Final Report Summary - BIRDSTRIKE (Investigation of Bird Strike criteria for Natural Laminar Flow wings)

Executive Summary:
The BirdStrike project aimed to develop a validated bird-strike numerical analysis tool, which would enable the Smart Fixed Wing Aircraft programme partners to simulate bird impact on a composite leading edge for a Natural Laminar Flow wing. This was achieved by setting up a combined program of numerical methodologies and models development and experimental tests to be used for numerical models validation. The main scientific and technical work performed in the frame of the project included:

• Development of a Finite Element numerical methodology based on the stacked-shell approach for the efficient simulation of bird-strike incidents on composite panels.
• Manufacturing of flat un- stiffened and stiffened composite panels that include supporting stringers, spar caps or other structural features.
• Design and analysis of a supporting frame for bird-strike impact tests on composite panels.
• Bird-strike tests and NDI analysis on composite panels.
• Development of FE models of the un-stiffened and stiffened panels bird-strike tests.
• Validation of analyses and numerical models based on experimental results and measurements.
• Development of a numerical model to predict the extent of damage in a representative Composite LE geometry.

Project Context and Objectives:
The work has been split in six clearly defined Work Packages (WP), each one dealing with a separate topic of the research work. More specifically:

In WP1, which has been the starting point of the project, all preparatory work required for the following work packages was performed. In cooperation with the SFWA partners, the structural concepts applied on the LE design, the material system to be used, the structural details of flat un-stiffened and stiffened panels, as well as complex monolithic CFRP leading edge structures have been defined. The basic structural details of these structures have been defined during the project negotiation phase. Furthermore, manufacturing, testing and certification issues was considered during the structural panels definition.

In the frame of WP2, panels of increasing complexity defined in WP1, have been manufactured in order to be used in the bird strike impact experimental testing programme of WP3. Test specimens designed in WP1 comprised simple flat specimens from the selected CFRP material system, as well as, complex monolithic CFRP panels with co-cured bonded stiffening elements, such as stringers, spar caps and stiffening rib feet. The manufacturing procedures followed the guidelines and procedures of SFWA partners and the WP1 preliminary work.

In the frame of WP3, bird-strike impact tests were performed on flat un-stiffened and stiffened composite panels. The structural response of the test panels was acquired utilizing load cells and high speed cameras, in order to collect all data for the thorough validation of the numerical simulations performed in the frame of WP4. Moreover, the laser shearography method was applied at the impacted panels for the determination of the developed damage due to bird strike. The bird-strike tests on a full-scale composite Leading Edge panel, initially planned to be performed in POLIMI facilities, have been finally decided in agreement with Airbus to be performed in SAAB’s establishments using real birds instead of surrogate birds. POLIMI laboratory cannot perform tests with real birds, but only with surrogate ones, due to hygiene and certification issues. An additional objective of WP3 has been the design, analysis and manufacturing of the experimental set-up, including supporting frames, suitable for gripping the composite panels during the bird strike impact tests. The special features of the panels, the ability of achieving different impact angles and the load-carrying capacity have been key factors affecting the design of the supporting frame. The analysis of the frame was based on structural FE analysis taking into account loads developed during the bird impact tests.

WP4 dealt with the numerical simulation of bird strike incidents. Proper material models have been applied in structural dynamic FE models for simulation of bird impact on flat panels and leading edge components. A building block approach was adopted, including the validation of numerical analysis at each step, based on the experimental results obtained in WP3. Starting from simple un-stiffened flat plates, structures of increased complexity have been analyzed towards the final objective of a complex monolithic CFRP leading edge section. All simulations involved impact response with damage initiation and growth, thus the
results of numerical analyses comprised prediction of the structural response and the evolution of any
damage mode of failure (e.g. delamination, fracture etc.). A stepwise approach has also been applied
concerning the complexity of the numerical simulation methodology used. Starting from modelling each
composite laminate with a single shell, which may simulate the global panel’s behaviour, but is
inappropriate for delamination damage prediction, to the stacked-shell approach, which is able simulate
the delamination damage evolution. For FE model development and numerical analyses LS-DYNA explicit
commercial explicit FE code has been used.

WP5 dealt with the integration of the results of all previous WPs, for the development and delivery of a
numerical tool capable to predict the structural response in a composite NLF leading edge structure, as
well as the extent of damage evolution, due to bird strike impact. This tool basically comprised a validated
numerical model of the structures of varying complexity that can be used by the SFWA partners during the
design and certification phases of an aircraft with NFL wings.

Finally, all the management, exploitation and dissemination activities of the present project have been
included in WP6.

Project Results:
Following the WP structure of the project initially the composite structures to be simulated, manufactured
and tested in the frame of BirdStrike project have been defined. Three different types of structural
components were planned to be manufactured, tested and simulated in the frame of BirdStrike project:
• flat un-stiffened panels
• flat stiffened panels
• full scale leading edge (LE) structure (this specific test item has not been manufactured in the frame of
BirdStrike project)

The defined flat un-stiffened and stiffened panels have been manufactured in order to be used at the bird-
strike impact tests in the frame of WP3. Test specimens were made of M21E/IMA UD composite material
and comprised simple flat specimens, as well as, complex monolithic composite panels with co-cured
bonded stiffening elements, such as stringers, spar-caps and stiffening rib feet. One large problem faced
by the BirdStrike project consortium, related to panels manufacturing, was the acquisition of M21E/IMA
material. The specific material is produced by Hexcel and is only available for Airbus and their
collaborating partners. Therefore, special non-disclosure agreements had to be signed following Airbus
agreement, so that BirdStrike partner CI could have access on the specific material. Even so, CI had
serious problems to acquire the material by Hexcel. It was, quite lately, revealed that the problem was that
Hexcel does not provide material to customers ordering material of less than a minimum budget. This
issue of material acquisition, was the main cause of project delays and extensions. Finally, a solution has
been found: SAAB purchased the required material from Hexcel together with other orders and then CI
bought the material from SAAB.

After material acquisition, several trials had to be performed so that the process parameters to be tuned,
as limited information has been available for the M21E/IMA UD composite material. Then, the flat un-
stiffened panels have been manufactured. The composite material layers have been laid up as in the ply-
book described. De-bulk in a vacuum bag has been repetitively applied to obtain a better material
quality. Finally, a solution has been found to extend the life of the material by Hexcel, which is to
perform a special de-bulk process for panels manufactured in quantities higher than a certain threshold.
consolidation of all plies. Composite material curing process took place in CI’s autoclave. After the curing process, the parts have been milled to the desired dimensions.

Consequently, flat stiffened panels have been produced. Due to the existence of multiple stiffening elements a complex mould has been required for the manufacturing of the stiffened panels. The mould consists of CNC-milled aluminium parts designed to take into account the individual process parameters e.g. thermal expansion during the curing process. Using the chosen mould concept for manufacturing the entire specimen could be manufactured in one curing step.

Bird-strike experimental tests have been performed on both stiffened and un-stiffened flat CFRP panels. Moreover, NDT inspections have been performed on the panels before and after the impact tests. More specifically, the CFRP panels have been machined and the necessary holes have been drilled on them. For drilling the panels a special CFRP drill has been used. Due to the existence of ribs at the stiffened panels, a special fixture had to be developed to accurately drill the desired holes. During the drilling process, the surfaces of the drilled areas for both stiffened and un-stiffened panels have been gradually milled from both sides.

A suitable constraint frame for the panels to hold composite panels during bird-strike tests has been designed and manufactured. The geometrical configuration of the frame has been identified to provide the possibility to test both stiffened and un-stiffened panels without introducing any change in the structure. The ability to withstand the stresses due to the impact event has been verified through finite elements numerical simulations. The supporting frame has been designed to properly fit in front of the load cells used during the bird-strike tests for the acquisition of the load magnitudes, thus correctly connecting with the whole structure which passes the loads to the ground. Particular attention has been paid to the way of constraining the panels to the supporting frame. Multiple rows of holes have been drilled on the plates of the frame and on the CFRP panels to be able to apply two different boundary conditions, one considered rigid and another semi-flexible (using Protectelast material).

Three impact tests have been performed on flat un-stiffened panels and two tests have been performed on flat stiffened panels. Bird-strike tests have been performed in the POLIMI bird testing facility. Two un-stiffened and two stiffened panels have been tested with rigid boundary conditions, while one un-stiffened panel has been tested with the semi-flexible boundary condition (using protectelast material). The projectile used was a surrogate bird made of ballistic gel (Permagel) with a weight of 1 kg and cylindrical shape. All the panels have been impacted at their centre. The impact events have been studied and evaluated through videos recorded with high speed cameras and data acquired from load cells. Impact speeds have been identified through the recorded videos.

Different degrees of delamination and failure have been observed during the experimental campaign, depending on the bird impact speed and on the type of the panel. Increase of the impact speed led to increase of loads and developed damages, as expected. Considering un-stiffened panels, it has been observed that the use of Protectelast material in the constraint region (semi-flexible boundary condition) reduced the obtained load values and led to a different failure mechanism (crack of the panel near the impact region). The presence of the Protectelast material is probably the cause of the different shape of the load curve obtained for load cell 3 in the Test #3; the second peak of force could be related to the fully
The impacts against stiffened panels have given higher force values but in Test #4, delamination are also accompanied by the failure of some stiffeners.

A Digital Image Correlation system and a shearography system (Q-800) have been used at the panels before and after the impacts. Analyses of the measurements before the impacts verified that no initial damages exist in the panels. Analyses after the tests have been perform to assess the damages developed in the panels due to the bird-strike events.

The following observations have been made from the application of laser shearography on the impacted un-stiffened and stiffened panels:

- For flat un-stiffened panels, a diffuse damage and a visible crack have been found for the panel used in the test where semi-flexible boundary conditions have been used. For the other 2 panels, delaminations are concentrated on the free edges of the panels.
- In the Test #3, a large crack is visible in the center of the panel while there are no more the large delaminations on the sides, which were present for the previous tests on un-stiffened panels.
- For Test #4, beside the delamination on the edges, larger area defects between the vertical stiffener and at the stiffener itself are visible. On the bottom area again delamination between the stiffener are visible. In the centre some smaller defects are detected. The backside shows beside the large and by eye detectable failures some smaller delamination.
- For Test #5, damages are less than for the previous bird-strike event. A smaller defect at a corner of a vertical stiffener is detected. At the side in the centre a large delamination is visible. Beside the by eye visible defects on the backside a delamination in the centre is detected. On the bottom area the delamination at the side is detected. In the centre area no defect is visible. On the rear side again the centre delamination and a small at the side are detected.

For the numerical simulation of bird-strike incidents on composite structures, the stacked-shell approach has been developed and applied, as a promising alternative to the classical solid and shell elements approach. The stacked shell approach (described as 2.5D approach) is based on First Order Shear Deformation Theory to approximate the behaviour of each discrete sub-laminate of the composite structure. This means that the behaviour of a laminated composite structure is expressed by the behaviour of an interactive set of sub-laminates, each of which exhibits constant through-thickness transverse displacement and shear strains. In this sense, the stacked shell method verges on the behaviour of laminates in a layer-wise manner, enabling a much more accurate determination of interlaminar stresses, compared to FSDT and Classical Laminate Theory single-sub-laminate solutions. The FE modelling procedure, when the tacked-shell approach is followed, involves two basic steps: initially sub-laminates are generated using shell elements, which constitute a fraction or a number of the layers of the composite structure; consequently, contact interfaces representing the matrix inter-layers are generated. The stacked-shell approach and all numerical simulation of bird-strike incidents have been implemented using LS-DYNA commercial explicit FE code.

Before applying the developed stacked-shell approach to dynamic problems, a set of pseudo-static numerical tests has been performed, to investigate and validate the applicability of the stacked-shell approach for the calculation of the elastic response of composite structures. Three well-known cases were selected to demonstrate the predictive capability of the 2.5D Approach:
This investigation has demonstrated that the stacked-shell methodology has been capable of predicting accurately both the in-plane and out-of-plane stress state of laminated composites of high and low slenderness ratios. The predictive capabilities, as far as the through-the-thickness interlaminar stresses distributions are concerned, tend to become excellent as the number of sub-laminates/interfaces increases.

Consequently, FE models for the simulation of flat un-stiffened and stiffened panels bird-strike tests have been developed, based on the stacked-shell approach. Un-stiffened panels have been modelled using four sub-laminates, i.e. four shell elements though-the-thickness. Proper contacts has been defined between each pair of sub-laminates able to simulate contact and delamination. In the respective FE models developed for the case of stiffened panels, panels have been modelled using at least one sub-laminate for every eight layers of composite material.

Results of numerical simulations of bird-strike on flat un-stiffened and stiffened panels have been compared to respective experimental measurements and findings. The purpose of this comparison was to validate the ability of the proposed stacked-shell approach to efficiently and accurately simulate the structural behaviour and damage evolution of composite panels. The basic findings of the numerical simulations and the comparison of simulation results and experimental measurements are:

- Extensive comparison of panels calculated global behaviour (deformed shapes) and the respective high speed camera images, have been performed for all simulated tests. It has been generally observed that the deformed shapes obtained by the FE analyses are in very good agreement to the respective high speed camera images. These observations led to the conclusion that the developed FE models simulate well the behaviour of composite structures under bird-strike impact loadings.
- However, the comparison of load-cell measurements of the reaction forces with the respective magnitudes obtained by the numerical simulations revealed differences in the calculated and acquired load values. In specific cases the maximum value of the total reaction force calculated by the FE analysis was 7-8 times larger than the respective acquired by the load-cells. On the contrary the duration of the first load pulse calculated by FE was about 5 times shorter than the respective experimentally measured. Studying the impact phenomenon as recorded by a high speed camera, it was found that the time required for the bird to collapse on the panel is quite close to the phenomenon duration as calculated by numerical analysis and quite shorter than the times recorded by the load-cells. Differences between load cell measurements and the respective FE model calculations may also be due to the global frame holding the impacted panel and the gripping frame via the load-cells. At the numerical simulations this frame has been considered rigid, while in reality its finite rigidity might effect load-cell measurements during the highly dynamic phenomenon of bird-strike.
- Delamination predictions for the high impact energy tests (e.g. test #4 on stiffened panel with impact speed of 175 m/s) are in good agreement with the respected experimental findings. However, at cases of lower impact energies (e.g. test #1 on un-stiffened panel with impact speed of 137 m/s) the predicted delamination is more expensive than the one observed at the experiments. This may be due to the fact that interlaminar strengths calculated by static DCB and ENF tests have been used in the simulation models, while during bird-strike tests high strain rates are developed at which interlaminar strengths might be quite
Finally, it is concluded that the numerical models developed based on the stacked-shell approach are efficiently simulating the composite structures behaviour. Some overestimation of the delamination is observed, that might be due to the static interlaminar material strengths used.

In the frame of WP5 the full Leading Edge FE model using shell elements developed by POLIMI has been the baseline for the more sophisticated stacked-shell approaches. The single-shell elements model is modified in the critical area around the impact spot to efficiently simulate composite material delamination. Proper boundary conditions have been applied at the edges of the stacked-shell and single-shell areas. Several bird impact locations have been considered and analyzed. The bird-strike impact conditions can be easily adjusted modifying the bird SPH model initial position and velocity, to parametrically study the bird-strike phenomenon. Using the developed numerical tool the LE structure behaviour and the evolution of damage in the composite material have been calculated for several characteristic bird-strike cases. For the case studied, predicted delaminations have been limited at the impact area, where no other significant failure type has been identified in the composite material. Unfortunately, no experimental results have been available that could be used for validation of the developed numerical tool validation.

Potential Impact:
BirdStrike project results will contribute to the objectives of reduced fuel burn and emissions reduction, by the application of Natural Laminar Flow applied to a Short Range Aircraft (SRA) concept. The introduction of a laminar wing section on the aircraft and the absence of leading edge slats results in a geometry that is outside of the range of validation for existing numerical models and bird strike simulation. Research performed and numerical simulation tools developed in the frame of the current project will close the gaps in knowledge that relates to this scenario. Developed numerical models validated using experimental data acquired by the test programme performed will be a useful tool that may be applied within the SRA design process.

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