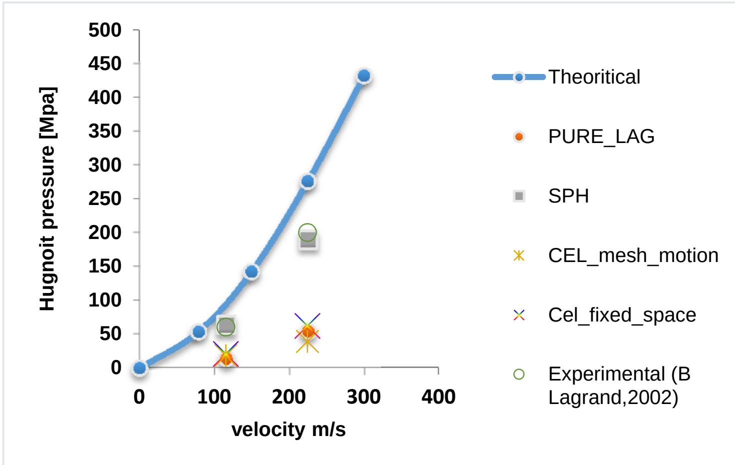

Figure 3 Hugoniot pressure vs. impact velocity

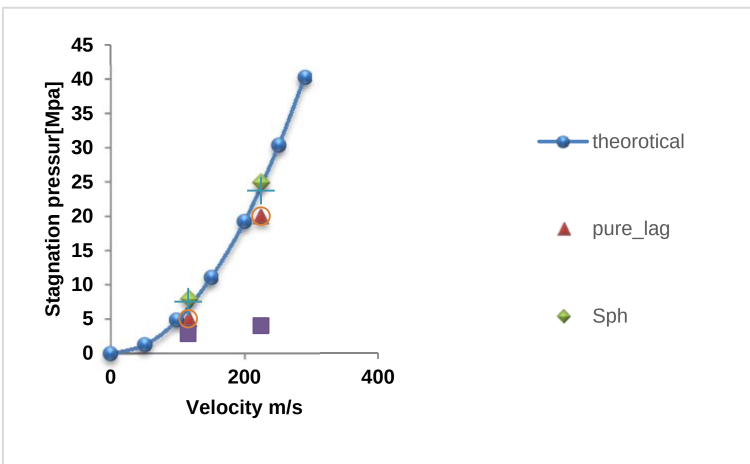

Figure 4 Stagnation pressure vs. impact velocity

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 which is impacting the target.

FE results from a Pure Lagrangian bird model assigned a hydrodynamic viscous fluid does not co-relate well with theoretical and experimental peak pressure, this shows that technique is not sufficient in capturing localized deformation due to high pressure applied at a very small area of impact, but at the same time from investigations of (Smojver,2010), of bird-strike on deformable metallic plate (correlation of FEM and experiment) has found 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.

When coming to CEL method with mesh motion it too does not co-relate well with theoretical and experimental peak pressure the reason for this is as stated by (Sebastian, 2011) the accuracy of the results obtained by CEL mesh motion is strongly mesh dependent and requires fine mesh. Therefore, the accuracy of the model with CEL mesh motion may be reduced for severe impactor deformations.

3. Bird strike onto metallic riveted aircraft frames

Modern aircrafts can include several fasteners, such as rivets, bolts etc. In the scenario of a high velocity impact like bird strike it’s expected that the fasteners will take both shear and tensile loads of a higher magnitude ,also failure of aircraft structures will be mainly expected at fastener locations. So connectors (fastener) were defined with coupled behavior that is fastener can fail due to shear load or tensile load or both shear and tensile load which is possible in Abaqus. Both tensile and shear damage definition was specified, along with stiffness for all connectors with respect to their orientation in Abaqus. 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 connector has damaged or not.

The metallic riveted frame was made of aluminum alloy (B. Langrand ,2001) of thickness 3.25mm, which have three riveted stiffeners at the two junctions of frame attachment locations as shown in Figure 5, the stiffeners were made of the same material (B. Langrand ,2001) and are impacted with a 1.81kg bird at a normal angle. Geometry of the framework is given in Figure 5 (Lagrand, 2002).Structures were rigidly mounted on steel frames (facing edge clamped with (51*6.35mm) BS4360 Grade 43A steel capping frame bolted through the plate) (Lagrand, 2002).The bird was striked with 3 different velocities 94 m/s, 111m/s and 131 m/s The frame and the stiffeners were modelled using shell elements S4R

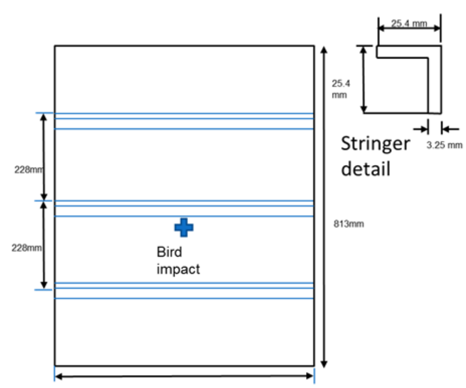

Figure 5 Geometry (Lagrand, 2002)

3.1 Metallic damage model

Failure of metallic structural items, with mechanical properties of aluminum alloy for the bird strike on deformable target in is taken from (FAA report), it has been modelled by shear failure criterion that is suitable for high strain rate dynamic problems and is based on the accumulated equivalent plastic strain, which is calculated as

$$\varepsilon^{pl} = \varepsilon_0^{pl} + \int_0^t \sqrt{(\frac{2}{3}\varepsilon^{\cdot pl} : \varepsilon^{\cdot pl}\, dt)} \qquad \text{equation 4 (Abaqus documentation)}$$

Here in equation 4 ε_0^{pl} is the initial value of equivalent plastic strain and $\varepsilon^{\cdot pl}$ is the equivalent plastic strain rate. An element is assumed to fail when the damage parameterω calculated as

$$\omega = \frac{\varepsilon_0^{pl} + \sum \Delta\varepsilon^{pl}}{\varepsilon_f^{pl}} \qquad \text{equation 5 (Abaqus documentation)}$$

exceeds the value 1. In equation 5, $\varepsilon_f^{pl}$is the strain at failure, $\Delta\varepsilon^{pl}$ is the plastic strain increment and the summation is performed over all increments in the analysis.

3.2 Fastener behavior modelling

The fasteners are modelled as connector element type CON3D2 in Abaqus assigned with connector type cartesian plus cardan where cartesian provide a connection between two nodes that allows independent behavior in three local cartesian directions that follow the system at a particular node and cardan provide a rotational connection between two nodes material. The elatic properties of fastener material (Lagrand, 2002) such as stiffness, fastener allowable and youngs modulus were taken from (MMPDS01, FAA)

The connector elasticity behavior was assigned to the connector, which included the assignment of elasticity in terms of axial stiffness and joint shear stiffness in respective directions, also the connector progressive damage behavior was assigned by defining force based damage initiation criteria and motion based damage evolution criteria available in Abaqus

3.3 Deflection on the metallic riveted airframe due to bird-strike

Pure Lagrangian method and SPH method was selected to simulate bird strike on metallic riveted panels because the equation of state validations were close for these two methods when compared to others. The deformation pattern can be seen in the figure 6 and 7

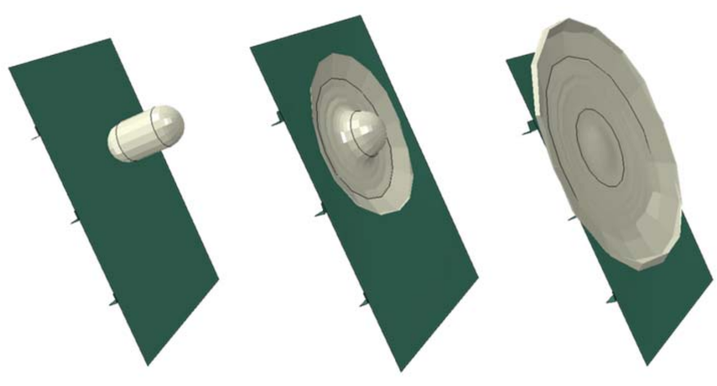

Figure 6. FE simulation of bird impact onto metallic riveted panel using pure Lagrangian method in Abaqus/Explicit 6.12

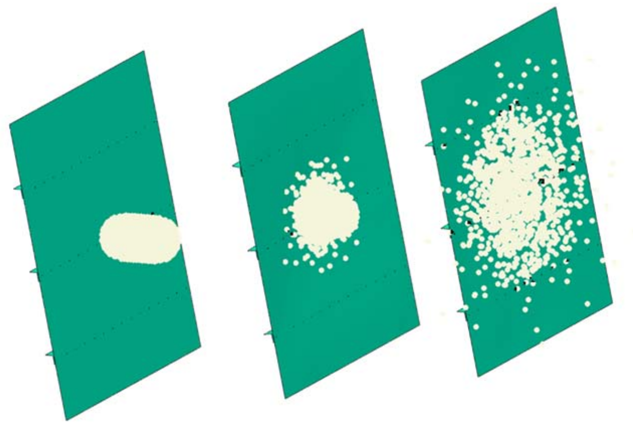

Figure 7. FE simulation of bird impact onto metallic riveted panel using SPH method in Abaqus/Explicit 6.12

Table 2 comparison of SPH and Pure Lagrangian with Experimental residual deflection

Impact velocity [m/s]	Pure Lagrangian defection (mm)	SPH residual deflection(mm)d_r	Experimental residual deflection (Willows, 2008) (mm)d_r
94	18.09	21.05	21
111	24.68	29.71	30
131	34.62	39	43

Residual deformations of the panel d_r, were measured at the impact point. FE results are synthesized in Table 2 for both Lagrangian and SPH formulation. With the SPH method, results are in a good agreement with the available experimental results (Figure 11). The difference between the numerical and experimental data is lower than 10 %. FE results are not so close to experiments in case of Pure Lagrangian numerical and experimental around 15-20%

3.4 Fastener damage modelling

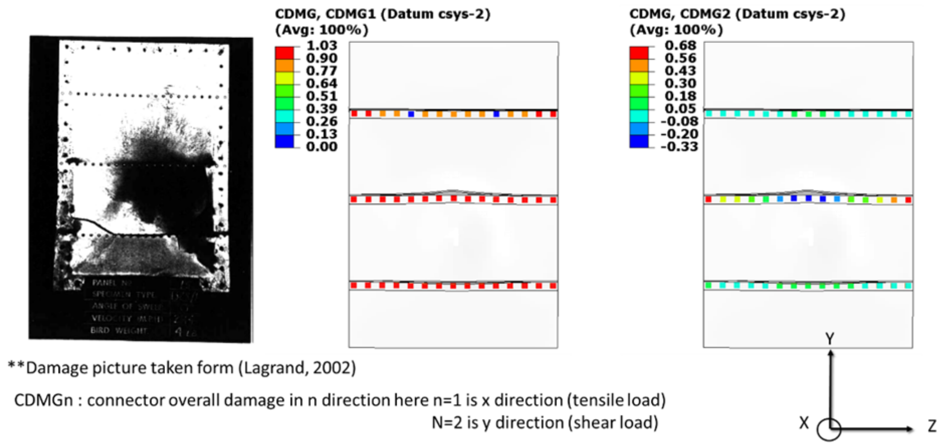

Figure 8. Correlation of fastener damage in experiment with connectors in Abaqus

Fastener failure was observed in both the method at impact locations but both methods did not succeed to predict modelling the structural failure which developed as crack propagation between riveted joints for bird-strike at velocity 131m/s as seen in Figure 12. To resolve this problem an attempt was made to achieve penetration by prolonging the fastener damage evolution by modifying the motion parameter of motion based damage evolution criteria. The result of which can be seen in Figure 9

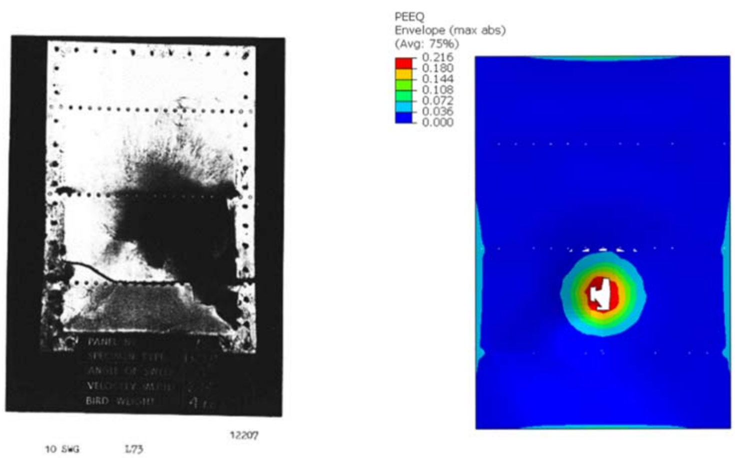

Figure 9. Correlation of penetration pattern in experiment with penetration pattern in Abaqus

3.5 Mesh refinement and fastener neighboring element volume reduction to obtain crack formation

Analysis was further continued in direction of mesh convergence to obtain a similar crack formation as it occurred in the experiment, a finer mesh was modelled form the intension of observing crack formation. Two mesh patterns were modelled by reducing the element size was reduced 2 times and 5 times the initial value as shown in Figure10. Also in real scenario the fastener hole created during the riveting process also results in stress concentration and forming a weaker region near at fastener location, so to replicate this fastener hole equivalent volume was subtracted by reducing the thickness equivalent to the hole volume from one of the neighboring elements of fastener.

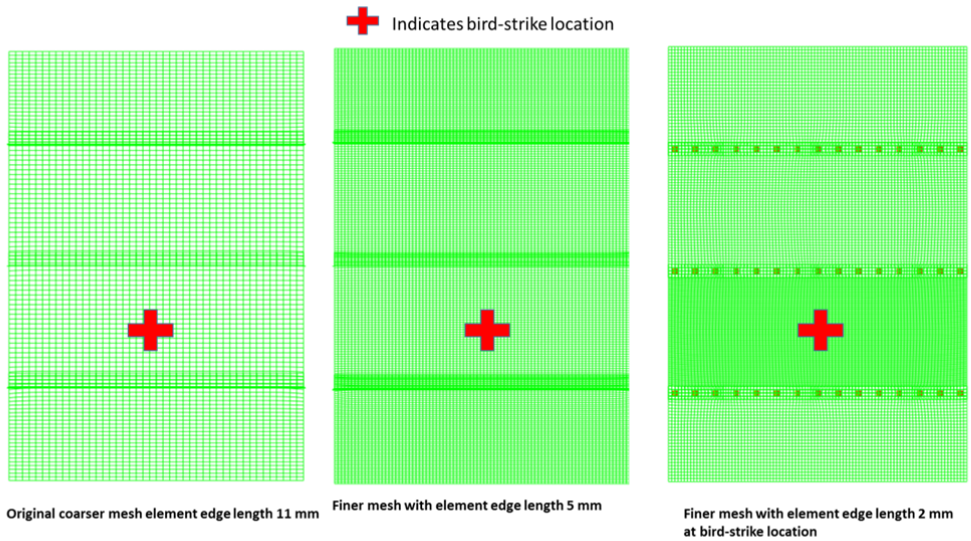

Figure 10. Mesh pattern to obtain crack formation

For the finer mesh with element edge length 5mm the penetration was observed relatively greater than the coarser mesh and for the mesh pattern which had element length reduced 5 times the original size a crack formation along with penetration was observed as seen in figure 11

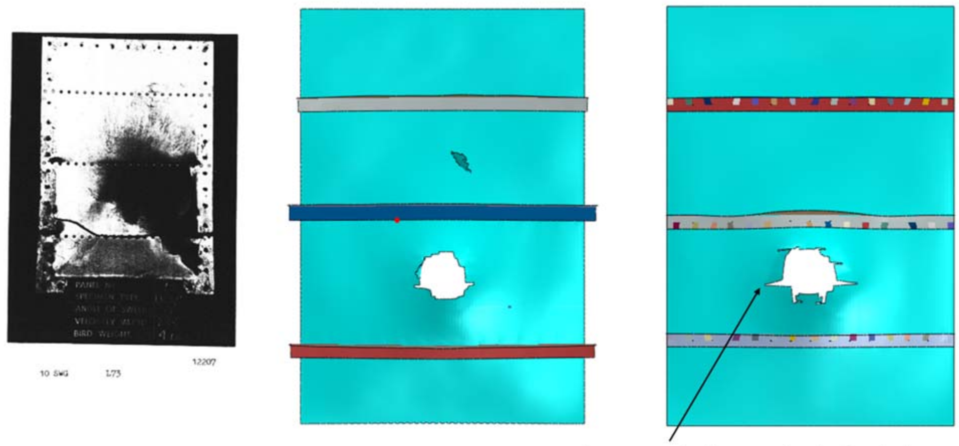

Figure 11. Correlation of penetration pattern and crack initiation in experiment with penetration pattern in Abaqus for riveted airframe with finer mesh and volume reduction at fastener location.

4. Conclusion

In the first part of the paper, benchmark anlysis have been carried out for bird impact onto a rigid panel. Available FE formulations and bird material modeling techniques in Abaqus have been assessed. Simulation results have been compared to experiments in terms of Hugoniot and stagnation pressures for two impact velocities. Analyses have shown that FE results from a SPH technique were close enough to experiment in terms of stagnation and Hugoniot pressures. The chosen methods have been applied to study the problem of bird impacts onto a metallic riveted panel. Available experimental results were given for three impact velocities in terms of residual deformation of the panel at the impact point. FE results were in good agreement compared with experiment. FE models initially did not predict the crack propagation failure mode observed for the highest impact velocity test .To resolve this problem an attempt was made to achieve penetration by prolonging the fastener damage evolution by modifying the motion parameter of motion based damage evolution criteria. The result of which penetration was observed for the highest impact velocity, though the penetration pattern was not close match.

A closer exact crack propagation pattern was obtained by using a very finer mesh at bird-strike location with volume reduction of element at fastener location as seen in figure 11. Also to obtain very close result and damage pattern as seen in the experiment, fasteners could be model leg by giving damage not only due to tensile and shear loads but also load acting due to moment. Further fastener element deletion could be defined to avoid un-reasltic stretching of fastener element after the connecter element getting deactivated from the analysis.

5. References

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