Italian Association of Aeronautics and Astronautics
XXVI International Congress
31st August – 3rd September 2021
On-line event hosted by the Tuscany AIDAA Section in Pisa

ADVANCED MODELS FOR THE ANALYSIS OF VARIABLE STIFFNESS COMPOSITES WITH MANUFACTURED-INDUCED GAPS AND OVERLAPS

A. Pagani*[1], A. R. Sanchez-Majano[1]

[1]Mul2 Group, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino

*alfonso.pagani@polito.it

ABSTRACT

The irruption of automated fabrication techniques has allows to increase the quality of aerospace components made out of laminated composites. For instance, Automated Fibre Placement (AFP) and Automated Tape Laying (ATL) helped to reduce the manufacturing times as well as increasing the robustness and repeatability of the composite parts, and allowed the possibility to create Variable Angle Tow (VAT) components. Albeit such advances, these processes produce undesired effects on the manufactures components, such as the appearance of gaps and overlaps throughout the wholse component. In order to circumvent these fabrication flaws, Continuous Tow Shearing (CTS) [1] was conceived in the early 2010s and permits to steer the fibres along curvilinear paths. Nevetheless, due to the shearing of the fibre tows, thickness variability occurs along the steering direction.

In this work, the effects of manufactures-induced defects, such as gaps, overlaps and thickness variability, are studied by coupling Defect Layer Method (DLM) [2] with advanced finite element models based on the Carrera Unified Formulation (CUF), which has already been demonstrated to provide efficient high-order numerical approximations in a hierarchic manner. Especially in the analysis of BAT components, some studies regarding the influence of fibre waviness, modelled as stochastic fields, have been conducted [3-4] in order to show the capabilities of CUF when accounting for manufacturing defects. In this new study, the effectiveness of hierarchical CUF-based finite elements for the analysis of VAT composites as well as defect characterization and through-the-scale propagation is further established.

Keywords: Manufacturing defects, Continuous Tow Shearing, Gaps and overlaps

1 VAT MODELLING IN UNIFIED FORMULATION

1.1 Preliminary considerations

The study of VAT components is studied with one-dimensional models. A cartesian coordinate system (x, y, z) is employed in this work. In this manner, the transposed vectors containing the displacements, strains and stresses are written as:

$$u = \{u_x, u_y, u_z\}^T \quad (1)$$

$$\boldsymbol{\varepsilon} = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{xz}, \varepsilon_{yz}, \varepsilon_{xy}\}^T$$

$$\boldsymbol{\sigma} = \{\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xz}, \sigma_{yz}, \sigma_{xy}\}^T$$

Strains and displacements are related by means of the geometrical relationships which, for the sake of brevity, are not reported in this paper but can be found in the continuum mechanics literature. Then, using the constitutive equations, stresses can be calculated as:

$$\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\varepsilon} \tag{3}$$

where C is the matrix containing the elastic coefficients of the material. It is worth mentioning that, for the case of composite structures, matrix C has to be rotated to the global reference system through the rotation matrix T. This matrix changes pointwise for the case of VAT. That is, the material elastic matrix in the global reference frame is calculated as:

$$\widetilde{\boldsymbol{C}} = \boldsymbol{T}(x,y)^T \boldsymbol{C}\boldsymbol{T}(x,y) \tag{4}$$

In this manuscript, two fibre orientation variation laws are used for the different manufacturing techniques. For the case of CTS, a linear variation pattern is chosen, and follows the following expression:

$$\theta(x') = \Phi + T_0 + \frac{T_1 - T_0}{d}|x'| \tag{5}$$

in which T_0 is the initial fibre orientation, T_1 is the final fibre orientation, d is the length along which the fibre orientation varies, and $x' = x\cos(\Phi) + y\sin(\Phi)$. The reader is invited to read the work by [5] for further information. Then, for the case of AFP, a constant curvature path is considered. This fibre pattern takes the upcoming formula:

$$\sin\theta = \sin T_0 + \kappa|x'| \tag{5}$$

in which T_0 plays the same role as in CTS, and κ is the inverse of the steering manufacturing radius, as explained in [2].

1.2 Kinematic assumptions

In this work, VAT structures are analysed employing 1D CUF models. Within the CUF framework, the 3D displacement field can be expressed in terms of an arbitrary expansion F_τ of the 1D generalised unknowns $\boldsymbol{u}_\tau$ laying along the longitudinal axis as:

$$\boldsymbol{u}(x,y,z) = F_\tau(x,z)\boldsymbol{u}_\tau(y) \tag{6}$$

where $\tau = 1, \dots, M$ denotes the summation over the M expansion terms. A plethora of functions has been used as expansion functions in the extensive CUF literature. For instance, Taylor (TE), Lagrange (LE), Hierarchical Legendre (HLE) have been employed for the analysis of beam-like structures. Moreover, these have been utilised for the study of VAT composite structures, as shown in [3-4]. Due to paper constraints, these expansion families are not reported in this manuscript, but can be found in [6].

Then, the Finite Element Method (FEM) can be used to approximate the in-plane generalised displacement vector by means of the shape functions $N_i(y)$ as:

$$\boldsymbol{u}_\tau(y) = N_i(y)\boldsymbol{q}_{\tau i} \tag{7}$$

in which $\boldsymbol{q}_{\tau i}$ denotes the unknown nodal variables and $i = 1, \dots, N_n$, where N_n is the number of nodes per element, and i indicates summation. Derivation of the governing equations is omitted for brevity, but can be found in [7].

2 NUMERICAL RESULTS

2.1 CTS modelling

As depicted in the CTS literature [1], this novel manufacturing technique allows the engineers to avoid undesired gaps and overlaps, and misalignments during the fabrication of VAT structures. However, due to the shearing of the fibres, a thickened-on-the-edges structure arise during the fabrication. For that reason, as a first numerical assessment, a two-ply VAT component is studied in this work. The individual thickness of each lamina is $t_0 = 0.05$ m, the width and length are $a = b = 1$ m, the stacking sequence is $\theta = [0 \pm < 0{,}15 >]$, a uniform constant pressure $P_z = 10$ kPa is exerted on the top surface of the laminate and all the edges are clamped. The variation in the thickness is represented in Figure 1.

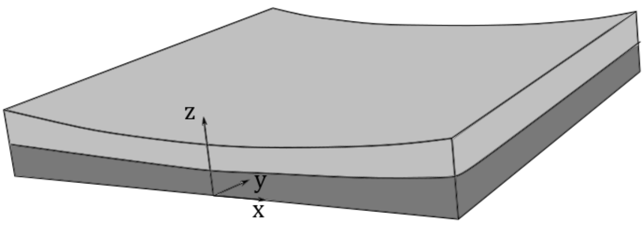

Figure 1. Representation of a CTS manufactured $\theta = [0 \pm < 0{,}15 >]$ VAT component.

To verify the proposed modelling approach, this is confronted against Abaqus. The Abaqus model uses a total of 40x40x20 C3D8R elements, leading to a total of 105930 degrees of freedom (DOF), while the finer CUF model, using a LW approach, employs 62181 DOF. The normal in-plane σ_{xx} and transverse shear σ_{xz} are represented in Figure 2. As it can be appreciated, there exists a good agreement between the in-house model and the commercial one.

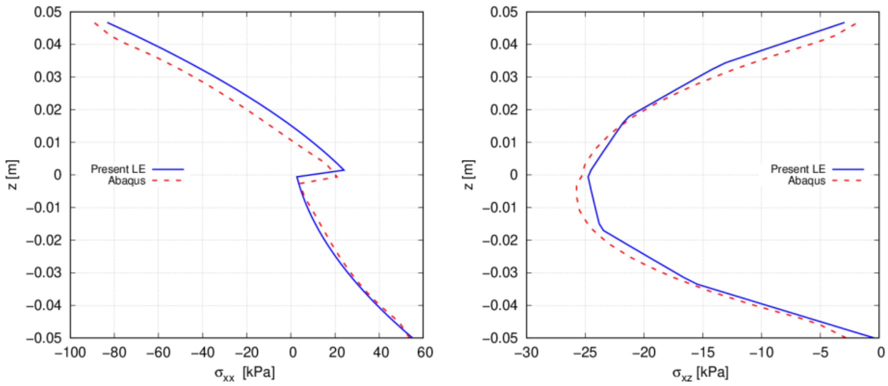

Figure 2. Through-the-thickness stress distribution of the CTS manufactured VAT plate. (a) σ_{xx};(b) σ_{xz}

Next, a study on the buckling response of CTS VAT plates is carried out. For such purpose, both TE and LE are employed to obtain an ESL and LW modelling approach, respectively.

These results are then compared to a 2D Abaqus model. The loading and boundary conditions of the plate are shown in Figure 3.

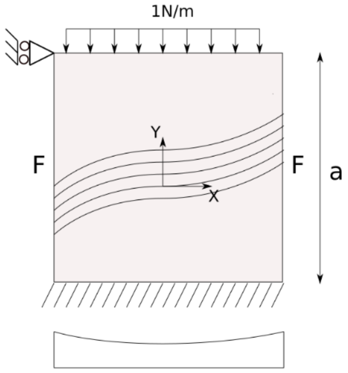

Figure 3. Loading and boundary conditions of the CTS $\theta = [0 \pm < 0{,}15 >]$ VAT plate. F stands for free edge.

The first five buckling loads, provided by the different models, are enlisted in Table 1. It is appreciated that the present in-house approaches present accurate results compared to Abaqus 2D model.

Model	DOF	$F_{cr1} \cdot 10^{-8}$ [N]	$F_{cr2} \cdot 10^{-8}$ [N]	$F_{cr3} \cdot 10^{-8}$ [N]	$F_{cr4} \cdot 10^{-8}$ [N]	$F_{cr5} \cdot 10^{-8}$ [N]
TE 1	558	0.289	0.548	0.963	1.307	1.723
TE 2	1116	0.297	0.563	0.679	0.974	0.989
TE 3	1860	0.295	0.557	0.572	0.809	0.977
TE 4	2790	0.294	0.555	0.558	0.790	0.974
Abaqus 2D	10086	0.296	0.551	0.565	0.790	1.012
LE	38130	0.294	0.541	0.555	0.773	0.974

Table 1. First five buckling loads of the CTS $\theta = [0 \pm < 0{,}15 >]$ VAT plate for different modelling strategies.

Then, the LE model is employed to characterise the first five buckling loads when T_1 is modified, that is, when the stacking sequence takes the following expression: $\theta = [0 \pm < 0, T_1 >]$. These results are included in Table 2.

T_1[°]	$F_{cr1} \cdot 10^{-8}$ [N]	$F_{cr2} \cdot 10^{-8}$ [N]	$F_{cr3} \cdot 10^{-8}$ [N]	$F_{cr4} \cdot 10^{-8}$ [N]	$F_{cr5} \cdot 10^{-8}$ [N]
15	0.294	0.541	0.555	0.773	0.974
30	0.359	0.644	0.668	0.915	1.152
45	0.555	0.873	0.976	1.234	1.599
60	1.195	1.343	1.361	1.457	1.741

Table 2. First five buckling loads of the CTS $\theta = [0 \pm < 0, T_1 >]$ VAT plate using LE model.

3 CONCLUDING REMARKS

This work has presented a novel approach for the modelling, within the CUF framework, of manufactured-induced defects that arise during the fabrication of VAT components. Particularly, the CTS and AFP methods have been analysed.

So far, outstanding results have been obtained for the CTS method, in which variability in the thickness appears throughout the steering direction.

Further results about the effects of gaps and overlaps will be discussed at the Conference.

4 ACKNOWELEDGEMENTS AND REFERENCES

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Gran agreement no. 850437).

REFERENCES

[1] B.C. Kim, P.M. Weaver, K. Potter. Manufacturing characteristics of the continuous tow shearing method for manufacturing variable angle tow composites. *Composites: Part A* **61**, pp. 141-151 (2014).

[2] K. Fayazbaksh, M.A. Nik, D. Passini, L. Lessard. Defect layer method to capture effect of gaps and overlaps in variable stiffness laminates made by automated fiber placement. *Composite Structures* **97**, pp. 245-251 (2013).

[3] A. Pagani, A.R. Sanchez-Majano. Stochastic stress analysis and failure onset of variable angle tow laminates affected by spatial fibre variations. *Composites Part C: Open Access* **4**, pp. 100091 (2021)

[4] A. Pagani, A.R. Sanchez-Majano. Influence of fibre misalignments on buckling performance of variable stiffness composites using layerwise models and random fields. *Mechanics of Adanved Materials and Structures*, pp. 1-16 (2020).

[5] Z. Gurdal, R. Olmedo. In-plane response of laminates with spatially varying fibre orientations – Variable stiffness concept. *AIAA Journal* **31(4)**, pp. 751-758 (1993).

[6] E. Carrera, M. Cinefra, M. Petrolo, E. Zappino. Finite Element Analysis of Structures through Unified Formulation. Wiley & Sons. 2014.

[7] A. R. Sanchez-Majano, A. Pagani, M. Petrolo, C. Zhang. Buckling sensitivity of tow-steered plates subjected to multiscale defects by high-order finite elements and polynomial chaos. *Materials* **14(11)**, pp. 2706 (2021).