

Prediction of the effect of temperature on impact damage in carbon/epoxy laminates

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Abstract. The effect of temperature on impact damage in Carbon Fiber Reinforced Plastic (CFRP) tape laminates produced by low velocity impact was studied by numerical simulations made to model drop weight tower impact tests on carbon/epoxy laminate composites. The damage model was implemented into a user subroutine of the finite element code ABAQUS. The model takes into account the thermal stresses resulting from the different thermal expansion coefficients in each ply of the laminate. The tests and simulations show how temperature affects the propagation of each damage mode. Matrix cracking and delamination are greatly affected by low temperature, while matrix crushing and fibre failure appear only in a small region at all the impact energies and test temperatures.

1. INTRODUCTION

Fibre reinforced plastics such as carbon/epoxy laminates are widely used for structural applications, in particular in the aerospace and aeronautical industries. During their operational life in these applications, the CFRP are subjected to low temperatures that could modify the mechanical properties of the material: cryogenic tanks, high-flying aircraft (-60 °C) and spacecraft orbiting the Earth (-150 °C when not exposed to solar radiation). At the same time, they can be exposed to impact loading. Unfortunately, carbon/epoxy laminates are very sensitive to low velocity impact, such as that of a drooped tool, which can damage the laminate and may result in catastrophic failure [1].

The behaviour of carbon fibre/epoxy laminates subjected to impact loads at room temperatures has been studied [2-7], but that of CFRPs under impact loading at low temperature is still an open question.

Considerable effort has gone into the numerical modelling of impact behaviour in composites [8-10]. Although different approaches to the analysis of impact events are available, finite element analysis based on accurate constitutive models provides the most detailed information on the spatial and temporal distribution of impact damage. The models differ in their formulation of the failure criteria used to signal the onset of damage in a ply, but most of the work published on this subject has neglected the interactions between the failure modes [11-13]. To take into account matrix cracking and fibre failure as stress raisers at laminate interfaces, and the influence of fibre failure, matrix cracking and through-thickness compression in delamination, Hou et al. [12] coupled the Chang-Chang failure criteria [11] with the delamination criterion of Brewer and Lagace [14].

Here we evaluate the applicability of the Hou et al. criteria to predicting the non-penetrating impact response of CFRP laminates at room and low temperatures, and to determine the influence of low temperature on impact damage, taking into consideration the thermal stresses in the laminate.

2. SOME EXPERIMENTAL EVIDENCE

We impacted CFRP laminates at 20, -60 and -150 °C using a drop weight tower with a climatic chamber. The specimens tested were $[0/90]_{3S}$ and $[+45/-45/0/90]_S$ plates of AS4/3501-6 tape (fibre volume fraction 0.6). The dimensions of the coupons were $80 \times 80 \text{ mm}^2$, of 2.3 or 1.6 mm thickness of the cross-ply and quasi-isotropic laminate. The impactor was a 3.62 kg steel rod with a spherically ended nose 20 mm in diameter, and impact energies ranged from 1 to 5 J. C-Scan inspection of the impacted specimens showed a clear influence of temperature on the damage extension: At -150 °C the damaged zone increased up to 50% compared to that at room temperature (Figure 1).

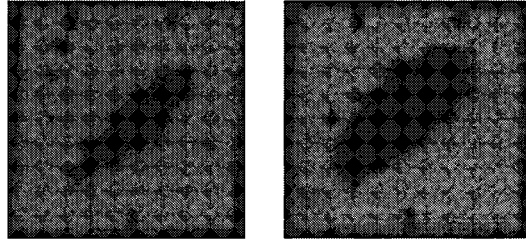


Figure 1. C-Scan image showing damage extension in the cross-ply laminate impacted at 4 J. 20 °C (left) and -150 °C (right).

3. NUMERICAL MODEL

3.1. Model Mesh

The above-mentioned tests were simulated with ABAQUS/Explicit finite element code to determine the effect of the thermal conditions on the generation and propagation of the different types of damage. The finite element model was based on the experimental device. The element type is an 8-node solid element with one integration point. The laminate was modelled with one element per ply, and a refined mesh was used in the vicinity of the impact zone. Boundary conditions were imposed on some surface nodes to simulate clamping. For simplicity, the impactor was modelled as a rigid body. Contact was applied between the plate and the impactor, whose initial velocity was 0.71 to 1.82 m/s. The model is shown in Figure 2.

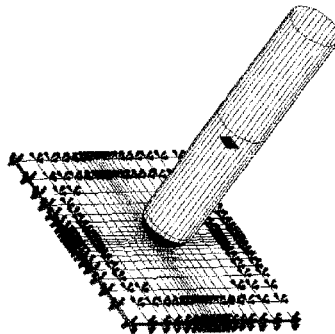


Figure 2. FEM model of the drop weight tower test.

3.2. Model material

The composite failure material model used is based on the Hou et al. quadratic criteria [12]. It considers four failure modes, each linked to a *damage factor*. When the value of a factor equals one, some stresses are set to zero (Table 1). Before failure, the material is considered as orthotropic linear elastic. The constitutive thermoelastic equation, as well as the failure model was implemented into the user material subroutine of the ABAQUS code. The elastic properties of the ply (Figure 3) and the strength values of the failure model (Table 2) at the three testing temperatures were obtained from the literature [15-19 and from Hexcel Composites].

Table 1. Hou et al. failure model.

Failure type	Damage factor equation	Stresses set to zero
<i>fibre failure</i>	$e_f^2 = \left(\frac{\sigma_1}{X_T}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{13}^2}{S_f^2}\right)^2$	$\sigma_1, \sigma_2, \sigma_3, \tau_{12}, \tau_{23}, \tau_{13}$
<i>matrix cracking</i> (for $\sigma_2 \geq 0$)	$e_m^2 = \left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{m23}}\right)^2$	σ_2, τ_{12}
<i>matrix crushing</i> (for $\sigma_2 < 0$)	$e_m^2 = \left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\frac{\tau_{23}}{S_{m23}}\right)^2$	σ_2
<i>delamination</i> (for $\sigma_3 \geq 0$)	$e_d^2 = \frac{1}{4} \left(\frac{\sigma_2}{S_{12}}\right)^2 + \frac{Y_C \sigma_2}{4S_{12}^2} - \frac{\sigma_2}{Y_C} + \left(\frac{\tau_{12}}{S_{12}}\right)^2$	$\sigma_3, \tau_{23}, \tau_{13}$

Table 2. AS4/3501-6 ply strengths at the three testing temperatures for the Hou et al. damage model.

Temperature	Strengths (MPa)								
	X_T	Y_T	Y_C	Z_T	S_{12}	S_{13}	S_f	S_{m23}	S_{l23}
20 °C	2137	80	160	160	105	105	135	105	84
-60 °C	2137	86	158	158	121	121	151	151	100
-150 °C	2138	97	155	155	139	139	169	139	118

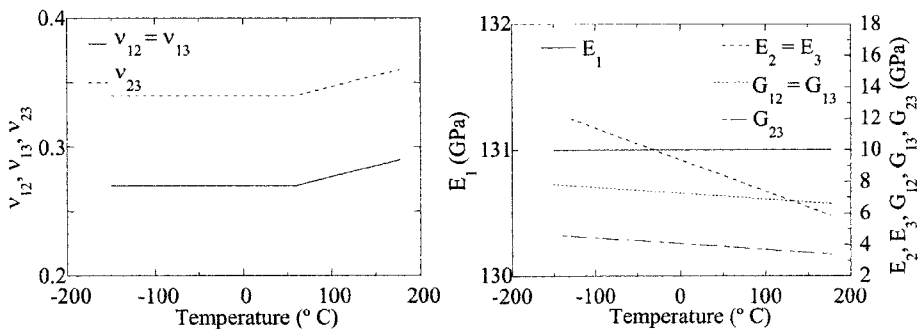


Figure 3. Variation with temperature of Poisson coefficient (left) and elastic moduli (right) of an AS4/3501-6 tape ply.

4. SIMULATION RESULTS

The simulation of the impact problem permitted a detailed analysis of the generation and propagation of damage. Figures 5 to 8 show the evolution during impact of the four damage factors considered in the Hou et al. model (e_f , e_m , e_d , e_l). The four corresponding contours are plotted on a quarter of the laminate mesh (Figure 4) at two different times of an 8 milisecond impact process. Matrix cracking and crushing start soon on the face impacted by the striker, due to the high local compression stresses. While crushing is confined to the upper face close to the contact surface, matrix cracking develops extensively in the lower plies under the tensile stress generated by the bending of the plate. These cracks propagate along the plies and through-thickness. Delamination occurs in the intermediate plies (layers subjected to high shear stresses), close to the impact zone due to the transverse and through-thickness tensile stress induced by contact, and also in the lower plies with the propagation of matrix cracking. Fibre fracture appears close to the contact zone and in the lower plies as a consequence of high in-plane stresses. This damage distribution, predicted by the numerical model, agrees with experimental observations of the specimens inspected after impact.

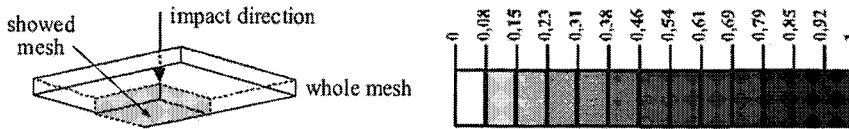


Figure 4. Left: mesh showed in Figures 5 to 10. Right: contour values for damage factors in Figures 5 to 10.

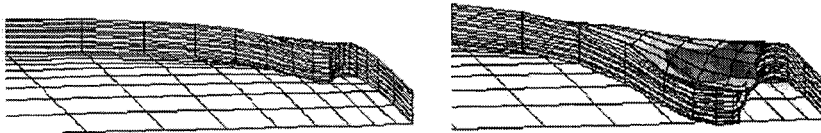


Figure 5. Fibre failure contours for a 6 J impact on a $[0/90]_{35}$ laminate at 20 °C. Left: 2 ms. Right: 6 ms.



Figure 6. Matrix cracking contours for a 6 J impact on a $[0/90]_{35}$ laminate at 20 °C. Left: 2 ms. Right: 6 ms.

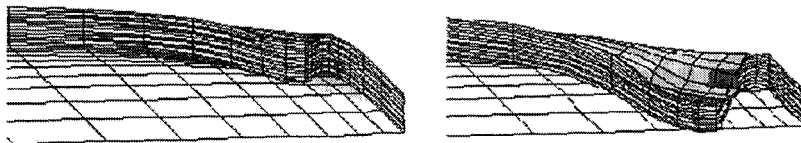


Figure 7. Matrix crushing contours for a 6 J impact on a $[0/90]_{35}$ laminate at 20 °C. Left: 2 ms. Right: 6 ms.

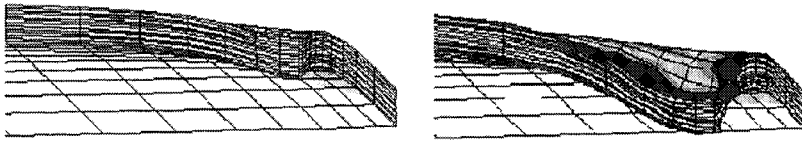


Figure 8. Delamination contours for a 6 J impact on a $[0/90]_{3S}$ laminate at 20 °C. Left: 2 ms. Right: 6 ms.

Once the material model showed its ability to predict damage generation and propagation in CFRP specimens subjected to low velocity impact, the effect of the low temperature was examined. The cooling process before impact was simulated with ABAQUS/Standard, and the subsequent impulsive load with ABAQUS/Explicit. Thermally induced stresses before impact affects damage factors, and although most are small, that corresponding to matrix cracking could be relatively high (60% of the critical value at -150° C). This means that matrix cracking develops easily when the specimen is impacted at low temperature (Figure 9). As matrix cracks precede delamination, the extension of this damage is also greater at low temperature, as is shown by the contours depicted in Figure 10.



Figure 9. Final matrix cracking contours of a $[0/90]_{3S}$ laminate impacted at 20 °C (left) and -150 °C (right). Impact energy: 3 J.



Figure 10. Final delamination contours of a $[0/90]_{3S}$ laminate impacted at 20 °C (left) and -150 °C (right). Impact energy: 3 J.

5. CONCLUSIONS

The Hou et al failure model for fiber-reinforced composite material was implemented into a commercial finite element code to predict the growth and extension of damage in CFRP laminates subjected to low velocity impact. The damage distribution predicted by the model agrees with the experimental results; failed fibres, matrix cracks and delaminated surfaces detected by inspection of the tested laminates were located in the same zones in the numerical model.

Low temperature has a marked effect on the failure of CFRP: both matrix cracking, due to the high in-plane thermally induced stresses, and delamination develop earlier during impact at low temperature and the damage extends more widely.

Acknowledgements

The authors are indebted to the Spanish Comisión Interministerial de Ciencia y Tecnología (Project MAT-98/0273) for the financial support of this work.

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