Development of a Weaving Technology for the integral manufacturing oft thick-walled nodal structures for media transport

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Within the IGF project 01IF22946N ("Durchströmbare Rohrknoten"), the ITM conducted the complex structural and weave pattern development of a woven thick-walled T- and Y-shaped pipe joint for media transport based on the application of reversing warp yarns.

Introduction

Pipeline systems constitute essential functional components in numerous industrial applications, particularly in chemical plant engineering, mechanical and automotive engineering, as well as in energy and environmental technologies. In addition to straight pipe sections, branches in the form of T- and Y-shaped pipe joints represent safety-critical components whose structural integrity decisively determines the operational reliability of the overall system. Especially in pressure-loaded media lines, complex three-dimensional stress states arise in the transition zone between the main pipe and the branch, imposing stringent requirements on both material and structural design. While established manufacturing processes such as filament winding and centrifugal casting are available for straight fiber-reinforced composite (FRC) pipes, no integral and industrially scalable solutions currently exist for highly load-bearing, fiber-reinforced polymer (FRP) pipe joints for media transport. Fiber-reinforced polymers (FRP) offer significant potential for pipeline systems due to their low weight, high specific strength, and corrosion resistance.

Metallic pipe joints are typically manufactured by welding and are associated with high mass, susceptibility to corrosion, and mandatory inspections of weld seams. Although filament-wound composite solutions enable a higher pressure resistance, the fiber orientation in the branching region is not aligned with the principal load paths, resulting in structural overdimensioning and increased material consumption. Consequently, textile-based approaches with load-path-oriented structural design are particularly promising. In particular, the weaving technology developed at ITM enables the realization of structurally complex pipe joints through sophisticated weave architectures. However, the previously developed woven 3D node elements are, due to weave and technological constraints, internally separated and therefore unsuitable for media-conveying pipeline systems [1, 2]. This results in a fundamental conflict between integral textile manufacturing and the required flow capability of the components. Against this background, there was a substantial need for research aimed at developing a novel weaving technology incorporating a dedicated warp yarn reversal module, enabling for the first time the integral production of flow-through FRP pipe joints with load-path-optimized fiber architecture.

Objectives

The objective of the project was the development of a simulation-based process chain for the integral manufacturing of woven pipe joints for media transport up to the consolidated composite component for internally pressurized FRP pipeline systems. First, a structural-mechanical design was carried out based on macro- and mesoscopic finite element models. The aim was to determine the principal stress directions in the joint region and to derive a load-path-oriented fiber architecture, particularly within the branching zone. Based on the simulated, load-adapted fiber orientations, the complete and highly complex weave architectures of the three-dimensional pipe joints were developed.

A key technological innovation was the development and implementation of a modular add-on system for warp yarn reversal on Jacquard weaving machines. This system enables, for the first time, the controlled deflection of selected warp yarns at the fabric edge and thereby establishes the prerequisite for forming an open, flow-through branching region while simultaneously realizing a load-path-optimized reinforcement structure. Only through the implementation of the warp yarn reversal module, fiber trajectories can be aligned with the principal stress directions without structurally separating the internal cavity between the main pipe and the branch. Material overdimensioning in the branching region, that is typical of filament-wound pipe joints, was completely eliminated using this approach. Validation was carried out using three functional prototypes and a three-dimensional FRP demonstrator in the form of T- and Y-shaped pipe joints. The developed FRP pipe joints were successfully manufactured and demonstrated.

Results

Process chain for the manufacturing of woven FRP pipe joints

Integrally woven three-dimensional FRP pipe joints are based on tubular multilayer fabrics produced on a shuttle weaving machine equipped with at least four shuttles. A prerequisite for forming a tubular structure is a circumferential weft yarn insertion, i.e., a closed fabric edge, enabling a seamless pipe wall configuration. This structural feature can only be realized using shuttle weaving technology. The primary challenge in manufacturing pipe joints lies in combining a tubular structure with a branching geometry that features a continuous wall structure while maintaining an open internal cavity.

The pipe joint is initially produced in a two-dimensional state as a 2.5D woven structure. The transformation into the three-dimensional geometry is subsequently achieved by the targeted and automated removal of excess lengths of floating warp yarn within the fabric, causing the textile structure to deploy into the intended three-dimensional shape.

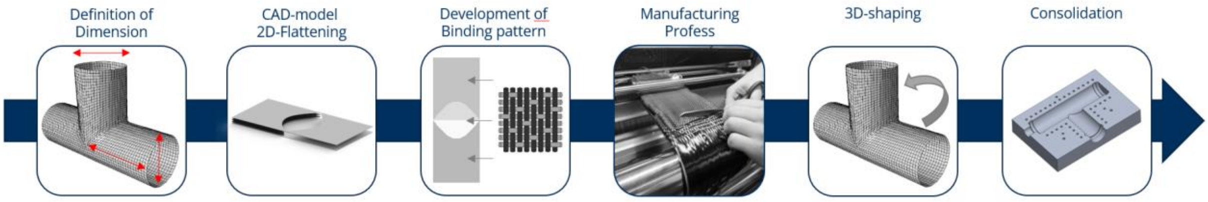

Figure 1: Process chain for the manufacturing of woven pipe joints

The complete manufacturing process (Figure 1) of an integrally woven pipe joint begins with the definition of the target geometry, including diameter, wall thickness, pipe lengths, and branching angle. Based on these parameters, a CAD model of the final geometry is created. The surfaces defined in the model are then flattened into the plane, taking into account the required layer architecture, in order to generate a colour-coded image from the developed surfaces.

Subsequently, an individual weave pattern is developed for each coloured area within this colour image. These partial weave patterns are combined into an overall weave pattern using weave design software (EAT DesignScope Victor). The corresponding machine control data are generated and transferred to the weaving machine. In the subsequent weaving process, the 2.5D preform is manufactured integrally according to the developed weave architecture. After completion of the weaving process, the textile preform is automatically shaped into the previously defined three-dimensional pipe joint geometry.

The final FRP component is produced by consolidating the preform using a resin transfer molding (RTM) process with a tool adapted to the outer diameter of the pipe joint. After demolding, the manufacturing process is completed by final trimming of the component.

Simulation-based design of pipe joints for media transport

The development of pipe joints for media transport requires a load-path-oriented design of the warp yarn systems. A boundary condition of the simulation was the arrangement of warp and weft yarn systems in such a way that no structural separation of the internal cavity between the main pipe and the branch occurs, thereby ensuring the flow capability of the pipe joint.

To this end, the stress distribution within the pipe joint geometry under internal pressure loading was first determined numerically. The highest stresses occur in the transition zone between the main pipe and the branch (Figure 2). This region therefore represents the governing design zone for the fiber architecture.

Based on the calculated stress distribution, a load-path-oriented architecture of the warp yarns was defined in order to fully exploit the tensile properties of the warp yarn material. This optimized warp yarn architecture forms the basis for the subsequent weave development of the pipe joints for media transport.

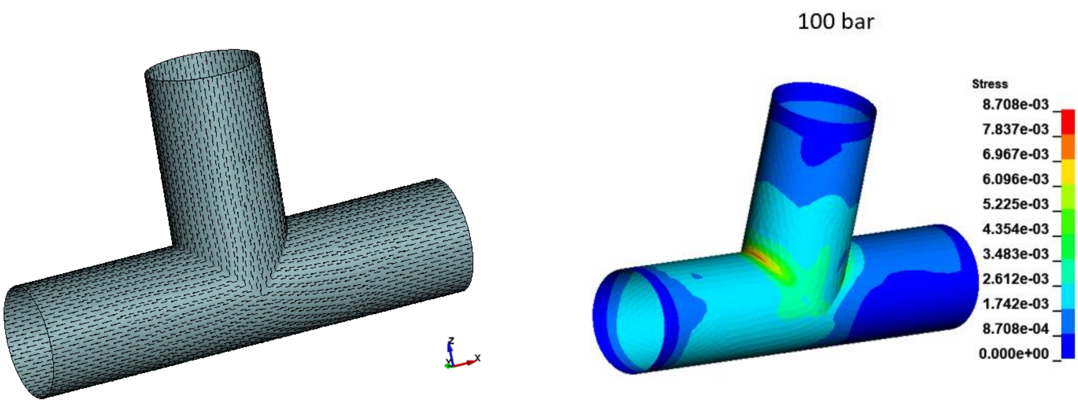

Figure 2: Ideal fiber orientation for woven t-shaped pipe joints (left); simulated stress distribution in the T-shaped pipe joint (right)

Development of Prototypes

The development of the weave architecture for an integrally woven pipe joint begins with a three-dimensional CAD model of the joint geometry. The simulated warp yarn systems and their trajectories are color-coded in Figure 3 (left).

Subsequently, the surfaces of the model are flattened into the plane and merged into a color-coded image. Each colored area represents a structurally induced modification within the woven architecture.

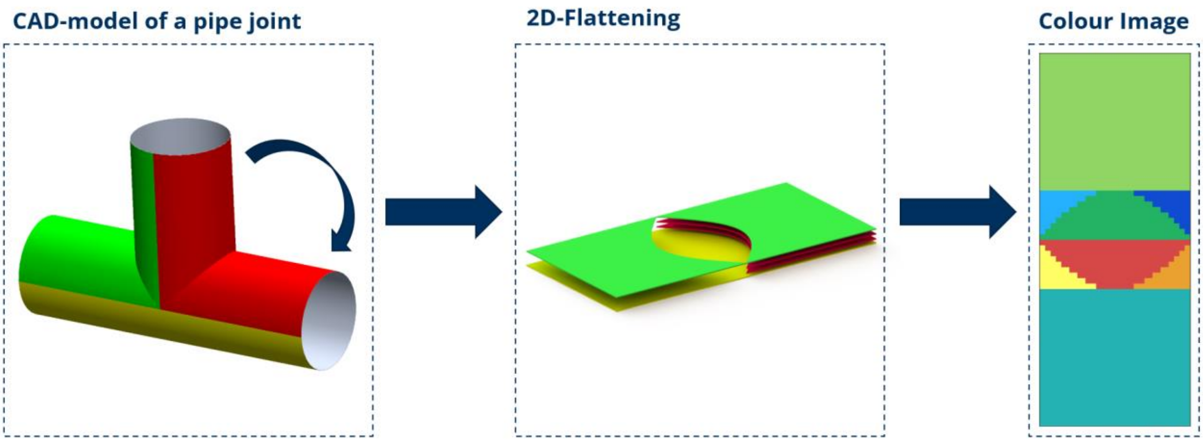

Figure 3: Determination of the warp yarn architecture and flattening of the pipe joint surface

For each color-coded area, individual weave patterns are developed and subsequently combined into a unified weave pattern of an integrally woven pipe joint for media transport using the software EAT DesignScope Victor. This integration is achieved through the coordinated control of the shuttles, the fabric take-up system, and the assignment of heddles.

Development of a Warp Yarn Reversal Module

The developed weave patterns were transferred to the shuttle weaving machine “Mageba SL RTEC1200/1” and manufactured using four shuttles. In order to realize the load-path-oriented warp yarn trajectories, an additional module for processing reversing warp yarns is required. This module was designed as a CAD model, taking into account the available installation space in the take-up area of the weaving machine, and subsequently integrated into the machine. The module can be implemented cost-effectively and is adaptable and retrofittable to other weaving machines.

The functional principle for processing reversing warp yarns is based on joining two predefined warp yarns prior to the start of fabric production, thereby forming a loop. The connection point is displaced from the weaving zone toward the creel to make sure it does not become part of the woven pipe joint to be produced. This procedure is repeated until all warp yarns designated for reversal in the two fabric layers are present as loops.

To apply a warp yarn tension comparable to that of the continuously running warp yarns, the loops are integrated into the fabric take-up system by means of the module. The warp yarn tensions of both yarn types were recorded and analyzed using a warp tension measuring device. Both the controlled fixation of the warp yarn loops and their integration into the fabric take-up system represent central functions of the developed warp yarn reversal module.

Application of the module and manufacturing of the prototypes

After the formation of the warp yarn loops, the textile preform is manufactured. In the first section of the pipe joint, the loop-forming warp yarns initially remain fully floating. Following the production of the oval branching region, these warp yarns are integrated into the structure in a regular manner.

From the oval region onward, the use of four shuttles becomes necessary in order to realize the superimposed tubular fabric layers in the second section of the pipe joint. Within the oval region, one shuttle inserts a separate weft yarn that supports the formation of the oval fabric edge. The manufactured textile preform is shown in Figure 4.

For the reproducible production of this highly complex weave architecture, uniform weft insertion is essential. In particular, during the fabrication of the oval region, the weft yarns must reverse within the fabric structure rather than being inserted across the full fabric width, as is typical in conventional weft insertion. The precision of this process step significantly influences both the quality of the three-dimensional pipe joint geometry and the quality of matrix infiltration during consolidation. The textile preforms were successfully manufactured (Figure 4).

Figure 4: Prototype manufacturing (left); in plane woven preform (center); proof of 3D-shape (right)

3D-shaping and consolidation of the woven prototypes

To transform the 2.5D preform into the three-dimensional structure, a dedicated 3D-shaping process developed specifically for pipe joints with flow capability is applied. A shape-defining internal core is inserted into the tubular structure, defining the target contour during the shaping process. The 3D-shaping is achieved by the targeted elimination of the excess warp yarn lengths introduced during the geometric flattening process. These excess lengths are withdrawn from the structure at the cut edge of the woven structure. A process-specific sequence to eliminate the floating warp yarns must be strictly followed in order to prevent material damage and to reproducibly achieve a precise warp yarn alignment after the shaping process. An automation concept for this shaping technology was developed.

Since the warp yarn loops in the first section of the fabric remain floating up to the edge of the oval region, the corresponding warp yarn excess lengths can be withdrawn. As a result, this warp yarn system is integrated into only one half of the woven structure within the pipe joint. After the preform has been shaped into its three-dimensional configuration, consolidation is carried out. An RTM tool specifically adapted to the contour of the flow-through pipe joint was designed and manufactured (Figure 5). The result after consolidation is a fully consolidated T-joint for media transport with high surface quality and reproducible geometric accuracy.

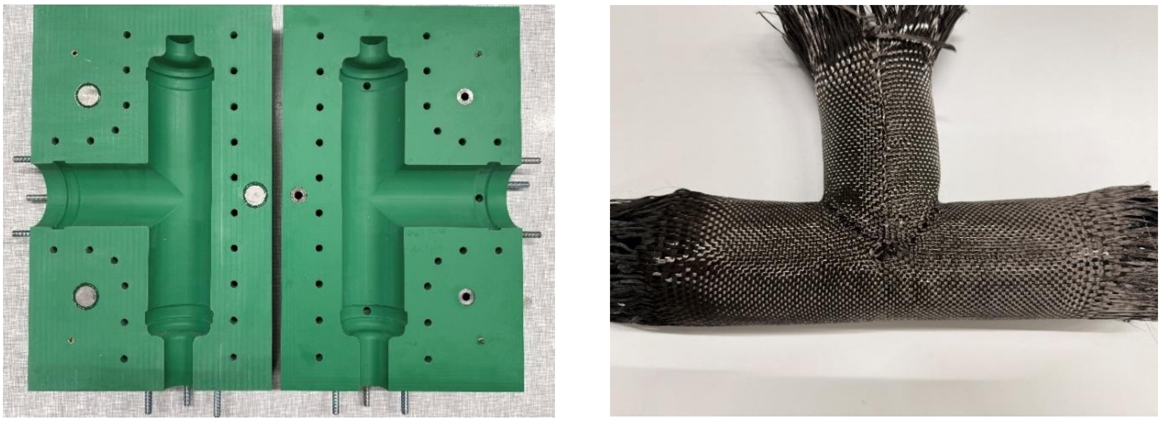

Figure 5: RTM tool for consolidation (left); shaped pipe joint (right)

The material overdimensioning in the branching region typical of filament-wound FRP pipe junctions was completely eliminated through the integral, fabric-based manufacturing approach employing reversing warp yarns.

Summary and Outlook

FRP pipe joints can, for the first time, be manufactured both integrally woven and flow-capable by means of an add-on module for existing shuttle weaving machines. The textile preform is produced in a single-stage weaving process. Following a 3D-shaping procedure specifically developed for the novel yarn architectures, the 2.5D preform can be consolidated into a load-bearing lightweight FRP pipe branch using established RTM processes.

The weave patterns developed, along with the underlying design methodology, can be made available to SMEs for industrial implementation. The geometry of the pipe joint (diameter, wall thickness, pipe lengths, and branching angle) can be individually adapted with minimal modification effort. In addition to T-joints, Y-shaped pipe joints can also be manufactured using the newly developed methodology and weave system, enabling application-specific realization of different topologies.

The results achieved within this project form the foundation for a scalable and load-path-optimized manufacturing technology for FRP pipe joints for media transport.

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