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On the Predictive Tools for Assessing the Effect of Manufacturing Defects on the Mechanical Properties of Composite Materials

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Abstract

Despite the recent advances in the field of manufacturing of composite materials, with both thermosetting and thermoplastic matrix, the presence of irregularities that influence their mechanical properties and behavior remains a critical issue to the industry. The defects with the form of porosity, fiber misalignment, delamination and poor consolidation are considered an unavoidable form of initial damage to composite materials. The reduction of the defects by optimizing the manufacturing process and the creation effective tools for predicting the residual properties of these materials during the design and/or the manufacturing phase are of great interest. In the present work, presented are these numerical tools and methodologies based either on the idea of optimizing the manufacturing process or by using data derived from non-destructive tests. Finally, the possibility of combining the two approaches is being proposed.

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Keywords: Manufacturing defects; Finite element modeling and simulation

1. Introduction

In the recent years, the use of composite materials of polymeric matrix reinforced either with carbon or glass fibers has been increasing due to their excellent mechanical properties with lower weight compared to conventional materials. Moreover, their architecture capabilities regarding the lay-up and the plethora of materials to be used as matrix have given to designers a lot more options when developing a component.

This increment of use has posed a lot of demands regarding the quality of these materials causing the amelioration of the manufacturing procedures in both thermosetting and thermoplastic-based composites. Moreover, a lot of research was conducted in mainly two directions namely optimizing the manufacturing procedure to eliminate as much defects as possible and producing predictive tools in terms of numerical methodologies for assessing the effect of the defects remained after the manufacturing procedure.

The defects occurred during manufacturing may be categorized into four major categories namely fiber misalignment, porosity, delamination and residual stresses. Each category affects specific mechanical properties, for instance porosity affects the shear properties of composite laminates [1] as they depend on the matrix quality while delamination affects the compressive properties [2]. Nevertheless, the most severe effect on the mechanical performance is observed while irregularities in the fibers may occur [3]. These irregularities correspond to fiber misalignment of the uni-directional composites and shear deformation of the textiles. Moreover, the previously mentioned defects correspond to different anomalies to the manufacturing procedure. Porosity is caused mainly by the entrapment of volatiles [4], inter or intra-laminar and it may be restrained to

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low levels using the high quality manufacturing procedures while delamination is caused either by large voids between the layers or by low quality manufacturing procedure (e.g. hand lay-up) [5]. On the contrary, fiber misalignment and wrinkling is not easily controlled and in a large part of the existing procedures is considered as inevitable, especially when the existing manufacturing parameters cannot variate and the design of a component cannot be changed.

In the present work, presented is a review of the existing methods to optimize some of the manufacturing procedures of thermoplastic based composite materials and to present a methodology for assessing the residual properties of components and parts which is the basis of a national research project, the C.R.AB. (Composites Research ABruzzo).

2. The Effect of Fiber Misalignment

As a form of damage introduced during manufacturing, the fiber misalignment affects severely many of the properties of composite materials, both UD and woven. As seen in [6], the fiber misalignment developed in the form of kink-bands influence the elastic properties of composites reducing also the compressive strength. The kink-band regions are causing fiber-matrix debonding after a critical load which is lower than usual [7]. In [8] observed is a propagation of the kink-band to the un-kinked material causing abnormal behavior and shear driven failure to the composite material. In most of the works conducted experimentally and analytically, the kink band formation is considered as a post buckling incident which affects the material first locally and then globally [10-11]. Among the highlights of [12] is the fact that the fiber misalignment affects the effective properties of UD composite materials as the traditional micromechanical approach for calculating them, and the corresponding homogenization in the microscale, is based in idealized geometries with no imperfections.

Another frequent defect regarding the fibers' alignment is the waviness which might be developed in both UD and textile composites. Joyce et al. [13] used optical microscopy to characterize the manufacturing induced waviness to composites. The effect of ply waviness seems to degrade significantly the compressive properties of these materials either in static [14-15] or compressive fatigue [16] loads. In the work of Wu et al. [17], the combined effect of the in-plane buckled fibers and out-of-plane waviness was investigated concluding to a massive reduction of the tensile and compressive properties while the Charpy impact strength is ameliorated by the in-plane and degraded by the out-of-plane waviness.

Generally, the textile composites tend to be used more compared to traditional composite laminates consisting of multiple layers of UD plies because of their superior out-of-plane properties and their adaption in complex geometries [18]. Nevertheless, during several procedures including draping or thermoforming, they are susceptible to shear deformation of the yarns as observed and analyzed in several works [19-20].

From all the research up to date, it is clear that irregularities of the fibers with the form of kink bands, shear deformation of the textiles and/or waviness are influencing the mechanical properties and the durability of these materials after having been manufactured. To this end, the use of numerical tools capable of predicting the regions with wrinkling and the shear deformation of composites may be considered as necessary.

3. Numerical Tools for Simulating the Manufacturing Procedure of CFRTP

Considering the severity of the effect of the fiber misalignment and waviness, the necessity of predicting the output of a manufacturing procedure especially in procedures like thermoforming or stamping of CFRP is considered high. To this end, predictive tools were created, specialized to simulate this procedures using finite elements.

In the work of De Luca et al. [21], the thermoforming process of CFRTP plate in double dome shaped forming tools was simulated using PAM-STAMP and validated experimentally. The influence of the blank holder and the number of plies of the composite plate were investigated leading to fruitful conclusions regarding the wrinkling and the shear deformation of the yarns (Fig.1).

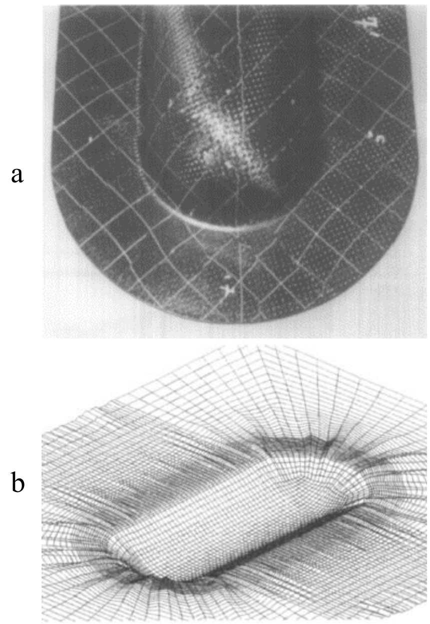

Fig. 1. The experimental (a) and numerical (b) investigation of the defects introduced during thermoforming to the double dome geometry [22].

The same tool geometry was also utilized in the work of Willems [22] where a number of material parameters' influence to the simulation and the tool force were investigated using PAMFORM (Fig.2). The authors made a large number of conclusions about the influence of these parameters and indicate the effect of viscosity to the procedure.

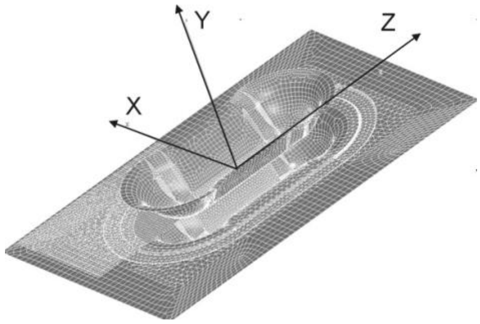

Fig. 2. Simulation of the thermoforming process using PAMFORM [22].

Recently, the AniForm software was developed by Haanappel [23]. This software utilizes information gained from several mechanical tests at different temperatures, namely torsion bar test, "picture frame" test and friction test, to simulate the same forming process (Fig. 3).

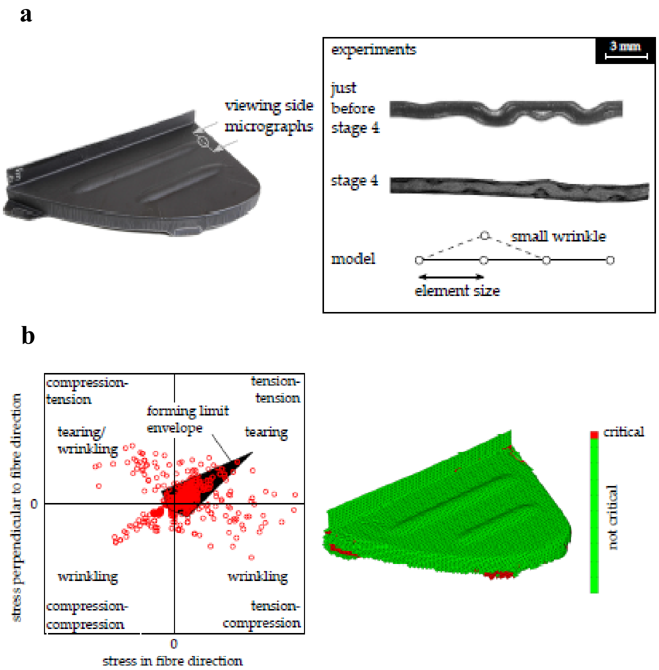

Fig. 3 The experimental (a) and numerical (b) investigation of the defects introduced to a manufactured CFRTP [23].

In addition, more conventional and universal software may be used that are not so specialized for simulating these manufacturing processes like Abaqus or LS-Dyna. In the comparative work of Dörr et al. [24], Abaqus, LS-Dyna, PAM-FORM and AniForm were used for simulating the stamp forming of a thermoplastic part. The advantages and disadvantages of the specialized (PAM-FORM, AniForm) and multi-purpose (LS-Dyna, Abaqus) were addressed and a comprehensive comparison of the results in terms of deformed shape and final part dimensions with an actual case (experimentally) was conducted. An interesting feature comparison is presented in the following table.

Table 1. A comparison between the features of several FE software packages for manufacturing simulation [24].

Comparing Feature	**PAM-FORM**	**AniForm**	**LS-Dyna**	**Abaqus***
Fully decoupled bending behavior	Yes	Yes	No	Yes
Assignment of characteristic curve	Yes	No	Yes	No*
Deformation described by constitutive models	No	Yes	No	Yes
Rate dependent membrane behavior	Yes	Yes	No	Yes
Rate dependent bending behavior	No	Yes	No	Yes
Rate dependent interface mechanisms	Yes	Yes	Yes	Yes
Thermo-mechanical modeling	Yes	Yes	Yes	No
Modeling of grippers/ blank holders	Yes	Yes	Yes	Yes
Tailoring determination	Yes	Yes*	No	Yes
Export fiber orientation	Yes	Yes*	Yes *	Yes*

*Only available by customized developments

In the same work, it is concluded that the multipurpose FE packages (Abaqus, LS-Dyna) require additional effort in order to be able to analyze this particular manufacturing process while the customized FE packages (PAM-FORM, AniForm) are quite straight-forward. In terms of results' quality, all the previously mentioned software may deliver quite accurate predictions while it is noted that the greatest accuracy is achieved when the user-defined modelling approaches are utilized by the corresponding software.

4. Numerical Tools and Methods for Conducting Progressive Damage Analysis

Another interesting aspect is the numerical tools and models developed in commercial software (e.g. ANSYS, Abaqus) aiming to predict the influence of specific defects (local) to the global (or macro) behavior of UD and textile composites. In most of the cases the lamina properties are calculated either by using micromechanical equations [25] or by recreating representative parts of the structures (RVE, RUC) to estimate the local properties of the lamina.

While the first approach is applicable only in UD laminates, the second is of great interest as it contains a number of assumptions concerning the purity of the RVE (Representative Volume Element) constituents (fiber, matrix), the interaction between them and, most of all, the geometry. For example, in the works seen at [26-27] ideal geometry of 3D woven composite material was simulated using continuum mechanics (Fig.4).

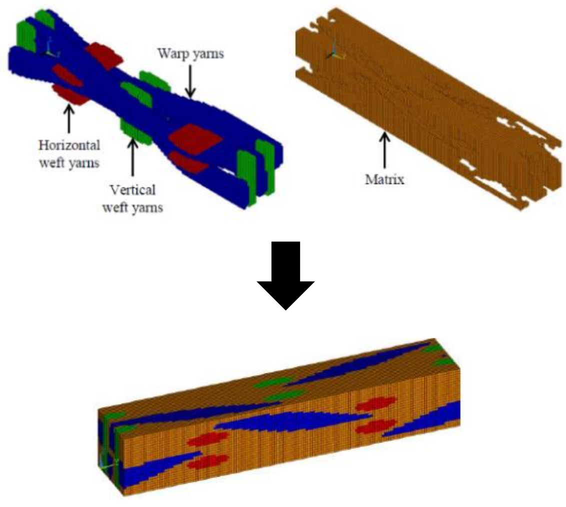

Fig. 4. Progressive damage modelling of RVE of 3D woven textile CFRP [26].

As the non-destructive methods have been increasingly used in the recent years, a lot of effort was given in producing more realistic geometries of textile composites, thus to overcome the assumptions of the ideal geometries. Among the most promising NDT methods is the X-Ray CT which was used by Straumit et al. [28] or Liu [29] to reproduce the misaligned fibers of woven textile composites into voxel models and calculate their effect into the elastic response locally (Fig.5).

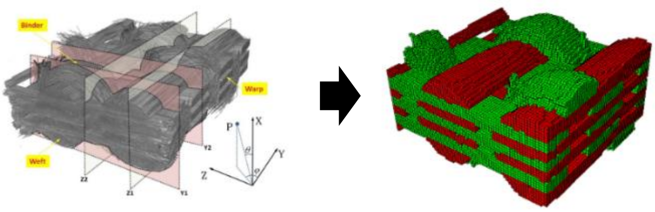

Fig. 5. Translation of the fibre structure to FE voxel model [29].

5. Combining Manufacturing and Structural Analysis – The C.R.AB project overview

From all the above, it is obvious than the structural analysis of a newly designed part is mostly based on assumptions and idealized geometries while a new trend is to be based on data derived from NDT tests conducted though after the manufacturing procedure (e.g. X-Ray CT). To this end, the two parts of a component development, manufacturing procedure and structural analysis can be considered separated.

Aiming to overcome this fact, the University of L'Aquila in collaboration with companies of the automotive sector has launched the C.R.AB project (Composites Research ABruzzo). Following the recent technological trend, several automotive parts are about to be manufactured using GFRTP (Glass Fibre Reinforced Thermoplastic) and substitute this way the conventional materials due to their advantages. Nevertheless, the initial product design is not about to change, thus the project is focused in the following major points:

- characterization of the ply properties for simulating the manufacturing procedure;
- simulation of the thermoforming process for estimating the shear deformation of fibers, the thickness deviation and for optimizing the process itself;
- characterization of the material behavior in several loading conditions and temperatures;
- structural analysis of the part utilizing the output of the manufacturing simulation.

Especially the last point may be the first step to a novel methodology that may provide the designer and the manufacturer with accurate predictions about the behavior and the properties of the part which is about to be constructed. The workflow of this project is presented in the block diagram shown in the following figure.

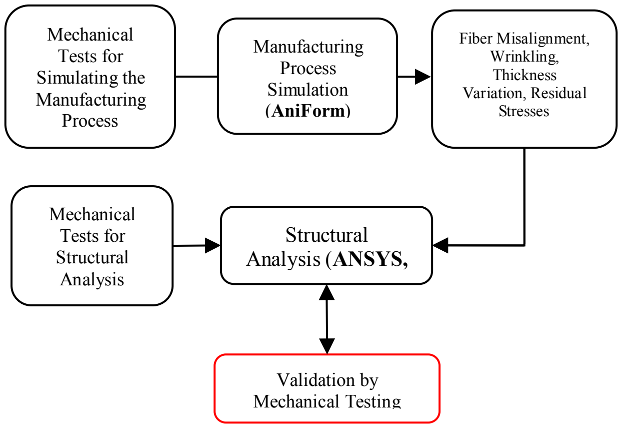

Fig. 6. The C.R.AB project main points and objectives

Considering the above, the project aims to exploit optimally the results of the manufacturing simulation for developing an optimized manufacturing procedure and to integrate the output of the analysis (information about the yarns shear deformation, residual stresses etc.) into the structural analysis of a part into several loading conditions. A number of more than 500 mechanical tests were designed so as to characterize the mechanical behavior of several composite materials based on the polypropylene matrix with either carbon or glass fibers. In addition a number of mechanical tests are designed to be conducted in high temperatures in order to characterize the mechanical properties of the thermoplastic composites while being manufactured. The final aim of the project is the substitution of conventional materials with composites fabricated optimally.

6. Summary

In the present paper, presented was the majority of the existing numerical tools for predicting the geometrical imperfections introduced while a part made of composite material is being manufactured. Among them, the imperfections of the fibers (misalignment, waviness, wrinkling) were briefly presented concluding about the necessity of using predictive numerical tools to optimize the procedure. The authors made a brief presentation of the existing methods of structural and progressive damage analysis indicating the fact that so far major assumptions have been made for constructing them. To this end, the necessity of correlating the manufacturing procedure simulation to the structural and design analysis was presented as the basis of the C.R.AB project which is a national Italian research project in the automotive sector.

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