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On the characterisation of transverse tensile properties of molten unidirectional thermoplastic composite tapes for thermoforming simulations

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ABSTRACT

The development of Finite Element (FE) thermoforming simulations of tailored thermoplastic blanks, i.e. blanks composed of unidirectional pre-impregnated tapes, requires the characterisation of the composite tape under the same environmental conditions as forming occurs. This paper presents a novel approach for the characterisation of transverse tensile properties of unidirectional thermoplastic tapes using a Dynamic Mechanical Analysis (DMA) system in a quasi-static manner. The relevance of the presented method is assessed by testing, under the same environmental conditions, a control material with both a universal testing machine and a DMA system. For simulation purposes, a unidirectional thermoplastic tape is characterised under environmental forming conditions using the presented test method. Experimental results, which include stress–strain behaviour and transverse viscosity, are eventually used to identify, via an inverse approach, simulation parameters of a thermo-visco-elastic composite material model (MAT 140, PAM-Form, ESI Group). Comparisons between simulated and experimental results show good agreement.

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1. Introduction

In his review of the 2014 annual report of the association Carbon Composites e.V. (german association which gathers composite companies and research institutes), Holmes expects the global carbon fibre market to grow at a rate of about 10% per year until 2020 [1]. His review also emphasises the increasing interest of the automotive industry in Carbon Fibre Reinforced Plastic (CFRP) materials. Facing new ecological challenges, such as the 2021 target set by the European Commission (40% reduction of car CO_2 emissions), the automotive industry sees great potential in CFRP materials because of their very good specific mechanical properties (stiffness-to-weight ratio) [2]. To address future ecological challenges, thermoplastic composite materials appear to be better suited than their thermoset counterparts because of their better recyclability capabilities [3,4]. Furthermore, their potential for short manufacturing cycle time make them particularly attractive to the automotive industry which aims to produce large volumes of components [3].

Since the 1990 s, automated processes such as Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) technologies have shown their efficiency to layup unidirectional pre-impregnated tapes. However, they also proved to be limited in the layup of complex mould geometries, e.g. tooling with double curved shapes and short radii [5,6]. To overcome such restrictions, sequential manufacturing methods have arisen. In a first step, the intrinsic advantages of automated technologies such as high layup rates and good reproducibility are used to layup flat multi-layer composite stacks. Such stacks are referred as tailored, or customised, since every layer is composed of unidirectional pre-impregnated composite tapes orientated in different directions. For thermoplastic composites, tailored stacks have to be consolidated using, e.g. a double-belt press [4,7] or a static press, before being processed by means of a thermoforming process. In thermoforming processes, consolidated thermoplastic stacks are formed in their molten state into complex 3D geometries. Throughout the years, several different variants of thermoforming processes have been developed, e.g. stamp forming, diaphragm forming [8].

Thermoforming processes are complex processes prone to the development of defects such as out-of-plane wrinkles [9]. In order to anticipate their occurrence, Finite Element (FE) thermoforming simulations have been developed over the last decades [10].

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The ability of such simulation models to accurately predict the occurrence of defects is mainly governed by the quality of simulation input, i.e. material properties. The characterisation of inter- and intra-ply behaviour, which has to be performed under the same conditions as forming occurs (in particular temperature), concern properties like inter-ply slip, intra-ply shear, out-of-plane bending and transverse tension, i.e. tension perpendicular to fibre direction [11–14].

This paper presents a novel approach for the characterisation, under forming conditions, of the transverse tensile properties of unidirectional thermoplastic composite tapes using a Dynamic Mechanical Analysis (DMA) system in a quasi-static manner. The need of a new approach is motivated by the difficulties encountered while characterising a molten thermoplastic tape using a universal testing machine [15]. The characterisation of transversal behaviour is particularly challenging because (i) the molten state of the thermoplastic material makes it difficult to keep specimen integrity, (ii) the high temperature, i.e. 280 °C, adds technological challenges and (iii) it is mostly governed by resin behaviour and is thus, rate dependent. The relevance of the presented method is assessed by testing, under the same environmental conditions, a control material with both a universal testing machine and a DMA system. In the scope of this study, a non-cured unidirectional thermoset pre-impregnated tape qualified for aerospace applications tested under environmental forming conditions is considered. The presented test method is subsequently applied to a unidirectional carbon fibre reinforced polyamide 6 tape to investigate the rate dependency of its transverse tensile properties (stress–strain behaviour and transverse viscosity) under environmental forming conditions, i.e. when the composite is molten. Experimental results are eventually used to identify, via an inverse approach, simulation parameters of a thermo-visco-elastic composite material model (MAT 140, PAM-Form, ESI Group).

2. Thermoforming simulations

Thermoforming processes are complicated manufacturing methods in which the quality of the final preform is influenced by multiple parameters. As reported by several researchers, process parameters, e.g. temperature, forming speed and die geometries, as well as stack properties, e.g. original blank dimensions and layup arrangement, play an important role on the final outcome of the forming process [7,9,16–21]. Amongst these, process temperature appears to be particularly important [9,17]. Because of their specific molecular structures, thermoplastic composites exhibit very different behaviour upon temperatures. When thermoplastic composites become molten, i.e. are heated above their melting temperatures, they weaken and behave as viscous materials [22]. Because of this change of behaviour, a good control of temperature inside the laminate during manufacturing is essential. The exhaustive understanding of thermoforming processes is complex and time consuming because of the amount of parameters to take into account. For efficiency purposes, the development of FE simulation models is nowadays favoured over "trial-by-error" approaches.

The main goal of thermoforming simulations is to detect (ideally ahead of any trials) the potential occurrence of defects. Localised thinning, fibre re-orientations, in-plane wrinkles and out-of-plane wrinkles (also referred as out-of-plane buckling) have been commonly reported defects induced by thermoforming processes [9,16]. Over the last decades, many research teams have been working on the development of FE thermoforming simulation models. In terms of numerical formulations, implicit [23–25] and explicit [26–31] methods have been investigated. Some researchers also implemented their material models for both implicit and explicit formulations [32,33]. Although implicit methods would be overall more efficient, explicit formulations are currently best suited for thermoforming simulations due to their better capacity to manage complex contacts [10].

In the scope of this work, simulations are developed with Visual-FORM (commercial software supplied by ESI Group) and solved using the explicit solver PAM-Form (v.2012 and v.2013). In a similar approach as Larberg et al. [34], simulations are built up on a macroscopic level such that every layer of the tailored blank is represented by a layer of elements, i.e. shell elements in this work. In PAM-Form, the material is considered as a viscous solid. Shells are said to be "bi-phase" as the material law includes both linear elastic and viscous models [26]. The constitutive model is composed of a thermo-visco-elastic matrix and elastic fibres. This material model, referred as MAT 140, consists of three elements in parallel (see Fig. 1):

- A stabilising elastic "parent sheet",
- A thermo-visco-elastic matrix component,
- Linear elastic springs.

The "parent sheet" behaves like an elastic material model dependent on the shear modulus G and the Poisson's ratio ν. The "parent sheet" is also used to stabilise the behaviour of shell elements. The matrix is considered as a thermo-visco-elastic component. It is represented by a Maxwell element, i.e. a spring and a dashpot in series. The behaviour of this component is controlled by the largest tensile modulus (E_1, E_2), i.e. E_1 for unidirectional composites, and the viscosity η. Viscosity can be modelled as either a constant value, a cross equation or a power-law equation. Linear springs E_1 and E_2 aim to depict material tensile behaviour. For unidirectional fibre-reinforced materials, E_1 and E_2 govern properties align with and transverse to fibre direction, respectively. Last but not least, bending properties are also accounted via B_1 and B_2 parameters, which are longitudinal and transverse out-of-plane bending parameters, respectively [35,36].

For the development of thermoforming simulations, each of the aforementioned deformation mode has to be characterised and, in a subsequent step, used for the identification of proper simulation input (inverse method). This paper focuses on the characterisation at forming temperature of transverse tensile properties of a unidirectional thermoplastic composite material, on the one hand, and on the identification of corresponding simulation input (E_2 and η), on the other hand.

3. Review of existing test methods

Since the 1960 s the characterisation of transverse tensile properties of unidirectional composite materials has been considerably investigated in the field of fracture and damage mechanics

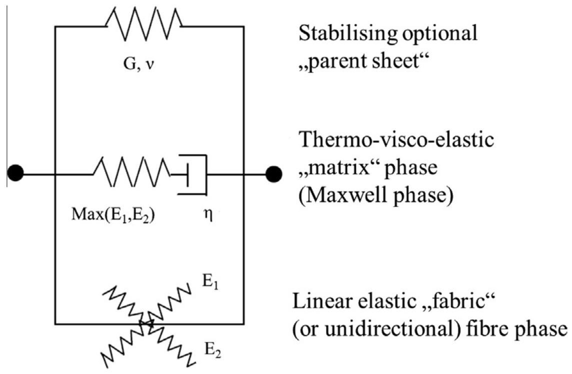

Fig. 1. Components of material model MAT 140 for fibre-reinforced materials (PAM-Form, ESI Group, adapted from [36]).

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