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Analysis of thermoplastic prepreg bending stiffness during manufacturing and of its influence on wrinkling simulations

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A B S T R A C T

Bending properties of thermoplastic prepregs used in aerospace are investigated at representative thermoforming temperatures. The influence of temperature is of principal importance because prepreg manufacturing is performed close to the resin's melting point. A cantilever test performed in an environmental chamber is presented. Bending properties of PEEK-carbon satin and PPS-carbon satin prepregs are measured in a range of temperature including manufacturing temperatures. It is shown that the bending stiffness of the fore-mentioned thermoplastic prepregs are greatly influenced by temperature. The measured bending properties are used to simulate a thermoforming process. The impact of these properties on the simulation results is shown as well. Particularly, bending stiffness during forming determines the size of wrinkles that may appear. The sensitivity of wrinkle size with regards to the measured bending stiffness is analysed.

1. Introduction

Textile composites' advantageous mass-mechanical properties make them materials of choice when saving mass is a crucial issue. Their development has been significant in the last few years, particularly in the aeronautics industry [1,2]. There is a growing interest in composite materials in other industries such as the car industry, but it is more recent [3,4]. The considerable production rate in automobile part manufacturing is hardly compatible with thermoset prepreg draping (with curing in autoclave) or LCM processes that are time demanding. Thermoforming of thermoplastic prepregs is an interesting manufacturing process given the previous line of thought. The cycle time is around one minute including the pre-heating of the prepreg stack, the forming at high temperature and the cooling after consolidation. Studies concerning this process started in the 1980's [5–10]. However, a strong interest in these processes has developed recently both in industry and in academia [11–16]. The development of these thermoforming processes is complex because many thermal and mechanical aspects affect the state of the final composite. In order to decrease the number of trial and error tests used in these process developments, simulation codes allow for a more efficient and cost-effective design approach. The modeling of each prepreg layer is usually made by a set of shell finite elements in frictional contact with its neighbor layers [15–18]. These F.E. simulation codes require knowledge of the prepreg ply mechanical behavior and of the tool-ply and ply–ply friction at the manufacturing temperature. The recommended manufacturing temperature is slightly above the fusion temperature of the resin. Nevertheless it can vary within the composite because of heat transfers to and from the tools. These temperature variations are important because they can significantly modify the mechanical behavior of the plies and can lead to defects [15]. Therefore, the mechanical properties during manufacturing must be known for a fairly wide range of temperatures. The in-plane shear behavior is the most important mechanical property during thermoforming on double curved shapes. The bias extension test and picture frame tests are generally used to measure in-plane shear properties [19–23]. A torsion bar test has been proposed recently for unidirectional prepregs to measure their shearing properties [24]. The biaxial tensile properties can be measured from biaxial tests on cross shaped specimens [25–28]. The tensile stiffness is large and mainly depends on the fibers and therefore is little affected by the temperature. Bending properties are also required when using a F.E. approach based on shell elements. Bending stiffness conditions the geometry of the computed wrinkles [29–31]. Wrinkling phenomena is frequent due to the fibrous internal structure of the reinforcements. Bending stiffness must be taken into account in order to verify that the wrinkles do not extend to the useful zones of the manufactured composite

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part. For thermoplastic prepreg, bending stiffness depends on the temperature.

The first objective of this paper is to propose an experimental method for the measure of the bending behavior of thermoplastic prepregs and its dependence on temperature. In [18], Haanappel et al. present formability analyses of textile reinforced thermoplastics for which "Bending properties have not been characterized due to the absence of a mature bending test for fibre reinforced thermoplastics at elevated temperatures". The experimental device described in the present paper proposes a first response to the fore-mentioned absence. It is based on a cantilever test in a thermal environmental chamber using optical measurements of deflection. The measured bending properties are then taken into account in thermoplastic prepreg thermoforming simulations. The influence and the importance of the prepreg's bending stiffness and of its dependency on temperature are investigated.

2. Virtual work theorem. Tension-bending decoupled approach

In any virtual displacement field $\underline{\eta}$ such as $\underline{\eta} = 0$ on the boundary under prescribed loads, the virtual work theorem relates the internal, exterior and acceleration virtual works:

$$W_{ext}(\underline{\eta}) - W_{int}(\underline{\eta}) = W_{acc}(\underline{\eta}) \quad (1)$$

In the case of a textile prepreg described by shell finite elements, the internal virtual work is assumed to be separated into [32]:

$$W_{int}(\underline{\eta}) = W^t_{int}(\underline{\eta}) + W^s_{int}(\underline{\eta}) + W^b_{int}(\underline{\eta}) \quad (2)$$

With

$$W^t_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\varepsilon_{11}(\underline{\eta}) {}^pT_1 {}^pL_1 + {}^p\varepsilon_{22}(\underline{\eta}) {}^pT_2 {}^pL_2 \quad \text{virtual internal work of tension} \quad (3)$$

$$W^s_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\gamma(\underline{\eta}) {}^pM_s \quad \text{virtual internal work of in-plane shear} \quad (4)$$

$$W^b_{int}(\underline{\eta}) = \sum_{p=1}^{ncell} {}^p\chi_{11}(\underline{\eta}) {}^pM_1 {}^pL_1 + {}^p\chi_{22}(\underline{\eta}) {}^pM_2 \, {}^pL_2 \quad \text{virtual internal work of bending} \quad (5)$$

where $\varepsilon_{11}(\underline{\eta})$ and $\varepsilon_{22}(\underline{\eta})$ are the virtual axial strains in the warp and weft directions, $\gamma(\underline{\eta})$ is the virtual angle between warp and weft directions, $\chi_{11}(\underline{\eta})$ and $\chi_{22}(\underline{\eta})$ are the virtual curvatures of warp and weft directions, ncell is the number of woven cells, ${}^pA$ is the quantity A for the woven cell number p, and L_1 and L_2 are the length of a unit woven cell in warp and weft directions.

Biaxial tensile tests have been developed to measure the tensions T_1 and T_2 as functions of axial strains ε_{11} and ε_{22} [25–28]. The in-plane shear moment M_s is related to the shear angle γ by bias extension tests or picture frame tests [19–24]. Finally, the bending moments M_1 and M_2 are obtained as functions of the curvatures χ_{11} and χ_{22} by bending tests that are specific to fibrous materials and that will be described in Section 3.

The three deformation modes are assumed to be decoupled for simplicity reasons. Nevertheless it has been shown that some coupling exists. Particularly in-plane shear stiffness can depend on the tensions [34–37]. Concerning the bending virtual work, the term $\chi_{12}(\underline{\eta})M_{12}$ that comes from the twisting curvature is neglected. The architecture of the woven cell can lead to this assumption, another reason is the absence of experimental data. Only the bending stiffness in the directions of the yarns is generally known.

The in-plane shear $M_s(\gamma)$ and bending behaviors, $M_1(\chi_{11})$, $M_2(\chi_{22})$ strongly depend on the temperature of thermoplastic thermoforming. High temperature tests have been proposed for in-plane shear measurements [19,23,24]. The first objective of the present paper is to propose bending tests for thermoplastic prepregs for a range of temperature including the manufacturing temperature. The data obtained will be taken into account in forming simulations.

Eqs. (1)–(5) are used to develop a forming simulation approach with the Plasfib software [32,33,38]. In order to simulate wrinkling and, particularly, wrinkle shape one must take into account bending properties. Consequently, a secondary objective of this article is to analyse the importance of bending stiffness and its dependence on temperature in thermoplastic thermoforming simulations.

Remark: The approach described in Eqs. (1)–(5) decouples the virtual tension and bending works and consequently the corresponding rigidities. These behaviors are coupled in classical plate or shell theories. This kind of coupling is not valid in fibrous composite reinforcement of prepregs over fusion temperatures because of the possible relative motion between fibers and yarns. For a given tensile stiffness, the bending stiffness of a fibrous reinforcement or of a prepreg with melt resin is much smaller than that of a plate made of a continuous material. A decoupled approach such as (1)–(5) is necessary.

3. Thermoplastic prepreg bending experiments

Bending of shell and plate is a large scientific domain and many models have been proposed in the field. Nevertheless, bending of fibrous materials, and among them bending of prepregs, is very specific. Actual sliding between fibres and between yarns decreases considerably the bending stiffness of a fibrous ply compared to a continuous material. It is as such for dry composite reinforcements, thermoset prepreg (because the resin is not yet polymerized) and thermoplastic prepregs (because the high manufacturing temperature melts the resin). The relations given by classical beam or shell theories (Bernoulli, Kirchhoff) are no longer valid and bending properties must be measured and modeled separately from tensile properties.

Because of the weak bending stiffness of the fibrous reinforcements and prepregs, the standard bending tests, such as three or four points bending, cannot generally be used. Two bending tests are used preferentially: The cantilever test [39,40] and the Kawbata bending test (KES-FB2) [41,42]. Fig. 1 shows the principle of the ASTM D1388 cantilever test. The specimen is initially positioned on a horizontal surface. Then the specimen is pushed over the edge at a predefined speed. The part of the specimen that is no longer supported by the horizontal surface bends under gravity. The sliding action must be stopped at the instant the tip of the specimen

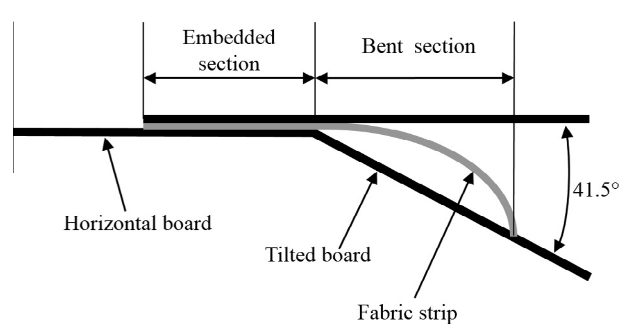

Fig. 1. Schematic representation of the standard cantilever test.