

## 3D woven near-net-shape preforms for CMC airfoils

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### INFO

CDAPT, ISSN 2701-939X

Peer reviewed article

2025, Vol. 6, No. 2, pp. 170-179

DOI 10.25367/cdatp.2025.6.p170-179

Received: 19 Juni 2024

Accepted: 15 November 2025

Available online: 20 December 2025

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### ABSTRACT

*Traditionally, high-density metallic airfoils are used in aircraft engines. Ceramic materials are much lighter and can operate at higher temperatures. However, as a monolithic material, they are not suitable for high reliability applications due to excessive brittle fracture behavior. By reinforcing ceramics with ceramic fiber structures, it is possible to increase fracture toughness and damage tolerance significantly. These CMC (Ceramic Matrix Composites) are one of the materials of the future due to their high strength, dynamic load capacity, thermal shock resistance and resistance to aggressive media in the high-temperature range. An efficient production of the textile preforms, which are required for CMC parts, is a prerequisite to bring them into widespread industrial use. This article describes the development of near-net-shape, load-path 3D woven structures made of ceramic materials that can be mass-produced on industrial equipment and optimally comply with the subsequent process of ceramic matrix insertion. Based on the simulation of two assumed load cases, the optimum structural design is determined. A multi-layer structure of the base fabric is used to achieve the required component thickness of 2-3 mm. In iterative infiltration tests, the optimum structure for the matrix injection is found using a pressure-assisted infiltration technique.*

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### Keywords

CMC, Ceramic Matrix Composites, Textile reinforcement, Preform, 3D weaving

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## 1 Introduction

Ceramic Matrix Composites (CMC) are on their way to establishing as a new innovative material class for key components in a wide range of applications, such as space, aviation, energy, automotive, the heat treatment sector and defense. They consist of a ceramic matrix reinforced with reinforcing fibers such as silicon carbide, silicon nitride or carbon. CMCs possess several unique properties that make them attractive for various high-performance applications. The key property of them is the high temperature resistance exhibited by exceptional thermal stability in extremely high temperature conditions, making them suitable for use in environments where traditional materials would fail. Because of lower densities CMCs are light weight, compared to conventional metallic materials. They have high strength and stiffness at room temperature and elevated temperatures because of reinforcement of ceramic matrices with fibers such as silicon carbide or carbon and corrosion and chemical resistance which makes them suitable for use in harsh environments where exposure to corrosive substances is common. They offer thermal shock resistance to withstand rapid changes in temperature without fracturing or degrading makes them suitable for crucial for applications subjected to thermal cycling, such as in thermal barrier coatings and aerospace components. Their oxidation resistance maintaining their structural integrity even in oxidizing environments at high temperatures as well as their tailorable properties by adjusting factors such as matrix composition, fiber type, orientation, and volume fraction offering flexibility in design and performance optimization. [1 - 4]

In the project "AirfOx" a woven near-net-shape 3D preform reinforcing CMC engine blades for gas turbines (airfoils) made of oxide ceramic fibers integrally and suitable for series production was developed. Using innovative weaving techniques, a new manufacturing method for 3D preforms with top surfaces of different lengths was investigated, with a support structure in the form of a rib being woven in one process. The challenges were the realization of the curvature and the implementation with highly brittle oxide ceramic fibers. The preforms were further processed to high-temperature O-CMC components. The material and component development was supported by multiscale simulation of the structure-property relationships to ensure a load-conforming fiber design. "AirfOx" was intended as a manufacturing study for the production of complex 3D fiber preforms in a one process step. This is applicable to other CMC types, e. g. SiC/SiC-CMC and other components. The focus of this publication is on the development of the near-net-shape fiber preform and the O-CMC component.

## 2 Development process

### 2.1 Preform production

The challenges in developing a near-net-shape preform for an airfoil were:

- Realization of the cover layers with different lengths
- Inclusion of a vertical rib
- Correct formation of the leading and trailing edges
- Low damage, easily infiltratable bond development for a multi-layer fabric (wall thickness 2-3 mm)
- Full implementation using oxide ceramic fibers on a double rapier weaving machine.

Based on the requirement profile for the airfoil, a finite element simulation was first carried out to determine critical zones in the component and to arrange the fiber rovings within the airfoil according to the local stresses. First the microstructure, then the mesostructure and finally the entire component were examined using this method (see Figure 1). At the micro level, the main focus is on the zirconium-aluminum oxide matrix in the component. The fibers and finally the fabric structure were then included in the simulation. The bond files from the EAT DesignScope Victor 3D Weave Composite software for creating woven fabric structures for complex preforms were transferred to ANSYS (FE simulation program). In this way, different fabric structures (canvas and multi-layer orthogonal weaves) could also be analyzed. The subsequent load simulations made it possible to calculate various load scenarios. Critical zones on the component could be identified, to which particular attention was paid during the development of the preform (see Figure 2).

Via an interface the binding was transferred to the weaving machine.

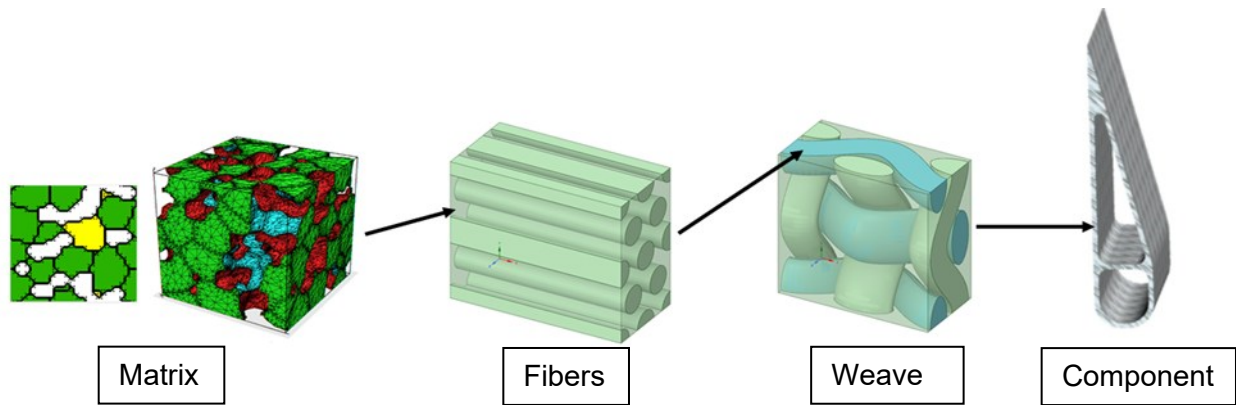


Figure 1: Computer simulation from the microstructure to the component.

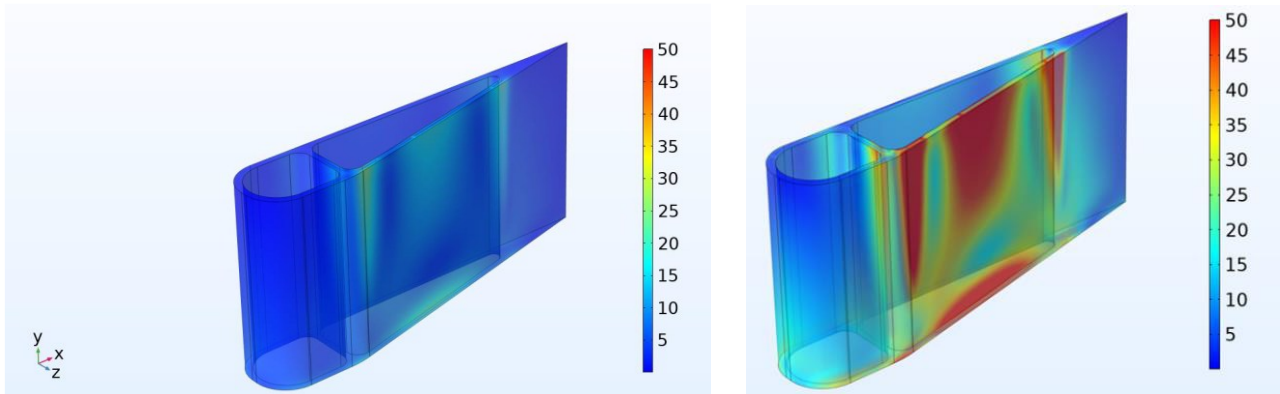


Figure 2: Distribution of the maximum stresses [MPa] in the airfoil made of the CMC material at different rotation frequencies  $n$ . left:  $n = 5000$  1/min, right:  $n = 10000$  1/min.

## 2.2 Fiber types

The mechanical properties of ceramic materials can be significantly improved by combining them with ceramic reinforcing fibers. The fibers are embedded in a ceramic matrix for this purpose. The fiber reinforcement gives CMCs a high damage tolerance and quasi-ductile material behavior. In order to fulfill their function, the reinforcing fibers have a significantly higher tensile strength than the matrix material. In CMC, a special design of the fiber-matrix connection and the fracture behavior of the matrix also ensures maximum energy dissipation during fracture. Oxide ceramic fibers have excellent oxidation resistance. They are characterized by outstanding high-temperature strength and creep resistance and are suitable for continuous use at temperatures above  $1000$  °C. One research focus at Fraunhofer is the development and production of ceramic fibers for research purposes. A special pilot plant for oxide and non-oxide fibers can produce fiber material on a ton scale. The ceramic fibers are synthesized from organometallic aqueous solutions or colloiddally dispersed precursors, which enable homogeneous mixing of the components on a nanometer scale. With spinning aids, the solutions can be spun into green fibers in a dry spinning process, which are converted into ceramic fibers of the desired mineralogical composition through temperature treatment. The synthesis and production of novel oxide compositions were initially developed on a laboratory scale before being transferred to the spinning of multifilament yarns. If fibers with the desired properties are obtained, various options for scale-up are then available. Depending on requirements, the fibers can be supplied in laboratory up to pilot scale. Figure 3 shows the processing line for oxidic fibers from spinning mass production in the atmosphere and adjustable parameters (temperature, volume, humidity) in the spinning shaft over the calcination/debinding process in batch furnaces under controlled atmosphere (humidity and volume flow) to continuous sintering and sizing application. [1 - 4]

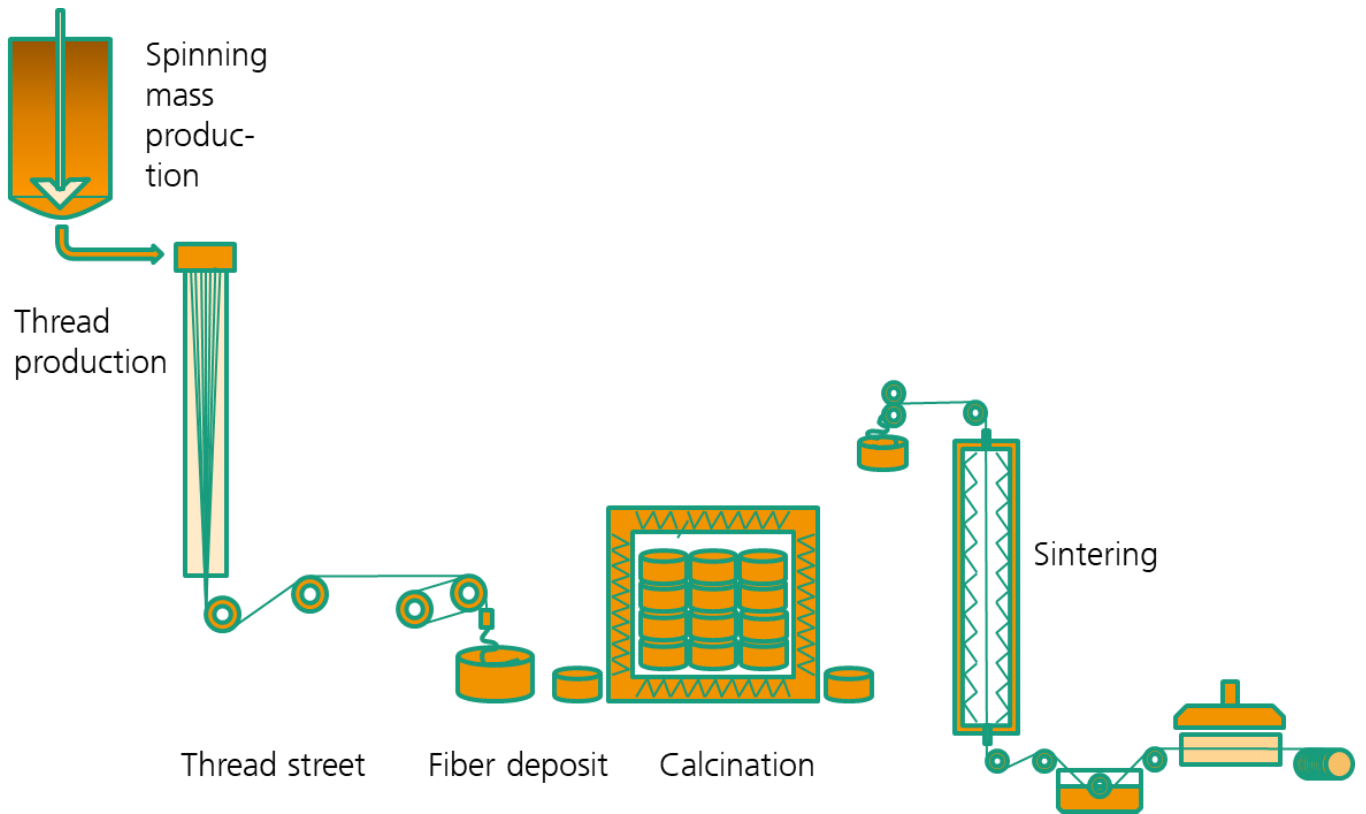


Figure 3: Processing line of oxidic fibers.

As ceramic fibers are very costly in the project, the structure development started with polyester and glass fibers, which are significantly cheaper compared with ceramic fibers. In preliminary tests, the airfoil structure was implemented on a semi-automatic laboratory weaving loom. The complex weave developed for the entire airfoil was initially implemented on a double rapier weaving machine using polyester fiber yarns, which are also the standard warp yarns of the weaving. The choice of oxide ceramic material to use for the airfoil structure was based on infiltrability, processing properties and its material cost. Nextel 720 roving from 3M and ALF R-1920 multifilament yarn from Hiltex were evaluated. Due to the limited budget, the mullite material Alf R-1920 was used. In the preliminary tests, this material showed very good processing properties but reduced infiltration properties. To further improve the processing properties, an olefinic coating was applied to the material. An overview of the materials used in this study is given in Table 1.

Table 1: Fiber types used during the course of the project.

Application	Fiber material	Titer
Initial tests on a semi-automatic laboratory loom	Glas fiber rovings	330 tex
First implementation on the double rapier weaving machine	Polyester multifilament yarn	167 tex
Preliminary tests for the infiltration with two different commercially available ceramic fiber types	Nextel™ 720 (3M) ALF™ R-1920 (Hiltex)	168 tex 200 tex
Conversion to produce the final airfoil using oxide ceramic fiber material Some with polyester yarns as sacrificial yarns	ALF™ R-1920 (Hiltex) Polyester multifilament yarn	200 tex 167 tex

### 2.3 Experimental procedure and development of binding

In the preliminary tests, the feasibility could be proven using a small amount of fiber, and initial approaches for optimizing the binding could be identified. A plain weave was used as the basic weave for testing the shape-forming weaving possibilities (see figure 4). To achieve the component wall thickness of 2 - 3 mm, the basic structure had to be changed into a multilayer construction. A variety of bindings were produced

on the laboratory loom (see figure 5) and based on infiltration tests, an angle interlock weave was chosen for these preliminary tests (see figure 6).

When selecting a suitable basic binding for the final preform, in addition to assessing the infiltration ability, the largest bending radius of the binding was examined, because the larger is this parameter, the better is the processability of the yarn (see Figure 7).

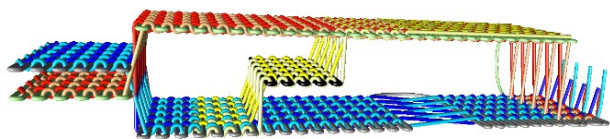


Figure 4: Basic weave with plain weave in all layers for the preliminary tests (left) and prototype made of glass fibers; manufactured on the semi-automatic laboratory loom (right).

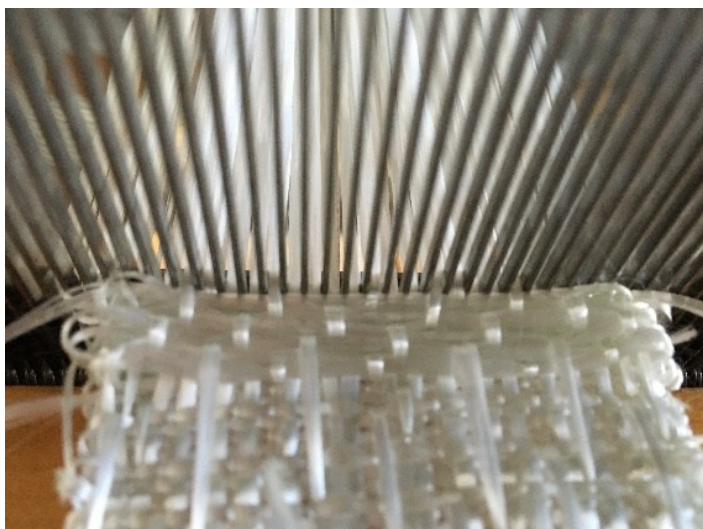


Figure 5: Multilayer fabric manufacturing.

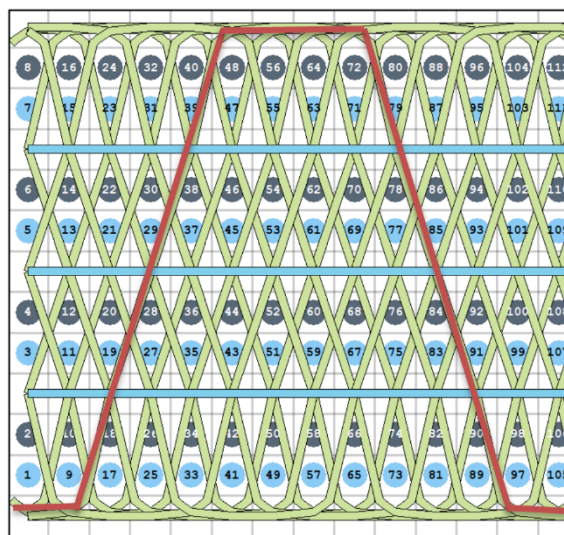


Figure 6: Weft cut of final basic binding.

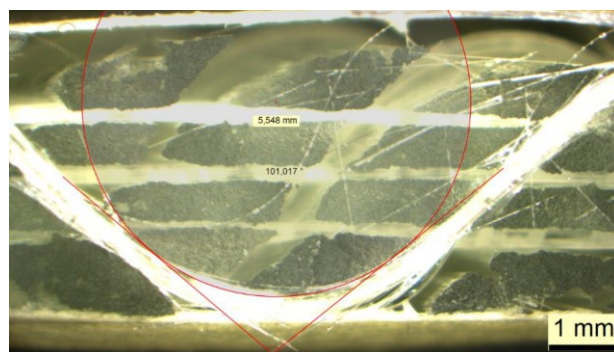
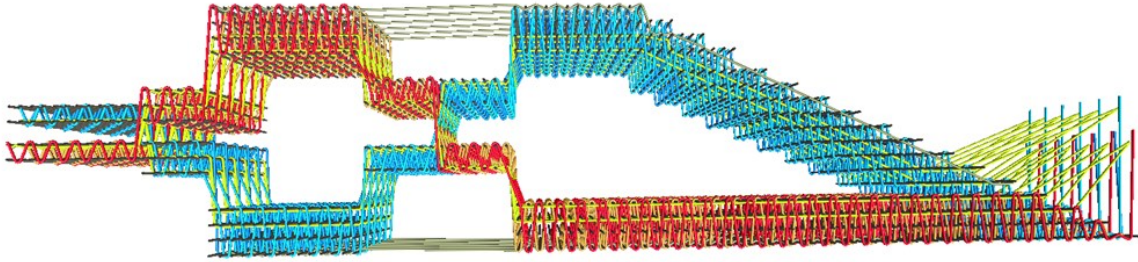


Figure 7: Assessment of the bending radius of a multi-layer fabric weave.

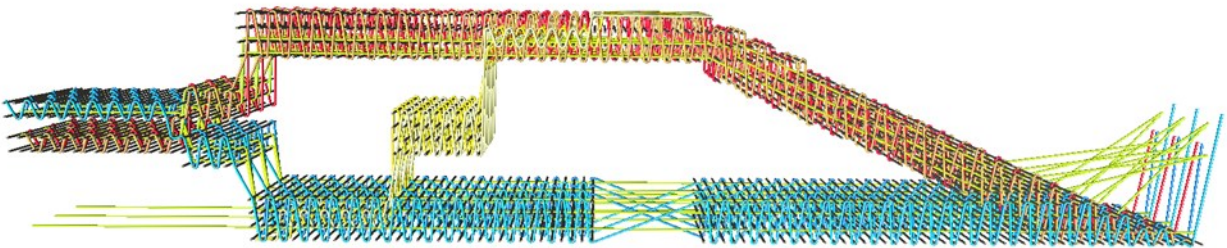
In order to achieve a shape that is as close as possible to the component and load path, various options for warp and weft yarn guidance were developed and adapted until the optimum shape was achieved (see figure 8). Figure 8 shows three variants in the weft section in pictures a, b and c. In variant a, the warp yarns in the structure change completely from the upper to the lower layer of the covering surfaces. In variant b, only some of the warp yarns in the structure change from the lower to the upper cover layer. This variant was further developed in variant c by adapting the tension warp yarns to achieve different

lengths of the cover surfaces. The latter came closest to the final shape and was implemented with ceramic fibers.

a)



b)



c)

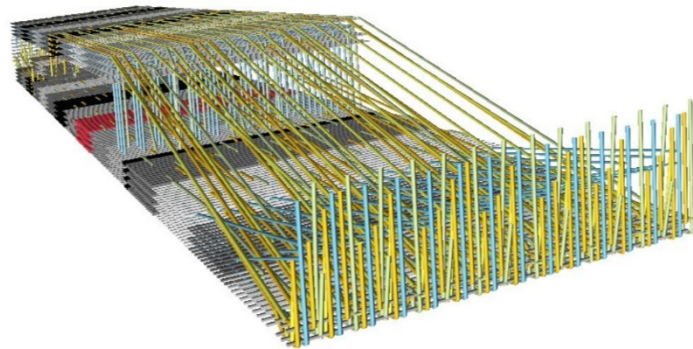


Figure 8: Development of the binding structure.

For the implementation of the 3D fabric structure, a double rapier weaving machine (Stäubli GmbH, Germany) was equipped with a special creel (Texmer GmbH, Germany), as seen in Figure 9. The creel allows the sensitive ceramic fibers to be fed in gently. To apply a pulling-back process [5 - 8], which is included in the binding to realize the cover layers of different lengths, sacrificial polyester yarns were fed from the warp beams. For this purpose, a warp beam device was installed and integrated into the electronic control of the weaving machine. The individual yarn control via the Unival jacquard unit enables a particularly fiber-friendly feeding of yarns. The linearly taking of the fabric minimizes possible damages that could be generated because of radial winding of the woven structure.



Figure 9: Double rapier weaving machine with single yarn control and linear take-off (left) and warp beam frame for two warp beams, as well as a creel with two special creels (Texmer) in the middle (right) at the textile technology center.

## 2.4 CMC component development – infiltration process

Using the airfoil as an example, an infiltration process was developed that makes it possible to completely infiltrate 3D fiber preforms. The initially planned implementation of the industrially well-known pressure slip casting process [9-13] had to be revised, because preliminary tests had already shown that the potential of this process for the infiltration of complex ceramic 3D fiber preforms is limited. Therefore, a multi-stage pressure-supported slurry infiltration process was developed to achieve significantly better results. To ensure that the infiltrated preforms were consolidated by drying as close to the final shape as possible, a 3D-printed polymeric core structure was used in combination with corresponding jacket shells. In order to form the inner contour of the component, the core structure was inserted into the slip-infiltrated preform, which was enclosed by the jacket shells during subsequent drying to form the outer contour of the component (see Figure 10).

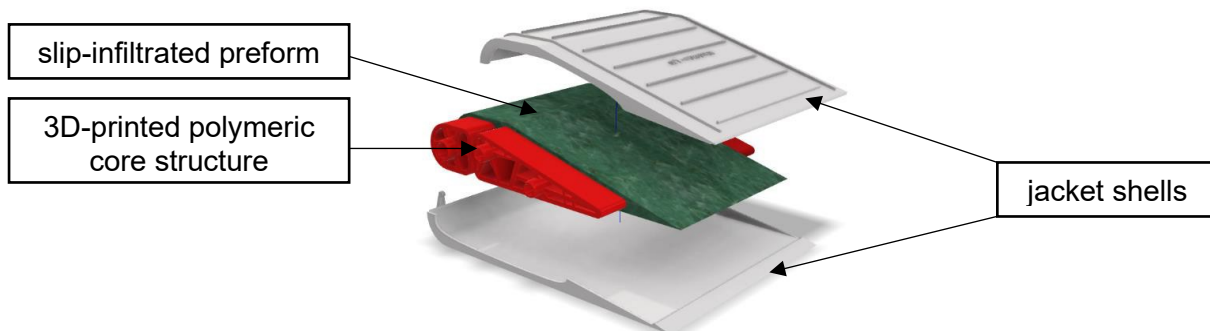


Figure 10: Component production with a 3D printed tool.

Images of the samples were taken by light microscopy to provide an assessment of the quality of the infiltration (in the fiber bundle and between the bundles). Furthermore, 3-point bending tests according to DIN EN 658-3 are performed to determine the mechanical properties of the O-CMC.

## 3 Results

### 3.1 Preform production

For the final preform, the four-layer angle interlock binding with floats at the top and bottom of the fabric over four weft layers is used, which was tested in comparison to other bindings. This binding was the most suitable binding in terms of its infiltration capability, thickness and gentle fiber flow. Some airfoil preforms were woven with sacrificial yarns to create additional flow channels in the preform to further improve infiltrability. Initially, the preform was made from pure PES material to adjust the machine parameters of the modules and find optimal settings (optimized shed geometry, speeds, warp yarn tensions etc.) (Figure 11). In addition, the complex binding was further optimized (e. g. adjustment of the binding areas to reproduce the target geometry as precisely as possible). Subsequently, an 8 cm wide strip was then fitted with ceramic fibers in the double rapier weaving machine. The implementation of ceramic fibers presents

many challenges. The binding, which contains over 2000 wefts, must be woven in a highly adjusted speed range. The risk of warp yarn breaks in the brittle material was very high. The binding had to be adjusted again in the area of the trailing edge (pointed end) due to excessive ondulation to avoid yarn breaks. As part of the project, five airfoil preforms were woven (some with sacrificial yarns, some made entirely of ceramic rovings), which were available for component infiltration, as seen in Figure 11 on the right.

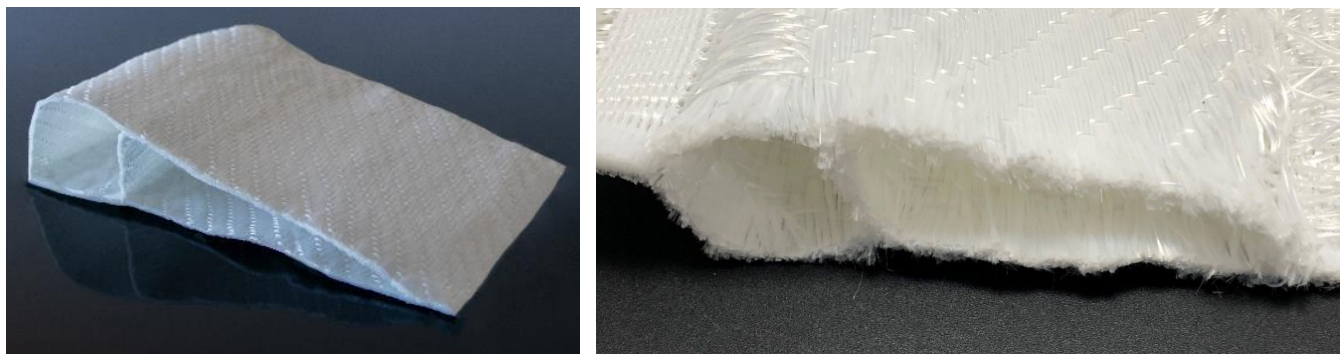


Figure 11: Left: Airfoil preform made from demonstrator fibers (PES); right: Airfoil preform made of ceramic fibers, both produced on the double rapier weaving machine.

Finally, the production of 3D airfoil preforms in a multilayer structure was achieved. The binding development for the application of ceramic materials requires special care with regard to ondulation angles and still has a lot of potential for optimization, also with regard to load-compliant structures.

### 3.2 CMC component development - infiltration process

Preliminary tests were carried out on woven samples using the initially targeted pressure slip casting process and the newly developed multi-stage infiltration process to evaluate the quality of the infiltration. The results are listed in Table 2. It can be seen that the mechanical properties determined in the 3-point bending test could be significantly increased with the optimized process. The O-CMC airfoil was manufactured using the ceramic fiber preforms and the newly established infiltration process (Figure 12).

Table 2: Comparison of the structural and mechanical characteristics of the CMC infiltration bodies produced by the two tested processes.

Pressure infiltrated plate	Pressure slip casting process		Newly developed multi-stage pressure-assisted process	
	Standard pressure casting slip (red. weave density)	Optimized pressure casting slip	Initial test	Optimized
Density [g/cm <sup>3</sup> ]	1.78	2.43	2.89	2.97
Fiber volume fraction [Vol.-%]	20.2	33.8	37.4	30.2
Matrix volume fraction [Vol.-%]	22.8	25.6	33.1	41.3
3-point-bending test (standard deviation) [MPa]	53	126	434* (124)	463* (65.8)
E-Modulus [GPa]	n.d.	n.d.	90	109
Elongation at break [%]	n.d.	n.d.	0.86	0.47

\*tested on specimen with preferential fiber direction

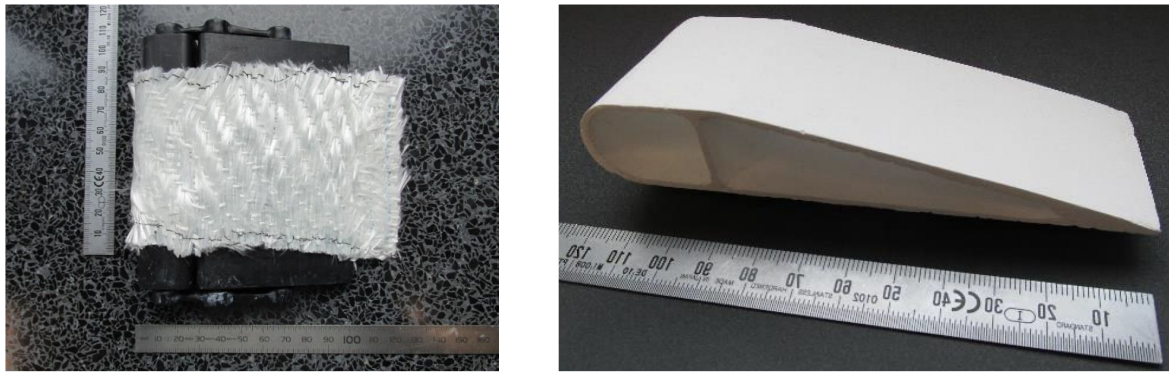


Figure 12: Ceramic fiber preform before infiltration (left); near-net-shape ceramic fiber-reinforced airfoil, sintered and provided with a glass-ceramic coating (right).

## 4 Discussion

### 4.1 Preform production

The processability of the materials in the weaving process could be adjusted through iterative adjustments over the course of the project, but could not be optimized due to the time limitations. The woven structure has some potential for development as well. 3D preforms could be successfully woven using the new creel – warp beam arrangement. Development of weaves for the use of ceramic materials requires special care with regard to undulation angles and still has a lot of potential for optimization with regard to load conforming structures.

### 4.2 CMC component development - infiltration process

From the analysis of the tests carried out, it became clear that the potential of the pressure slip casting process for the infiltration of ceramic 3D fiber preforms is limited. The reason for the low bending strength values was that the degree of infiltration of the fiber bundles was too low, which was evident from the light microscopy images. It became clear that the need to form an initial particle coating on the mold surface and the required infiltration ability compared to the fiber preform represent opposing requirements for the casting slip. Particularly for fiber preforms with a high fiber volume content, the test results suggested that a suitable compromise between the stated requirements cannot be achieved by a targeted formulation of the slip. Even by adjusting the slip pressure profile, the degree of infiltration of the preforms could not be significantly increased. Therefore, it was decided to develop an alternative, pressure-supported slip infiltration process for 3D fiber preforms based on an infiltration-optimized slip. In order to maximize the infiltration of the preforms, a multi-stage process was designed. With this process, good infiltration results were achieved (see Figure 13; right), and the O-CMC airfoil could be produced.

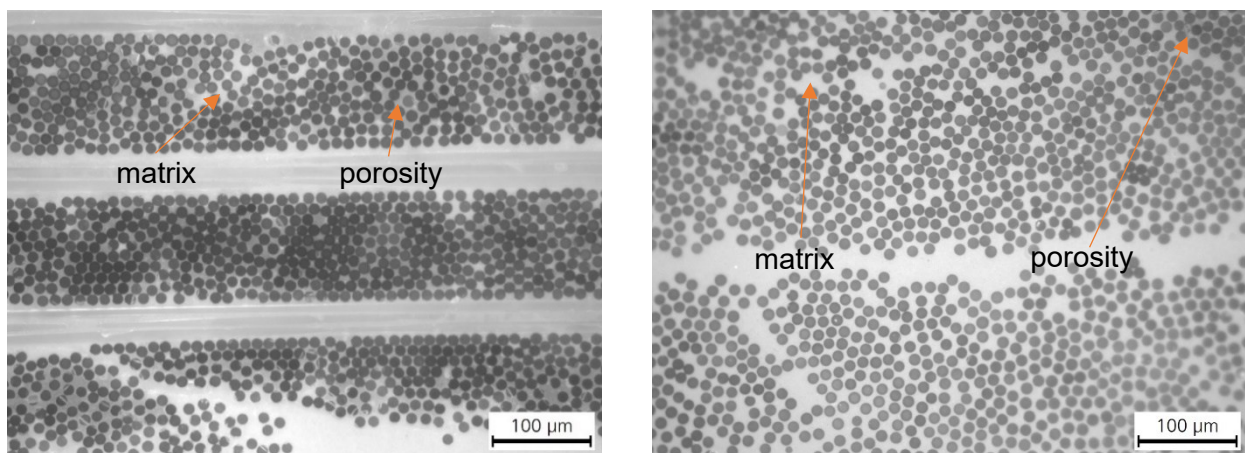


Figure 13: Pressure slip casting process: the sample still has a very high porosity (left); optimized multistage pressure-supported slip infiltration process: the matrix was able to penetrate the fiber bundles much better (right).

## 5 Author Contributions

D. Albert: writing – original draft preparation, S. Grosch: project administration, Ch. Eckardt: matrix development, H. Ziebold: computer simulation, A. Bauer: investigation: preform, R. Kocaman: investigation: preform, F. Ficker: supervision

## 6 Acknowledgements

Financial support of the project AirFOx by the Bavarian ministry of economics is gratefully acknowledged within the program BayLu25, program line 1: Eco-efficient flying.

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