A Numerical Study on the impact behaviour of an all-Composite Wing-box

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Abstract

In this work a numerical study on the impact behavior of an all composite wing-box is presented. The numerical analyses have been performed by means of advanced numerical models implemented in Abaqus/Explicit. The aim was to estimate the intra-laminar and inter-laminar damage behaviour in a localized area, and, by a Global-local approach, to investigate the impact influence on the overall structural behaviour. The numerical investigation of complex composite structures under several impact conditions in terms of impact position and energy can complement the experimental results potentially leading to a reduction of the experimental tests to be performed with considerable time and cost saving.

Keywords: impact behaviour; carbon fibre laminates; delamination; wing-box.

1. Introduction

The highly specific mechanical properties of composite laminates have allowed their increased usage in a number of engineering fields such as the aeronautical, railway, automotive and marine ones by replacing metal alloy structural elements. Composites application requires a deep knowledge of the response of composite components and structures to a wide range of loading conditions, some of which may be severe causing internal damages that could lead to the structural collapse [1]. In aerospace industry, in particular, impact damage in laminated composite materials continues to be of major concern. Typically both low and high velocity impacts can start complex damage mechanisms (such as delaminations and intra-laminar damages) in composites depending on the thickness of the component. Delaminations can occur for low velocity impacts, while fragmentation or perforation are likely to occur in case of high velocity impacts. The damage induced by low velocity impacts is of major concern being able to drastically reduce the loading carrying capability of the impacted structure without being clearly detectable form the surface of the laminate.

Several examples of numerical and experimental investigations on the impact induced damages on composite material specimen can be found in literature [2-12]. The experimental test is often simulated by finite element models to get additional information on the damage formation and propagation at ply level. Usually the intra-
laminar failure is simulated by an appropriate damage criterion such as Hashin, Tsai-Wu, etc. while the delamination is modeled by means of numerical techniques such as the VCCT (Virtual Crack Closure Technique) [13-15] or the cohesive zone approach (cohesive elements or cohesive surfaces) [16-20]. In this study the inter-laminar and intra-laminar damage behavior in a limited area of a full composite wing-box have been investigated simulating a realistic impact scenario and assessing the influence of impact threat on the wing-box structural response. Delamination and fiber/matrix ruptures have been simulated through Continuum Damage Mechanics [21-24] and using a global-local approach [3-5] available in Abaqus/Explicit [24].

2. Model description

The wing-box is composed by two flat panels, two spars and four ribs. The ribs are equally spaced and present mouse-holes in order to let the pass-through of the stringers. Stringers’ webs are 30 mm high while stringer foots are fully integrated within the stacking sequence of skin. The stringers, moreover, are tapered at the wing tip. The model has been created by surfaces linked by means of Multi-Point Constraints. At the wing-box root, the upper and lower skins have been reinforced with tapered doublers bonded to the skins in order to give more stiffness to the wing-box root shifting the pick of strains far from constrained extremity. The thickness variation of the doublers has been simulated splitting the geometry in five regions at which a different number of plies has been associated. In Figure 1 the distribution of shell thickness at wing-box root is schematically shown.

Fig. 1: Doublers thickness.

As already mentioned, the stringers have been designed as fully integrated in the skin leading to the not symmetric lay-up for each bay, presented in Table 1 and Figure 2. The doublers at root location have been made of Cytec HTA fabric material system and laid-up according to the stacking sequence of [(+45,-45,0,90)3s]. The tapering of this component has been obtained dropping the inner plies until the design thickness was reached. The rest of wing-box has been manufactured with the Cramer carbon fabric material system and the stacking sequences used for the different components of the wing-box have been reported in Table 1 and Figure 2.

Table 1. Stacking sequence of wing-box components

| Component         | Stacking Sequence          |
|-------------------|-----------------------------|
| Skin (layup A)    | [+45,-45, 0, 0,-45,+45, 90,+45, 0, 90,-45, 90,90,-45,90,0,+45,90,+45,0,0,-45,+45] |
| Skin (layup B)    | [+45,-45, 0, 0,-45,+45, 90,+45, 0, 90,-45, 90,90,-45,90,0,+45,90,+45,0,0,-45,+45] |
| Stringer (layup AB) | [+45,-45, 0, 0,-45,+45, 0, 0, 0, 0,-45,-5, 0, 0,-45,+45]          |
| Stringer (layup BA) | [+45,-45, 0, 0,-45,+45, 0, 0, 0, 0,-45,+45, 0, 0,+45,-45]           |
| Spar              | [(+45,-45, 0,90)3s]        |
| Rib               | [+45,-45,90, 0,90]s         |
| L-shaped flange   | [+45,-45,+45,-45]s         |
A 4 node shell element formulation (S4R) has been adopted for all the wing-box components. The use of MPCs has allowed to overcome mesh discontinuity problems and to use a coarser mesh in some regions of the model. In Figure 3 details of the FEM model are reported. It is possible to notice the mouse-holes in the ribs allowing the pass-through of the stringers and the tapered edge of the stringers. Table 2 reports the material properties of each lamina for both materials models used in the wing-box design:

| Material        | Cramer          | Cytec HTA fabric |
|-----------------|-----------------|------------------|
| $E_{11}$        | 88.5 GPa        | 68.5 GPa         |
| $E_{22}$        | 21.25 GPa       | 68.5 GPa         |
| $E_{33}$        | 9.7 GPa         | 6.9 GPa          |
| $G_{12}$        | 2.9 GPa         | 5.9 GPa          |
| $G_{13}$        | 2.4 GPa         | 5.4 GPa          |
| $G_{23}$        | 2.4 GPa         | 5.4 GPa          |
| $\nu_{12}$     | 0.05            | 0.07             |
| $\nu_{13}$     | 0.27            | 0.28             |
| $\nu_{23}$     | 0.27            | 0.28             |
According to the experimental data available from the European Thales project DAMOCLES II [34], the impact location has been selected within the central bay of the top skin. Since the impact involve a relatively small area of the wing-box, a global-local approach [4, 5, 26] has been used to obtain a considerable computational cost reduction preserving the results accuracy in the impacted area. Furthermore, the global-local approach is useful, for the analysed case study, because it allows to investigate the progressive failure only in a small area around the impact point. This area has been linked to the rest of the structure by means of TIE constrains [25, 27]. The impact energy is 35 J with an initial velocity of 6 m/s.

In Figure 4, the impact location and a detailed view of the discretized impact event are shown. In particular, an exploded view of the first two plies of the laminate shows how the impact site has been modelled.

The local model has been discretized using solid modelling together with the adjacent skin. Each ply was discretized using continuum shell elements SC8R allowing the use of Hashin failure criterion available within the CAE interface. The CZM, by means of COH4 elements, has been adopted in order to take into account the delamination onset and growth phenomena [28-30]. TIE constraints have been used to guarantee the load transfer among all interfaces. The described approach has been chosen to be able to fully characterize the inter-laminar and intra-laminar damage. The local model has been implemented through a parameterized Python routine; such a routine was parameterized in terms of stacking sequence, position on the skin, thicknesses and geometric and inertial characteristics of the impactor allowing a considerable time saving for further models preparation.

3. Damage simulation

For each failure mode, the constitutive model of cohesive elements is based on a bi-linear traction-separation law, relating the inter-lamina stress ($\sigma$) and the displacement ($\delta$) considering a characteristic length in order to alleviate the mesh dependency [21, 25]. As the equivalent displacement increases, the traction through the interface linearly increases according to a defined slope (i.e. penalty stiffness $k_p$ related to initial thickness), up to a maximum value ($\sigma_0$) corresponding to the effective displacement at the damage onset ($\delta_0$). The damage is assumed to start when a quadratic criterion on stress ratios reaches a critical value [25]. After damage initiation, the traction through the interface decreases linearly up to $\delta_{\text{max}}$ at which the element is completely damaged. In the range between $\delta_0$ and $\delta_{\text{max}}$ the damage evolution is driven by the scalar parameter “$d$“, which can vary between 0 (undamaged interface case) and 1 (completely damaged). The evolution phase is usually based on an energy criterion in which the total fracture energy must be specified [7]. The fracture energy, defined as the area under the constitutive response curve, is obtained by experimental tests. As for inter-lamina failure modes, the intra-lamina failure model is bilinear and combines an initiation phase followed by a propagation phase. The Hashin failure criteria [31, 32] have been adopted [33] to model intra-lamina damages onset, as fibers and matrix failures, while a linear constitutive law for the damage propagation has been considered.

4. Results

In Figure 5 a global view of the impacted wing box is presented while in the next images the results in the impact area are shown.
In Figure 6 the main results obtained for the analysed test case are presented. Figure 6.1 shows the impact force–time curve. The red markers named as a, b and c are referred to three different time steps of the analysis: a) onset of the inter-laminar damage, b) maximum deflection of the laminate and c) detachment of the impactor from the structure surface. Figure 6.2 reports a cut-off of the laminate at steps a, b and c with a contour plot of the inter-laminar damage evaluated by the cohesive elements at the plies interfaces. Finally, Figure 6.3 an overlapped image of the inter-laminar damage throughout the whole lay-up is shown.

Impact induced delamination can be observed at 3rd-4th and 5th-6th ply interfaces as shown in Figure 7, where a contour of the inter-laminar damage variable is presented. The delaminated area corresponds to about 650 mm² that is in agreement with DAMOCLES II experimental data (Figure 8).
Figure 7 shows some important parameters related to the impact event. The duration of the impact event is about 4 ms. The first inter-laminar damage occurs at 0.6 ms and the max impactor displacement occurs at 1.5 ms with a 6 mm depth, and a peak force of 9kN. The force-displacement curve shows that the contact point of the structure go back to initial position, while the energy lost throughout the analysis (difference between initial and final values) is representative of the energy absorbed by the structure during the damage formation and propagation.
6. Conclusions

In order to understand the influence of the boundary conditions on the impact behavior of complex composite structures, the simulation of an impact event on an all-composite wing-box has been performed. Indeed, the analysis of an impacted complete wing-box has given the chance to examine the realistic boundary conditions and to take into account correctly the inertias of the impacted zone. Moreover, it is expected that the numerical investigation of complex composite structures under several impact conditions in terms of impact position and energy can complement the experimental results potentially leading, in a near future, to a reduction of the experimental tests to be performed with considerable time and cost saving.

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