IMPACT DAMAGE IN WOVEN FABRIC REINFORCED COMPOSITES

R. Akkerman, L.L. Warnet & E.C. van de Ven
Composites Group, Dept. of Mechanical Eng., University of Twente
P.O. Box 217, NL-7500 AE Enschede, the Netherlands

INTRODUCTION

Very often, woven fabrics are used as the reinforcement in advanced composite materials. Although the resulting inplane stiffness is lower than of their unidirectional counterparts, the excellent drapability of these materials eases the production of more general doubly curved components. In addition, the inherently low out-of-plane strength of these layered materials improves due to the undulating yarns.

This paper considers both the initiation and growth of defects in these woven fabric reinforced plastics. Ten Cate Advanced Composites' 5H Satin carbon reinforced PPS is taken as the model system. A 5H satin fabric exhibits very good drapability and PPS has a low viscosity above its melting point, enabling good yarn impregnation. Apart from this PPS has approved solvent resistance for aerospace applications and good temperature resistance. For a thermoplastic matrix, however, the material is fairly brittle.

DAMAGE DEVELOPMENT

Three regions can be distinguished in a cross section of the woven fabric reinforced composite: fill yarns, warp yarns and pure resin (Fig.1).

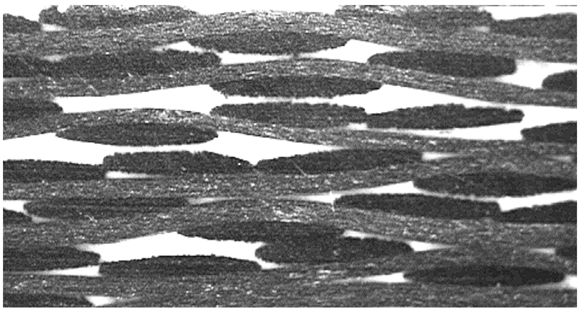

Fig.1 Microscopic image of a cross section of an undamaged 0°/90° woven fabric reinforced PPS laminate

The possible damage mechanisms in the composite are distinguished as matrix cracking, interyarn fracture (a delamination type failure) and intrayarn fracture. The interyarn delaminations can occur within one fabric layer or between two subsequent plies. In order to classify the intrayarn fracture types, we use the standard yarn coordinate system: *1* is the average fibre direction, *2* is normal to the fibre direction in the plane of the laminate and *3* is normal to the plane of the laminate. Three basic intrayarn fracture types are distinguished: transverse cracks in the yarn (in the *13*-plane of the yarn); inplane yarn splitting (in the *12*-plane) and fibre fracture (*23*-plane).

Each basic damage mechanism will have its own specific failure criterion. Stress-based failure criteria are often used for crack initiation, either on a macroscopic level (considering the composite as a homogeneous orthotropic material) or on a microlevel (distinguishing between the separate constituents) (2,3). Certainly for damage growth transverse to the fibres (1) an energy-based criterion seems more appropriate.

EXPERIMENTS

As a preamble to the impact analysis quasi-static bend tests were performed on nominally 12×50×3.4mm beam specimens. In the $[90°/0°]_{5s}$ specimens (having the 90° orientation of the 5H satin fabric predominately on the surface) the first damage starts on the tensile face as transverse cracks in the yarns. These cracks grow uncontrolled until being arrested at the yarn crossover points. During testing they were observed in the 90° yarns only (Fig.2[A]), post-testing inspection also showed cracks of the same type in the 0° yarns (Fig.2[B]). In the $[0°/90°]_{5s}$ specimens the first cracks occurred on the compressive face as microbuckling (of .2mm length over the width of several yarns, Fig.2[C]). In $[-45°/45°]_{5s}$ specimens firstly transverse cracks develop on the tensile face, both in the -45° and +45° yarns, which are later on connected by matrix cracks in the 90° direction. Increasing the load leads to fiber fracture and transverse cracks on the compressive face.

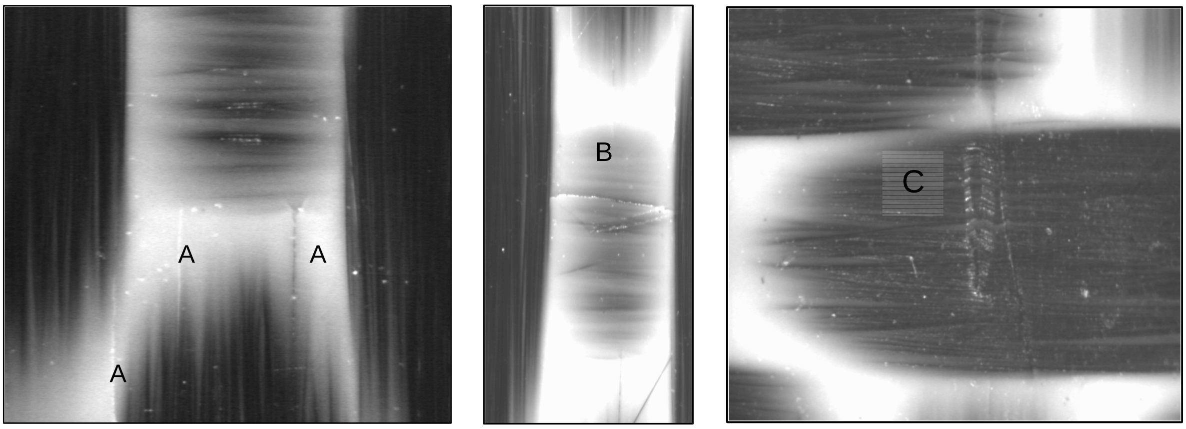

Fig. 2 Damage initiation in quasi-static beam bend tests; A: transverse cracks in the predominate 90° yarns on the tensile face; B: transverse cracks in the 0° yarns on the tensile face; C: microbuckling in the predominate 0° yarns on the compressive face.

Also a 100×150×3.4mm $[-45°/45°]_{5s}$ plate was loaded transversally under quasi-static conditions. Here the initial damage was similar to the $[90°/0°]_{5s}$ beams, with transverse cracks in the predominate yarn direction between cross-over points. Increasing the load leads to crack extension past the crossover points on the tensile face.

Secondly, the critical energy release rate under mode *I* crack growth, G_{Ic}, was determined according to the Esis protocol (4). Both $[90°/0°]_{4s}$ and $[0°/90°]_{4s}$ specimens were tested. The crack followed the yarn/matrix interface in the 0° direction, with the 90° yarns acting as crack stoppers. Averaged values of 250 J/m^2 and 325 J/m^2 were found on the predominately 0° and 90° interface respectively.

Instrumented Falling Weight IMpact (IFWIM) tests were performed on 3.8mm thick quasi-isotropic laminates of 100×150mm size. A range of 5,9,16 J impact energy levels was used. The damage was assessed by subsequent ultrasonic inspection and microscopic evaluation of the surfaces and cross sections.

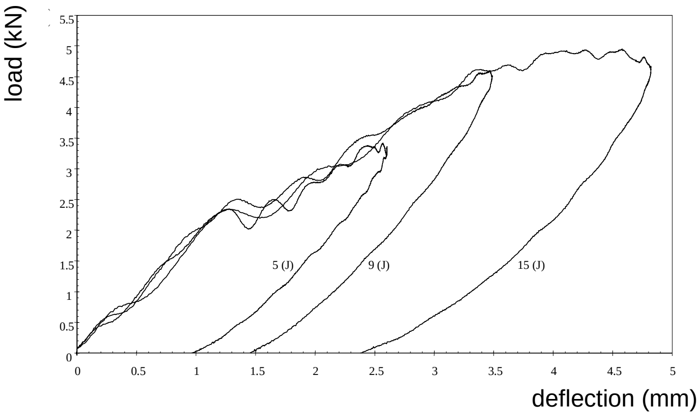

Fig. 3 Load-deflection curves from IFWIM experiments at 5,9,15 J incident energies.

At a force level of 2.5 kN and a deflection of 1.25mm the load-deflection curves (Fig.3) show a clear change in stiffness, indicating some form of structural degradation of the laminates.

At the lowest impact energy mainly matrix cracks were observed on both the tensile and the compressive face, accompanied by some transverse cracks in the *12*- and *13*-planes. Interyarn delaminations occurred mainly within the fabric layers. The amount of every type of damage increased with the impact energy. For the higher energies also fibre fracture (in the *23*-plane) was observed.

ANALYSIS

Three-dimensional finite element simulations were performed on simplified (sinusoidal) woven fabric geometries to estimate the local stress state. Residual stresses were taken into account, estimating that stress build-up starts from the glass transition temperature at 90°C. A proper description of the crystallisation of PPS (and the resulting residual stresses) is still under development. These simulations indicated that for the transverse loading on the 100×150mm plates the von Mises stress soon exceeds the matrix strength on the yarn interface, near the tensile face of the laminate. In the same region also the transverse stresses in the yarns were considerable.

Further simulations were performed in two dimensions, to estimate the order of magnitude of the possible energy release rates due to crack growth. Now the yarn cross section geometry was simplified to a hexagonal shape in order to prevent excessive element distortions. An exact solution for the displacement field for a centrally loaded rectangular elastic plate was imposed on the laminate midplane nodes.

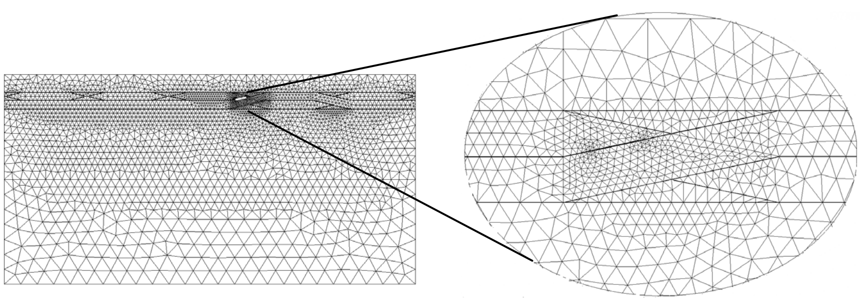

Fig.4 Finite Element mesh of a fabric layer with a tilted interyarn crack, with homogeneous material outside the layer.

Cracks were modelled using singular crack tip elements as well as contact elements to prevent penetration of the two crack faces. Four different interyarn cracks were modelled within one fabric layer, of which the position was varied in order to find the maximum energy release rates.

Subsequent crack growth was analysed using Virtual Crack Closure and Virtual Crack Extension methods. Horizontal cracks (in the *12*-plane) have a relatively low energy release rate. Cracks under a small angle with the *12*-plane (Fig.4) show a significantly larger energy release rate (G). This G-value increases with the distance to the laminate midplane, and it is slightly higher at the tensile face of the specimen than at the compressive face. All interior cracks are shear dominated, having a large G_{II} component. The highest energy release rates were found for cracks that have an open end at the surface of the specimen. At a central deflection of 1.25mm a value of G=184 J/m^2 was found (for comparison: neglecting the internal stresses results in a value of 150 J/m^2) for the tilted crack on the surface, now with only a 30% G_{II} contribution.

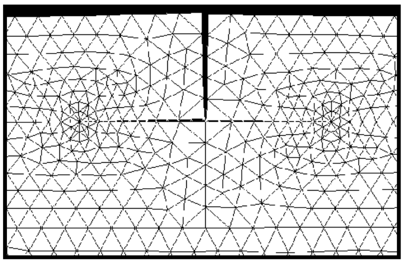

Fig. 5 Detail of the FE mesh for the analysis of delamination growth in the presence of a transverse crack.

As a subsequent exercise the effect of a transverse crack was studied for a 'horizontal' 0.2mm long interyarn delamination (Fig.5). The same central deflection now leads to an energy release rate of 208 J/m^2 (without the transverse crack G=10 J/m^2), approaching the average critical energy release rate in the DCB experiments. This 2D modelling does, however not take the crossover points into consideration, hence neglects the crack arrests at the surface.

DISCUSSION

Damage initiation in woven carbon fabric reinforced PPS under transverse loading was observed as matrix damage and transverse cracks in the yarns. This can be explained in terms of stress criteria. For the growth of interyarn defects energy criteria appear to be applicable. According to these criteria, internal delaminations can grow at larger deflections, as observed in experiments. When surface defects are present, energy criteria predict interyarn delaminations, also in accordance with the experimental data. A more precise description requires three-dimensional crack growth modelling as well as the critical stress and energy values on the microscale.

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