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Design and testing of a composite bird strike resistant leading edge

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ABSTRACT
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Nationaal Lucht- en Ruimtevaartlaboratorium

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Design and testing of a composite bird strike resistant leading edge

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Summary

The paper describes several innovative designs for a bird strike resistant, composite leading edge for a Horizontal Tail Plane of a transport aircraft. These designs are based on a novel application of composite materials with high energy-absorbing characteristics: the tensor-skin concept. This paper describes the development of this energy-absorbing concept and its application to an impact resistant aircraft structure. The design philosophy, the fabrication and test of the first prototypes are discussed. Three improved leading edge structures with different energy-absorbing tensor concepts were manufactured. Bird-strike tests on these leading edges with a 4 lb synthetic bird at impact velocities around 100 m/s were performed. Finite element models were developed to simulate the unfolding of the tensor ply. Before each test was carried out, pre-test bird impact simulations were used to determine the impact test parameters and to predict the dynamic behaviour and failure mode of the structure.

Contents

(14 pages in total)

List of acronyms

CRAHVI	Crashworthiness of Aircraft for High Velocity Impact
CEAT	Centre d'Essais Aéronautique de Toulouse
DLR	Deutsche Zentrum für Luft- und Raumfahrt
EoS	Equation of State
FE	Finite Element
GARTEUR	Group for Aeronautical Research and Technology in EURope
HPPE	High Performance Poly Ethylene
HTP	Horizontal Tail Plane
LE	Leading Edge
PE	Poly Ethylene
SPH	Smooth Particle Hydrodynamics
UHMW-PE	Ultra High Molucar Weight – Poly Ethylene

1 Introduction

Within the framework of the European Union's Fifth Framework project CRAHVI (Crashworthiness of Aircraft for High Velocity Impact), the National Aerospace Laboratory NLR, the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the Centre d'Essais Aéronautique de Toulouse (CEAT) and the University of Patras investigated three innovative designs for a composite Leading Edge (LE) for a Horizontal Tail Plane (HTP). These designs were based on a novel application of composites with high energy-absorbing characteristics. Three Leading Edge structures were designed and manufactured by NLR. The composite LE structures and the soft body synthetic bird were modelled on the basis of FE methods, and the high velocity bird impact event was simulated by DLR and the University of Patras, using the PAM-CRASH code. Bird strike tests with a 4 lb synthetic bird were performed by CEAT, to validate the designs and models. Pre-test simulations were carried out, to determine the critical impact velocity for the structures, to be used during the tests.

2 The energy-absorbing skin concept

A leading edge is the front edge of a wing, a horizontal stabiliser, or a vertical stabiliser, and has several important functions during flight:

- Aerodynamic function
- Offering space to high lift devices like flaps, slots, and slats
- Offering space to ice protection systems.
- Protecting the torsion box and control devices.

The leading edge described in this paper was designed for a composite horizontal stabiliser. The leading edge is vulnerable with respect to bird strike. However, it has to protect the wing torsion box from significant damage, so that the aircraft can land safely [1].

Design requirements for the HTP being considered, state that the bird strike load acting anywhere on the leading edge must not exceed 200 kN to avoid excessive loads on the stabiliser brackets. The bird impact event, of a fast flying aircraft hitting a quasi-stationary bird, can be considered similar to the case of a fast flying bird hitting a stationary aircraft. Then, prior to a bird strike, the bird possesses a certain amount of kinetic energy, depending on the bird speed and mass. To prevent exceeding the maximum load, it is important that the leading edge skin fails at or below a load of 200 kN, to ensure that a load build-up is no longer possible, while deflecting or absorbing the remaining bird kinetic energy. If the skin fails and the wing or stabiliser is made of composite material, the bird approaches the brittle composite front spar, which is not usually capable of absorbing energy. Therefore, a solution in which the complete bird kinetic energy can be absorbed by the leading edge alone, is required. This is not easy, as the available space within a leading edge is relatively small, while transversely loaded composite structures have poor energy absorption capabilities. Consequently, a leading edge containing a highly efficient composite energy absorbing structure had to be developed.

A concept, which was developed for energy absorption of a transversely loaded structure, that can be applied within a limited space, is the “tensor skin” concept. This concept was initially developed by NLR to increase the survivability of helicopter crashes on water surfaces [2], [3]. In case of a helicopter crash on a land surface, the spars in the subfloor section, the landing gear and the occupant seats are designed to absorb crash energy. However, in case of a crash on water, these components will not absorb a significant amount of energy, while the brittle composite skin is expected to fail. By replacing this brittle composite skin by a polyethylene (PE) tensor skin with loops for skin elongation, the bottom skin is not expected to fracture and break away at impact. The tensor loops unfold, allowing the skin to form a membrane, which induces a vertical crash load component on the attached spars.

The core of the tensor skin is formed by a laminate, made of polyethylene fibers in an epoxy matrix. Dyneema is a high performance polyethylene fibre (HPPE), invented by DSM [4]. During production, polyethylene with an ultra high molecular weight (UHMW-PE) is used as the starting material. In the production process of Dyneema, the molecules are disentangled to create filaments; the fibre is drawn and a high level of macromolecular orientation is acquired. This results in a fibre with high specific strength and modulus, as shown in figure 1. Dyneema fibre fabrics are suitable for impregnation by epoxy resin and for laminating within a conventional composite laminate [5]. The limited adhesion of the PE fibers to the epoxy contribute to the successful unfolding mechanism of the tensor skin concept.

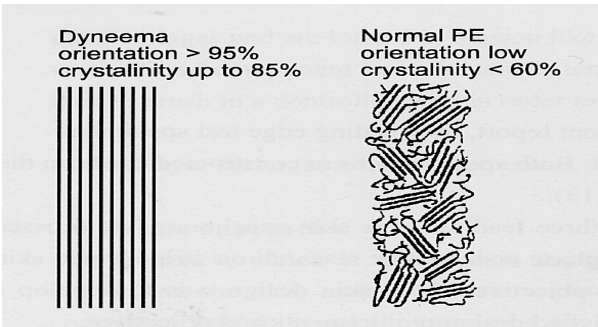


Fig. 1 Dyneema and normal PE [4]

Applying the tensor skin concept in the composite horizontal stabiliser implies, that the leading edge skin laminate contains the unfolding tensor loops of Dyneema fabric, and that the ribs function as energy absorbers. Figure 2 shows a 2-dimensional view of the bird strike process on a leading edge and the structure of the leading edge skin, when the tensor skin concept is applied.

The composite skin laminate consists of multiple plies, of which the load carrying plies transfer the normal operational aerodynamic load to the ribs. These plies therefore provide the usual leading edge skin stiffness. The second group of plies, the tensor plies, contain folded loops between the ribs, which are to unfold when a relative high lateral load is applied to the skin. Under normal conditions, these plies are present without any function. In case of a relative high lateral load, like the load at bird impact, all plies except the tensor plies fail. The unfolded plies act comparably to plastic hinges and are loaded in tension like a membrane. When completely unfolded, the vertical load component from the tensile tensor skin is loading the ribs in compression, which are then crushed in a controlled way in order to absorb sufficient kinetic energy of the bird.

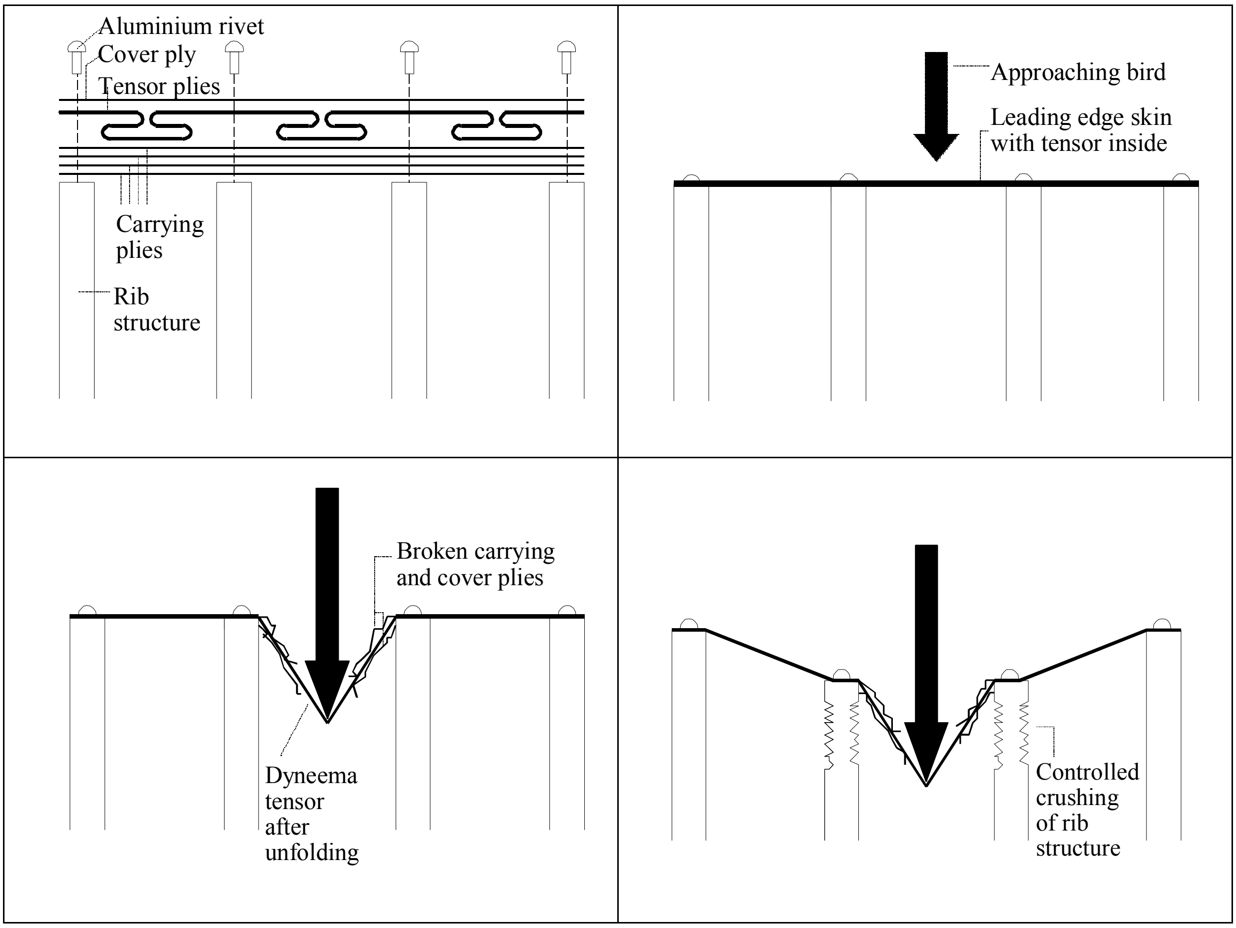


Fig. 2 Energy absorption process in tensor skin

3 Design procedure

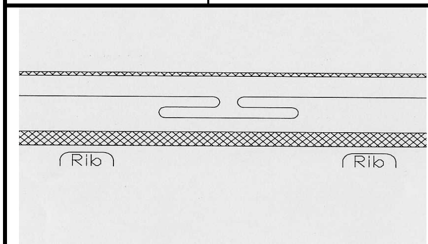
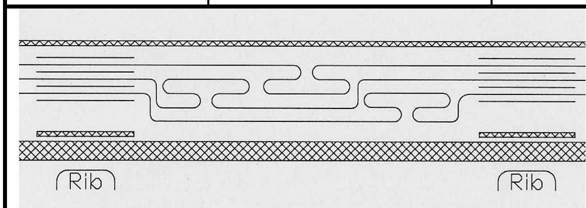
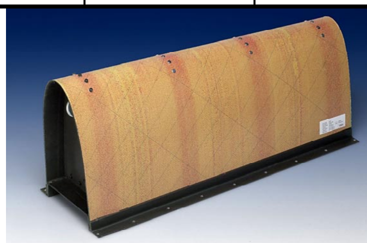
Analysing the leading edge design problem, several design variables were found to be important, taking into account geometric boundary conditions like the predetermined leading edge contour. The most important design variables are rib pitch, maximum unfolding depth, loop geometry, skin to rib attachment, fibre and matrix material, skin stiffness and strength properties, laminate lay-up and laminate thickness. Important design aspects are listed here.

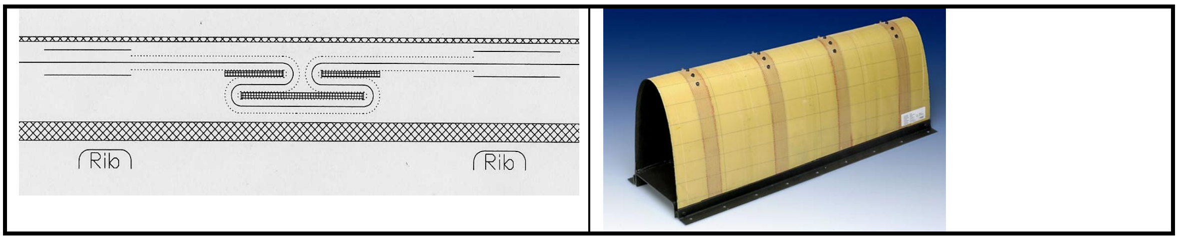
- The boundary conditions limit the maximum load working laterally on the leading edge skin to 200 kN. When, during bird strike, a bird hits the leading edge between two ribs, the vertical load to each rib equals a maximum value of 100 kN after the tensor loop is unfolded.
- The unfolding depth is a function of the tensor elongation (provided with a certain loop geometry) and the rib pitch. Since the total kinetic bird energy has to be absorbed within the leading edge volume, there are limitations to the unfolding depth. Both energy absorption displacement and unfolding depth must fit within the available leading edge space, determined by the predetermined leading edge contour.
- Tensor strength and the strengths of the carrying and cover plies depend on the lay-ups of the subsequent laminates i.e. the numbers of plies, fibre orientations and stacking sequences.
- The skin to rib attachment is realised with fasteners in conformance with common aviation types of attachment.
- The total leading edge weight is directly related to the type and amount of material that is used. All above-mentioned items are therefore of influence on the weight. It is desirable to increase the rib pitch in the composite design to attempt to use a lower total rib weight and a lower number of fasteners.

4 The Leading Edge specimens for bird-strike tests

Based on the static crush tests on 1-dimensional tensor loop specimens and several leading edge specimens, three leading edge skin designs were selected. To demonstrate the new innovative skin design, a bird mass of four pounds (equal to 1.82 kg) was initially maintained in the design process and the pre-test simulations. Because the maximum load acting laterally on the skin was set to 200 kN, there is no difference in tensor load level in case of an impact of a 4-pound bird or an 8-pound bird (American bird strike requirements maintain a bird mass of 8 pounds on the HTP). To study the energy-absorbing capabilities of the composite skin laminate in impact, aluminium ribs and a steel front spar were used to minimise rib deformations. The lay-up of the skin laminates, a schematic cross section of the tensor and photographs of the specimens is presented in table 1 for the three LE structures.

Table 1 Design and lay-up of three Leading Edges for bird impact tests

Specimen #	Sub-laminate	Lay-up	Laminate ID	Remarks
NLR-LE-1 **rib-pitch: 160 mm** **length: 550 mm**	Dyneema SK65 fabric with AF163-2U	$[0]_4$	Tensor	Style 351 (Cramer) 180 gr/m^2
	Carbon/Aramid hybrid prepreg	[45, 0, 90, 0, 45]	Carrying	73210 (Hexcel) 210 gr/m^2
	Glass/epoxy prepreg	[45]	Cover	07781 (Hexcel) fiber: 75 $^1/_0$, 303 gr/m^2
	Aramid/epoxy prepreg	$[45]_2$	Protection-strip (40 mm)	90285 (Hexcel) fiber: K49, 170 gr/m^2
				
NLR-LE-2 **rib-pitch: 230 mm** **length: 850 mm**	Dyneema SK65 fabric with AF163-2U	$\{[0]_2\}_3$	Tensor	
	Carbon/Aramid hybrid prepreg	[45, 0, 90, 0, 45]	Carrying	
	Aramid/epoxy prepreg	[45]	Cover	
	Aramid/epoxy prepreg	$[45]_2$	Protection-strip (40 mm)	
				
NLR-LE-3 **rib-pitch: 230 mm** **length: 850 mm**	Dyneema SK65 fabric met AF163-2K	$[0_3,45,0_3]$	Tensor	**Note:** No adhesive film between the 3 tensor sub-laminates.
	Carbon/Aramid hybrid prepreg	[45, 0, 90, 0, 45]	Carrying	
	Aramid/epoxy prepreg	[0]	Cover	
	Aramid/epoxy prepreg	$[45]_2$	Protection-strip (40 mm)	



The high velocity impact tests were performed by CEAT with a 4 pound substitute bird (1.82 kg) at an impact speed which was determined by pre-test simulations. These simulations were performed by DLR and the University of Patras, using the PAM-CRASH code.

5 Simulation of ‘bird’ impact on LE concept structures

In this section a finite element (FE) model capable of predicting the tensor unfolding concept is described, which may be used as a design tool to predict failure modes and energy absorbed during impact by an artificial bird. The FE model is confined to the LE shell between the two central ribs, with the LE shell laminate fixed at the ribs. This geometrical simplification is justified by the test structures which had very stiff ribs with the LE shell bonded and riveted to the ribs, so that on loading all significant deformations took place in the LE shell. Figure 3 shows the FE model developed for

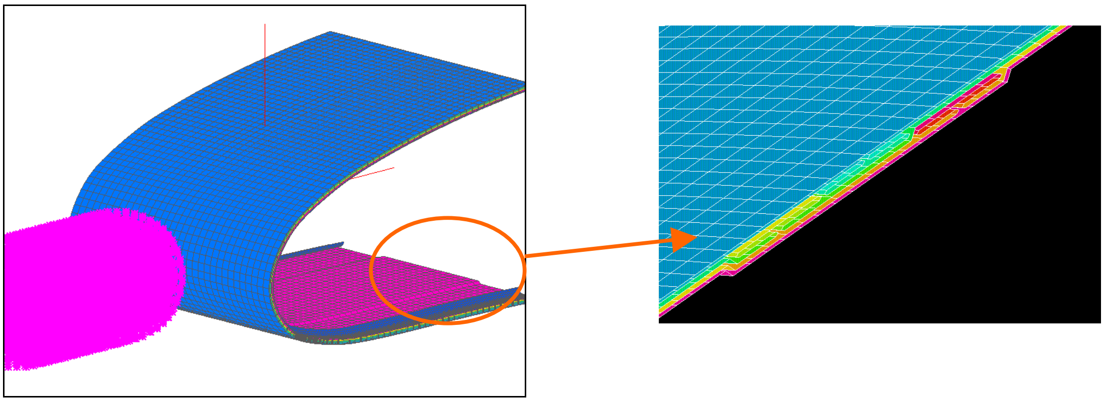


Fig. 3 FE model of NLR-LE-2 with SPH bird and tensor geometry (inset)

NLR-LE-2 with an inset figure showing details of the laminate stacked shell model containing cover laminate, tensor laminate with three embedded loops, and carrying laminate. These laminates are each modelled in PAM-CRASH [6] as single layered shell elements, connected through their thickness by tied contacts which are shell-to-shell sliding interfaces with failure. They allow a through-thickness tension/shear fracture condition to be defined so that when an appropriate multiaxial failure value is reached the interface fails at that element and the adjacent shells may separate. This is a convenient method of allowing separation between the cover, tensor and carrying laminates, and for modelling separation within neighbouring elements in the folded tensor laminate.

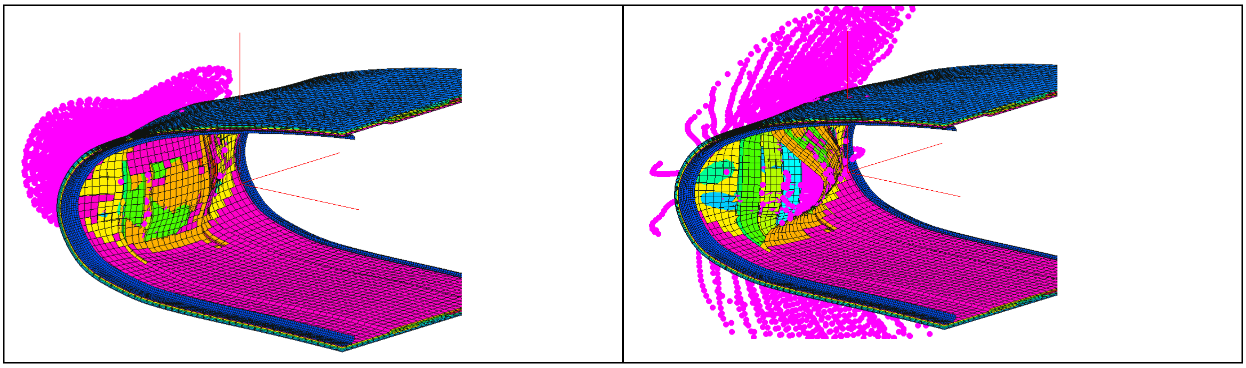


Fig. 4 Bird strike simulation of NLR-LE-2 with 1.82 kg bird at 100 m/s

PAM-CRASH currently has several layered shell elements and ply types available for composites. The best choice depends on the composite material behaviour, available data for different ply models and on user experience. For the aramid cover laminate and carbon/aramid fabric carrying laminate a layered composite shell is used, together with the bi-phase fabric ply model, which models ply damage prior to failure and allows for the re-orientation of fibres under large in-plane deformations. The tensor laminate was modelled as a layered shell with both bi-phase composite plies and elastic/plastic plies. In this 'hybrid' model it is possible to simulate the observed ductility in the Dyneema/epoxy laminate as measured in [7], allowing it to unfold without immediate fracture. Parameter studies on unfolding of tensor strips in 3-point bending were then used to optimise the model parameters by comparing NLR test data with FE simulations. This showed that the interfacial contact tension/shear strengths had a strong influence on tensor unfolding and failure. If these are too low the tensor unfolds very easily, but too high values prevent unfolding and lead to a laminate fracture. The tensor design concept in LE shells was demonstrated at NLR by a series of quasi-static loading tests up to failure on the LE structures by a rigid cylindrical indenter applied at the LE nose tip. These tests were simulated with the FE model and showed cover and carrying laminate failures at the indenter, with unfolding of the tensor and finally tensor failure at large deflections, typically 120 –200 mm. With the ply materials and contact strength failure parameters chosen in the model there was satisfactory quantitative agreement between measured and predicted load-deflection curves and energy absorbed.

Soft bodies such as gelatine are used by the aircraft industry as 'substitute birds' and are observed to flow over the structure on impact, spreading the impact load over a significant surface area which limits local impact damage. The two main problems in simulating the bird behaviour are defining the materials model for the soft material, and overcoming the high mesh distortion which causes numerical problems with the time step in explicit codes. The approach adopted [8] is to use the smooth particle hydrodynamic (SPH) method to model the flow and large deformations in the impactor, in which the FE mesh for the impactor is replaced by discrete interacting particles. This is combined with a materials law for a 'hydrodynamic solid' in which the pressure–volume relation is modelled by an equation of state (EoS). In a GARTEUR group dedicate to the subject [9], literature data from pressure pulses measured during gelatine impact on rigid plates were used to calibrate material parameters for a gelatine material EoS for use with the SPH method.

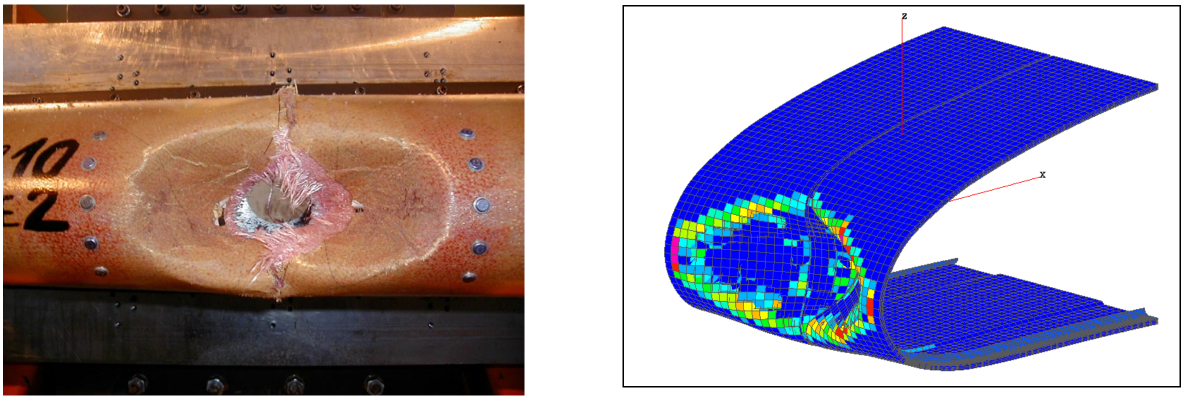


Fig. 5 Impact damage in LE-2 after 1.82 kg bird impact at 100 m/s

The SPH bird model was then used with the validated FE model to simulate bird strike from a synthetic gelatine bird on the LE structure, to provide information on the extent of structural damage in the bird impact test programme and to demonstrate further the validity of the LE model. Figure 4 shows typical simulation results for NLR-LE-2 impacted normally midway between the ribs by a 1.82 kg 'synthetic bird' at 100 m/s impact velocity. This represents a bird kinetic energy of 9.1 kJ at a typical landing speed of a commuter aircraft when bird impacts are likely and where the LE is required to absorb bird energy to prevent damage to the wing spar. There is extensive damage and fracture in the cover and carry plies with unfolding of the tensor. The SPH bird model flows in a realistic way over the LE structure, with part of the bird trapped in the tensor ply. The tensor ply is activated and unfolds to absorb the kinetic energy of the penetrating parts of the bird. Simulation results compare well with the damaged structure after the CEAT test with a 1.82 kg synthetic bird at 100 m/s as shown in figure 5.

The simulation predicts that bird impacts of about 100 m/s are survivable with a damaged Leading Edge which has absorbed sufficient bird energy to prevent spar damage. From the point of view of the bird test programme on the composite LE structures, it would appear that 100 m/s is a critical velocity at which observable structural damage takes place.

6 Bird strike tests performed by CEAT

CEAT carried out bird strike tests on the three Leading Edge specimens with a substitute bird of 4 pounds (1.82 kg). The test set-up is shown in figure 6.

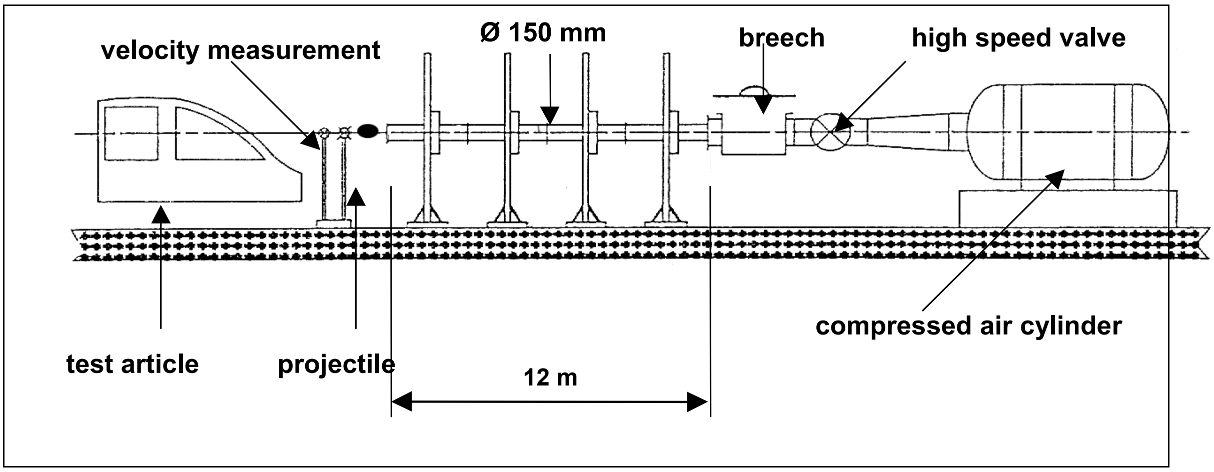


Fig. 6 CEAT's test set-up for high velocity impact tests

The specimens were impacted at the centreline, between the third and fourth rib, at the apex of the specimen. The impact velocities were: NLR-LE-1: 80 m/s, NLR-LE-2: 100 m/s, NLR-LE-3: 100 m/s. The specimens were instrumented with two strain gauges "rosettes" and 6 load cells. The impact event was recorded, at a ¾ front view, with a high-speed video camera (2000 frames/s). The results for NLR-LE-3 are shown in figure 7. For this LE structure the substitute bird does not penetrate the skin at 100 m/s. The penetration has been stopped by the tensor skin unfolding process which verifies the design concept and agrees with FE simulation results.

7 Conclusions

NLR manufactured three improved leading edge structures with different energy-absorbing tensor concepts. Bird-strike tests on these leading edges with a 4 lb synthetic bird at impact velocities from 80-100 m/s were successfully performed by CEAT.

FE models were developed by the DLR and University of Patras to simulate the unfolding of the tensor ply. Before each test was carried out, pre-test bird impact simulations were used to determine the impact test parameters and to predict the dynamic behaviour and failure mode of the structure.
For specimens NLR-LE-2 and NLR-LE-3, the tensor skin unfolding process stopped the penetration of the bird. The contact force diagrams show that the leading edge forces during impact do not cross the design limit of 200 kN. The forces on the ribs are smaller than 100 kN-per-rib limit. These results demonstrate the satisfactory tensor laminate behaviour and global skin behaviour of the NLR-LE-design concept.

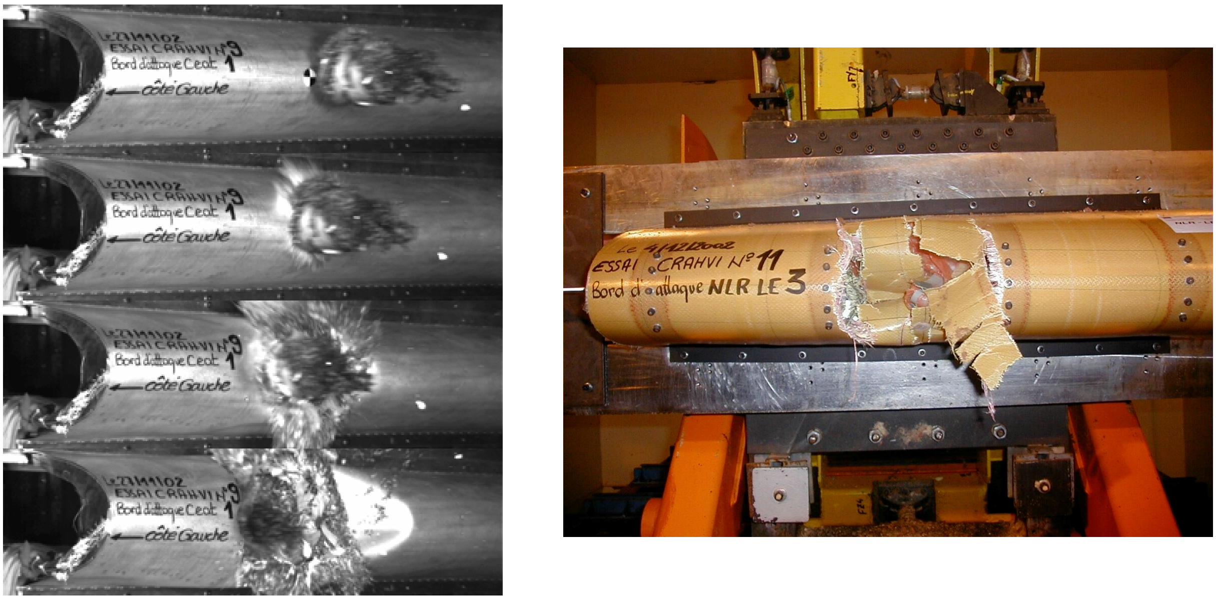


Fig. 7 Bird strike test on NLR-LE-3

8 Acknowledgements

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