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Forming induced wrinkling of composite laminates with mixed ply material properties; an experimental study

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ABSTRACT

One disadvantage of multi-layer forming of unidirectional (UD) prepreg tape is the risk of out-of-plane wrinkling. This study aims to show how mixed ply material properties affect global wrinkling behaviour.

An experimental study was performed using pre-stacked UD prepreg on a forming tool with varying cross sections. Parameters studied include local interply friction, effects of co-stacking and fibre stresses in critical fibre directions. Experimental evaluation was performed on out-of-plane defect height, type and location. The study shows that fibre stresses in some fibre directions were crucial for the shearing required to avoid wrinkling. The same fibre stresses may cause wrinkling if the lamina is stacked in a non-beneficial order. Changing the friction locally, or reducing the number of difficult combinations of fibre angles, improves the forming outcome slightly. However, in order to make a significant improvement, co-stacking or different fibre stacking is required.

1. Introduction

ATL (Automatic Tape Lay) of UD (unidirectional) prepreg tape is a widespread process in the aerospace industry, due to the advantages of high lay-up rates, its capability in manufacturing large-scale parts and its simplified offline machine programming [1]. One disadvantage of this process is limited geometric complexity capability. However ATL can be combined with multi-layer forming, such as Hot Drape Forming (HDF), in order to obtain a cost competitive manufacturing route for large-scale composite components [2–4].

One known disadvantage of multi-layer forming of UD prepreg is the risk of decreasing the mechanical performance of the structure due to out-of-plane fibre wrinkling. Such wrinkles can cause a 40% strength knock-down [5]. A recently-performed study [6] has also shown in-plane fibre buckling/kinking during forming.

The aim of this paper is to study experimentally whether wrinkle development can be avoided by either making the lamina more wrinkle resistant or by reducing the compression developed. The latter is achieved by locally changing the friction properties in critical layers, thereby enabling sliding, by reducing the number of interfaces causing compression or by, in fact, reducing the compression through reducing the global tensioning. Improved wrinkle resistance is obtained by using locally stiffer fibres or using co-stacked layers.

The study presented in this paper is a continuation of the research presented in [4]. This previous research showed a dependency between stacking sequence of UD prepreg laminate and wrinkle development when forming a spar geometry with a shallow recess area. The paper explained this effect as that the combination of [45] and [0] layer may reduce the material's ability to deform through shear which was originally shown in [7]. Hallander et al. [4] also involved some work on co-stacking by using plies of different thicknesses. Åkermo et al. [8] gives a further explanation to the coupling effects by showing increased interply friction for the combination of [0] and [45] layers compared to other ply direction combinations tested.

Together the studies presented above [4,8] show that during forming, single layer/fibre directions, may cause compression in the recess area although the laminate is globally under tension. These highly-compressed areas commonly coincide with wrinkle-prone areas. However no previous study goes any further into explaining how local ply or laminate properties affect global wrinkle development.

Below follows a summary of other research related to wrinkle development. Several studies e.g. [4,9] have looked at wrinkling during forming of a recess area, such as a joggled spar flange area. A larger number of studies e.g. [10,11] have been performed on hemispheres with woven composite preforms. These studies mostly take the intraply shear and shear locking angles into account and do not give the same wrinkling conditions as UD prepreg formed on a joggled spar flange. However, Boisse et al. [11]

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state that there is no direct relationship between shear angle and wrinkling and that wrinkling is a global phenomenon dependent on strains and stiffness and also on boundary conditions.

Generally, existing theories of forming consider several material- specific, inherent mechanisms such as intraply shear, interply shear, ply bending, intraply axial loading and compaction/consolidation [12]. Considering these mechanisms, out-of-plane wrinkling often occurs due to a combination of in-plane shear and ply compression [13]. Wrinkling is most likely to start in the ply with least stiffness in the load direction, i.e. where the fibres are perpendicular to the load. This has been shown in several studies e.g. Lightfoot et al. [14].

Tam and Gutowski [15] showed that multi-layer forming of a joggled spar flange require in-plane shear to avoid ply buckling. When buckling occurred, the fibres followed geodesic paths creating non-uniform fibre spacing. When buckling did not occur, the fibres followed an ideal path and remained parallel.

In several studies, e.g. Pandey and Sun [16], the dependency of increased friction on wrinkling behaviour has been described. The friction has, in these cases, been changed as a function of the forming temperature.

Haanappeal et al. [17] have examined the forming of a product involving double-curved surfaces. Wrinkle-free forming of a laminate having more than two unique fibre directions must invoke both interply slippage and intraply deformations according to their results.

2. Experimental

The experimental study was performed on a spar with a recess area in one flange (joggled area, geometry according to Fig. 1). The geometry was chosen to create a 3-D forming.

Multi-layer forming of the geometry described in Fig. 1 requires three major forming steps which are explained in detail in [4]. A brief summary of the forming steps: ply bending accompanied by interply shear, compensation for the recess geometry and ply compaction. The second forming step, compensation for the recess geometry is most critical for wrinkle formation according to [4]. This forming step could be divided into three, essential forming sub-steps: A. Fibre rotation due to "folding" when entering or leaving the transition zone, B. Tension towards the centre of the spar and in a direction parallel to the radius develops in all layers, C. Shear to move excess material just outside the transition zone towards the centre.

2.1. Materials

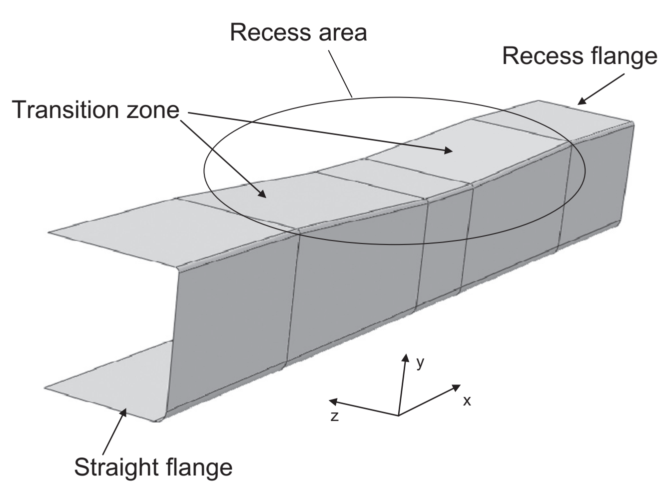
Two different 180 °C cure epoxy prepreg materials were used in the study: one containing HT (High tenacity) fibre and the other containing IM (Intermediate Modulus) fibre. The matrix was, however, practically the same and contained the same type of resin with thermoplastic toughener particles. Both materials showed relatively high interply friction [2] and nearly ideal shearing behaviour (correlation with the Pin Jointed Net assumption) for a cross plied [45, −45] laminate [18]. However friction measurements made by Sjölander et al. [19] showed 40–50% higher friction coefficient for the material with the HT fibre than for the material with IM fibre; see Table 1. The intraply shear was also measured using a bias extension test showing that the deformation resistance was approximately 30% higher at the same strain level for the HT fibre prepreg compared with the IM fibre prepreg; see Table 1.

2.2. Examining lay-up parameters

The lay-up parameters studied are summarised in Table 2. All prepreg used in the study had a theoretical cured ply thickness (CPT) of 0.131 mm. All variations to references were aimed at either reducing the effect of difficulties arising when combining the [0] and [90] fibre directions, reducing the stresses in the recess area, or stiffening the lamina through use of higher modulus fibres or co-stacking the fibre directions. In this study, co-stacking refers to four consecutive plies of the same ply orientation.

The lay-ups studied were:

- $[(-45, 0, 45, 90)_4]_s$ (referred to as QI Ref HT) was used in HT fibre prepreg reference sample.



Spar length [mm]	480
Web width [mm]	70
Flange length [mm]	55
Chamfer length [mm]	125
Chamfer depth [mm]	6.25
Nominal thickness [mm]	4.192
Inner Radii [mm]	2

Fig. 1a. Spar geometry with a flange recess area.