Scientific Research Publishing

Advances in Aerospace Science and Technology, 2022, 7, 32-51
https://www.scirp.org/journal/aast
ISSN Online: 2473-6724
ISSN Print: 2473-6708

High-Velocity Impact Studies on Scaled Leading Edges of Horizontal Tail with Smart Composite Layers

Basavanna Rangaiah[1], Dhayanidhi Jeevarathinam[2], Raja Samikkannu[2]*, Karisiddappa[3]

[1]Department of Civil Engineering, Visvesvaraya Technological University, Belagavi, India
[2]Structural Technological Division, CSIR-National Aerospace Laboratories, Bangalore, India
[3]Visvesvaraya Technological University, Belagavi, India
Email: *raja@nal.res.in

How to cite this paper: Rangaiah, B., Jeevarathinam, D., Samikkannu, R. and Karisiddappa (2022) High-Velocity Impact Studies on Scaled Leading Edges of Horizontal Tail with Smart Composite Layers. *Advances in Aerospace Science and Technology*, 7, 32-51.
https://doi.org/10.4236/aast.2022.71003

Received: February 12, 2022
Accepted: March 13, 2022
Published: March 16, 2022

Copyright © 2022 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

Bird strike studies on typical aluminium leading edges of the Horizontal Tail (HT) with and without Glass Fibre Shape Memory Polymer (GF-SMP) layers are carried out. A one-fifth scaled model of HT is designed and fabricated. The parameters like bird dimension and energy requirements are accordingly scaled to conduct the bird strike tests. Two leading-edge components have been prepared, namely one with AL 2024-T3 aluminium alloy and the other specimen of the same dimension and material, additionally having GF-SMP composite layers inside the metallic leading edge, in order to enhance its impact resistance. Bird strike experiments are performed on both the specimens, impacting at the centre of the leading edge in the nose tip region with an impact velocity of 115 m/s. The test component is instrumented with linear post-yield strain gauges on the top side and the PZT sensors on the bottom. Furthermore, the impact scenario is monitored using a high-speed camera at 7000 fps. The bird strike event is simulated by an equation of state model, in which the mass of the bird is idealized using smooth particle hydrodynamics element in PAMCRASH® explicit solver. The strain magnitude and its pattern including time duration are found to be in a good correlation between test and simulation. Key metrics are evaluated to devise an SHM scheme for the load and impact event monitoring using strain gauges and PZT sensors. GF-SMP layers have improved the impact resistance of the aluminium leading edge which is certainly encouraging towards finding a novel solution for the high-velocity impact.

Keywords

Glass Fibre Shape Memory Polymer (GF-SMP), Scaled Model, High-Velocity

Impact, Leading Edge (LE), Piezoelectric Sensor (PZT)

1. Introduction

The aircraft flight may face the risk of colliding with foreign objects during its life cycle. Birds are one of such foreign objects; when birds collide with the aircraft structure, the damage may turn out to be catastrophic and this collision is defined as "Bird Strike". Importantly, the onset of such collision may cause serious structural damage at the impact location of the aircraft. Therefore, design needs to cater to the provision for such an event. As a result, extensive tests and simulations have to be conducted to make the structure more resilient towards the bird strike. The airworthiness certification authorities, namely FAA and EASA have defined the bird Strike regulations for large civil aircrafts. The certification clauses demand that the aircraft be able to successfully land after the collision with a bird at an impact velocity, which is decided based on the cruise velocity of the aircraft.

Barber *et al.* [1] were the first to conduct the bird-strike test, impacting on a rigid plate. The purpose of this study was to determine the pressure-time variations generated by birds, while impacting the rigid plate. X-radiography and photography were used to verify bird orientation and integrity prior to impact. The loading behaviour of birds at impact was characterized, to develop design methods and criteria. Luo *et al.* [2] investigated the impact-induced damages on carbon/epoxy composite plates. A three-dimensional finite element model was used to analyse the impact incidents, considering the delamination between the layers and polymer matrix failure. Subsequently, the experimental and numerical results were compared.

In an effort to develop energy absorbing composite leading edges for the horizontal tail of a transport aircraft, Ubels *et al.* [3] employed the tensor-skin approach to realize the futuristic damage-tolerant structures to resist the impact loadings. A finite element analysis tool was effectively utilized which helped the researchers to conduct the 4-pound bird impact experiments, in a meaningful way to get test parameters beforehand. Alastair and Martin [4] developed the material's model for soft body impactors, namely gelatine that represents the bird or ice. They further implemented this procedure in an explicit Finite Element Method (FEM) using a particle approach, to study lamina and interlaminar-related damages. The cylindrical shells made of glass-epoxy fabric composites were used in the experiments.

A study of Eulerian and Lagrangian representations of the bird have been carried out [5] [6]. In a bird strike simulation found that a realistic representation of the bird was possible with an Eulerian model. However, the integrity of the component was not vulnerable as the impact in both cases was such that the impact forces/energy would have largely dissipated before they reached the constraint locations. Impact/crash codes use reduced integration elements and explicit integration schemes.

Souli *et al.* [7] explored a hybrid concept, combining Eulerian-Lagrangian coupling scheme to overcome the limitations in element distortions, handling large deformations and non-linear effects in fluid-structure interaction problems by Lagrangian method. McCarthy *et al.* [8] made an attempt to design and develop fibre metal laminates based on leading edges, to find solutions for runway debris as well as bird impacts. The Smooth Particle Hydrodynamics approach was incorporated in numerical simulation, which correctly captured the breaking of bird mass into particles. Importantly, the test-simulation correlation predicted the event accurately, showing the significance of skin to ribs connection through rivets in the transient dynamic phenomenon. Kermanidis *et al.* [9] proposed a damage-tolerant composite leading edge design for a horizontal stabilizer based on tensor skin panels. The process of unfolding layers to absorb the impact energy was demonstrated through testing and simulation under high-velocity impact experiments.

Airoldi and Cacchione [10] proposed an improvement for the Lagrangian approach by correctly modelling the spatial and temporal pressure variations, generated due to impact of a bird. In order to remove the over distorted elements in the finite element analysis, a trial and error-based automatic scheme was adopted. The parameters such as material hydrodynamics, and its calibration were considered in the sensitivity analysis of polycarbonate plate. In an interesting study, Hanssen *et al.* [11] developed a mixed numerical scheme, involving an Arbitrary Lagrangian Eulerian (ALE) modelling procedure for the bird's motion and Lagrangian approach to idealize a sandwich panel structure that consists of aluminium cover with aluminium foam core. A material constitutive model, which describes the continuum mechanics-based damage was adopted to simulate the failure of the aluminium face sheet. In the similar line, Johnson and Holzapfel [12] investigated the influence of damages namely, between plies and delamination in laminated composite structures. Continuum damage mechanics was used to capture the effect of damages, considered in the composite shells, which were subjected to high-velocity impact events, and with a focus laid on failure energy criterion for the delamination.

Steve *et al.* [13] developed a certification procedure for bird impact on moving CFRP trailing edge of Boeing 787 aircraft by adopting an explicit solver in PAM-CRASH, along with available test data. Michele *et al.* [14] proposed a FML-based design scheme for leading edge of a wing, which would provide the needed impact resistance, using a simulation method and subsequently validated with testing. Lagrangian finite element procedure was adopted to predict the large deformations, including the perforations in the FML structures. It was generally noticed that a good correlation could be found between the tests and numerical predictions. Some interesting studies were conducted by Salehi *et al.* [15] on bubble windows of the airplane, using three different methods namely, Lagrangian, Smooth Particle Hydrodynamics (SPH) and Arbitrary Lagrangian Eulerian, to capture the dynamic motion of birds and their mechanics.

Adams *et al.* [16] devised a scale modelling technique for fuselage airframe using a non-linear numerical scheme and applied it on various geometrically scaled models like 1:5, 1:10, 1:15 and 1:20 model was drop tested on a hard floor, which was prepared to generate a specified "g" level, corresponding to the velocity of impact. Few notable impact studies were reported in the literature; Reglero *et al.* [17] on the use of aluminium foams in the leading edges as filler structures; Diamantakos *et al.* [18] on the development of certification procedure, related to the impact resistance of composite structures as leading edges; Jun Liu *et al.* [19] proposed a design method based on experimental and simulation (SPH, FEM) approaches for the bird-strike resistant leading-edge aircraft structure.

Orlando *et al.* [20] addressed the certification requirements of the full-scale CFRP flap structure to show the compliance for a 4-pound bird, at a velocity of 100 m/s. Both simulation and test results were compared for validation purposes. Using the scaled models, Yiou Shen *et al.* [21] investigated the impact behaviours of full-scale structures, in terms of impact force, displacement, time duration of contact, area of damage and amount of energy absorbed during drop experiments. Importantly, a correlation was found for elastic deformation and internal damage like delamination through geometric scaling law. Yadong *et al.* [22] studied the non-linear dynamic characteristics of composite layers in the design of laminated structures under impact loadings. Numerical case studies were conducted with different ply angles to evaluate the best ply design to demonstrate the crash worthiness using SPH and FEM schemes. They further extended this investigation [23] to various composite materials and found that the impact-induced damage patterns were distinctly identifiable in those materials.

Basavanna *et al.* [24] reported the prediction of impact damage and its propagation with the impact scenarios. The major emphasis is given to interface the smart material towards monitoring the structural behavior and also predicting the residual structural strength after the impact event with the advanced simulation technique mathematical model to address the transient dynamic impact problem.

Recently Basavanna *et al.* [25] reported the low-velocity impact response on the glass fibre composite laminates using two different resin systems, namely aircraft grade epoxy and shape memory polymer under various impact loadings (4J, 6J, 12J). A new signal analysis scheme was adopted to handle the very high frequency sample data (MHz). The high frequency structural waves were monitored during the impact event to diagnose the Barely Visible Damage (BVID) in the laminates using the distributed PZT patches. The SPH model available in ANSYS Autodyn solver was used by Talha and Hampson [26] to study the impact response of the leading edge of the aircraft wing at a velocity of 155 m/s. Aluminium panels with varying thicknesses were employed in the simulations and the results were subsequently compared with the test data of Cessna Aircraft. Other noteworthy studies [27] [28] [29] [30] are reported in this vital field of impact, which certainly bring out the criticalities, involved in the design of leading edges for lifting surfaces.

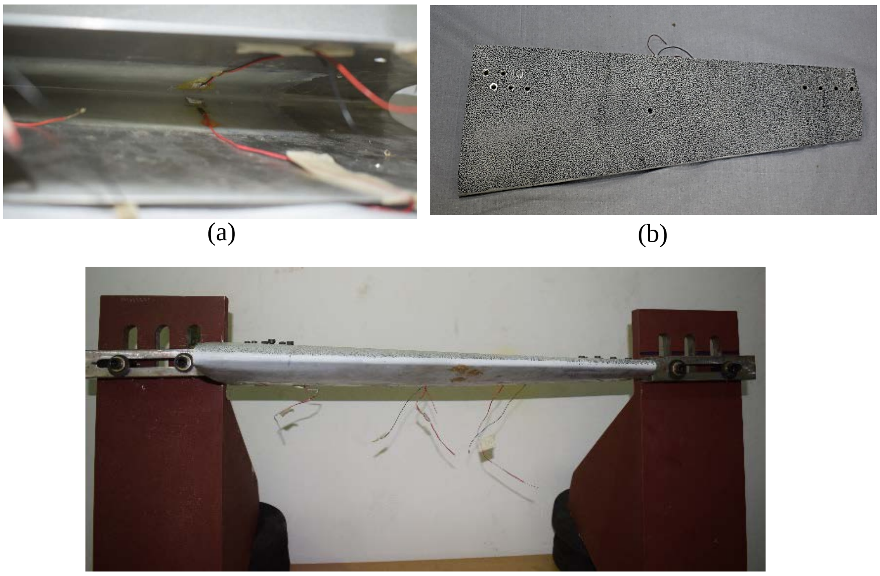
The relevant literature review indeed has revealed that mostly epoxy-based composites and sandwich constructions were considered to develop impact-resistant leading edges for the horizontal tail and win structures. Nevertheless, now worldwide, many multifunctional polymer materials are emerging through recent research works [31], which can be potentially used along with existing glass or carbon fabric to develop the impact-resistant composite leading edge structures. The Shape Memory Polymer (SMP) is more viscous, compare to epoxy and also has the shape recovery nature. A proper tailoring is however required to use this resin system for making the composite layers to augment the energy absorbing capability to have higher impact resistance. In this direction, the present study has focussed to demonstrate the use of glass fabric-SMP layers as energy absorption structure inside the aluminium leading edge, where the use of a scaled modelling approach for high-velocity impact studies is explored. Since, the bird strike is one of the design drivers for the wing and horizontal tail, a load monitoring approach is further devised using the standard strain gauges and electromechanically coupled PZT (Lead Zirconate Titanate) patches.

The main emphasis is laid on the prediction of the high velocity impact event and its propagation to capture the transient dynamic behaviors.

2. Methodology

A scaled modelling approach is adopted to investigate the high velocity impact events and the respective scaling parameters considered are impact velocity, mass, and geometry of the projectile and target component, following the reference [16]. The Horizontal Tail (HT) of a 14-seater aircraft (SARAS-PT1N, CSIR-NAL, India, 2016) was scaled to one-fifth times and two scaled aluminium Leading Edges (LE) were fabricated as test specimens. Subsequently, the bird strike studies had been conducted with an eight-pound bird against the metal leading edges with and without glass fiber-SMP layers. The LE was instrumented with strain gauges and PZT sensors (See **Figure 1(a)**), to capture the dynamic event using high speed DAS (NI system®) at high sampling frequency 1 MHz and the event was also captured by high speed cameras of 3D DIC system (**Figure 1(b)**). To accommodate the LE component, a test fixture was designed and fabricated (**Figure 1(c)**).

After performing the characterisation and validation of the LE impact response behaviour through tests and simulations, a parametric simulation study is carried out by impacting at various locations from the root to the tip of the LE, with and without composite smart layers. The primary focus here is to develop a load and health monitoring framework, by using the electro-mechanically coupled piezoelectric sensors, to predict impact event and the damage verses time signatures. It is to be noted that piezoelectric material (PZT) is able to generate electric potential in response to external stimuli like mechanical loading and thermal energy. Therefore, the distributed PZT patches are surface bonded inside


(a) (b)

(c)

Figure 1. Test specimen. (a) Strain gauges & PZT sensors; (b) Speckling for 3D-DIC measurements; (c) 1/5th scaled aluminium LE specimen mounted on the fixture.

the LE skin to monitor the overall impact response behaviour. Further, the impact event monitoring is required to assess not only the damage intensity level but also to decide the periodic or scheduled maintenance requirement. Importantly, the history of recorded impact events would certainly provide the necessary structural response data for the structural reliability analysis, besides monitoring the structural health itself. The instrumentation scheme is graphically explained in Figure 2. The computational models are built using commercial explicit solver like PAMCRASH, where the bird is idealised by smooth particle hydrodynamics approach.

3. Test Setup: Bird Strike Test Facility

The 8/4-lb airgun impact test facility at CSIR-NAL has been built (Figure 3) to meet the FAR certification requirements for civil/military aircrafts for Foreign Object Damage (FOD) due to High Velocity Impact (HVI). This type of 8/4-lb airgun facilities is the first of few in the world. The expertise developed at CSIR-NAL on bird strike testing and simulation capability has assisted to meet the HVI requirements of military and civil aviation programs in India. The following are the key features of this facility:

- HVI Spectrum: starting from Bird strike and ice impact to tyre fragment and FOD on aerospace structures;
- ▪ 204 mm diameter, 6.5 m long;
- ▪ Projectiles of 5 kg mass up to 250 m/s velocity;
- Evaluation of structural damage using High Speed Data Acquisition Systems (DAS), High Speed Camera, dynamic load and strain measurements.

For the present bird strike experiments on the LE components, this airgun test

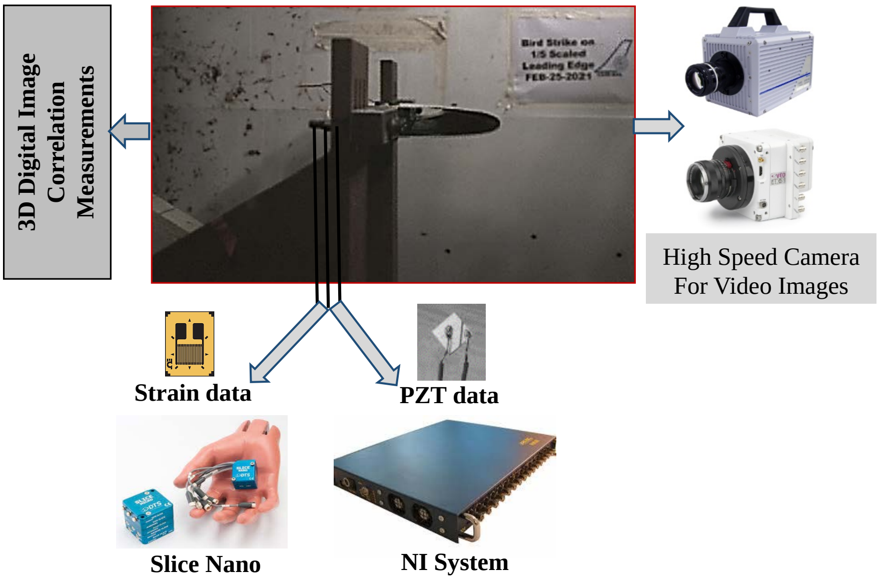


Figure 2. Instrumentation scheme.

Figure 3. 8/4-lb Bird strike test facility at CSIR-NAL, Bangalore, India.

facility is used. Sufficient care is taken to capture the impact events and its time histories with appropriate sensors (Strain gages, PZT patches, high speed cameras, DIC measurements).

4. High Velocity Impact Experiments and Simulations

4.1. Experimental Study

The leading edge is fixed against a specially designed high velocity impact test fixtures as shown in Figure 1(c). The component is aligned to the gun centre such that the bird strikes the target at the middle of the LE nose tip. Here, an in-house calibrated synthetic bird (gelatine bird) is used as a substitute for the real bird. This artificial bird has got a length to diameter ratio of 2:1. The gelatine bird is accurately characterised such that it replicates the dynamic behaviour of actual bird for the velocity under consideration [32] [33] [34]. The experimental setup, measurement and visualisation of high speed projectile impact [35].

The target LE component is geometrically scaled and fabricated with the same aircraft grade aluminium material to represent the actual LE of a civil aircraft horizontal stabilizer **Table 1**. One-fifth scaling is adopted, both for the LE and the bird. It is to be noted that, an 8-lb bird is considered as per the FAR-25 requirements to qualify an empennage structure of the aircraft.

4.2. Simulation Study

Conducting the feature level impact tests on various LE components is really expensive; therefore, the well-established simulation approach in PAM-CRASH is used to develop the LE structure (FEM) and the bird (SPH) to obtain additional parametric results. **Figure 4** and **Figure 5** show the FE models of the LE components, without and with the smart composite layers, respectively.

To perform the transient dynamic response analysis, the essential requirements are to use the right material data for the structure and the impactor bird. So, the material to represent the bird is taken as hydrodynamic type and the LE aluminium structure is assumed to be elasto-plastically deformable one. Accordingly, Johnson-Cook's elasto-plastic material law that defines isotropic aluminium in terms of elastic-plastic stress-strain curve is adopted. Indeed, the Johnson-Cook'

Table 1. Details of scaled LE test components and bird projectile.

Test No.	Test component	Velocity (m/s)	8-lb bird dimension and mass after scaling		
			Dia. (mm)	Length (mm)	Mass (gm)
1	Aluminium LE	115	32	61	46
2	Aluminium LE with GF-SMP layers	115	32	60	47

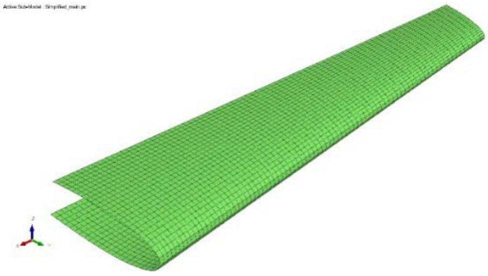


Figure 4. Aluminium LE structure simulation model.

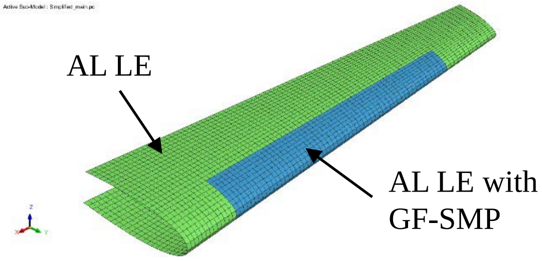


Figure 5. Aluminium LE structure simulation model with GF-SMP layers.

material model expresses the stress flow in a material as the function of strain, strain rate and temperature. The material properties used in the simulation for the bird, LE structure and GF-SMP lamina are given in Table 2.

5. Results and Discussion

The aluminium LE feature level specimens with and without GF-SMP layers were impacted at a velocity 115 m/s using a scaled gelatine mass, which is equivalent to an 8-lb bird. As discussed in Section 2.0, the LE structure was instrumented with strain gauges and PZT sensors and the impact response data was accordingly acquired using the high-speed data acquisition systems (refer to Figure 2).

High speed cameras and 3D DIC system were employed to capture the event, displacement and strain distributions on the top surface of the LE. The comparison of the test and simulation results is shown in Figures 6-8. For the sake

Table 2. Material data for bird, LE structure and GF-SMP layers.

Material Property	Bird (SPH)	LE Structure (Al 2024)	GF-SMP Layer
Young's Modulus GPa)	-	72.4	15.0
Shear Modulus (GPa)	-	28.0	5.0
Bulk Modulus (MPa)	2200.0	-	-
Density (kg/m^3)	930 - 950	2785.0	2000.0
Poisson's Ratio	-	0.33	0.35
Yield Stress (MPa)	-	277.0	245.0
Tensile Failure Strain	-	15%	2.22%

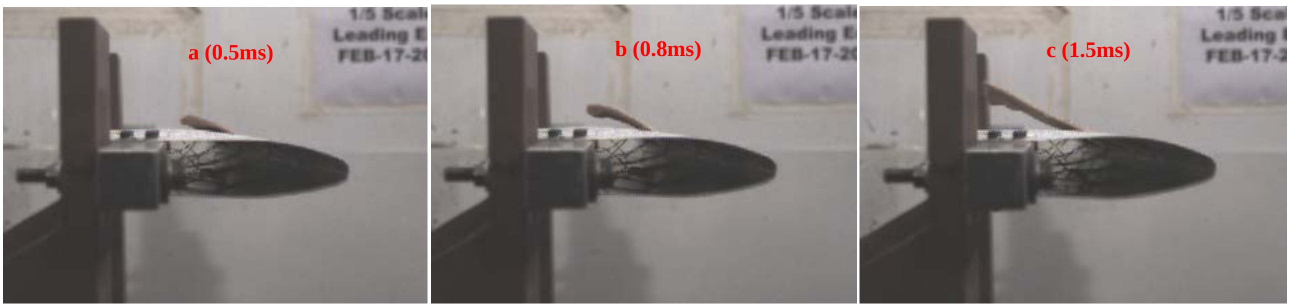


Figure 6. Test at different state during impact event against AL-LE.

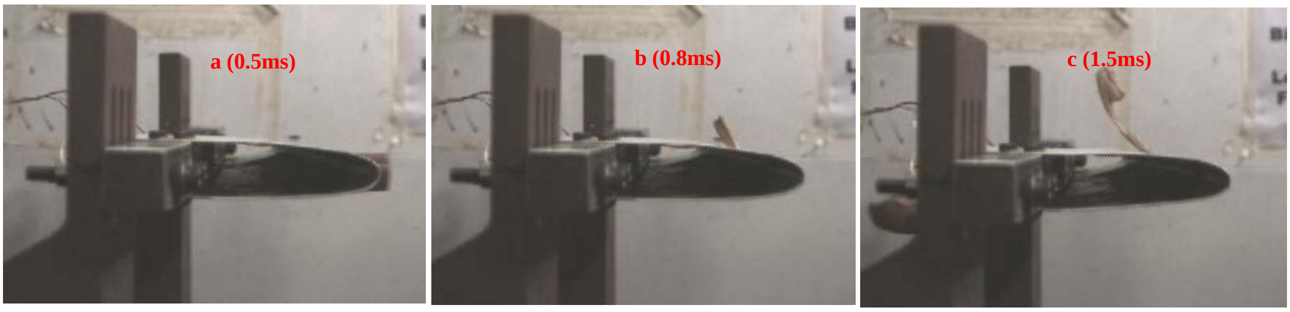


Figure 7. Test at different state during impact event against AL-LE with GF-SMP.

of brevity, simulation plots are presented only at time 1.5 ms. Further, the test-simulation strain time histories are presented in **Figures 9-16**. The simulation strain time history shows a comparative correlation with the measured strains in terms of maximum strain during the initial shock phase of the impact events.

Further, the duration of the test and simulation strains have compared reasonably well, within the event is completed (1.5 ms), as can be seen in **Figures 10-12** and **Figures 14-16**, respectively for both LEs with and without GF-SMP layers. However, it is observed that there is a marginal reduction seen in the maximum strain value (strain gauge in the mid region) due to GF-SMP layers, where the impact occurred. In contrast, considerable amount of reduction in maximum strain value is noticed in the other strain gauges, located away from the region of bird impact, namely on the RH and LH of the LE because of

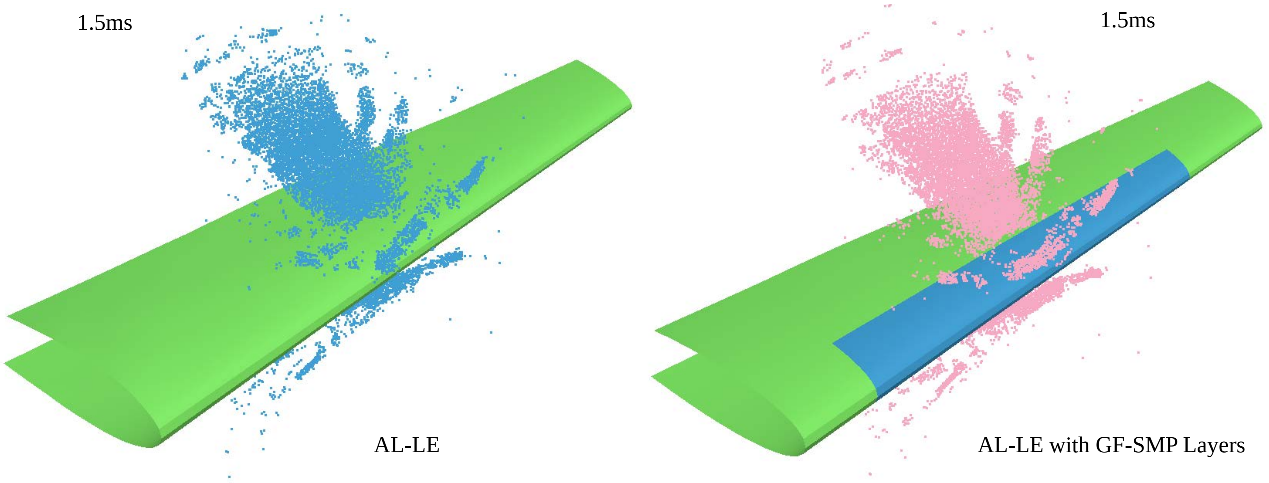


Figure 8. Simulation at 1.5 ms during the impact event.

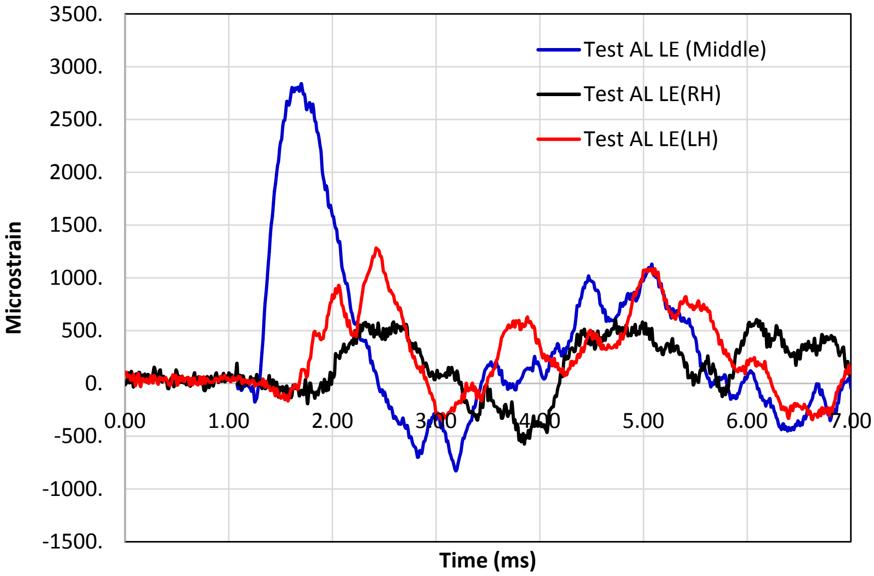


Figure 9. Strain time history of gauges at middle, RH and LH of AL LE during the test.

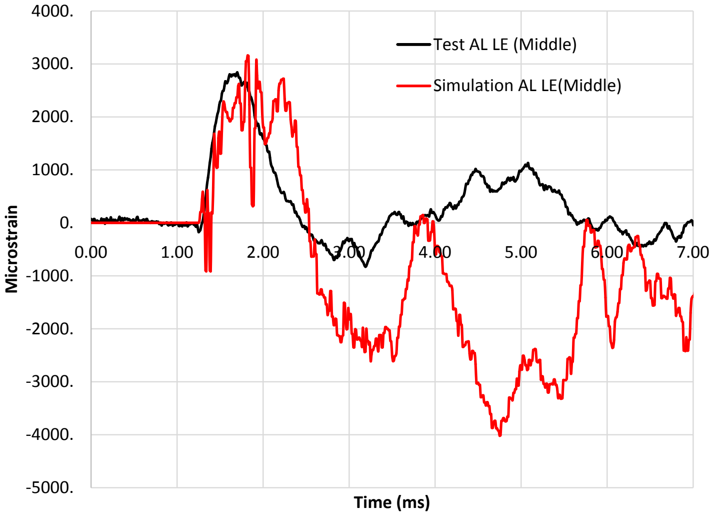


Figure 10. Test-analysis comparison of strain time history at middle gauge of AL LE.

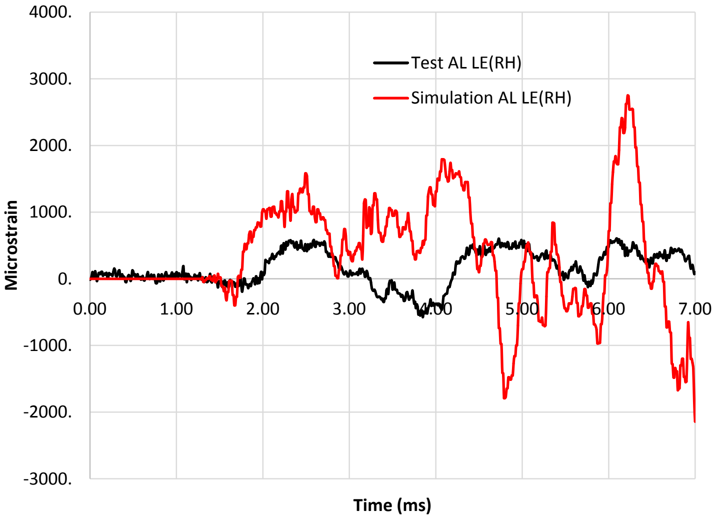


Figure 11. Test-analysis comparison of strain time history at RH of AL LE.

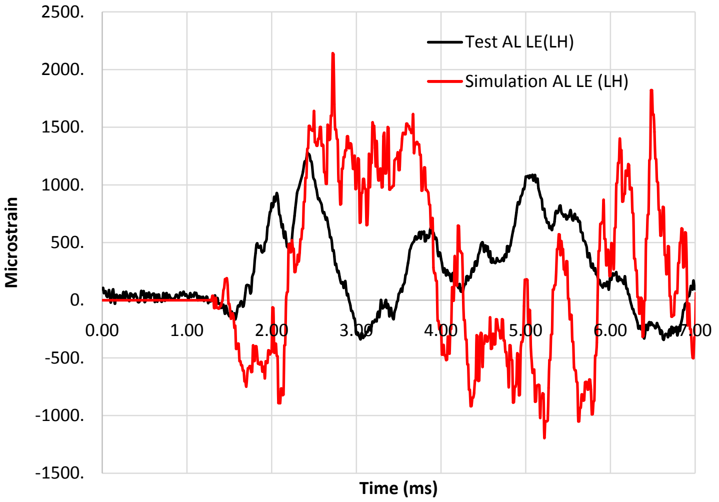


Figure 12. Test-analysis comparison of strain time history at LH of AL LE.

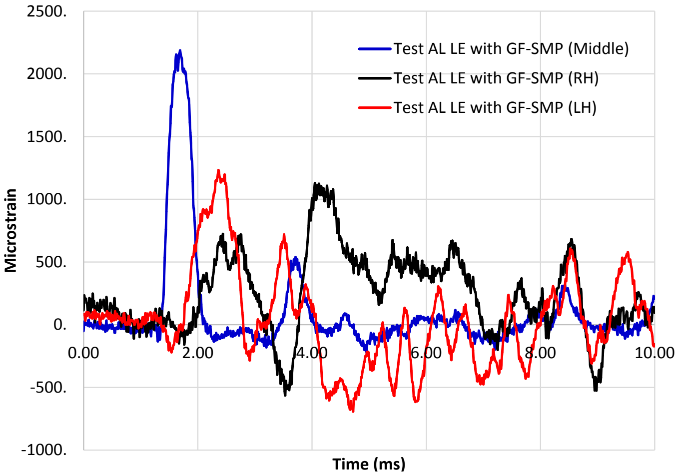


Figure 13. Strain time history at middle, RH and LH of AL LE with GF-SMP composite layers during the test.

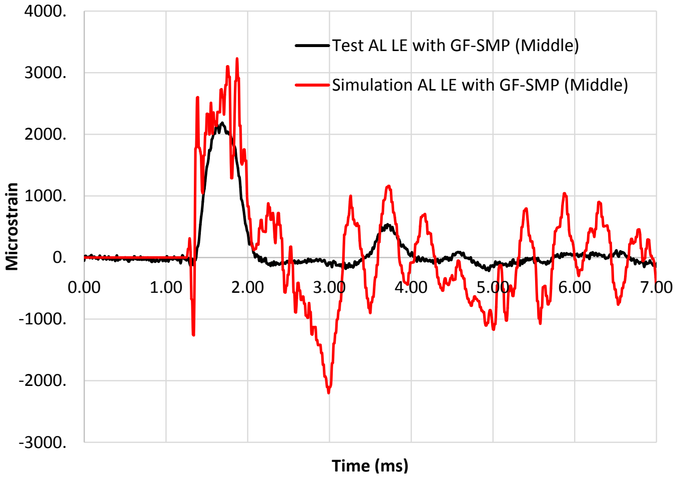


Figure 14. Test-analysis comparison of strain time history at middle of the AL LE with GF-SMP composite layers.

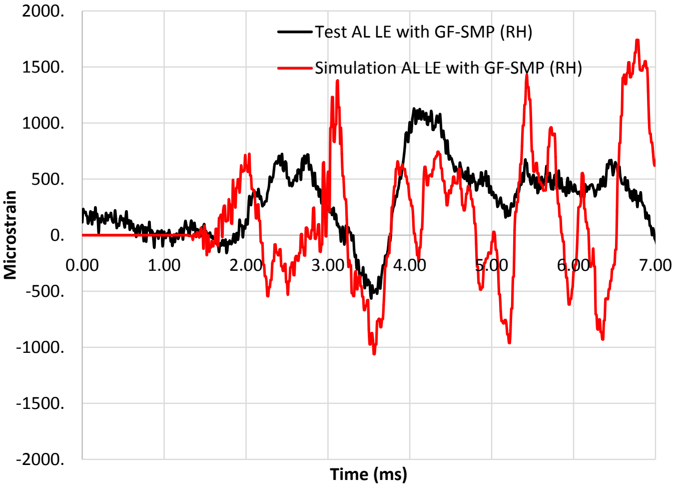


Figure 15. Test-analysis comparison of strain time history at RH of the AL LE with GF-SMP composite layers.

GF-SMP layers. It is therefore clear that SMP resin based composite layers have improved the impact resistance of the LE structure. Also, it is noticed that the oscillations after the impact event are properly damped out.

6. Parametric Simulation to Identify Impact Event Monitoring Key Metrics

After the validation of test-analysis methodologies, a parametric simulation study is carried out to investigate the influencing parameters for the identification of impact event, such that a SHM framework can be worked using PZT patches and strain gauges Figure 17. Accordingly, the bird strike simulations were

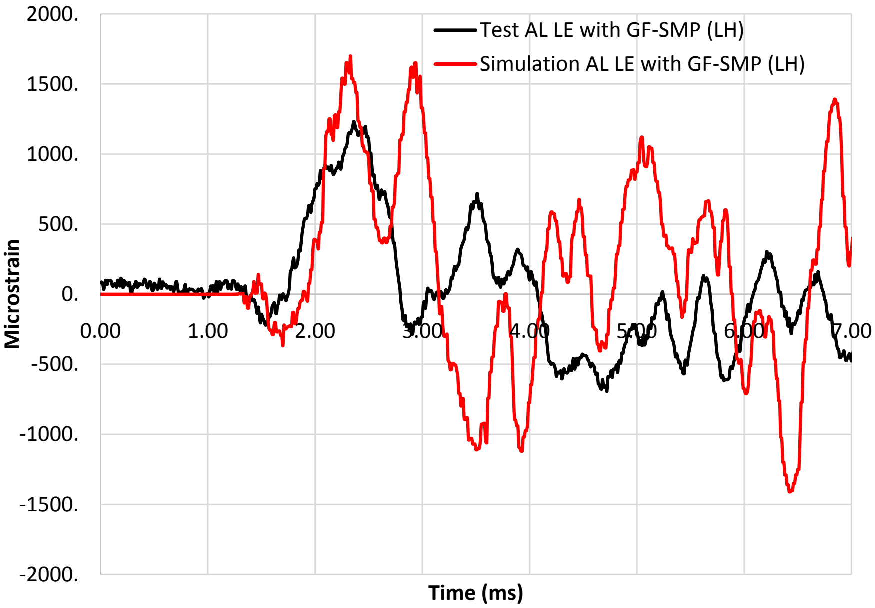


Figure 16. Test-analysis comparison of strain time history at LH of the AL LE with GF-SMP composite layers.

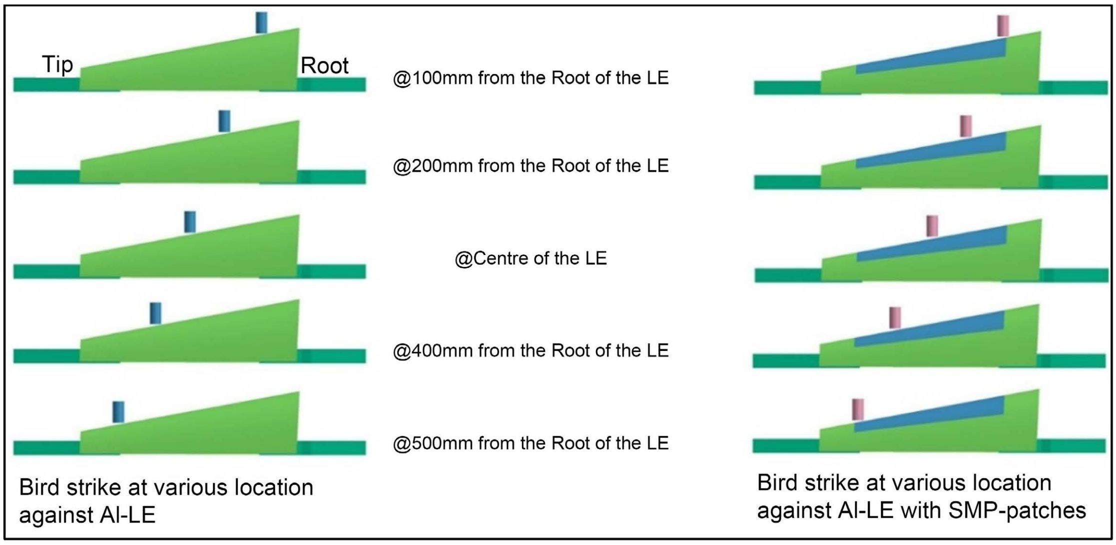
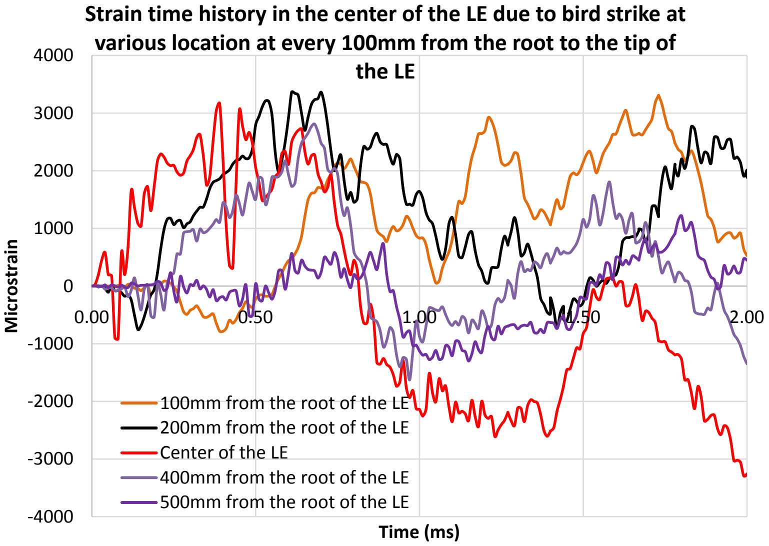


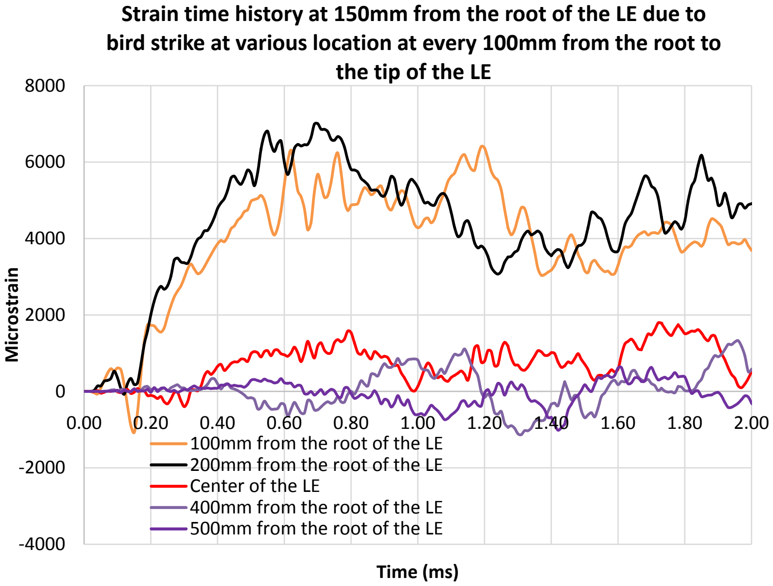
Figure 17. Parametric study details.

carried out at every 100 mm spacing along the span of the LE, from the root to the tip of the LE component with and without GF-SMP layers. This exercise was done to evaluate the variation of the maximum strain value with respect to the location of the impact event and further to understand the damping behaviour of SMP material system to assist in localising and trimming down the impact damage area. It is to be noted that the fluid behaviour of the bird may be examined through the contact surface area of the bird during the event, which can provide useful information like optimal positions for the PZT sensors or gauges, along the span of the LE for SHM application, besides impact event magnitude and its time signature.

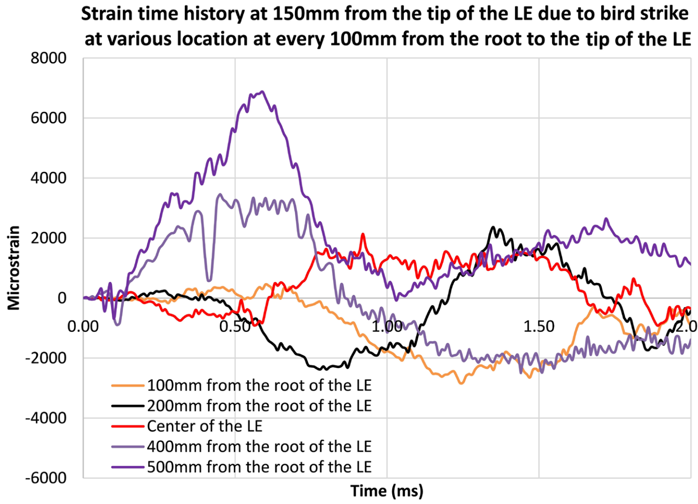
The Figures 18(a)-(c) and Figures 19(a)-(c) provide the results of the parametric study on both the specimens. It can be seen that there is a significant change



(a)

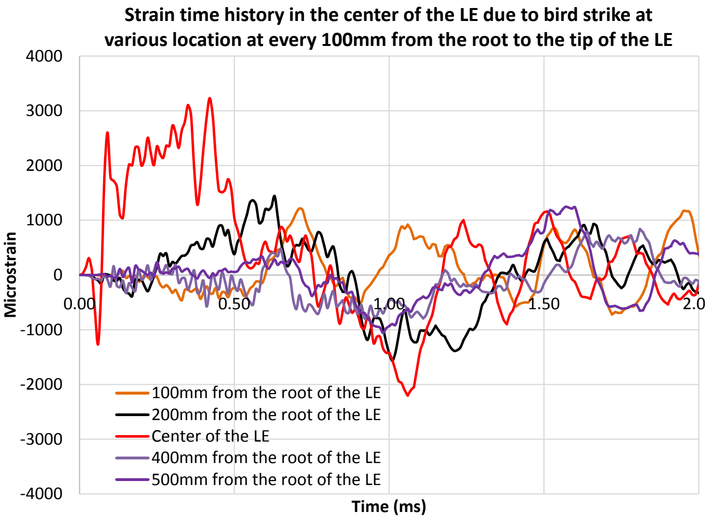


(b)

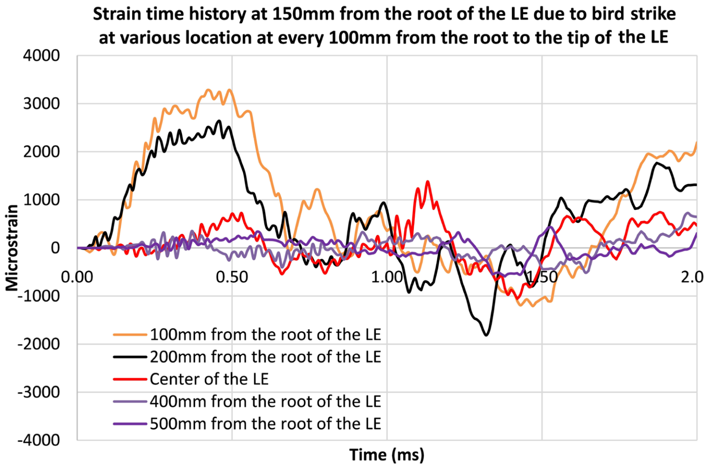


(c)

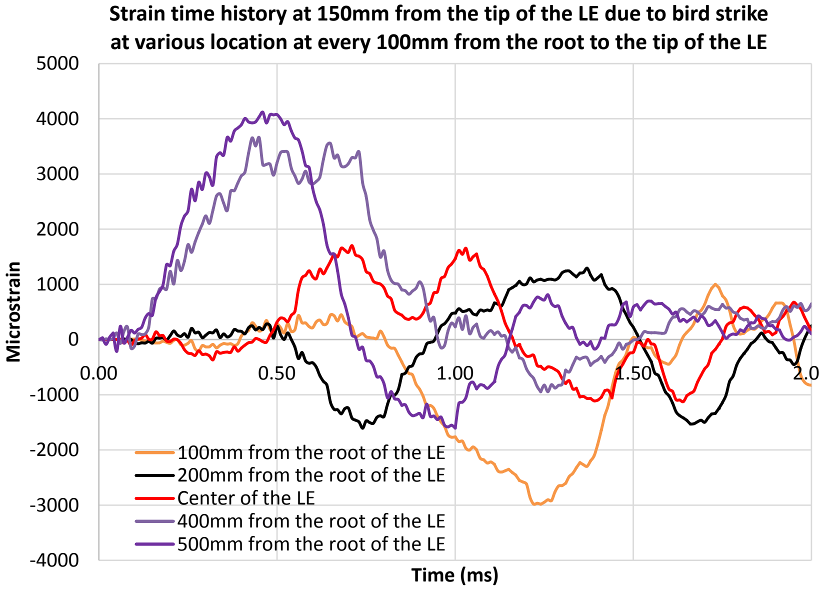
Figure 18. (a) Parametric strain time history on AI-LE; (b) Parametric strain time history on AI-LE; (c) Parametric strain time history on AI-LE.



(a)



(b)



(c)

Figure 19. (a) Parametric strain time history of AI LE with GF-SMP layers; (b) Parametric strain time history of AI LE with GF-SMP layers; (c) Parametric strain time history of AI LE with GF-SMP layers.

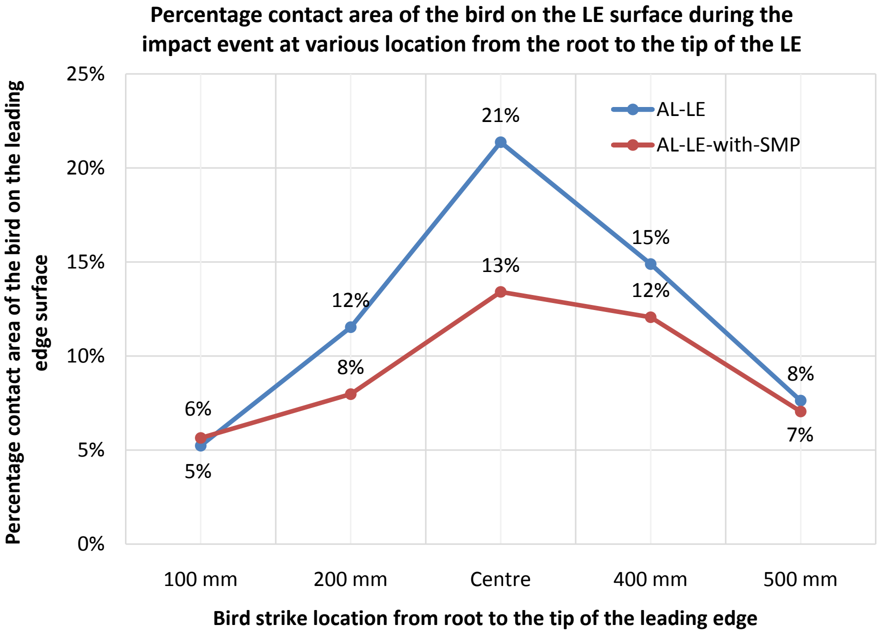


Figure 20. Percentage contact area due to bird strike at various locations.

in the magnitude and duration of the impact event based on the location of the impact event. Likewise, the contact area is found maximum, when the event occurs at the centre of the LE and eventually decreases, when the event occurs either towards the root or tip of the LE (**Figure 20**). This is very important parameter that can be observed to predict the signature of the projectile or FOD, which will impact the aircraft LE during its flight. Hence, a data driven approach can be devised using advanced tools such machine learning algorithms to arrive a SHM based load and event monitoring mechanism in near future.

7. Conclusion

In the present study, the high-velocity impact experiments are conducted on 1:5 scaled LE components, where the projectile is also scaled to represent an 8-lb bird. The LE is impacted at an impact velocity of 115 m/s and a numerical model is accordingly developed to simulate the bird strike process. The SPH bird model is employed to simulate the behaviour of the bird at a high-speed impact. The simulated behaviour of the bird strike event against the LE target is found in good agreement with the high-speed video-based image analysis. Test and simulation correlation in terms of strain time history at various locations of the LE has shown very good agreement. The temporal and spatial variation of the test and simulation results has been observed to be close. In fact, the duration of event energy dissipation also has confirmed a good relationship. The addition of 1 mm thick GF-SMP layers has demonstrated its capability to enhance considerably the impact resistance of aluminum LE structure. PZT sensors and strain gauges have provided vital response information, using which the influencing parameters of the impact event are first identified. Afterwards, the parametric numerical studies have established the key metrics for the load and event monitoring schemes to be developed in the future.

Acknowledgements

We would like to extend our gratitude to the fabrication, testing and instrumentation team that assisted in carrying out the research work successfully.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Barber, J.P., *et al.* (1975) Characterization of Bird Impacts on a Rigid Plate: Part 1. Dayton University, Dayton, Technical Report AFFDL-TR-75-5. https://doi.org/10.21236/ADA021142

[2] Luo, R.K., Green, E.R. and Morrison, C.J. (1999) Impact Damage Analysis of Composite Plates. *International Journal of Impact Engineering*, **22**, 435-447. https://doi.org/10.1016/S0734-743X(98)00056-6

[3] Ubels, L.C., Johnson, A.F., Gallard, J.P. and Sunaric, M. (2003) Design and Testing of a Composite Bird Strike Resistant Leading Edge. *The SAMPE Europe Conference & Exhibition*, Paris, 1-3 April 2003, 1-15.

[4] Johnson, A.F. and Holzapfel, M. (2003) Modelling Soft Body Impact on Composite Structures. *Composite Structures*, **61**, 103-113. https://doi.org/10.1016/S0263-8223(03)00033-3

[5] Souli, M., Sofiane, Y. and Olovsson, L. (2004) ALE and Fluid/Structure Interaction in

LS-DYNA. *Emerging Technology in Fluids, Structures, and Fluid-Structure Interactions*, Vol. 1, San Diego, 25-29 July 2004, PVP2004-2870. https://doi.org/10.1115/PVP2004-2870

[6] Basavanna, R. and Chandra, S. (2003) Bird Strike Simulations of a Horizontal Stabilizer Using Explicit FEA Codes. ISSMACS-2003, NAL Bangalore.

[7] Basavanna, R. and Chandra, S. (2003) Typical Bird Strike Analysis on Leading Edge Using Explicit Code. *International Conference on Impact Mechanics and Plasticity* (*IMPLAST*-2003), New Delhi, 16-19 March 2003, 1111-1117.

[8] McCarthy, M.A., Xiao, J.R., McCarthy, C.T., Kamoulakos, A., Ramos, J., Gallard, J.P. and Melito, V. (2004) Modelling of Bird Strike on an Aircraft Wing Leading Edge Made from Fibre Metal Laminates: Part 2: Modelling of Impact with SPH Bird Model. *Applied Composite Materials*, **11**, 317-340. https://doi.org/10.1023/B:ACMA.0000037134.93410.c0

[9] Kermanidis, T., Labeas, G., Sunaric, M. and Ubels, L. (2005) Development and Validation of a Novel Bird Strike Resistant Composite Leading Edge Structure. *Applied Composite Materials*, **12**, 327-353. https://doi.org/10.1007/s10443-005-3441-z

[10] Airoldi, A. and Cacchione, B. (2006) Modelling of Impact Forces and Pressures in Lagrangian Bird Strike Analyses. *International Journal of Impact Engineering*, **32**, 1651-1677. https://doi.org/10.1016/j.ijimpeng.2005.04.011

[11] Hanssen, A.G., Girard, Y., Olovsson, L., Berstad, T. and Langseth, M. (2006) A Numerical Model for Bird Strike of Aluminium Foam-Based Sandwich Panels. *International Journal of Impact Engineering*, **32**, 1127-1144. https://doi.org/10.1016/j.ijimpeng.2004.09.004

[12] Johnson, A.F. and Holzapfel, M. (2006) Influence of Delamination on Impact Damage in Composite Structures. *Composites Science and Technology*, **66**, 807-815. https://doi.org/10.1016/j.compscitech.2004.12.032

[13] Georgiadis, S., Gunnion, A.J., Thomson, R.S. and Cartwright, B.K. (2008) Bird-Strike Simulation for Certification of the Boeing 787 Composite Moveable Trailing Edge. *Composite Structures*, **86**, 258-268. https://doi.org/10.1016/j.compstruct.2008.03.025

[14] Guida, M., Marulo, F. and Polito, T. (2009) Design and Testing of a Fiber-Metal-Laminate Bird-Strike-Resistant Leading Edge. *Journal of Aircraft*, **46**, 2121-2129. https://doi.org/10.2514/1.43943

[15] Salehi, H., Ziaei-Rad, S. and Vaziri-Zanjani, M.A. (2010) Bird Impact Effects on Different Types of Aircraft Bubble Windows Using, Numerical and Experimental Methods. *International Journal of Crashworthiness*, **15**, 93-106. https://doi.org/10.1080/13588260903047689

[16] Adams, A., Thorbole, C.K. and Lankarani, H.M. (2010) Scale Modelling of Aircraft Fuselage: An Innovative Approach to Evaluate and Improve Crashworthiness. *International Journal of Crashworthiness*, **15**, 71-82. https://doi.org/10.1080/13588260903047663

[17] Reglero, J.A., Rodríguez-Pérez, M.A., Solórzano, E. and de Saja, J.A. (2011) Aluminium Foams as a Filler for Leading Edges: Improvements in the Mechanical Behaviour under Bird Strike Impact Tests. *Materials & Design*, **32**, 907-910. https://doi.org/10.1016/j.matdes.2010.08.035

[18] Diamantakos, I., Fotopoulos, K., Jamin, M., Eberhardt, A. and Lampeas, G. (2017) Investigation of Bird Strike Events on Composite Wing Panels. *Fatigue & Fracture of Engineering Materials & Structures*, **40**, 1538-1550. https://doi.org/10.1111/ffe.12644

[19] Liu, J., Li, Y.L., Yu, X.C., Gao, X.S. and Liu, Z.X. (2018) Design of Aircraft Structures against Threat of Bird Strikes. *Chinese Journal of Aeronautics*, **31**, 1535-1558. https://doi.org/10.1016/j.cja.2018.05.004

[20] Orlando, S., Marulo, F., Guida, M. and Timbrato, F. (2018) Bird Strike Assessment for a Composite Wing Flap. *International Journal of Crashworthiness*, **23**, 219-235. https://doi.org/10.1080/13588265.2017.1342521

[21] Shen, Y., Jiang, B. and Li, Y. (2019) Scale Effect on Impact Performance of Unidirectional Glass Fiber Reinforced Epoxy Composite Laminates. *Materials*, **12**, 1319. https://doi.org/10.3390/ma12081319

[22] Zhou, Y.D., Sun, Y.C. and Huang, T.L. (2019) SPH-FEM Design of Laminated Plies under Bird-Strike Impact. *Aerospace*, **6**, 112. https://doi.org/10.3390/aerospace6100112

[23] Zhou, Y.D., Sun, Y.C. and Huang, T.L. (2020) Bird-Strike Resistance of Composite Laminates with Different Materials. *Materials*, **13**, 129. https://doi.org/10.3390/ma13010129

[24] Basavanna, R., Raja, S. and Siddappa, K. (2018) High Speed Impact Damage Prediction Using the Smart Materials. *ICMAMS* 2018 *Conference*, Torino, 17-20 June 2018, 91 p. http://www.mul2.polito.it/icmams2018/images/Proceedings/ICMAMS2018_PROCEEDINGS.pdf

[25] Basavanna, R., Raja, S. and Karisiddappa (2020) Low Velocity Impact Response on GFRP and GF-SMP Panels in Structural and High Frequency Bands. *Advances in Aerospace Science and Technology*, **5**, 58-70. https://doi.org/10.4236/aast.2020.52004

[26] Talhah, I. and Hampson, P. (2021) Smooth Particle Hydrodynamics Bird-Strike Analysis on Aircraft Wing Leading Edge. *International Journal of Multiphysics*, **15**, 291-309. https://doi.org/10.21152/1750-9548.15.3.291

[27] Liu, D. and Raju, B. (1998) Size Effect on Impact Response of Composite Laminates. *International Journal of Impact Engineering*, **21**, 837-854. https://doi.org/10.1016/S0734-743X(98)00036-0

[28] Yang, F.J. and Cantwell, W.J. (2010) Impact Damage Initiation in Composite Materials. *Composites Science and Technology*, **70**, 336-342. https://doi.org/10.1016/j.compscitech.2009.11.004

[29] Abisset, E., Daghia, F., Sun, X.C., Wisnom, M.R. and Hallett, S.R. (2016) Interaction of Inter and Intralaminar Damage in Scaled Quasi-Static Indentation Tests: Part 1—Experiments. *Composite Structures*, **136**, 712-726. https://doi.org/10.1016/j.compstruct.2015.09.061

[30] Shen, Y.O., Jiang, B. and Li, Y. (2017) Low Velocity Impact Response and Energy Absorption Behaviour on Glass Fibre Reinforced Epoxy Composites. *Science China Technological Science*, **60**, 1339-1346. https://doi.org/10.1007/s11431-016-9061-3

[31] Antony, G.J.M., Aruna, S.T. and Raja, S. (2018) Enhanced Mechanical Properties of Acrylate-Based Shape Memory Polymer Using Grafted Hydroxyapatite. *Journal of Polymer Research*, **25**, Article No. 120. https://doi.org/10.1007/s10965-018-1511-9

[32] Shepherd, C.J., *et al.* (2009) The Dynamic Behaviour of Ballistic Gelatine. *AIP Conference Proceedings*, **1195**, 1399-1402.

[33] Cronin, D.S. (2011) Ballistic Gelatine Characterization and Constitutive Modelling. In: Proulx, T., Ed., *Conference on Experimental and Applied Mechanics*, Springer Science & Business Media, Berlin, 51-55. https://doi.org/10.1007/978-1-4614-0216-9_7

[34] Aslam, M.A., Rayhan, S.B., Zhang, K. and Wang, J.Y. (2020) Ballistic Gelatine Lagrange

Mooney-Rivlin Material Model as a Substitute of Bird in Finite Element Bird Strike Case Studies. *Latin American Journal of Solids and Structures*, **17**, e298. https://doi.org/10.1590/1679-78256215

[35] Masaki, C., Suzuki, K. and Watanabe, Y. (2018) Visualization of High-Speed Impact of Projectile in Granular Sheet with Destructive Collision of Particles. *Journal of Flow Control, Measurement & Visualization*, **6**, 136-151. https://doi.org/10.4236/jfcmv.2018.63012