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Mechanical performance of carbon fibre-reinforced composites based on preforms stitched with innovative low-melting temperature and matrix soluble thermoplastic yarns

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ABSTRACT

In order to achieve a superior overall mechanical performance of composites based on stitched preforms for demanding aircraft applications, innovative thermoplastic stitching yarns are comparatively evaluated in carbon fibre-reinforced epoxy composites. Low-melting temperature yarns based on polyamide and phenoxy in comparison to a standard polyester yarn allow prestabilisation of the dry preforms by thermobonding and lead to significantly reduced laminate disturbances following liquid composite moulding; thereby minimising the degradation of the resulting composite strength properties. While the softening polyamide yarns allow partial rearrangement of the carbon fibres during the resin injection process, the dissolution and subsequent phase-separation of the phenoxy can induce a further local toughening of the epoxy matrix. The improvements in overall composite performance when using stitching yarns are partly due to the particular yarn material but also depend on variations in linear yarn density. Last but not least, it is demonstrated that stitching seams close to a bolted joint have only little effect on the bolt bearing strength of the stitched composite whereas seams running directly through the hole and oriented in the load direction induce small degradation of the bolt bearing strength.

1. Introduction

Modern stitching technologies are considered to be one of the key approaches towards the cost-reduced manufacture of complex textile preforms used for liquid composite moulding (LCM) of high-performance fibre-reinforced polymer composites [1]. However, depending on various parameters including the used yarn materials, the stitching parameters as well as the particular type of composite and the loading conditions, the use of such stitched preforms has been shown to both improve or seriously degrade the in-plane and out-of-plane composite performance [2–8].

A key parameter influencing the overall in-plane mechanical performance of composites based on stitched preforms has been identified as the induced undulations of the reinforcement fibres [3]; an effect that is strongly related to the stitching yarn thickness and yarn tension. Although some predictive models have been proposed [9–13], it still is rather difficult to accurately predict the resulting mechanical properties of stitched composites by clear calculable formulas considering all relevant parameters.

A feasible approach to resolve these challenges is the evasion of the main origin of the performance reduction, namely the disturbing and undulating presence of a solid, tensile loaded stitching yarn. This can be realised using yarns that either melt or soften during the LCM process or even dissolve in the matrix during the resin injection process. In order to accomplish the softening/melting event, a low-melting temperature thermoplastic yarn replacing the usual carbon, aramid, glass, polyester etc. yarns is required. For complete dissolution, a good miscibility of the yarn material in the matrix for the used LCM-parameters is necessary. Once the thermoplastic yarn builds up a more or less well connected phase or dissolves in the matrix, additional toughening effects can be anticipated as a result of different toughening mechanisms such as crack pinning, micro cracking, localised shear yielding or banding, particle bridging, crack path deflection etc. [14].

The general toughening benefits of incorporating thermoplastics in epoxy resins have already been demonstrated [15–23]. Recent studies [7] showed no decrease of the composite compression, interlaminar shear strength and compression after impact properties when using low-melting temperature polyamide-stitched (2*23 dtex) laminates. This kind of low-melting tem-

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perature thermoplastic also offers the additional advantage of allowing a prestabilisation of the dry preforms by thermobonding. Exploiting this potential, the handability of the preforms should be significantly enhanced without inducing negative effects on the mechanical stability and the preforming time due to high stitch densities; a critical issue for the desired use of automated manufacturing approaches.

In this study, a detailed comparison of the mechanical performance of non-crimped carbon fibre-epoxy composites stitched with various thermoplastic yarns is provided. In addition to a standard polyester yarn (2*53 dtex), two low-melting temperature polyamide yarns with differing linear yarn density (2*23 and 2*75 dtex) as well as a thick phenoxy yarn (300 dtex) are evaluated. The resulting variations in composite performance are explained based on morphological differences induced by the different yarn materials.

2. Materials and experimental details

2.1. Materials

The fibre reinforcement of the epoxy laminates was built up of layers of commercial non-crimped carbon fibre (NCF) fabrics. The particular NCF is based on either (0°/90°), (90°/0°) or (−45°/+45°), (+45°/−45°) biaxial layers of carbon fibres (Tenax HTS 12 k) with a polyester 40 dtex knitting thread as a binding yarn, manufactured by Hexcel; with a carbon fibre weight per unit area of approximately 250 g/m^2 per biaxial layer.

For stitching of the non-crimped fabrics, polyamide yarns (Grilon K 140) by EMS-Griltech, Switzerland, twined from two yarns with either 23 or 75 dtex, respectively, or a polyester (standard) yarn (Serafil 200/2) by Amann, Germany, twined from two yarns with a linear density of 53 dtex, were used. Additionally, a phenoxy yarn (Grilon MS300) with a linear density of 300 dtex was employed. All yarns were not washed separately and were used as delivered.

The epoxy matrix used for all composites was HEXFLOW RTM6 aerospace grade, supplied by Hexcel, and was used as-received.

For determination of the composite bearing strength, an additional prepreg laminate common for aerospace applications was prepared in order to allow the determination of a baseline value for this property. This particular laminate was built up of a commercial prepreg (HexPly M18/1) manufactured by Hexcel consisting of a bidirectional (0°/90°) 4 harness satin weave fabric (Tenax HTA 3K) with an area weight of 220 g/m^2 and an impact modified epoxy resin.

2.2. Specimen manufacturing

The preforms for the compression, tensile, tensile fatigue and interlaminar shear strength (ILSS) tests were stitched at ±45° (α = ±45°) with a modified lock-stitch arranged in the geometry schematically shown in Fig. 1, using a 2D-CNC sewing machine manufactured by KSL, Germany. The stitch row spacing r was set at 40 mm. In order to ensure a good handling of the dry preforms and to obtain a high dimensional (bending) stability in either direction (parallel and perpendicular to the preform outline), two crossing seams were employed. The layer stacking sequence used for the intended compression, tensile, tensile fatigue and ILSS tests was $[(0/90)]_{4s}$. In contrast, the layer sequence for the preforms intended for the compression after impact (CAI) tests was $[(+45/-45)/(90/0)]_{4s}$ (quasi-isotropic). In this case, the preforms were also stitched with a modified lock-stitch with a nominal stitch pitch of 3 mm but the stitch row spacing was set at 20 mm and the orientation of the seams was α = ±22.5°.

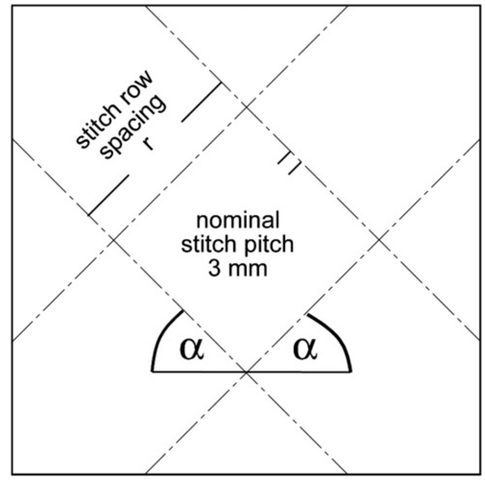

Fig. 1. Schematic representation of the assembly seam stitching pattern used in this study.

All composites (except the prepreg reference for the bearing strength described in the following paragraph) were fabricated using vacuum-assisted resin transfer moulding (VARTM). The square mould was preconditioned with release agent (Loctite 770-NC Frekote), evacuated and heated up to 120 °C prior to impregnation of the dry preforms with the epoxy resin at 120 °C, applying a pressure of 0.1 MPa. After complete impregnation, which took about 10 min, a dwell pressure of 0.2 MPa was applied for 10 min. The final curing temperature of 180 °C was kept constant for 2 h, followed by a slow cooling to room temperature. The final RTM panels were 420 × 420 mm^2 in size, with a nominal thickness of 2.0 ± 0.1 and 3.9 ± 0.1 mm for the $[0]_{4s}$ lay-up and the CAI laminates, respectively.

For the bearing strength specimens, a quasi-isotropic $[(0/90)/(+45/-45)]_{4S}$ lay-up was chosen. The seams had a nominal pitch of 3 mm and were either orientated in the subsequent load direction (α = 0°) or perpendicular to it (α = 90°). For stitching, only the polyamide 2 × 75 dtex yarn was employed. Composite manufacturing of plates with a nominal thickness of 3.9 mm was carried out as described above.

The reference prepreg composite for the bearing strength test also had a quasi-isotropic $[(0/90)/(+45/-45)]_{4S}$ lay-up comparable to the RTM bearing strength specimens introduced above and was consolidated using a hot-press. Curing was realised in a stepped heating cycle with a first heating step at 80 °C for 1 h followed by a second step at 180 °C for an additional 2 h. The final size of the panel was 450 × 450 mm^2 with a thickness of about 3.9 mm.

In order to investigate the effect of phenoxy in the RTM6 epoxy matrix in more detail, compact plates of both the neat resin as well as of modified RTM6 were prepared according to the following procedure:

The epoxy matrix was heated to 120 °C for mixing. The hot mixture was placed in a vacuum oven at the same temperature for 45–60 min for degassing. The modified resin was subsequently cured in a convection oven as follows: the curing cycle started by a 2 K/min ramp from room temperature to 180 °C. This temperature was held for 2 h and curing was completed with a −2 K/min ramp from 180 °C to room temperature. Thus, cured 110 × 110 × 3–4 mm^3 epoxy resin sheets were obtained and were subsequently machined to the desired specimen size for further testing.

2.3. Panel quality assessment

The quality of all manufactured composite panels with regard to the homogeneity, delaminations and porosity was verified by