Composites Part A 114 (2018) 327–337

Contents lists available at ScienceDirect

Composites Part A

journal homepage: www.elsevier.com/locate/compositesa

Experimental and numerical investigation of the shear behaviour of infiltrated woven fabrics

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ARTICLE INFO

Keywords:
Textile characterisation
Forming
Wet compression moulding (WCM)
Process simulation
Finite Element Method (FEM)

ABSTRACT

Wet compression moulding (WCM) as a promising alternative to resin transfer moulding (RTM) provides high-volume production potential for continuously fibre reinforced composite components. Lower cycle times are possible due to the parallelisation of the process steps draping, infiltration and curing during moulding. Although experimental and theoretical investigations indicate a strong mutual dependency arising from this parallelisation, no material characterisation set-ups for textiles infiltrated with low viscous fluids are yet available, which limits a physical-based process understanding and prevents the development of proper simulation tools. Therefore, a modified bias-extension test set-up is presented, which enables infiltrated shear characterisation of engineering textiles. Experimental studies on an infiltrated woven fabric reveal both, rate- and viscosity-dependent shear behaviour. The process relevance is evaluated on part level within a numerical study by means of FE-forming simulation. Results reveal a significant impact on the global and local shear angle distribution, especially during forming.

1. Introduction

Wet compression moulding (WCM) provides high-volume production potential for continuously fibre reinforced components as a promising alternative to resin transfer moulding (RTM). The simultaneous draping, infiltration and curing (viscous draping) enables reduced cycle times. Experimental and theoretical investigations indicate strong mutual dependencies between the key process parameters, such as resin amount and resin application position/technique, infiltration time, tool settings (closing profile, temperature, pressure) and stack weight [1–3]. Beyond that, an influence of resin amount and infiltration time on the structural performance is observed by Heudorfer et al. [4].

Despite that, there is hardly any literature available, which investigates the cause of these mutual dependencies. This includes the impact of infiltration on the draping behaviour, as well as the effect of higher fluid pressures superimposed to the forces during draping. This impedes a comprehensive and physical-based understanding of the above outlined interactions and thus limits the development of reasonable process simulation methods for the WCM process [1,5].

The investigated thermoset-based WCM process consists of five process steps simular to the process investigated by Bergmann et al. [1,2] (cf. Fig. 1). After the laminate is cut and stacked (1), the topside of the stacked laminate is impregnated with resin using a wide-slot nozzle (2). While the resin slowly seeps into the laminate, the partially impregnated stack is transferred to the mould (3). The stack is simultaneously draped and fully impregnated within the next process step (4), which is called viscous draping. The part can be demoulded when shape stability is reached, which is determined by the curing velocity of the resin (5). Since significant cavity pressures develop only towards the end of the tool stroke, the influence of resin on the draping is mainly limited to the intra-ply and interface behaviour. Therefore, the investigation of infiltrated material behaviour provides important information to understand and model the mutual dependencies between the process parameters within the WCM process. To the author's knowledge, no test benches for the characterisation of infiltrated engineering fabrics are available yet, although research in the field of prepreg thermosets and thermoplastic UD-tapes revealed strong dependencies between the matrix material state (viscosity) and mechanical properties during shear [6,7] or bending [8] deformation.

In the first part of this study, a modified version of the bias-extension test (IBET: Infiltrated bias-extension test), which enables infiltrated shear characterisation of unidirectional or woven/bidirectional reinforced textiles, is presented (Section 2) and validated (Section 3), since in-plane shear provides the main deformation mechanism of engineering textiles during draping [7]. For characterisation of the shear behaviour of dry woven and non-crimed fabrics (UD-NCF), the bias-

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https://doi.org/10.1016/j.compositesa.2018.08.018
Received 11 July 2018; Received in revised form 17 August 2018; Accepted 17 August 2018
Available online 23 August 2018
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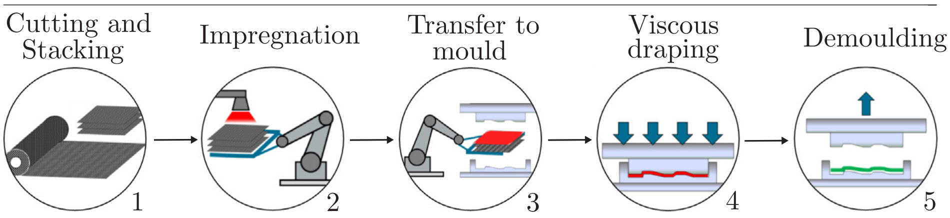

Fig. 1. Schematic illustration of the principle WCM process steps. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

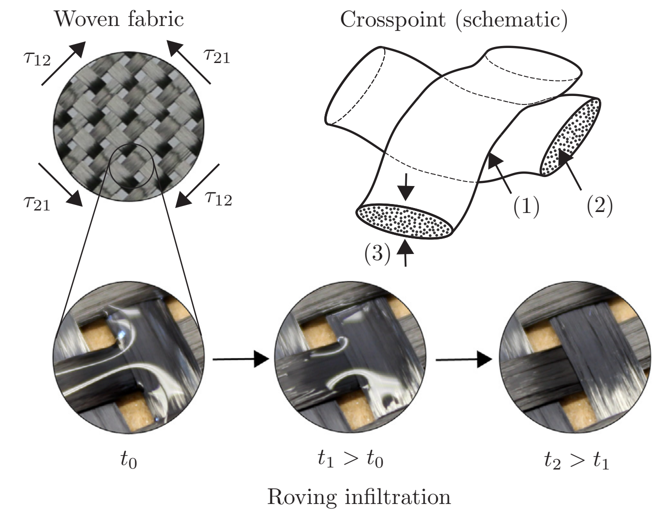

Fig. 2. Illustration of the expected infiltration mechanisms: Change of friction at crosspoints (1), change of internal friction and bending behaviour (2), as well as change of compaction behaviour due to infiltration of the rovings (3); bottom: A visualisation of the impregnation process (t_0–t_2) at a crosspoint and into the roving. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

extension tests (BET) [7,9,10] or picture frame tests (PF) [9,11–13] are usually applied. Both tests provide their own advantages and disadvantages [10,14]. While the BET provides a quite simple and fast characterisation approach, several authors observed drawbacks in terms of mesoscopic effects (inter-tow slip, crossover slip, fibre bending) during the characterisation of dry fabrics [14–16]. On the contrary, the deformation modes shear and tension can be decoupled using PF tests, which enables the investigation of shear tension coupling for woven fabrics, except for UD-NCFs [10]. However, miss-alignment and in-plane bending of the fibers can provide challenges when using the PF test [12,17–19]. The modified design is based on a BET set-up, rather than a PF, since its enables shear characterisation for a wider range of textiles, including unidirectional non-crimp infiltrated fabrics [10]. Additional picture frame tests and optical evaluations are performed to estimate and evaluate the impact of mesoscopic effects on the predictive accuracy of the locking angle.

In the second part of this study (Section 4) FE-forming simulation is used to access the process relevance of infiltration-dependent shear behaviour on part level. FE-forming simulation is used, since it enables a detailed analysis of the resulting deformation by means of constitutive modelling of the material behaviour, considering process and boundary conditions [20–22]. Representation of forming behaviour is based on constitutive modelling of the relevant deformation mechanisms, which are usually separated into intra-ply mechanisms for the single plies (membrane and bending) and interface mechanisms (friction and adhesion) [20,23]. On a macroscopic scale, membrane and bending behaviour have to be decoupled, since in-plane fibre tensile stiffness is several decades higher than the bending stiffness [8,24]. This is often achieved by stacking of membrane and shell elements or by an internal physical decoupling within one element [22].

In this study, a macroscopic FE-forming simulation approach is used, including a hyperviscoelastic membrane model, which is parametrised with the results of the infiltrated shear characterisation (Section 4.2). The membrane model is implemented by means of invariants, similar to the approaches presented by [25–27] within a material subroutine (VUMAT) in the commercially available FE-solver Abaqus. A nonlinear shear modulus, depending on shear angle and shear rate analogue to the approach presented by Machado et al. [6] is used. Straightening of the fibers is taken into account, since it is required for a correct parametrisation with the BET set-up [28]. However, a direct implementation of a tension-shear coupling, as among others proposed by Komeili et al. [29], is neglected since the modified IBET does not provide the possibility to measure this mechanism yet. To account for bending behaviour, a hypoelastic non-orthogonal material model, implemented via a user subroutine (VUGENS) in Abaqus by Dörr et al. [8], is used within a superimposed shell element.

2. Characterisation set-up for infiltrated shear behaviour

2.1. Requirements and infiltration mechanisms

Beyond dry textile shear characterisation, the new set-up is designed to allow the investigation of a wide range of fully infiltrated textiles, including fluids with low viscosity (≈20 mPa s). The use of pre-infiltrated specimens within a common vertical BET reveals several drawbacks. On the one hand, a homogeneous infiltration state, especially for lower viscosities, cannot be guaranteed during testing, since resin constantly seeps downwards due to the gravity. Beyond that, the residual weight of the resin overlays the measured force response. On the other hand, it is expected that the fluid within the rovings and around the crosspoints contributes to the shear resistance, especially for higher viscosities and shear rates. This mechanism could be influenced by the absence of fluid around the sample. A reproducible and homogeneous infiltration state of the specimens during testing is anticipated to be of high importance, because of three main infiltration mechanisms that are expected to have an impact on the measured shear behaviour response (cf. Fig. 2(1–3)). Preliminary investigations show, that the resin seeps into the rovings and thickens them, which is expected to influence shear behaviour due to a change in bending stiffness (1) as well as in compaction behaviour (3) of the rovings. Furthermore, resin could form a lubrication layer at the crosspoints of the rovings, which changes frictional behaviour (2), depending on fluid viscosity and possibly slip-rate. All of these mechanisms significantly depend on a homogeneous infiltration state of the specimens. Hence, to ensure a homogeneous infiltration state during testing, the characterisation set-up should provide shear testing in a fluid reservoir. This makes a horizontal alignment reasonable.

2.2. Design of the modified infiltrated bias-extension test (IBET)

The IBET is designed as a horizontal bias-extension test within an additional fluid reservoir (cf. Fig. 3). As shown in Fig. 3(b), the rear fixture remains fixed during the test, while the front fixture is pulled by a steel rope with a low bending stiffness, which is mounted on a load cell of a tensile testing machine. To ensure a reproducible initial positioning and to prevent initial deformation of the specimen, the

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