STRUCTURAL BENDING BEHAVIUOR OF AN ALL-COMPOSITE WING-BOX WITH DELAMINATION

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Carbon-fibre reinforced structures are more and more used in aerospace due to their excellent mechanical properties and their significant weight reduction. However, due to their complex damage mechanisms, composite structures can have significant local reduction in strength which can influence the global structural behaviour. Among the different failure mechanisms, the delamination between two adjacent fibre reinforced layers of a laminate, caused by a low velocity impact threat, can be very dangerous especially under compressive loading conditions. If a delamination exceeds a certain size, it will progressively grow under the service load conditions. The resulting loss in strength and stiffness may cause the premature failure of the damaged component.

In order to characterize the on-set and the growth of the impact induced delaminations in wing-box composite stiffened panels, an integrated numerical tool has been developed within the ANSYS FEM code.

Starting from the impact energy and impact location, the delamination size and location along the panel thickness is found by means of the Davis & Zhang procedure [1]. Then, a geometrically non linear analysis is carried out on the panel with delamination so as to find its residual strength. The delamination growth is taken into account using an Energy Release Rate based approach. The delaminated area has been modeled using shell elements placed in the mid-planes of the sub-laminates and the Energy Release Rate has been calculated by means of the Virtual Crack Closure Technique [2] for shell elements which has been implemented in the ANSYS FEM code. Finally, a sensitivity analysis has been performed to evaluate the influence of the impact energy and the impact location on the residual strength of the wing-box composite stiffened panels under investigation.

Theoretical Background

By means of the Davies & Zhang procedure we can predict the stiffened panel's impact characteristic parameters. By using as data-input the results obtained from the Fem model (force - displacement relation and interlaminar shear stresses distributions) it is possible to estimate the threshold energy for the onset of delamination.

First of all the critical threshold force for the onset of delamination, has been determined by adopting the following expression [1]:

$$P_C = \sqrt{\frac{8.\pi^2.E.t^3.G_{IIC}}{9.\left(1-\upsilon^2\right)}}. \qquad (1)$$

Where G_{IIc} is the energy release rate mode II, t is the thickness of the laminate, E and ν are the equivalent Young's modulus and Poisson's ratio respectively of the composite laminate.

Then, the calculation of the equivalent circular delaminated area has been performed by adopting the expression [1]:

$$A_C = \frac{9}{16.\pi.t^2}.\left(\frac{P_C}{\tau}\right). \qquad (2)$$

Finally the energy balance together with numerical integration techniques, have allowed calculating the threshold impact energy *Wcr*:

$$W_C = \frac{k}{n+1}.\left(\frac{P_C}{k}\right)^{\frac{n+1}{n}} + \int_0^{\delta_{MAX}} P.d\delta \qquad (3)$$

The first term in the previous equation (3) is related to the indentation, while the second term represents the energy associated to the elastic deformation. This second term can be calculated by integrating the non linear load - displacement curve up to the critical threshold displacement δ_{max}. The load – displacement curve can be easily obtained by means of a preliminary geometrical non linear static analysis simulating the impact event on the panel.

Once, the threshold energy for the onset of delamination has been obtained, it is possible to calculate the area of the equivalent delamination due to an impact energy > *Wcr*.

Subsequently, a Fem model of the panel with delamination can be easily built. The local buckling (buckling of delamination) and the global buckling (buckling of the panel) can be easily investigated by adopting a linearised buckling approach of by performing a non linear buckling analysis.

In the ANSYS Fem code, the linearised buckling approach is based on the use of eigenvalues and eigenvectors to determine the critical loads and the corresponding deformed shapes while the non linear buckling analysis can be performed by using an iterative procedure Newton – Raphson like.

In the non linear analysis, when the structure presents geometric symmetry or load symmetry, an initial geometry out of plane imperfection can be required in order to correctly drive the first buckling mode.

In association with the non linear buckling analysis, the Energy Release Rate has been evaluated along the delamination front in order to analyze the delamination growth initiation in the all-composite wing-box at the analysed impact location.

The approach used for this purpose is the Modified Virtual Crack Closure Technique (MVCCT) applied to eight - noded shell elements which permit to evaluate the G - distribution for the main three fracture modes by using relations (4), (5), (6) and (7) evaluated at the delamination front as explained in figure 1.

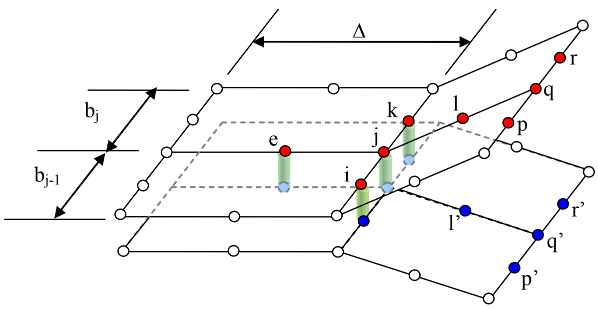

Fig. 1

$$G_I = -\frac{1}{2B_j\Delta}\left\{\begin{aligned} &\left[\begin{aligned} &F_{z_j}\left(w_q - w_{q'}\right) + F_{z_e}\left(w_l - w_{l'}\right) + M_{x_j}\left(\theta_{x_q} - \theta_{x_{q'}}\right) + \\ &M_{x_e}\left(\theta_{x_l} - \theta_{x_{l'}}\right) + M_{y_j}\left(\theta_{y_q} - \theta_{y_{q'}}\right) + M_{y_e}\left(\theta_{y_l} - \theta_{y_{l'}}\right)\end{aligned}\right] \\ &+\left[\frac{1}{2}F_{z_i}\left(w_p - w_{p'}\right) + \frac{1}{2}M_{x_i}\left(\theta_{x_p} - \theta_{x_{p'}}\right) + \frac{1}{2}M_{y_i}\left(\theta_{y_p} - \theta_{y_{p'}}\right)\right] \\ &+\left[\frac{1}{2}F_{z_k}\left(w_r - w_{r'}\right) + \frac{1}{2}M_{x_k}\left(\theta_{x_r} - \theta_{x_{r'}}\right) + \frac{1}{2}M_{y_k}\left(\theta_{y_r} - \theta_{y_{r'}}\right)\right]\end{aligned}\right\} \quad (4)$$

$$G_{II} = -\frac{1}{2B_j\Delta}\left[F_{x_j}\left(u_q - u_{q'}\right) + F_{x_e}\left(u_l - u_{l'}\right) + \frac{1}{2}F_{x_i}\left(u_p - u_{p'}\right) + \frac{1}{2}F_{x_k}\left(u_r - u_{r'}\right)\right] \quad (5)$$

$$G_{III} = -\frac{1}{2B_j\Delta}\left\{\begin{aligned} &\left[F_{y_j}\left(v_q - v_{q'}\right) + F_{y_e}\left(v_l - v_{l'}\right) + M_{z_j}\left(\theta_{z_q} - \theta_{z_{q'}}\right) + M_{z_e}\left(\theta_{z_l} - \theta_{z_{l'}}\right)\right] + \\ &\left[\left[\frac{1}{2}F_{y_i}\left(v_p - v_{p'}\right) + \frac{1}{2}M_{z_i}\left(\theta_{z_p} - \theta_{z_{p'}}\right)\right] + \left[\frac{1}{2}F_{y_k}\left(v_r - v_{r'}\right) + \frac{1}{2}M_{z_k}\left(\theta_{z_r} - \theta_{z_{r'}}\right)\right]\right]\end{aligned}\right\} \quad (6)$$

$$B_j = \frac{1}{2}\left[b_{j-1} + b_j\right]. \quad (7)$$

For mixed mode propagation the Ed - distribution along the delamination front gives important information about the growth initiation. The expression of the Ed can be written as:

$$E_d = \left(\frac{G_I}{G_{I_{CR}}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{II_{CR}}}\right)^{\beta} + \left(\frac{G_{III}}{G_{III_{CR}}}\right)^{\lambda}. \quad (8)$$

When $Ed \geq 1$ at a particular location, the delamination growth is supposed to take place during the simulation at that location.

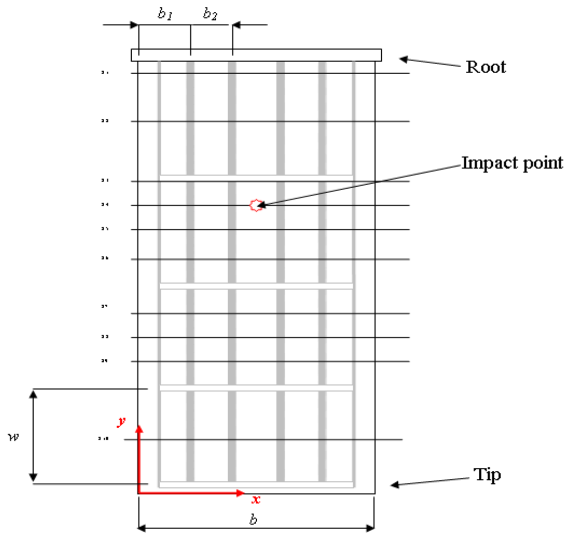

Fig. 2

Application

As an application of the above mentioned theory, the optimized composite wing – box selected within the DAMOCLES II project (WEAG JP 3.29) have been analyzed. In Figure 2 a geometric description of the selected wing box is shown. An impact point located at x= b/2; y=11/4w. has been considered.

For an impact energy of 35 J, the equivalent delamination radius has been found to be 6,7 mm. According to the most critical location for the interlaminar shear, the delamination has been placed between the 5^{th} and the 6^{th} layer along the thickness.

The all composite wing box has been modelled by using the ANSYS code. The eigth-noded layered shell elements (SHELL 99) have been used for skin, doublers, spars, stringers and L-shape attachment flanges. Not all the shell elements have been placed at the mid-planes of the wing box componelts. indeed in order to simulate the real distribution of the layers in the structure, offset shell elements have been adopted to model the upper skin at the root (bay 1 and doublers) the lower skin while mid-plane shell elements have been adopted in the rest of the upper skin

(Bay 2, bay 3 and bay 4) due to delamination modelling constraints. Non linear coupling conditions at the interface between offset and mid-plane shells and between the spar, stringers and skin have been introduced. In Figure 3 a schematic representation of the position of shell elements along the thickness in the whole wing box model, is presented.

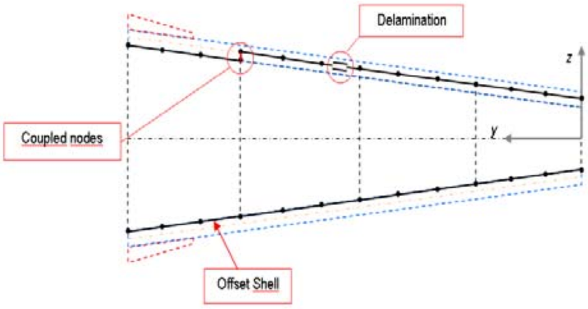

Fig. 3

A Full Fem model representation is shown in figure 4.

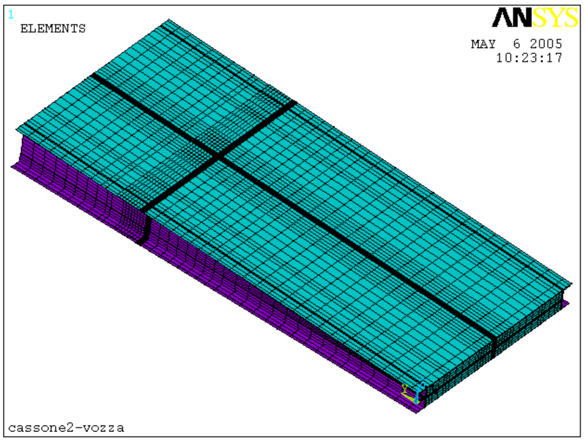

Fig. 4

A close view of the delamination can be appreciated in figure 5.

Analysis of results

The model has been fully constrained at the root and a vertical tip displacement has been applied at the tip to give a simplified representation of the in - service loads.

In figures 6 and 7 the obtained results in terms of deformed shapes, for a tip displacement 41.7 mm and 101.2 mm are introduced.

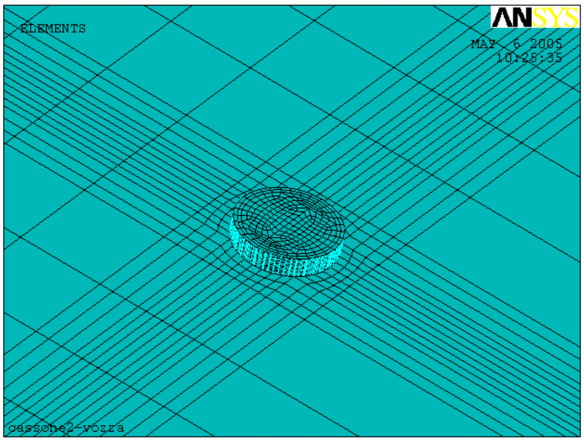

Fig. 5

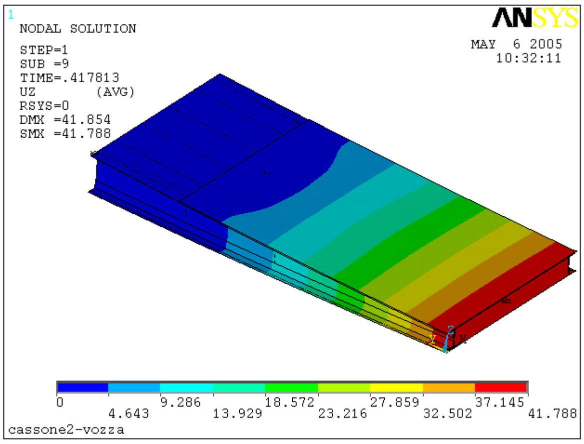

Fig. 6

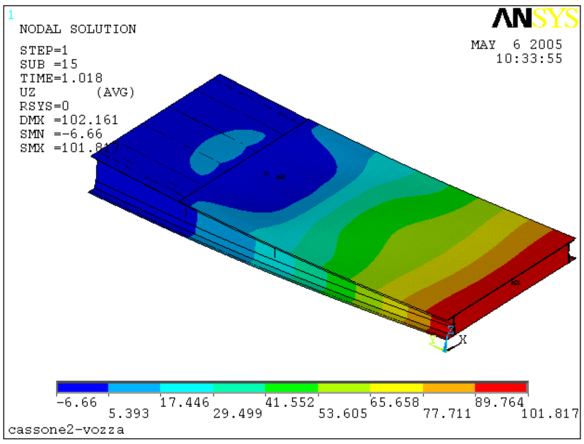

Fig. 7

In figure 7 it is possible to note that the structure bends inward in the second bay (from the root) and outwards in the third bay.

The load applied at the tip able to produce a constant distributed compressive load of 1500 N halfway the second bay, has been considered as the reference load. For this configuration this load was found to be 160 kN and the load acting on the wing-box is presented as a fraction of it.

The Force-Displacement diagram of the tip of the wing box shows a non linear behaviour at a load factor of about 0.6. (Figure 8).

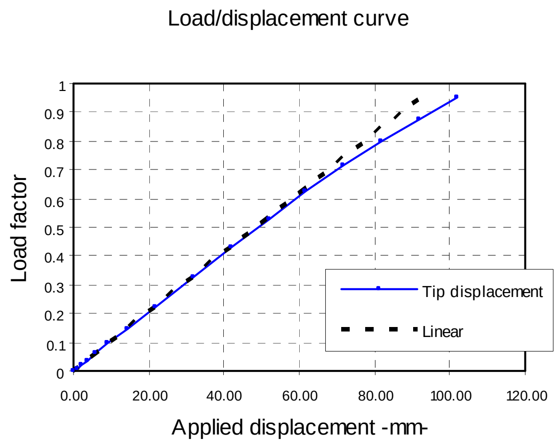

Fig. 8

The delamination growth has been found to take place for a tip displacement of about 41 mm.

In figures 9, 10 and 11 the deformed shapes of the delaminated area at delamination growth initiation, for the Ux, Uy and Uz displacement are presented.

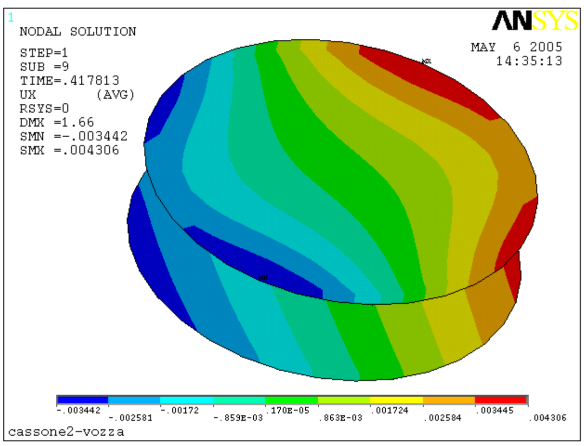

Fig. 9

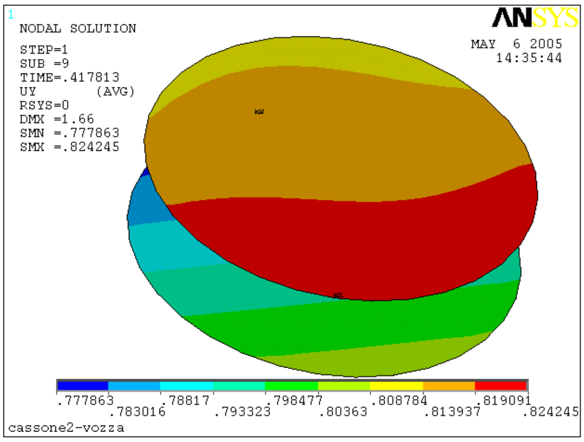

Fig. 10

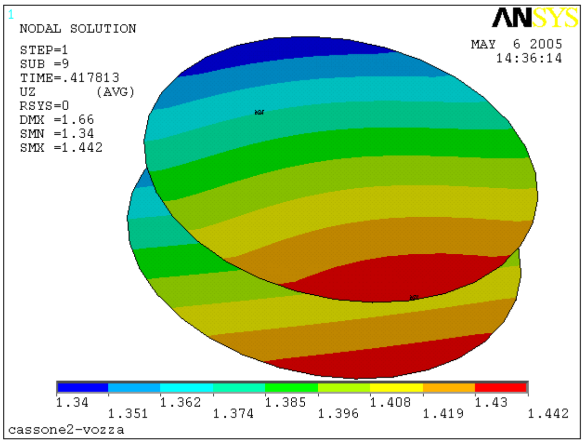

Fig. 11

Figures 12 and 13, show the Load/out of plane displacement curves at centre of delamination and at the middle of the upper panel in the second bay.

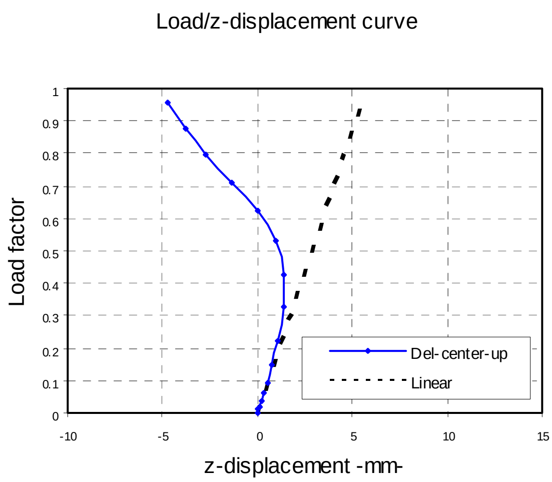

Fig. 12

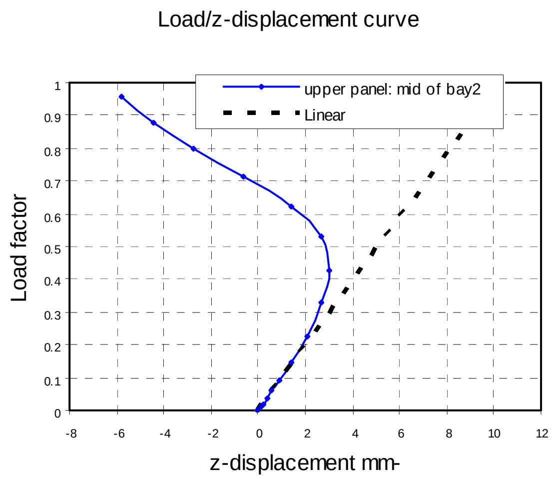

Fig. 13

From the previous figures it is clear that the delamination growths following the mode II because no relevant differences in the Uz displacements between upper and lower sublaminates are appreciable.

This is also confirmed by the energy release rate distributions.

In the followings diagrams, figures 14 and 15, the different components GI, GII and GIII distributions of the "energy release rate" along the delamination front (Fig. 14) and the distribution of Ed. (Fig 15) are presented.

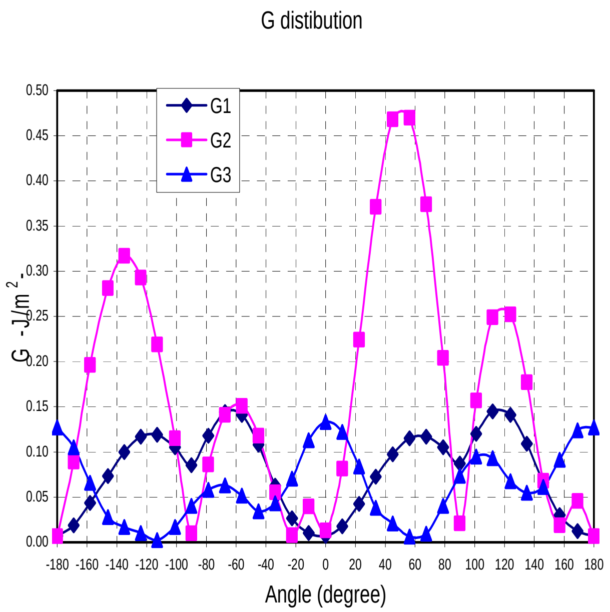

Fig. 14

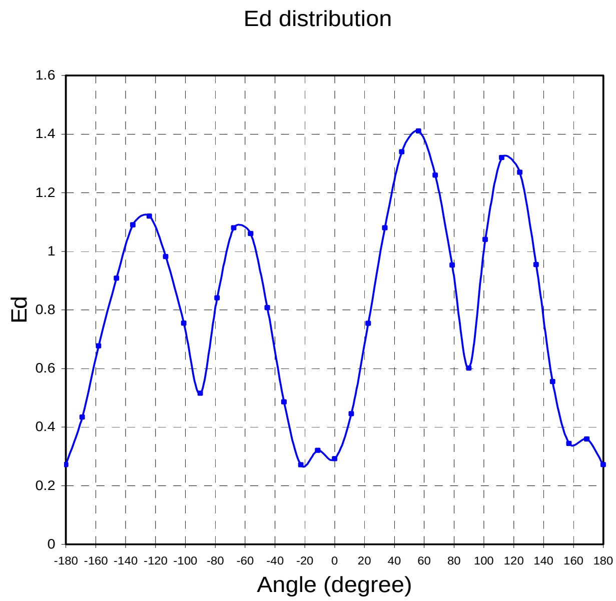

Fig. 15

From figures 14 and 15 it is noticeable that the main contribution to the delamination growth is given by the second component, G_{II} , that reaches the maximum value, about 0,48 J/m^2 of "strain energy release rate" between 40 and 60 degrees measured starting from the "X" axis of the global model.

The other components G_I and G_{III} don't overcome the limit of 0.15 J/m^2. This pronounced contribution of the second component influences the distribution of Ed that reaches its maximum value in the same degree range (50° - 60°). According to figure 14 the delamination growth initiation has been predicted between -110° /10°, -70°/-55°, 30°/80° and 100°/130°.

Concluding remarks

An effective tool for the simulation of the onset and growth of impact induced delamination in composite wing boxes has been introduced.

An application to the composite wing box designed, manufactured and tested in the DAMOCLES II project has been presented.

The simulation of the impact on the wing box has shown, as we expected to found, very high values of the damage resistance for the impact point under consideration. This is proved by the very small radius (6,7 mm) of the equivalent delamination induced by a value of the impact energy of about 35 J.

Due to the size of the delamination and due to its position along the thickness, the growth initiation has been found to be driven by the mode II of fracture.

This kind of information about the delamination growth load and mode in such complex composite structures can be extremely important when counter measures have to be adopted to predict the growth initiation (though the thickness reinforcements etc.).

Acknowledgments

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