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Final Report

Post-test Simulation of Birdstrike against Commuter Composite/Metal Hybrid Wing Leading Edge using SPH bird model

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**CRAHVI – European Partners**

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1 Introduction

In sub-task 2.2 of the European Union research Programme “CRAHVI”, the University of Limerick (ULIM) is to perform simulations of birdstrike against structures representative of the leading edge of a commuter aircraft. The skin of these structures is made from a metal/composite hybrid material (GLARE). The inputs to this task were as follows:

- Pre-test report on birdstrike against GLARE (D2.2.4 [1])
- Experimental Strain and Load Results provided by CEAT
- Video Sequences of Bird Strike Tests provided by CEAT
- Experimental Test Report D5.3.2 [2]

In this report the pre-test simulations [1] are compared with the tests carried out at CEAT [2]. From this comparison, attempts are made to improve the behaviour of the models with respect to the experiment. Additionally the model is extended to include details of the loading frame to allow more quantitative comparisons between test and simulation.

2 LE Impact Response - Comparison Between Experiment and Pre-test Simulation

Before presenting the work of the post-test simulations, the pre-test simulations are compared with the experiments on the GLARE leading edge structures carried out at CEAT [2]. As will be detailed in Section 3.1, the strain gauge results on the GLARE LE tests had limited value because most of the gauges disconnected upon impact. However, the load results were of good quality, but to extract this information from the model considerable extensions to the model were needed and this forms the work of the post-test simulations in Section 3.3. Hence, the only information available from the pre-test simulations for comparison with the test was the deformed shape and rivet failure locations. Section 2.1 and 2.2 present these comparisons for both the FML3 and FML5 lay-ups respectively.

2.1 FML3 Skin (A/0/90/A/0/90/A/90/0/A)

The shot sequence for the first 2 ms of impact for the FML3 skin test and simulation is shown in figure 2.1. When generating these images care was taken to ensure that the time when both the experimental and simulation shot sequences started (i.e. the time = 0 point) was just as the bird impacted the LE structure. The experimental sequence was taken from the test video provided by CEAT while the simulation sequence was taken from the ULIM FML3_Law1_Lms model in D2.2.4 [1] (see table 4.1 in [1]). The FML3_Law1_Lms model was chosen here over other rivet failure law models in D2.2.4 [1] because this rivet failure law was also implemented in the FML5 skin (in the pre-test simulations [1]) and so direct comparisons between these lay-ups can be made. The law assumes a rivet failure criterion from [3] but fails the rivet gradually over a period of 1 ms, which allows the absorption of some energy during failure (the assumption being that the riveted materials (skin and ribs) may absorb some energy during rivet failure that would not be accounted for in the tests on rivets in rigid fixtures in [3]).
Figure 2.1 Shot sequence comparison between experiment and pre-test simulation for FML3 (0 – 2 ms)
As can be seen in figure 2.1, the general behaviour of the LE model and SPH bird is in good agreement with the experiment. The deformation behaviour of the SPH bird appears to be in excellent agreement with the video stills, with the flow around the structure and break-up into debris particles well modelled. Considering that when the pre-test simulations were performed, no previous bird strike test results on this leading edge material were available to compare with, and considering the lack of input data on the glass layers in the FML material, and the rivets in this structure, the result in Fig. 2.1 was considered a very positive one.

However, it is clear that there is more deformation occurring in the experiment from approximately $t = 1$ ms onwards. Figure 2.2 shows the same comparison as figure 2.1 but over a later time duration ($t = 3$ ms to $t = 9.5$ ms). In this case, some of the simulation images have the SPH bird removed for clarity. Again, it is clear that there is less deformation in the simulation. It is interesting to note that “spring back” starts in the simulation at approximately 4.5 ms whereas this did not start occurring in the experiment until approximately 7.5 ms. In addition there appears to be more spring back in the model than the experiment. A possible reason for this discrepancy is that plasticity is ignored in the model due to lack of availability of the necessary model input parameters. If such parameters become available, they will be incorporated into the model and will be reported on in a future publication.

The FML3 experimental and simulation rivet failure maps are shown in figure 2.3a and 2.3b respectively. The experimental rivet failure map was taken directly from D5.3.2 [2]. As can be seen the model correctly predicts that most rivets fail in the two interior ribs (ribs 2 and 3) but incorrectly predicts that extensive rivet failure occurs in the two outer ribs (ribs 1 and 4). Similar observations were noted for the other rivet failure laws investigated in D2.2.4 [1] (not shown).

A comparison between the experiment and simulation for rib deformation is shown in figure 2.4. In the experiment, extensive damage occurred in ribs 2 and 3 and rib 3 crushed in a Mode 1 type buckling deformation state while rib 2 crushed in a higher order buckling deformation mode. Ribs 1 and 4 remained essentially undamaged but were rotated considerably inward toward the impact point. Turning to the model in figure 2.4b, it can be seen that ribs 2 and 3 were predicted to crush considerably, which concurs with the experiment, but both ribs were predicted to crush in a higher order buckling deformation mode (compared to one in the experiment). Hence, in the model, the two interior ribs would offer more resistance to crushing in the impact direction than the experiment and this could be a reason for less skin deformation in the simulation. It can also be seen that the two outer ribs are rotated toward the impact point but the degree of rotation is much less than in the experiment. This is most likely due to the high number of rivet failures in these ribs (which was not seen in the experiment) which would cause less force to be transferred from the skin and hence less rotation of the ribs. Finally, it should be noted that two large folds occurred in the skin in the experiment (as shown in figure 2.4a) while only one fold occurred in the simulation. This could be attributed to the different crushing mechanism of rib 3 coupled with a high number of rivet failures in the outer ribs.
Figure 2.2 Shot sequence comparison between experiment and pre-test simulation for FML3 (3 – 9.5 ms)
Figure 2.3 Rivet failure map for FML3 (simulation is FML3_Law1_1ms in D2.2.4)

Figure 2.4 Rib and skin deformation in FML3 (interior view)
2.2 FML5 Skin (A/0/90/0/90/A/90/0/90/0/A)

The shot sequence for the first 2 ms of impact time for the FML5 skin test and simulation is shown in figure 2.5. The experimental sequence was taken from the test video provided by CEAT while the simulation sequence was taken from the ULIM FML5_Law1_1ms model in D2.2.4 [1] (see table 4.1 in [1]). As can be seen, similar trends to those seen in the FML3 case above, such as less deformation in the simulation are also seen in the FML5 case. Figure 2.6 shows the shot sequence for FML5 over a later time duration (t = 3 ms to t = 10 ms) and again it is clear that there is less deformation occurring in the simulation. Similarly to the FML3 skin case above, “spring back” starts in the simulation at approximately 4.5 ms whereas it did not start occurring in the experiment until approximately 7.5 ms.

By comparing figures 2.1, 2.2, 2.5 and 2.6 it is clear that the FML5 specimen deformed considerably more than the FML3 specimen in the test and it is also clear that the models correctly predicted this. A possible reason for this is that the FML5 skin is slightly thinner than the FML3 skin (2.2 mm compared to 2.35 mm) and would thus offer less resistance to bending. In addition, the FML3 skin has more layers of aluminium alloy and since the elastic modulus of the aluminium layers is considerably higher than that of the glass layers (in any direction) it would be expected that the FML3 skin would offer more resistance to bending.

The FML5 skin experimental and simulation rivet failure maps are shown in figure 2.7a and 2.7b respectively. Again, the experimental rivet failure map was taken directly from D5.3.2 [2]. As can be seen, the model and experiment are in reasonable agreement for the two interior ribs (ribs 2 and 3) but in poor agreement for the two outer ribs (ribs 1 and 4). Similarly to the FML3 experiment, no rivet failures occurred in ribs 1 and 4 in the FML5 experiment. However, the FML5 simulation (like the FML3 simulation) predicted that considerable rivet failure occurred in these ribs. One could thus conclude that rivet failure law 1 with 1ms rivet failure duration (see D2.2.4 [1]) does not accurately model the rupture behaviour of the rivets. This will be investigated further in Section 4.

A comparison between the experiment and simulation for rib deformation in the FML5 specimen is shown in figure 2.8. As can be seen, very similar trends to the rib behaviour in the FML3 test and simulation are seen in the FML5 test and simulation and so a detailed explanation is omitted.
Figure 2.5 Shot sequence comparison between experiment and pre-test simulation for FML5 Skin (0 – 2 ms)
Figure 2.6 Shot sequence comparison between experiment and pre-test simulation for FML5 Skin (3 – 10 ms)
Figure 2.7 Rivet failure map for FML5 skin (simulation is FML3_Law1_1ms in D2.2.4)

Figure 2.8 Rib and skin deformation in FML5 (interior view)
2.3 Summary

In the conclusions of the pre-test report on birdstrike against the GLARE LE structures [1] a number of predictions regarding the structural behaviour of the LE structures were made before the experiments were carried out:

1. The bird will not penetrate the skin in either test
2. The FML5 lay-up will result in greater skin deformation than the FML3 lay-up
3. Rivet failures will occur in the forward region of ribs 2 and 3 and possibly elsewhere also

As can be seen in Sections 2.1 and 2.2 of the present report, these predictions have been found to be quite accurate indicating that the pre-test models were successful in providing predictive capability. However, a number of failings of the model have been identified such as insufficient skin deformation and too many rivet failures. In addition, no quantitative comparison has yet been made. Thus, the remainder of this report will concentrate on improving the structural behaviour of the pre-test models and carrying out a quantitative comparison between experiment and simulation.

3 Post-test Modelling Details

In this section extensions to the FE model are described. The primary aim of the extensions was to allow a quantitative comparison with the experiments carried out at CEAT [2]. In addition some changes were made to the rib geometry and boundary conditions, as detailed in Section 3.3. For comparison with experiment, two comparison metrics are available:

1. Strain readings at selected locations on the LE Skin
2. Reaction forces on the LE support frame

The experimental strain and load results were sent by CEAT to ULIM in the form of an ASCII file. These files were very large and difficult to work with and so a FORTRAN program was written to filter and reduce the size of the data files.

3.1 Experimental Strain Measurements

The locations of the strain gauges on the GLARE leading edge structures are shown in figure 3.1. The strain histories for the FML5 test are shown in figure 3.2. As can be seen most of the signals “bottomed out” just after the bird impacted the LE skin. There may be a number of reasons for this but it is most likely that the strain gauges saturated or disconnected in the early stages of impact. A visit was arranged by one of the authors to ALENIA in order to inspect the tested specimens and it was found that most of the strain gauges had in fact disconnected. Hence, disconnection was most likely the source of the poor strain readings. When examining the experimental data for the FML3 lay-up it was also found that most strain readings (not shown) had bottomed out. Thus, it was felt that the strain readings were too unreliable to use for post–test comparison and no more consideration will be given to them in this report.
Figure 3.1 Strain gauge locations on GLARE LE Structure (taken from [2])
Figure 3.2 Strain Gauge readings on the FML5 LE Structure
3.2 Experimental Load Measurements

Fortunately, the experimental load results were of good quality and it was decided to use these for quantitative post-test comparison. The experimental load results will be shown along with those obtained from the models in Section 4. In this section the measurement system is described in some detail. There are six load cells in total, two acting in the x-direction labelled FX1 and FX2, three in the z-direction labelled FZ1, FZ2 and FZ4 and one in the y-direction labelled FY as shown in figure 3.3. The load cells were attached to a rectangular support frame (shown in figure 3.3). The LE structure was attached to the support frame via two interface beams which themselves were joined at their ends. When examining a photo of the support frame (also shown in figure 3.3) it was realised that the exact positions of the load cells may be somewhat different to that shown in the line drawing. The exact location of the load cells relative to the LE structure must be known in order to accurately model the support frame and interface beams and recover the reaction forces from the model. For example, if the load FY was recovered at the location shown in the line drawing (figure 3.3), the result would be inaccurate because the load is reacted at a distance offset from the support frame as shown in the photograph in figure 3.3. With this in mind, it was decided to visit CEAT for detailed examination of the load cell and support frame arrangement.

Figure 3.3 LE Support frame and interface beams (line drawing taken from D5.3.2 [2])

Figure 3.4 shows photographs of the support frame and loads cells used for both the FML3 and FML5 tests. As can be seen, this entire mechanism is quite complex so it was decided to
take detailed measurements of each load cell and the support frame. The interface beams were not present at the time of the site visit. From the measurements taken a 3D CAD model was generated to aid understanding of the mechanics of the system and some rendered views of this model are shown in figure 3.5. As will be discussed in Section 3.3, this CAD model proved very useful for extending the finite element model of the LE structure and application of new boundary conditions. The CAD model has been distributed to ALENIA, DLR, and UPAT and is available to any other interested partner.

Figure 3.4 Photographs of the Support Frame and Load Cells
Figure 3.5 3D CAD model of support frame, load cells and interface beams
3.3 Extensions to the LE Finite Element Model

In order to extract the load results from the existing pre-test LE finite element model a number of extensions to this model must be made. For accurate correlation, it is necessary to explicitly model the interface beams, support frame and load cells. It is also necessary to connect the existing LE model to the interface beams and also connect the interface beams to the support frame. This section describes these new developments.

When reviewing the experimental test report on the GLARE LE structures [2], it was noticed that the geometry of the ribs did not match that which was modelled in the pre-test simulations. Figure 3.6 shows the LE structure before it was tested and corresponding pre-test LE finite element geometry. As can be seen, there is a distinct difference in the shape of the ribs that were tested and those modelled in the pre-test simulations. The distance “x” in the model is significantly larger than that in the test and as a result the semi-elliptical cut out is much smaller in the model.

![Figure 3.6 LE Structure and corresponding pre-test model](image)

It was decided to change the geometry of the ribs but as limited time remained in the project it was decided to estimate the geometry rather than re-request it from ALENIA. Known measurements on the LE structure were used to generate a scale for the photograph in figure 3.6a. From this, the geometry of the visible rib in figure 3.6a could be estimated with reasonable accuracy. It was then assumed that the other ribs corresponded approximately to the one measured and from this a new geometry for all the ribs was established. The finite element meshes for the modified ribs are shown in figure 3.7. There are 339 nodes and 304 elements in rib 1, 435 nodes and 386 elements in rib 2, 440 nodes and 387 elements in rib 3 and 371 nodes and 321 elements in rib 4. The re-meshing was performed in MSC.Patran and imported into PAM-Generis where material properties were re-assigned to the rib elements. Details for the material properties of the ribs can be found in [1].
As shown in figure 3.6a, the LE structure was attached to the interface beams by two angle brackets manufactured from aluminium alloy. In the finite element model, the original clamped boundary conditions that were used to fix the skin root (see figure 3.8 in D2.2.4 [1]) were removed and replaced with two angle brackets as shown in figure 3.8 (in the present report). Each bracket consisted of 126 nodes and 100 shell elements. The thickness of the shell elements was assumed to be 4 mm. In the experiments the angle brackets were riveted to the LE skins, but as a first order approximation, a node to surface tied contact interface was used to attach the angle brackets to the LE Skin in the FE model.

The 3D CAD model shown in figure 3.5 was exported from AutoCAD as an IGES file and imported into MSC.Patran so that the components could be meshed. Four-noded shell elements were used to discretise the interface beams and the resulting mesh is shown in figure 3.9. The mesh for the entire interface structure consisted of 3788 nodes and 3752 elements. The beams are manufactured from steel plates welded together and the thickness of the webs, flanges and the plates that joined the two beams together are respectively 5mm, 13mm and
8mm as shown in figure 3.9. The beams were assumed to remain elastic throughout the entire loading history and so were modelled with an elastic material model (type 101 in PAM-CRASH - elastic for shell elements). The entire interface structure was assumed to have a Young’s Modulus of 210 GPa and Poisson’s ratio of 0.3.

Figure 3.9 Finite element model of the interface beams showing the thicknesses of the shell elements

In the experiments the angle brackets were bolted to the interface beams as shown in figure 3.6a. As with the connection between the LE Skin and the angle brackets, a node to surface tied contact interface was used to attach the angle brackets to the interface beams in the position shown in figure 3.10.

The geometry of the support frame was discretised using eight node solid elements and the resulting mesh is shown in figure 3.11. This mesh consisted of 606 nodes and 232 elements. The support frame was manufactured from steel and was assumed to have a Young’s Modulus of 210 GPa and Poisson’s ratio of 0.3. As with the interface beams, the support frame was assumed to remain elastic throughout the entire loading history and so was modelled with an elastic-plastic material model (type 1 in PAM Crash – elastic-plastic for solid elements) with plastic components switched off. The interface beams were joined to the support frame using a node to surface tied contact interface in the position shown in figure 3.12.
Figure 3.10 LE structure, angle brackets and interface beams

Figure 3.11 Finite Element Mesh of the Support Frame
Figure 3.12 Interface beams joined to the support frame

Figure 3.13 shows a simplified line drawing of one of the load cells. Examining the photographs in figure 3.4, the load cell device connects the support frame to a rigid support through two connector pins. The load is inferred from a single strain gauge located at the centre of the connecting device orientated in the local r-axis. Since only one longitudinal (in the local r-axis) strain gauge was used, it was assumed that the connector device was only capable of resisting force in its local r-axis. This could only be possible if the pins were mounted in rubber bushings so it was assumed that this was the case. From this, it was concluded that the load cells only suppressed one degree of freedom with stiffness in their local r-direction.

Figure 3.13 Simplified line drawing of a load cell
In the model, each load cell was modelled using a 6-DOF Spring/Dashpot element as shown in figure 3.14. The location of each load cell was determined from the 3D CAD model shown in figure 3.5. Since it was assumed that the load cell only had stiffness in its local r-axis (see above), all stiffnesses apart from that in the r-direction in the 6-DOF Spring/Dashpot elements were set to zero. In the local r-axis, an estimated stiffness value based upon that of a round bar of dimensions close to that of the load cells (in figure 3.4) was used. Since it was assumed that rubber bushings were used to connect the components of the load cells, damping was introduced to the spring elements in the r-direction. The free ends of the spring elements had all six degrees of freedom fixed so as to simulate the rigid supports in the experiment. The completed finite element model including the SPH bird model is shown in figure 3.15.
4 Results and Discussion

This section presents the results from the extended finite element model and makes comparisons with experimental results generated at CEAT [2]. Section 4.1 and 4.2 present these comparisons for the FML3 and FML5 lay-ups respectively.

4.1 FML3 Skin (A/0/90/A/0/90/A/90/0/A)

As a starting point, the extended finite element model shown in figure 3.15 was run with rivet failure law 1 with 1 ms failure duration (i.e. the same law as in the pre-test simulations shown in Fig. 2.1) and the results for each load recovered in each spring element is shown in figure 4.1. The response in the local x – direction is given by FX1 and FX2 in figure 4.1a and 4.1b respectively. As can be seen, the frequency of the response is well matched with the experiment but the magnitude of the peak forces are overestimated by the model. It is also apparent that the rate of decay of the signals is higher in the model. The response in the local z – direction, given by FZ1, FZ2 and FZ4 shown in figure 4.1c, 4.1d and 4.1e respectively shows similar trends as those in the x –direction except the peak forces are considerably higher than the experiment. The response in the local y – direction, given by FY in figure 4.1f shows good agreement for the peak force values but in this case the frequency of the models response is considerably higher than that of the experiment.
Figure 4.1 Load results from FML3 experiment and FML3_Law1_1ms model

Figure 4.2 shows the displacement history of a node located on the LE skin at the impact point (node 307712, see D2.2.4 [1]) for both the pre- and post-test models. Both of these models used rivet failure law 1 with 1 ms failure duration (see Table 4.1 in D2.2.4 [1]). Also shown in figure 4.2 is the residual displacement of the impact point in the FML3 experiment. This measurement was taken during the site visit to ALENIA and should only be considered as approximate. As no displacement history was recorded during the test, the residual displacement is represented by a point on the graph. As can be seen in figure 4.2, the pre- and post-test simulations gave a quite similar response with the residual displacement predicted by both models to be considerably less than that of the experiment.

Looking at the deformed shapes after impact in figure 4.3, it is also evident that the deformation of the skin in the pre- and post-test simulations are very similar but as before the deformation in both simulations is considerably less than that of the experiment.
Figure 4.2 Displacement of the impact point with FML3 Lay-up (Rivet failure Law 1 with 1ms failure duration)

(a) Pre-test Simulation   (b) Post-test Simulation
(c) Experiment

Figure 4.3 Deformed Shape after the impact

It is apparent from figure 4.3 that more rivet failures occurred in the outer ribs in the post-test simulations. Figure 4.4 takes a closer look at this and shows the rivet failure maps for the pre-test simulation, post-test simulation and experiment. As can be seen, there is an increased...
number of rivet failures in the two outer ribs (ribs 1 and 4) in the post-test simulation (compared to the pre-test simulation) which is undesirable because there were no rivet failures in these ribs in the experiment. The only changes made to the LE parts (ribs and skin) in the post-test simulations were removal of material from the ribs and a change of boundary conditions on the LE skin. These changes must therefore be responsible for the increased number of rivet failures in the post-test models.

![Diagram](a) Pre-test Simulation ![Diagram](b) Post-test Simulation

![Diagram](c) Experiment

Figure 4.4 Rivet failure map for FML3 (rivet failure law 1 with 1 ms failure duration)

By examining the results of the post-test model run with rivet failure law 1 with 1ms rivet failure duration, discussed above, it was postulated that too much energy was being absorbed by the rivets which resulted in less energy available to crush the LE skin and ribs. This was making the structure too stiff which would also help to explain the overestimation of the peak forces recovered at the spring elements (load cells). It was also apparent that failure law 1 resulted in too many rivet failures and thus underestimates the true strength of the rivets. From this, two failings of the model were identified:

1. The rivets are absorbing too much energy
2. The rivet failure law underestimates the true strength of the rivets

To try and overcome these failings, it was decided to reduce the failure duration time to 0 ms and increase the strength of the rivets. This should have the net effect of increasing the energy available to crush the LE skin and ribs and hence lead to more deformation in the skin, and also a reduction in the number of rivet failures, both of which should improve the correlation
between the simulation and experiment. A higher strength rivet failure law with 0 ms failure duration was investigated in D2.2.4 [1] and was thus chosen here to try and improve the simulation with respect to the experiment. This failure law is given by equation 3.2 in D2.2.4 [1] and was referred to as rivet failure law 2 with 0ms failure duration.

The extended finite element model shown in figure 3.15 was re-run with rivet failure law 2 with 0 ms failure duration and the results for each load recovered in each spring element is shown in figure 4.5. Firstly, the response in the local x – direction, given by FX1 and FX2 in figure 4.5a and 4.5b respectively, has significantly improved as both the magnitude and the frequency are well matched with the experiment. In addition, the rate of decay of the model’s response is in better agreement with the experiment than that of failure law 1 with 1ms failure duration (see figure 4.1). Looking at the responses in the local z – direction, given by FZ1, FZ2 and FZ4 shown in figure 4.5c, 4.5d and 4.5e respectively, one can see the magnitude of the peak forces matches that of the experiment very well for FZ1 and FZ2 and has improved significantly over the previous case (failure law 1 with 1 ms failure duration) for FZ4. The response in the local y – direction, given by FY in figure 4.5f shows little change from the previous case and can be considered to be in good agreement with the experiment. Considering the complexity of the system, it can be concluded that the force response from this model is in excellent agreement with the experiment.
Figure 4.5 Load results from FML3 experiment and FML3_Law2_0ms model

Figure 4.6 shows the displacement history of a node located on the LE skin at the impact point (node 307712, see D2.2.4 [1]) for both the pre- and post-test models. Both of these models used rivet failure law 2 with 0 ms failure duration (see Table 4.1 in D2.2.4 [1]). Again the residual displacement of the impact point in the FML3 experiment is shown as a point on the graph. Differently from the FML3_Law1_1 ms model (figure 4.2) there is a significant difference between the pre- and post-test simulations. The peak displacement in the post-test model almost reaches the residual displacement in the experiment and is a significant improvement over the pre-test model. However the residual displacement of the post–test simulation is still approximately 20% below that of the experiment. This could again be due to plasticity being ignored in the model.
Figure 4.6 Displacement of the impact point with FML3 Lay-up (Rivet failure Law 2 with 0ms failure duration)

Figure 4.7 shows the deformed shape of the FML3 experiment and simulation. In this case both pre- and post-test simulations used failure law 2 with 0 ms failure duration. From this figure, it is evident that the global skin deformation predicted by the post-test simulation is greater than that predicted by the pre-test simulation but more importantly, it is closer to that of the experiment and significantly improved over the failure law 1 with 1ms failure duration case (see figure 4.3). This, combined with the improvements in the reaction forces and total deformation indicates that an increase in rivet strength and a reduction in rivet failure duration time gives a better reflection of the structure’s behaviour in the test.

Figure 4.8 shows the rivet failure maps for the pre-test simulation, post-test simulation and experiment. Both pre- and post-test models were run with rivet failure law 2 with 0 ms failure duration. As with the rivet failure law 1 with 1 ms failure duration case (figure 4.4), there is an increased number of rivet failures in the two outer ribs (ribs 1 and 4) in the post-test simulation (compared to the pre-test simulation) which again can be attributed to removal of material from the ribs and a change of boundary conditions on the LE skin. This suggests that the rivet strengths are still too low and it is therefore suggested that experiments be carried out on these rivets to determine their strength for any future analysis.
Figure 4.7 Final deformed shape of FML3

Figure 4.8 Rivet failure map for FML3 (rivet failure law 2 with 0 ms failure duration)
4.2 FML5 Skin (A/0/90/0/90/A/90/0/90/0/A)

From Section 4.1 above, it was found that rivet failure law 2 with 0 ms failure duration gave good agreement with the experiment for the FML3 case. It was therefore decided that this rivet failure law would be implemented into the FML5 skin model. The results for each load recovered in each spring element are shown in figure 4.9. The response in the local x-direction, given by FX1 and FX2 in figure 4.9a and 4.9b respectively, shows good agreement with the experiment for peak load values and reasonable agreement for frequency of response. However differently from the FML3 lay-up, the forces seem to be out of phase with the experiment (particularly FX2 which appears to be 180° out of phase). The responses in the local z-direction, given by FZ1, FZ2 and FZ4 shown in figure 4.9c, 4.9d and 4.9e respectively, are better since the magnitude of the peak forces and the frequency of the responses are in good agreement with the experiment. The response in the local y-direction, given by FY in figure 4.9f is somewhat different from the experiment as the peak forces are lower in the model.

Figure 4.10 shows the FML3 and FML5 leading edges just before they were tested and as can be seen the shot target is not centred (between the two interior ribs) in the FML5 case. This suggested that the substitute bird might have impacted in the wrong location, which could be the reason for the discrepancies between the simulation and experiment for FX1, FX2 and FY in the FML5 case. Figure 4.11 shows the deformed shape of the FML5 experiment and simulation. From this figure, it is evident that the global skin deformation predicted by the post-test simulation is in reasonable agreement with the experiment. As can be seen the deformed shape of the FML5 experiment is unsymmetrical unlike the FML3 experiment (shown in figure 4.7a). This again suggested that the shot might have been off centre. Due to the way the FML5 Skin deformed it was difficult to measure the maximum residual displacement and so no quantitative comparison between experiment and simulation is given here.

Figure 4.12 shows the rivet failure maps for the post-test simulation and the experiment. As can be seen ribs 2 and 3 are in reasonable agreement but agreement is poor for ribs 1 and 4. This further suggests that the rivet failure law used (Law 2 with 0 ms failure duration) underestimates the true strength of the rivets in the test.

As discussed above, it was postulated that the substitute bird in the FML5 experiment might have impacted off centre. To investigate this, it was decided to carry out a simulation with the SPH bird positioned off centre, as shown in figure 4.13. Figure 4.14 shows the results from this model for the loads recovered in each spring element. The response in the local x-direction, given by FX1 and FX2 in figure 4.14a and 4.14b respectively, have disimproved significantly over the “on centre” case shown in figure 4.9 in terms of magnitude, although the frequency and phase are better matched. The responses in the local z-direction, given by FZ1, FZ2 and FZ4 shown in figure 4.14c, 4.14d and 4.14e respectively, show a slight disimprovement over the on centre case but can still be considered to be in good agreement with the experiment. The response in the local y-direction, given by FY in figure 4.14f shows little change over the on-centre case in figure 4.9f. Figure 4.15 shows the deformed shape of the experiment and off-centre FML5 simulation. Interestingly, the off-centre case shows a more symmetric deformation than the on-centre case (shown in figure 4.11b), which is in less agreement with the experiment. Hence, it appears that the on-centre simulation is in better
agreement with the experiment for loads and deformed shape and it can thus be concluded that the bird in the FML5 experiment was probably fired on centre.

Figure 4.9 Load results from FML5 experiment and FML5_Law2_0ms model

Figure 4.10 LE Structures just before impact
Figure 4.11 Final deformed shape of FML5

(a) Experiment     (b) Simulation

Figure 4.12 Rivet failure map for FML5 (rivet failure law 2 with 0 ms failure duration)

Figure 4.13 SPH bird fired off centre in model
Figure 4.14 Load results from FML5 experiment and FML5_Law2_0ms model (bird fired off centre in model)

(a) Experiment  (b) Simulation (off centre case)

Figure 4.15 Final deformed shape of FML5
5 Summary

As a starting point in this report, the pre-test simulations carried out at ULIM [1] and experiments carried out at CEAT [2] were compared and it was found that the pre-test models correctly predicted that:

1. The bird did not penetrate the skin in either test
2. The FML5 lay-up had greater skin deformation than the FML3 lay-up
3. Rivet failures occurred in the forward region of ribs 2 and 3

The pre-test models can thus be considered successful in providing predictive capability, although the models incorrectly predicted that rivet failures occurred in the two outer ribs and also underestimated the amount of skin deformation.

In an attempt to improve the pre-test simulations, and provide a more quantitative comparison with experiments, a number of changes were made to the model, which included changing the rib geometry, and modelling the surrounding support structure. With this new model, a number of findings were evident:

- In the FML3 case, generally good agreement with the load cell data was achieved with the first model tried. However, in this model, which used rivet failure law 1 with 1ms failure duration, the peak forces were somewhat overestimated, the skin deformation was too low and there were too many rivet failures. It was postulated that a rivet law with higher strength but instantaneous failure would alleviate these problems.

- This was found to be true, since rivet failure law 2 with 0ms failure duration gave excellent agreement for the forces recovered at the spring elements (load cells) and only underestimated the displacement of the impact point by 3%. However this failure law still resulted in too many rivet failures.

- In the FML5 case, the rivet failure law 2 with 0ms failure duration gave good results for the forces in the impact direction (z-direction) but only reasonable agreement for forces transverse to the impact direction (x and y direction) and resulted in too many rivet failures. A second run with the bird off-centre (i.e. positioned to hit at the target symbol on the structure) did not improve correlation, so it is believed that the bird did in fact hit on-centre (and not at the target symbol location).

6 Conclusions

1. The SPH method proved to be very effective for modelling of bird strike on these structures. The calibrated bird model provided by ESI was used with no changes. The loads transferred to the structure seem to be very realistic, the deformed shape of the bird matches the experiment very well with break-up into debris particles captured, and importantly no stability problems were encountered. The pre-test simulations were run to 12 ms, while the post-test simulations were run to 100 ms for comparison with the load cell data. The pre-test simulations took 2-3 hours on a Pentium 4 PC, while
the post-test simulations took of the order of 36 hours. The addition of the load frame in the model did not greatly affect the run times. These run times are quite reasonable to work with. Another potential advantage of the SPH method may be in modelling situations where the skin is penetrated and parts of the bird hit the front spar, which would be very difficult to model with traditional Lagrangian methods. However, this case was not modelled here, so this is speculative.

2. The two FML leading edge structures appear to have performed well, although no comparison with a metallic leading edge with this geometry was available to compare with.

3. The continuum damage mechanics model used for the FML skin (described in [1]) appears to have very successfully predicted the behaviour of the skins, despite the amount of input data that was not available and had to be estimated.

4. The rivets have been shown to have a quite profound effect on the performance of the structure. Clearly improved methods for modelling rivets, which rely less on post-test tuning would be desirable.

5. Both rivet failure laws used in the present report inadequately represented the true strength of the rivets and experiments would be needed on these rivets to determine their strength before any future modelling of these structures.

6. Considering the complexity of the LE structure and support frame mechanism, the finite element models developed here and in [1] gave excellent agreement with the experiments.

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References

