Composite Structures 116 (2014) 94–103

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

# Effect of tow-drop gaps on the damage resistance and tolerance of Variable-Stiffness Panels

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## ARTICLE INFO

*Article history:*
Available online 19 May 2014

*Keywords:*
Carbon fibre reinforced polymer
Defects
Variable-Stiffness Panels
Automated Fibre Placement

## ABSTRACT

This paper presents an experimental study of the effects of tow-drop gaps in Variable Stiffness Panels under drop-weight impact events. Two different configurations, with and without ply-staggering, have been manufactured by Automated Fibre Placement and compared with their baseline counterpart without defects. For the study of damage resistance, three levels of low velocity impact energy are generated with a drop-weight tower. The damage area is analysed by means of ultrasonic inspection. Results of the analysed defect configurations indicate that the influence of gap defects is only relevant under small impact energy values. However, in the case of damage tolerance, the residual compressive strength after impact does not present significant differences to that of conventional straight fibre laminates. This indicates that the strength reduction is driven mainly by the damage caused by the impact event rather than by the influence of manufacturing-induced defects.

## 1. Introduction

Currently, most composite laminates for structural applications in aircraft programs are manufactured using only the traditional straight fibre configurations, which consist mainly of quasi-isotropic layups. As a consequence, neither the full advantage of the Automated Fibre Placement technology (AFP), available since the 1990s, nor the novel laminate concepts are being used efficiently [1]. The increasing trend toward the development of lighter structures based on an optimised use of composites with Non-Conventional Layups (NCLs) is possible by tailoring the direction and placement of fibre laminates—also referred to as variable angle tow composites.

NCLs are defined as disperse stacking sequence laminates [2], or layups, produced by steering tows that follow curved paths. They are also called Variable Stiffness Panels (VSP) [3]. In the past, researchers have studied the advantages of these VSP over conventional laminates and VSP have been proven to be effective in enhancing the buckling and post-buckling response by in-plane load redistribution [4–6]. Also, VSP showed potential for lessening notch sensitivity and for reducing stress concentration effects [7–10]. However, a better comprehension of the mechanical response, failure and damage mechanisms in VSP has prevented its extended application. In addition, due to the versatility and design complexity of VSP, the introduction of these advanced concepts will become feasible only if two major issues are considered. Firstly, by developing reliable design methodologies to predict the mechanical response from damage onset up to structural collapse. Secondly, by certifying VSP using high-level component tests in order to understand the process-induced defects.

Nowadays, there are efficient methodologies to design the optimal fibre orientation so as to maximise the structural efficiency of VSP [11–15], accounting for the manufacturing defects as well [16–18]. These defects appear during the tow-steering process and are inherent to the AFP head mechanism [3]. The process-induced defects include local tow buckling or wrinkling and thickness change due to tow-drop gaps or overlaps. These defects become potential spots for the initiation of matrix cracking or even delaminations [19], and are key issues which need to be addressed to guarantee performance. Another crucial problem in VSP is related to fibre discontinuities. It is worth mentioning that a novel fibre placement technique called Continuous Tow Shearing (CTS) [20] has been developed to avoid most of the problems mentioned above. This technology relies on the shear deformation capability of dry tows. Although this implies some thickness variation, the CTS technique avoids tow-drop defects and allows radii of curvature in the order of tens of millimetres.

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http://dx.doi.org/10.1016/j.compstruct.2014.05.005
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Experimental tests are needed to evaluate the influence of the gap or overlap defects originated in the real AFP environment. A wide variety of failure and damage mechanisms appear in the NCLs as a result of design complexity and manufacturing process. In order to fully exploit the possibilities of NCLs and their use in composite structures, the effect of process-induced defects requires specific attention. In the past, researchers have studied the effect of converging gap defects [21,22]. These studies demonstrated that the un-notched tension and compression tests showed significant reductions in strength due to the gaps. Whereas, open hole tension tests were unaffected by the presence of gaps. This was attributed to the hole effect dominating the gap effects. It also was demonstrated that the compression tests are more sensitive to the gap defects than the tension tests are. In addition, failure predictions depended on the gap locations and the number of gaps. Another author, Nicklaus [23], demonstrated that the presence of gaps produce higher fracture toughness values in the areas close to the hole.

Recently, Croft et al. [24] presented an experimental study quantifying the effect of the main manufacturing-induced single defects under tensile, compression and shear loading. Their work reveals that the in-plane shear strength decreased when there was tow-overlapping along the perpendicular direction to the load. A further study on the influence of tow-drop gap defects, gap-coverage parameter and the staggering technique under in-plane tensile loading in VSP has been presented by the present authors (Falcó et al. [25]). That work shows that the configurations where gaps are not covered and plies are not staggered present the most critical strength reduction as a consequence of the clustering of gaps. Large delaminations are initiated in the vicinity of the tow-drop defects, which are then followed by extensive matrix cracking and finally fibre failure. The present contribution deals with a similar sub-domain of VSP, but focuses on the damage resistance and damage tolerance to a drop-weight impact event.

Damage tolerance to low-velocity impacts is a key factor in the design of the majority of aircraft structures due to the low out-of-plane strength of the composites. Such impacts can happen during manufacturing, servicing or maintenance operations. Several experimental investigations have studied the damage response of dispersed laminates to low-velocity impact, and their improvement over conventional laminates [19,26,27]. The differences are related to the effects of bending stiffness, ply clustering and mismatch angle between the plies. It has been demonstrated that the dispersion of ply orientations through the whole $[0^\circ - 90^\circ]$ range has beneficial effects in terms of impact resistance [28]. By reducing the mismatch angles between the adjacent layers, the response presents smaller indentation—which reduces the damage detectability—, less damage dissipated energy, smaller delaminations and higher residual strength. In addition, even for laminates with good stiffness properties, the clustering of plies can lead to large delaminations because there are less potential interfaces for delaminations, resulting in a lower damage resistance of the structure [29].

In VSP, all these aspects are combined in a more complex environment which includes process-induced defects. Additionally, mismatch angles appear not only between adjacent layers, but also within the plies, between adjacent shifted courses. Impact events in VSP is a relatively new field of research. Dang et al. [30] performed a numerical study on impact and Compression After Impact (CAI) using finite element analysis. Their results conclude that the main reason for the reduction in compressive strength is related to significant delamination. However, their numerical model only considers the effect of fibre steering, while process-induced defects were not considered. Rhead et al. [31] present the effect of tow gaps on the compression-after-impact strength of fibre-placed laminates. The results show that the position, width and depth of tow gaps have a significant effect on damage resistance i.e. the tow gaps close to the non-impacted surface can inhibit sublaminate buckling and growth of laminations. In the design of their specimens the shape of the tow gaps is continuous as a consequence of complex 3D geometry. In a variable-stiffness laminate, the proper nature of the course shifting method [3] originates fibre angle discontinuities in the vicinity between two adjacent courses. Also, small triangular fibre-free areas (gaps) are created in order to avoid overlapping. In this work, this tow-drop defect pattern has been reproduced in a laminate which could be a representative sub-domain of a real VSP. According to the usual strategy of the designers, the tow-steered layers are placed between conventional layers, thus forming a hybrid laminate. These preferred designs prevent the existence of process-induced defects near the laminate surface. The main goal here is to study the influence of internal gap defects on the damage resistance and on the compressive residual strength of three laminates under low velocity impacts. Also, the effect of the staggering technique, used to avoid the co-location of the gaps, has been analysed. The staggering technique reduces the effect of ply clustering and produces a more uniform distribution of the process-induced defects. Both configurations, with and without staggered plies, have been compared with a traditional straight fibre laminate. All configurations analysed present similar bending stiffness in order to avoid misinterpreting the results and reaching ambiguous conclusions.

## 2. Specimen with tow-drop gaps: design and manufacturing

The test specimens for the experimental work reported in this paper was designed to represent the ply discontinuities at the edges of adjacent courses in VSP configurations. Gap-coverage zones was included in order to study the influence of the process-induced defects and the staggering technique, under drop-weight impact. Each specimen represents a sub-domain of a whole Variable Stiffness Panel at the boundary between the courses. The effects to be studied are very localised, this makes it possible to use relatively small specimens and to use straight-fibre laminates instead of curved trajectories. Some layers in the laminate have one portion with the fibres at 51° and another at 39°, thus creating an angle discontinuity at the mid-length of the specimen. In order to avoid more complexity, these plies with angle discontinuity were balanced with plies at $-45^\circ$.

Two configurations with tow-drop defects and 0% gap-coverage where designed and tested under low-velocity impact. The configurations are described in Fig. 1(a). The difference between them is in the use of ply staggering. In the first case, the fibre-resin areas are co-located through-the-thickness. Whereas for the second case, the co-location of gaps is avoided by staggering the plies in relation to each other (see Fig. 1(b)). Soft-tooling was used in the manufacturing of the panels to apply a uniform pressure on the panel surface and prevent defects and residual stresses. This technique produces thickness variation where gaps are present. The pressure of the curing process forces the adjacent layers into the gap [25] as observed in Fig. 1(c)).

The composite material used in this investigation is the HexPly AS4/8552 pre-impregnated CFRP in 6.35 mm (1/4 in.) wide tows ($t_w$), with nominal ply thickness after curing of 0.18 mm. The manufacturing process was done in the National Aerospace Laboratory-NLR (The Netherlands), with a Coriolis Fibre Placement Machine which lays courses of up to 8 tows at a time with a total width ($C_w$) of 50.8 mm per course. The mechanical properties of the material system are $E_{11} = 138.0$ GPa, $E_{22} = 8.6$ GPa, $G_{12} = 4.9$ GPa and $\nu_{12} = 0.35$. The tests are performed on flat rectangular plates of 150 × 100 mm. The stacking sequence analysed is $[45/0/-45/90/(-45_2/(51|39)_2)_2]_s$, where the 0° fibre orientation is aligned with the largest in-plane dimension. The design of the