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Discrete ply modelling of open hole tensile tests

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ABSTRACT

The Discrete Ply Modelling (DPM) method, previously applied with success to out-of-plane loading such as impact or pull-through, is used to model open hole tensile tests. According to the literature, this kind of test is relevant to assess the efficiency of a modelling strategy. Four different stacking sequences are tested and the failure scenario and patterns are well predicted. The main advantages of DPM are the very small number of parameters required and the robustness of the models. The main drawback is the computation cost.

1. Introduction

The open hole tensile test is a challenge for the virtual testing of composites [1]. The complex failure modes and patterns described, for example in US-Mil-Hbk 17 [2], depend on many parameters, such as fibres and resin, stacking sequence, hole diameters, Width/Diameter ratios, ply thickness, and others. To correctly model this test, the approaches should be able to find the failure scenarios and, especially, to capture sub-critical damage developing before the final failure of the specimen [3]. Modelling strategies must not only be able to take account of the damage modes of laminated structures (fibre breakage, matrix cracking and splitting, delamination) and their interactions but also capture the stress gradients at the hole edge. This papers aims to apply the method of Discrete Ply Modelling (DPM), originally developed for the impact on laminates, to the open-hole tensile test. In recent years, many of the latest modelling techniques have been applied to this test case. Hu et al. [4] used it to demonstrate the effectiveness of peridynamics [5] for modelling fracture in laminates. Abisset et al [6] tested a damage meso-model on the experimental results of Hallet and Wisnom [1,3]. Despite good correlation, the authors pointed out that models based on damage mechanics have difficulties in correctly representing the splitting and intra- and inter-ply interactions otherwise than by ad hoc coefficients. This point has also been highlighted by Van der Meer and Sluys [7].

Therefore, several modelling strategies have recently been developed to better take the discontinuous nature of the damage in laminates into account. In 2008, the method of discrete ply modelling was proposed by Bouvet et al. [8] for modelling low velocity/low energy impacts on laminates stacked with unidirectional plies. A refined and complex mesh is made with an element per ply and interfaces for matrix cracking and delamination. In this way, the coupling between intra- and inter-laminar damage is naturally taken into account. Mapping areas of matrix cracking chosen a priori assumes that diffuse damage is not taken into account. Moreover, only through-the-ply cracks are assumed to be important for damage propagation. This approach predicts splitting very correctly and naturally, as was shown when it was applied to pull-through [9]. In this case, however, the edge of the hole was not correctly modelled and this point should be improved. In the latest developments of the approach, its robustness has been validated [10]. It has been extended to compression after impact [11] by a modification of the breaking law of fibre in compression. Finally, by considering the non-closure of matrix cracks, permanent indentation after impact can be calculated [12]. This type of discrete modelling has also been used by Wisnom and Hallet [1] to model the failure of open-hole specimens. However, in this first approach, the paths of possible failures are limited.

Other researchers have tried to take account of the discrete nature of the damage of composite structures. Prabhakar and Waas [13] propose a triangular finite element enabling matrix crack failure by a splitting of the element in two parts. The approach has been validated on open-hole tensile test specimens fully oriented at 90°, 45° or 0°. This stacking limits the scope of the approach for the moment but, nevertheless, the use of elements enabling splitting is developing. Most of the very recent approaches are based on XFEM [14]. Van der Meer [15,16] uses phantom node elements (a variation on XFEM) to model matrix cracking. Associated with cohesive elements for delamination, this method eliminates

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the complexity of the mesh of DPM. This method has also been validated on open-hole tensile tests performed by Wisnom and Hallet [3]. Recently this approach has been extended to the representation of diffuse damage [17]. Iarve, Swindeman et al. [18–20] used regularized X-FEM, which differs from the previous approach by interpolation functions that are based on the integration of the initial Gauss scheme. According to the authors, the cracks remain "encapsulated" within the element and this provides a straightforward three-dimensional implementation. Once again, the open tensile test was used for validation and very good correlation was found with this approach. An analysis of the recent literature shows that recent research has been strongly oriented towards discrete numerical methods for modelling failures in laminates.

In this paper, open hole tensile tests are performed with four different stacking sequences and are analysed by means of the DPM method. The following section gives details of the tests and samples. Then DPM is presented and compared with experimental results. Failure scenarios and the influence of the position of the 0° plies are discussed.

2. Experimental analysis

The specimens were made from layers of unidirectional, intermediate modulus carbon/epoxy prepreg composites. Four types of stacking sequences were studied and are given in Table 1. Two laminates were highly oriented at 0° and the other two were quasi-isotropic with a different layout in thickness. The second orientation was obtained by cutting at 90° from the first. The choice of these layups was based on "benchmark" industrial laminates. The thicknesses ranged from 1.1 mm to 2.6 mm. The layups Iso-Q 1, Q 2-Iso-, oriented 1 and 2 were draped with 0.13-mm-thick plies and layup Oriented 1 was draped with 0.18-mm-thick plies.

The specimen geometry is given in Fig. 1, where the dimensions are in mm. A 4.2-mm hole was drilled at the centre. The machining quality was guaranteed by the use of new carbide tooling, with a sacrificial plate affixed and tightened on each side of the laminate to limit the damage (particularly delamination). The machining quality was verified by X-ray and no damage induced during drilling was found. The edges of the specimens were trimmed using a diamond disc. The absence of damage on the edges was checked with the aid of a binocular. Local reinforcement, made of 4 fibreglass plies at 0°, was bonded to the specimen. The quasi-static tests were performed at a speed of 1 mm.min^{-1} on a 100 kN Instron machine at ambient temperature and humidity (Fig. 2). The hole deformation was measured by an Instron extensometer fixed symmetrically to the median planes of the test specimens (Fig. 2). The forces applied were measured by the load cell of the machine.

Three tests were performed up to final failure for each layup. The dispersion found (CV) on the reference specimens was low (<4%) but, for the open-hole specimen, it was very low (<1%). It seems that the presence of the hole had the effect of reducing the variance. The moduli also showed little dispersion (<3%). The stress/strain experimental responses are plotted in Fig. 3. For each layup, the stresses were normalized. The four laminates had fairly

Table 1
Laminate stacking sequences.

Laminate	Lay up	Number of plies	Overall thickness (mm)
Oriented 1	[−45/0/0/45/0/90/45/−45/90/0/45/0/0/−45]	14	2.6
Oriented 2	[45/−45/0/0/90/0/0/−45/45]	9	1.143
Q-isotropic 1	$[0/45/90/-45]_{2s}$	16	2.1
Q-isotropic 2	$[90/-45/0/45]_{2s}$	16	2.1

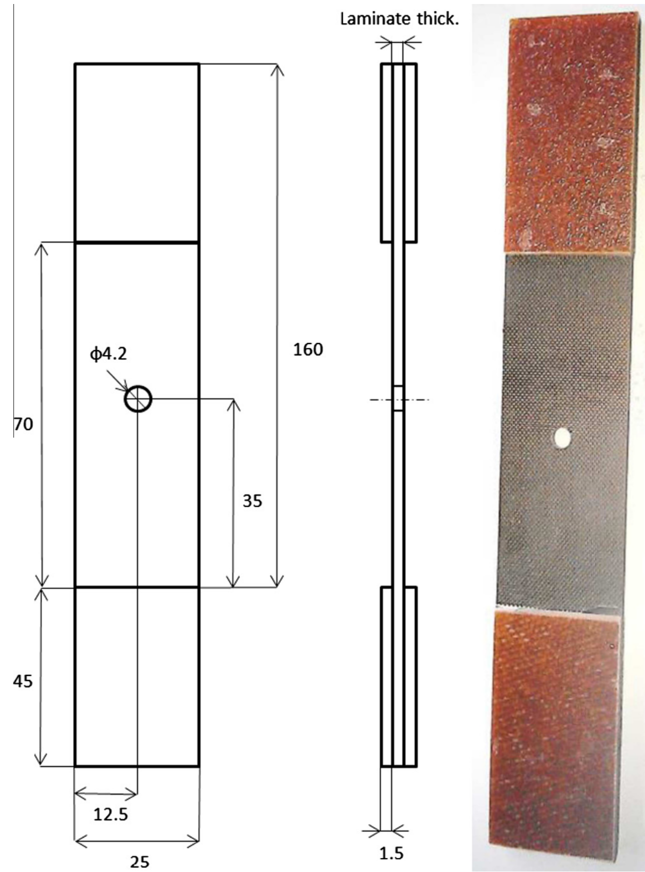

Fig. 1. Specimen description.

equivalent behaviour: a first linear response without apparent loss of rigidity followed by a chaotic plateau showing a series of damage events before final failure of the specimen. The sharp drop in force that occurred at the end of the plate is not shown on these curves because the extensometer could not capture it. For highly oriented specimens 1, the plateau was short. If structural failure is defined as the first occurrence where a load drop of more than 5% is recorded in a quasi-static test [9], the dispersion is very small (about 1%). Failure patterns and X-ray analyses that were performed on stopped tests are presented in the model validation subsection.

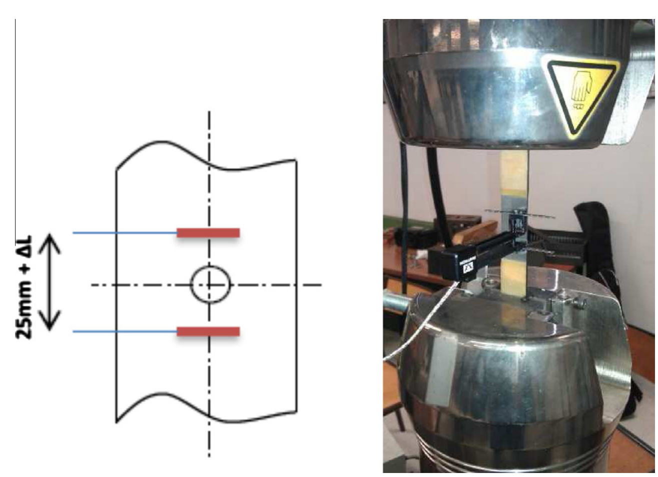

Fig. 2. Position of the extensometer on tensile specimen and view of the test.