Modeling of Steel Ropes

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Abstract: Steel ropes are used in lifting applications, aerial ropeways, structures and buildings. To suit all these applications, ropes exist in a large variety of constructions. Their commonality is the build-up from individual wires. They are arranged in a spiral geometry and are in contact with each other.

The first rope in an industrial application was used in 1854 and ever since engineers have tried to predict geometry and properties of ropes by analytical methods. Due to the complex build-up of ropes and their nonlinearity in geometry and material this has only been partially achieved. It often resulted in painfully long and complicated formulae which additionally rely on assumptions and varies generally unknown parameters.

FE predictions of rope properties started in the early 1970s but it was restricted at the time. The developments in finite element software as well as in computer technology in respect to contact and model size in the recent years have made it much more feasible not only from a scientific but also from a practical point of view.

The paper shows an approach in modeling steel ropes with Abaqus with the goal to simulate properties like elongation, torque and turn. The FE predictions are compared with proven analytical methods and test results.

1. Introduction

1.1 Types of ropes

Ropes are prefabricated tension components made from individual wires. The company Bridon is one of the world's leading manufacturers of wire and ropes in all applications including ropes for offshore platforms, cranes, mining and structures. A large variety of ropes exists to suit all these applications. The ropes for structures as bridges, roofs and stayed masts are used in the following to describe the principles in the build-up of different ropes.

The commonality of all ropes is that the individual wires are arranged in a spiral geometry. The wires are made from high carbon steel and have a nominal tensile strength of up to 1770 N/mm^2. The most straight forward rope is a spiral strand (Figure 1). It is made using round wires in several layers. The layers are usually spun in opposite directions to minimize the residual torque. The typical range starts at 13 mm in diameter and goes up to 165 mm.

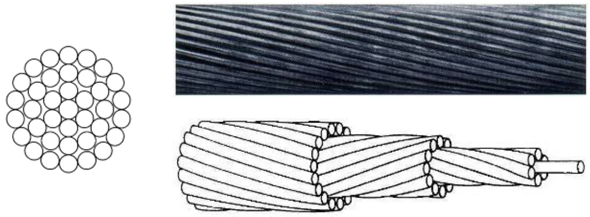

Figure 1: Spiral strand cross section and side view

Locked coil strands (Figure 2) are a special type of spiral strand. They are built up with a core of spirally spun round wires in several layers onto which covers of spirally spun full lock wires in several layers are added. Full lock wires are wires of non-circular cross section. Again the layers are usually spun in opposite directions to minimize the residual torque. The typical range starts at 20 mm in diameter and goes up to 180 mm.

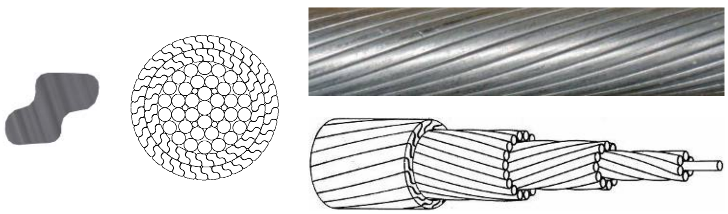

Figure 2: Full lock wire, locked coil strand cross section and locked coil strand side view

Stranded ropes (Figure 3) use strands in a spiral arrangement. The typical range starts at 13 mm in diameter and goes up to 100 mm.

Figure 3: Stranded rope cross section and side view

A stranded rope provides a suitable basis to describe the terminology used for steel wire ropes:

- Wire – a single element
- Strand – a number of single wires twisted together
- Rope – a number of strands twisted around a central core of steel or fibre

However when a strand is a finished product like in the case of a spiral strand or a locked coil strand it is also referred to as a rope and to complete the confusion sometimes the term cable is used instead of rope.

1.2 Manufacturing of ropes

Ropes are made in several manufacturing steps. Figure 4 shows the manufacturing process in a sketch and several pictures. The wires (or strands in the case of a stranded rope) for each manufacturing step are wound on bobbins on a closing machine. This machine rotates around the existing rope which is pulled through the centre of the machine. At the very beginning the existing rope would be a single wire.

Wires (or strands in the case of a stranded rope) which lay in the same spiral direction can be applied in the same manufacturing step but every time when the direction of the spiral changes a new manufacturing step is needed.

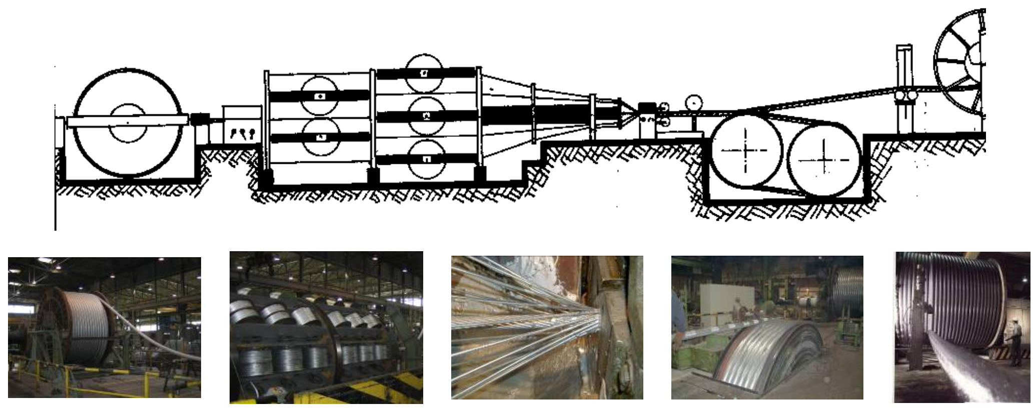

Figure 4: Manufacturing of steel wire ropes

2. Modeling

2.1 General

The aim of the FEA model is to simulate the rope properties on a macroscopic scale. Properties and details of interest are

- extension under load,
- torque under load,
- turn under load,
- bending stiffness,

- effect of bending on the geometry of the wire arrangement,
- load sharing between the wires.

The FEA efforts so far mainly went into establishing a stable modeling technique.

Abaqus version 6.8-1 was used on a 64 bit computer with 4 gigabyte RAM and four processors of 2.5 GHz. The analyses as described in this paper took approximately 15 minutes.

The repetitive tasks to be performed to create the rope make it suitable for scripting. This was done using the Python language built into Abaqus.

2.2 Description of the rope build-up

The rope chosen for this paper is a spiral strand with a diameter of 29.9 mm. It is build up from a so called 25 Filler core and one layer of round wires (Figure 5). The 25 Filler core consists of 25 wires which are all spun in the same direction in one manufacturing step. The next layer consists of 18 round wires that are laid in the opposite direction in a second manufacturing step.

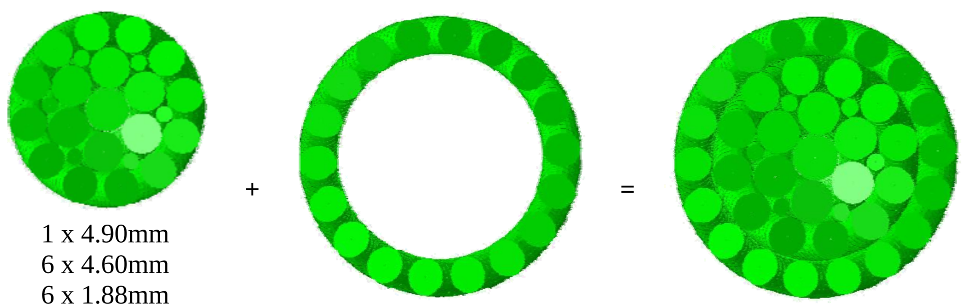

Figure 5: Rope build-up

The lay length describes the length after which a wire reappears at the same angular position along the longitudinal axis of the rope. As the wires in the 25 Filler core are lying parallel in the same direction their lay length is the same. The lay length of the final cover is independent from the core.

The minimum breaking load (MBL) of a rope is the load that will always be exceeded in a breaking load test on an undamaged rope. The MBL of the present rope is 762 kN. The sum of the cross section of all wires is 528 mm^2.

2.3 Modeling of the wires

The relatively small rope chosen for this paper consists already of 43 wires. One additional layer of round wires would increase the number of wires to 67 and the subsequent layer to 97. The number of wires is highest for stranded ropes and can go up to the order of 1000. This clearly makes it unfeasible to model the wires as volumes with 3-dimensional elements.

The individual wires are therefore modeled as beam sections integrated during the analysis (Section 24.3.6 of the Analysis User’s Manual). A beam section integrated during the analysis

- is used when section properties must be recomputed as the beam deforms over the course of the analysis; and
- can be associated with linear or nonlinear material behavior.

A section shape can be chosen from the library of beam section shapes and the section's dimensions can be defined, in this case a circle with a radius. A material definition is used to define the material properties of the section which is then associated with the section definition. A linear elastic, linear plastic material stress strain curve has been assumed. Abaqus provides for a possible uniform cross-sectional area change by specifying an effective Poisson's ratio for the section in a geometrically nonlinear analysis. This models the reduction in the cross-sectional area when subjected to large axial stretch. The value of the effective Poisson's ratio is taken as 0.3 which is a typical value for steel. Beam sections do not allow considering deformations from lateral pressure and do not provide details about contact stresses.

Beam sections can be in contact with each other in an explicit analysis. General contact in Abaqus/Explicit can effectively deal with the large number of contacts (Chapter 30 of the Analysis User’s Manual).

By default, the general contact algorithm requires that the contact thickness does not exceed a certain fraction of the surface facet edge lengths or diagonal lengths (Section 30.3.6 of the Analysis User’s Manual). This is to avoid self-contact with neighboring facets. The general contact algorithm will scale back the contact thickness automatically where necessary without affecting the thickness used in the element computations for the underlying elements.

In the present case of wires Abaqus starts reducing the contact thickness when the element length becomes smaller than 1.667 times the wire diameter. This restriction on the element length is not acceptable as a finer meshing is needed to model the curvature of the wires in the rope. Element lengths between 2.8 mm and 4.0 mm have been used depending on the curvature of the wire in the rope.

It is possible to exclude self-contact via the contact exclusion definition and as self-contact is not occurring in the rope it does not compromise the analysis:

```
*CONTACT CONTROLS ASSIGNMENT,
        CONTACT THICKNESS REDUCTION=NOPERIMSELF
```

This lines need to be added in the keyword editor in the “**Interaction: contact” section of every step. It does not automatically get forwarded to subsequent steps.

2.4 Modeling of the rope geometry

The geometry of a rope and especially of a stranded rope is complex. It was therefore decided to build up the rope similar to the manufacturing process. The wires are modeled as straight cylinders which are placed in approximate positions. In the first analyses step they are twisted into their spiral arrangement. This is done in Abaqus/Explicit as a quasi static analysis.

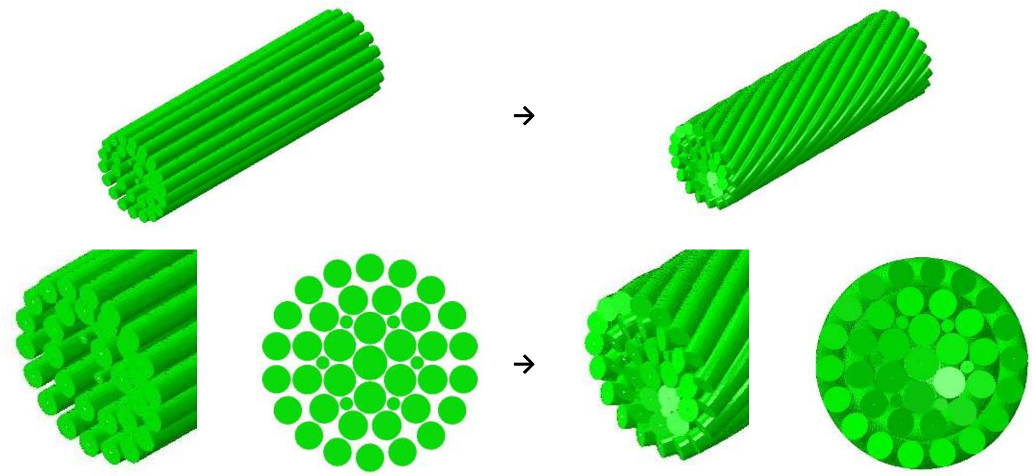

Figure 6: Twisting of the wires in the analysis

It can be seen that

- the straight wires need to be of different length to compensate for the spiral arrangement,
- the wire ends need to be free to rotate.

The rope length modeled and shown in Figure 6 is half the lay length of the outer layer. If the wires would describe a perfect helix and therefore would have a constant curvature throughout the rope then in theory the length of rope modeled could be infinitesimal small. In reality the wires of the outer layer are only supported 12 times per lay length on the wires of the underlying layer and will therefore describe a polygon under load rather than a constant curvature helix. The length of the rope and the density of the wire mesh need to capture these effects. At half the lay length of the outer layer these effects are considered. It has not been investigated now by how much that length could be reduced.

2.5 Boundary conditions

The formulation of the boundary conditions is essential for the interaction between the wires and the behavior of the rope. Connectors have been used to control the wire ends and to apply the twist to the rope. Connectors allow modeling a connection between two points in an assembly. A connector consists of an assembly-level wire feature, a connector section, and a connector section assignment that associates the connector section with selected wires.

At each rope end the following reference points have been created:

- One master reference point where the rope can be held and where a force can be applied to the rope
- One link reference point per layer as defined in Figure 7
- One twist reference point per layer as defined in Figure 7

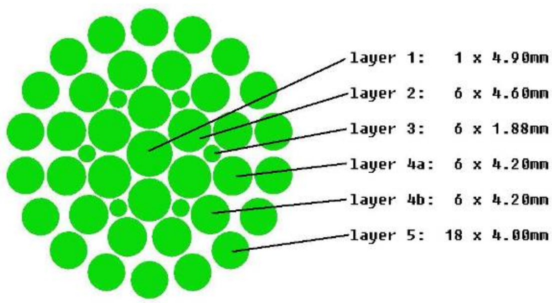

Figure 7: Definition of the individual layers in the rope

Each beam section end is connected to its layer link reference point via a "cylindrical connector". "Cylindrical connectors" are assembled connectors (Figure 8) (Section 26.1.5 of the Analysis User's Manual). They allow

- the wire to freely rotate around the connectors axis,
- the wire to travel towards or away from the rope centre to be in contact with the underlying wires,
- the whole layer to be twisted by applying a rotation to the layer link reference point.

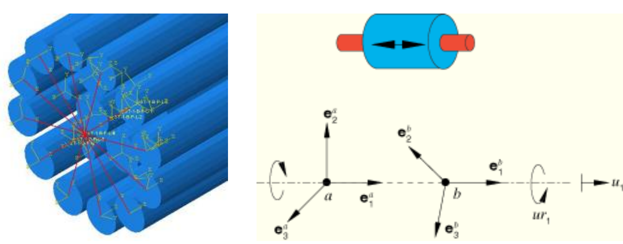

Figure 8: Connections between beam section ends and the layer link reference point

Each layer link reference point is connected to the master reference point (Figure 9). Again the "cylindrical connector" was chosen. It allows

- the individual layers moving into the ropes longitudinal axis during the twist,
- locking the movements in the ropes longitudinal axis after the twist allowing the layers to act together.

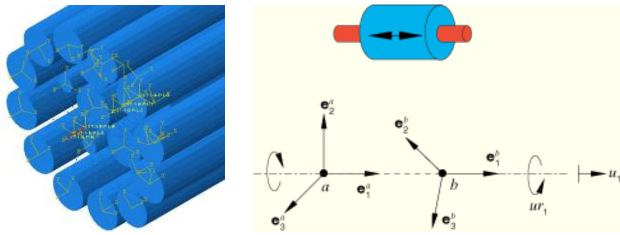

Figure 9: Connection between a layer link reference points and the master reference point

Each layer link reference point is additionally connected via a "constant velocity connector" to the layer twist reference point (Figure 10) (Section 26.1.5 of the Analysis User's Manual). This connection type models physical connectors that transmit a constant spinning velocity about misaligned shafts. The twist for the individual layers is applied as a rotation to the twist reference points which can be placed at any location.

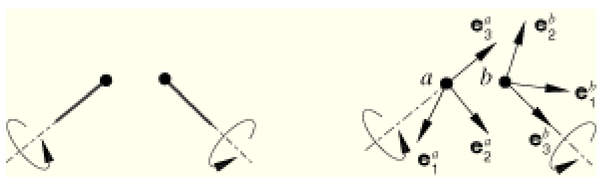

Figure 10: Connection between a layer link reference point and a layer twist reference point

2.6 Analysis steps

The analysis is done in Abaqus/Explicit as a quasi static analysis. It consists of three steps:

Step 1 (time=0.005):

- The twist for the individual layers is applied as a rotation to the layer twist reference points.
- A small tension is applied to the layer link reference points to stabilize the twisting.

Step 2 (time=0.002):

- The axial movement of the cylindrical connectors in the ropes axial direction is set to zero.
- The rotational degree of freedom of the cylindrical connectors in the ropes axial direction is set to zero.
- The rotation of the master point is set to zero.
- The rotation on the layer twist reference points is freed.

Step 3(time=0.0125):

- A force of 457 kN (60% of the MBL) is applied to the rope.

The modeling of the manufacturing process has primarily been chosen because it makes generating the actual rope model easier. This might not be obvious for the relatively easy geometry of the rope described in this paper but it will show its full benefit when it comes to stranded ropes. There might also be benefits in considering the non-linear pre-loads during manufacturing if these affect the resulting rope properties. However this has not been proven now. The drawback of the method of course is the longer time for solving.

3. Results

3.1 General

The development of modeling ropes is still ongoing. The first results are promising and it looks like the rope properties can be predicted reasonably precise. However a detailed study about how parameters like the material definition, the mesh density, the rope length and the step times are influencing the results is ongoing.

3.2 Energy

In a quasi static dynamic analysis it needs checking if the kinetic energy is small enough to neglect its influence on the results. Figure 14 shows the total energy ALLIE, the plastic dissipation energy ALLPD and the kinetic energy ALLKE. Obviously a lot of energy goes into plastic deformation of the wires and the kinetic energy is very small.

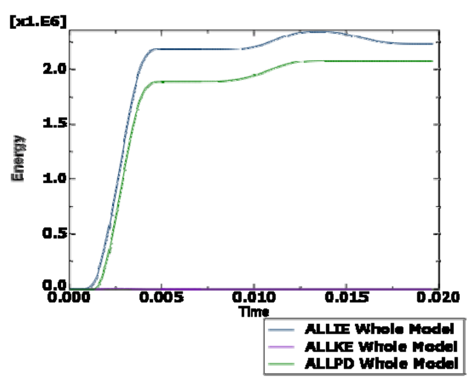

Figure 11: Total, plastic and kinetic energy

3.3 Wire forces and stresses

The load sharing between wires of different layers is displayed in Figure 12. The comparison with values calculated with an analytical method at the peak load of 60% MBL shows good correlation (Table 1). When calculating the stresses it can be seen that the stresses decrease from the inside to the outside of the rope even resulting in permanent elongation of the king wire. This uneven distribution of stresses is because of the fact that the length of the wires per rope length due to the spiral assembly usually increases from the inside to the outside of a rope.

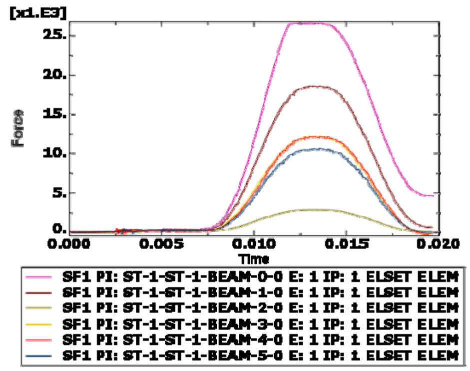

Figure 12: Wire forces

Table 1: Wire forces and stresses

	Analytical method		FEA result	
	Force [kN]	Stress [N/mm^2]	Force [kN]	Stress [N/mm^2]
1 x 4.90mm	21.1	1120	26.6	1411
6 x 4.60mm	17.4	1049	18.6	1119
6 x 1.88mm	2.8	997	2.9	1045
12 x 4.20mm	12.6	908	12.2	881
18 x 4.00mm	11.0	873	10.6	844

3.4 Load elongation

Figure 13 shows a typical load elongation graph of a rope from a physical test. During the first loading quite significant settlements are taking place but after five to ten loading cycles in the working load range the rope behaves elastically. After unloading a permanent elongation remains.

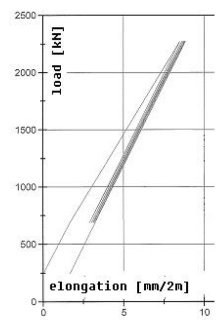

Figure 13: Typical load elongation graph

The calculation of the elastic axial stiffness is a well established method. The elastic axial stiffness is the product of the elastic strand modulus and the metallic cross sectional area. The elastic strand modulus is not a material property but a phenomenological property which describes the elongation characteristics of the strand. It considers the material elastic modulus of the wires as well as the geometrical arrangement of the wires in the strand. The analytically calculated value for the elastic strand modulus between 30 and 40% of the rope's MBL is 145 N/mm^2.

The load elongation graph from the FEA calculation is displayed in Figure 14. Unfortunately there is no full test graph of this rope to compare it against but it shows the typical settlement during the first load cycle and a linear behavior after that. The elastic strand modulus between 30 and 40% of the rope's MBL is 147 N/mm^2 which is very close to the 145 N/mm^2 mentioned above.

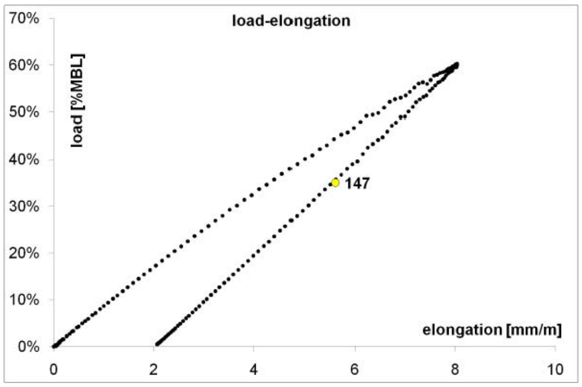

Figure 14: Load elongation graph from the FEA results

3.5 Torque

The spiral geometry of the individual layers of wires creates a load dependent torque around the ropes longitudinal axis. The effects partially balance out between the layers of different lay direction. The remaining torque, if of interest, can be determined in a load-torque test. This is a test on a length of rope which is fixed at both ends in terms of displacement as well as rotation. During the loading of the sample the moment needed to prevent the rope from turning is measured.

This test is relatively complicated and therefore not very often undertaken. The behavior is usually assumed to be linear and theoretical predictions exist which are less accurate than those for the load elongation characteristic. The value for the torque at 25% MBL is calculated with analytical methods to be 197 Nm. The FEA prediction confirms the linear relationship but predicts a value of 162 Nm (Figure 15) between zero load and 25% MBL.

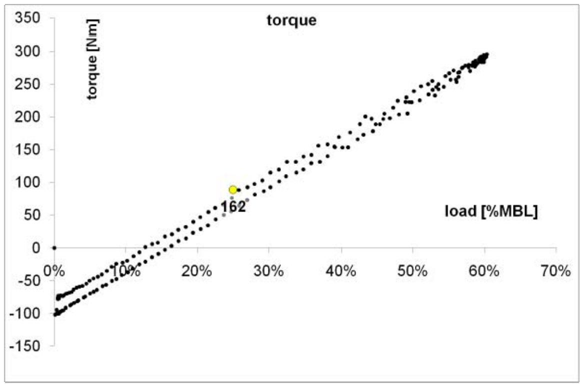

Figure 15: Load torque graph from FEA results

3.6 Turn

In a similar test to the load-torque test the load-turn characteristic can be determined. Instead of fixing the rotational movement it is left free. During the loading of the sample the rotation of the free end is measured.

To model the load-turn behavior the rotation of the master point must not be set to zero in step 2. The analysis for turn was less stable with the rope length being half the lay length of the outer layer. Therefore the rope length modeled was taken as a quarter of the lay length of the outer layer.

As with load-torque testing, load-turn testing is relatively complicated and therefore not very often undertaken. The behavior is usually assumed to be linear and hand calculations exist which are less accurate than those for the load elongations characteristic. The value for the turn at 25% MBL is calculated with analytical calculations to be 7.7 degrees/m. The FEA prediction confirms the linear relationship only after the first loading. The first loading itself is relatively non-linear. The turn predicted by the FEA analysis at 25% MBL is 11.7 degrees/m during the first loading and 12.1 degrees/m in subsequent loadings (Figure 16) between zero load and 25% MBL.

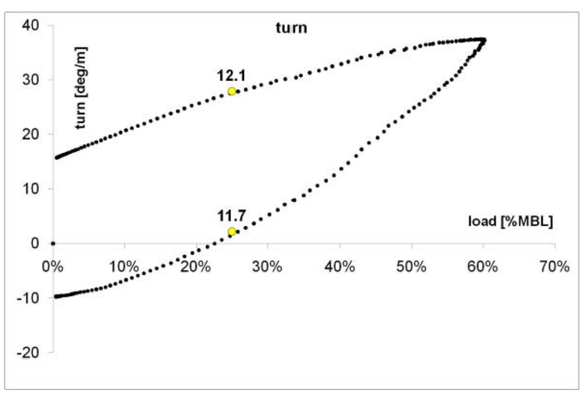

Figure 16: Load turn graph from FEA results

4. Conclusion

The paper shows the modeling of ropes in Abaqus/Explicit as a quasi static analysis using beam sections integrated during the analysis for the individual wires. This method allows efficiently modeling the big number of wires and contacts as well as the build-up of the complex geometry. It provides a method to simulate the rope properties on a macroscopic scale.
As an example a rope with 43 wires consisting of a 25 wire core and an additional layer of 18 wires was chosen and the comparison with calculations and qualitative behavior shows good correlation.

5. Outlook

A detailed study needs to be performed to clarify how parameters like the material definition, the mesh density, the rope length and the step times are influencing the results.

When envisaging modeling full lock ropes a different approach is needed for the non-circular full lock wires. First attempts have been done using a general beam section. Nonlinear properties can be defined for axial, bending and torsional behavior by tables.

When modeling a stranded rope the geometry of a strand would need to be twisted in an additional calculation step. The principle way forward for the boundary conditions should stay the same.