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Article

Prediction of Gaps in Automated Tape Laying and Their Influence on Porosity in Consolidated Laminates

Tobias Link [1,*], Philipp Rosenberg [1] and Frank Henning [1,2]

[1] Fraunhofer Institute for Chemical Technology ICT, Joseph-von-Fraunhofer Strasse 7, 76327 Pfinztal, Germany; philipp.rosenberg@ict.fraunhofer.de (P.R.); frank.henning@ict.fraunhofer.de (F.H.)
[2] Institute of Vehicle System Technology (FAST), Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
* Correspondence: tobi.link@arcor.de

Abstract: An efficient way to reduce direct operating costs in aerospace applications is to lower the overall weight. In this context, thermoplastic composites offer a high potential for weight reduction. However, their application requires time and cost-optimized process technologies. Thermoplastic tape laying with subsequent out-of-autoclave consolidation represents such a process technology. Typical process chains consist of several automated steps that can influence the component's quality. Hence, a cross-process approach is applied to identify relevant process parameters. This paper focuses on minimizing the gaps between parallel-placed tapes and thereby reducing their influence on the laminate's porosity. A geometrical model is developed and validated to predict the maximum gap sizes for a tape-laying process as a function of process accuracy, material accuracy, and process parameters. Based on this, a methodological approach is presented to minimize the influence of gaps on porosity. It is validated using automated tape laying and a novel low-pressure consolidation process. The findings make an important contribution to understanding the development of porosity along the process chain for the manufacture of thermoplastic composites for aerospace applications. It can be shown that the approach enables the prediction of gap sizes and allows to minimize their influence on porosity.

Keywords: thermoplastic composites; automated tape laying; consolidation; out-of-autoclave; poly(ether ketone ketone); UD tape

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1. Introduction

Fiber-reinforced polymers (FRP) have a long history in aerospace engineering applications. Since being first used in 1972 for non-structural components in civil aviation, their range of application has steadily increased [1]. Nowadays FRPs are even used for primary structures and security-relevant components [2]. Here, the main motivation is their ability to reduce the overall weight to decrease the direct operating costs (DOC) [3]. In recent years, the focus in research and development has moved towards FRPs with a thermoplastic matrix due to their high potential to reduce material costs even further. However, this implicates the use of cycle time and cost-optimized process technology [4]. Currently, certified thermoplastic composites, which are mainly part of the poly (aryl ether ketone) (PAEK) family, are in high demand. However, due to the required high processing temperatures and the material's high viscosity, some manufacturing processes cannot be used [5,6]. In addition to the material-specific requirements for processing, there are high-quality requirements for the usage of parts in aerospace engineering. This applies not only to the final component but also to each semi-finished product along the process chain [7]. In particular, the requirements for morphology characteristics are very important. Here, the focus is put on crystallization and porosity as they are critical for the mechanical performance of the final component [8–10].

This paper focuses on the porosity of semi-finished products that are processed in a process chain based on technology that allows short cycle times for high-temperature thermoplastic composites. This includes a novel low-pressure consolidation process to manufacture laminates from unidirectional fiber-reinforced tape layups called radiation-induced vacuum consolidation (RVC). This technology was developed at Fraunhofer ICT and represents an out-of-autoclave (OOA) process that uses only vacuum pressure and infrared radiation as a heat source [11,12]. Due to the low pressure, the possibilities to heal defects in high-viscous materials are limited compared to state-of-the-art technologies based on autoclave or hydraulic presses. Some research has already been conducted to analyze the influence of processing parameters and process configurations on the porosity in OOA processes. Most of the work is based on carbon fiber (CF)-reinforced poly (ether ether ketone) (PEEK) tapes that are processed with oven vacuum bag (OVB) processes.

Zhang et al. [13] analyzed the influence of process configurations during OVB processing of thick carbon fiber PEEK layups on porosity. They focused on the void reduction mechanisms for various edge conditions. They applied heating and cooling cycles with a ramp of 2.8 °C/min and a target temperature of 380 °C resulting in comparatively long cycle times of over five hours. They concluded that it is possible to achieve low porosity via the OVB process and that the edge conditions, e.g., open edge or closed edge, are a key aspect of void reduction. In a previous work, Zhang et al. [14] also investigated the impact of the dwell time on porosity in OVB processes concluding that void-free laminates can be obtained with a minimum dwell time of 10 min and that the void content increases to 0–1% for a shorter dwell time. In this study, they also applied a ramp of 2.8 °C/min for heating and cooling.

Saenz-Castillo et al. [15] processed PEEK-CF tape with different process technologies including vacuum bag only (VBO), hot press, and automated fiber placement (AFP) with in situ consolidation. They varied the processing temperature from 340 to 500 °C and the applied pressure from 0.25 to 1.5 MPa and studied the parameter impact on the void content. Based on their results, they found that the different process technologies have different effects at the same processing temperature resulting in void contents from 0 to 19%. Therefore, they stated that each process should have its own quality control criteria.

One of the few approaches where the effects of process parameters on porosity are analyzed for more than one process step during the manufacturing of thermoplastic composites is the work of Slange et al. [16,17]. The authors focused on different methods for the consolidation or pre-consolidation of tape layups and studied their impact on the final components' quality regarding the void content and mechanical performance. They compared a tape layup, which is only locally spot-welded using ultrasonic spot welding (USSW) and a laminate manufactured in AFP with in situ consolidation, to a reference consolidated in a press. The subsequent component manufacturing based on these semi-finished products used infrared (IR) heating and a hydraulic press. They concluded that the consolidation quality of the final component is affected by the whole process chain where the laminate quality plays a key role. A high void content in the (pre-)consolidated laminate leads to higher degrees of deconsolidation during IR heating and results in increased porosity in the final part.

In previous research works that are based on the processing of carbon fiber-reinforced poly (ether ketone ketone) (PEKK) tapes, high-pressure consolidation technologies, such as autoclave or press consolidation, are mainly applied. One of the first publications was from Chang [18] who processed PEKK-CF tape in a hydraulic press with varying process parameters to analyze their influence on mechanical performance such as bending and shear behavior.

Donadei et al. [19] conducted a similar study and analyzed the impact of varying process parameters on porosity and mechanical performance across multiple process steps. First, they manufactured consolidated tape layups based on PEKK-CF tape with autoclave consolidation. Afterward, they applied different heat treatments comprising drying at 150 °C and annealing at 240 °C with varying dwell times. Their work focused on the following IR heating step for which they investigated the influence of the heat treatment on deconsolidation and void content. They concluded that an annealing step can dramatically reduce the void content with reduced porosity for increasing dwell times.

In contrast to Slange and Donadei, the work from Saffar et al. [20] was based on an OVB process for manufacturing laminates out of PEKK-CF tape layups. They applied two different temperature cycles with target temperatures of 360 °C and 230 °C both with a dwell time of 15 min, a heating rate of 5 °C/min, and a free cooling rate. Furthermore, different vacuum pressures were used to identify the minimum compaction pressure required to obtain good consolidation quality in terms of void content and interlaminar shear strength. They found that it is possible to achieve a feasible consolidation quality even at low compaction pressures below 0.1 MPa.

This summary of the current research shows that only a few approaches consider more than one process step in the process chain for manufacturing components with thermoplastic composites. Additionally, the process of tape laying is not considered as in most of the publications, tape layups were manufactured manually. However, in an industrialized process chain, tape laying is usually an automated process and therefore influences the resulting porosity as the processing tolerances lead to gaps and/or overlaps in the tape layup.

To compensate for this lack of investigation, this article considers two processing steps of the process chain. Therefore, the effects of automated tape laying on gap sizes and the resulting porosity in a low-pressure consolidation process are analyzed. The aim is to identify the process and material-specific properties that have an influence on the accruing gaps and overlaps and how their effect on the porosity can be minimized. Therefore, a geometrical model is developed to predict the maximum gap and overlap sizes. Based on this model, a methodological approach is presented to address the tradeoff between minimizing gaps and overlaps in a tape layup.

2. Materials and Methods

2.1. Materials

PAEKs are also referred to as high-temperature thermoplastics due to their comparatively high glass transition temperature (Tg) of 143 °C and melting temperature (Tm) of 334 °C. Furthermore, they provide good solvent and chemical resistance making these materials attractive for aerospace applications. [21]. The outstanding thermal properties are due to their chemical constitution regarding the ratio of keto and ether molecules. Keto molecules increase the stiffness and thus result in a higher glass transition temperature. Additionally, they enhance the intermolecular bonding force, which increases the melting temperature [21–23]. As a result, the PEKK homopolymer has the highest thermal properties with Tm = 400 °C, which is close to its degradation temperature making processing very challenging. However, through the synthesis of isomeric copolymers, terephthaloyl (T) and isophthaloyl (I), molecules can be modified towards lower melting temperatures, which leads to increased processing windows [22–24]. Common PEKK copolymers have a T/I-ratio of 80/20, 70/30, or 60/40 of which a ratio of 70/30 is mainly used for manufacturing thermoplastic composites. They require processing temperatures between 370 and 380 °C. For manufacturing laminates, processing via autoclave consolidation is often recommended. This process has limited heating and cooling rate capabilities resulting in high cycle times of several hours. Additionally, long processing times at elevated temperatures may cause cross-linking and thereby degradation of the matrix [23].

The material system used in this study is APC PEKK-FC from Solvay Group which is a carbon fiber-reinforced PEKK tape with an areal weight of 145 g/m^2 and a resin weight content of 34%. It has a melting temperature of Tm = 337 °C and a glass transition temperature of Tg = 159 °C [25]. The consolidated ply thickness (CPT) is given at 0.14 mm.

2.2. Experimental Setup

Unidirectional fiber-reinforced tapes (UD tapes) are processed into components in a process chain that includes the steps of *tape laying*, *consolidation*, and *stamp forming*. This study focuses on the first two steps of this process chain for which the used equipment is briefly introduced in the following sections.

2.2.1. Tape Laying

The UD tape was processed with a Fiberforge system from Dieffenbacher, which is classified as an automated tape-laying (ATL) process. First, the tape is unwound from custom spools and cut into the desired length. A transport system transfers the cut tape to the layup beam, which places the tape on top of a vacuum-assisted motion table. The first ply is fixed by vacuum. Subsequent plies are fixed by ultrasonic spot welders onto the previous ply. Figure 1 shows the Fiberforge system at Fraunhofer ICT.

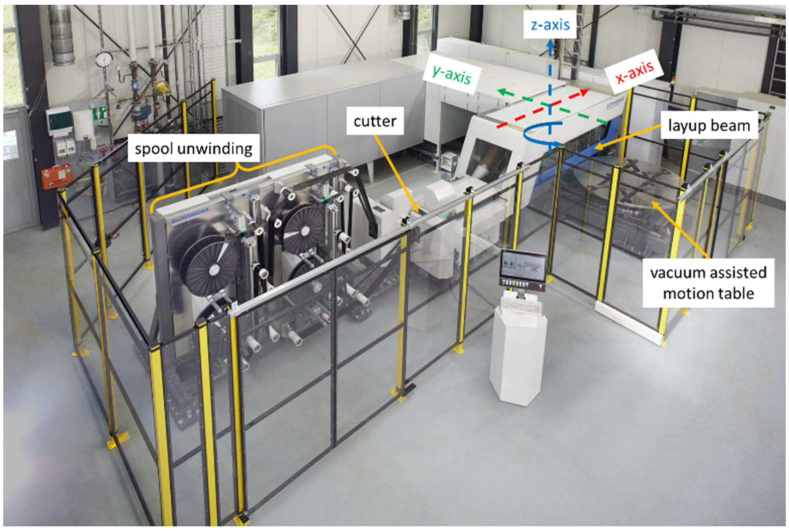


Figure 1. Dieffenbacher Fiberforge automated tape-laying system at Fraunhofer ICT.

The applied tape-laying process consists of several single handling operations, each with its very own tolerance zone. Their range is influenced by the material-specific accuracy as well as the accuracy of the single pneumatic and electrical actuators. Sequentially combined, they result in a tolerance chain that is determined by two main factors defined as guiding and repeat accuracy. The guiding accuracy describes the accuracy of the material guiding system before the tape is cut into stripes. It can be calculated by the difference between the tape target width and the distance between the guiding system profiles. The repeat accuracy describes the accuracy in the y-direction for placing the same tape stripe repeatedly. It can be calculated by the difference between the target and the actual position of the tape in the y-direction. However, it must be considered that the system's operating speed can influence the repeat accuracy. To manufacture tape layups with the Fiberforge system, the process parameters for tape width and target gap size must be specified. Both influence the resulting gaps as the tape width has a certain tolerance due to the previous slitting process and the target gap is affected by the equipment's accuracy.

2.2.2. Consolidation

In this study, consolidation is defined by heating the tape layup to its material-specific melting temperature and cooling under pressure to obtain a monolithic laminate [26].

It is realized in a novel low-pressure consolidation process called radiation-induced vacuum consolidation (RVC), which was developed at Fraunhofer ICT [11]. Figure 2a shows the prototype equipment used that was industrialized by Dieffenbacher and is now commercially available as a Fibercon system. In Figure 2b the single process steps for consolidation are explained. Relevant process parameters for consolidation are target temperature and dwell time. The RVC process uses a vacuum to apply a maximum of 1 bar pressure on the tape layup, similar to vacuum-bag-only (VBO) processes. The use of infrared radiation allows high heating rates of up to 90 °C/min for laminates with a thickness of 2 mm. Cooling is realized subsequently by contact cooling with cooling rates up to 70 °C/min. Thus, the RVC process can reduce cycle times for consolidation down to 10 min for the processing of PEKK-CF tape layups at a target temperature of 395 °C.

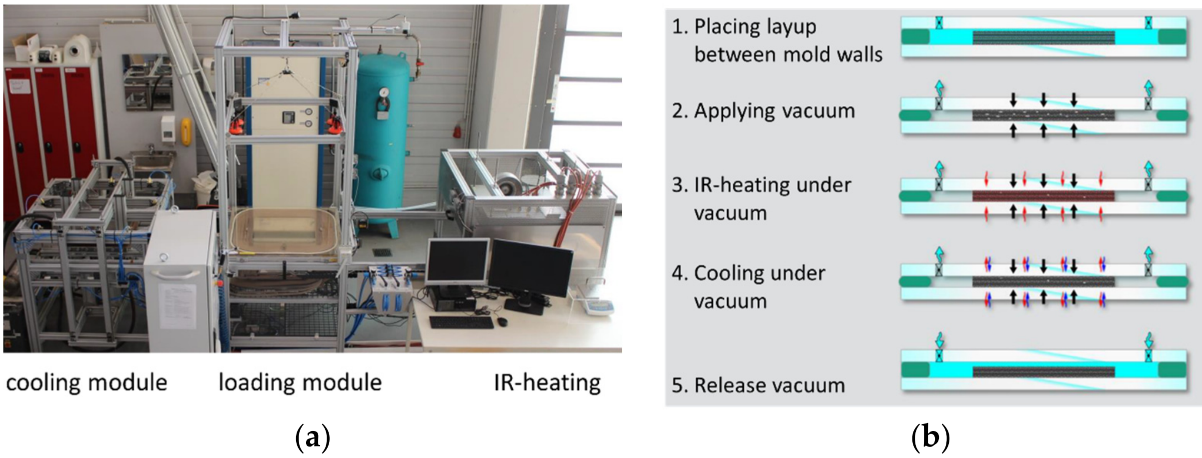


Figure 2. (**a**) RVC process equipment; (**b**) processing steps of RVC.

2.3. Methods

2.3.1. Analysis of the Tape-Laying Process

During automated tape laying, various processes and material-specific factors influence the position of the tape stripes within a ply. As a result, gaps or overlaps can occur. The local thickness increases due to overlaps lead to pressure inhomogeneities during consolidation but are not considered to be a critical factor in porosity. Therefore, this study focuses on the cavities accruing through gaps and overlaps between the tape stripes within a ply. In order to compare the effects of overlaps and gaps, the areas $A_{Overlap}$ and A_{Gap} are analyzed. They represent a cross-section of the resulting cavities and are visualized in Figure 3, which also shows the local thickness increase due to an overlap (Figure 3a).

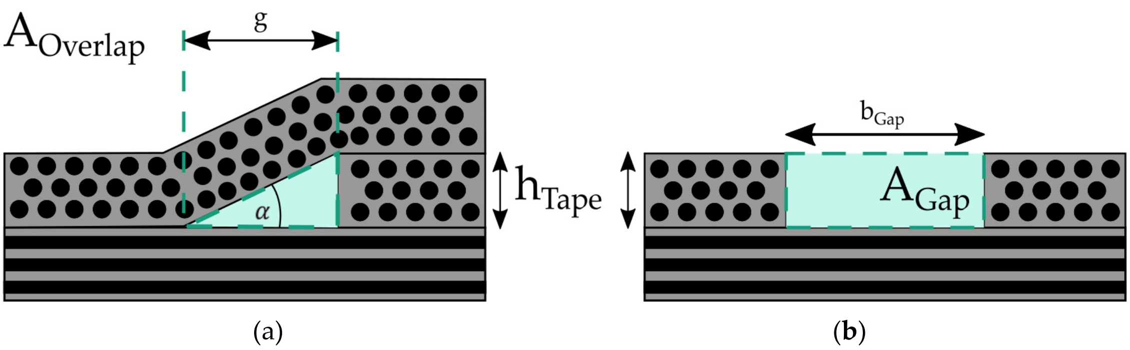


Figure 3. (**a**) Overlap with resulting area $A_{Overlap}$ and thickness increase; (**b**) gap with resulting area A_{Gap}.

In the tape-laying process, UD tape is placed in plies. If there is an overlap in one ply, another tape stripe will be placed onto it in the next ply. While being placed, pressure is applied on the tape stripe, which compresses the stripes in the plies below. This increases the angle α and results in angles of $\alpha \geq 45°$ as shown in Figure 4.

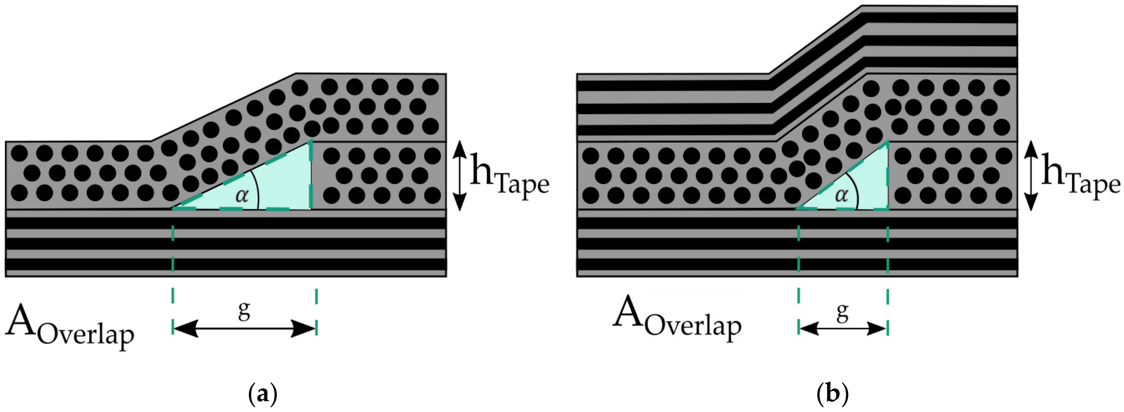


Figure 4. Area $A_{Overlap}$ without (**a**) and with (**b**) a tape stripe placed on top. This shows the increase in angle α when a tape stripe is placed onto an overlap in the ply below.

By assuming that the tape height h_{Tape} is identical for Figure 3a,b, the following relation between $A_{Overlap}$ and A_{Gap} can be derived:

$$A_{Overlap} < A_{Gap} \leftrightarrow \frac{{h_{Tape}}^2}{2tan(\alpha)} < h_{Tape} * b_{Gap} \leftrightarrow arctan\left(\frac{h_{Tape}}{2b_{Gap}}\right) < \alpha \tag{1}$$

It should be shown that the area generated by a gap is more critical to porosity than the area generated by an overlap. Based on the tape's CPT of 0.14 mm, the size of the area $A_{Overlap}$ is calculated for angles of 90° > α ≥ 45°. Table 1 shows the results for $A_{Overlap}$. Using Equation (1) allows deriving the minimum gap size for which the area A_{Gap} is bigger than the area $A_{Overlap}$. These values are also included in Table 1.

Table 1. Calculated sizes of the area $A_{Overlap}$ for different angles α and the corresponding gap size b_{Gap} for an area $A_{Gap} > A_{Overlap}$.

Angle α (°)	**45**	**50**	**60**	**70**	**80**
area $A_{Overlap}$ (mm^2)	0.0098	0.0082	0.0057	0.0036	0.0017
gap size b_{Gap} (mm)	0.0700	0.0587	0.0404	0.0255	0.0123

The results show that for an angle of α = 45° a gap with a size of 0.07 mm will already generate a bigger area than an overlap. Due to the process accuracy and the material variations in its width, it is probable that accruing gaps are bigger than 0.07 mm. Thus, it can be shown that cavities generated through gaps are bigger and therefore more critical to porosity.

To avoid increased porosity due to gaps generated by automated tape laying, the aim of this study is to minimize the size of the accruing gaps and thereby minimize their influence on porosity in consolidated laminates. However, this leads to a tradeoff as there are two opposite targets that must be equally fulfilled.

The first target is to avoid gaps. This requires setting the process parameters, tape width, and target gap size, according to a theoretical gap of zero. To avoid gaps in any case, the tape width is set to the minimum tape width of the material obtained from a quality inspection and the target gap size is set to zero. However, this will result in overlaps at all positions where the tape width is wider than the minimum measured tape width.

The second target is to avoid overlaps. Although their contribution to porosity is low as shown in the previous section, they cause inhomogeneous thickness distributions and result in pressure peaks during consolidation. Again, the process parameters must be set accordingly but in this case, the maximum tape width is chosen as the set value, whereas the target gap size remains at zero. This will result in gaps at all positions where the tape is narrower than the maximum measured tape width. These effects are increased when considering the guiding and repeating accuracy.

This tradeoff illustrates the need for an approach that enables the choice of the required process parameters, tape width and target gap size. To develop this approach, a geometrical model is necessary that allows the calculation of the minimum and maximum possible gaps. This model requires some boundary conditions that need to be defined. First, the guiding accuracy T_{guide} is analyzed. Therefore, a target tape width b_{set} is defined so that the Fiberforge's guiding system moves to this defined position. The distance between the lateral tape guiding profiles b_{guide} is measured. Afterward, the system's position is altered manually. Setting the target value to the same width as before restarts the movement of the guiding system and the distance can be measured again. This process is repeated five times. T_{guide} is obtained as the mean value of all measurements by Equation (2).

$$T_{guide} = \frac{\sum_{i=1}^{n}\left(b_{guide,\ i} - b_{set}\right)}{n} \quad (2)$$

Second, the repeat accuracy T_{repeat} for a defined operating speed is analyzed by laying the same tape stripe repeatedly and measuring the deviations between the resulting positions y_i in the y-direction. The position of the first stripe is used as a reference, y_{ref}. For each operating speed, the procedure is repeated five times. T_{repeat} is obtained as the mean value using Equation (3).

$$T_{repeat} = \frac{\sum_{i=1}^{n}\left(y_{ref} - y_i\right)}{n} \quad (3)$$

Finally, the tape-width distribution of the processed APC tape must be measured with a digital caliper to obtain the values for minimum $b_{tape,min}$ and maximum $b_{tape,max}$ tape width. For the methodological approach, three cases regarding the real tape width are defined to simplify the geometrical model. All these cases can occur during tape laying but only one tape width can be set as the process parameter for the whole tape-laying process.

Case 1 describes a scenario in which the real tape width is equal to the set tape width $b_{tape} = b_{set}$. In this case, the tape's position in the y-direction is only depending on the guiding and repeat accuracy. The maximum and minimum positions in the y-direction result from the maximum or minimum values, respectively, for T_{guide} and T_{repeat}. On this basis, the position of the left and right tape edges can be calculated as shown in Figure 5. Here, the index S1 stands for the first tape stripe (S) to be placed. Max. or min., respectively, describe the maximum and minimum positions of the left (L) and right (R) tape edges.

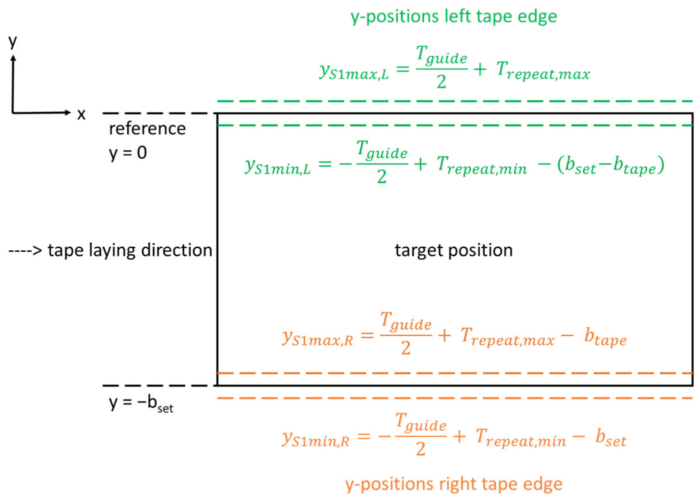


Figure 5. Tolerance fields of tape-edge positions of one single tape stripe for case 1 $b_{tape} = b_{set}$. Green: left tape-edge position; orange: right tape-edge position; black: target position.

When placing two consecutive tape stripes next to each other, the maximum gap size $b_{gap,max}$ and minimum gap size $b_{gap,min}$ can be calculated by subtracting the corresponding y-positions of the first (S1) and second (S2) tape stripes using Equations (4) and (5).

$$\begin{aligned} b_{gap,\ max} &= y_{S1max,R} - \left(y_{S2min,L} - b_{tape} - b_{gap,set}\right) \\ &= T_{guide} + T_{repeat,\ max} - T_{repeat,\ min} + b_{gap,set} \end{aligned} \tag{4}$$

$$\begin{aligned} b_{gap,min} &= y_{S1min,R} - \left(y_{S2max,L} - b_{tape} - b_{gap,set}\right) \\ &= -T_{guide} + T_{repeat,\ min} - T_{repeat,\ max} + b_{gap,\ set} \end{aligned} \tag{5}$$

Case 2 describes a scenario in which the real tape width is smaller than the set tape width $b_{tape} = b_{tape,min} < b_{set}$. In this case, the tape position in the y-direction is additionally dependent on the real tape width. The maximum and minimum gap sizes are again obtained by subtracting y_{S1} and y_{S2} but here the minimum tape width $b_{tape,min}$ has to be considered when calculating the maximum gap size. Thus, the maximum gap size is obtained using Equation (6), whereas Equation (5) can be used for the minimum gap size.

$$b_{gap,\ max} = T_{guide} + T_{repeat,\ max} - T_{repeat,\ min} + 2b_{set} + b_{gap,set} - 2b_{tape,min} \tag{6}$$

Case 3 describes the last possible scenario in which the real tape width is wider than the set tape width. Again, the position in the y-direction is dependent on the real tape width. However, this case must be subclassified. Therefore, *case 3a* describes the scenario where the real tape width b_{tape} is between the set tape width b_{set} and the sum of the set tape width and the guiding accuracy T_{guide}: $b_{set} + T_{guide} \geq b_{tape} > b_{set}$. For this case, the minimum gap size can be calculated using Equation (5). However, the maximum gap size is different and can be calculated using Equation (7).

$$b_{gap,\ max} = -T_{guide} + T_{repeat,\ max} - T_{repeat,\ min} + b_{gap,set} \tag{7}$$

Case 3b describes the scenario where the real tape width b_{tape} is wider than the sum of the set tape width and the guiding accuracy T_{guide}: $b_{tape} > b_{set} + T_{guide}$. Figure 6 shows the possible positions of the tape edges for this case.

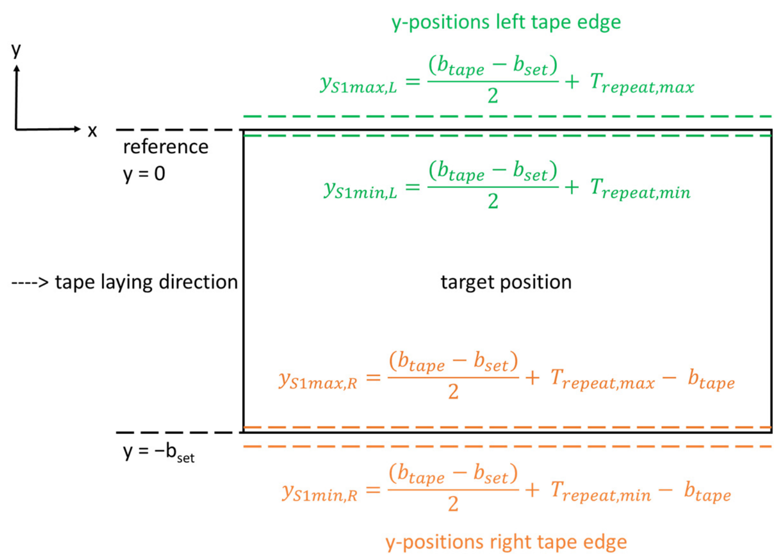


Figure 6. Tolerance fields of tape-edge positions of one single tape stripe for case 3b. Green: left tape-edge position; orange: right tape-edge position; black: target position. Compared to case 1, the minimum positions are closer to the target position as the tape is wider.

Based on the assumption that the tape is pinched between the guiding system and expands symmetrically to its longitudinal axis, the minimum and maximum gap sizes are calculated using Equations (8) and (9).

$$b_{gap,\ max} = T_{repeat,max} - T_{repeat,min} + b_{set} + b_{gap,\ set} - b_{tape,max} \quad (8)$$

$$b_{gap,min} = T_{repeat,min} - T_{repeat,max} + b_{set} + b_{gap,\ set} - b_{tape,max} \quad (9)$$

Based on Equations (5)–(9), it is possible to calculate the minimum and maximum gap size depending on the guiding and repeat accuracy, the set tape width, and the target gap size for the four different cases. These equations represent the geometrical model. To use this in the methodological approach, it is necessary to define a maximum target gap size that is material-specific. This was realized by manufacturing tape layups without using the methodological approach and measuring the resulting gap sizes. The layups were then consolidated and samples were extracted at the measuring locations. Cross-sections were prepared and the status of the initial gaps was analyzed by measuring the gap size in the consolidated layup and subtracting it from the corresponding gap size in the tape layup. The mean value of the achieved flow path lengths with an additional safety factor was defined as the maximum target gap size. For the application of the methodological approach, three target conditions are defined that must be fulfilled:

1. The two conflictive targets, minimization of gaps, and minimization of overlaps, are equally important. Therefore, the probability p for cases two and three must be identical.
2. The maximum gap size calculated by the geometrical model has to be smaller than the maximum target gap size $b_{gap,max.target}$.
3. The maximum overlap calculated by the geometrical model must be smaller than two times the maximum target gap size.

Although the aim of the approach is to limit the gap size to the target gap size, it is expected that gaps will occur that are bigger than the target gap size due to material-specific tolerances and the process accuracy. However, the number of these gaps will be minimized. The procedure of the methodological approach is summed up in Figure 7.

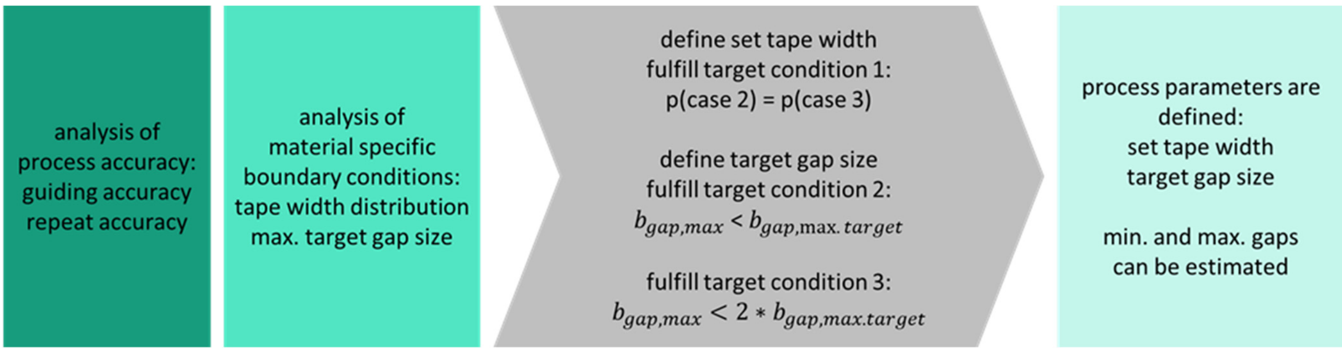


Figure 7. Procedure of the methodological approach to defining optimized process parameters for tape laying to minimize the resulting gap size.

2.3.2. Characterization Methods

To analyze the effects of gaps in tape layups on the porosity of consolidated laminates, samples with a size of 10 × 15 mm were extracted from the laminates by water jet cutting. Hereby, no additional heat is introduced into the material that could potentially influence its morphology. The samples were then analyzed with computer tomography (CT) using a CT scanner, type *Y.CT Precision* from *XYLON*. Six specimens were analyzed at once with a voxel size of 12.63 µm. Porosity measurements were carried out with the software *VGSTUDIO MAX* from *Volume Graphics*. Here, each specimen was separated into a region of interest (ROI). For each ROI, the surface was determined and the void content was measured using the software-specific algorithm *VGEasyPore*.

3. Results

3.1. Parametrization of the Geometric Model

In the first step, the developed geometric model was parametrized. The parametrization of the material-specific boundary conditions requires a quality inspection of the tape width. In total, 31 tape stripes of the APC tape were analyzed. Therefore, the width was measured at 10 positions on each stripe. From the results, the two values for $b_{tape,min}$, and $b_{tape,max}$ are obtained with $b_{tape,min}$ = 98.65 mm and $b_{tape,max}$ = 99.80 mm.

The maximum target gap size was identified through the initial trials described in Section 2.3.1. Without the application of the approach, the tape width was set to 99.00 mm and the target gap size to 0.50 mm. The resulting gaps were measured in three plies at nine different positions per ply. Afterward, six tape layups were consolidated to laminates. Samples were extracted at the gap positions where the measurements were taken. These samples were analyzed with CT measurements. If there was a gap in the laminate, the gap size was measured and subtracted from the original gap size in the tape layup. Through this, the average flow path was calculated at 0.80 mm. This means that there are gaps that are smaller and bigger than this value that were filled with material during consolidation. Therefore, the maximum target gap size was identified as 0.40 mm including a safety factor of S = 2. Figure 8 shows a CT scan with two gaps that were not entirely filled during consolidation.

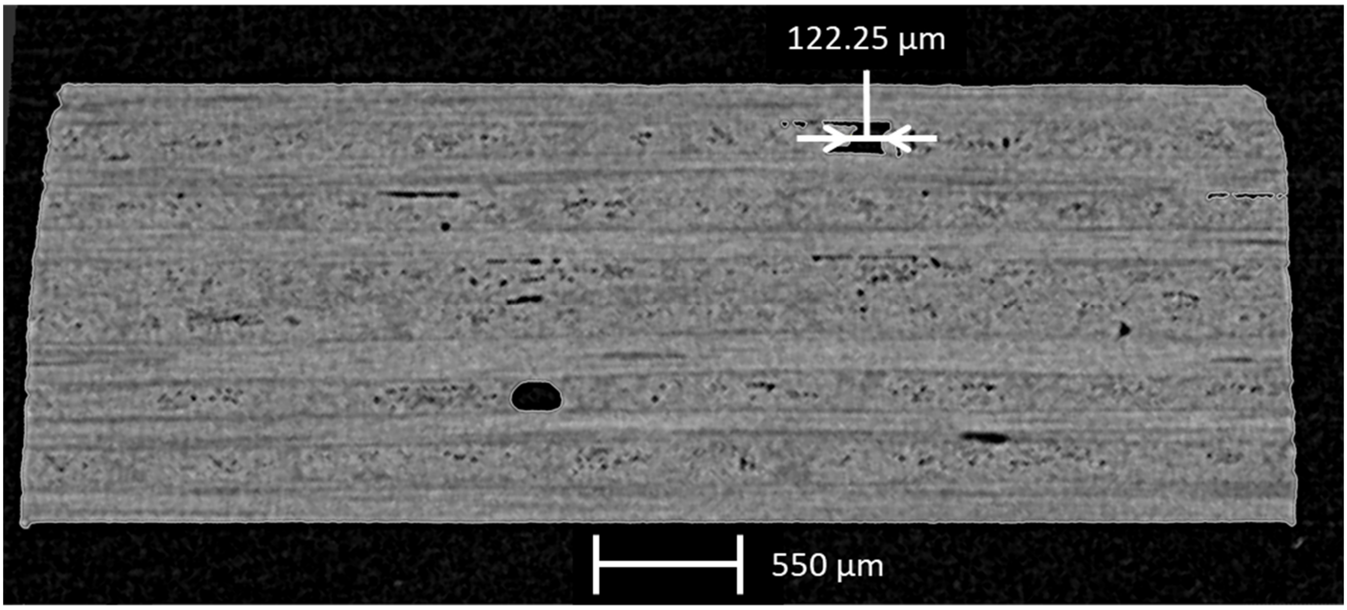


Figure 8. CT cross-section of a laminate with remaining gaps after consolidation.

The process-specific boundary conditions were identified with the Fiberforge automated tape-laying system at Fraunhofer ICT. In the beginning, the process accuracy was quantified. To measure the guiding accuracy, the tape width b_{set} was set to 99.00 mm, which was also the target width for the tape. The distance between the lateral tape guiding b_{guide} was manually altered by +/− 45.00 mm. The resulting distance after repositioning was measured and the deviation from the target value was calculated. Table 2 shows the obtained results. Hence, T_{guide} is defined as 0.10 mm.

Table 2. Results for quantification of T_{guide}.

Set Value in mm (Target Value +/− 45 mm)	Target Value in mm	Measured Value in mm	Deviation in mm
144.00	99.00	99.03 99.11 99.12 99.14 99.07	0.03 0.11 0.12 0.14 0.07
54.00	99.00	99.19 99.06 99.13 99.08 99.11	0.19 0.06 0.13 0.08 0.11

Next, the repeat accuracy was identified for operating speeds of 25, 50, and 75%. The results are given in Table 3. A positive value indicates a deviation in the positive y-direction and a negative value indicates a deviation in the negative y-direction. Although the mean value for T_{repeat} at 25% operating speed is lower, the standard deviation is twice as high as for 50%. Therefore, an operating speed of 50% was chosen for manufacturing tape layups to obtain results with small variabilities.

Table 3. Results for quantification of T_{repeat}.

Operating Speed in %	$T_{repeat,min}$ in mm	$T_{repeat,max}$ in mm	$T_{repeat,mean}$ in mm	σ T_{repeat}
25	−0.25	0.18	−0.07	0.16
50	−0.28	−0.09	−0.14	0.08
75	−0.52	0.00	−0.20	0.19

Considering the three target conditions given in Figure 7, the methodological approach was used to define tape width and target gap size. Based on all width measurements of the APC tape, the tape width b_{set} was set to 99.12 mm. This tape width fulfills the first target condition. Next, the target gap size $b_{gap,\,set}$ was set to 0.11 mm to fulfill target conditions two and three. Table 4 summarizes the results from the parametrization and the defined process parameters. Table 5 shows the calculated minimum and maximum gap sizes that can theoretically occur in the tape layups.

Table 4. Summary of parametrization and process parameters.

Parameter	Value
Guiding accuracy T_{guide} (mm)	0.10
Minimum repeat accuracy $T_{repeat,min}$ (mm)	−0.28
Maximum repeat accuracy $T_{repeat,max}$ (mm)	−0.09
Operating speed (%)	50
Maximum target gap size (mm)	0.40
Set tape width (mm)	99.12
Target gap size (mm)	0.11

Table 5. Results for calculation of minimum and maximum gap sizes.

Case	Minimum Gap [1] $b_{gap,min}$ in mm	Maximum Gap [1] $b_{gap,max}$ in mm
1		0.40
2	−0.18	1.34
3a		0.20
3b	−0.76	−0.38

[1] negative values represent an overlap.

3.2. Validation of the Methodological Approach

For the chosen process parameters b_{set} = 99.12 mm and $b_{gap,set}$ = 0.11 mm, the probability distribution for each case is given in Table 6. The absolute and relative frequencies are based on the width measurements. This shows that cases 1, 3a, and 3b have a combined probability of 52%. Therefore, more than half of the gaps occurring in the tape layup are expected to be definitively smaller than 0.40 mm (cf. Table 5). For all width measurements assigned to case 2, the maximum possible gap can be higher than 0.40 mm. Hence, the possible gap sizes were calculated using the geometrical model. The results are given in Figure 9. The histogram shows the frequency and cumulative percentage for gap sizes from 0.40 mm to the maximum possible gap of 1.34 mm. The gap size is divided into steps of 0.10 mm given as upper limits on the x-axis. As the maximum target gap size was defined with a safety factor of S = 2, it is theoretically possible that gaps with a size of 0.80 mm can also be filled during consolidation. The geometrical model calculates a cumulative percentage of 97% for case 2 and a gap size of 0.80 mm. Combined with the relative frequencies for cases 1, 3a, and 3b, the cumulative percentage for a gap less than or equal to 0.80 mm is 98%.

Table 6. Absolute and relative frequencies of cases 1 to 3b for the chosen process parameters.

Case	Absolute Frequency	Relative Frequency in %
1	22	7
2	150	48
3a	79	26
3b	59	19

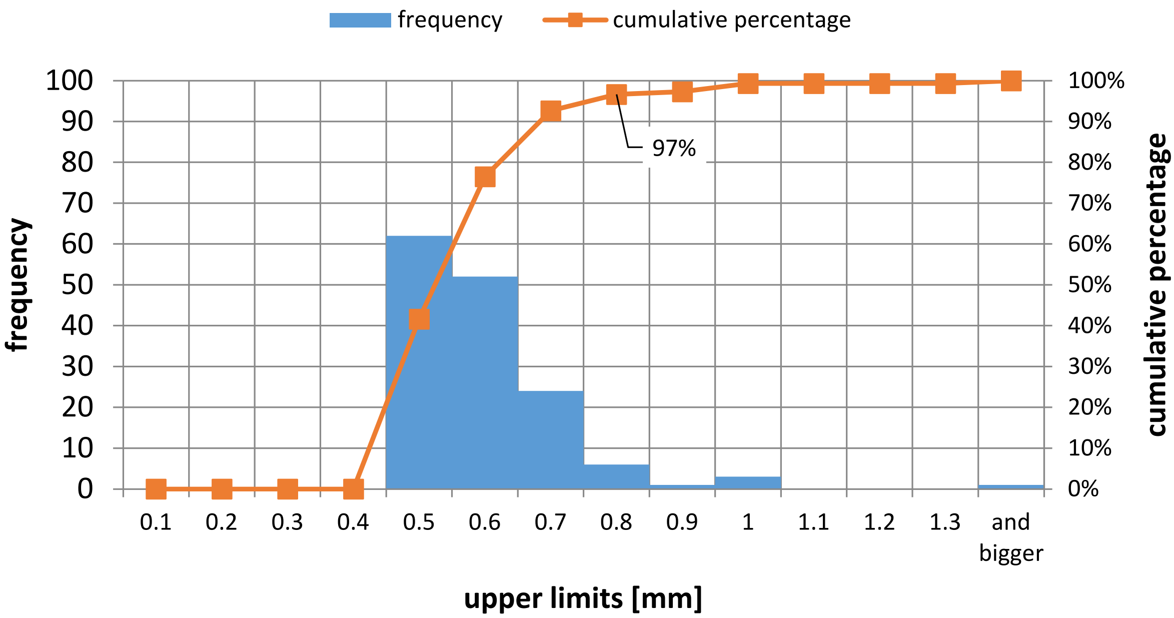
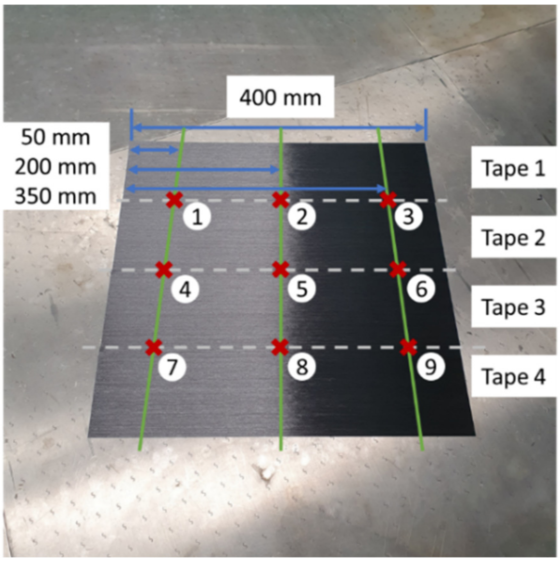
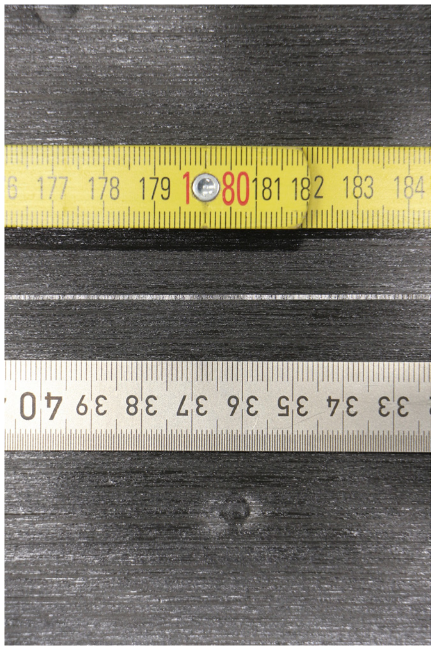


Figure 9. Frequency and cumulative percentage for possible gap sizes in case 2.

To validate the methodological approach, tape layups were manufactured using the Fiberforge system. In total, six layups were manufactured and the gap size was measured at nine locations in three different plies resulting in 162 measurements. A caliper from *MAHR* type *MarCal 16 EWR* with an accuracy of 0.01 mm was used. Figure 10 shows where the measurements were carried out and an exemplary gap between two tapes.



(a)



(b)

Figure 10. (**a**) Measurement locations of gaps; (**b**) Exemplary gap between two tape stripes.

The results of all measurements are shown as a histogram in Figure 11. A total of 63% of all measured gaps are smaller or equal to 0.40 mm. Based on the methodological approach, a 52% probability was calculated for the gaps to be smaller or equal to 0.40 mm. Here, the real probability is higher than the theoretical value. Hence, the approach underestimates the actual probability by 11%. A gap size of less than or equal to 0.80 mm has a cumulative percentage of 92%. For this gap size, the approach estimated a probability of 98% and, therefore, overestimates the real probability by 6%. The maximum measured gap has a size of 1.107 mm, which is smaller than the maximum calculated gap of 1.34 mm. Thus, all measured gaps are within the estimated maximum from the methodological approach. In summary, it was possible to validate the methodological approach by manufacturing tape layups with the Fiberforge system. The cumulative percentage of the measured gaps is in good agreement with the estimated probabilities and gap sizes.

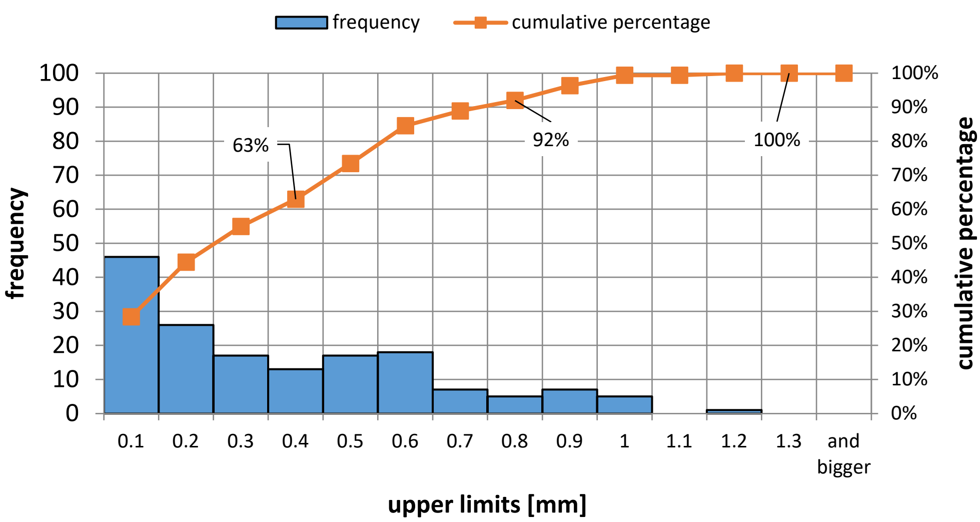


Figure 11. Frequency and cumulative percentage for results of validation trials.

3.3. Influence of Gaps on Porosity

Manufactured layups with measured gaps were processed to laminates using RVC to investigate if the resulting gaps in automated tape laying have an influence on porosity. As a reference, additional laminates were made using manual layup without any gaps in between the tapes and were subsequently consolidated. Three laminates from each automated and manual layup were consolidated at a target temperature of 390 °C and a dwell time of 120 s. Six samples with a size of 15 × 10 mm were extracted from each of those laminates by water jet cutting. All samples are located at the positions where the gap measurements were taken (see Figure 10) and analyzed in CT. The void content for each sample was analyzed with *VGEasyPore*. The average void content was calculated from all measurements for the automated and manually manufactured layups. The results are shown in Figure 12. They show that the manual layup leads to a slightly higher mean value of void content compared to the automated tape layups, for which the presented approach was applied. However, considering the standard deviation of all measurements, the samples show a comparable void content. Therefore, it can be concluded that the resulting gaps in automated tape laying, even if some are bigger than the maximum target gap, have no influence on the final porosity. Hence, the aim of the approach, that is, to minimize the influence of gaps in automated tape laying on porosity, was achieved. The authors noted that the void content is at a high level compared to the requirements for aerospace applications. Due to the void content of the reference laminate that was manufactured manually without any gaps, it can be excluded that the void content is a result of the remaining gaps. Hence, the high void content must be a result of a different mechanism during consolidation, which is currently subject to further investigations.

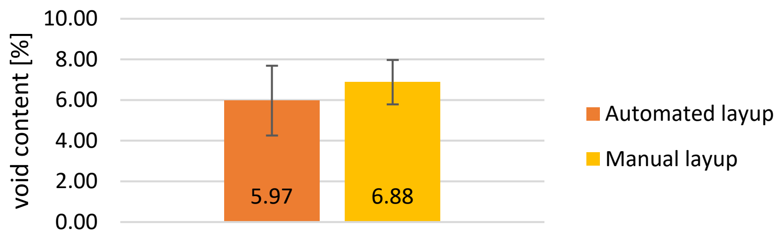


Figure 12. Calculated porosity using CT measurements for automated and manual layups.

4. Conclusions and Discussion

The overall aim of the presented methodological approach is to minimize the gaps in automated tape laying and thereby reduce the influence of automated tape laying on the resulting porosity in consolidated laminates. This cross-process approach makes an important contribution to understanding the development of porosity along the process chain for the manufacture of thermoplastic composites for aerospace applications. One of the first findings is that the optimization of automated tape laying toward zero gaps/overlaps will always lead to a tradeoff. This is due to the variations in the process and the material accuracy. Therefore, three target conditions were defined in the development of the methodological approach that must be considered when choosing the relevant process parameters:

(1) The probability for gaps and overlaps must be equalized by setting the process parameter tape width accordingly.
(2) The estimated maximum gap size must be smaller than the material-specific maximum target gap size by setting the target gap size accordingly. The maximum target gap size must be identified through initial consolidation trials.
(3) The maximum overlap size must be smaller than two times the maximum target gap size to avoid excessive pressure inhomogeneities.

The results from the validation trials presented in Section 3.2 show that the accruing gaps are in good agreement with the estimations made by the methodological approach. Also, the maximum detected gap is within the range predicted by the geometrical model.

Based on the validation trials, it could be shown that the model underestimates the cumulative percentage of gaps up to the maximum target gap size of 0.40 mm. Above this value, the model slightly overestimates the actual results. As the maximum target gap size was defined with a safety factor S = 2, the frequency of gaps up to 0.80 mm was also investigated. Here, the cumulative percentage is above 90% so that fewer than 16 of the measured 162 gaps are wider. To analyze the effects of the resulting gaps on the porosity, layups that are manufactured using the methodological approach and manually manufactured layups were consolidated. Samples from both laminate types were extracted and analyzed using CT measurements. The results show that there is no relevant difference visible. In summary, the developed methodological approach based on a geometrical model allows to minimize gaps and reduce the influence of the tape-laying process on the resulting porosity. However, the calculated void content is at an elevated level, which is not influenced by the gaps. Therefore, the causes for the high void content are subject to further research.

Furthermore, the boundary conditions of the approach are material-specific and validated only for one material system, APC PEKK-FC tape. To optimize the model and validate the application for other material systems, layup configurations, and operating speeds, additional trials are required and could be the subject of future research. This will help to set up a holistic database for various matrix systems. Furthermore, gaps that are not entirely filled with material during consolidation might influence the laminate thickness in the form of shrink marks. Therefore, the laminates' thickness distributions at the gap positions should be considered in future research as they have a potential impact on the mechanical properties.

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Conflicts of Interest: The radiation-induced vacuum consolidation (RVC) equipment developed at Fraunhofer ICT has been industrialized/commercialized by Dieffenbacher as the Fibercon system.

References

1. Schürmann, H. *Konstruieren Mit Faser-Kunststoff-Verbunden: Mit 39 Tabellen, 2, Bearb. und Erw. Aufl*; Springer: Berlin/Heidelberg, Germany, 2007; ISBN 978-3-540-72189-5.
2. Fischer, F.J.C. On Readiness in Advanced Thermoplastic Composite Production. Ph.D. Thesis, DLR, Deutsches Zentrum für Luft-und Raumfahrt, Augsburg, Germany, 2018.
3. Gilani, M.; Sinan Körpe, D. Airline Weight Reduction to Minimize Direct Operating Cost. In Proceedings of the 4th International Aviation Management Conference (4th INTAVIC), Ankara, Turkey, 18–19 October 2019.
4. Favaloro, M. Thermoplastic Composites in Aerospace—The Future Looks Bright: The Real Impediment to Use of Thermoplastic Composites in Critical Control Surfaces Is an Education Gap. Available online: https://www.compositesworld.com/articles/thermoplastic-composites-in-aerospace-past-present-and-future (accessed on 14 July 2021).
5. Salek, M.H.; Hoa, S.V. Effects of Processing Parameters on the Mechanical Properties of Carbon/PEKK Thermoplastic Composite Materials. Master's Thesis, Concordia University, Montreal, QC, Canada, 2005.

6. Hou, M.; de Weger, D. Optimisation of Manufacturing Conditions of Carbon Fibre Reinforced Polyetherketoneketone (PEKK) Composite. *AMR* **2011**, *399–401*, 289–293. [CrossRef]
7. American Society for Testing and Materials. Aerospace Material Standards. Available online: https://www.astm.org/Standards/aerospace-material-standards.html (accessed on 14 July 2021).
8. Ageorges, C.; Ye, L. *Fusion Bonding of Polymer Composites*; Springer: London, UK, 2002; ISBN 978-1-4471-0171-0.
9. Ferrara, J.A.; Seferis, J.C.; Vassilatos, G. Processing characteristics of PEKK matrices and their composites. In *Proceedings of the Advanced Materials—Affordable Processes: Concord Resort Hotel, Kiamesha Lake, NY, USA, 21–24 October 1991*; Carri, R.L., Ed.; SAMPE Internat; Business Office: Covina, CA, USA, 1991; pp. 1137–1148. ISBN 093899462X.
10. Bucher, R.A.; Hinkley, J.A. Fiber/Matrix Adhesion in Graphite/PEKK Composites. *J. Thermoplast. Compos. Mater.* **1992**, *5*, 2–13. [CrossRef]
11. Baumgärtner, S. Beitrag zur Konsolidierung von Thermoplastischen Hochleistungsfaserverbundwerkstoffen. Ph.D. Thesis, Fraunhofer ICT, Pfinztal, Germany, 7 December 2017.
12. Link, T. UD-Tape Basierte Bauteile in Kurzer Zykluszeit: Strahlungsinduzierte Vakuumkonsolidierung Beschleunigt Ud-Tape-Verarbeitung. Available online: https://www.plastverarbeiter.de/verarbeitungsverfahren/ud-tape-basierte-bauteile-in-kurzer-zykluszeit.html (accessed on 1 December 2021).
13. Zhang, D.; Heider, D.; Gillespie, J.W. Void reduction of high-performance thermoplastic composites via oven vacuum bag processing. *J. Compos. Mater.* **2017**, *51*, 4219–4230. [CrossRef]
14. Zhang, D.; Heider, D.; Advani, S.G.; Gillespie, J.W. Out of Autoclave Consolidation of Voids in Continuous Fiber Reinforced Thermoplastic Composites. In Proceedings of the SAMPE-Long Beach, Long Beach, CA, USA, 6–9 May 2013.
15. Saenz-Castillo, D.; Martín, M.I.; Calvo, S.; Rodriguez-Lence, F.; Güemes, A. Effect of processing parameters and void content on mechanical properties and NDI of thermoplastic composites. *Compos. Part A Appl. Sci. Manuf.* **2019**, *121*, 308–320. [CrossRef]
16. Slange, T.K. *Rapid Manufacturing of Tailored Thermoplastic Composites by Automated Lay-Up and Stamp Forming*; University of Twente: Enschede, The Netherlands, 2019; ISBN 9789036547284.
17. Slange, T.K.; Warnet, L.; Grouve, W.J.B.; Akkerman, R. Influence of preconsolidation on consolidation quality after stamp forming of C/PEEK composites. In *ESAFORM 2016, Proceedings of the 19th International ESAFORM Conference on Material Forming, AIP, Nantes, France, 27–29 April 2016*; AIP Publishing: Nantes, France, 2016. [CrossRef]
18. Chang, I.Y. PEKK as a new thermoplastic matrix for high performance composites. *SAMPE Q.* **1988**, *19*, 29–34.
19. Donadei, V.; Lionetto, F.; Wielandt, M.; Offringa, A.; Maffezzoli, A. Effects of Blank Quality on Press-Formed PEKK/Carbon Composite Parts. *Materials* **2018**, *11*, 1063. [CrossRef] [PubMed]
20. Saffar, F.; Sonnenfeld, C.; Beauchêne, P.; Park, C.H. In-situ Monitoring of the Out-Of-Autoclave Consolidation of Carbon/Poly-Ether-Ketone-Ketone Prepreg Laminate. *Front. Mater.* **2020**, *7*, 195. [CrossRef]
21. Domininghaus, H.; Elsner, P.; Eyerer, P.; Hirth, T. (Eds.) *Kunststoffe: Eigenschaften und Anwendungen; mit 275 Tabellen*; Springer: Berlin/Heidelberg, Germany, 2012; ISBN 978-3-642-16172-8.
22. Spahr, T. *An Introduction to the Polyether Ketone Ketone (PEKK) Co-Polymer*; Arkema Inc.: Galesville, WI, USA, 2015.
23. Choupin, T. Mechanical Performances of PEKK Thermoplastic Composites Linked to Their Processing Parameters. Ph.D. Thesis, ENSAM, ParisTech, Paris, France, 7 December 2017.
24. Gardner, K.H.; Hsiao, B.S.; Matheson, R.R.; Wood, B.A. Structure, crystallization and morphology of poly (aryl ether ketone ketone). *Polymer* **1992**, *33*, 2483–2495. [CrossRef]
25. Solvay. *APC (PEKK-FC): PEKK-FC Thermoplastic Polymer Prepreg*; Technichal Data Sheet, Solvay: Alpharetta, GA, USA, 11 October 2017.
26. Henning, F.; Moeller, E. (Eds.) *Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung*; Hanser: München, Germany; Wien, Austria, 2011; ISBN 978-3-446-42267-4.