Offline Robot-Path-Planning and Process Simulation for the Structural Analysis of Coreless Wound Fibre-Polymer Composite Structures

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Abstract. In the coreless filament winding process (CFW) pre-impregnated fibre bundles (Towpregs) are wound around anchor points in a defined chronological order. With this process, fibre-polymer composite structures with a very high lightweight potential and very little material consumption can be manufactured for different applications in the automotive, aeronautical, sports and architectural sector. The winding sequence and the fibre interaction thereby does have an influence on the final fibre architecture and thus on its structural behaviour. To take this into account a process chain for path planning and process simulation out of a design model is presented. To achieve flexible considerations of different design concepts a parameter-based method for the necessary path planning of the final three-dimensional fibre architecture is introduced. The approach is evaluated on different kinds of specimen.

Introduction

Coreless wound fibre-polymer composite systems are upcoming and increasingly used in architecture as they allow geometric flexibility and do have a high lightweight potential. As an efficient and reliable approach to manufacture a wide variety of complex structural components robotic coreless filament winding techniques have been developed by several researchers [1, 2, 3, 4]. Here a robot system is combined with a winding head, which winds multiple pre-impregnated fibre bundles around anchor points in a predefined sequence to form the final load-carrying structure in a continuous additive process. In an initial design phase the structural behavior is determined using an approximation of the fibres, where the winding around the anchor points is not taken into account. On that level several fibre syntaxes and structures can be evaluated efficiently. After that, the path for the robot needs to be programmed in the manufacturing domain. Here the path for the winding head is generated, where all manufacturing constrains have to be considered. After programming the robot, the path is evaluated using a dry fibre equivalent and is manually adapted until the final program can be used for the manufacturing. As a result, a path planning needs to be flexible enough to consider changes in design or the robotic setup. Furthermore, an evaluation and adjustment of structural design or manufacturing data in the context of data exchange between different domains and interdisciplinary research areas requires a data feedback loop [4, 5].

Methods

Path Planning and Trajectory generation. Robot-assisted manufacturing requires a transfer of the fibre syntax into a program that can be executed by the robot control. This requires a calculation of a trajectory of the tool centre point (TCP) for the winding path, a scheduled motion discretised in a pose (cartesian coordinates and orientation) and the related time step. In addition to the dimensions of the anchors, their position, their orientation, the workspace of the robot setup and its kinematic boundary conditions must be considered. Furthermore, a collision model of the fibres is required to avoid a collision of the TCP with wound fibres through a correction of the TCP path.

In the developed parameter-based method for path planning the initial data out of a design model is used to calculate the required path using an analytical sequential TCP path generation approach. This includes the winding syntax, the respective hooking motion required at the anchor points, a

polyline model of the estimated fibrenet as a geometrical representation of the syntax and the anchor position, dimensions and orientation. The typically used hooking types are shown in Fig. 1. A motion of type U is a winding with a change of direction under minimal contact on the anchor. In contrast, the types X and Y define a crossing of the fibre during redirection as inner or outer loop. When linking a hooking type for the respective anchor points in the winding syntax, the required movement of the winding head can be assigned. The hooking type and the direction of the approach vectors of the hooking motion do define the required rotation for each point in the winding syntax including a dependency between the adjacent anchor points of the syntax. The election of hooking types and their sequence thereby do have an influence on the resulting final fibre architecture.
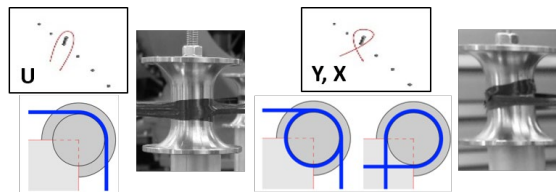

Fig. 1 Hooking motions: U type and Y or X type

The path of the TCP needs to be calculated with an offset distance to anchors and already wound fibres to prevent a collision during the manufacturing process. Thereby uncertainties in fibre position have to be considered. For this purpose, a vector must be defined to determine the offset direction. A simple but effective way for complex structures is to use a reference surface of the estimated final structure or a boundary surface of the construction space. The path points are projected on the reference surface and the normal vector at the projection point is used to define the offset direction. If the projection is located inside the reference mesh, the offset is in the normal direction of the mesh. Thereby the orientation of the anchors is considered to define the correct direction. A projection on the borders of the reference mesh results in an offset vector in the plane of the reference mesh and thus allowing for an ideal path or an avoidance of a physical frame. As a further boundary condition, a fibre-protecting deposition direction should be considered. The normal direction of the idealized elliptical fibre cross-sectional area of the fibre should be oriented in the same direction as the deposition direction. This reduces the twisting of the fibres or an inevitable twist can be positioned under controlled conditions. The principle is shown in Fig. 2. During a layup on the anchor, the ideal direction is perpendicular to the anchor orientation. At a crossing of several fibres a stacked layup does result in an ideal fibre layup. This requires a controlled twist of the fibres in the crossing area between the anchors.
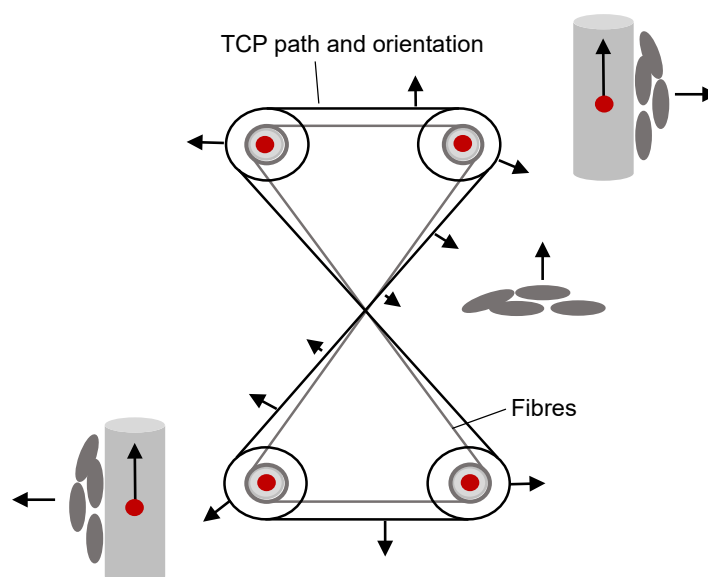

Fig. 2 Schematic sketch of the ideal fibre deposition orientation

An example for the initial geometrical data for the model used in Fig. 2 using a rectangular reference mesh is shown in Fig. 3 (left side). The result out of an implementation of the path planning approach for a hooking type U for the anchors is shown on the right side. Additionally, an analytical calculation of the resulting fibre path can be used to evaluate the expected path.
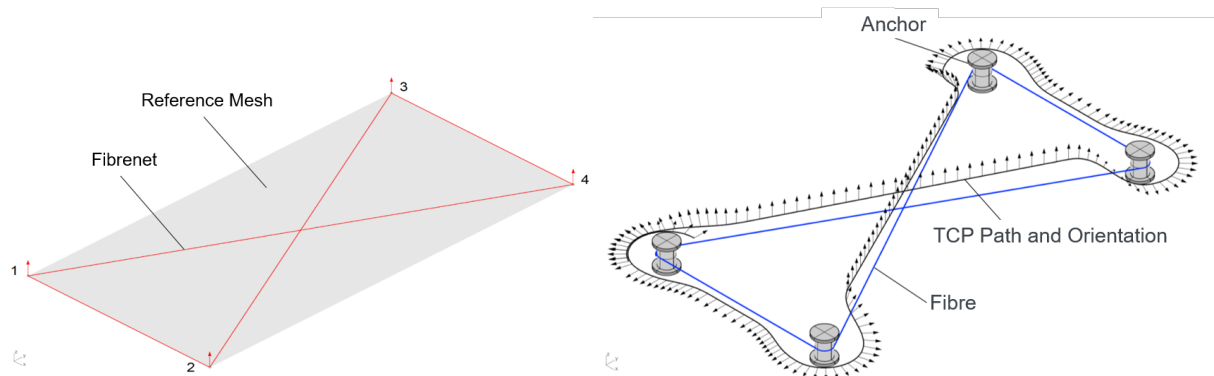

Fig. 3 Geometric initial data for trajectory generation (left) and resulting simplified trajectory output of the software component for an ideal path orientation (right).

For the algorithmic implementation of the procedure, as well as for the consideration of the change of the necessary direction of a rotation at the anchor point, a sequential processing of the syntax is used along the fibrenet. To generate a path segment for an anchor point in the syntax, the segment in the polyline between the current and previous anchor point and, in the same procedure, the following segment in the syntax are used as the basis for the calculations of the respective sections. Subsequently, a sphere around the anchor point is defined as the volume that is used for the hooking movement, which is replaced by the required hooking movement. The remaining segment of the fibrenet outside of a hooking area is defined as a travel segment. The vector between the respective intersection points of the fibrenet segments with the sphere and the position of the anchor point is used as definition for the direction vector of the respective segment defining the rotation direction of a hooking movement. Different hooking types require different rotation directions. For a U-type hooking motion this is the direction of the larger angle between the direction vector of the old and the new segment to avoid slippage of the fibres. After the initial path generation, the offset direction can be applied. The approach enables the use of arbitrarily complex intermediate segments in the fibrenet and thus also an implicit manual specification for a collision avoidance movement without further input data. In addition to the topology and orientation of the anchors and path parameters, for example to specify the offset distance for travel and hooking segments, additional path inclination parameters and parameters to adjust the hooking path are taken into account.

The compaction, the nesting and the orientation of the fibres is controlled by the prestress of the fibres [6]. A high prestress results in a larger compaction of the fibres and thus a higher fibre volume content. Furthermore, a variation during the winding process might result in a slippage of the fibres. If the prestress is to low it might result in additional undulations or buckling in the fibres, where as a high prestress might result in fibre defects and inhomogeneous compaction [6, 7].

During the complex three dimensional path of a CFW process a change of directions and changes in velocity do influence the prestress of the fibres. Especially the hooking motion at an anchor can result in fibre slippage. Besides an active control mechanism in a winding head during the winding process the prestress can be controlled by the trajectory. Therefore a spiral hooking path is aimed at. The characteristics of a spiral curve are constant accelerations around its centre point. Furthermore, the distance from a spiral path point to the contact point on the anchor is always increasing, resulting in a reduction of fibre slippage. An example for this approach as well as three dimensional application for the path planning algorithm is shown in Fig. 4 for a cylindrical structure.
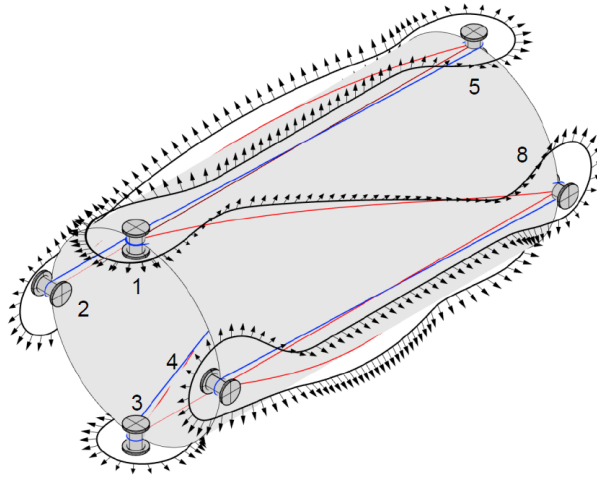
Fig. 4 Three dimensional example for path planning for a cylindrical structure using a spiral hooking motion at the anchors. The initial reference surface is shown in grey, the fibrenet is shown in red and the estimated fibre architecture in blue.

In a subsequent work step, the calculated TCP trajectory has to be transferred to a robot simulation for a verification of a kinematic executability using inverse kinematics. Possible restrictions out of the robot setup or kinematic limitations (e.g. reachability, collisions or singularities) can be adjusted by a manual repositioning of the winding frame, a path adaptation or an adjustment of the robot's joint angles. After a possible additional manual adjustment, the robot program can be generated and used for a fabrication of the structure.

Process Simulation. To enable a verification of the winding trajectory regarding the fibre winding behavior and process induced effects on the final fibre architecture a process simulation approach has been investigated. The simulation set-up is based on an explicit FEM process simulation with the software PAM-CRASH (ESI-Group), adapted to the requirements of a coreless winding process. In the simulation approach the winding head is reduced to a discretized feed-eye and a moving spool with a yarn supply (direct approach). In this approach, the majority of the elements are moved, making more complex modeling strategies for the yarn more difficult. For this reason, an indirect approach with fixed yarn supply and moving anchor points has additionally been investigated. In both approaches, the orientation vectors of the trajectory have to be transferred in spatial angles of the fixed global coordinate system of the simulation model. In the direct approach the trajectory can be directly used, whereas in the indirect approach the relative movement of the anchor points needs to be calculated to reproduce the winding heads trajectory.

Results

In this publication, methodologies have been presented to establish a process chain for a flexible trajectory generation and structural evaluation out of a winding syntax. As a validation for the approaches three different types of specimen have been modeled and evaluated. Results of the FEM process simulation show a basic suitability for the modelling of fibre bundles in the winding process. Due to the large curvatures at the anchor points and the large spans of the fibres connecting the anchor points a tradeoff between a good discretization at the anchor points and element reduction for an acceptable simulation time has to be identified.

In the indirect approach instability problems occurred the more fibre bundles are wound. These instability problems are due to accelerations and rotations of the anchor points as soon as the fibres are bound to the moving parts of the simulation. Furthermore, a calculation of the required indirect kinematics is not trivial. However, a winding trajectory with small rotation angles resulting in limited dynamic effects or a segmented winding approach between the anchor points are possible using this

approach. Nevertheless, it showed that the approach is not suitable for large or complex structures and thus the direct approach has been continued.

Winding Strategy. To evaluate the effects of different orientation approaches a specimen like structure with a simple winding syntax around two anchors has been evaluated. The fibrenet for the model is a linear connection between the anchors.

In the first model a specimen is created using a simple winding path around two anchor points including an offset and a U-type hooking movement. The resulting path for the ideal trajectory pose orientation is shown in Fig. 5 on the left and a static orientation during the path on the right side.
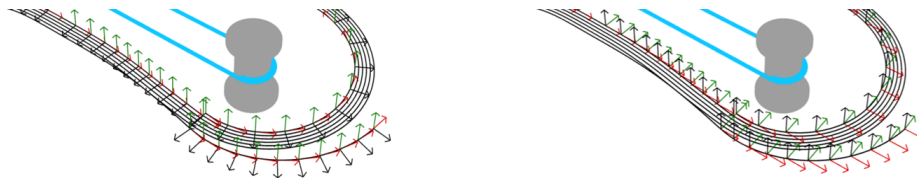

Fig. 5 Specimen winding path using ideal orientation (left) and static orientation (right) for trajectory poses.

The results of the process simulation for the ideal orientation are shown in Fig. 6 on the left and the one for the static orientation is show on the right. A comparison shows limited differences between the approaches. As the fibres are able to twist each other under the applied prestress both approaches show fibre twisting, but a more stacked layup for the ideal orientation.
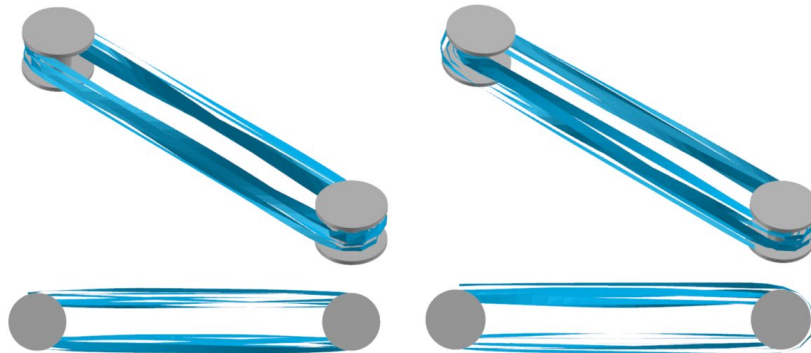

Fig. 6 Simulation results for the specimen structure with ideal orientation (left) and static orientation (right) showing fibre twisting, but a more uniform stacked layup for the ideal orientation.

The second model is created using a modification of the winding path by changing the winding direction between the two anchor points, which results in a wound cross structure. The resulting winding paths for the ideal and static orientation are shown in Fig. 7.
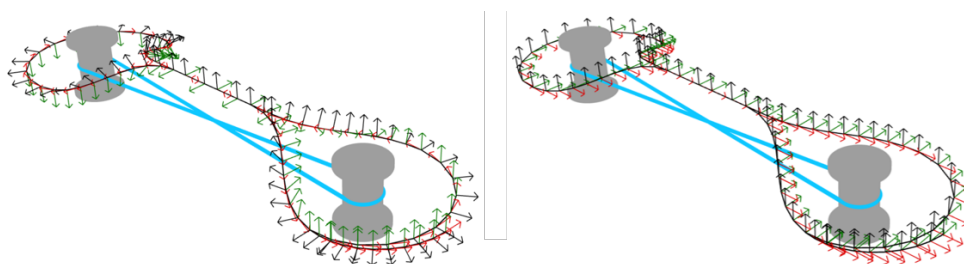

Fig. 7 Cross wound specimen winding path with ideal orientation (left) and static orientation (right).

The result of the process simulation for the ideal orientation is shown in Fig. 8. Due to multiple repetitions and the over winding of already wound fibres, strand-like cross-sectional areas form near the anchor point area. In the intermediate area, the constant contact thickness in the simulation model causes the structure to thicken. In reality, the occurring normal force would result in a compaction of the fibres. As a result, this area would become significantly flatter and tend to widen. Furthermore, the resulting cross sections of the structure show an effect of the path orientation on the fibre layups. The path related ideal orientation results in a more stacked bundle layup, whereas the path with a static orientation results in a wider distribution of the fibres. If the orientation of the winding head is static during winding, a twisting of the fibres occurs. A reorientation during the path results in a controlled guided layup of the fibres without a fibre twist and therefore less fibre deformation. However, this approach is often not possible due to a limitation imposed by robotic kinematics.
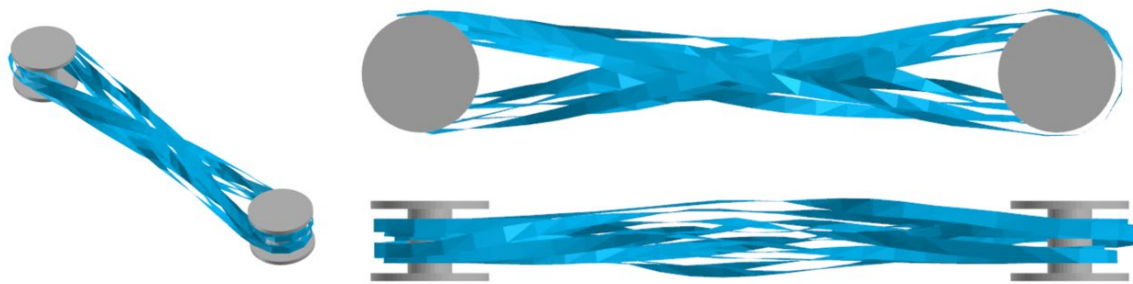

Fig. 8 Result of the process simulation for the cross wound structure using the ideal orientation (Fig 7 right side).

Practical applicability. As a more realistic and larger example a lattice structure with a curved reference surface has been modelled and investigated. The target fibrenet geometry out of the design domain is shown in black in Fig. 9 on the left side. The blue arrows symbolize the winding sequence along the fibrenet. The required pass of some of the anchor points is taken into account by a modification of the corresponding intermediate segments of this reference fibrenet (Fig. 9 on the right side). A usage of the initial fibrenet for the path planning would result in a collision with the anchors.
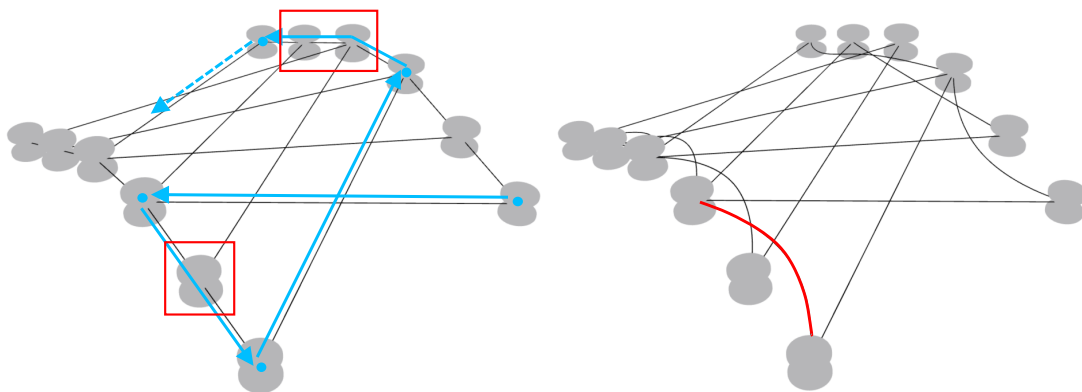

Fig. 9 Fibrenet model for lattice structure (left: initial design model with syntax illustration and exemplary collision zones, right: adapted design model using a spline to avoid anchor collision).

The resulting initial winding path for the lattice structure using a X-type hooking movement is shown in Fig. 10. It has been automatically generated using the path planning approach with a path inclination in the travel segments between the anchors to reduce damage to the fibres during winding. In contrast to the hooking area, the orientation of the winding head can be varied more easily due to the longer distances and less collision objects in this area.
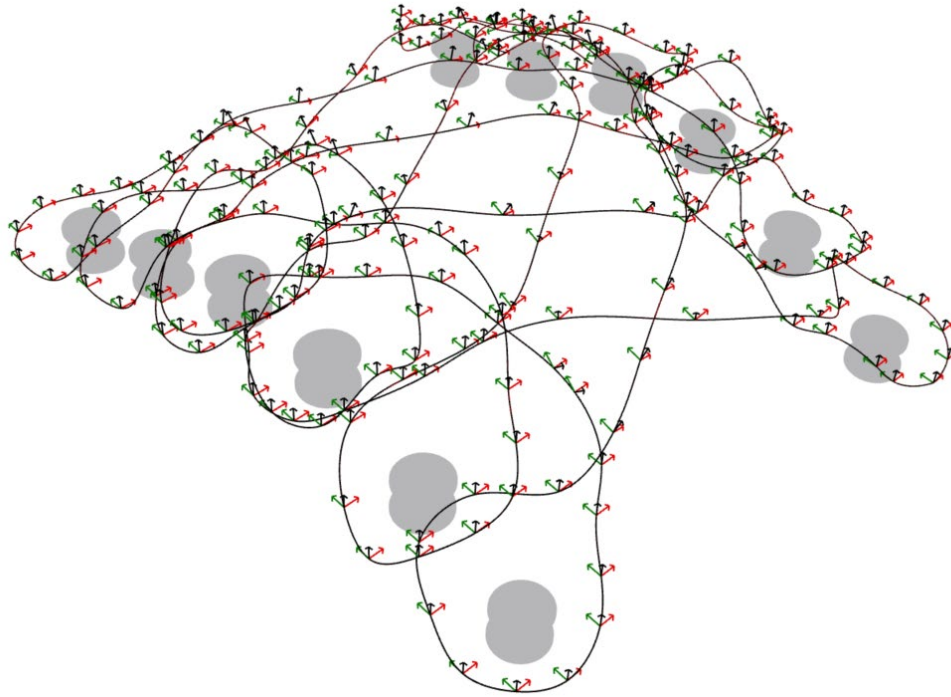
Fig. 10 Initial path for the lattice structure using a static orientation and inclination of orientation in the travel segment between the anchors.

A state of the process simulation for the initial collision free path is shown in Fig. 11. An analyzation of the simulation steps, as well as a comparison between the simulation result and the expected lattice structure for that state shows a non-successful hooking movement for some anchor points and thus resulting in a deviating fibre structure. Using a manual approach, the critical poses of the path have been manually adapted. In Fig. 12 the deviation between the initial path (colored red) and the adapted path (colored black) is shown. A resulting state of a re-run of the process simulation using the adapted path is shown, using the identical state shown in Fig. 11. By comparing the images, it can be determined that the resulting structures overlap and a possible path has been found.
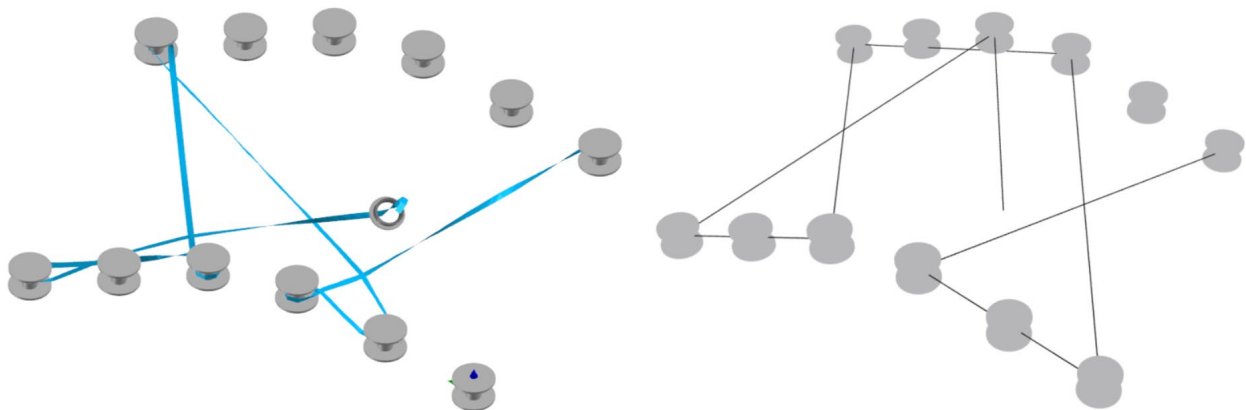

Fig. 11 State of the process simulation for the initial path without hooking at anchor (left) and expected lattice structure for state of process simulation (right).
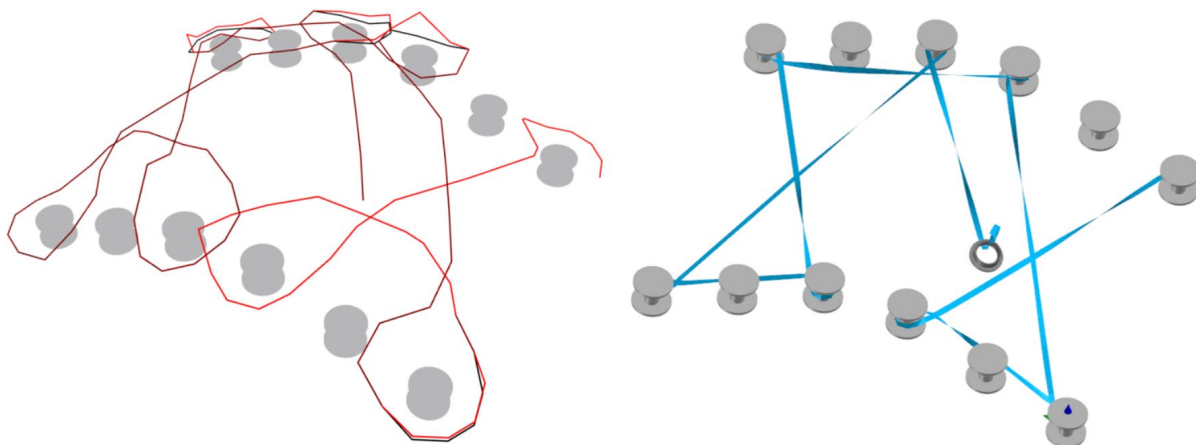
Fig. 12 Initial path (red) and adapted path (black) for the lattice structure (left) and resulting state of process simulation for the adapted path including

Simulation results showed that a variation in fibre tension induced by the path also affects the slippage of the fibres. During the process, the fibre interaction results in a deformation of the fibre structure itself. The undeformed state of that simulation is shown in Fig. 13 on the left, the deformed state is shown on the right.
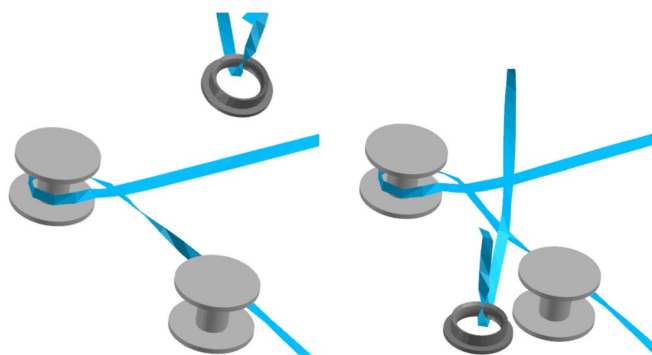

Fig. 13 Undeformed (left) and deformed state (right) of fibres of the lattice structure during two states of the winding process simulation.

Discussion

The proposed methods can be used to evaluate and manually adjust the winding syntax and manufacturing process for a coreless wound structure in a design phase prior to first physical manufacturing. Effects of a decrease and increase in fibre tension induced by the path resulting in a slippage or deformations of the fibres and thus influencing the final structures architecture/geometry can be evaluated. The predicted final architecture can be used for a subsequent structural simulation for a validation or adjustment of the initial design.

Using a manual visual approach, critical steps in the simulation can be recognized and the corresponding poses of the path planning can be adapted. After a rerun of the simulation using the adapted path the new results can be re-evaluated. This process can be iteratively repeated until a trajectory can be wound without collisions or non-successful hooking movements. Furthermore, previously non-detectable collision free space can be identified and used for a correction of the winding path. An example for this is a movement perpendicular to the anchor point orientation or the reference surface area in a space with high fibre density. Such an area is difficult to detect using only the design model or even during physical winding. The resulting trajectory can then be used for a

physical manufacturing of the structure. A path adaption might be necessary since fibre interaction during the process might result in a fibre behavior that might not be predictable out of the analytical model. Additionally there is a direct influence of the trajectory on the resulting fibre behavior. Furthermore, a layup of several fibre bundles or fibre twist can result in a thickening of the structure that can result in a collision of winding head and fibres. As a result, the intended trajectory for the TCP of a winding head can be evaluated regarding undesirable fibre behavior.

As a further development, a calibration for the process parameters and the structural models should be undertaken for different materials and fibre bundle types. The process induced compaction of the fibres that results in flattening and widening of the fibre cross section and thus has an effect on the final structure should be included into the simulation model.

In a subsequent step the path planning method has to be adapted with an automated approach for a collision avoidance using the initial or simulated fibrenet as a reference. Furthermore, the path planning should be directly coupled with the process simulation and a simulation of the robot kinematics in an automated approach to reduce manual adjustments.

Acknowledgements

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