Numerical simulation of composite structures under impact

Th. Kermanidis\textsuperscript{a}, G. Labeas\textsuperscript{a}, C. Apostolopoulos\textsuperscript{a} and Louis Michielsen\textsuperscript{b}

\textsuperscript{a} Laboratory of Technology and Strength of Materials
Mechanical Engineering Department, University of Patras,
26500 Patras, Greece

\textsuperscript{b} National Aerospace Laboratory – NLR
Antony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

Abstract

Within the European research program ‘Design for Crash Survivability’, CRASURV [1], simulation of the crash behavior of aircraft subfloor components, like sine-wave beams and ‘tensor skin’ panels, is performed by Univ. Patras. These substructures, which are made of composite materials, were initially developed by NLR and originally suggested in [2] and [3], as energy absorbing elements in helicopter subfloor structures subjected to water impact. The practical application of the ‘tensor skin’ concept was found in a sandwich corrugated panel configuration. In order to identify their ability to transfer impact loads and absorb impact energy, preliminary static crush tests were performed in one and two-dimensional strips, as well as, in three-dimensional square panels. In the present paper, the modeling methodology of these crashworthiness substructures, using the Finite Element (FE) technique, is described. Numerical simulations of selected initial proof tests of the ‘tensor skin’ concept and sinewave beam tests, using FE PAM-CRASH code by ESI [4], are presented. A good correlation between experimental and numerical results was achieved. The development of composite material damage and property degradation models, which is a crucial step in the modeling procedure, is discussed in detail.
1. Introduction

The utilization of composite materials in aircraft structures has been increased in recent years. In cases that composite materials are used in fuselage subfloor components, an important issue is the proof of their ability to withstand impact loading, which occurs in crash situations. Since a major problem of composite materials is their limited ability to absorb impact energy, special design techniques for composite components are required, to enable crashworthiness structures. Within the European research program ‘Design for Crash Survivability’ CRASURV, which is a RTD projet partially funded by the European Union in the Aeronautics Area of the Industrial and Materials Technologies (BRITE/EURAM) program, NLR developed crashworthiness composite subcomponents, namely, the sinewave beam and the tensor skin panel. These substructures are suitable for implementation in subfloor boxes of helicopter and aircraft fuselages, as energy absorbing elements. In order to identify the suitability of the tensor skin structure and the sinewave beam for a crashworthiness design, preliminary static crush tests were performed by NLR. However, tooling, manufacturing and testing of components is quite expensive. To allow parameter studies and minimize the tests, prediction techniques for crash behavior of composite structures are required.

Impact analysis of composite structures involves high material non-linearity, large deformations, local heating and initiation and propagation of impact failures within the structure. As a result, local damages of structural components and subsequently partial or total collapse of the entire structure may occur. Explicit non-linear dynamic FE codes, such as PAM-CRASH by ESI, which is used in the present analysis, are best suited for the modeling of impacted structures. However, less experience exists in the utilization of such codes in the case of composite structures, compared to the metallic ones. Major difficulties of the numerical simulation are the proper representation of the composite material behavior, the prediction of the complex failure modes of composites, the selection of suitable contact algorithms and the development of adequate FE meshes which will lead in accurate results in reasonable solution times.

In the present work, the static crush tests of three specific composite substructures, i.e the sinewave beam, the 1-D tensor strip and the 3-D tensor panel are numerically simulated. It arises that all structures can transfer properly the impact loads and can be designed in a way that the control of the peak loads during the crush is possible. Very good agreement is observed between the numerical and the experimental results.
2. Simulation methodology and development of material damage models

For the simulation of the crush tested composite substructures the PAM-CRASH FE code is used. One of the major subjects for a successful numerical simulation of an impacted structure, using non-linear dynamic FE codes, is the development and calibration of suitable material damage models. Such models have to represent properly the material response, as well as, their stiffness and strength degradation at high deformation rates.

The subcomponents which are studied in the present work, are the sinewave beam and the two realizations of the ‘tensor skin’ concept. The sinewave beam materials are Carbon-Aramid/epoxy fabric (Ten Cate CV-170-40-8475) and Carbon/epoxy UD (Fibredux F155). Uniaxial stress-stain data for these materials are provided by NLR in [2]. The tensor skin concept has found its practical application in a sandwich configuration, shown in figure 1, consisting from a corrugated panel surrounded by an inner and an outer skin.

![Figure 1: Cross section of a corrugated tensor skin panel](image)

The material systems utilized for the inner and outer ‘tensor skin’facings are Carbon-Aramid/epoxy hybrib fabric (Hexcel 73210-2-1220-F155-45%) and Aramid/epoxy fabric (Hexcel F-155-49-285-52%) respectively. The corrugated core of the panel is made of Dyneema fabric (DSM SK 60-132 TEX) with RTM resin (Ciba Geigy 5052). Experimental tension, compression and shear coupons tests for these materials were provided by NLR in [5].

The PAM-CRASH code enables the modeling of composite layered structures, using four node shell elements with one integration point per layer, combined to a material type, coded ‘type 130’, which represents the anisotropic material behavior. The elastic fiber-matrix damaging behavior, or elastoplastic behavior with damage can be modeled by material ‘type 130’. Different material properties can be defined for each layer, requiring
for each of them stiffness, strength, and damage progression data. For each layer the initial undamaged inplane stiffness properties $E_{11}$, $E_{22}$, $G_{12}$, and $v_{12}$ should be provided, for the calculation of the initial modulus matrix $C_0$. A damage function $d$ [4], enables the representation of the degradation of the initial modulus matrix $C_0$, when an initial undamaged phase is exceeded. The modulus matrix behaves according to the formulae:

$$C(d) = C_0 (1-d)$$  \hspace{1cm} (1)$$

The damage function $d$ is a scalar parameter that depends upon strain:

$$d(\varepsilon) = d_v(\varepsilon_v) + d_s(\varepsilon_s)$$  \hspace{1cm} (2)$$

where $d_v$ is the volumetric damage due to a volumetric equivalent strain $\varepsilon_v$, and $d_s$ is the shear damage due to a shear equivalent strain $\varepsilon_s$. The equivalent volumetric and shear damage values are defined as:

$$\varepsilon_v = \varepsilon_{kk} = (1-v_{12} - v_{13})\varepsilon_{11}$$ \hspace{1cm} (3)$$

$$\varepsilon_s = [(1/2) \varepsilon_{ij} \varepsilon_{ij}]^{1/2} = (\varepsilon_{11}/\sqrt{3}) (1 + v_{12} + v_{13} + v_{12}^2 + v_{13}^2)^{1/2}$$  \hspace{1cm} (4)$$

In equations 3 and 4, $\varepsilon_{kk}$ is the trace of the total strain tensor and $\varepsilon_{ij}$ are the components of the deviatoric strain tensor. The scalar parameter $\varepsilon_v$ represents the first invariant of the volumetric strain tensor, while the scalar $\varepsilon_s$ represents the second invariant of the deviatoric strain tensor. The implemented damage law in PAM-CRASH assumes that the fracturing damage parameter $d$ is zero for an equivalent strain between zero and $\varepsilon_i$ (figure 2-i). After the value $\varepsilon_i$ is reached, the fracturing damage factor $d$ grows linearly between the values $\varepsilon_i$ and $\varepsilon_1$. Between $\varepsilon_1$ and $\varepsilon_u$ the damage factor $d$ grows linearly again, with a different slope. The damage parameters which correspond to the strains $\varepsilon_i$, $\varepsilon_1$ and $\varepsilon_u$ are $d_i$, $d_1$ and $d_u$, respectively, where $d_u$ is the stage, where the ultimate damage is reached. The elasticity modulus is assumed to degrade according to fig. 2-ii and is related to uniaxial data according to fig. 2-iii.

Figure 2: Fracturing damage function, modulus degradation and stress-strain diagram, after[4]
The calibration of the material damage models can be performed either using the tension-compression stress-strain curves to introduce only volumetric damage, or using the shear stress-strain curves to introduce only shear damage. In the former case, the slopes can be calculated from the tension-compression uniaxial data as:
\[
E_{v0} = \frac{\sigma_i}{\varepsilon_{vi}} \quad E_{vl} = \frac{\sigma_i}{\varepsilon_{vl}} \quad E_{vu} = \frac{\sigma_u}{\varepsilon_{vu}},
\]  
(5)

The volumetric damage values then arise:
\[
d_{vl} = 1 - \frac{E_{vl}}{E_{v0}} \quad d_{vu} = 1 - \frac{E_{vu}}{E_{v0}}
\]  
(6)

The use of either only volumetric, or only shear damage, can lead to the successful representation of the experimental tension and compression data. However, this is not the case for the shear behavior, which is overestimated or underestimated, if only volumetric or only shear damage is used. To face this problem, the damage models are calibrated starting with the calculation of the shear damage from the shear coupons tests. After selecting a set of values for the strains \(\varepsilon_r, \varepsilon_i\) and \(\varepsilon_u\), the slopes \(G_r, G_i\) and \(G_u\) and the corresponding shear damage parameters \(d_i\) and \(d_u\) are calculated. Different combinations of \(\varepsilon_r, \varepsilon_i\) and \(\varepsilon_u\) were tried to achieve a good prediction of the \(\tau-\gamma\) curves for each material. The obtained results, using shear damage only, have shown an enormous overestimation of the tension / compression strengths, because of the fact that the composite fabrics which are used here, have a completely different behavior in tension / compression (\(\varepsilon_{\text{max}}\) is between 1% and 3%) and shear (\(\gamma_{\text{max}}\) is between 10% and 18%). For this reason, volumetric damage parameters are introduced afterwards, to cut-off the final strength and match the tension / compression data.

The bonded interfaces of the corrugated tensor skin (figure 1) are modeled using a tied contact algorithm, coded in PAM-CRASH as contact ‘type 2’. This algorithm requires the input of normal \(N_s\) and shear \(T_s\) strengths of the bond and enables the contact failure, after the contact force of the tied nodes is exceeded. The failure occurs [4] when:
\[
\left(\frac{N}{N_s}\right)^2 + \left(\frac{T}{T_s}\right)^2 \geq 1
\]
(7)

For the modeling of the contact between the structure interfaces, the self contact algorithm, coded in PAM-CRASH as contact ‘type 26’ is applied. This contact algorithm automatically searches for elements
contacting each other and introduces an internal contact force between these elements.

The tools which introduce the deformation are modeled as moving rigid walls with infinite mass. The real tool velocity in the simulated experiments is constant with values between 5mm/min and 20mm/min. As velocities of this magnitude would lead to very long simulation times, the rigid walls velocity is considered higher. However, in order to avoid a sudden impact at the beginning of the simulation, a linearly increasing rigid wall velocity for all the simulations is supposed, ranging from zero (at time=0) up to 1m/min (at time=1sec).

3. Simulation of the sinewave beam test

The subfloor sinewave beam, shown in figure 3, is tested in vertical compression. All the data of the static crush test, are obtained from [2].

![Geometry of the sinewave beam](image)

The FE mesh comprises 3018 layered shell elements (5183 nodes), combined to material type 130. The trigger mechanism, which is located 35mm from the bottom flange, is modeled by introducing dummy plies of reduced elasticity modulus in the lay-up of the corresponding elements. The role of the trigger is to introduce an eccentricity at this area and cause the failure initiation earlier and from this location, reducing the peak force. It is very important to model the trigger area properly, otherwise global buckling of the web occurs and the simulation can not predict the real failure modes. The simulation of the folding process is shown in figure 4, where deformed shapes of the beam are plotted at various time intervals.

The calculated rigid wall force versus time is plotted in figure 5. The predicted peak force of 83KN corresponds to the failure initiation at the trigger area and is equal to the measured value, from [2]. After that point, the web touches the bottom flange and starts to fold until its final collapse.
During this stage the mean force which is found to be between 22KN and 30KN, which is very close to the measured at the test mean force value of 34.31KN, [2]. The oscillation of the calculated force value is due to the loose of contact between the web and the lower flange just after the elements elimination.

Figure 4: Deformed shapes of the sinewave beam at various time intervals

![Figure 4](image)

Fig. 5: Calculated rigid wall force of the sinewave beam test

![Figure 5](image)
4. Simulation of the 1D tensor skin strip tests

The tensor skin strip was developed by NLR in different configurations, [3]. It is made of polyethylene (PE) fibers embedded in epoxy matrix (Dyneema layers), which allow ‘strain to failure’ limits much higher than the common 1% to 2% of the ordinary composite systems. Its main advantage is that when loaded in tension or bending, the beam unfolds and deflects by forming “plastic hinges” before it stretches and fails in tension, which allows the absorption of the impact energy. Static crush bending tests were performed by NLR, [3], at 1-D tensor strips of length 250mm, width 50mm, thickness of 1mm at lay-ups [0/90] and [±45/90/±45]. These tests are simulated here, using a FE mesh consisting of 3300 layered shell elements combined to material type 130. Two semi-spherical rigid walls are used to model the clamping system. In figure 6 the unfolding process which occurs during the test is shown.

![Fig. 6: Deformed configurations of the 1-D tensor strip](image)

The calculated deformed shapes, for the [0/90] lay-up, at various time intervals, are plotted in fig. 7.

![Fig. 7: Calculated deformed shapes of the 1-D tensor beam](image)
Comparing figures 6 and 7, it is observed that the unfolding process is successfully simulated. The rigid wall force is less than 500N during the whole unfolding process and increases sharply only before the final failure. The predicted peak force was measured at 34.83KN for the [0/90], and 17.25KN for the [±45/90/±45] lay-up, respectively. These peak forces were calculated at values within 10% of the measured ones.

5. Simulation of the 3-D tensor skin panel tests

The 3-D tensor skin panel is a square panel of 540x540mm, with a cross section shown in figure 1. The outer face is made from three Aramid/epoxy layers at [±45/0/±45] lay-up and of the inner hat shaped face is made of three hybrid Carbon-Aramid/epoxy layers, at the same lay-up. The corrugated core consists of three Dyneema layers oriented at ±45 degrees. The FE mesh comprises 3300 elements (3837 nodes). Deformed shapes of the three layers of the 3-D tensor panel at various time intervals, indicating the damage propagation, are shown in fig. 8.

Figure 8: Calculated deformed shapes of the Aramid (left), Dyneema (middle) and Carbon/Aramid hybrid (right) faces of the 3D tensor panel at various time intervals
The measured tool force and the calculated rigid wall force are plotted in fig. 9. As it can be seen from the figures, at tool displacement of 40mm, which corresponds to 425ms in the simulation process, the rupture of the outer and inner facings occurs. The rigid wall force at this point is measured at 30.89KN and calculated as 36.14KN. The Dyneema layer unfolds and fails at tool displacement of 140mm, which corresponds to 765ms in the simulation process. At this point the rigid wall force value is measured 74.7KN and is calculated 68.8KN. Thus, the panel failure process and the rigid wall force are simulated successfully.

![Fig. 9: Calculated and measured impactor force of the 3-D panel test](image)

6. Conclusions

The PAM-CRASH FE-code has been successfully applied for the simulation of the proof process of three crashworthiness composite subfloor components. The developed composite material damage models are capable to represent successfully the properties degradation. The failure process of all the simulated structures was accurately predicted. Very good agreement is observed between the calculated and measured tool forces. At present, the described simulation methodology is applied in dynamic drop tests of the subfloor components, within CRASURV project.

7. References