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# Analysis of the manufacturing signature on AFP-manufactures variable stiffness composite panels

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**Abstract.** Variable stiffness composites broaden the design space, in comparison with straight-fiber composites, to meet fixed mechanical performance. Nevertheless, the manufacturing of these advanced composites incurs into the presence of undesired fabrication defects such as gaps and overlaps, which alter the mechanical behavior of the laminated parts. In this work, the authors couple the Defect Layer Method, utilized to model defects, with the Carrera Unified Formulation in order to study how the manufacturing signature affects the fundamental frequency of variable stiffness laminates.

## Introduction

Novel manufacturing techniques, such as Automated Fiber Placement (AFP), have permitted to conceive new families of laminated structures, namely Variable Stiffness Composites (VSC) or Variable Angle Tow (VAT), in which fiber tows are steered conforming curvilinear paths. Olmedo and Gürdal [1] investigated the buckling of VAT plates for different boundary conditions and rotations of the fiber path. Nevertheless, in the cases that Olmedo and Gürdal considered, the minimum turning radius, which determines whether a laminate is manufacturable or not, was not taken into account. Therefore, not all the solutions were feasible from a fabrication point of view. Besides, due to the manufacturing features inherent to AFP, imperfections are prone to arise during the fabrication process, namely gaps and/or overlaps, and affect the structural performance [2].

Many authors have proposed numerical methods to investigate the effect of gaps and/or overlaps on the mechanical properties of variable stiffness composites. Blom et al. [2] investigated how gaps affect the strength and stiffness of VAT using the Finite Element Method (FEM). They concluded that increasing the laminate's total gap area deteriorates strength and stiffness. Fayazbakhsh et al. [3] proposed the Defect Layer Method (DLM), which permits to capture the gap and/or overlap areas that appear in the laminate without incurring into an excessive computational burden as in [2].

In this manuscript, we tackle the influence of gaps and overlaps on VAT laminates by coupling DLM with the Carrera Unified Formulation (CUF) [4]. CUF permits obtaining the governing equations of any structural theory without making *ad hoc* assumptions. So far, CUF has proven to predict accurate stress states [5], as well as capture the influence of multiscale uncertainty defects on the mechanical performance of VAT plates [6].

## Variable stiffness composite plates and defect modeling

VAT laminated components are fabricated by steering fiber bands along curvilinear paths. Throughout the years, different variation laws have been investigated. This work focuses on the linear variation, in which the local fiber orientation, $\boldsymbol{\theta}$, varies along the $\boldsymbol{x'}$ direction as follows:

$$\theta(x') = \phi + T_0 + \frac{T_1 - T_0}{d}|x'|. \qquad (1)$$

The physical meaning the parameters involved above is depicted in [1], and are illustrated in Figure 1.

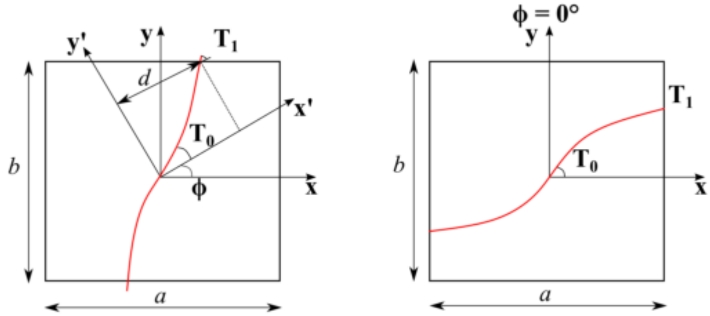


*Figure 1. Representation of the fiber parameters involved in the definition of a VAT laminate.*

Despite the steering capability of VAT plates, the AFP machines that manufacture them present some limitations, being one of them the curvature of the laid fiber path. A manufacturing feature inherent to AFP is the presence of gaps and overlaps in the final part, thereby affecting the structural performance. DLM [3] is considered to model these imperfections. As mentioned in [3], the defect area percentage is the only parameter to modify the elastic properties or the thickness associated to the finite element. Note that the elastic properties vary if gaps are considered, whereas an increase in the thickness is provided in the case of overlap.

**Unified finite elements**

2D FE are implemented within the CUF formalism. According to [4], the 3D field of displacement can be expressed in terms of arbitrary through-the-thickness expansion functions, $\boldsymbol{F_\tau(z)}$, of the 2D generalized unknowns laying over the $\boldsymbol{x-y}$ plane. That is,

$$\boldsymbol{u}(x,y,z) = F_\tau(z)\boldsymbol{u}_\tau(x,y).\ \tau = 1,\dots,M \quad (2)$$

Therein, $M$ denotes the number of expansion terms, and $\boldsymbol{u}_\tau(x,y)$ is the vector containing the generalized displacements. The analysis of multi-layered structures is commonly conducted by following an Equivalent-Single-Layer (ESL) and Layer-Wise (LW) approach. In this manuscript, ESL models are built using Taylor polynomials as $F_\tau$ in the thickness direction. On the other hand, LW utilizes Lagrange polynomials over the single layers and then imposes the continuity of displacements at the layer interfaces, as in [7]. In this context, TE$n$ denotes a TE of the $n$-th order, whilst LE$n$ indicates the usage of an LE with $n$-th order polynomials. Moreover, $X$LE$n$ means that $X$ Lagrange polynomials of $n$-th order are used to describe each layer of the laminate.

Utilizing the FE and shape functions $N_i(x,y)$, the displacement field becomes:

$$\boldsymbol{u}(x,y,z) = N_i(x,y)F_\tau(z)\boldsymbol{q}_{\tau i}(x,y).\ i = 1,\dots,N_n \quad (3)$$

In Eq. (3), $\boldsymbol{q}_{\tau i}$ denotes the unknown nodal variables, and $N_n$ indicates the number of nodes per element. In this work, 2D nine-node quadratic elements, referred to as Q9, are employed as $N_i$ for the $x-y$ plane discretization. For the sake of brevity, the governing equations that calculate the fundamental frequency are not reported but can be found in [4].

**Machine simulation: identification of defected regions**

The steering of fiber bands along a fixed direction, and shifting the AFP head in its perpendicular direction to generate the subsequent fiber course, leads to the presence of gaps and/or overlaps. The location in which they appear depends not only on $T_0$ and $T_1$ but also on the steering strategy. Figure **2** illustrates the case of a [⟨0,45⟩] plate in which the fiber courses touch each other at the edge (Figure 2 left) and at the center of the plate (Figure 2 right). The yellow area indicates a gap area, whereas the green area highlights an overlap area.

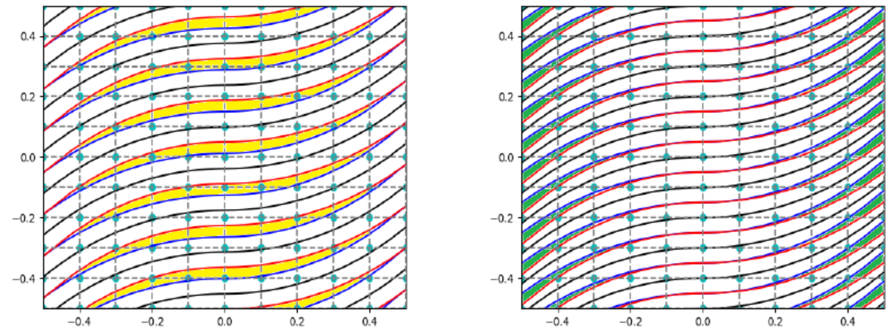

*Figure 2. Example of a plate with* $[\langle \mathbf{0}, \mathbf{45} \rangle]$ *stacking sequence with full gap (left) and full overlap (right) manufacturing strategy.*

The previous imperfections affect such large areas because the course width is kept constant throughout the steering process. In order to reduce the defect area, the course width has to decrease or increase whenever a course intersects the successive one or it does not reach the precedent course's edge, respectively. The increase or decrease of the course width is achieved by cutting an individual tow and restarting its deposition. This comports the generation of small triangular defected regions, as evidenced in Figure 3.

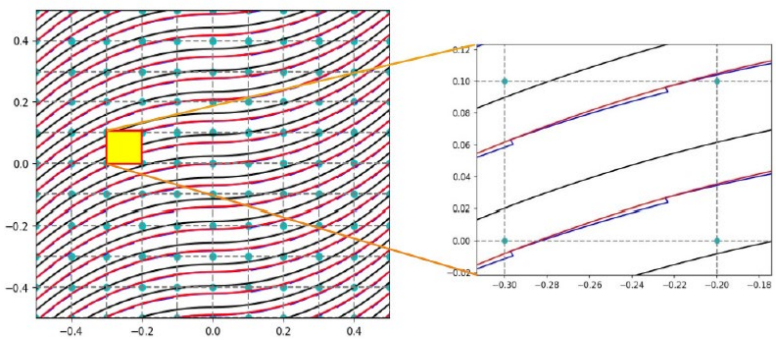

*Figure 3. Gap defect correction over a* $[\langle \mathbf{0}, \mathbf{45} \rangle]$ *ply The zoomed area shows the triangular gaps that are generated.*

**Effect of gap defects on fundamental frequency**

In this section, the effect of manufacturing defects is addressed. As depicted in the previous section, two manufacturing strategies are considered: without and with defect correction. These two strategies are denoted as Type 1 and Type 2, respectively. For the following analyses, the tow paths are conformed by sixteen tows, each with a width of $t_w = 3.125$ mm. The FE mesh comprises 10x10 Q9 elements, based on a convergence analysis performed beforehand.

Table 1 presents the effect of gaps on the first five fundamental frequencies of the $[\langle 0{,}45 \rangle, \langle -45, -60 \rangle, \langle 0{,}45 \rangle]$ plate from [8]. An LW-1 LE2 model is employed since, when gaps are considered, the thickness of the laminate remains unaltered, and no additional computational effort is required when compared to the ideal plate. It is observed that gaps lead to a decrease in the fundamental frequency because resin-rich areas are present within the layers. Type 1 defects present a much lower frequency than the ideal case, whereas Type 2 limits the fundamental frequency reduction.

*Table 1. Effect of manufacturing gaps on the* $[\langle \mathbf{0}, \mathbf{45} \rangle, \langle \mathbf{-45}, \mathbf{-60} \rangle, \langle \mathbf{0}, \mathbf{45} \rangle]$ *plate.*

| Model | $f_1$ [Hz] | $f_2$ [Hz] | $f_3$ [Hz] | $f_4$ [Hz] | $f_5$ [Hz] |
|---|---|---|---|---|---|
| No defects | 609.91 | 903.93 | 1216.18 | 1328.88 | 1469.58 |
| Gap Type 1 | 547.82 | 797.10 | 1083.41 | 1159.71 | 1295.57 |
| Gap Type 2 | 599.10 | 888.99 | 1193.21 | 1306.87 | 1442.75 |

## Conclusions

This manuscript has discussed the effect of manufacture-induced gaps on the fundamental frequency of VSC laminates. The position where gaps and overlaps will appear during manufacturing has been predicted. These defects were incorporated into the FE model by means of the Defect Layer Method. As it was expected, the presence of gaps incurred a decrease in the fundamental frequency. Future works will be related to the optimization of VAT plates in which the aforementioned manufacturing imperfections are considered.

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