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Understanding and predicting defect formation in automated fibre placement pre-preg laminates

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ABSTRACT

Fibre path defects are detrimental to the structural integrity of composite components and need to be minimised through process optimization. This requires understanding of the uncured pre-preg material, which is influenced by multiple process parameters, and sophisticated multi-scale modelling tools. Even though the capabilities of process modelling techniques have been improved over the past decades, the occurrence of localised wrinkles remains challenging to predict. One of the processes known to influence the formation of fibre path defects is the consolidation of laminates manufactured by automated fibre placement. The particular focus of this paper is to understand how out-of-plane wrinkles form during debulking and autoclave curing of laminates with embedded gaps and overlaps between the deposited tapes. Predictions are made using a novel modelling framework and validated against micro-scale geometry characterisation of artificially manufactured samples. The paper demonstrates the model's ability to predict consolidation defects for the latest generation of toughened pre-pregs.

1. Introduction

Current trends in composite manufacturing technologies for the aerospace industry are focussed on the automatic deposition of composite tapes and new multi-component materials systems, such as toughened prepregs, for improved component performance, damage tolerance or added functionality. The automation and material technologies enabling these advances have progressed much further than the capability to understand, predict, and optimise the manufacturing processes [1,2]. As a result, even though automatic fibre deposition technologies promise higher manufacturing rates, in practice lack of understanding of the prepreg behaviour often leads to limited improvement in laydown rates. The complexities in processing present a high risk of defect generation and requires substantial investments in empirical optimisation.

Two of the main technologies for automated deposition of prepreg material are Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) [3–5]. The two techniques use very similar machines, consisting of a computer-controlled poly-articulated robot, with a placement head that lays bands of prepreg strips onto a mould in order to construct the layup (Fig. 1). ATL is employed to deliver wide prepreg tapes onto a surface whilst automatically removing the ply backing and is well adapted for the manufacturing of large parts of relatively simple geometry, e.g. an aircraft wing skin. AFP is similar to ATL but utilises narrow prepreg strips (the width of which can vary from $\frac{1}{8}''$ to $\frac{1}{2}''$), which are collimated on the head and then delivered together. As narrower tapes can steer over sharply curved surfaces better than wider tapes (that cannot be placed without buckling some of the fibres), AFP can be used to manufacture much more complex geometries e.g. wing spar C sections. In order to obtain good layup quality, it is essential to control all the process parameters (heating temperature, compaction pressure, placement speed, etc) [6–10] and the machine trajectories. Over the years, design rules have been implemented to optimise these trajectories for maximum final mechanical properties (stiffness and strength) of the component being constructed [11,12]. This is, however, insufficient to ensure the production of defect free components as the tolerance in the fibre placement head movement, steered fibres, and tow width variation all contribute to the introduction of gaps and overlaps within the laminate [3,13]. In addition, the optimisation process of the machine trajectory can itself be responsible for the introduction of further defects. What is not often taken into account in manufacturing practices and analysis of such defects is that the influence on final fibre path and ply geometry from gaps and overlaps is not their nominal as-deposited position, but a function of what happens to

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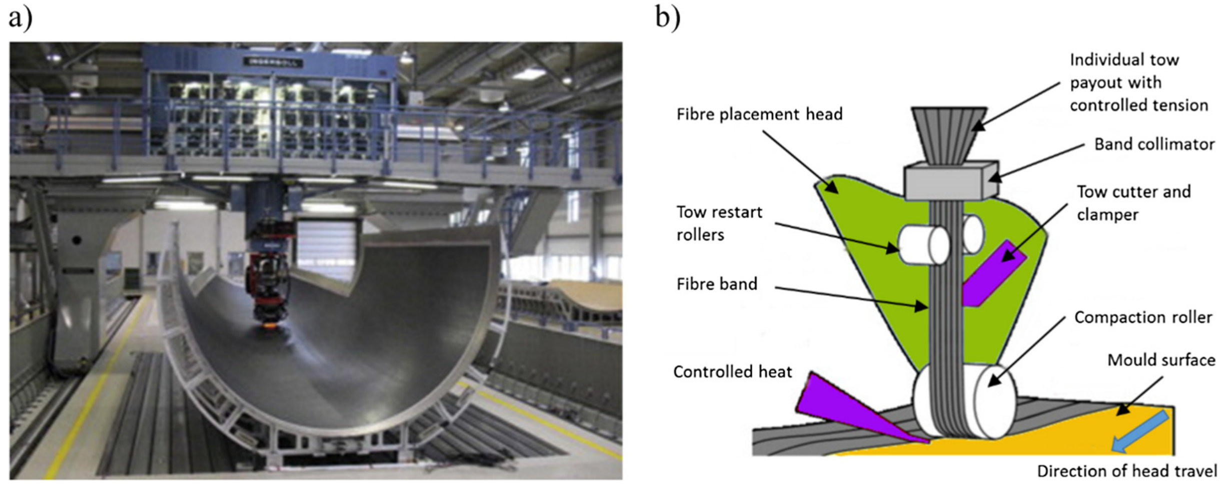

Fig. 1. (a) An AFP machine laying into a female mould [3] – (b) Automated fibre placement head, redrawn from [11].

the laminate in the subsequent processes, such as debulking or consolidation. The through-thickness deformation of the laminate with the gaps or overlapping tapes may lead to an additional fibre crimp or wrinkles, which can have a major impact on composite properties.

In recent years there have been a number of experimental and numerical studies carried out to predict and characterise the knockdown effect of gaps and overlaps on final mechanical properties of components manufactured by AFP. Amongst others, Sawicki and Minguet [14] have shown the reduction of compressive strength of samples with various distributions and sizes of gaps in 90° plies; Turoski [15] studied the knockdown effect under both tensile and compressive loading of isolated and interacting gaps with different stagger repeats; Croft et al. [16] investigated the effect of tensile, compressive and in-plane shear loading on the strength of laminates with a gap, an overlap and a half gap/overlap embedded in the through-thickness symmetry plane; and Elsherbini and Hoa [17] showed similar trends with respect to fatigue loading. More recently, Li et al. [18] generated sophisticated meshing tools which allowed them to easily create a series of finite element models with various combinations and permutations of gaps and overlaps. They were, then, able to systematically investigate the influence of defect size and distribution on the strength knockdown of the modelled specimens. The main conclusion of all these studies was that the introduction of gaps and overlaps during the layup process results (after consolidation and curing of the laminate) in the introduction of out-of-plane waviness of the load bearing 0° plies (i.e. wrinkles) adjacent to the gapped or overlapped layers and to local thickness variation which, in turn, are responsible for the decreased mechanical properties. This was later confirmed by Lan et al. [19,20] who showed that the use of a caul plate favours resin flow thus leading to reduced thickness variation and improved mechanical properties.

To limit the variation in strength of composite components made by automated manufacturing, it is absolutely imperative to establish more clearly how wrinkle severity and thickness variation can be reduced and, in the best case scenario, mitigate against it. With application to ATL of thermoplastic-based systems, Wang and Gutowski [21] studied analytically the possibility to remove (through processing) gaps and laps embedded in a lay-up. Although these studies were very informative, the authors only considered a very idealised geometry where the overlaps were described as cubical blocks of material superimposed with each other. Moreover, the evolution under processing conditions of only one embedded defect (i.e. one gap or one overlap) was considered. A real component manufactured by AFP, however, contains a very large number of different and complex combinations and permutations for gaps and overlaps, which can be of different sizes. A full exploration of the possibility to mitigate, through processing, defects in realistic engineering structure laid-up by AFP would therefore necessitate a very large and costly test plan. In comparison, composite process modelling offers the possibility to test a much larger range of possible combinations in a virtual sense and to optimise the processing parameters in order to minimise the defect sizes in a cured component. Process modelling could also advantageously replace or at least reduce empirical methods [18] and imaging techniques (which necessitates specimen/component manufacture) [22,23] for the generation of the internal ply geometry that is used as input to failure models. This would open the way for a fully virtual optimisation and strength prediction tool for composite components produced by AFP.

Most of the models available in the literature for the flow of resin in beds of reinforcement are based on Darcy's law [24,25]. These methods work very well to describe the evolution of the average thickness and fibre volume fraction in a large piece of prepreg when the edge effects can be neglected [26–29]. The principal modelling assumption is that bleeding flow (i.e. the pressure gradient causes resin flow relative to the fibre) is the main mechanism leading to the thickness variation of the laminate when processed. This is however not always fully representative as it has been known for a number of years [30] that squeezing flow (i.e. the laminate behaves as a highly viscous incompressible fluid) can also occur. Recently, Nixon-Pearson et al. [31] have shown that this can greatly affect the deformability of toughened thermoset prepreg under compaction. They highlighted that the smaller a prepreg volume with unconstrained boundaries (external or internal as in the case of tapes with gaps), the bigger the effect of squeezing flow on thickness evolution. This is important for the study of the consolidation of laminate produced by AFP as unconstrained narrow strips of prepreg and gapped and overlapped regions can locally affect the tape thickness to width ratio. This has been shown [31] to greatly influence the deformability of prepreg stacks. Hence, numerical tools for consolidation-induced deformation of laminate produced by AFP need to be able to capture these phenomena. The model recently proposed by Belnoue et al. [32] takes account of both bleeding and squeezing flow. It was shown to predict accurately the evolution of thickness and width over time of laminates subjected to complex pressure and pressure rate