CRASHWORTHINESS OF AIRCRAFT COMPOSITES STRUCTURES

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ABSTRACT
More and more aircraft components are made of fiber reinforced composite material because of high stiffness, strength and low weight. These composites are made of glass or carbon fibers embedded into a polymer matrix. In some case, for equivalent energy absorption, composite components can be 50% lighter than steel components. The resistance of aircraft composite components to impact of various debris or birds must be assessed.

Extensive literature exists describing the energy absorption mechanism of composite laminate tubes crushed between two rigid plates. Triggers are usually used to initiate material peeling inside and outside of the tube. The energy is absorbed by more complex mechanisms than for metallic tubes, such as delamination, fibers debonding, pulverization of material and friction. A constitutive model using damage mechanics is described in this paper. The model has been validated on composite tube crushing.

This paper also describes the numerical results obtained with RADIOSS for the crash of composite sine wave beam and of sub cargo floor structure. Bird strike simulation results are also shown in the case of impact on a commuter leading edge structure. Comparison with tests results is shown.

RADIOSS is an explicit finite element code developed by MECALOG, used for non linear simulations and validated industrially for crash analysis of metallic structures in automotive and aeronautic applications.

INTRODUCTION

The use of composite material in airframe component manufacturing is becoming widespread and this trend will continue. The understanding of how composite materials behave as load-carrying material is being developed continuously. Some of these loads are service loads an airframe is subjected to in day-to-day operations. Others are less frequently experienced nevertheless they are critical and have to be taken into consideration. These include crash loads.

Whilst crash avoidance has been and will continue to be the main theme in aircraft safety, the survivability of many crashes has been demonstrated in recent work, hence, the design for crash survivability has become of increasing importance. Crashes on take-off and landing around the airfields were shown to be the most common survivable crash scenarios, for which the loading conditions can now be performed readily, especially for metallic airframes. The same is potentially feasible for airframes with a significant amount of composite materials used in their primary structure, provided that the specific behavior of the composite materials under impact conditions is known.

Basic ideas are coming from experience with helicopters, assuming that the kinetic energy is dissipated in the bottom part of the structure under the passenger floor, which should not be damaged during a crash. Another constraint occurring in the case of an airliner fuselage is that the cargo bay volume cannot be used in the energy absorption process because it should be kept free for container loading and transport purposes. The other major objective is, of course, to keep the passenger cabin volume undeformed during the crash in order to enhance survivability.

So the design is governed by these two major assumptions leading to a location of the kinetic energy absorbing concept below the cargo floor level combined with a very stiff upper structure (cargo bay plus cabin area).
1. RADIOSS composite shell material law 25 [1]

The composite thin shell is a stack of several layers having an orthotropic behavior. The layers can have different material parameters, different orthotropic angles and different thicknesses. Each layer is in plane stress state:

\[ \sigma_{11} = \sigma_{22} = \sigma_{33} = 0, \sigma_{12} = \sigma_{13} = 0, \sigma_{23} = 0 \]

where subscript 1 and 2 refer to orthotropic directions.

The yield criterion is given by Tsai-Wu function for a plane stress state:

\[ F = F_1 \sigma_{11} + F_2 \sigma_{22} + F_3 \sigma_{33} + F_4 \sigma_{12}^2 + F_5 \sigma_{13}^2 + F_6 \sigma_{23}^2 + F_7 \sigma_{11} \sigma_{22} \]  \hspace{1cm} \text{Eq.1}

\[ F_i = 1/\sigma_{iy}^i - 1/\sigma_{iy}^c \quad i = 1,2 \]

\[ F_{ii} = 1/\sigma_{iy}^i \sigma_{iy}^c \quad i = 1,2,4 \]

\[ F_{12} = -\sqrt{F_1 F_{22}} \]

If \( F < 1 \) the behavior is elastic otherwise the behavior is plastic. The yield stresses are given by a hardening law function of the plastic work and of the rate of plastic work:

\[ \sigma_{iy}^n = \sigma_{iy}^m (1 + b_n w_p^s)(1 + c_n \ln w_p^s) \]  \hspace{1cm} \text{Eq.2}

with:

\[ \alpha = c_i \gamma, \quad i = 1,2,4 \]

\[ \sigma_{iy}^c = \sigma_{iy}^a \]

\[ \sigma_{iy}^m \leq \sigma_{iy}^a \]

Tensile failure can occur in orthotropic directions if a maximum strain \( \varepsilon_t \) is reached and the tensile yield stress eventually reaches zero for a maximum strain \( \varepsilon_m \). Softening is modeled with a damage model.

Excessive plastic deformation is modeled with a threshold criteria on plastic work \( w_p \geq w_p^\text{max} \).

A simple criterion is used for shear delamination based on an equivalent shear strain \( \gamma = \sqrt{\gamma_{13}^2 + \gamma_{23}^2} \). The elastic transverse shear stresses are given by \( \sigma_{13} = G_{13} (1-d_3) \gamma_{13} \), where the damage parameter varies between 0 and 1, \( d_3=0 \) if \( \gamma \leq \gamma_t \) and \( d_3=1 \) if \( \gamma \geq \gamma_m \).

In total the material model has 38 parameters: 6 elastic modulus, 25 parameters to define the yield criterion and 7 parameters to define failure modes.

2. Material law calibration

A procedure to obtain the material parameters using an identification optimization process is described in [2]. It consists in characterizing first the static hardening parameters \( b_n, n^a \) in tension, compression and shear and to evaluate the plastic work \( w_p \). Then the parameters \( c_n^a \) are derived from tests at various speed. Finally the failure parameters are set.

The testing machine is derived from Hopkinson’s bar apparatus and allows strain rate measurements up to 500 s\(^{-1}\).

3. Sine wave beam crushing

The sizing of the sine wave beams is governed by the requisite amount of absorption of kinetic energy. Numerical simulations with RADIOSS and experiments have been performed to evaluate the energy absorption.
The calibrated material laws are used and the results are compared to sine wave beam crushing tests. The results are displayed figure 4 for a crushing velocity of 500 mm/mn. The sine wave beam FE model has 20,000 shell elements, the web crushing behavior being described by an equivalent material law for the whole laminate.

One can observe that under these quasi-static conditions the trigger mechanism doesn’t function correctly, this is also shown by FE analysis (initiation of failure not located in the lower part of the web).

This absorber is designed with four sine wave beams based on the previous carbon – kevlar configuration. The two metallic beams are representing the cargo floor cross beams of the full fuselage section. A view of this sub cargo floor structure is shown figure 6.

4. Airliner sub cargo floor structure

The next step of the design and sizing validation of the absorber is the drop test of a full scale absorber representative of the one included in the design of the composite fuselage section. Typical airliner dimensions and cargo floor position are used [5].

This absorber is designed with four sine wave beams based on the previous carbon – kevlar configuration. The two metallic beams are representing the cargo floor cross beams of the full fuselage section. A view of this sub cargo floor structure is shown figure 6.

4.1 Airliner sub cargo floor structure drop test

The test objectives are defined as follows:
- assessment of the global structure behavior
- validation of the sine wave beam concept
- evaluation of the energy absorption
- measurement of the deceleration time history.

The test article is 1000 mm length, 270 mm height and 1675 mm width. Both internal sine wave beams are 177 mm height and the external ones 136 mm. To introduce loads more uniformly into the sine wave beams, steel corner brackets are riveted between the cross beams and the upper flange of the sine wave beams.
The test conditions are defined on the basis of the airliner section drop test performed at CEAT in 1995 [5]. First the impact velocity is fixed at 7 m/s. The sub cargo floor structure loading is estimated to 730 kg representing one third of the airliner section. The weight is applied by fixing steel plates on the cross beams.

Because of the structure geometry and the necessity to enforce a perpendicular impact with the ground, the specimen must be guided during its fall. Therefore CEAT has designed and manufactured a specific test facility able to:
- lift the specimen at the predetermined height,
- release the structure by a pyrotechnic system controlled through a firing board
- guide the structure up to the impact

Many tests have been performed with dummy structures to validate this new test facility. They have helped to identify the friction factor of the guiding system, information required to get an accurate drop speed at the point of impact with the ground.

To achieve the objectives above mentioned, several kinds of sensors are set up:

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine wave beams</td>
<td>10</td>
</tr>
<tr>
<td>Load plates</td>
<td>2</td>
</tr>
<tr>
<td>Reaction platform</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>17</strong></td>
</tr>
</tbody>
</table>

To complete the recording of the sub cargo floor structure behavior during the test, two high-speed motion cameras (500 fr/s) and a standard video (25 fr/s) are installed.

The films and measurement data indicate that too much energy is applied to the structure due to an inefficiency of the sine wave beams. Indeed the energy absorbing devices are well designed to absorb the initial kinetic energy, but the load distribution leads to failures close to sine wave beam/cross beam attachment whereas the central parts of the sine wave beam are not crushed sufficiently (see figure 7).

![Figure 7: Airliner sub cargo floor structure after the test](image)

Accelerated curve for the dummy mass is giving a maximum value of 38 g at time 40 ms corresponding to a maximum impact force with the ground of 460 KN. This is due, as explained above, to the fact that the level of energy absorbed by the sine wave beams reach only 88% of the total kinetic energy to absorb so that lower part of transverse beams entered in contact with the ground at time 40 ms, generating a very high pulse.

![Figure 8: Acceleration (g) versus time (ms) and contact force (KN) versus time (ms)](image)

### 4.2 Airliner sub cargo pre and post test simulations

Initially, pre test simulations have been performed with RADIOSS. During the design phase of the sub cargo floor structure results have contributed to:
- improve the design of the brackets
- optimize the material choice
- increase the stiffness of the upper flange of the sine wave beams (UD plies)

After the drop test of the sub cargo floor structure, differences have been studied and some modifications or improvements needed in the FE model have been made:
- modeling of the shock table located at the bottom of the test apparatus
- metallic material law modified (brackets)
- riveted joints modeling added, including failure criteria

The first modification of the model is fundamental to catch the real behavior of the structure during the test. This is due to the fact that the shock table used to measure the contact force between the structure and the ground is not fully rigid and works in a bending mode combined to the stiffness of the three load cells used.

After this update of the FE model, the post test simulation results are showing a good correlation between numerical and test deformed shape.
Considering the measurements made during the test compared to numerical results, figure 10 is showing a quite good agreement between test and simulation. G levels are satisfactory but peaks are shifted w.r.t. time.

The next step is to optimize the design of the absorber, in order to increase its absorption efficiency while trying to reduce the g-levels observed during the test. The major modifications of the design are concerning:

- design with two sine wave beams instead of four
- stiffer brackets included
- crushable height increased (from 135 mm to 180 mm)

The simulations performed at this stage give satisfactory results regarding the behavior of the absorber during the crash phase (see figure 11) and acceptable g-levels are predicted, with maximum peaks of approximately 14g. This g-level corresponds to the limit of what is acceptable in term of sizing of the upper structure, taking into account manufacturing constraints.

5. Bird strike on composite wing leading edge

Thirteen bird strike tests have been performed on five different commuter wing leading edges. The approach was to perform pre-test simulations in order to gain a first reference to be used mainly for test preparation and to perform post-test correlation for the validation of the models.

All the tests were performed in CEAT. The test gun and the specimen to test are shown figure 12.

5.1 Test specimens

The test specimens considered are commuter composite (sandwich Kevlar-Nomex) wing leading edges, their shape
being quite cylindrical and their length being in the range of 2 to 2.7 m approximately. The five test specimens are different in the sense that some of the specimens are coming from the internal part of the wing, others from the external part of the wing and some specimens include a deicing system. During the tests, each specimen is fixed to a rigid support as shown figure 13.

Each test panel is instrumented with 13 strain gauges (see figure 14) and a rigid table is installed behind the leading edge impact area in order to measure the loads applied by the impactor in case of penetration. This table is instrumented with three load sensors in order to allow correlation on residual bird effects after penetration. Each test is filmed with two high speed cameras and pictures are taken before and after test. Sampling rate for the different gauges and sensors was equal to 1 MHz filtered at 500 KHz.

**5.2 Test conditions**

The following parameters are varied during the test campaign and determined prior to each test in accordance with pre-test simulations performed. At this stage the criteria was to choose a combination of the parameters (velocity, incidence) so as to be close to perforation.

These parameters are chosen in the following range:
- impact velocity : 111 to 153 m/s
- variable location of impact along the leading edge.

The impactor characteristics are:
- impactor mass : close to 0.908 kg (2 lbs.) ± 6%
- impactor type : real bird (chicken) for 3 tests and substitute for 10 tests.

**5.3 Test results**

The qualitative test interpretation is firstly based on damage observation. The following pictures (figure 15 to 17) are presenting the type of damage observed for the different shots in case of penetration or not.

Simulations performed using RADIOSS FE code are presented hereafter. All the simulations have been performed in two different phases. The FE model used for pre-test simulations is shown figure 18.
Pre-test simulations have been performed for all tested configurations (13 simulations). The pre-test simulation results have been used to help prepare the different tests especially to define the impact velocity and also to evaluate strain levels in order to better choose the type of strain gauges to use. The metallic support (positioning the wing leading edge) was included in the pre-test models following the conclusions of previous studies performed on flat panels.

Post-test simulations have been performed in order to highlight the correlation level between tests and simulations leading the model to be modified taking into account observations made during or after the tests. The required modifications are of two types:

- the wing leading edge sandwich modeling needed improvements especially concerning the Nomex modeling. At this stage it was necessary to be very close to the real geometry of a sandwich and to use more realistic material characteristics coming from specific tests.
- additional simulation with the real impact velocity are needed due to scatter during the test (real impact velocity usually differs slightly from the required value).

Some of the results highlighted during the post-test phase are presented below focusing on:
- perforation velocity prediction
- strain gauge comparison
- damage comparison

**Perforation velocity prediction**

Among all the considered cases the local impacted structure properties differ depending on different parameters: internal or external wing leading edge part, deicing system included or not, one or two sandwich panels across the thickness.

A perforation limit case is shown figure 19 and what is called “door opening” damage case with projectile perforation is shown figure 20.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Specimen</th>
<th>Predicted Perforation Velocity (m/s)</th>
<th>Test Velocity (m/s)</th>
<th>Perforation Type of Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WLE 4</td>
<td>120</td>
<td>111.4</td>
<td>No Initiation</td>
</tr>
<tr>
<td>2</td>
<td>WLE 4</td>
<td>125</td>
<td>132.9</td>
<td>No Initiation</td>
</tr>
<tr>
<td>3</td>
<td>WLE 4</td>
<td>130</td>
<td>133.6</td>
<td>No Initiation</td>
</tr>
<tr>
<td>4</td>
<td>WLE 5</td>
<td>130</td>
<td>152.7</td>
<td>Yes Hole</td>
</tr>
<tr>
<td>5</td>
<td>WLE 5</td>
<td>130</td>
<td>153.6</td>
<td>Yes Hole</td>
</tr>
<tr>
<td>6</td>
<td>WLE 5</td>
<td>125</td>
<td>112.1</td>
<td>No Initiation</td>
</tr>
<tr>
<td>7</td>
<td>WLE 5</td>
<td>120</td>
<td>134.6</td>
<td>Yes Door</td>
</tr>
<tr>
<td>8</td>
<td>WLE 2</td>
<td>135</td>
<td>138.1</td>
<td>Yes Door</td>
</tr>
<tr>
<td>9</td>
<td>WLE 2</td>
<td>120</td>
<td>136.5</td>
<td>Yes Door</td>
</tr>
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</tr>
<tr>
<td>11</td>
<td>WLE 3</td>
<td>135</td>
<td>138.2</td>
<td>No Initiation</td>
</tr>
<tr>
<td>12</td>
<td>WLE 1</td>
<td>135</td>
<td>139.2</td>
<td>Yes Door</td>
</tr>
<tr>
<td>13</td>
<td>WLE 1</td>
<td>120</td>
<td>121.5</td>
<td>Yes Door</td>
</tr>
</tbody>
</table>

**Table 1 : Test performed and observations**

As shown in table 1, all the pre-test simulations are slightly conservative. The number of cases for which we have noticed an inconsistency in the prediction is equal to three (shots 2, 3 and 11). Next, one can see that concerning the predicted
perforation velocity the maximum difference (in case of inconsistency in the prediction) is equal to 8 m/s for shot 2 that is corresponding to a 5% difference only.

The post-test simulations performed with improved sandwich Kevlar-Nomex material law and improved Nomex FE modeling (see figure 21) have correctly predicted perforation for both shots 3 and 11, the predicted perforation velocity becoming higher than the test velocity for these non perforating cases. However it was not possible to improve the result of shot 2.

**Figure 21 : Improved modeling : solid elements for Nomex and shell elements for skins**

**Strain gauge comparison**
Post-test strain versus time curves are presented in case of shot 9 on figure 22 and 23 and one can see that the correlation is good. Differences have been observed for other strain gauges located in high bending and curvature areas.

**Figure 22 : Strain versus time curve – Gauge J4 / shot 9**

**Figure 23 : Strain versus time curve – Gauge J13 / shot 9**

**Damage comparison**
Damage is compared for shot 8. Both test and simulation results are highlighting the same type of failure for internal face view and external face view (see figure 24 and 25).

However it was found that the panel mesh properties (mesh density, element shape,...) have an influence on the results especially in term of damage aspect.

**Figure 24 : Comparison between test and simulation**
**Internal view**
5.5 Discussion

Pre-test simulations for the thirteen impact tests performed on Commuter wing leading edge have shown a good agreement in term of perforation velocity prediction. This has allowed testing the different specimens at optimal velocity level (close to their perforation velocity). Taking into account the model improvements introduced between pre and post-test simulations (such as Nomex material modeling) only one shot among the thirteen shots performed was showing a limited contradiction (5% difference in term of velocity) between simulation and test, one should notice that the simulation is conservative in this case.

Only static material characteristics have been used in this study and the use of dynamic material characteristics should slightly increase the predicted perforation velocities, therefore improving the predictions.

The strain time histories have acceptable correlation for strain gauges not located in areas subjected to high bending and curvature. For these areas the results are very sensitive to material law and mesh density.

For the majority of tests, the damage prediction was shown to be sufficiently correlated with test results in term of damage size and shape.

6. Conclusion

This paper shows the use of explicit FE code for designing and sizing a full scale airliner composite fuselage section for a defined crash loading.

The approach used by Airbus is based on calibration of test results in the FE environment at different levels: basic laminates specimens, elementary composite absorbers, sub cargo floor absorbing structure. Next, the calibrated material laws and component behaviors will allow using RADIOSS code to design and size the full composite fuselage.

To conclude from the survivability point of view, it is shown that the control of energy absorption is absolutely necessary to ensure occupant safety.

Concerning the problem of bird impact on composite sandwich wing leading edges of the commuter, a good level of correlation is found between simulation and tests (perforation velocity prediction, strain history prediction and damage prediction).

Numerical tools can offer now the possibility to integrate crash and impact sizing in the development of structure design. Further developments must be performed for more accurate predictions of some composite failure modes like delamination.

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REFERENCES