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Development of a parametric CAD model for braided ropes

Master's thesis in Product and System Design

Supervisor: Henry Piehl

June 2019

NTNU
Norwegian University of Science and Technology
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“No one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art.”

- Henry Petroski -

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Abstract

Braiding has been around for centuries and is most commonly known in the form of hair plaiting. Today twisted- and braided ropes and structures have a wide range of applications. From shoelaces and jewelry in the textile industry, to stents for medical applications, reinforcement of components in the aerospace industry and ropes for marine applications, such as fishing gear, mooring lines and ropes for heavy lifting. The motivation for this thesis is from Reidar André Skarbøvik's Ph.D., where he is investigating how synthetic fiber ropes affects the integrity of the winch drum with multilayer spooling. These forces varied from forces generated by traditional steel wires and formed the basis for this research. There is a need for smart ways to calculate and understand the properties and behavior of the rope. The objective is to contribute in this field by developing a parametric CAD model of a braided rope using Siemens NX; intended for structural strength analysis using the finite element method. Two main models are made, twisted rope and braided rope, with different configurations. The mathematical description of the twisting pattern is described as a helical curve, and the equations for a helix is used as a basis to create a model of a twisted rope with multiple layers. The braiding pattern was best described with the rose curve equations. The generalized rose curve equation was used to develop a successful CAD model of a diamond braid. During the modeling process, it was discovered limitations in the software, that prevented further modeling with other patterns. To show an application for the model and to investigate the suitability of a commercial multi-purpose software like Siemens NX, a finite element analysis was performed on a simple case with two strands twisted together. Due to the rope's properties and behavior, a non-linear steady solver is used and to create contact between the strands a contact-to-contact simulation.

During this research, it was concluded that the software, Siemens NX, is not suited for this type of parametric models and finite element analysis on multi-strand ropes. Even though a model of a diamond braid was successfully made, and an analysis of a simple rope gave results. For further work, it is advised to investigate if there is any other way of implementing the needed equations in Siemens NX or the possibility of using a numerical computing program for the mathematical description of the curve combined with 3D modeling in Siemens NX. The main recommendation is to use special software for the finite element analysis intended for such structures, and look more into the work done by (Ning, Potluri, Yu, & Hearle, 2017) on their models of braided ropes. It is unknown of the reusability of their models and their modeling approach, but they manage to make models of different types of braids using SolidWorks.

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Preface

Before you lies many hours of pondering and work, writing and rewriting, good days and bad days. After all this, it can now be presented as my final thesis to complete my MSc degree in Product- and System Design at The Norwegian University of Science and Technology (NTNU) Aalesund.

This thesis is written during the spring of 2019 with the supervision of Associated Professor Henry Piehl, Department of Ocean Operations and Civil Engineering at NTNU. The thesis aims to contribute to the field of strength analysis of synthetic fiber ropes used in offshore applications by developing a parametric CAD model of a braided rope using Siemens NX.

I want to express my sincere gratitude to my supervisor Professor Henry Piehl for all the help and support during this thesis. Thanks to his extensive knowledge

I would also like to thank my husband, Kristoffer Rødal, for his patience and support through these years, and making it possible for me to peruse my interests and an MSc at NTNU.

Aalesund, June 11, 2019



Bodil Rødal

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Nomenclature

Abbreviations

CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
DOF	Degrees of Freedom
FEA	Finite Element Analysis
FEM	Finite element method
Siemens NX	Commercial CAD/CAM/CAE software
NTNU	Norwegian University of Science and Technology

Symbols

A	The amplitude of rose curve petals
a	The major axis of an ellipse in the rose curve equation
α	Half central angle
b	The minor axis of an ellipse in the rose curve equation
β	Contact point angle
C	Rope center
c	constant
C_d	Diameter center strand
clt	Length of center strand
D_s	Diameter strand
H	The total height of the helix
L	Lead
λ	Lambda direction of rotation of lay
N	Number of strands
\vec{n}	Contact point normal
O	Origin of the coordinate system
φ	Phase difference
R	Radius of central circle in a rose curve
r	Radius of helix
r_1	Minor radius of ellipse (Strand radius)
r_2	The major radius of the ellipse
r_3	Radius from the center to the point of tangency
T_n	Number of turns/loops
t	Dimensionless time variable
\vec{t}	Contact point normal
θ	Lead angle
X	Strand-to-strand contact point

1 Introduction

1.1 Background

Braided fiber ropes are more and more common in offshore operations, due to their high strength, good mechanical properties and, most important of all, neutral buoyancy. In deep-sea lifts, the weight of a steel wire will increase with the depth, and at one point the weight of the steel wire reaches the safe working load of the crane, leaving it with no payload left. Using braided fiber ropes, the same crane can lift almost its full safe working load in any depth because the rope is naturally buoyant.

Steel wires have been used for decades and the behavior well documented through all these years. Classification societies like DNV-GL have good knowledge and regulations for the use of steel wires. Even though braided ropes are nothing new, its first in the last years it has been used in offshore operations. Fiber ropes behave differently than steel wires, and even though the strength in the rope is known, there are still many unknown factors involved. For instance, when the fiber rope is spooled in multiple layers on a winch with tension, it creates forces and stresses different from spooling with steel wires. The rope also cuts into the previous layer, making the spooling of the next layer difficult. The fiber rope is more ductile than the steel wire and in multi-layer spooling the rope is being pressed flat which changes the cross-section of the rope, from round to more rectangular shape. The winch drums used today are designed for steel wires, and there is a need for new designs on the equipment and more knowledge about forces created from fiber ropes. To develop new equipment that can handle these forces, a good understanding of the ropes behavior is essential.

1.2 Motivation

The motivation for this thesis is from Reidar André Skrabøvik's Ph.D., where he investigates how synthetic fiber ropes affect the structural integrity of the winch drum with multilayer spooling. To get a better understanding of the rope's behavior, the finite element method (FEM) can be used to perform analysis of ropes, and how the strands affect each other. Having good computer-aided design (CAD) models is vital for the finite element analysis (FEA). A poor geometry can set limits for the mesh, and boundary conditions in the processing of the analysis, the quality of the mesh decides whether the results are accurate or not. Making CAD models of complex geometry are consuming both time and resources. By creating a parametric model where variables like the number of strands, thickness, and braid angle can be changed, the threshold of analyzing braided ropes can be lowered and contribute to more research on the field. Braided ropes and structures have a diversity of applications and can contribute to stronger structures and lower manufacturing cost. Braided structures are used in the industry today, but because of little research and knowledge, the use is scarce (J.P., et al., 2016). Although

braided ropes are widely used and are utilized more and more frequently in heavy industrial and offshore applications (Pasternak, Shelton, & Gilmore, 2011). This growing use of braided fiber ropes has led to an increased need for extensive knowledge of the properties and behavior of the rope. By understanding the force profile given from the rope, components like the winch drum can be redesigned.

1.3 Objectives and research questions

The objectives in this thesis are to use computer-aided design to make a parametric model of a braided rope. This model is intended for analyses using the finite element method to get more knowledge about the forces acting in the rope under different conditions. Different thicknesses, braid angle, and the number of strands can be applied to the model before performing the analysis with different loads and constraints. The main software used is Siemens NX, which is commercial multi-purpose software, where the CAD model can be made, and the finite element analysis can be performed.

1.3.1 Research questions

Research question 1:

What is the design parameter of a braided rope, and how can they be used to define a parametric 3D CAD model?

Research question 2:

How can the mechanical motion of a 'maypole braiding machine' be formulated in terms of a spatial curve for a rope strand, and how can this curve be implemented in a CAD modeling algorithm?

Research question 3:

Does the modeling procedure generate realistic inter-strand contact conditions? Can the rope CAD model be used in a finite element analysis to study the tensile and transverse strength of different rope configurations?

1.4 Scope and limitations

The scope of this thesis is between the topics braided structures, computer-aided design, and finite element method, as illustrated in Figure 1.1. Where a parametric CAD model will be developed using commercial CAD software intended for further strength analysis using FEM.

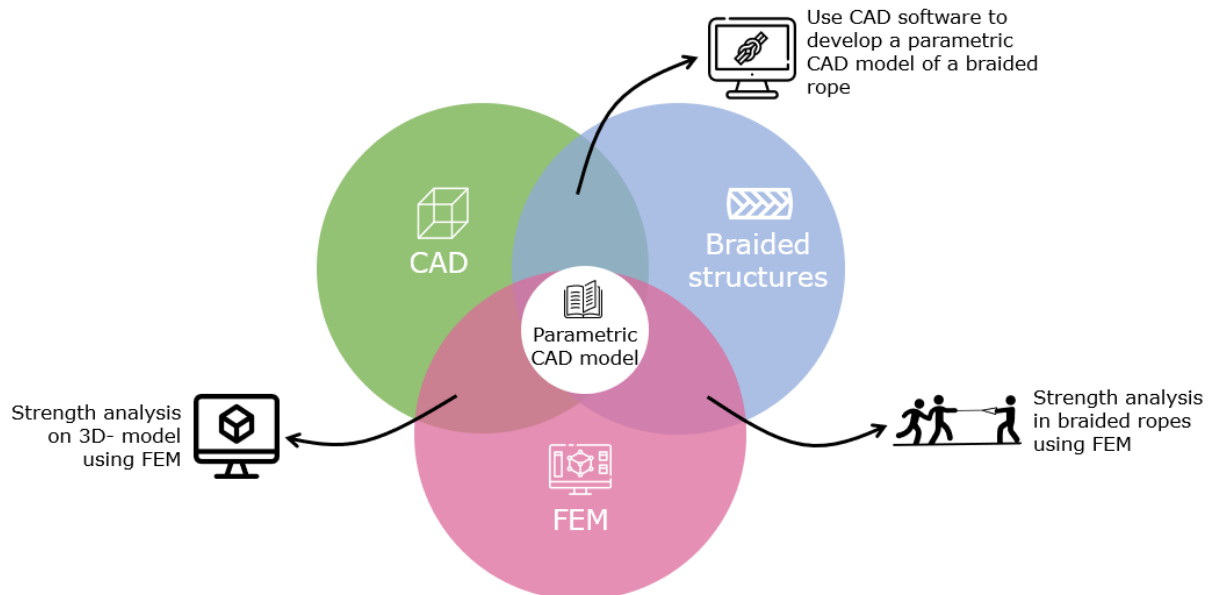


Figure 1.1 Scope of the thesis

Computer-aided design has a wide specter of applications, and there are many different approaches when modeling in 2D or 3D. Direct modeling is the most common approach. In this thesis, it will be focused on making a parametric model, where variables like the number of strands, the thickness of strands and braid angle can easily be altered. The modeling methodology is essential for the final quality of the model, and the possibilities in Siemens NX needs to be investigated to find a good approach.

Braiding is used in different applications and can be made in many different and complex structures. This parametric model will be confined to braided ropes used for offshore operations. But as the braiding pattern might be equal to ropes for other applications, it can be adapted to other industries.

The purpose of the CAD model is to perform analyses using the finite element method in Siemens NX and to verify that the model is applicable a finite element analysis will be performed, using a contact simulation with a non-linear static solver. All modeling and simulation will be performed in Siemens NX, and MATLAB will be used for help and verification during the process.

2 Literature research

2.1 Parametric CAD model

The term CAD denotes the use of computers to create 2D or 3D designs models. CAD has many applications; it is used in architecture, product design, civil engineering, and simulation modeling. Using CAD, complex 3D products and animations, and detailed 2D drawings can be made (Techterms, 2018). The CAD software is common in engineering, and the majority of the design information is stored digitally within the CAD models. This makes the CAD model the main data source used by the stakeholders and is a central point of the development process. Due to all the information stored in the CAD model, design reusability is dependent on CAD reusability. By reusability in CAD, one means how the model can be changed with minimum effort to make it suitable for other applications. This can be simple or impossible depending modeling procedure chosen by the original creator. To deal with this, parametric models can be made. In parametric models, the geometry is controlled by non-geometric features called parameters, which can be defined by dimensional, geometric, or algebraic constraints. By editing the values, for instance, dimensions, the model will change and all its adjacent features accordingly. Today's most common parametric CAD is dominated by the history-driven approach, where all features in the model are connected hierarchically called a design tree. This creates a network structure where every node represents a feature, and every connection represents a dependency between two features. (Camba, Contero, & Company, 2016)

"The adaptable nature of the design tree allows CAD users to quickly model complex parts with relative ease while increasing the flexibility and reusability of their designs." (Camba, Contero, & Company, 2016)

When the dependencies are proper defined, the CAD-model will react to changes in a predictable manner, but this is also the root of many problems when regenerating the model. In large complex models, there are a lot of feature dependencies when these are not properly defined, even minor alterations can cause the model to be unstable. This makes the model useless for the new application, and the designer needs to use more time altering the model. If a parametric model is not correct, and the designer must use the time to alter it, the intent of the model is not fulfilled. Given this, it is essential to make good parametric models and select a well-thought modeling methodology to ensure that the parameters can be changed without altering the structure in the model. Many of these methods are developed internally in companies and are kept secret or patented because it may lead to competitive advantages for organizations. As a result, there are little scientific research published about effective parametric CAD modeling methodologies. The three major modeling methodologies used today are horizontal-, explicit reference-, and resilient-modeling. Each has different advantages and challenges (Camba, Contero, & Company, 2016).

Camba did experiments on these three models in (2016). Multiple parts were modelled with the three different modeling methodologies. The models were given to groups of

engineering students given 20 min to perform several model alterations. They discovered that horizontal modeling requires the creation of numbers of datum planes before creating solid bodies, which is a time-consuming process. Regeneration problems are rare using horizontal modeling, but the logic of the modeling process may not be intuitive, especially for novice designers.

From a reusability standpoint, our experiments show that horizontal modeling is prone to modeling errors when users are not entirely familiar with the CAD model and its modeling intent. The fact that no regeneration errors occur when a feature is changed (errors do occur, but many go unnoticed because the application does not return any error messages) may lead designers to falsely believe the part is correct without paying attention to collateral effects. This was by far the most common problem our participants experienced while performing the assigned tasks with the horizontal models (Camba et al., 2016)

The explicit reference modeling makes the designer able to change each function without affecting other functions. But (Camba et al.) discovered that some of the problems of the horizontal modeling could be inherited by the explicit reference strategy. Dependent features may not be updated as expected when functional elements are not clear or certain features overlap.

“Nevertheless, our results show a significant improvement of this methodology in terms of alteration time over the horizontal strategy.”(Camba et al., 2016)

During this study, it was found that the resilient modeling strategy was easy to use and well structured. The participants found the approach effective in terms of model quality, alterations time, and reusability.

2.1.1 Commercial CAD software

Siemens NX is a commercial multi-purpose software for CAE and CAD. Siemens NX allows one to create 3D models, 2D technical drawings, rendered pictures, motion simulation, animations and strength analysis using FEM.

In Siemens NX, expressions dialog can be used to control relationships between the features of a part or between parts in an assembly. All features that are made are listed in the expressions dialog, and one can go in and alter the numbers, make new relationships, give them names, divide them into groups, and make new expressions. Instead of going into each sketch of your model, one can go into the expressions dialog and change the parameters and dependencies, and the model will update. The expressions menu contains various functions, operators, numbers, symbols, and variables that can help make the model (Siemens, 2017). Figure 2.1 and Figure 2.2 show an example of a box that is driven by expressions where length and depth are dependent on the width. A list of options is made for selecting width.

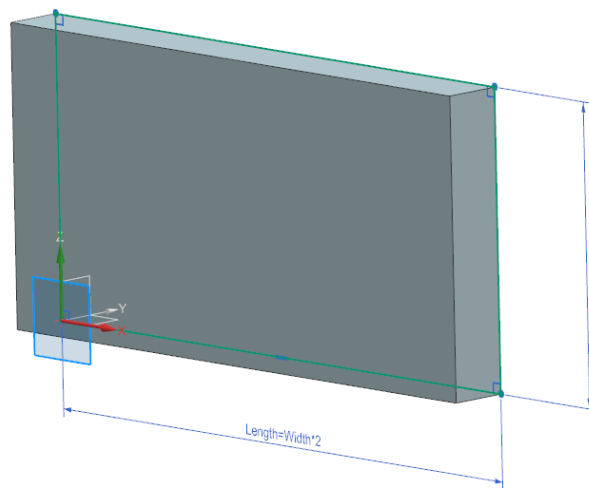


Figure 2.1 Example of a CAD model of a simple box using expressions

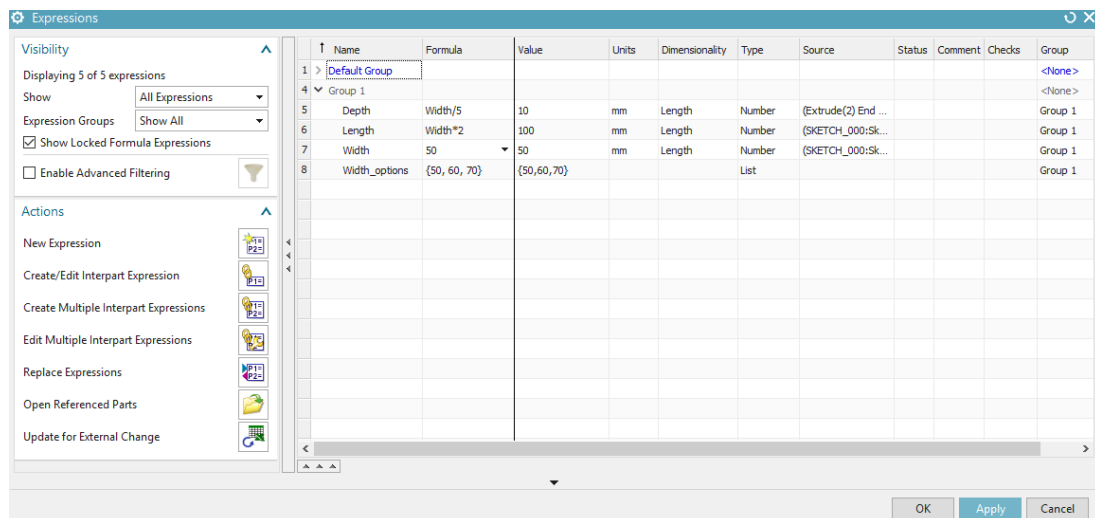


Figure 2.2 Expressions dialog for CAD model of a simple box

Table 2-1 Expressions syntax operators

Name	Operator
Addition	+
Subtraction and negative sign	-
Multiplication	*
Division	/
Modulus	%
Exponential	^
Assignment	=
Greater than	>
Less than	<
Greater than or equal	>=
Less than or equal	<=
Equal	==
Not equal	!=
Negate	!
Logical AND	& or &&
Logical OR	or

Table 2-1 shows the mathematical operators available in the expressions dialog; these can be used to create formulas. As seen in figure Figure 2.2, the expressions dialog is like a spreadsheet with a column for the different features. They will give valuable information in the model and are essential for making expressions and dependencies in the model. Table 2-3 explains each column, what choices one has in each, and how to use them. When modeling in Siemens NX, it is essential to know that it is a history driven approach, where each feature added will have a time stamp that tells when the feature was created. For instance, if one created a circle in the plane and then extruded it into space to make a cylinder, the sketch will have timestamp (1), and the extrude function timestamp (2). The extrude is dependent on the sketch, and the order can not be changed, or if the first feature is deleted or altered, it will affect the next. Not all features will be dependent on the previous, but it is important to keep in mind to avoid problems. It is also a good way of spotting the right feature in the expressions dialog when making expressions and dependencies.

In this thesis, equations used will be entered in the expressions dialog for modeling in Siemens NX. Equation 2.1 and Table 2-2 demonstrates how the syntax from the equation will be displayed in the next chapters. This syntax can be entered directly in Siemens NX.

$$x(t) = r \cos(t)$$

2.1**Table 2-2 Example. Syntax to enter in Siemens NX from equation 2.1**

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
turn_number	1	Unitless
r	5	Length
xt	r*cos(t*360*turn_number)	Lenght

Table 2-3 Explanation of different options in the expressions dialog (Siemens, 2017)

Name	Give the expression a name. Expressions made by NX are automatically given the name p followed by the number of the feature but can be changed.									
Formula	Enter functions, numbers, or measurements. Other expressions can be included using their name.									
Value	The calculated value of the formula entered									
Units	Choose the unit for the value									
Dimensionality	Specify the kind of dimension to use for the expression. Common ones in modeling are, constant, length, area, and angle. It is important that your units match. For example, if two lengths are multiplied the new dimension is area. Otherwise one gets a unit inconsistency error.									
Type	<p>Specifies the expression data type.</p> <p>Number Creates expression using numeric data type</p> <p>String Creates expression using string data type. It represents text and not numbers.</p> <p>Boolean Creates an expression to support alternate logical states using values of "true" and "false"</p> <p>Integer Creates an expression using numerical counts without units</p> <p>Point Creates an expression by defining a position using X, Y, and Z dimensions. Point(0,0,0)</p> <p>Vector Creates an expression by defining a direction using cartesian I, J and K coordinates. Vector(0,0,0)</p> <p>List Creating a list in the expressions containing a drop-down menu with selections.</p> <table border="1"> <thead> <tr> <th>NAME</th> <th>FORMULA</th> <th>TYPE</th> </tr> </thead> <tbody> <tr> <td>Name_options</td> <td>{1, 2, 3}</td> <td>List</td> </tr> <tr> <td>Name</td> <td>(drop-down list)</td> <td>Number</td> </tr> </tbody> </table>	NAME	FORMULA	TYPE	Name_options	{1, 2, 3}	List	Name	(drop-down list)	Number
NAME	FORMULA	TYPE								
Name_options	{1, 2, 3}	List								
Name	(drop-down list)	Number								
Source	<p>For expressions made by NX. Identifies the feature associated with the expression.</p> <p>(SIMPLE_HOLE(4) Diameter)</p> <p>Represents the diameter of a simple hole feature with time stamp 4</p>									
Status	Tells if the expression is up to date, out of date, failed to update or interpart expression is broken									
Comment	Comment on the expression									
Checks	Shows any check requirements									
Group	Select a group for the expression									

2.2 Braided ropes and structures

Ropes have been around for centuries and have been manufactured for over two thousand years, first using plant-fibers until the invention of synthetic fibers like nylon and polyester (Weller, Johanning, Davies, & Banfield, 2015). Today the use of twisted or braided ropes are wide. It is used in climbing equipment, sailing boats and mooring. Recent years, ropes with higher breaking force have been made and used in offshore and marine applications. Nylon ropes were first used in the 1950s for towing, and later in the '80s testing of aramid mooring ropes for offshore applications was initiated (Corbetta & Sloan, 2001). Fiber ropes are chosen for offshore application mainly because of their great mechanical properties, natural bounciness, and the ability to absorb energy during cyclic loading, which is important in case of rapidly applied snatch loads. (Weller, Johanning, Davies, & Banfield, 2015).

Davies did in (2011) mechanical test on two types of synthetic fiber ropes most used for deep sea handling operations. The two fibers tested was one specific grade of aramid copolymer from Technora and one specific grade of high modulus polyethylene (HMPE) from Dyneema. As the fibers are twisted and braided, it leads to a reduction in properties; therefore, the fiber properties cannot be used directly to design ropes. By analyzing the fiber properties along with the rope geometry, the properties can be given, but they still need experimental validation for different constructions. From experimental testing in the laboratory and at sea from a research vessel, they got the following findings:

The aramid rope stiffness is less sensitive to bedding-in and shows lower permanent residual strains. It also creeps less. The HMPE rope is lighter, and stiffer after bedding-in with higher damping. Resistance to cyclic loading on sheaves is superior for dry aramid but experience from tests on soaked aramid and in-service experience suggests that wet fatigue behavior of aramid is not as good as that of wet HMPE. Measurements of apparent stiffness at sea appear consistent with laboratory values but loading history and in particular the maximum load seen previously by the rope determine the apparent stiffness. (Davies, Reaud, Dussud, & Woerther, 2011)

Braiding is most commonly seen in ropes, but it has a versatile use and is found in, for instance, high-pressure hoses, aerospace- and medical engineering. By adding multiple horn-gears in the Maypole braiding machine and arranging them in specific patterns, they can create complex structures. Braiding is a rapid process, and during the braiding, the cross-section and pattern can be changed without interrupting the process, making new structures. There is no secret that braiding can give components with great strength. Braided structures also have high resistance to delamination in relation to other laminated composites and provide high notch resistance due to the strand interlacing (J.P., et al., 2016, s. 181). The versatility of the design and manufacturing and the elastic and mechanical properties is one of the most important advantages using braiding, and it can be adaptable to most applications (J.P., et al., 2016, s. 180).

One of these applications is in aerospace. Figure 2.3 shows braiding being used by Airbus to manufacture aircraft components, but their use is still in its infancy. So far, the findings indicate that the behavior of braided composites often remains unpredictable and thus cannot be used widely in the aerospace industry. There is still a lot to assess

when it comes to structural behavior. But compared to other composite materials, the performance of braided structures is very good. The Finite element method is the most applicable tool for analyzing textile materials in two or three dimensions and gives very good strength predictions. But the models can be complex and take years to develop. Other behaviors in braided composites that desperately needs attention are fatigue. Fatigue in braided composites is affected by high-stress concentrations and especially for those with high undulation angles. Using numerical methods, the stress can be assessed in each strand and the overall structure. There are some challenges using braided composites but as Carey so well put it: "Further development and use of fully validated predictive models will greatly aid in increasing braided composite use in the aerospace field" (J.P., et al., 2016, ss. 175-212)



Figure 2.3 Braiding of aircraft component for Airbus (Airbus, 2017)

As the weight is an important factor in the aerospace industry composite materials are often used. Carbon fiber is preferred, not only for its light weight but also because it is stiff and strong. Carbon fiber must be reinforced with matrices like polymers, metals, or ceramics to be functional (J.P., et al., 2016, ss. 181-182).

The components in aerospace can be quite large, and when using braiding, producing large parts can be costly and impractical. Therefore, techniques for joining braided parts with traditionally manufactured parts are explored. Rivets and connection holes can be created during the production with proper planning.

(Gause & Alper, 1987) showed that tensile strength did not decrease with an open hole in the structure; it was found that bearing and transverse strength, as well as transverse stiffness properties were lower than those of traditional laminated composites. (J.P., et al., 2016, s. 204)

Even though there are challenges using braided composites and the use is not that common yet, there are components made today. Two-dimensional braiding is used to reinforce aircraft ducts, fuselage J frames, and helicopter rotor blade spars. There has also successfully been made three-dimensional components such as C- J and T-section

panels, but only for demonstration purpose. In an article written by Thuis in (2014) he explains how they manufactured a composite trailing arm for helicopter landing gear. The conclusion was that using braided composites for the landing gear components are a feasible cost-effective alternative for steel and should be further assessed for use in the next generation of aircraft.

A&P technology produces several components for aircrafts using braiding as a manufacturing technique. Using a layer of aramid braid followed by an overlay of carbon fiber braid the Honeywell jet engine stator vanes were produced. They also produce wing flaps for Bombardier with braided reinforcement. For a low-emission jet engine being developed for the Boeing 787 aircraft, the fan case is produced by A&P Technology using an isotropic-behavior braid pattern. This provides better impact and fatigue properties than other materials and will reduce the manufacturing time. (J.P., et al., 2016)

2.2.1 The maypole braiding machine and different braiding patterns

Several methods for machine braiding have been developed over the years, and the maypole braiding machine is the most common. It can be used manually with weights pulling the braid down as a person braids and in industrialized machines. The industrialized maypole braiding machine consists of multiple horn gears with tracks that hold carriers. In the carrier, bobbins are mounted which holds the yarn and keeps the yarn tension. The carrier with the yarn will be moved from gear to gear in a pattern depending on how the horn gears and tracks are arranged. The carriers can move in both directions creating different patterns, see Figure 2.4. These machines can create a variety of patterns which can be divided into two categories, flat and tubular braids.

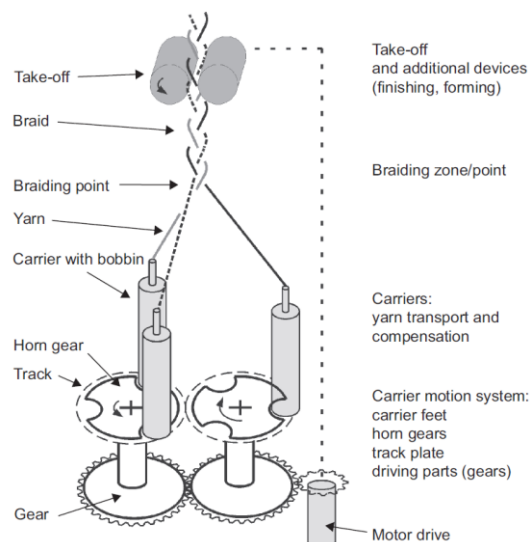


Figure 2.4 Basic principle of the Maypole braiding machine (Kyosev, 2015, s. 116)

Flat braids have a front and a back and can be represented in 2D drawings. The horn gears are arranged in a line. A flat braid can be made of minimum three yarns, using two gears with three carriers, Figure 2.4. But can also be made of multiple yarns to create wider braids with different patterns. This type is mostly seen in the textile industry, used to make bracelets, shoelaces, etc. (Kyosev, 2015, ss. 47-61).

The second category is tubular braids. Tubular braids are used to make ropes, but also to create three-dimensional objects like the braiding of components for the aerospace industry. Tubular braids can also be represented in 2D drawings, but then only half the side is visible. In difference to flat braids the horn gears are arranged circularly. This is showed in Figure 2.5, where the carriers will alternate around the circle of gears, making a flower pattern. The most common braiding patterns are known as Diamond braid, Regular braid, and Hercules braid.

Diamond braid is where each strand passes alternately over and under one of the other, and the floating length is 1, Figure 2.6a. A regular braid is when a strand passes alternately over and under two other strands with floating length 2, Figure 2.6b. Hercules braid is when one strand passes alternately over and under three strands, Figure 2.6c (Kyosev, 2015).

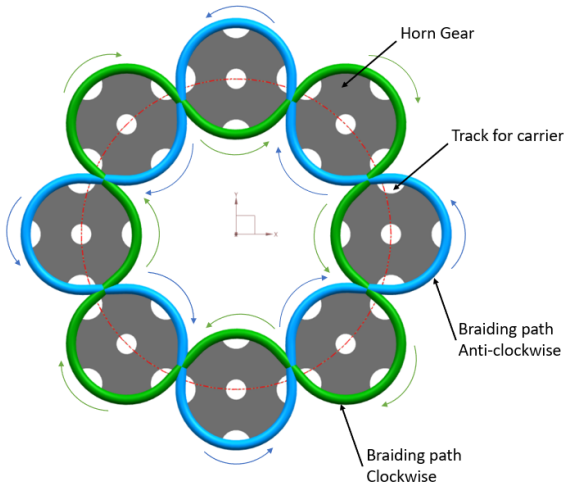


Figure 2.5 Tubular braid

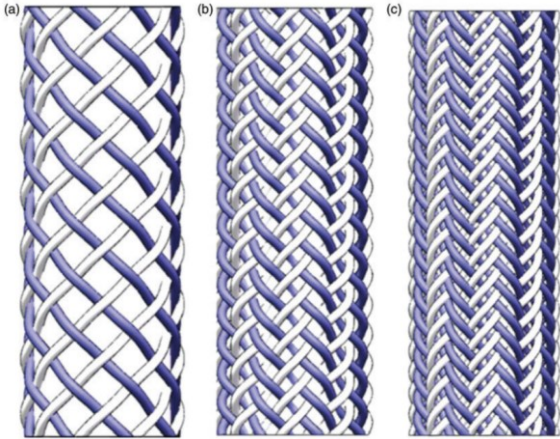


Figure 2.6 Braiding pattern. a) Diamond braid b) Regular braid c) Hercules braid (Ning, Potluri, Yu, & Hearle, 2017)

2.2.2 Twisted Rope

Most ropes are mainly twisted and can be of natural- and synthetic fibers and steel. Twisted steel wires are commonly used in all cranes and lifting equipment and have a long history of application and testing, where the behavior is well documented. Therefore, steel wires are the preferred choice for many applications. A steel wire consists of multiple steel threads that are twisted in a clockwise or anti-clockwise direction to create a thicker strand. Then multiple strands are again twisted together to create a wire, Figure 2.7. One wire can have many layers, a core and the layers can be twisted in opposite directions to create different properties and qualities.



Figure 2.7 CAD model of steel wire (Dylami, 2015)

3 Methods

The following chapter is divided into three sub-sections, theory, CAD, and FEM. And will explain the mathematical theory and the methodology for creating a parametric CAD model of a twisted- and braided rope in Siemens NX. The finite element analysis is described in the last section, and the procedure for the set-up is similar for both cases

3.1 Mathematical theory

3.1.1 3D curves/helix

A helix is a three-dimensional curve with a constant slope that revolves around an axis with constant radius, Figure 3.1. The helix can be either right-handed or left-handed.

A helix can be described mathematically using the following parametrization in cartesian coordinates:

$$\left. \begin{aligned} x(t) &= r \cos(\lambda t) \\ y(t) &= r \sin(\lambda t) \\ z(t) &= ct \end{aligned} \right\} 0 \leq t \leq 2\pi \quad \mathbf{3.1}$$

Where a helix is created as t increases, with radius r and $2\pi c$ is a constant giving the vertical separation of the helix's loops, called Lead or pitch. (Weisstein, u.d.). λ decides which way the helix rotates. $\lambda=1$ for anti-clockwise and $\lambda=-1$ for clockwise direction.

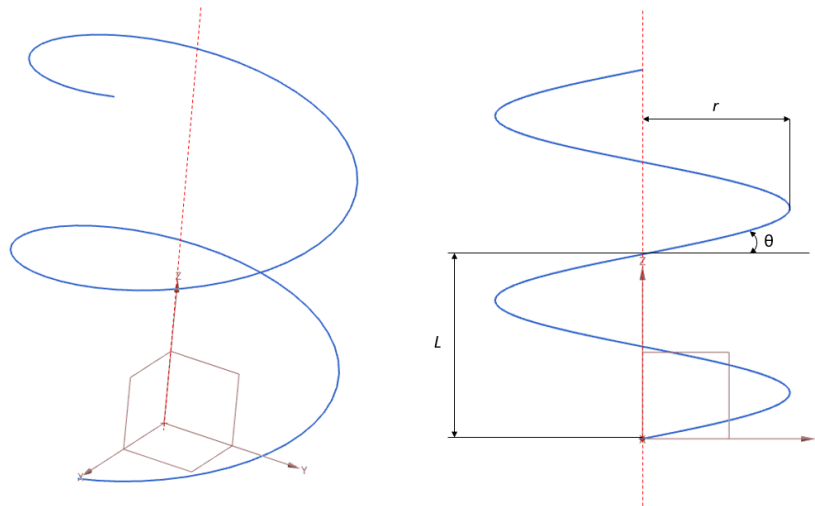


Figure 3.1 Illustration of a helix with two revolutions and its parameters.

Lead L is the axial distance from start- to end-point of the helix in one complete revolution (360°). θ from Figure 3.1 is called lead angle and are expressed in equation 3.2 (Juvinall & Marshek, 2006).

$$\theta = \arctan\left(\frac{L}{2\pi r}\right) \quad \mathbf{3.2}$$

3.1.2 Rope cross-section

To create a twisted wire, multiple strands must be aligned together in a circle. They can't intersect the neighboring strand but must be tangent to each other. One strand in a twisted wire has a circular cross-section, but as the helix is twisted with a lead angle to the normal plane, the cross-section forms an ellipse, Figure 3.2. To make the ellipses tangent to each other, the radius r_3 from the center of the circle they are aligned around to the point of tangency must be found, see Figure 3.3.

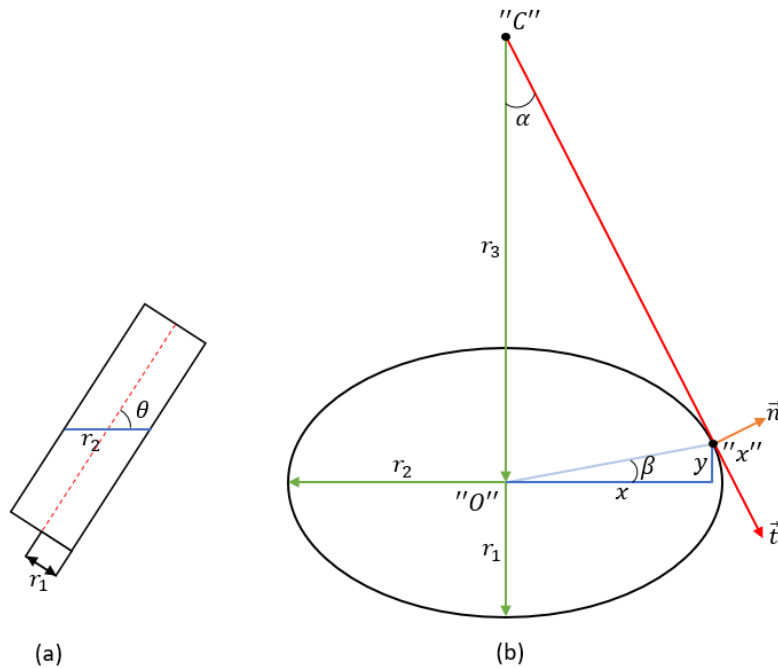


Figure 3.2 (a) Radius and lead angle in one strand, (b) Ellipse dimensions

Table 3-1 Geometric parameters

Name	Symbol
Number of strands	N
Lead	L
Origin of the coordinate system	$O = (0,0)$
Rope center	$C = (0, r_3)$
Strand-to-strand contact point	$X = (x, y)$
Strand radius (ellipsis minor radius)	r_1
Ellipsis major radius	r_2
Rope radius \overline{CO}	r_3
Twisting slope angle	θ
Contact point angle	β
Half central angle	α
Contact point normal	$\vec{n} = [n_x, n_y]^T$
Contact point normal	$\vec{t} = [t_x, t_y]^T$

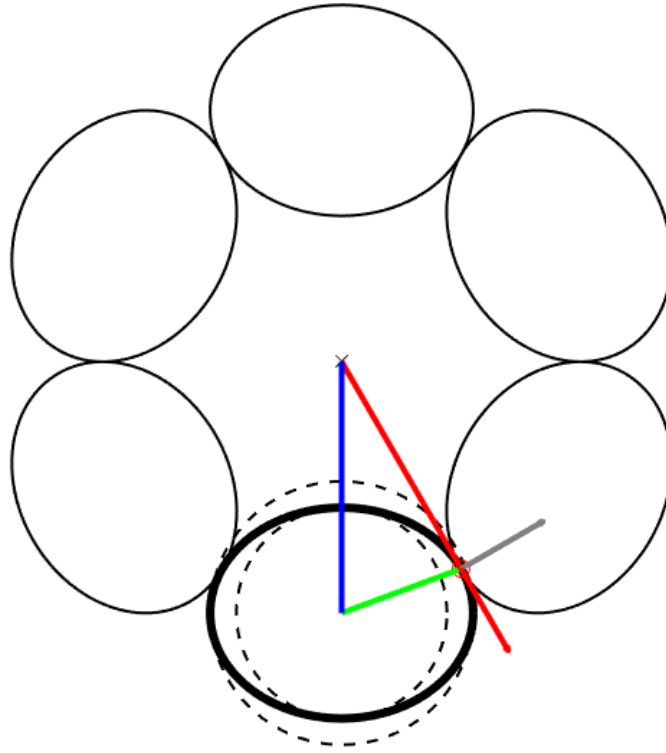


Figure 3.3 Cross-section of wire with $N=6$, $r_1=2$ and $L=40$

By inserting equation 3.3 - 3.10, in MATLAB, Appendix 1, equation 3.10 can be solved with regards to r_3 giving equation 3.11

Circular sector for each strand

$$\alpha = \frac{2\pi}{N} \rightarrow \alpha = \frac{\pi}{N} \quad \mathbf{3.3}$$

Major radius of ellipse

$$r_2 = \frac{r_1}{\sin \theta} \quad \mathbf{3.4}$$

Point on ellipse

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} r_2 \cos \varphi \\ r_1 \sin \varphi \end{pmatrix} \quad \mathbf{3.5}$$

Normal vector at point on ellipse

$$\begin{pmatrix} n_x \\ n_y \end{pmatrix} = \begin{pmatrix} r_1 \cos \varphi \\ r_2 \sin \varphi \end{pmatrix} \quad \mathbf{3.6}$$

Geometric condition: angle is equal to the angle of the ellipsis normal at point X:

$$\tan \alpha = \frac{n_x}{n_y} = \frac{r_2 \sin \varphi}{r_1 \cos \varphi} = \frac{r_2}{r_1} \tan \varphi \quad \mathbf{3.7}$$

$$\rightarrow \tan \varphi = \frac{r_1}{r_2} \tan \alpha \quad \mathbf{3.8}$$

$$\varphi = \arctan \left(\frac{r_1}{r_2} \tan \alpha \right) \quad \mathbf{3.9}$$

Equation for r_3

$$f(r_3) = r_3 - y - x \frac{n_x}{n_y} = 0 \quad \mathbf{3.10}$$

With x , y , n_x and n_y from equation 3.5 and 3.6

Equation 3.10 solved for r_3

$$r_3 = Lr_1 \sqrt{\frac{\left(\tan \frac{\pi}{N} \right)^2 + 1}{\left(L \tan \frac{\pi}{N} \right)^2 - (2\pi r_1)^2}} \quad \mathbf{3.11}$$

3.1.3 Rose curve

A rose curve, also known as a Rhodonea curve, is a sinusoid plotted in polar coordinates. It can also be expressed as Cartesian parametric equations in equation 3.12. The rose curve will have N petals if N is odd and $2N$ petals if N is even (Cundy & Rollet, 1961).

$$\begin{cases} x = \sin(Nt) \cos(t) \\ y = \sin(Nt) \sin(t) \end{cases} \quad \mathbf{3.12}$$

By adding parameters R and A in equation 3.12, a generalized rose curve is developed in equation 3.13, where R is the mean radius of the curve, and A is the amplitude of the petals. λ gives the direction of the lay, $\lambda=1$ for counter-clockwise and $\lambda=-1$ for clockwise. φ is the starting point (Ning, Potluri, Yu, & Hearle, 2017).

$$\begin{cases} x = R + A \sin(\lambda Nt) \cos(t + \varphi) \\ y = R + A \sin(\lambda Nt) \sin(t + \varphi) \end{cases} \quad \mathbf{3.13}$$

For braid with $2N$ strands, the number of strands in the same direction is N , and the phase difference is shown in equation 3.14.

$$\Delta_{\varphi} = \frac{2\pi}{N} \quad \mathbf{3.14}$$

In (2017), Ning found that generalized rose curves where $R < A$ is not the desired curves as the large petals will surround the smaller ones. For $R \geq A$, the petals will arrange equally around the circle, and the petal number is N , Figure 3.4. These types of curves simulate the braiding track and can be used to describe braiding curves.

Table 3-2 List of symbols used

Name	Symbol
Number of petals	N
Amplitude	A
Phase difference	φ
Rotation direction	λ

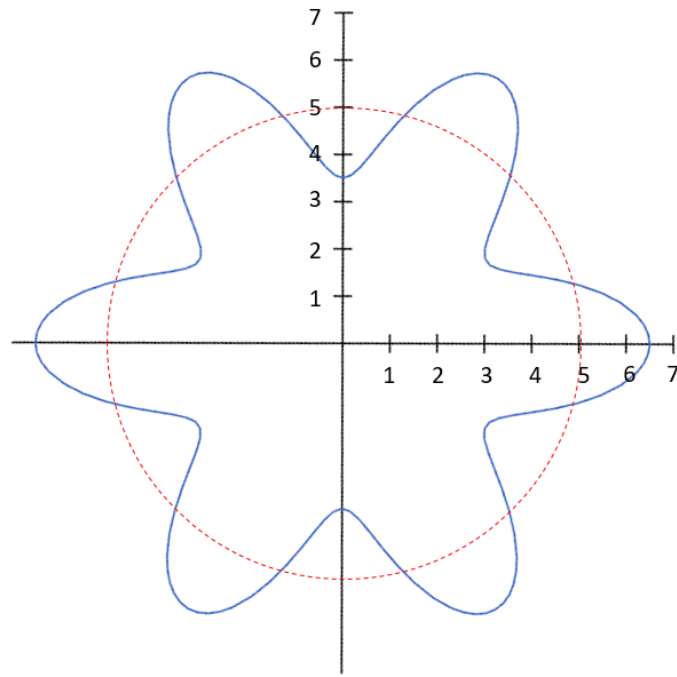


Figure 3.4 Generalized rose curve with $R=5$, $A=1,5$, and $N=6$

As mentioned in chapter 2.2.1, there are several different patterns where multiple strands alternate under and over one other strand. In the generalized rose curve, the trough and crest are very sharp and are not suited for other than diamond braids. To solve this problem (Ning, Potluri, Yu, & Hearle, 2017) introduced a modified rose curve where an ellipse replaces the unit circle. In Figure 3.5, one can see that this cuts the sharp trough and crest of the sine curve, making them flatter and allowing multiple strands to pass through.

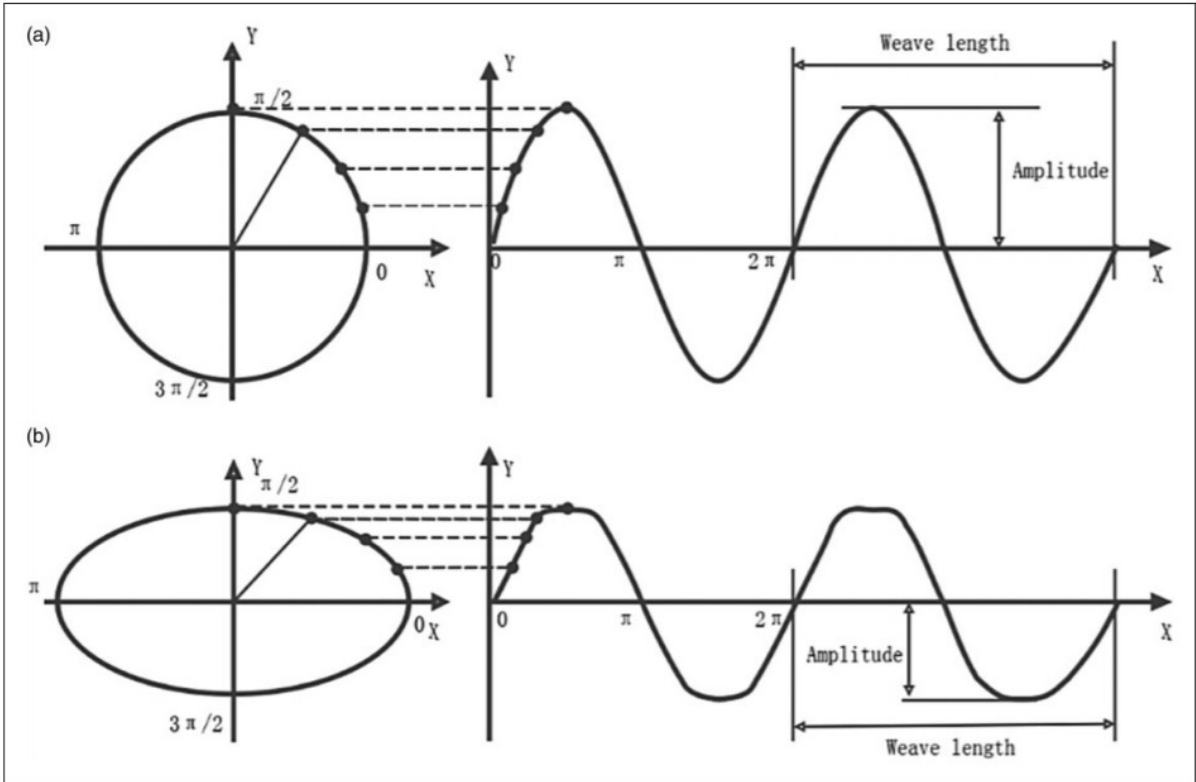


Figure 3.5 “Relationship between motion and relevant curve: a) circle and sine curve; b) ellipse and large span curve” (Ning, Potluri, Yu, & Hearle, 2017)

By transforming the generalized rose curve and inserting the relationship between y and the position angle θ , (Ning, Potluri, Yu, & Hearle, 2017) found the equation for the modified rose curve, equation 3.15.

$$\left. \begin{aligned}
 x &= \left(R + \frac{ab}{\sqrt{a^2 + b^2(\cot Nt)^2}} \right) \cos(t) \\
 y &= \left(R + \frac{ab}{\sqrt{a^2 + b^2(\cot Nt)^2}} \right) \sin(t)
 \end{aligned} \right\} 0 \leq \theta \leq \pi$$

$$\left. \begin{aligned}
 x &= \left(R - \frac{ab}{\sqrt{a^2 + b^2(\cot Nt)^2}} \right) \cos(t) \\
 y &= \left(R - \frac{ab}{\sqrt{a^2 + b^2(\cot Nt)^2}} \right) \sin(t)
 \end{aligned} \right\} \pi \leq \theta \leq 2\pi$$

3.15

Where a and b are the major and minor axis of the ellipse.

3.2 Computer-Aided Design

3.2.1 Siemens NX

This sub-section is based on the theory from sub-section 2.1.1 and will explain the procedure for the case in NX and the limitation discovered in the process. Any deviations from the procedure will be explained when needed.

As sub-section 2.1.1 states, the expressions dialog is used to make mathematical expressions and dependencies in a 3D model. A mathematical description of the curve is needed before creating the expressions, and this is carefully described in the previous chapter.

Working with the expressions dialog has revealed some limitations and tricks needed to make the model work. The parameter t is a value predefined by NX to be between 0 and 1, where the timestep is also predefined. This cannot be changed to other values. It can, however, be manipulated by multiplying it with the wanted number in the equation. The expression dialog is preset to work in degrees, but radians can be selected in the "units" column for each formula. As expressions made by NX always will be in degrees, this can make some difficulties. Values that are in radians can also be changed to degrees by multiplying with $180/\pi$ in the formula. The expressions dialog support the function modulus (syntax $a \% n$) but only using integers and not variables like t .

Procedure

The following procedure is used in all three cases that will follow in chapter 3.2.2, 3.2.3, and 3.2.4. Any deviations will be described in the appurtenant chapter.

I. Creating expressions

Input the syntax as described. For multiple layer models, arrange them in groups for each layer.

II. Law curve

To create the splines from expressions, the law function command is used. This gives three options for each direction, X, Y, and Z to define the spline. Each direction can be defined by a linear law, an equation law or a constant law. Create a law curve using "by equation" and t as a parameter. The function is xt , yt , and zt , for multiple layers, they will be given a corresponding index number.

III. Tube

Use the tube function to create a thickness to the law curve, making it one strand of the rope. Set inner diameter to zero to make it solid and set the outer diameter to 1mm. This is one of the variables in the model and can be changed later.

IV. Pattern feature

Pattern feature gives the opportunity to copy the strands along an appointed path. This is used to make several strands using the following settings:

Layout: circular

Vector: positive Z-direction

Point: origin

Spacing: Count and span

Count: 6

Span angle: 360°

V. Customize Expressions

Once step III and IV are done, new expressions for these features will appear. They are given new names and arranged in groups to make it more perspicuous. They are also connected to other expressions, so that parameters only need to be changed in one expressions and others depending on it will follow.

The expression for the diameter of the tube is given the name D_s , and expressions from the pattern function are given names for span angle and N for number of strands. The different expressions can be recognized by looking at the source. See the following syntax:

Table 3-3 Syntax for patter feature

NAME	FORMULA	DIMENSIONALITY	SOURCE
D_s	1	Length	(Tube(1)limit 1)
N_1	6	Unitless	(Pattern feature(2)number of copies)
span_angle	360	Angle	(Pattern feature(2)span angle)

3.2.2 Case 1 – simple twisted

Case 1 is the initial model of a twisted wire. As the procedure for creating a model in NX is accounted for in chapter 3.2.1, this chapter will explain the mathematical functions used and any deviations from the original procedure.

To create a parametric CAD model of a twisted wire, the mathematical description of the curve is needed. The curve of one strand can be described as a helix, and by adding multiple helixes around a circle, the initial model is made.

As mentioned in chapter 3.1 the expressions dialog in NX have some restrictions and specific ways to describe mathematical expressions. The mathematical equations for a helix are described in equation 3.1 and needs some alterations to work in NX.

Creating a curve

As the variable t only runs between 0-1, it needs to be multiplied with 360° to take one complete revolution; this can be multiplied with turn number T_n to get several revolutions. The number multiplied with t in $z(t)$ is the total height H of the helix with n turns. r is the radius of the helix. This is showed in equation 3.16.

$$\left. \begin{aligned} x(t) &= r \cos(T_n * 360 * t) \\ y(t) &= r \sin(T_n * 360 * t) \\ z(t) &= H * t \end{aligned} \right\} \quad \mathbf{3.16}$$

Equation 3.16 will give a counter-clockwise helix with a fixed height and a fixed number of turns. Low height with large turn number will give a small lead angle, where high height and small turn number will give a large lead angle. Initial thoughts were to get more control over the lead angle, and an expression for the relationship between total height, number of turns, and lead angle were found in Figure 3.6 and equation 3.17. The syntax to enter in expressions are shown in Table 3-4.

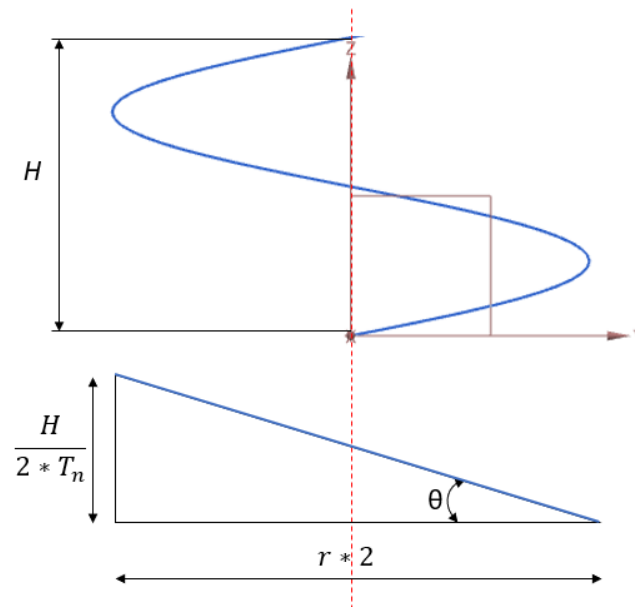


Figure 3.6 Relationship between height H , number of turns T_n and lead angle θ in a helix

$$\tan \theta = \frac{\frac{H}{2 * T_n}}{r * 2} \rightarrow T_n = \frac{H}{4 * r * \tan \theta} \quad \mathbf{3.17}$$

Table 3-4 Syntax for helix curve

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
H	30	Length
Theta	60	Angle
Tn	$H / (4 * r * \tan(\theta))$	Unitless
r	5	Length
xt	$r * \cos(t * 360 * Tn)$	Length
yt	$r * \sin(t * 360 * Tn)$	Length
zt	$H * t$	Length

Creating a 3D model

The next step is to create the model. Follow step I to V from chapter 3.2.1 and enter the syntax above.

In this model, there is no control over the distance between the strands or if they intersect each other as there is no connection between strand radius and helix radius. To make the strands tangent to each other, the law curve is patterned like the tube. In the expressions dialog, the new formulas for the new pattern are set to be dependent on the first pattern dimensions; this is so the values only need to be changed in one place. See the following syntax:

Table 3-5 Syntax for tube and pattern feature

NAME	FORMULA	DIMENSIONALITY	SOURCE
Ds	2	Length	(Tube(1)limit 1)
N_1	6	Unitless	(Pattern feature(2)number of copies)
span_angle_1	360	Angle	(Pattern feature(2)span angle)
N_2	N_1	Unitless	Pattern feature(3)(number of copies)
span_angle_2	Span_angle_1	Angle	Pattern feature(3)(span angle)

Align strands together

The option to measure distance is used to create an expression dependent on the distance between two objects. This is used to find the distance between the center of two strands and is measured perpendicular to the curve. This distance will be the same as the diameter of one strand. NX will create a new expression with the measurements; this can be inserted as a formula for the diameter of the tube, Table 3-6.

Table 3-6 Syntax for measurement expression

NAME	FORMULA	DIMENSIONALITY	SOURCE
p3	(measurment)	Length	(Distance measurment(4))
Ds	p3	Unitless	(Tube(1)limit 1)

This gives a model of a twisted wire with one layer, with N , θ , H , and r as variables.

3.2.3 Case 2 – twisted

As case 1 had several limitations, further development of the twisted wire model is needed and are presented in this chapter. The procedure is stated in chapter 3.2.1, and this sub-section will explain mathematical functions used and any deviations from the original procedure.

First layer

The main equation is the same as equation 3.16 in case one. However, small changes are made in this case. L , T_n , D_s , and N are variables. To get control over the lead, H from equation 3.16 is the sum of lead multiplied with turn number in $z(t)$. In chapter 3.1.2, the twisted wire cross-section is discussed, and from this, an equation for the radius of the point of tangency is derived. The first layer will rotate counter-clockwise. $\lambda=1$ and can be neglected from the equation. These changes give equation 3.18 and the syntax to enter in expressions in Table 3-7.

$$\left. \begin{aligned} x(t) &= r_3 \cos(T_n * 360 * t) \\ y(t) &= r_3 \sin(T_n * 360 * t) \\ z(t) &= L * T_n * t \end{aligned} \right\} \quad \mathbf{3.18}$$

Table 3-7 Syntax for the first layer

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
N	6	Unitless
L	100	Length
Tn	1	Unitless
Ds	2	Length
r1	Ds/2	Length
r3	$L * r1 * \sqrt{((\tan(\pi() / N * 180 / \pi()))^2 + 1) / ((L * \tan(\pi() / N * 180 / \pi()))^2 - (2 * \pi() * r1)^2)}$	Length
Xt	$r3 * \cos(t * 360 * Tn)$	Length
Yt	$r3 * \sin(t * 360 * Tn)$	Length
Zt	$L * Tn * t$	Length

To create the model, follow step I to V in chapter 3.2.1 and enter the syntax above.

Core/center strand

The core of the wire is a straight line with the same length as the helix height, see c/t in Table 3-8. Use law curve function with the following settings to add the straight line in Z-direction:

X Law	Y Law	Z Law
Law type: Constant	Law type: Constant	Law type: By equation
Value: 0	Value: 0	Parameter: t
		Function: clt

Use the tube function on the straight line and name the diameter C_d . The core must be tangent to the first layer. The diameter of the core can be expressed by equation 3.19 and the syntax to enter in the expressions dialog in Table 3-8.

$$C_d = (r_3 - r_1) * 2 \quad \mathbf{3.19}$$

Table 3-8 Syntax for core

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
clt	L*Tn*t	Length
Cd	(r3-r1)*2	Lenght

Create list expressions

The number of strands N must be an integer and can't be less than three. This is because the inner layer of a twisted wire normally doesn't have less than three strands and because the model crashes when it is set to one. To constrain the values used for N , a list of options is made. There is also a need for a set of values for the strand diameter, and this is shown in Table 3-9.

Table 3-9 Syntax with list expressions for N and D_s

NAME	FORMULA	TYPE
N_1_options	{3, 4, 6}	List
N_1	3 ▼	Number
Ds_options	{2, 4}	List
Ds	2 ▼	Number

Second layer

To create the second layer, the procedure from page 26 is repeated. All expression names are given the index "2" to separate the expressions in each layer and are made in an own group called layer 2. This layer will have an opposite rotation to the first. This is changed by multiplying the parameter t with -1 in x_t and y_t . The diameter of the strands is set as the same as in layer one. Table 3-10 shows the syntax to enter in the expressions dialog.

Table 3-10 Syntax for layer two

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
L_2	100	Length
N_2	12	Unitless
Tn_2	1	Unitless
Ds_2	Ds_1	Length
r1_2	Ds_2/2	Length
r3_2	$L_2 * r1_2 * \sqrt{((\tan(\pi()/N_2 * 180/\pi()))^2 + 1) / ((L_2 * \tan(\pi()/N_2 * 180/\pi()))^2 - (2 * \pi() * r1_2)^2)}$	Length
xt_2	$r3_2 * \cos(-t * 360 * Tn_2)$	Length
yt_2	$r3_2 * \sin(-t * 360 * Tn_2)$	Length
zt_2	$L_2 * Tn_2 * t$	Length

Third layer

For the third layer, the procedure is the same as in layer two in the previous paragraph, the expressions are given the index "3" and sorted in group 3. The rotation will be anti-clockwise, $\lambda=1$, same as in layer one, see Table 3-11.

Table 3-11 Syntax for layer three

NAME	FORMULA	DIMENSIONALITY
t	o	Unitless
N ₃	18	Unitless
L ₃	120	Length
Tn ₃	1	Unitless
Ds ₃	Ds	Length
r1 ₃	Ds ₃ /2	Length
r3 ₃	$L_3 * r1_3 * \sqrt{((\tan(\pi()/N_3 * 180/\pi()))^2 + 1) / ((L_3 * \tan(\pi()/N_3 * 180/\pi()))^2 - (2 * \pi() * r1_3)^2)}$	Length
xt ₃	$r3_3 * \cos(t * 360 * Tn_3)$	Length
yt ₃	$r3_3 * \sin(t * 360 * Tn_3)$	Length
zt ₃	$L_3 * Tn_3 * t$	Length

Restricting the model

With three layers, there is a lot of variables and thousands of combinations of these, where several combinations will cause the model to either crash, layers will intersect each other or have a gap. To simplify the model, the variables are defined and restricted to a list of values and where variables in layer two and three are dependent on layer one.

$$D_s = \{2,4\}$$

$$N_1 = \{3,4,6\}$$

Lead angle θ is decided to be 75°. As lead is the variable in this model and not theta, MATLAB, Appendix 1, is used to find the lead for each combination of Ds and N. The numbers are presented in Table 3-12.

Table 3-12 Table of strand diameter with the corresponding number of strands and lead in each layer

Ds [mm]	Layer 1		Layer 2		Layer 3	
	N ₁ [-]	L ₁ [mm]	N ₂ [-]	L ₂ [mm]	N ₃ [-]	L ₃ [mm]
2	3	28	10	79	16	125
2	4	34	11	86	17	132
2	6	50	12	94	18	140
4	3	53	10	157	16	249
4	4	68	11	172	17	265
4	6	97	12	188	18	280

Boolean operation is used to update the variable when D_s and N in layer one are selected. The numbers from Table 3-12 is used and gives the following syntax for D_s , N , and L in each layer.

Table 3-13 Syntax using Boolean operations for N and L in all three layers

NAME	FORMULA	DIMENSIONALITY
Layer 1 (Group)		
Ds_options	{2,4}	List
Ds	2 ▼	Number
L_1	if(Ds==2 && N==3) (28)else if(Ds==2 && N==4) (34)else if(Ds==2 && N==6) (50)else if(Ds==4 && N==3) (53)else if(Ds==4 && N==4) (68)else if(Ds==4 && N==6) (97)else(10)	Unitless
Layer 2 (Group)		
N_2	if(N==3) (10)else if(N==4) (11)else if(N==6) (12)else(12)	Unitless
L_2	if(Ds_2==2 && N_2==10) (79)else if(Ds_2==2 && N_2==11) (86)else if(Ds_2==2 && N_2==12) (94)else if(Ds_2==4 && N_2==10) (157)else if(Ds_2==4 && N_2==11) (172)else if(Ds_2==4 && N_2==12) (188)else(10)	Length
Ds_2	Ds	Length
Layer 3 (Group)		
N_3	if(N==3) (16)else if(N==4) (17)else if(N==6) (18)else(18)	Unitless
L_3	if(Ds_3==2 && N_3==16) (125)else if(Ds_3==2 && N_3==17) (132)else if(Ds_3==2 && N_3==18) (140)else if(Ds_3==4 && N_3==16) (249)else if(Ds_3==4 && N_3==17) (265)else if(Ds_3==4 && N_3==18) (280)else(10)	Length
Ds_3	Ds	Length

3.2.4 Case 3 – Braided rope

Case 3 is the main case in this thesis and are the development of a parametric model of a braided rope. The procedure is stated in chapter 3.2.1, and any deviations will be explained consecutively.

Expressions

The generalized rose curve describes the pattern of a diamond braid. As in previous cases, the equation needs some alterations to work in NX. The generalized rose curve from equation 3.13 in chapter 3.1.3 is altered for expressions in NX in equation 3.20. Table 3-14 shows the syntax to enter in the expressions dialog.

$$\begin{cases} x = R + A \sin(\lambda Nt * 360) \cos(\lambda t + \varphi) * 360 \\ y = R + A \sin(\lambda Nt * 360) \sin(\lambda t + \varphi) * 360 \end{cases} \quad \mathbf{3.20}$$

For the clockwise lay, xt , yt and, zt :

$$\lambda = 1 \text{ and } \varphi = 0$$

For the anti-clockwise lay, at , bt and ct :

$$\lambda = -1 \text{ and } \varphi = \frac{360}{2N}$$

Table 3-14 Syntax for diamond braid

NAME	FORMULA	DIMENSIONALITY
t	0	Unitless
A	1	Length
R	5	Length
L	50	Length
N	6	Unitless
Phi_1	0	Unitless
Phi_2	360 / (2*N)	Unitless
xt	(R+A*sin(N*t*360)) * cos(t*360+phi_1)	Length
yt	(R+A*sin(N*t*360)) * sin(t*360+phi_1)	Length
zt	L*t	Length
at	(R+A*sin(-N*t*360)) * cos(-t*360+phi_2)	Length
bt	(R+A*sin(-N*t*360)) * sin(-t*360+phi_2)	Length
ct	L*t	Length

3D model

Follow step I to V in chapter 3.2.1 to create the 3D model using the syntax above. Make two law curves using xt , yt , and zt as functions in one and at , bt and ct as functions in the other.

The tube function will give two expressions for the diameter; these must be connected to each other. To make the strands align, D_s equals two multiplied with the amplitude. But can cause them to intersect and needs to be adjusted down depending on the other values used in A , N , and R , Table 3-15. From an FEA point of view, it is better with a small gap rather than the strands intersecting. The software has a function that can create contact between geometries with small gaps.

Table 3-15 Syntax for tube expressions

NAME	FORMULA	DIMENSIONALITY	SOURCE
Ds	$A*1.xx$	Length	(Tube(4)Limit 1)
p2	Ds	Length	(Tube(5)Limit 1)

It is worth reminding that N , in this case, is number of petals in the rose curve and not number of strands as used in case one and two. However, the number of strands in one direction must be the same as number of petals, making them the same variable. After patterning the two strands, the number of strands in each pattern must relate to the number of petals, N , Table 3-16.

Table 3-16 Syntax for pattern feature expressions

NAME	FORMULA	DIMENSIONALITY	SOURCE
N_options	{2, 3, 4, 5, 6}		
N	6 ▼	Unitless	
p3	N	Unitless	(Pattern Feature [Circular](5) Angular Direction: Number of Copies)
p4	N	Unitless	(Pattern Feature [Circular](6) Angular Direction: Number of Copies)

Regular braid

To create a regular braid, the modified rose curve from equation 3.15 in chapter 3.1.3 is used. The procedure is the same as for a diamond braid in the previous pages; with some changes in expressions to create the curve. The curve will alternate around a mean circle using the two equations. As the expressions dialog in NX work in degrees, this will be used in the equation. To check if θ is between 0° - 180° or 180° - 360° modulo operation is used and Boolean operation is used to tell which of the two equations for x and y to use within their range. The syntax to enter in expressions with these changes are shown in Table 3-17.

Notice that theta θ is the position angle on the unit circle and not lead angle in this situation, and a and b is the minor and major radius of the ellipse.

Table 3-17 Syntax for modified rose curve

NAME	FORMULA	DIMENSIONALITY
t	0	Unitless
R	5	Length
L	50	Length
a	2	Length
b	1.5	Length
N	6	Unitless
Theta	$(\sin(N*t*360)) \% (2*360)$	Unitless
Eq1x	$(R + ((a*b) / (\sqrt{a^2 + b^2 * (\tan(\pi() / 2 - N*t*360))^2}))) * \cos(t*360)$	Length
Eq1y	$(R + ((a*b) / (\sqrt{a^2 + b^2 * (\tan(\pi() / 2 - N*t*360))^2}))) * \sin(t*360)$	Length
Eq2x	$(R - ((a*b) / (\sqrt{a^2 + b^2 * (\tan(\pi() / 2 - N*t*360))^2}))) * \cos(t*360)$	Length
Eq2y	$(R - ((a*b) / (\sqrt{a^2 + b^2 * (\tan(\pi() / 2 - N*t*360))^2}))) * \sin(t*360)$	Length
xt	$\text{If}(\text{theta} \leq 90) (\text{Eq1x}) \text{ else } (\text{Eq2x})$	Length
yt	$\text{If}(\text{theta} \leq 90) (\text{Eq1y}) \text{ else } (\text{Eq2y})$	Length
zt	$L*t$	Length

3.3 Finite element method

Finite element method is used in this thesis to show one application of the model and to verify that the model is applicable for this type of analysis using a commercial software. As the FEM is not the primary emphasis in this thesis, the analysis is not performed on all models.

The procedure for an FE analysis

1. Create geometry
2. Generate mesh
3. Material assignment
4. Choose solver
5. Apply constraints
6. Apply loads
7. Solve
8. Post processing

Degrees of freedom (DOF) refers to the movement of the geometry along X, Y, and Z axis and around X, Y, and Z axis. Where 1,2,3 refers consecutively to translation along X-, Y- and Z axis and 4, 5, 6 refers consecutively to rotation around X-, Y- and Z axis.

3.3.1 Mesh

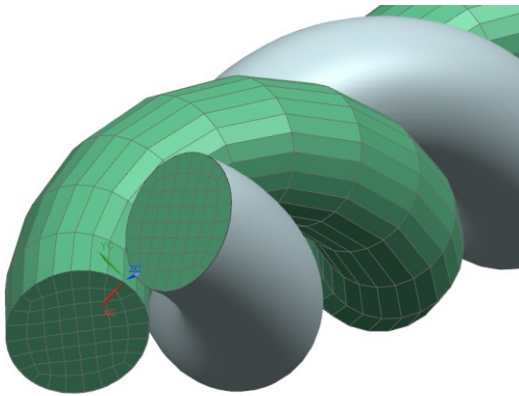


Figure 3.7 3D swept mesh

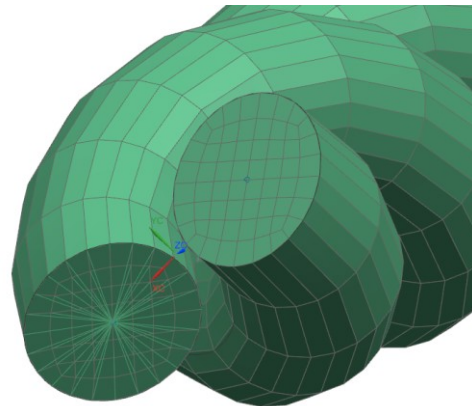


Figure 3.8 1D connection made from the face to the center point on the strand to the right

To mesh the geometry, 3D swept mesh is used. First, a 2D mesh using quadrilateral elements with a small size (2mm), is created on the cross-section of the strands. Then this is swept layer by layer through the solid body, propagating 3D elements to fill the solid body, Figure 3.7, using hexahedral elements with a large size (10mm). Now there is no need for the 2D mesh, and this must be deleted to prevent it make problems in the solution. To evenly distribute the forces, a mesh point is created in the center of the cross-section on each strand in both ends, then 1D connection with RBE2 elements are used to make a rigid connection between the face and the mesh point, Figure 3.8. For

models with multiple strands, it might be necessary to create a point at the center of the geometry (rope) at a distance, and then connect all the cross-sections to this point.

The next step is to assign material. Twisted wires are normally made of steel, and braided ropes can be made of many different synthetic materials, as mentioned in chapter 2.2. As this FE analysis is only for validation of the CAD model steel is used.

3.3.2 Boundary conditions

As this is not a rigid geometry, a linear static solver cannot be used. When creating the new simulation, set solution type to "SOL 601, 106 Advanced Nonlinear Statics" in the solution dialog box and check the box for "Large displacement (LGDISP)" in the parameters tab. Non-linear because of large geometrical displacement in the rope and static because there are no dynamics.

Then the geometry needs to be constrained. When a force is applied, the rope may untwist if not constrained correctly. We want to create a sliding support with axial tension. The mesh point in each strand on the right side is fixed in all DOF. The two mesh points on the other end are fixed in all rotational DOF 4, 5, 6 and X and Y translation 1, 2. A force working in the rope's axial direction, Z-direction, is applied in the two mesh points in the left side.

The surface-to-surface contact simulation is used to create contact between the strand when tensions are applied. Using manual paring, two target regions are made. Both regions contain the whole geometry. The search distance must be equal to or greater than the distance between the objects. In this case, it is set to search in a distance of -1 and 1. The yellow arrows in Figure 3.9 show the contact-to-contact simulation applied to the geometry.

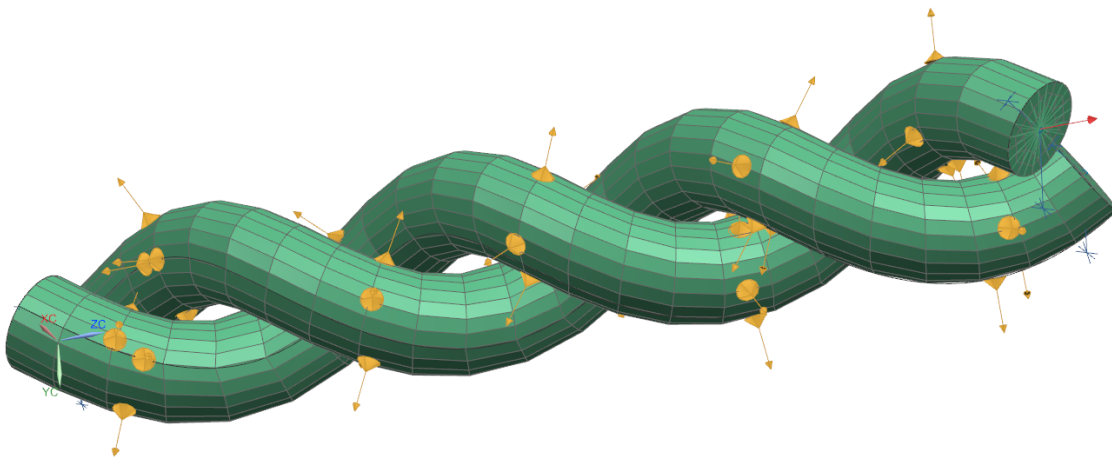


Figure 3.9 Boundary conditions

4 Result and discussion

The result will be presented in four sections, one for each case and at last, the results from the finite element analysis. Each result will be discussed consecutively in each chapter.

4.1 CASE 1

Case 1 is an initial test case on creating a parametric model of a twisted wire and is created using the method from chapter 3.2.2. The case generation procedure results in a simple model of a twisted rope with one layer and no core.

The model is simple and lacks many desired features but works very good as is. The variables are N , r , θ , and H . Were $r > 0$ and $0 \leq \theta \leq 90$. Even though the model works with any angle and radius, some common sense must be exerted. Angles below 10° are not very applicable, at least for ropes. An angle at 90° will give straight strands, and $90 \leq \theta \leq 180$ will change the direction of the lay to clockwise. To change the direction of the lay, it is more sensible to do this using $\lambda = \pm 1$ in the equation for x_t and y_t . The list with numbers of strand is set to be from 3-12, but the model will work with even higher number of strands. When using a large number of strands, it is important to increase the rope radius, or the strand diameter will be microscopic, or maybe at some point, the model will crash. To make the strands tangent to each other, the distance between the center of the strand to the center of the neighboring strand is measured. This measure is embedded in the expression for strand diameter, D_s . Because of this, it is not possible to choose the desired strand diameter; it will be given when the wire radius and number of strands are set. The advantage of this is that one can choose the desired outer diameter of the rope directly, which may be more favorable as the ropes outer diameter is stated in the manufacturer catalogs and ropes in the same grade gets stronger when the thickness increases.



Figure 4.1 Simple twisted rope with $N=6$, $\theta=70^\circ$, $r=10mm$ and $H=50mm$



Figure 4.2 Simple twisted rope with $N=6$, $\theta=70^\circ$, $r=10mm$ and $H=50mm$

Figure 4.1 and Figure 4.2 shows a model with $N=6$, $\theta=70^\circ$, $r=10\text{mm}$, and $H=50\text{mm}$. Figure 4.3 shows the model with the same variables but with an increased number of strands, $N=12$. Figure 4.4 shows that the model also works with small angles, $\theta=20^\circ$.

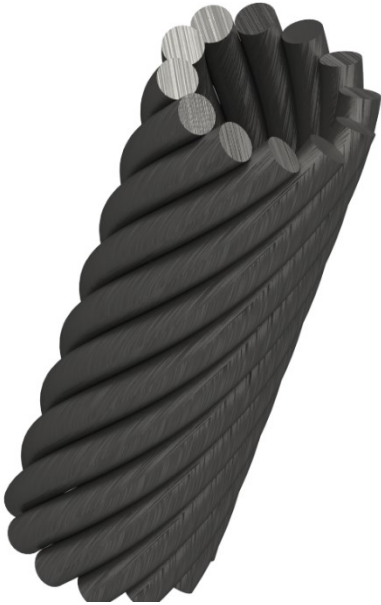


Figure 4.3 Simple twisted rope with $N=12$, $\theta=70^\circ$, $r=10\text{mm}$ and $H=50\text{mm}$

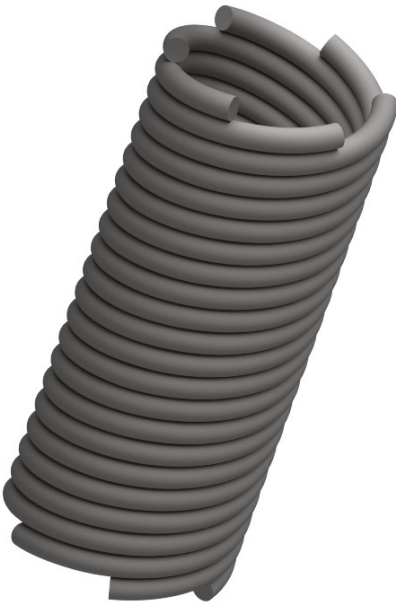


Figure 4.4 Simple twisted rope with $N=6$, $\theta=20^\circ$, $r=5\text{mm}$ and $H=25\text{mm}$

The initial model shows that it is possible to create a simple parametric model using the expressions dialog in NX.

4.2 CASE 2

In the following section, the results for case 2 are presented. Case two is a further development of a twisted rope using the experience from case one. This model is created using the method in chapter 3.2.3 with a core and three layers. This model has variables $N_1, N_2, N_3, L_1, L_2, L_3,$ and D_s . Where the index 1,2,3 stands for each layer. For further reading N and L will be shortened $N_{123}=a, b, c$ and $L_{123}=a, b, c$, where a, b, c stands for the value used in each layer.

This model uses the equation 3.11 for r_3 to get the correct radius to make the strands tangent to each other, and not the measure feature as in case one. This made it possible to make a core and multiple layers. As this model is more complex, it also brought more challenges. The main challenge is the distance between each layer. The inner radius of the second layer should be the same as the outer radius of the first layer, making them tangent to each other. This is challenging to comply with as the mean radius r_3 depends on number of strands, their diameter and the lead (that decides the lead angle).

Figure 4.5 and Figure 4.6 shows how the layers can intersect each other at certain values. This case has the following values: $N_{123}=6, 10, 15, L_{123}=50, 94, 140$ and $D_s=2$. The main influence on the radius is the number of strands and diameter of the strands. Lead has minimal effect.

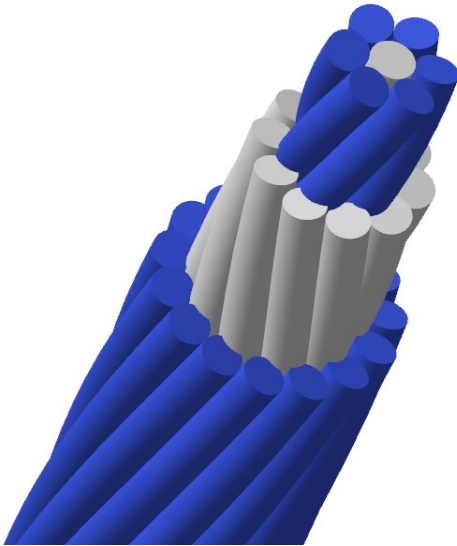


Figure 4.5 Twisted wire where layers intersect each other with values: $N_{123}=6, 10, 15, L_{123}=50, 94, 140$ and $D_s=2$

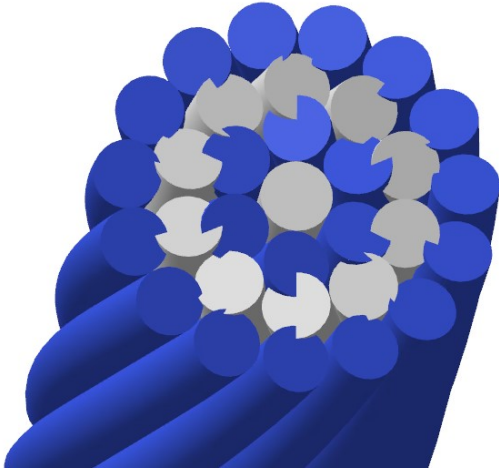


Figure 4.6 Cross-section of twisted wire where layers intersect each other with values: $N_{123}=6, 10, 15, L_{123}=50, 94, 140$ and $D_s=2$

To resolve the problem, the model was limited as described in the last section of chapter 3.2.3. Figure 4.7 and Figure 4.8 shows the model where the lead angle θ is set to 75° and $N_{123}=6, 12, 18, L_{123}=50, 94, 140$, and $D_s=2$. Notice that D_s and L for each layer are the same as in Figure 4.5 and Figure 4.6. The only difference is the number of strands in layer two and three; this shows how significant influence the number of strands has on the radius. The attempt to control the values still results in some strands slightly intersecting each other. By looking closely at the layers in Figure 4.8, one can see some strands are tangent to each other, some intersecting and some having a small gap. This is due to the layers are twisted in the opposite direction to each other; if one shifts the position of the cross-section, this will change.

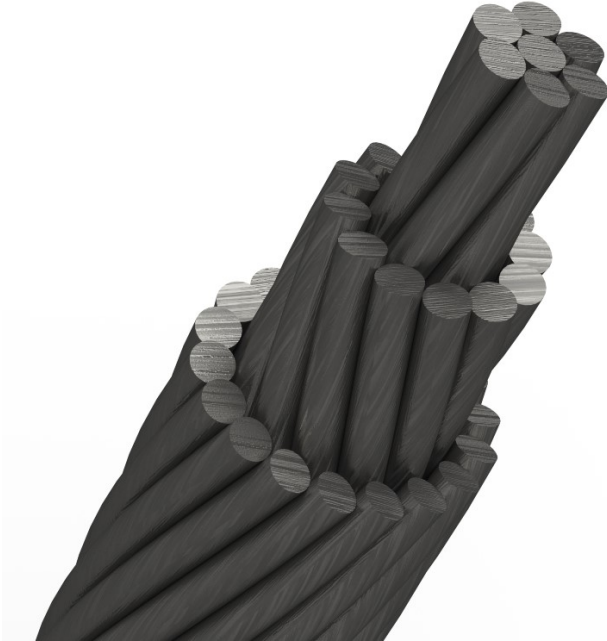


Figure 4.7 Three-layer twisted rope with $N_{123}=6, 12, 18, D_s=2, L_{123}=50, 94, 140$

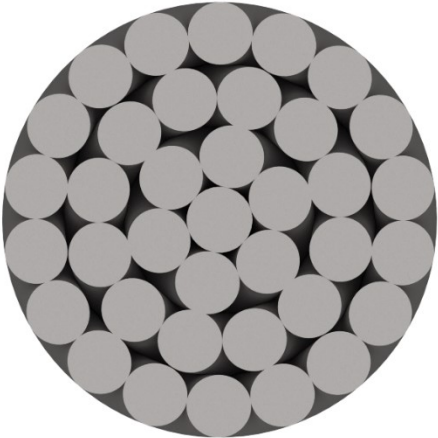


Figure 4.8 Cross-section of three-layer twisted rope with $N_{123}=6, 12, 18, D_s=2, L_{123}=50, 94, 140$

Seeing that the model where the lead angle θ is fixed and layer two and three depend on values in layer one does not act as desired, a model where all variables N_{123} , L_{123} , and D_s can be set are used instead. This gives the user full control over the variables, but it can be challenging to find the right combination of numbers to get the wanted result. If the lead angle is too small, which happens when the lead is small, the strands intersect each other. When doing this in MATLAB, the script failed to solve, why is not clear. By turning the equations to make the lead angle a variable instead of the lead, a new equation for r_3 was found, and the MATLAB scrips worked with given any angle. Unfortunately, this was not successfully implemented in Siemens NX.

Figure 4.9 shows a model with $N_{123}=6, 12, 18$, $L_{123}=50, 70, 100$, and $D_s=2$, which gives a small gap, measured to be $0,06mm$, between each layer. A model with small gaps will work better in an FE analysis as there are ways to create contact between geometries with a small distance.

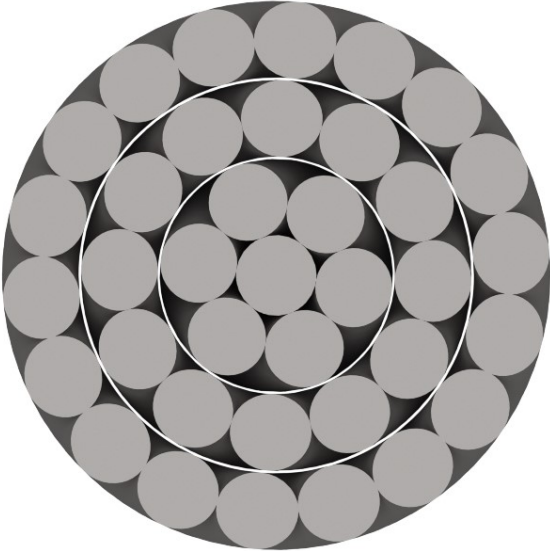


Figure 4.9 Cross-section of three-layer twisted rope with a small gap between the layers.
 $N_{123}=6, 12, 18$, $L_{123}=50, 70, 100$ and $D_s=2$.

4.3 CASE 3

This section will present the results from case 3. Case 3 is a parametric CAD model of a braided rope and is developed using the method in chapter 3.2.4. Variables in this model are amplitude A , mean radius R , number of strands in one direction N , the diameter of strands D_s , and lead L .

The generalized rose curve gives a good representation of the diamond braid pattern, and using this gives the opportunity to make an applicable parametric CAD model of a braided rope. Figure 4.10 and Figure 4.11 shows two working configurations with different amplitude and diameter of strands; where there is a slight gap between the strands. Note the rose curve pattern (see Figure 3.4) of the strands in the top view in Figure 4.12.

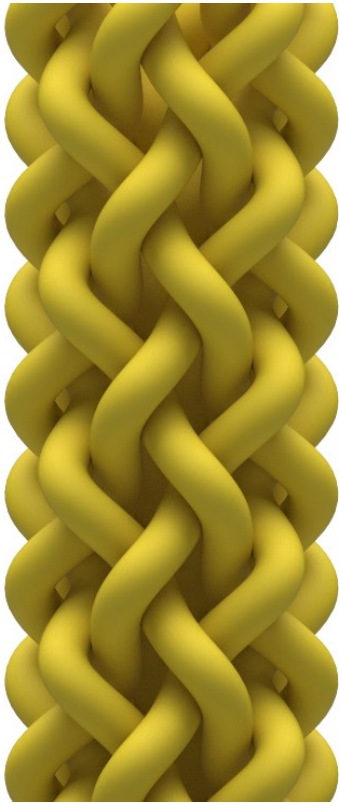


Figure 4.10 Diamond braid with $A=3$, $L=100$, $2N=12$, $D_s=4,5$ and $R=10$

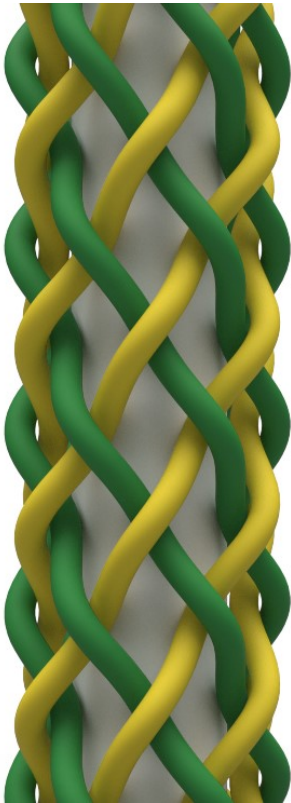


Figure 4.11 Diamond braid with $A=1,5$, $L=100$, $2N=12$, $D_s=2,7$ and $R=10$. (A core has been added in this model to make the visualization of the braiding pattern better)

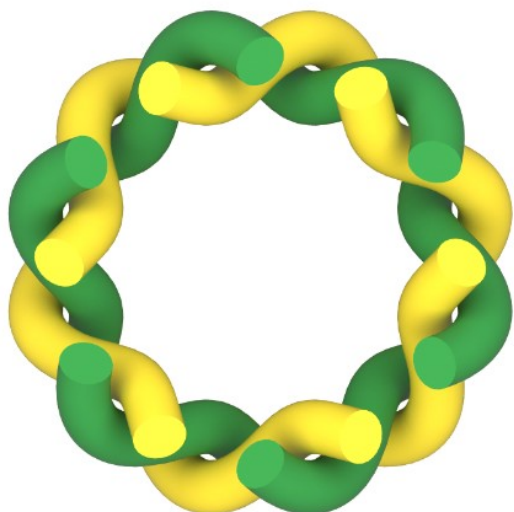


Figure 4.12 Top view of Figure 4.10

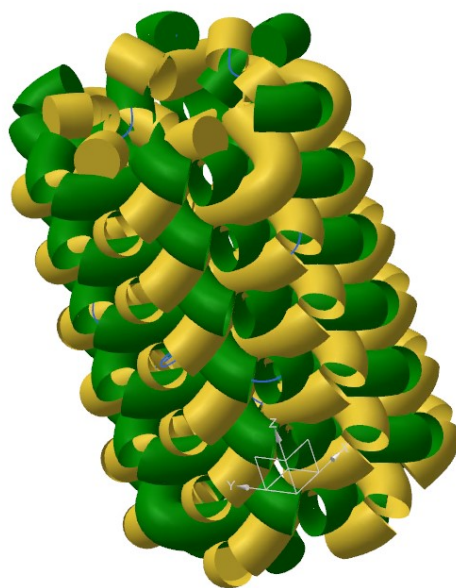


Figure 4.13 Model crashes when a short lead is combined with high amplitude.
 $2N=12$, $A=1,5$, $Ds=2$, $R=5$ and $L=20$

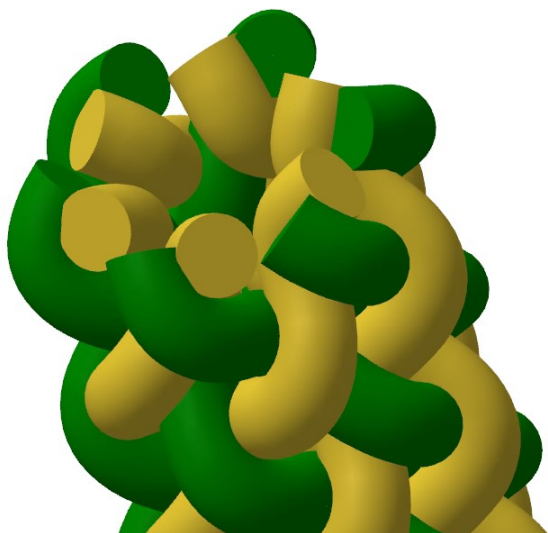


Figure 4.14 Braided rope where $2N=12$, $A=1,5$, $Ds=3$, $R=5$ and $L=50$. Due to large Ds , the strands are intersecting

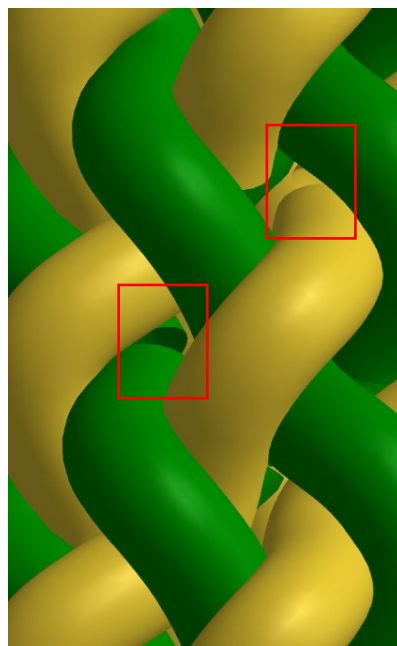


Figure 4.15 Due to large Ds the strands are intersecting and causing a discontinuity in the tube function

As there are no layers in the diamond braid model, it is in many ways easier than the twisted rope; but there are some challenges with this as well. Figure 4.13 shows how the model crash when a short lead is combined with high amplitude and large diameter of the strands. Another issue is shown in Figure 4.14 and Figure 4.15; where the strands intersect when the diameter of the strands is too large and creates a discontinuity in the tube function. If this happens, one can start with adjusting one of the three variables A , L , and D_s . The model will update and work properly when the values are adjusted correctly. Some of these problems can be avoided by staying within limits found for some of the variables. The limits are as follows:

$$R > A \qquad R > D_s \qquad D_s < 2A$$

All this shows that a parametric CAD model, with some limits, can be made of a diamond braid using expressions in NX. In addition, a model of a regular braid, which is explained in chapter 2.2.1, is developed using the equations for the modified rose curve. The equations were first plotted in MATLAB, see appendix 2 for the script, to verify that the equations were correct and would give the desired curve. In the script the variables, N , a , b and R can be changed, and a curve is plotted in the xy -plane, Figure 4.16. This gave good results, and by using the same method from chapter 3.2.4 the modified rose curve equations, adding a vertical component in Z -direction, were entered in expressions to make a regular braid. The result of this was deceptive as the equations could not be used in expressions. As mentioned in chapter 3.2.1 the modulo operation that is used to alternate between the two equations, making the modified rose curve, can't be used with the parameter t . This was an obstacle that could not be overcome, and a parametric model of the regular braid could not be developed using the expressions dialog in Siemens NX.

Another attempt at the regular braid was to use the same equations as for the diamond braid. A model was developed by moving the start point of the strands and adjusting the values to make the strands fit under and over each other. This is not parametric, and the values cannot be changed without spending a lot of time moving the start point again, making them fit. Figure 4.17 shows that using the generalized rose curve is possible, but it is a bad substitution of the modified rose curve.

Early in the process a helical curve was developed in Python and imported as a dwg . file in NX. This could be a way of using more complex equations, such as the modified rose curve equation, to make spatial curves, were using the expressions dialog in NX is insufficient. When the curve was imported in NX, it was divided into several small segments, which created trouble when applying a thickness to the curve.

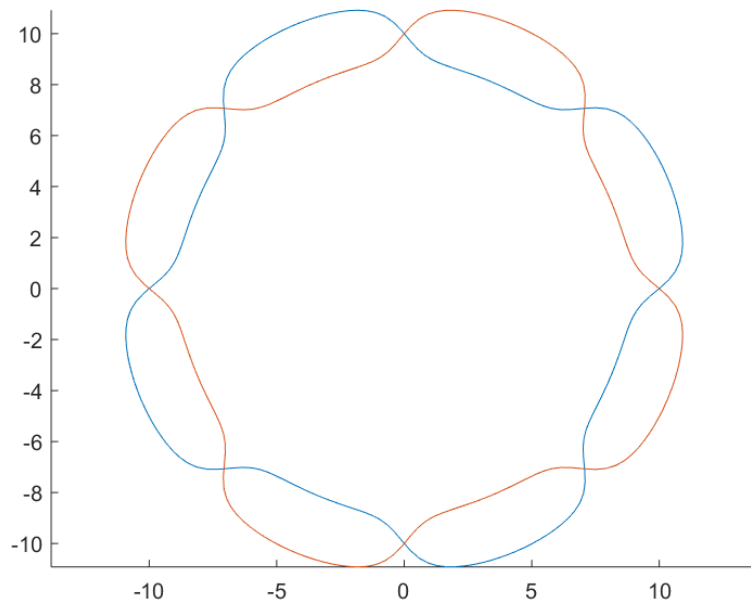


Figure 4.16 MATLAB plot of two modified rose curves. $N=4$, $a=2$, $b=\pm 1,5$ and $R=10$

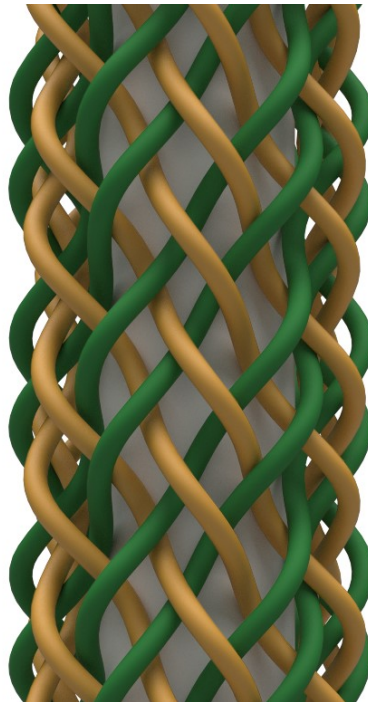


Figure 4.17 Regular braid using the generalized rose curve equation and manipulating the values to make it fit.

4.4 Application of parametric rope models in FEA

This section will present the result from the finite element analysis. The objective was to show one application of the model and to verify the suitability of a commercial software for this type of analysis.

Different models have been tried, primarily of twisted ropes. Although there has been little success getting good results, valuable information and experience have been achieved. A rope is a relatively small geometry with large forces acting in its length. The tension applied to the end of the rope creates contact and forces between the strands. These forces are relatively small in proportion to the large force applied at the end. This creates inconsistencies in the analysis. A simple test case is used, with two strands twisted together, as described in section 3.3. The geometry is imported, and the meshing and boundary conditions are applied as desired. Even though the distance between the strands is small, 2mm, it requires a large axial force to make contact between them. In this case, the force applied is 1000kN. The analysis converges and proves that a simulation of this kind of geometry is possible using Siemens NX. Figure 4.18 and Figure 4.19 shows the results of the simulation.

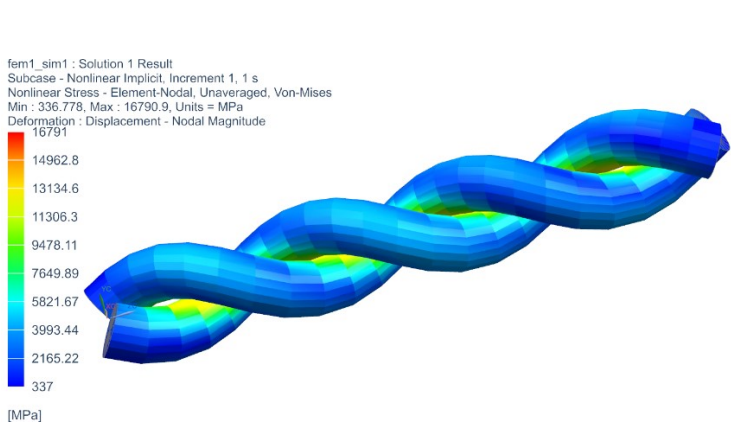


Figure 4.18 Stress plot of two strands twisted model

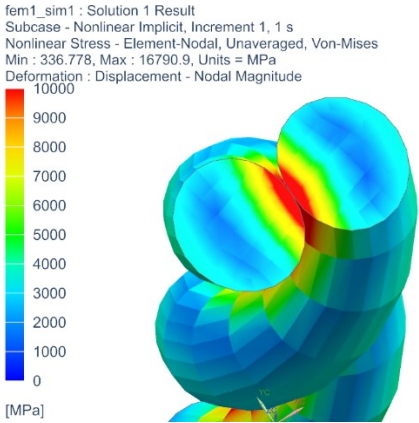


Figure 4.19 Stress plot. Cross-section of two strands twisted.

When analyzing more complex geometries with several strands, the automatic contact algorithm struggles, as there will be thousands of contact combinations between each strand. This complicates the analysis and may be one reason the solutions fail to converge. Other reasons the solver fail is due to the large difference in axial and radial forces and displacement, as mentioned in the previous paragraph. Figure 4.20 illustrates how the forces act in the rope. When tension is applied, it will compress the strands together increasing the force between them. There will be small displacement and large forces in the rope's axial direction and small forces with large displacement in the radial direction and this ill-posed, stiff problem, the numerical solver fails to handle

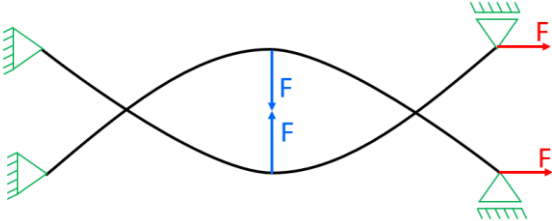


Figure 4.20 Boundary conditions and force distributions

5 Conclusion and future work

5.1 Conclusion

Fiber ropes are becoming more and more common in heavy lifting operations, and there is a need for smart ways to calculate and understanding the properties and behavior of the rope. In this thesis, the objective was to contribute in this field by developing a parametric CAD model of a braided rope; intended for structural strength analysis. The model was developed using the expressions dialog in Siemens NX and validated using NX Nastran for analysis. Initial models were created of a twisted wire as the spatial curve for a twisted rope can be easily described using the mathematical equations for a helix. Further, the rose curve equations from (Ning, Potluri, Yu, & Hearle, 2017) was used to develop a model of a braided rope. A diamond braid was made successfully. During the process of modeling a regular braid it was discovered major limitations in Siemens NX's expressions dialog. As a result, a model with the regular braid pattern could not be developed. Finite elements analysis was performed on two strands twisted together. The objective was to show one application for the model and to check if a multipurpose software like Siemens NX is suitable for analysis of such geometries.

The work and research that has been done in this thesis show that creating a parametric model of a twisted and braided rope is possible using Siemens NX. The diamond braid was the most successful model where the limits of each value were clear, as opposed to the twisted wire. The twisted wire model initially had problems with strands intersecting, but this was solved by deriving an equation for the radius, from the center to the point of tangency of the ellipses. When adding several layers, the layers would intersect or have large gaps depending on the values used. There was no clear relationship between the values to prevent this. To make the model as desired, one would have to proceed tentatively, which is not a good outcome. As mentioned, the diamond braid was the most successful, by following the marginal values for the variables the model will update and work correctly. Common sense is a necessity when using the model as it is not foolproof; there may still be errors that have not yet been discovered. In addition, a model with other braid pattern was initiated. Early it was discovered that Siemens NX could not handle the needed mathematical operators, and therefore, the model could not be made. Other alternatives to apply the equations in NX should be investigated as Ning managed to do this in (2017) in a similar software, SolidWorks. The overall impression from this research is that Siemens NX is not the best-suited software for this type of modeling. Even making the spatial curve in other programs made for mathematical programming, such as MATLAB and Python, and importing it in NX created problems when giving the curve a thickness. If this obstacle is overcome, the idea of using a numerical computing program for the mathematical description of the curve is appealing, as NX's expressions dialog are so inelegant. By making a good script in MATLAB or Python, the desired curve can be created and used for 3D modeling in NX. However, this makes the modeling more complex and requires more from the user as he or she must import the curve in NX and

make the 3D model. It would be satisfying if all the steps, mathematical equations, 3D model and FEA, could be done directly in the same software.

Nevertheless, the model of the diamond braid can be said to be fulfilling the requirements. As for the finite element study, the results showed that a simple case with two strands was possible to solve using the contact simulation. Using a high axial force, the strands came into contact with each other. The force between the strands where one percent of the force applied and these large differences in axial and radial force and displacement created problems in the solution. Combined with the complex contact simulation when having a model with multiple strands, the analysis failed to converge and gave no solution. It can seem that the NX Nastran is not suited for this type of geometries, even though it managed to solve the simple case.

Looking back at the research questions from chapter 1.3.1, this thesis has answered as comprehensive as possible with the tools and information available. Research and work done gave good results on the parameters of both twisted and braided ropes and the mathematical description of the maypole braiding machine pattern was best described by the rose curve equations. It was discovered that it was challenging to implement these equations in Siemens NX, and some equations could not be implemented due to limitations in the software. When it comes to the finite element analysis, the research question can't be answered with a simple yes or no. NX Nastran managed to give results on a simple case, but not other configurations. Based on the analysis in this research it can be concluded that Siemens NX might not be the best suited for this type of geometries, and other special software's intended for this type of structures may be more suitable. Further research is recommended in both Siemens NX and software specialized for these types of geometries.

5.2 Future work

Even though a model of a diamond braid was successfully made, there is still a lot to deal with. If one would like to proceed using Siemens NX, other ways of implementing the modified rose curve need to be further investigated. As the expressions dialog in NX is so limited, the possibility to use a numerical computing program for the mathematical description of the curve and then using it in NX to make the 3D model may be the way to go. The main recommendation for further work is to use another software where the mathematical equations can be implemented and used directly in the making of the 3D model. (Ning, Potluri, Yu, & Hearle, 2017) made their 3D model of braided ropes/structures in SolidWorks, the article does not mention anything about the reusability of their model, and how good SolidWorks are for these types of parametric models, but it may be worth to investigate further and contact them for more information. FEA has a lot of potential for further work. As the geometry might be too complex for analysis in Siemens NX, other software's intended for this type of problems can be used for further research on the inter-strand contact and to study the tensile and transverse strength of different rope configurations.

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Appendix 1 – MATLAB script for twisted rope cross-section

Using symbolic to find an expression for radius r_3 .

```
syms N r1 r3 phi2 L
alpha = pi/N;
theta = atan(L/(2*pi*r3));
r2 = r1/sin(theta);
phi = atan(tan(alpha)*r1/r2);
x = r2*cos(phi);
y = r1*sin(phi);
nx = r1*cos(phi);
ny = r2*sin(phi);
fun = r3 - y - x*nx/ny;
sol = simplify(solve(fun,r3))
```

Twisted rope cross-section

```
clear all; close all;
%% parameter
N = 6; % number of strands
r1 = 1; % strand radius
L = 86 % lead = length per rotation
%% calculation
alpha = pi/N;
r3 = L*r1*((tan(pi/N)^2 + 1)/(L^2*tan(pi/N)^2 - 4*pi^2*r1^2))^(1/2);
% r3 = abs(r3) % in case small lead results in complex solution for r3 use
% slope angle
theta = atan(L/(pi*2*r3))
% major radius
r2 = r1/sin(theta);
% contact point angle
phi = asin(r1/r3);
% contact point
x = r2*cos(phi);
y = r1*sin(phi);
% normal vector
nx = r1*cos(phi);
ny = r2*sin(phi);
% normalizing normal vector, just for plotting
mag = sqrt(nx^2+ny^2)/r1;
```

```

nx = nx/mag;
ny = ny/mag;

% tangent vector
tx = ny;
ty = -nx;

%% results
fprintf('r1 = %f\nr2 = %f\nr3 = %f\nalpha = %f\ntheta = %f\nphi = %f\n', [r1,r2,r3,alpha*180/pi,theta*180/pi,phi*180/pi])

%% plotting
points_ellipse = get_ellipse(r1,r2,100,0,0,0);
points_minor = get_ellipse(r1,r1,100,0,0,0);
points_major = get_ellipse(r2,r2,100,0,0,0);

hold on

plot(points_ellipse(:,1),points_ellipse(:,2),'-k','linewidth',3)

for i=2:N

    points_tmp = get_ellipse(r1,r2,100,0,r3,(i-1)*alpha*2);
    plot(points_tmp(:,1),points_tmp(:,2),'-', 'color','k','linewidth',1)

end

plot(points_minor(:,1),points_minor(:,2),'--k','linewidth',1)
plot(points_major(:,1),points_major(:,2),'--k','linewidth',1)
plot(x,y,'or')
plot(0,r3,'xk')

plot([0,x],[0,y],'-g','linewidth',2)
plot([x,0],[y,r3],'-r','linewidth',2)
plot([0,0],[0,r3],'-b','linewidth',2)
quiver(x,y,nx,ny,'color',[0.5,0.5,0.5],'linewidth',2)

quiver(x,y,tx,ty,'color','r','linewidth',2)
axis equal

% grid on

set(gca,'visible','off')
print('wire_cross_section','-dpng','-r200')

```

Appendix 2 - MATLAB script for modified rose curve

```
function [] = parametric_rose_curve()

close all;
N = 4;
a = 2;
b = 1.5;
R = 10;

nt = 200;
t = linspace(0,2*pi,nt);

xy = para_rose(N,a,b,R,t);
xy2 = para_rose(N,a,-b,R,t);

hold on
plot(xy(:,1),xy(:,2));
plot(xy2(:,1),xy2(:,2));
axis equal

end

function [xy] = para_rose(N,a,b,R,t)

nt = size(t,2);
xy = zeros([nt,2]);

for i=1:nt

theta = mod(sin(N*t(i)),2*pi);

if (0<=theta) && (theta<=pi)

x = ( R + a*b/sqrt(a^2+b^2+cot(N*t(i))^2 ) ) * cos(t(i));
y = ( R + a*b/sqrt(a^2+b^2+cot(N*t(i))^2 ) ) * sin(t(i));

elseif (pi<theta) && (theta<(2*pi))

x = ( R - a*b/sqrt(a^2+b^2+cot(N*t(i))^2 ) ) * cos(t(i));
y = ( R - a*b/sqrt(a^2+b^2+cot(N*t(i))^2 ) ) * sin(t(i));

else

disp("out of range")
x = 0;
y = 0;

end

xy(i,:) = [x,y];

end

end
```

