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Finite element forming simulation of locally stitched non-crimp fabrics

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ABSTRACT

Locally stitched non-crimp fabric preforms are stacked fabric layers that are sewn together. Using a seam improves the manufacturing process by providing tailored and easy to handle preforms. On the other hand, local stitching modifies the forming behaviour of the layup. Single-lap shear tests and modified bias-extension tests are used to characterise and model the seam behaviour during forming. The modelling of such a stitching is performed using the commercially available finite element software PAM-Form® (ESI Group). The mechanical behaviour of the seam is modelled by a simple multi-linear approach. A comparison between experiment and simulation of the double diaphragm forming of a generic helicopter side frame with a locally stitched non-crimp fabric preform shows valuable benefits gained from such a model. After improvements, the finite element model can be used to determine the influence of the seam on the forming behaviour and thus optimise the arrangement of the stitches.

1. Introduction

Due to high strength- and stiffness-to-weight ratios, Carbon Fibre Reinforced Polymers (CFRPs) prove to be an eminent material type for aerospace applications. CFRPs are highly demanded by aircraft industries that continuously aim at improving the performances of their aircrafts and, in the same time, lower their weights in order to reduce their ecological footprint. As early as the 1980s, the load carrying structures of military helicopters such as TIGER and NH90 consisted of 95% of CFRPs [1].

The main drawback of CFRPs lies in their high cost caused by the high price of the resource, i.e. carbon fibres, and their manufacturing complexity. Since the 1960s, pre-impregnated composites have been the state-of-the-art for structural applications [1]. Still today, hand-layup followed by autoclave curing is extensively used. However, important cost savings could be achieved by moving from pre-impregnated to Liquid Composite Moulding (LCM) processes using, for example, non-crimp fabric (NCF) reinforcements. NCFs are an advanced type of textile fabrics that can consist of multiple plies of unidirectional fibres stacked with varying fibre orientations. This fabric construction combines a good processability, due to the presence of dry fibres, with great mechanical properties [2].

Components made with LCM processes are commonly manufactured in several consecutive steps. This step-by-step approach reduces the complexity of the process and increases the quality of the final product. One of the first steps, called preforming, is of major importance. Here, the shape of the final part is determined by forcing a flat reinforcement layup into a defined geometry. When composed of several plies, the flat reinforcement layup can be prepared with different techniques, e.g. stitching, welding [3]. The stitching approach is used to create so-called stitched tailored reinforcements, or stitched layups, that are ready-to-use batches of stacked plies joined with a seam [4]. Such layups, often produced in an automated work flow, are tailored cut-outs, i.e. they are sewn and cut into a desired shape.

Depending on the type of application, a variety of different seams can be used. Usually, the seams can be divided into two different groups whether they increase the mechanical performances of the final component (structural stitching) or the processability of the product (local stitching) (Fig. 1) [5,6]. The application of a glass, aramid or carbon through-thickness thread in the case of a 3D stitching may improve the structural performances as well as the functionality of the final component [6,7]. On the other hand, it may also lower its in-plane properties. Thus, the environment in which the final component will operate must be identified prior to defining a special reinforcement arrangement [7].

The aim of the local stitching is to improve the handling of the layup. To minimise its influence on the mechanical properties of the final component, the seam position must be optimised and its density must be kept as low as possible. Local stitching might influence the deformation behaviour of the reinforcement and, in particular, reduce its shearing capacities or transfer the shear force from one zone to another during forming [8].

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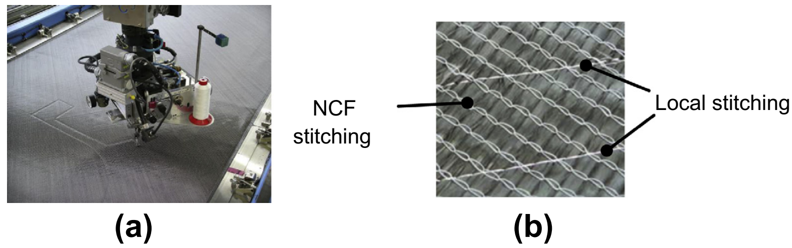

Fig. 1. Local stitching of a NCF ply stack (a) sewing machine and (b) stitching detail. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this study, the local stitching, also referred to as assembly seam, behaviour is characterised by single-lap shear tests and modified bias-extension tests. A simple modelling approach using the commercially available finite element software PAM-Form® (ESI Group) is applied. The draping simulation of a locally stitched NCF layup over a generic helicopter side frame tooling is performed. A comparison between simulation and experiment is eventually held using an automated measuring system called EuroPAS®.

2. Characterisation of the stitching behaviour

2.1. Shear behaviour of stitched NCF preforms

To the best of the authors' knowledge, there has not been any published investigation or testing method focusing on the relative displacement of locally stitched NCF preforms. When draping a stack of plies, inter-ply shear is a common phenomenon [9]. Thus, the most critical load case that an assembly seam can experience is shear stress. Such a stress can be produced with a tensile testing machine according to a standard developed by the textile industry [10]; the so-called single-lap shear test (Fig. 2). This test involves two overlapping coupons, joined by the to-be-characterised bonding method, i.e. a seam in this work. By pulling on both sides of the coupon, a shear stress is introduced within the stitching.

However, test standards from the textile industry cannot easily be applied for the characterisation of stitched NCFs. As NCF layups are less robust than interwoven textiles, the stability of the specimen's edges may be problematic while testing. When a stitched NCF sample is clamped on one side and pulled on the other side, the tensile force, which is transferred via the local seam (Fig. 2), pulls the NCF tows apart. This pulling leads, in most cases, to the degradation of the edges and thus, to a complex load case.

Besides, the boundary conditions within a single-lap shear test are usually not representative of real forming processes. Tows in single-lap shear tests are of finite length, whereas they can be considered as infinite in real forming processes due to the substantial geometry of the manufactured components. Furthermore, the fibres are subjected to pressure and friction resistance during the forming process. All these factors need to be taken into account for the testing of stitched NCF specimens. Hence, a support to stabilise the edges of the specimens has to be developed such that only the dry area near the seam deforms under the applied force. This support requires an adaptation of the considered test method.

2.2. Single-lap shear test

2.2.1. Specimen

A norm, developed by the textile industry [10], prescribes the specimen dimensions (length of 180 mm and width of 100 mm) for slippage resistance measurements of a seam. These dimensions are also applied in this study for testing stitched NCFs. Taking the surrounding edge stabilisation concept into account, these dimensions represent only the "effective area" to which the assembly seam is applied (Fig. 3). The overall specimen size, including the stabilised zones, is thus of 230 mm × 190 mm (length × width). These overall dimensions were, on one hand, prescribed by the dimensions of the clamps, and, on the other hand, defined by preliminary tests. The exact dimensions of the surrounding area may slightly vary from one stabilising method to another.

To control the self-locking behaviour of the stitches, the provider of the stitching machine recommends a minimum seam length of 30 mm and five stitches in a row. These criteria are applied to this work.

The shear behaviour of stitched NCF layups is analysed through four parameters inherent to the material (NCF) and the assembly seam:

- Fibre orientation: 0°/90° and ±45°.
- NCF stitching orientation: 0° and 90°.
- Assembly seam orientation: 0° and 90°.
- Assembly seam length: 30 mm and 60 mm.

The following nomenclature is used to define the configuration of each test: {fibre orientation; NCF stitching orientation; assembly seam orientation; assembly seam length}. All the angles are

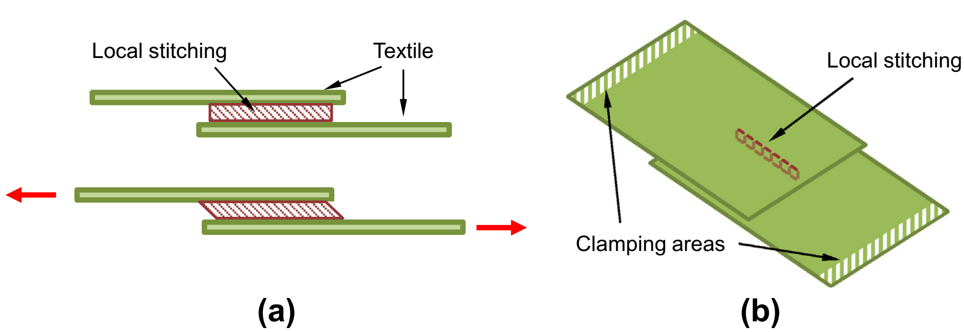

Fig. 2. Single-lap shear test (a) side view and (b) 3D view. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)