Hybrid thermoplastic composite beam structures integrating UD tow, stamped fabric, and over-injection/compression moulding

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Abstract

To investigate thermoplastic composite structures combining multiple material forms and processing techniques, a generic beam tool was developed that enabled over-moulding of stamped fabrics and robotically placed unidirectional tows (UDtow). Beams produced from different material and process combinations were tested in flexure. Compared with a glass mat thermoplastic (GMT) beam, the maximum force for 'free-free' and 'fixed-fixed' end conditions was respectively increased by: 30% and 242% for GMT/UDtow, 69% and 224% for GMT/fabric, and 79% and 460% for GMT/UDtow/fabric. Compared with a plain short glass fibre injection moulded (IM) beam, the maximum force for 'free-free' and 'fixed-fixed' end conditions was respectively increased by: 26% and 213% for IM/UDtow, 64% and 286% for IM/fabric, and 63% and 411% for IM/UDtow/fabric. Standard in-mould cycle times and tool temperatures (50^{o}C) were used. The fabric over-moulding process window was examined in detail. The fabric preheat temperature dominated the process. Both global beam testing and coupon-based testing showed that the average interfacial temperature between the fabric insert and the over-moulded material at the moment of contact needed to be above the melt temperature of the polymer. The inserts did not need to be heated above melt temperature, thereby maintaining integrity during the high pressure over-moulding processes.

Key words: Integrated processing, robotic tow placement, fabric stamping, over-moulding

1. INTRODUCTION

An integrated processing methodology has been developed that combines the design freedom, cost efficiency, and net-shape processing of injection and compression-flow moulding with stamped fabrics and robotically placed unidirectional (UD) thermoplastic composite yarns (Figure 1) [1]. Load can hence be introduced into the component, the creep resistance improved, and the stiffness and strength increased, while working with the same or reduced cross-sectional areas. Design freedom is maintained with the flow-based moulding process, where the infrastructure of conventional flow moulding processing equipment and cycle times can be adopted. The objectives of this work were to investigate hybrid material structures using a generic beam geometry (Figure 2) that enabled the combination of different materials and processing techniques. This enables structural properties to be locally achieved by efficiently placed loops or 'wire-frame' inserts of UD material and fabrics.

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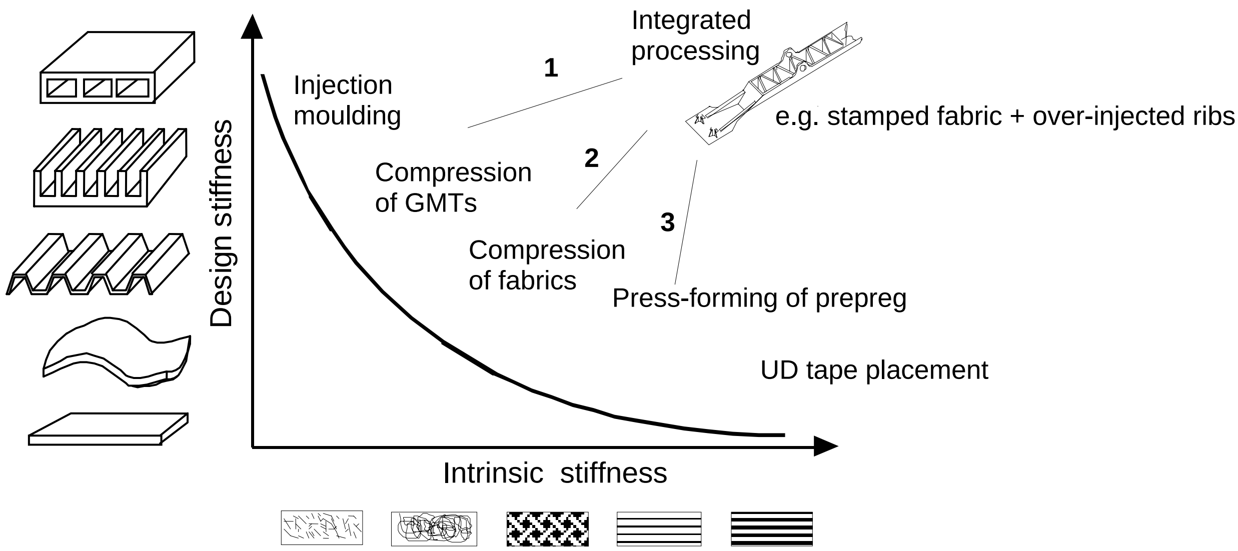

Figure 1 Combination of intrinsic and design stiffness via integration of multiple material forms and processing techniques

2. DEVELOPMENT OF GENERIC BEAM TOOL

A generic beam tool was developed to enable investigation of the material and process phenomena governing hybrid processing. This was of indicative industrial complexity, while still being generic in nature. The tool incorporated a shear edge design enabling both over-injection and compression moulding to be performed.

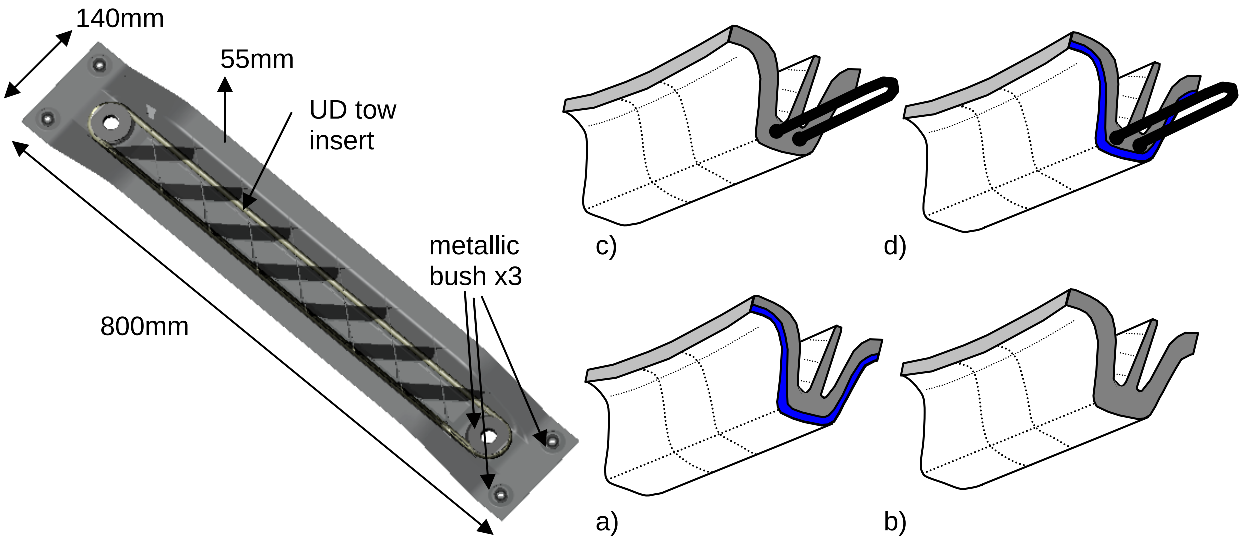

Figure 2 Generic beam tool geometry and cross-sections:
a) over-moulded fabric, b) plain flow moulding,
c) over-moulded UD tow, d) over-moulded UD tow and fabric

2.1 Drape analysis of stamped fabric insert

In order to predict that the desired woven glass/polypropylene beam insert geometry could be processed, forming analyses were performed by the University of Nottingham [2]. This was of particular relevance as the fabric inserts were net shape to the tool during the over-moulding process, where wrinkles or large internal stresses should be avoided. A mesh of 1922 nodes and 3650 triangular elements was used, with the material at $0/90^{o}$ to the component axis. A geometric (kinematic) mapping algorithm was used, representing the fabric as a pin-jointed net, which was mapped onto the tool surface by assuming that the inextensible tow segments shear at the tow crossovers. The remaining tows were positioned using a geometric mapping with geodesic generator paths, with a tow spacing of 5mm corresponding to the material used. Three layers of Vetrotex preconsolidated Twintex^{TM} 2x2 twill weave, 60% glass by mass, were used to give the desired minimum beam insert thickness of 1.5mm. Picture frame shearing and hemisphere forming trials showed that the material locking angle was above 60^{o}, and that shear angles below this level should not lead to wrinkling unless the material was subject to in-plane compression.

No shear deformation was required over the majority of the component surface (Figure 3a), whilst maximum deformation was predicted close to the corners of the part. The maximum shear angle was 28^{o}, which was below the material locking angle and hence wrinkling would not be expected. Figure 3b shows the predicted component thickness distribution based on constant material volume. The minimum (un-sheared) thickness was assumed to be 1.5mm. This increased to 1.70mm in the most highly sheared region.

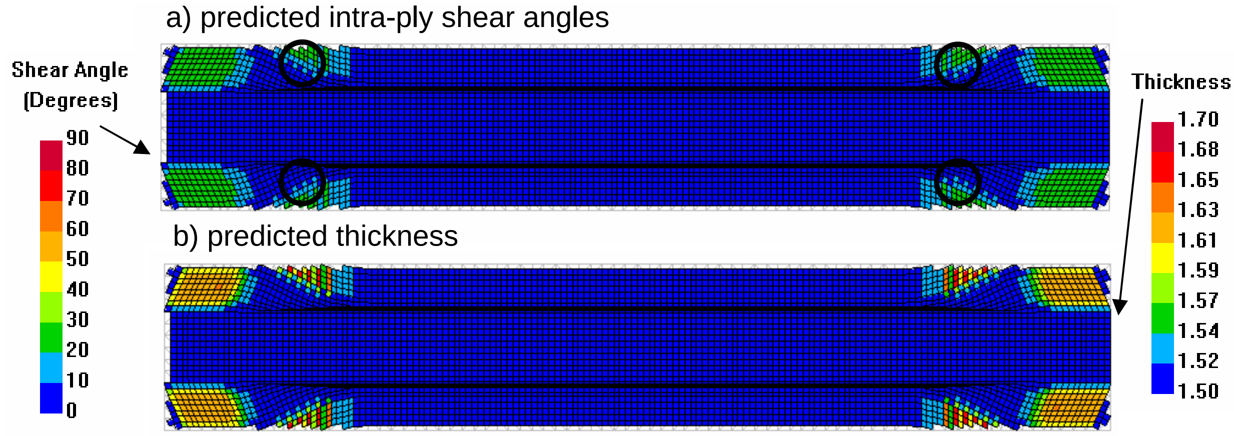

Figure 3 a) Predicted intra-ply shear angles for beam draped at 0/90^{o}. The maximum shear angle is 28 degrees (circled).
b) Predicted thickness variation for 0/90^{o} beam

2.2 Analysis of tool fill and temperature fields

Manufacture by one integrated cycle is achieved by optimising the temperature of the over-injected or compressed composite with that of the initially processed sub-component (fabric or UD tow insert) [3] to achieve an average interfacial temperature above the melting point (T_m) of the polymer (165^{o}C for PP).

MoldFlow simulations were therefore performed to predict temperature distributions as a function of the number of injection gates to ensure that large temperature gradients, with the corresponding potential for variations in interfacial bond quality, were minimised. Additionally, this provided a prediction of the processing parameters required for tool fill.

The wall thickness of the beam profile was reduced in proportion to the fabric insert thickness. Simulations were made for a polypropylene injection temperature of 260^{o}C and a tool temperature of 40^{o}C. Predicted temperature variations across the part surface corresponded to 50^{o}C with 2 gates, reducing to 30^{o}C with four gates. Figure 4 shows the predicted temperature variation at the moment of tool fill with 2 and 4 injection gates.

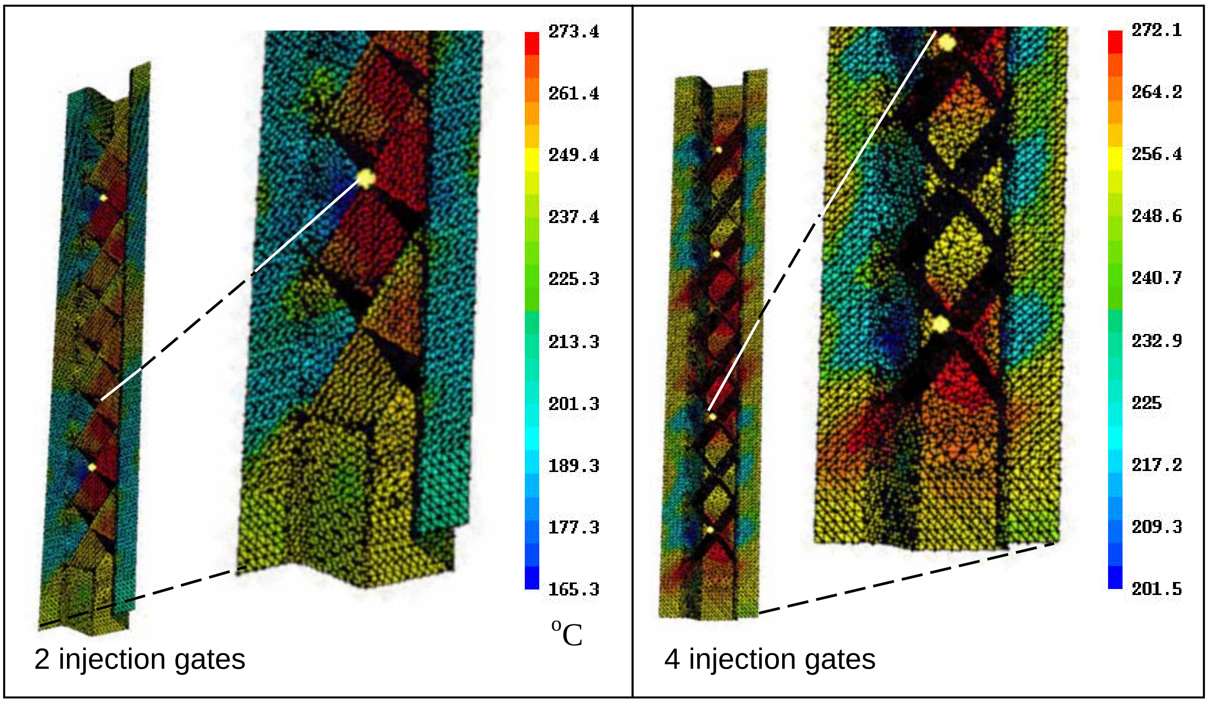

Figure 4 MoldFlow predicted temperature variations at 100% tool fill for: a) 2 injection gates, and b) 4 injection gates *(note separate temperature scales)*

If best and worst case temperature gradients are taken, then the interfacial conditions would require a fabric insert temperature after transfer of 80°C or 110°C for the corresponding over-moulded polymer temperatures of 260°C and 230°C.

3. STRUCTURAL INSERT MANUFACTURE

3.1 Robotic tow placement

A tow placement cell, consisting of a Staubli multi-axis robot and a placement head, was used to place the UD tow onto a metallic jig [4]. The UD tow was a commingled yarn of glass (60 wt.%) and polypropylene fibres, (Vetrotex International, Twintex™). Here 5 UD tows were brought simultaneously into a heating tube before a final, independently controlled, heating nozzle. In this case, a UD tow insert was comprised of 30 consolidated yarns. A metallic roller provided the consolidation force and directed the tow in the desired path on the temperature controlled metallic jig. Metallic bushes were placed onto the jig before the start of tow placement, such that they were partially embedded during the tow placement process. Compaction pressure was applied by the roller in the straight regions, while the roller was retracted and UD material wrapped under tension around the bushes. An air-cooling system was used to cool the tow after placement, reducing deconsolidation effects. Standard tow placement conditions, which were previously optimised [4], were applied. Figure 5a) illustrates the over-moulded fabric and UD insert. Figure 5b) and c) show the stamped fabric insert and the UD tow insert before over-moulding.

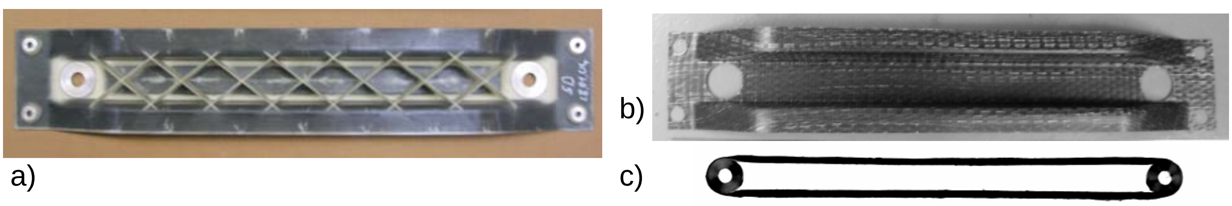

Figure 5 Hybrid beam and inserts
a) over-moulded beam, b) stamped fabric insert, c) UD tow insert

3.2 Fabric stamp-forming

Commingled glass and polypropylene (GF/PP) preconsolidated fabric inserts (Figure 5b) were manufactured by non-isothermal compression moulding, with 65s time at pressure. Fabric sheets were preheated in an infra red oven before rapid transfer to the stamping tools. For demonstration purposes, the lower stamping tool was machined from aluminium and a silicon rubber form (shore A hardness 50) was used as the upper stamping tool (matched steel tooling would be used for production volumes, with shorter cycle times dues to faster heat transfer).

4. MECHANICAL TESTING OF BEAM STRUCTURE

4.1 Flange area testing

Flexural and ILSS coupon tests were performed on the beam flange regions to study the effect of process conditions on interfacial healing between the fabric and the over-moulded polymer. Three point flexural tests were performed to ISO 14125 at a test speed of 4mm/min with specimen dimensions of 80x30mm with a 64mm span and 5mm diameter loading pins. Interlaminar shear strength (ILSS) tests (BS 2782) were also performed, with sample dimensions 40x30mm, with a span of 32mm.

4.2 Beam testing

Three point bending tests were performed on the resulting beam structures (Figure 5a, 6), in both ‘free-free’ and ‘fixed-fixed’ conditions. For the latter, the beam was bolted through the metallic bushes to the test fixture. An initial force was applied at a crosshead rate of 150mm/min until the preload of 100N was reached. From this point onwards, a rate of 10mm/min was used, with data acquisition of force for every 10µm of deflection. The beam modulus of elasticity and strength were then derived on the basis of these results. The compliance was calculated as the gradient of the force vs. displacement curve before the first peak, determined by linear regression. Displacements are given as normalised data where 100% is the plain GMT beam displacement to failure in ‘fixed-fixed’ end conditions.

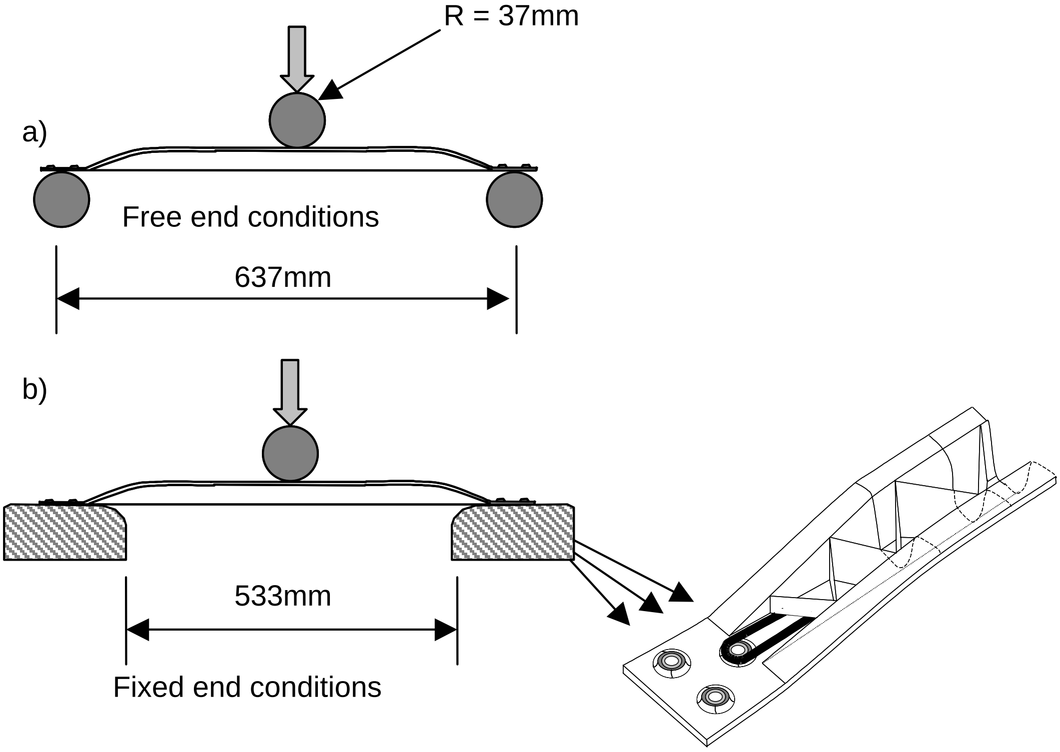

Figure 6 Beam testing: a) free-free end conditions, b) fixed-fixed end conditions