PHYSICAL-VIRTUAL TESTING METHODOLOGY FOR EFFICIENT PROPERTY DETERMINATION OF TAILORED FIBER-REINFORCED COMPOSITE STRUCTURAL VANES FOR FUTURE JET ENGINES

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Abstract
This paper presents a virtual-physical testing methodology for the design and dimensioning of a variable-axial structural guide vane manufactured by Tailored Fibre Placement (TFP). Within the context of a jet engine, a validation pyramid based on the building block approach is developed, considering different levels of complexity from coupon- up to system-level. Both virtual and physical sections of the validation pyramid are defined. Focussing on the coupon- and element-level, a method to determine a material model for the TFP structural vane is proposed, considering the complex environment of the jet engine. A work flow for the specific TFP element-specimen design process using the software EDOstructure for variable-axial components is developed.

1. Introduction

The use of lightweight materials in the aerospace sector can significantly contribute to the European Union's ambitious goal of reducing CO2 emissions by 75% by 2050 [1]. This potential is especially evident when employing innovative technologies such as TFP to produce stress-adapted structures [2]. However, designing novel tailored, variable-axial (VA) carbon fibre reinforced polymer (CFRP) structures presents complex challenges. The assessment of their load-bearing capacity is particularly demanding due to the intricate relationship between geometry, composition, and the manufacturing process [3]. Figure 1 illustrates the evolution of the intermediate case (IMC) in the Rolls-Royce Pearl engine architecture: transitioning from the traditional function-separated intermediate case on the left, through the newer generation of IMC with a function-integrated metallic design in the centre, to a future architecture featuring a hybrid metal-composite design on the right [4]. In this hybrid design, CFRP is utilised in areas where load transmission is indirect and straightforward, while metal is employed in regions subjected to complex loads due to its isotropic properties.

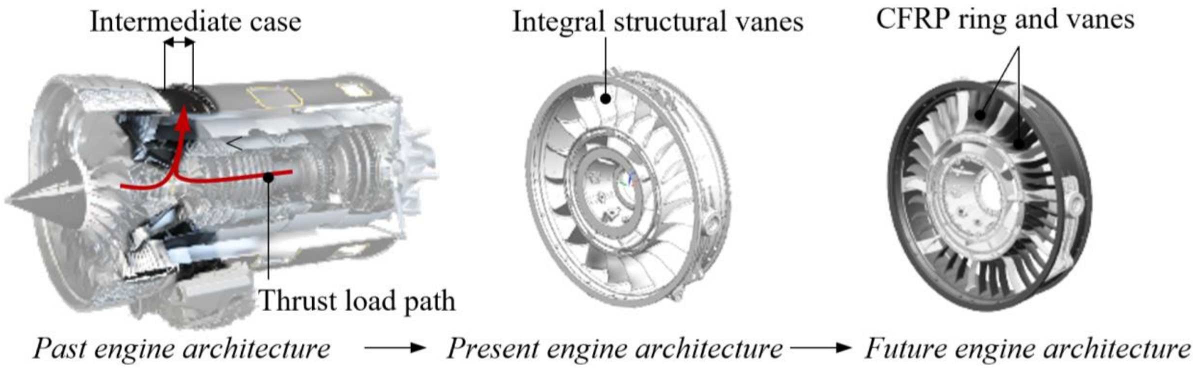

Figure 1. Intermediate cases of Rolls-Royce jet engines [4]

In order to increase the efficiency of the Engineering Design Process, it is essential to use reliable mechanical properties that take the influence of TFP process into account. For a complex system such as a jet engine and its different scales, the material scale provides important input parameters for the higher scales that follow. Furthermore, the modelling of tailored structures proves to be challenging when conventional simulation software is used [4, 5].
The TFP technology, designed for creating curvilinear fibre patterns, was invented and developed at the Leibniz Institute for Polymer Research Dresden e.V. [6] and is shown in Figure 2 [5]. The adjustable process parameters are the stitch width, stitch distance (R-value), oscillating movement of the roving placement, roving distance, number of layers and the deposit radius.

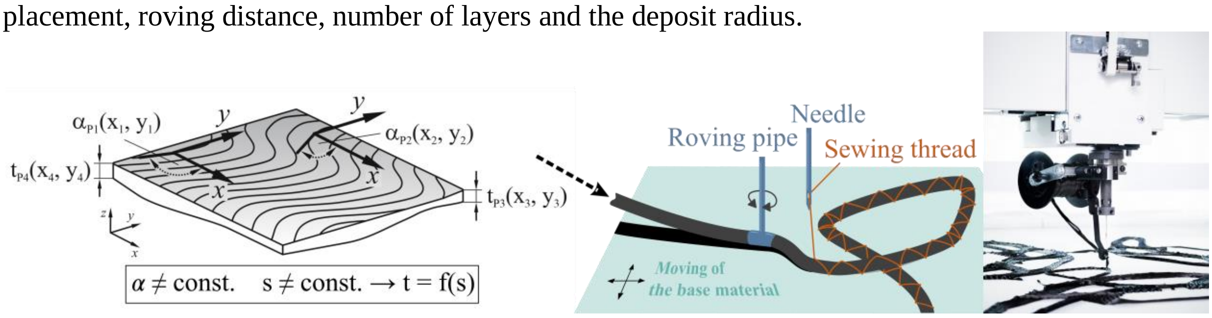

Figure 2. Principle of a VA composite design (left), TFP manufacturing principle (centre), and TFP fibre placement head (right) [5]

Preliminary experimental research on how TFP process parameters affect the tensile modulus and strength was carried out by Spickenheuer [7]. Uhlig et al. demonstrated in one work [8] that variations in TFP parameters significantly influence local fibre volume content and in-plane waviness of composite materials. In a further work [9] they concluded, that the stiffness reduction due to the TFP process is minor compared to a unidirectional (UD) material, but can be significant for strength properties.

2. Development of a physical-virtual testing methodology

This paper presents a virtual-physical testing methodology to efficiently determine the material properties of variable-axial structural vanes for future jet engines. The developed validation strategy is based on the building block approach [10] as shown in Figure 3.Various levels are defined in a validation pyramid (VP) to determine the material model at the coupon- and element-level, analyse the structural behaviour from the virtual component- to system-level, and validate the numerical models with a physical test campaign extending from the physical element- to system-level. This work specifically focuses on the two lower levels—coupon and element—which provide critical input parameters for the subsequent levels. The levels above the element level are included in the VP for completeness only.

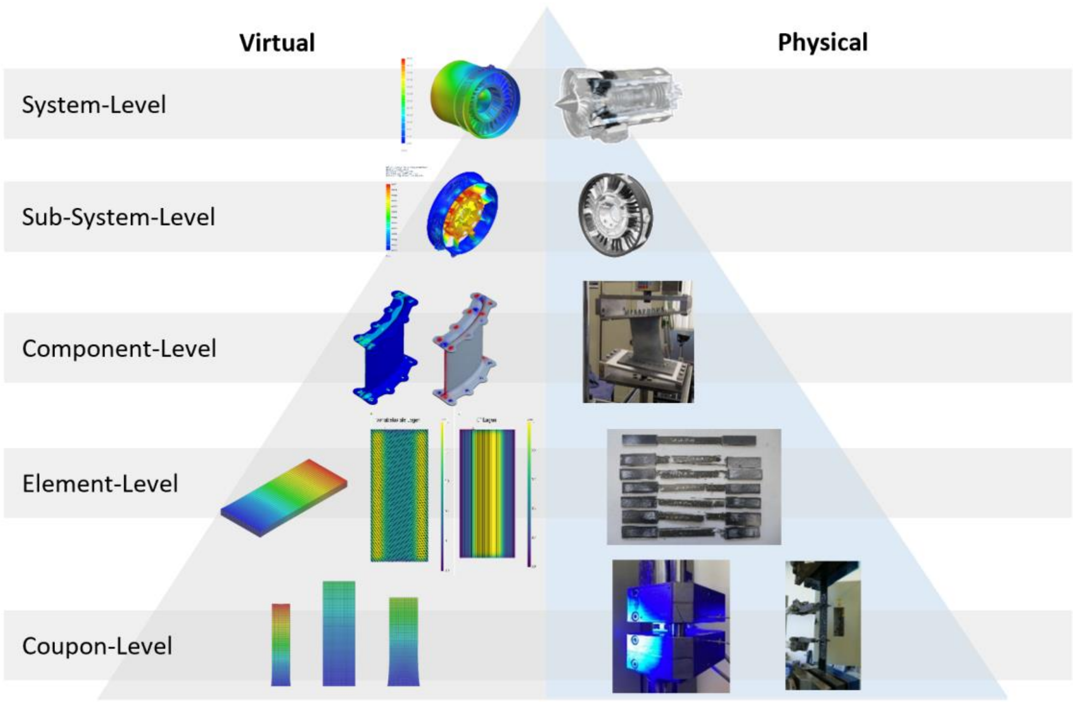

Figure 3. Virtual-physical validation pyramid

For VA structures, it is necessary to capture the influence of the TFP process parameters on the material properties. On the coupon-level, the material parameters are determined to define the initial material model. Two material models are determined: one without the TFP influence considered, which serves as a baseline, and another one with TFP influence considered. By that, a knock-down factor is determined for the TFP process influence on the material properties. Subsequently, the component simulation is solved in Ansys APDL with an isotropic shell model including load and boundary conditions as an input. The result file .rst format is the compatible file format for the TFP component structural vane design process. Here, a specific TFP software called EDOstructure from Complex Fibre Structures GmbH [11] is used (version 1.0.2193). A vane TFP pattern is realised, which is used to derive an element specimen design. The pattern is exported as a DXF file and transmitted to Hightex Verstärkungsstrukturen GmbH [12] to manufacture the specimen. Furthermore, the element test is performed and the initial material models are calibrated. Finally, the calibrated material model is implemented in the vane simulation model and further analysis can be performed. The process flow chart is shown Figure 4.

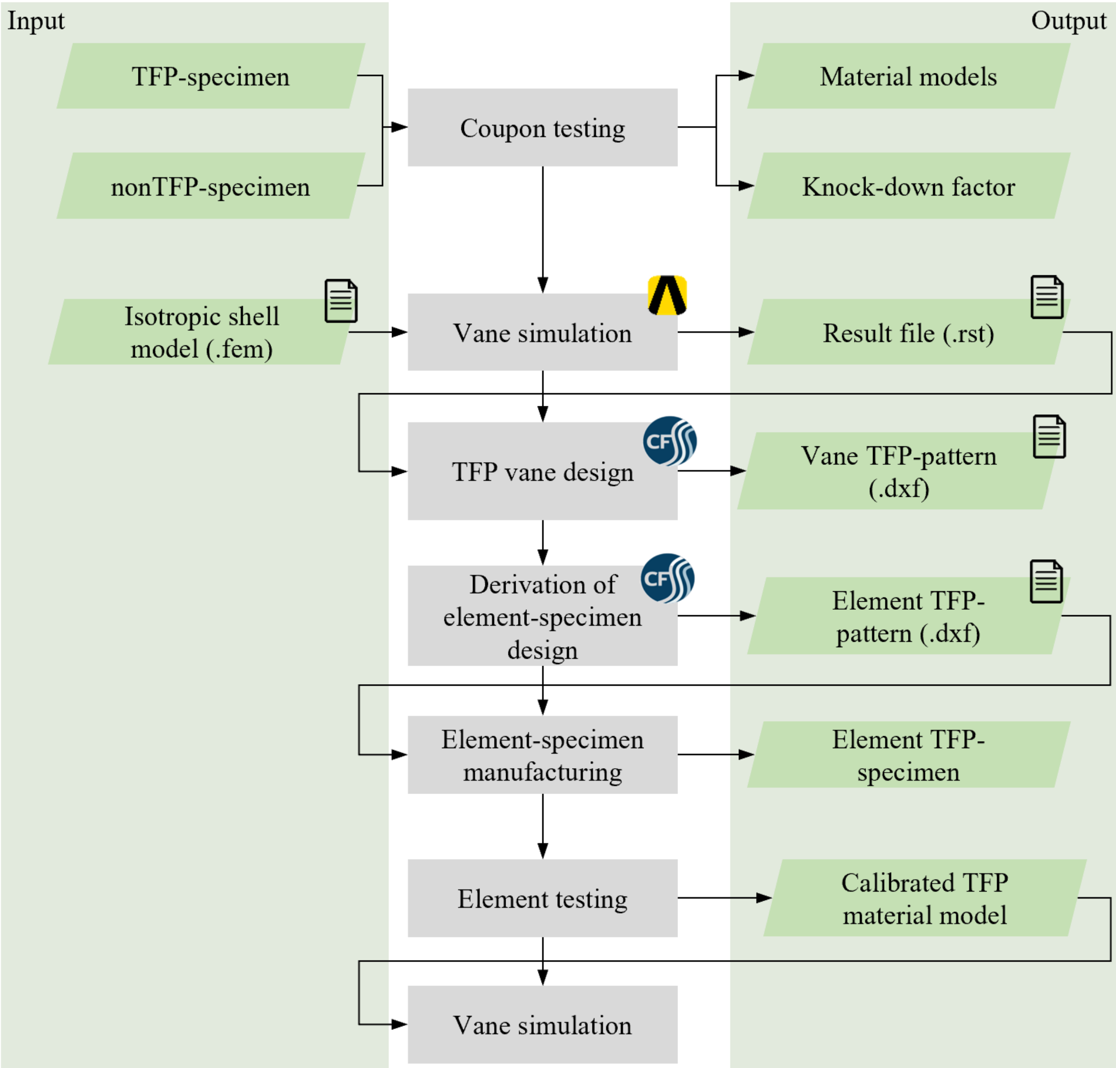

Figure 4. Process flow chart for the determination of the TFP material model

3. Results

Specific TFP element-specimens were designed, considering component, sub-system- and system-level factors (cf. Figure 5). The design parameters were derived from the component model. From the sub-system, relevant interface information was obtained, and from the engine system, load and boundary conditions were extracted. An isotropic shell model was developed and solved; its solution was imported into EDOstructure. The VA pattern for the vane was generated, and a specific design feature, referred to as the S-curve, was identified. To accurately map the fibre orientations on the mesh of the vane finite element (fe) model, a mesh size equal to half of the roving width was selected.

Subsequently, a simple specimen model was created to project the S-curve pattern from the vane onto a plate model. Load and boundary constraints were appropriately set, and the .rst file was imported into EDOstructure to verify the directional field and generate the DXF pattern for producing the TFP element-specimen.

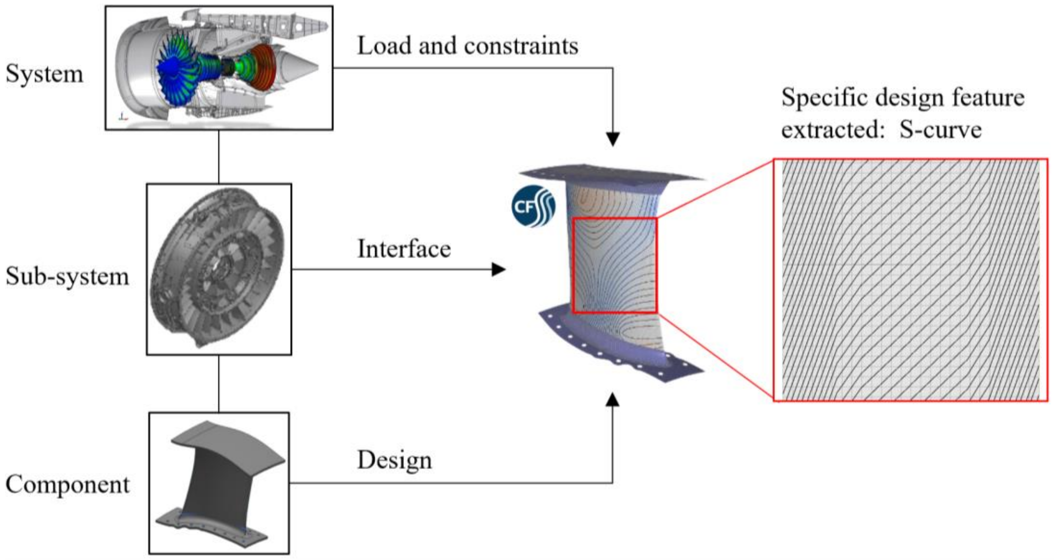

Figure 5. TFP element design determination considering component, sub-system and system-level

The pattern was modified by Hightex into a manufacturing-oriented design, and the adaptations were retransferred and mapped onto the specimen model by re-importing an HGT DXF file into EDOstructure. The preform for the TFP element-specimen was produced and infiltrated using a Resin Transfer Moulding plate tool. The consolidated plate was cut by a water jet into the specimens. The process of designing the specimen and plate preform, as well as the actual preform, is shown in Figure 6. The green frame marks the TFP specimen.

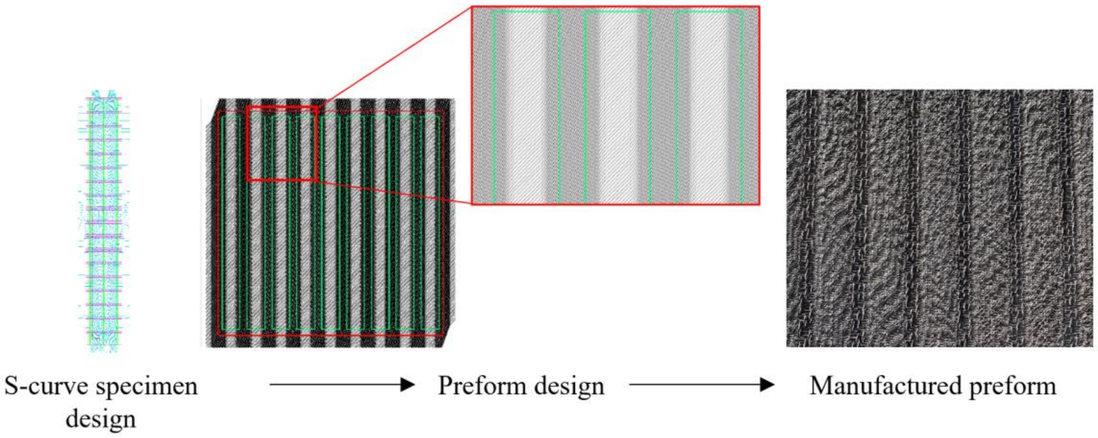

Figure 6. Process from specimen design to manufactured preform

While the input file for EDOstructure must be an Ansys .rst file, several export options for the fe-model export were available. Here, the fe-model was exported as a bulk data file (bdf) and imported into Siemens NX.

4. Conclusions and outlook

This paper successfully introduced a virtual-physical testing methodology for determining the material properties of variable-axial structural vanes for jet engines, integrating both TFP technology and a multi-level validation strategy. By effectively considering the influence of TFP parameters on material properties through both theoretical and experimental approaches, this research provides insights for optimising the design and manufacturing of lightweight, efficient aerospace components, supporting the broader goal of reducing environmental impact in the aviation industry. The presented numerical methods enable an efficient modelling of the tailored structures by plotting the fibre patterns (as DXF files) from the manufacturing process directly on the model as initially explained in [13]. This paper also shows the needed interacting process steps as well as the data flow between the different software

tools used. The proposed method facilitates an effective and efficient design and dimensioning of variable-axial engine structures based on reliable data for future applications.
Further work should focus on comparing physical and virtual test results within the developed framework. Moreover, analysing the higher levels in the validation pyramid will allow for the capture of additional effects of the developed material model on those levels. Through this analysis, the required structural behaviour at the component, sub-system, and system level could be investigated by appropriately setting the TFP process parameters.

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