

Numerical Simulation of Joining Ropes by Sewing Stitches

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ABSTRACT Braided structures are widely used in numerous contexts including everyday practice. In most cases, rope ends are knotted to form various types of loops or tie them to rigid body parts; however, knots take up space that may not be available in some application scenarios, thus making them unsuitable for certain purposes. Hence, this paper introduces first development steps of a method for the numerical simulation of rope ends connected by sewing stitches.

KEYWORDS finite element method, rope, sewing stich, joint modelling

1. Introduction

Braided ropes are widely used in climbing sports as well as e.g. the transportation, building, marine sectors (1). In most cases, rope ends are knotted to form various types of loops or tie them to rigid body parts; however, knots take up space that may not be available in some application scenarios, thus making them unsuitable for certain purposes. Within past years, special sewing machines for the sewing of ropes with a diameter of up to 12 mm were developed. This paper introduces first development steps of a method for the numerical simulation of rope ends connected by sewing stitches. After verification, this method can be used for the optimization of rope seams and the modelling of tensile behaviour at connection areas.

2. State of the Art

The modelling of the mechanical behaviour of textile products requires in-depth knowledge of their 3D geometry. Because textile yarns are compressible, their cross section is deformed during the production process. However, this deformation cannot be considered when generating geometric models of textile structures. In order to solve this issue, different

approaches can be applied. Some researchers used Micro-CT images to create the geometry (2, 3) of textiles or composite reinforcements. This approach yields to a very precise geometrical representation, but unfortunately also requires expensive equipment and a physical object for investigation. Other authors simulated the braiding process in order to consider the load affecting yarns during formation (4). This approach involves long preparation and computational times and is therefore currently unsuitable for optimization purposes. An alternative, less accurate modelling approach generates textile structure geometries relatively quickly and is based on parametrical models, thus representing the structure topology (5). In this case, a generalized model of the yarn axis is obtained from the carrier motion process (6). There are several numerical simulations of ropes employing FEM (7) in addition to numerous analytical models (8, 9). In contrast, there are no known reports on the simulation of the mechanical behaviour of sewn joints. Therefore, the research presented in this paper focuses on this type of simulation; initial development steps will be introduced in the following sections.

3. Method

The preparations for modelling (pre-processing) were performed in several steps. In a first step, a tubular braid was generated with the help of a parametrical model (5), implemented via Software Braider (10). This software is implemented in C++ language, using the library *eigen* (11) for matrix computations, the library VTK (12) for 3D visualization and wxWidgets for the graphical user interface (13). Figure 1 represents the yarns of both tracks (with S- and Z-orientation) building each braid and the modelled sewing stitch of class 301 by means of the parametrical description of yarn axes (5). The final braid structure was then duplicated and the copy was translated to the new position. Next, they were integrated together with the sewing yarns prepared for test simulations, where the upper edges were displaced in the perpendicular direction to the braid axis.

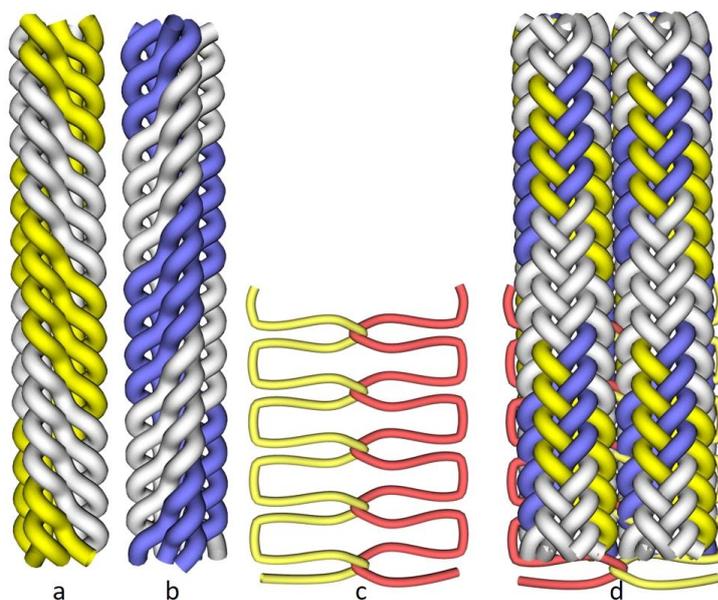


Figure 1: Components of braids joined by sewing:

- a) 3D model of the S-oriented yarn system of the rope,
- b) Z-yarn system of the rope,
- c) threads of the sewing stitch,
- d) two rope pieces joined by sewing, prepared for loading perpendicularly to the braid axis.

Another configuration was created based on an additional translation of the second rope in the vertical direction (Figure 2) so that tensile load can be applied to both ends.

In case of the first configuration as boundary condition, a constant horizontal displacement was applied to the upper edges (Figure 3a), whereas vertical displacement was applied to the second configuration (Figure 3b).

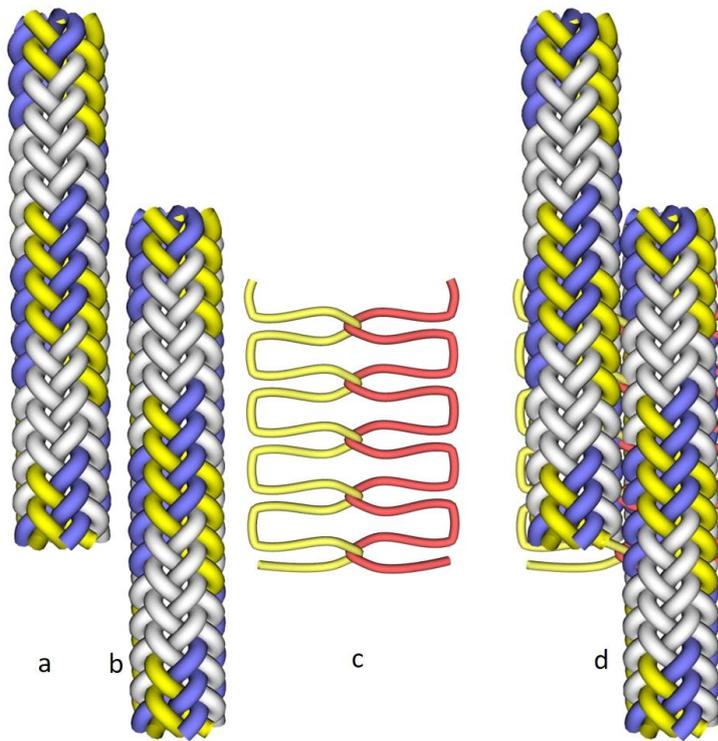


Figure 2: Components of stitched braid pieces for longitudinal loading:
a) modelled piece of rope,
b) copy of the rope, translated to the new position,
c) sewing threads,
d) complete model ready for FEM.

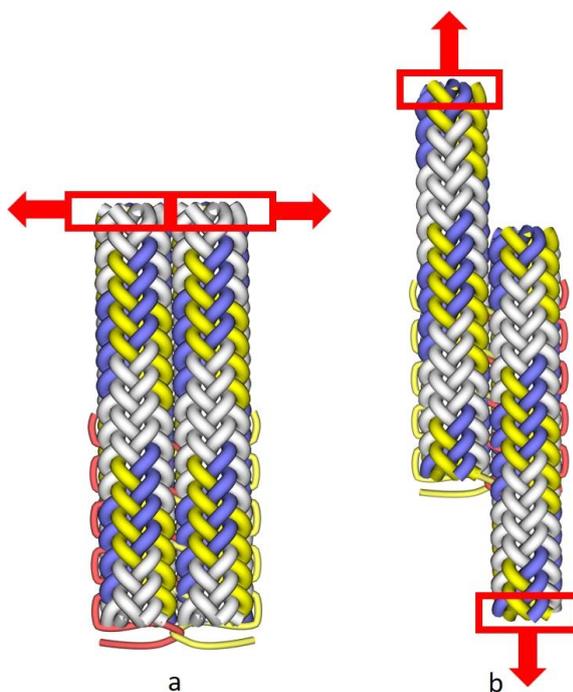


Figure 3: Load cases for the sewed joint:
(a) displacement, perpendicularly to the braid axis.
(b) displacement parallel to the braid axis.

The coordinate translations of single braids and sewed stitches were performed within the software TexMind Assembler, based on which the complete assembly geometry was exported as a beam based finite element mesh into LS-Dyna and Abaqus formats.

The finite element model was created in the software MSC.Marc 2019.0 (MSC.Software, Czech Republic) using the previously obtained geometrical data. The yarn diameter of the braids was 1 mm. The diameter of the sewing threads was 0.5mm. Two-node elastic beam elements were used for discretization. The material model fibres in yarn were elastic and isotropic. A Young's modulus of 100 MPa and a Poisson's ratio 0.3 were taken as ad hoc arbitrary values during initial testing. The parameters of the model can be easily changed so their exact values were not decisive for the current investigation, where the main modelling steps, exchange formats, and software procedure were tested.

The modelling of friction was simplified to an idealistic model. Between fibres, a segment-to-segment contact constraint with a Coulomb's friction model was defined:

$$\|F_t\| < \mu \sigma_n \text{ (stick) and } F_t = -\mu F_n t \text{ (slip)} \quad (1)$$

where F_t is a tangential friction force, F_n is a normal force, μ is a friction coefficient and t is the tangential vector in the direction of the relative velocity. The friction coefficient (μ) was a parameter achieving a value 0.3.

The following boundary conditions were applied:

Case 1

- Nodes corresponding to the lower end of braids and sewing threads are connected via rigid body links (RB) to another control node positioned below. This node is kinematically constrained so that it permits no displacement degree of freedom at three axes.
- Nodes corresponding to the left and right upper ends of braids are connected via rigid body links (RB) to another control node positioned farther left (right). This node is kinematically constrained so that it permits a displacement degree of freedom at three axes. The rigid movement of 15 mm (-15) in the horizontal axis is described to the control node, thus achieving the pull out of selected fibres.

Case 2

- Nodes corresponding to the lower right end of braids are connected via rigid body links (RB) to another control node positioned below. This node is kinematically constrained so that it permits no displacement degree of freedom at three axes.
- Nodes corresponding to the upper right end of braids are connected via rigid body links (RB) to another control node positioned farther up. This node is kinematically constrained so that it permits a displacement degree of freedom at three axes. The rigid movement of 10 mm in the vertical axis is described to the control node, thus achieving the pull out of selected fibres.

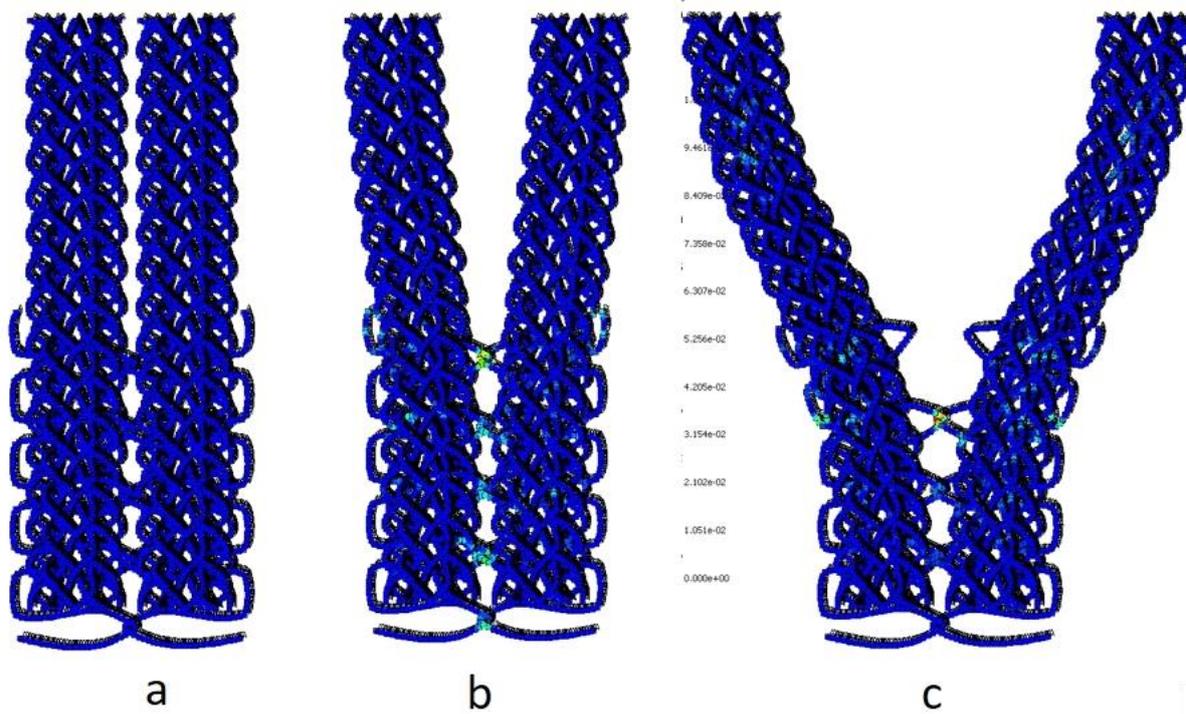


Figure 4: Stages of simulated joints during loading perpendicularly to the braid axis opening a) initial state with FEM beams, b) opening of one diameter, c) advanced state, where the sewing yarn interlacement lost its topologically correct state

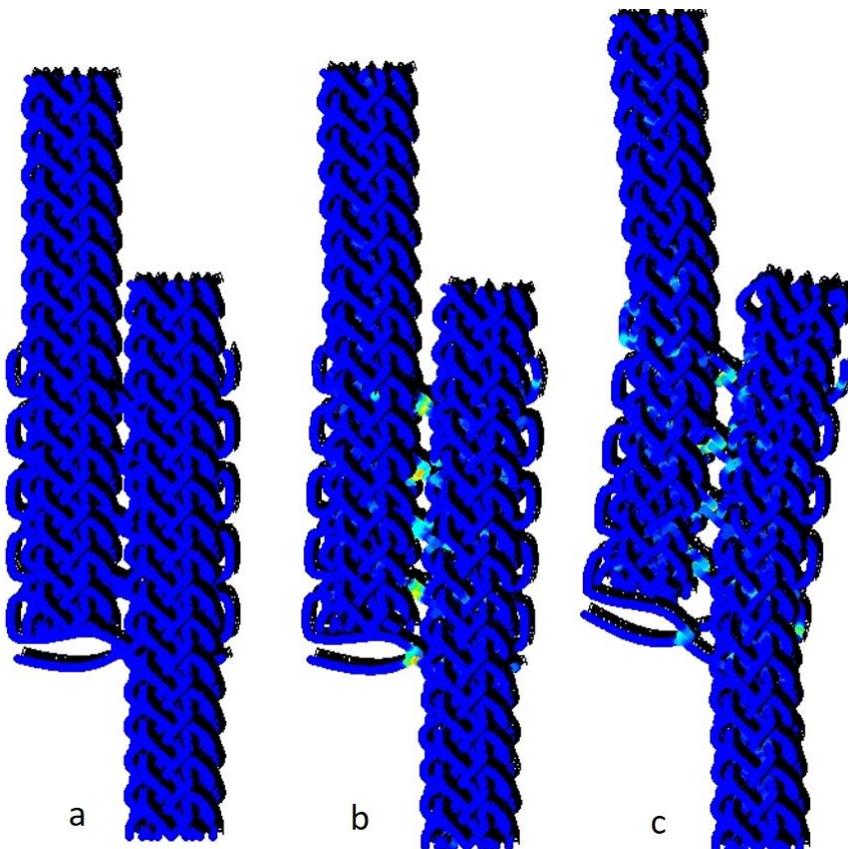


Figure 5: Stages of loading in the longitudinal direction a) initial mesh, b) and c) states after several time steps

4. Results

Figure 4 presents the initial configuration, the configuration after opening of the upper ends at one rope diameter (b) and after opening at four rope diameters (c). At the initial time steps, the majority of load acts on parts of the sewing yarns and the braids. In case (c), it was observed that the contact between the first stitches was interrupted, however the yarn still remained complete. This is due to a numerical error of the contact detection algorithm and demonstrates that in case of higher yarn tension, the settings for penalty stiffness's and time increments must be adjusted.

Figure 5 presents several simulation stages with axial loading of the sewed position. The loading acting on the sewing yarn increases significantly; also, in this case, a minor lateral motion of the braid yarns can be detected as well.

5. Discussion

The use of parametric models for braids and stitches enabled the creation of a FEM model for the loading behaviour simulation of sewed joints. The first load case demonstrated that at higher tensions, the contact algorithms in the currently used software Marc-Mentat do not provide a stable topology so that yarn contact may be interrupted. In terms of future investigations, this problem must be carefully evaluated, for example by manual setting trials using smaller time increments and reduced contact stiffness. If the software does not allow for stable computation, solid models may be used instead of efficient beam models. Solid models can be created based on the same principles used for beam models, however special attention must be paid to the intersection between elements.

6. Conclusion

This paper introduced a method for the efficient simulation of loading acting on ropes that are connected via sewing stitches, modelled using beam elements. At low loads, the simulation is stable; for higher loads, however, the contact between beams was interrupted. If a solution to this problem can be found, this method can provide an efficient option for the optimization of rope seams.

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