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On the role of kinking in the bearing failure of composite laminates

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ABSTRACT

Fibre kinking is one of the main failure modes of composite laminates under compression loading. In this paper, the role of kinking in the failure of quasi-isotropic composites subjected to a bearing load is investigated. High-resolution CT scans show that kinking is largely involved in the events leading to laminate collapse, notably by triggering other damage modes such as delamination. Kink bands develop extremely progressively, leading to the formation of a wide localization zone (or FPZ, failure process zone). Such behaviour calls for a non-local modelling approach. Local damage models would lead to overly conservative sizing. A simple model, based on Hashin failure criteria and non-local effective stresses is confronted to experiments, and its limits are highlighted. It will be shown that proper modelling of the bearing failure requires the characteristic behaviour of kink bands to be taken into account.

1. Introduction

Bearing failure has been widely studied, both experimentally and numerically [1]. However, the complex nature of this failure mode still makes it a challenging test case for damage models [2]. Most experimental studies have focused on the bearing behaviour of pinned or bolted composite joints, with typical bearing strength (Eq. (1)) ranging from 400 MPa to 1000 MPa.

$$\sigma_{bearing} = \frac{F}{t \cdot d} \tag{1}$$

Thus, the boundary conditions pertaining to each joint configuration appear to have considerable influence on the bearing strength. The most influential ones are the lateral restraint due to bolt preloading [3], the bolt-hole clearance [4], or secondary bending for single lap shear joints. The damage mechanisms involved in the bearing failure of bolted joints have been studied by Xiao and Ishikawa [5], who showed that kinking (often referred to as fibre microbuckling) plays an important role in the failure process, as did Seike et al. [6]. Camanho et al. [7] showed that the progressiveness of the bearing failure could be explained by the accumulation of subcritical damage. They emphasised the role of delamination, suggesting the use of three-dimensional failure criteria, which they did in a later paper [8]. However, cohesive zone models do not seem to be an absolute requirement [9]. Despite the many models proposed in the literature, which are often based on traditional failure criteria [8,10–12], the sizing of composite joints is still mainly based on allowable bearing strengths obtained for different joint configurations.

Hence, there still is a need for improved failure models built upon a sound physical basis. Mutual feedback should be established between the numerical models and the experiments to look beyond the load–displacement curve. To do this, it would be desirable to use very simple experiments, such as pinned contact [13] or half-hole pinned bearing [14–17], in order to reduce the number of unknown or uncertain variables and to focus on the damage mechanisms. A more general knowledge of the bearing failure would also make it possible to diverge from the traditional bolt/rivet mechanical assemblies in specific industrial applications.

In this paper, bearing failure and the role of kinking are further investigated using a half-hole pinned bearing test and modern experimental techniques such as computed tomography (CT) and digital image correlation (DIC), for both woven and UD-fabric laminates, with the same epoxy matrix. An enhanced engineering failure model is then introduced, exhibiting large similarities with most of the existing failure theories dedicated to bearing failure simulation. The enhancement mainly stems from the use of an embedded non-local approach, which prevents an excessive impact of subcritical damage on the failure load. However, the aim of this paper is less to propose a new failure theory than to point out the deficiencies of such theories, and to suggest other

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modelling strategies based on the observed damage mechanisms, with a special emphasis on kinking, which will be shown to play a prominent role. The need for advanced damage models dedicated to the compressive failure of composite materials will be highlighted.

2. Experimental study

2.1. Experimental procedure

To study the intrinsic bearing behaviour, it was decided to carry out half-hole bearing tests. One of the main advantages associated with this kind of test is the fact that the full strain field on the free surface of the laminate can be obtained using digital image correlation (DIC). The small coupon size and the simple test set-up (Fig. 1) both help to render experiments simpler to analyse and models faster to run. The gauge length can be made arbitrarily small, so that global buckling problems are avoided.

The indenter, or "pin", was the aft part of a ϕ 6.35 mm Diager reamer, of the same type as the one used to ream holes after a three-step drilling process.

Two types of prepregged fabrics with the same resin system were chosen: a UD-fabric and a 4-harness satin weave (Fig. 2). The tows were made of 3 k HTA fibres, and the thermoset resin was a second generation toughened epoxy.

A quasi-isotropic layup $[90, +45, 0, -45]_{ns}$ was selected for both materials. The number of stacking sequences, n, was determined so as to obtain panels of similar thickness, which were laid-up by hand and cured in a press, at 180 °C under a pressure of 4 bars. The UD-fabric laminates were 4 mm thick and the woven-fabric laminates 3.75 mm thick.

An INSTRON 250 kN machine was used for the static tests. As strain softening was expected, tests were run under displacement control, with a displacement rate of 0.2 mm/min. A VIC-2D digital image correlation system was used, with an AVT Pike F505B camera having a resolution of 2452 × 2452 pixels. Stereo-correlation was not deemed necessary as the coupon mainly deformed in plane when not heavily damaged.

Three static tests were performed for both materials.

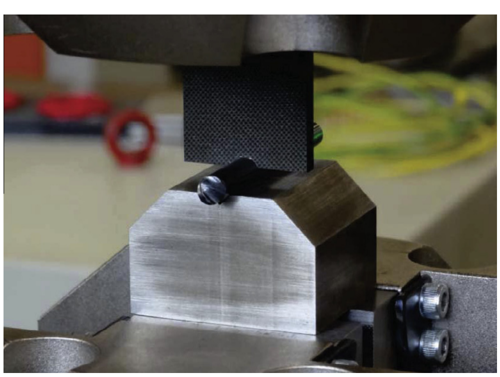

Fig. 1. Half-hole pinned bearing coupon and test set-up.

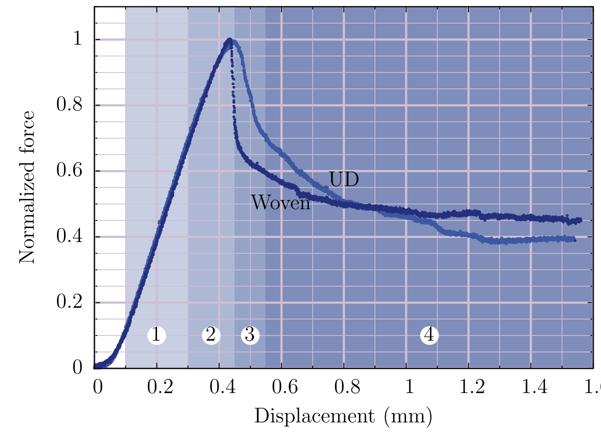

Fig. 3. Typical force–displacement data points for woven and UD-fabric laminates, with a quasi-isotropic layup.

2.2. Macroscopic bearing behaviour

The load–displacement curve (Fig. 3) showed four main behaviours and was repeatable.

1. The first part was essentially linear, except for the very beginning, where the non-linearity could be attributed to the existence of a small perpendicularity defect (<1°), as revealed by a careful analysis of DIC results. The initial non-linearity could not be explained by varying contact conditions in relation with clearance, since the hole and the indenter had the same diameter.
2. At about 70% of the peak strength, the load–displacement relationship became slightly non-linear.
3. Just after the peak strength, a sharp load drop occurred, accompanied by a loud cracking noise.
4. As displacement increased, the load then stabilized and oscillated around a residual value approximately equal to 40% of the peak strength, and it continued to do so even for displacement magnitudes of the same order as the hole radius. It was noted that this proportion was identical for UD-fabric and woven fabric laminates.

The failure point was easy to define, as a sharp load drop occurred just after the peak strength. Hence, there was no need to define a bearing failure strain, though this is defined in most

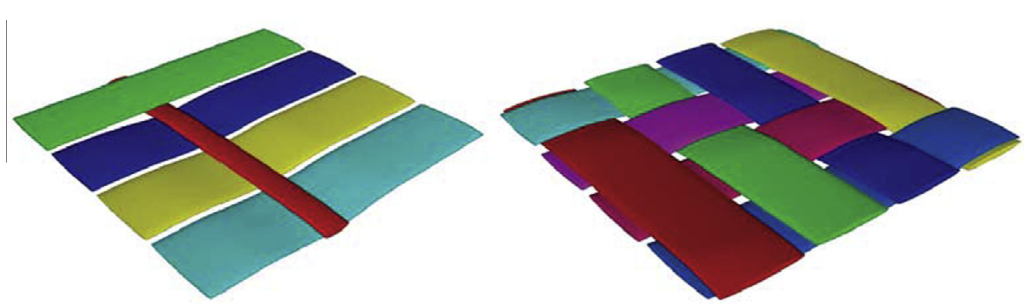

Fig. 2. Architectures of the UD (left) and woven (right) fabrics. The UD-fabric contains a small proportion of weft glass yarns.