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Geometrical deviation analysis of CFRP thin laminate assemblies: Numerical and experimental results

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ABSTRACT

During the cure process, the anisotropic characteristics of composite material, combined with high temperature and high pressure to which the material is subjected, cause the development of residual stresses. Consequently, laminate deformations arise and dimensional and geometrical requirements are not reached. Laminate deformations transfer into product distortions through assembly process. Distortions result in uncertainty in the performance of manufactured goods and they require effective management to ensure correct performance.

The present work shows a numerical approach suitable to determine the geometrical deviations of an assembly constituted by thin laminates in composite material. The proposed model considers the geometrical deviations of the assembly parts, due to the manufacturing process, the assembly sequence and the presence of adhesive to put together the parts.

The proposed model was experimentally verified by considering a T-shaped assembly constituted by flat and L-shaped components. The obtained results show a good agreement with the experimental ones.

1. Introduction

Composite materials are used in many applications requiring high dimensional and geometrical accuracy. During cure process, anisotropic characteristics of composite material, combined with high temperature and high pressure to which the material is subjected, make residual stresses to develop; consequently laminate deformations arise and dimensional and geometrical requirements are not reached [1,2]. Residual stresses can be defined as self-balanced stresses which arise in the material even if there is not any structural or thermic load [3].

Laminate deformations arising during cure process can be classified in two main groups: spring-in and warpage. The former is typical of curved parts, while the latter can be found in flat parts. Spring-in is defined as the difference between the measured and the theoretical value of the flange-to-flange angle at the end of the manufacturing process; the warpage is the curving of flat laminates, that produces a deviation from the original shape [4].

There are several phenomena causing residual stresses and distortion, they are illustrated in detail as follows. Resin and fibres present different coefficient of thermal expansion (CTE), moreover fibres CTE is usually orthotropic. This mismatch produces the residual stresses leading to cracking and failure [5]. However, these stresses are not responsible of distortions since they develop on a too local scale and their effects average out on the whole material volume [6]. Another mechanism is due to the orthotropic behaviour of the CTE at ply level, that causes in-plane stresses. These stresses do not lead to deformation if they are enabled to self-equilibrate, for example in flat laminates with balanced and symmetrical lay-up, but they can give rise to distortion in unbalanced or unsymmetrical plates or else in non-planar laminates, such as U or L shaped profiles, even if their lay-up sequence is symmetrical and balanced [7]. The shifting of the neutral axis of the section, due to curvature, combined with the residual stresses, causes this distortion. Considering the whole laminate, the through-thickness CTE is higher than in-plane one: this, associated to the curved geometry, produces the deviation from the tool geometry [8]. Chemical shrinkage is another factor that causes laminate distortion. During cure, molecular cross-linking lessens resin specific volume, augmenting the density. Because of fibre presence, composite contraction is anisotropic: through-thickness shrinkage is larger than in-plane one. Therefore, chemical shrinkage achieves the same effects on residual deformation as those ones due to CTE contraction [9].

There are other factors that provoke deformation, especially the warpage of plates made of composite material [10]. A gradient in fibre volume fraction can arise along the thickness, due to resin flow [11]. This affects the mechanical characteristic of the laminate and consequently it induces the warpage. Moreover, the greatest impact on the

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final shape of the laminate is imputable to the material interaction with the tool [12]. In fact, during the cure cycle the different CTE of mould and laminate makes shear stress arise between them, since the mould tends to expand more than laminate and to stretch this latter [13]. However, the plies closest to the mould surface are more tightened than those furthest, because mould expansion happens in the early part of the cycle, when the shear modulus of composite material is too low to spread the shear stress along the thickness. This uneven stress distribution remains frozen in the material as the cure degree increases and resin shear modulus develops. When the part is released from the mould, these residual stresses are discharged and make bending moments arise, leading to warpage [9]. The effects due to mould interaction are more important for vacuum bag technology, since in this case the mould exercise its effect on one surface only, while the other one is subjected to the bag interaction, that is less severe.

Distortions cause problems during assembly of parts: if the matching surfaces are not in contact, shimming operations are necessary, causing the growth of costs and of product weight [14,15]. In fact, small subparts have to be shaped according to the gap formed by mating surfaces and then they have to be inserted in the assembly, since post–moulding repair/reshaping of the distorted shape is often difficult due to the high stiffness of the composite material. Moreover, a connection of deformed parts can lead to a massive increase of the part internal stress level that deteriorate the part performance. This is a labour-intensive task, that extend the delivery time too.

The effects of spring-in are so evident to require a model to foresee and compensate them, as shown in Ref. [16] for curved composite parts.

In a previous work the influence of some geometrical and structural parameters on the spring-in angle of L-shaped parts was numerically modelled and validated [17]. Now, a numerical tool that starts from the geometrical deviations of thin laminates, such as the spring-in of L-shaped parts and the warpage of the composite parts, to foresee their transfer into the geometrical deviations of an assembly constituted by them, is presented. It takes into account the assembly sequence and the use of adhesive to put together the parts.

The numerical model was applied to a T-shaped assembly made up of three parts. This is a type of structure commonly used in the design of components in composite material. All parts are joined by adhesive and their surfaces present warpage. However, only the L-shaped parts have spring-in. Some L-shaped and flat parts were produced and, then, measured to evaluate their deviations in terms of warpage and spring-in. Those measured geometrical distortions were given as input to the numerical model.

The numerical model transferred those geometric deviations of the L-shaped and flat parts into the assembly and it combined them with the compliant material of all parts, by involving an internal stress level that varies the geometry and, therefore, the performance of the assembly. The obtained numerical results in terms of geometrical distortion of the T-shaped assembly were compared with those obtained experimentally by putting together the previously produced components by adhesive.

2. Material and method

A T-shaped assembly was considered to easily present the developed numerical tool that, however, is a general instrument. The T-shaped assembly is constituted by two L-shaped parts and one flat part, as shown in Fig. 1. The sides are 80 mm and the thickness is 1 mm for the L-shaped part; the dimensions are $160 \times 80\,\text{mm}^2$ and the thickness is 1 mm for the flat part.

2.1. Material and equipment

The material used was a unidirectional carbon-epoxy prepreg produced by Cytec with a designation of Cycom970/T300; the nominal thickness of the single prepreg ply was 0.2 mm and the nominal fibre volume fraction was 60%. Each single hand-cut ply of prepreg was $100 \times 200\,\text{mm}^2$.

To manufacture the composite parts, the hand lay-up of prepreg was carried out on a mould. The mould was a U-shaped male aluminium tool. The tool had two corners of radii 6 mm and 12 mm and a maximum dimension of $380 \times 130 \times 130\,\text{mm}^3$. The mould had a U-shape in order to use it both for the manufacturing of parts and as a tool for the clamping of the parts during the measurement and the assembly. In fact, the mould had two surfaces for the manufacturing and a surface for the measuring and the assembly of parts, as shown in Fig. 2a.

The cure cycle was carried out in the N 120/65 HACDB oven of Nabertherm. It is a single chamber oven with convective heating and it is able to ensure a good temperature uniformity. In fact, the manufacturer ensures a maximum ΔT in its interior of about 8 °C. A very important tool of the oven is the controller of the temperature in the chamber, because it allows the setting of the desired thermal cycle; this controller is provided by Nabertherm and it is called P300.

The mould position, with all stacked materials for the manufacturing of parts, was defined and unchanged during the parts manufacturing in order to always ensure the same thermal flow conditions in the oven and the production repeatability. This position is shown in Fig. 2b.

At the end of the manufacturing process of all parts, a cutting machine was used to trim the edges of the laminates in order to respect the dimensions of the parts. It uses a diamond cutting disk and it runs in a tank that prevents the spread of dust.

2.2. Manufacturing process

The vacuum bagging process was used. A batch of two parts was manufactured in a single curing process in the oven, as shown in Fig. 2c. Therefore, six flat and twelve L-shaped parts were manufactured by three and six batches respectively.

A release film was applied over the surface of the mould, which allows an easy removal of cured parts and a good slip of the prepreg on the mould. Each ply was carefully laid-up on the mould to form a stack. The lay-up sequence of prepreg plies was $[0^\circ, 90^\circ, 0^\circ]_S$. The stack was then covered with a release film and a breather fabric before applying a vacuum bag with the help of a sealant tape. A vacuum of -10^5 Pa was applied after laying up the parts, to remove entrapped air and to minimize the possible effect of corner bridging. Finally, the cure cycle, which consisted of one dwell, was started. During the heating, the part is heated up to 140 °C at 2.5 °C/min. After manufacturing, the mould was left to cool down up to the ambient temperature before the composite parts were removed from the mould. Fig. 2d reports the manufactured parts.

2.3. Measurement of part deviations

A Prismo Vast MPS coordinate measuring machine (CMM) of Zeiss® was utilized to measure the geometrical deviations of the manufactured part.

The fixturing equipment was designed in order to avoid shape variations of part during inspection. Moreover, it was necessary to make accessible all the features constituting the datum reference system or the design specifications. The used equipment was constituted by the U-shaped mould, standard trading components and modular elements that may be assembled to adapt to different part shape, as shown in Fig. 3. The mould was fixed by clamping elements, called tapered clamps, on the measurement surface of CMM and an analogical probe was used to acquire spatial data, whose tip diameter was 3 mm and stylus length was 40 mm.

The measurements of L-shaped and flat parts were carried out in two distinct stages respectively. In the former, the surfaces of parts directed towards the mould during the manufacturing process were