Specialization: Transport Engineering and Logistics
Report number: 2016.TEL.8007
Title: Introducing friction in a parametric FEM model of multi-layer drums
Author: T. Kleefstra

Assignment: Research
Confidential: no
Initiator (university): ir. W. van de Bos
Supervisor: ir. W. van den Bos
Date: June 9, 2015

This report consists of 24 pages and 1 appendix. It may only be reproduced literally and as a whole. For commercial purposes only with written authorization of Delft University of Technology. Requests for consult are only taken into consideration under the condition that the applicant denies all legal rights on liabilities concerning the contents of the advice.
Summary

Increasing rope length in maritime and transportation appliances demand for multi-layer winches where multiple layers of rope winding stack on top each other. The stacking layers will deform the layers of rope winding underneath them. The effect of this has already been researched. However, the effect of friction between the ropes has always been ignored. This paper continues the work done by W. van den Bos, by including new contact elements between rope windings that can handle friction forces.

The model used in this study is a simple representation of a winch build-up with standard elements. The cables are represented by a combination of tension elements for axial tensile strength, and volume elements for radial stiffness. In between the rope windings of two different layers are CONTA178 node-to-node contact elements used to represent friction forces.

Two versions of the same winch model are compared. The first with a coefficient of friction of $\mu = 0.5$ and the second model without friction. This coefficient is representative for dry steel-on-steel friction.

Changes are made to the script files in order to cope with wire tension problems. The previous model had trouble with finding the proper wire tension for higher rope layers. Adjustments are made to the way of iterating per layer, restart between iterations, and determination of initial wire tension for each new layer.

The effect of friction between layers reduces the flange forces significantly while the pressure on the barrel is only slightly increased. The lower flange forces result in lesser flange displacement and less bending moment stresses at the connection of flanges and barrel. The introduction of friction also shows a less conservative result compared to the DNV certification for lifting appliances, than the frictionless model does.
Contents

1. Introduction .................................................................................................................................................. 5
2. FEM model description ................................................................................................................................. 7
3. Changes to the Ansys script files ................................................................................................................ 9
4. Results ......................................................................................................................................................... 16
5. Conclusion .................................................................................................................................................. 24
6. References .................................................................................................................................................. 24
Appendix A. CONTA178 element description ................................................................................................. 25
1. Introduction

Many machines in the maritime and transportation industry make use of ropes and winches to do heavy lifting. The use of increasingly longer ropes makes for a higher demand of winches with multiple rope layers on the drum. This stacking of tensioned ropes on a winch drum increases the complexity of strength calculation. However the industry will usually prefer to use simple certification rules [1].

In order to better understand the complexity of multi-layered rope winches research has been done on both winch design[2] and rope behaviour[3]. High pressure values build up on the winch drum as well as the first layers of rope on a multi-layered winch. Besides the influence on the structural strength of the winch drum, these high pressures can also cause damage to the ropes themselves and reduce its fatigue life[4], [5].

An attempt has also been made to study the combined effect of winch stiffness and rope behaviour by use of a FEM model. In 1971, Dietz[6] build a simple FEM model which was limited in its use due to computer power limitations. Relatively complex elements were used with only as much degrees of freedom as necessary. Also non-linear effects were not taken into account, such as contact between ropes and the difference between tension and compression stiffness.

Later, a new axisymmetric FEM model, proposed by W. van den Bos[7] was used as an extension to the Dietz FEM model. Computing power was considerable increased which allowed for standard elements with more degrees of freedom, instead of the limited complex elements used before. This new FEM model showed pressure results on the winch drum which were much closer to measured values than the old Dietz model as can be seen in Figure 1. However, the non-linear effect of friction between the windings was still ignored in this new model.

Figure 1 C-value for different layer numbers and different radial rope stiffness. Dietz FEM results (black) and the axisymmetric model (coloured) versus measured data [6].
This study is a continuation of the work by W. van den Bos which was presented at the OIPEEC Conference 2015. In this paper the FEM model will be extended with new node-to-node contact elements between rope windings. With this new CONTA178 element, the influence of friction between rope and winch and in between windings can be investigated. Especially the influence of friction between rope windings on the reduction of flange pressure is of interest. A reference of the CONTA178 element is provided in Appendix A. CONTA178 element description, together with a description of its input parameters.

In the previous study, two different loading situations were used to test the winch model. The first load case is hoisting, for which tension in the rope is constant for all layers. The second load case is mooring, where the first two layers have a significant lower initial tension (40%) due to the lower forces involved in mooring of ship to shore. The two load cases will be regarded in this paper as well to see whether friction between the layers has an influence on the results.

The previous model also had a problem with finding the proper wire tension for higher layers of rope windings. This study presents a solution by changing the FEM model script files. Changes are made to the way calculation iterations are done per layer. Also the restart procedure during these calculations is changed. And finally the way in which the initial wire tension for each layer is calculated.
2. FEM model description

The axisymmetric FEM model used in this paper is the same as used by W. van den Bos[7]. It models the ropes by a combination of standard elements, which combined describe the axial and radial rope behaviour. Tension only elements (orange) are used on the circumference of the rope for axial stiffness. The radial stiffness is provided by standard volume elements (green). In this paper a radial stiffness is used with $E_{\text{radial}} = 950$ MPa.

![Figure 2 Rope model. Left: a schematic cross section of the actual rope. Right: combination of tension only rod elements (orange) and standard volume elements (green). Rod elements show equal effective rope area.](image)

Contact between ropes and winch is modelled by different elements. Contact between ropes on the same layer and between rope and winch is modelled by pressure only rod elements (red). Between different layers contact is modelled by contact elements (blue) that also allow for the effects of friction. In this paper the node-to-node contact element CONTA178 is used.

![Figure 3 Contact between ropes. Pressure only elements between ropes and winch on same layer (red). Contact elements with friction between ropes on different layers (blue).](image)
The difference in contact elements is chosen due to the layering geometry of the model. The new layer of ropes is cradled in the gaps left by the previous layer. The deformation of the ropes due to change in wire load allow for more movement in these gaps and thus for friction forces to occur. Between ropes on the same layer there will hardly be any movement. Therefore the contact can be modelled by pressure only elements.

The winch is built with solid elements and a standard good mesh. The geometry allows for 40 windings per layer and up to 8 layers are used for the calculations.

Figure 4 Complete axisymmetric model of the winch with eight layers of 40 windings.
3. Changes to the Ansys script files

To investigate the influence of friction in the winch model, a couple of changes had to be made to the Ansys script files. This not only included the input of the contact element themselves, but also some other changes in the apply temperature script file. In this chapter the changes to the script files are explained.

3.1. Contact element

```plaintext
!with friction
ET, 43, CONTA170
KEYOPT, 43, 2, 1 !Pure Penalty Method
KEYOPT, 43, 4, 1 !Gap defined by Real Constant
KEYOPT, 43, 10, 4 !No separation between between contact, sliding allowed
MP, mu, 4, friction
R, 43, , 0, 3, , , !no gap at start
```

The new contact elements were created in between rope winding layers by the EINTF procedure. This procedure automatically creates elements between two offset nodes. The old contact elements without friction were created with the same procedure. Therefore only the mesh properties for element type, material type and real constants had to be changed.

```plaintext
!between the cables
allsel, all
csys, 11
nsel, s, loc, x, -r_barrel+(d_cable)/2, n_wonlay*spoed+(d_cable)/4
type, 43 $ mat, 4 $ real, 43
eintf, (r_cable*2-d_cable)
```

3.2. Apply temperature

Changes have been made to the apply temperature file as well. In order to get the resulting wire forces equal to the required wire tension, iteration of the solution is needed. This because applying tension forces to the rope wires of the new layer will deform the rope wires of under laying layers as well. This deformation will reduce the resulting tension forces in the current layer. Therefore the applied wire load has to be increased in order to get to the proper resulting wire forces.

3.2.1. Iteration

The old version of the input file iterated each layer for just three times to get to the proper wire load. However, these three iterations were not enough to get to the proper resulting wire forces for all layers, as can be seen in Figure 5.

The apply temperature script had these three iterations written out after each other within a new layer do-loop. Meaning for every layer these three iterations would always be done. In the new script, these iterations are part of a do-loop as well. Therefore the solution will be iterated as long as no proper solution for the resulting wire forces is found, or a maximum number of iterations have been made. This maximum number was arbitrarily set to 8 iterations, but for most layers the right wire forces were found after less than 5 iterations.
Figure 5 Average rope tension per layer. Note that layer 5 through 8 do not reach up to the proper wire load.

Following is a schematic overview of the adjusted script file showing the iteration do-loop within the new layer loop. The comments represent the other processes done within the input file.

```plaintext
!Add new layer to the solution
*do,layer_,start,no_layer,1
  !Clear storage files to clean up excel files
  !Create 'calc' group with vinch and current layers
  !Determine wire tension for first iteration
  !Solver settings for first iteration
     antype,,new

  !Start new iteration
  *do,iter_,1,no_iter,1
    !Restart solution after initial run
    parset,all,inbetween,PARAM
    antype,,restart
    parset,inbetween,PARAM
    !Copy previous wireloads and resulting forces for corrections

  !Apply corrected wireloads
  *do,wind_,1,n_wonlay,1
    !Iteration correction method
    1. wload(new) = tension + deltaT
    2. wload(new) = wload(old)+dtemp1
    3. wload(new) = wload(old)+dtemp2/delta
    !Apply wload as BFE,all,TEMP
  *endo  !Loop for number of wires on layer

  !Store applied wireloads
  !Solve solution
  !Save resulting cable forces for corrections in current layer
  !Store resulting cable forces
  !Stop iterating when solution is correct
  *endo  !Loop for number of iterations

  !Save final solved cable forces
  !Save results per layer and continue with previous solution for next layer
  !Export result arrays to excel
     /imp,export,ans,batch
  *endo  !Loop for number of cable layers on vinch
```
3.2.2. Wire tension correction

Another adjustment to the old script file was made to the way the initial wire tension was chosen. In the previous version the initial wire tension for the first iteration was determined by looking at the displacement of under laying wire nodes. These would be translated into a force (deltaT) by multiplying the displacement (deltaR) with cable stiffness (A*E). However, this regularly created cable pressure instead of tension forces, requiring more iterations to get to the proper wire tension.

The new iteration starting point has been chosen to be the final wire load from the previous calculation. Due to wire deformation of previous layers, this method is justified, because the required wire tension will always be higher than in the previous layer. In order to cope with differences in required wire tension (i.e. for mooring load cases), the required tension was subtracted from this previous wire load. By doing so only the gained wire tension was transferred to the new layer.

```plaintext
!Determine wire tension for first iteration
  *do,winding_,1,n_wonlay,1
    *if,layer_/GE,2,THEN
      deltaT(winding_,layer_)=wload(winding_,layer_-1)+tension(layer_-1)
    *elseif,calc_res,EQ,0,THEN
      deltaR=0
      deltaT(winding_,layer_)=deltaR/(1000/(pi*r_cable**2))/E_cable
    *endif
  *endo

For the first layer no adjustment to the wire tension was required. Therefore, the deltaT has to be zero, which is done in the *elseif statement. This was unadjusted from the old script version.

Since the old script version had the three iterations written out in order, the correction methods had to be put together into an *if statement in order to get them within one do-loop. There are three different methods for correcting wire loads. These were already used in the old version but will be explained in this report once more.

```plaintext
//Iteration correction method
  *if,iter_EQ,1,THEN
    wload(wind_,layer_)=tension(layer_)+deltaT(wind_,layer_)
  *elseif,iter_EQ,2,THEN
    dtemp1=abs(tension(layer_)*2/wloads(wind_,layer_)*1000)+tension(layer_)
    wload(wind_,layer_)=wload(wind_,layer_)+dtemp1
  *else
    dtemp2=tension(layer_)*1000-wloads(wind_,layer_)
    delta=(wloads(wind_,layer_)-wload_0(wind_,layer_))/(wload(wind_,layer_)-wload_0(wind_,layer_))
    wload(wind_,layer_)=wload(wind_,layer_)+dtemp2/delta
  *endif

The first method, for the first iteration is as already specified before. Here the wire load is corrected by the addition of deltaT to the required wire tension. This results in the same final wire tension of the previous layer, if the required tension for both layers is the same. For different wire tension, only the increase in wire tension is added to the required load. This works fine for increasing wire loads, however, it has not been tested for situations where the new required tension is lower than the previous one.
The second correction method is for the second iteration only, where it will use the results from the first iteration. It will linearly extrapolate to a new wire load as can be seen in Figure 6.

![Figure 6 Second correction method: linear extrapolation from previous result.](image)

For all other iterations the third correction method is used. Here the previous two results are used in order to more accurately extrapolate towards the new wire load as can be seen in Figure 7.

![Figure 7 Third correction method: linear extrapolation from previous two results.](image)

With these correction methods the required wire load will be approached from below. This is important because of the non-linear effect of wire tension. Overshooting the required wire tension will require a decrease in wire tension. However, a restart cannot be made from this overshoot position because the effect of friction is too great. Resulting in inaccurate results for the current and following layers.
3.2.3. Restart procedure

The restart procedure has been changed as well. For the first iteration the solver settings are used that are defined outside the iteration do-loop.

```
!Solver settings
!For first iteration start new analysis
antype,,new
rescontrol,,last,last
outres,all,-1
*if,friction,GT,0,THEN   
nsubst,100/friction*tension(1),100/friction*tension(1),20
*else
  nsubst,100*tension(1),100*tension(1),20
*endif
eqslv,PCG,1E-6
```

Here the final solution is saved by RESCONTROL as the starting point for the next iteration restart. The number of sub steps is taken rather large because of the large difference in new wire tension. With more sub steps the program can better handle the deformations and displacements in the lower laying layers. This is even more important for low values of friction. Here the gap between sliding and sticking is rather small requiring small sub steps in order to get a properly converged solution. Therefore the number of sub steps is increased for lower coefficient of friction values.

The restart solution settings are made inside the iteration do-loop. When an analysis is restarted, Ansys reverts back to the parameters as they were declared before the first new analysis. Therefore, all newly gained parameters, such as resulting wire forces, need to be saved and reload after restart. The number of sub steps can be much lower, since the increase in wire tension is much less than for the first iteration. This speeds-up the calculation considerably.

```
!Restart solution after initial run
*if,iter,,GE,2,THEN
  parsav,all,inbetween,PARAM
  antype,,restart
  outres,all,-10
  *if,friction,GT,0,THEN
    nsubst,tension(1)/friction,10/friction*tension(1),10
  *else
    nsubst,tension(1),10*tension(1),10
  *endif
  parres,,inbetween,PARAM
*endif
```

This iterative restart procedure will get the resulting wire tension as is required. However, not every layer requires the same amount of iterations. Where the first layer needs only two iterations, the other layers often need more. Especially when the required wire tension is increased as for the mooring load case. To speed-up calculation a results test is applied, in order to exit the iteration loop when the test criteria is met.

The criterion used is the ratio between resulting average wire tension and required wire tension. The average wire tension is calculated by the total resulting wire tension divided by the number of rope wires on the layer. When the criterion is greater than 0.99 it will stop the iteration loop. This
boundary is chosen instead of 1 because of the gaps at the beginning or end of each layer. This gap leaves more room for the rope winding to deform, resulting in higher a higher tension for that specific wire compared to the rest. A criterion of 0.99 results in acceptable wire tensions throughout the layer.

```plaintext
!Stop when iteration is enough
   rfor_a = rfor_s / n_wonlay
   iter_test = -rfor_a / tension(layer_) / 1000
   wtest(layer_,iter_)=iter_test

!Loop for number of iterations
   *if,iter_test,LT,0.99,CR,iter_test,GT,1.01,EXIT
   *endif
```

An upper limit is included as well. This should restart a new iteration when the average wire tension is higher than 1.01 of the required wire tension. However, this should not restart a new calculation from that last position, but from the previous last position. This is due to the non-linear friction effect as explained earlier. This has not yet been implemented in the script. However, for the load cases in this paper it proved not to be necessary.
3.2.4. Export stored results

In order to read and process the results from the storage arrays more easily, a new script was created. This script exports the result arrays, wload, rfor and wtens into comma separate value files. These files could then again be imported into excel to better be read and processed.

```fortran
!Create Wload storage csv file
*cfopen, lay%layer & _wload, csv, exlresults
*vwrite, n_wonlay, no_lay, iter_ (F10.6)
*do, c_it, 1, iter_ , 1
  *do, c_lay, 1, no_lay, 1
    *vwrite, wload_g(1, c_lay, c_it) (F20.6)
  *endo
*endo
*cf clos

!Create Resultant force storage csv file
*cfopen, lay%layer & _2rfor, csv, exlresults
*vwrite, n_wonlay, no_lay, iter_ (F10.6)
*do, c_it, 1, iter_ , 1
  *do, c_lay, 1, no_lay, 1
    *vwrite, wload_r(1, c_lay, c_it) (F20.6)
  *endo
*endo
*cf clos

!Create Actual resultant force in vires csv file
*cfopen, wtens, csv, exlresults
*vwrite, n_wonlay, no_lay, no_lay (F10.6)
*do, c_it, 1, no_lay, 1
  *do, c_lay, 1, no_lay, 1
    *vwrite, wtens(1, c_lay, c_it) (F20.6)
  *endo
*endo
*cf clos
```
4. Results

To investigate the effect of friction between the windings of the rope a coefficient of friction of \( \mu = 0.5 \) has been chosen. The rope that represents the FEM model is said to be lubricated. Furthermore are the contact surfaces always steel-on-steel. Usually a lubricated steel-on-steel contact allows for a coefficient of friction of \( \mu = 0.15 \). For dry steel-on-steel contact the coefficient of friction is in the range of \( \mu = 0.5 - 0.8 \). However, the FEM model showed great difficulty to converge the solution for low values of \( \mu \). The value of \( \mu = 0.5 \) has therefore been chosen because it allowed for a converging solution while it still represents steel-on-steel contact. Although friction is considered as non-linear behaviour, the results for low valued \( \mu \) can still be expected to be between the non-friction and the \( \mu = 0.5 \) results.

Sideway stiffness to resist rope movement is only provided in a frictionless model by the side flanges. With the introduction of friction between the windings, part of these sideway loads can be transferred to the barrel of the winch. A decrease in contact forces on the flanges is what should be expected when friction is introduced, while the equivalent barrel stress should increase. This effect can be seen in Figure 8 and Figure 9 where the equivalent stress in the winch is plotted. Especially at the area where flange and barrel connect can the difference be observed. The bending moment in this connection is reduced due to the reduced side forces from the rope on the winch.

![Figure 8 Equivalent stress [Pa] in winch for no friction between the windings.](image-url)
Figure 9 Equivalent stress [Pa] in winch for $\mu = 0.5$ between windings.

The decrease of flange forces can be more clearly seen in Figure 10. The image on the left shows the model without friction between the layers of windings. It can be observed that with increasing layers, flange forces are more or less equal and even decreasing slightly at the top layers. Greater displacements are allowed at the location of the top layers due to the poor bending stiffness of the flange plate. This will explain the slight decrease in flange force.

The image on the right in Figure 10 shows a steady increase in flange forces, which are significantly lower compared to the frictionless result. The lower layers are being compressed by the higher layers on the winch, resulting in higher normal forces between the windings and thus higher friction forces. This allows for more sideways forces to be transferred through the rope windings to the winch barrel, resulting in lower flange forces at the lower layers.

Figure 10 Flange contact forces [N]. Without friction (left) and with friction (right).
The same contact forces on the right flange can be seen in Figure 11. Here the same difference between friction and non-friction can be observed. A decrease can be observed at the top of the flanges which is greater when compared to the left flange from Figure 10. This decrease is due to the flange displacement due to bending moment. This will create more space for the rope windings deformation, resulting in lower side forces on the flanges.

This large flange displacement can eventually cause problems for the winch model, because the gap will eventually be large enough for an extra rope winding to fit in. This will then increase flange forces even more, resulting in higher bending moment and thus in even larger displacements. This problem could be prevented with flange stiffness requirements.

The decrease in flange forces can be more clearly seen in Figure 12, where the sum of forces on the left flange is plotted for both situations. The flange forces are reduced up to 58% of the frictionless model with the introduction of friction.

![Figure 11 Flange contact forces [N]. Without friction (left) and with friction (right).](image1)

![Figure 12 Sum of flange forces for both left flange(solid) and right flange(dashed).](image2)
Figure 12 also shows another difference. In this figure the difference between left and right flange can only be observed when friction is in effect. It can be seen that the right flange has to endure higher forces than the left flange. While at the frictionless model there is no difference at all. As mention at the beginning of this chapter, the resistance for side way forces in a frictionless model comes only from stiffness of both flanges. Therefore they will experience the same flange forces.

When friction is introduced, part of the side forces is resisted by the winch barrel. Each newly applied layer will increase the flange. However, the effect is greatest at the side where the fist winding is closest. For the right flange (dashed line in Figure 12) this is at the even numbered layers, where for the left flange (solid line in Figure 12) this is at the odd numbered layers.

Displacements due to these flange forces can be seen in Figure 13. At the first layer it can be seen that the right flange shows higher displacements than the left flange. This is due to elongation of the barrel due to the flange forces. Figure 13 also shows a difference in displacement for the left and right flange for the frictionless situation. This is due to the fact that the bending stiffness of the right flange is less than the bending stiffness of the right flange, because of its geometry. This will cause the right flange to deform more under the influence of the same flange force as seen in Figure 12. For the situation with friction between windings can the same stepped effect be seen as with the flange forces. Furthermore is the importance of stiffness requirements made clear in this figure. The spike at the right flange for both friction and frictionless situation show that displacements will increase progressively with each new layer.

The effect of friction between the layers and the barrel of the winch is best represented by comparing the C-values for barrel pressure. The barrel pressure is expected to increase with the introduction of friction between windings as mentioned earlier. This can be observed in Figure 14 where the C-values for both hoisting and mooring situations are plotted.
An increase in C-values can be observed for both loading conditions with the introduction of friction to the FEM model. However, this increase in C-value is only slight when compared to the effect of different radial stiffness [7]. As can be seen in Table 1, the increase in C-value is a mere 4 – 6 %.

The increase of barrel pressure due to friction can be observed in Table 2, but the effect is very small. A rather conservative friction value of $\mu = 0.5$ has been chosen which shows a maximum difference of 2%.

The effect of friction on the wire tension is negligible as can be seen in Figure 15. Here the average rope tension is plotted for each layer in hoisting condition. It shows a slight difference in rope tension for the first layer. Furthermore, the effect of reduced wire tension is still observed in both situations which is discussed in [7].
More or less the same effect can be seen for the wire tension in the mooring load case. However, a major difference with the hoisting load case is that the wire tension becomes positive (compression) for the second and third layer. The first layer also shows compression in the wires but only slightly in comparison with the layers above. This can be due to the fact that rope windings in the second layer and above are compressed by 4 contact points from the surrounding layers. The first layer has only three compression points. The gaps between first layer and winch barrel is larger, allowing for larger deformations and thus for less stresses in the windings.

Figure 15 Average rope tension per layer without friction (left) and with friction (right) for hoisting load case.

Figure 16 Average rope tension per layer without friction (left) and with friction (right) for mooring load case.
The introduction of friction in the FEM model reduces the pressure on the flanges. The DNV regulations for lifting appliances[1] give the following requirements for flange pressure.

“The drum flanges shall be designed for an outward pressure corresponding to the necessary lateral support of the windings near the drum ends. Unless a lower pressure is justified by test (special test may be required), the pressure is assumed to be linearly increasing from zero at the top layer to a maximum value [...] near the barrel surface.”

This maximum pressure is calculated according to the following formula.

\[
p_f = \frac{2 \cdot t_{av}}{3 \cdot D} \sigma_h
\]  

(4.1)

With the hoop stress being.

\[
\sigma_h = C \cdot \frac{S}{p \cdot t_{av}}
\]  

(4.2)

D[m] is the outer diameter of the winch barrel, p[m] the pitch of rope grooving, S[N] the maximum rope tension under spooling and C[-] the C-value as can be seen in Table 1 and Table 2. This results in the following two maximum DNV flange pressures

<table>
<thead>
<tr>
<th>C-value [-]</th>
<th>( p_f ) [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = 0.0 )</td>
<td>2.14</td>
</tr>
<tr>
<td>( \mu = 0.5 )</td>
<td>2.23</td>
</tr>
</tbody>
</table>

Table 3 Maximum flange pressure according to DNV rules.

Figure 17 and Figure 18 show the calculated flange pressures in comparison with this DNV regulation. In both figures it can be seen that, obviously, friction reduces flange pressure. But what is also clear is that with the addition of friction in the FEM model, the DNV regulations become more conservative. At the right flange, pressure is largely under DNV regulation, but at the left flange the difference is even more clear.

However, as mentioned before, the results were gathered with a coefficient of friction of \( \mu = 0.5 \). Although this coefficient is of valid value for steel-on-steel contact, it is rather high when lubrication is involved. A lower friction coefficient will result in higher flange forces and thus in higher flange pressures. For this particular winch model, that will probably result in flange pressures that will be slightly more conservative than DNV regulation.
Figure 17 Flange pressure left side from FEM model (solid) compared to DNV rules (dashed)

Figure 18 Flange pressure right side from FEM model (solid) compared to DNV rules (dashed)
5. Conclusion
Introducing friction between rope winding layers on the axisymmetric FEM model has a great influence on the side loading of the flanges. Flange forces are reduced to up to 58% with \( \mu = 0.5 \) compared to the frictionless model, resulting in less bending moment and deflection in the flange plates. The increase in stress on the barrel is only small, with an increase of C-value of 4% for hoisting and of 6% for mooring operations. Friction has no significant influence on the tension in the wires themselves. The inclusion of friction effects also shows a less conservative result when compared to the DNV regulations for flange pressure.

The results in this report have been generated with a friction value of \( \mu = 0.5 \). Although this friction value can be used for dry steel-on-steel contact, it will be less when using lubricated wires. The contact element CONTA178 requires an iterative solution due to its nonlinearity. For lower friction coefficient values the solution becomes unstable and no converged solution could be found.

6. References
[1] DNV, Rules for Certification of Lifting Appliances, June 2013
Appendix A. CONTA178 element description

Contact between layers of rope windings is modelled with ANSYS CONTA178 elements. This appendix presents a description of the element along with theory and input data used.

CONTA178 Element Description

CONTA178 is a 3D node-to-node contact element that can represent sliding between any two nodes of any type of elements. Because it models contact between two nodes, the contact location must be known beforehand. The element will support compression in the contact normal direction and Coulomb friction in contact tangential direction. User-defined friction and interaction is also allowed for this element by using USERFRIC and USERINTER subroutines.

![CONTA178 Geometry](image)

**Figure 19 CONTA178 Geometry**

<table>
<thead>
<tr>
<th>Nodes</th>
<th>I,J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees of Freedom</td>
<td>UX,UY,UZ</td>
</tr>
<tr>
<td>Real Constants</td>
<td>FKN,GAP, START,FKS</td>
</tr>
<tr>
<td>Material Properties</td>
<td>MP command: MU</td>
</tr>
<tr>
<td>Body Loads</td>
<td>Temperatures T(I), T(J)</td>
</tr>
<tr>
<td>KEYOPT</td>
<td>(1) Gap type</td>
</tr>
<tr>
<td></td>
<td>(2) Contact Algorithm</td>
</tr>
<tr>
<td></td>
<td>(3) Weak Spring</td>
</tr>
<tr>
<td></td>
<td>(4) Gap size</td>
</tr>
<tr>
<td></td>
<td>(5) Basis for contact normal</td>
</tr>
<tr>
<td></td>
<td>(6) Select degrees of freedom</td>
</tr>
<tr>
<td></td>
<td>(7) Element level time incrementation control / impact control</td>
</tr>
<tr>
<td></td>
<td>(8) –</td>
</tr>
<tr>
<td></td>
<td>(9) Initial gap step size application</td>
</tr>
<tr>
<td></td>
<td>(10) Behaviour of contact surface</td>
</tr>
<tr>
<td></td>
<td>(11) –</td>
</tr>
<tr>
<td></td>
<td>(12) Contact status</td>
</tr>
</tbody>
</table>
**Input data**

Following is a description of the real constants, material properties and key options used in the axisymmetric model in order to introduce friction into the FEM model.

<table>
<thead>
<tr>
<th>Real Constants</th>
<th>GAP START</th>
<th>0</th>
<th>No gap between contact nodes at beginning of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>Contact is initially closed, with sliding dependent on $\mu$</td>
</tr>
</tbody>
</table>

| Material Properties | MU 0.0 0.5 | Friction less model, contact is initially sliding |
|                     | Friction of $\mu = 0.5$, contact is not initially sliding |

| KEYOPT | (1) 0 | Unidirectional gap |
|        | (2) 1 | Pure Penalty method |
|        | (3) 0 | Not used |
|        | (4) 1 | Gap size based on real constant GAP (ignore node location) |
|        | (5) 0 | Node locations |
|        | (6) 0 | UX,UY,UZ |
|        | (7) 0 | No control |
|        | (9) 0 | Initial gap size is step applied |
|        | (10) 4 | No separation (always) |
|        | (12) 0 | Does not print contact status |

**Real Constants**

Despite there being gaps between the rope windings in the FEM model, in reality all windings are in direct contact with each other. Also the windings will stay in contact during the entire analysis. Therefore the gap size is determined by a GAP constant of zero, instead of using the initial node locations. A START parameter of 3 is chosen because the cables are initially closed and sliding depends upon the coefficient of frictions. This way the model can be used for a situation with and without friction.

**KEYOPT**

For all element Key Options, only the non-default choices will be discussed.

**Contact algorithm, $= 1$, Pure Penalty Method**

Pure Penalty Method requires both contact normal and tangential stiffness values FKN and FKS. Penetration is no longer controlled which makes it faster than other algorithms. Default FKN is based on the Young’s modulus $E$ and size of underlying elements. A value of $E = 1x10^9$ is assumed when no Young’s modulus $E$ is found. Default FKS is given by FKN x MU. Values can be overridden by inputting in real constants.

Newton-Raphson load vector:

$$\{F_l^{nr}\} = \begin{bmatrix} F_n \\ F_{sy} \\ F_{sz} \\ -F_n \\ -F_{sy} \\ -F_{sz} \end{bmatrix}$$

Where: $F_n = $ normal contact force
\( F_{sx} = \) tangential contact force in \( y \) direction

\( F_{sz} = \) tangential contact force in \( z \) direction

\[
F_n = \begin{cases} 
0 & \text{if } U_n > 0 \\
K_n U_n & \text{if } U_n \leq 0 
\end{cases}
\]

Where:

\( K_n = \) contact normal stiffness (input FKN on R command)

\( U_n = \) contact gap size

\[
F_{sy} = \begin{cases} 
K_s u_y & \text{if } \sqrt{F_{sy}^2 + F_{sz}^2} - \mu F_n < 0 \text{ (sticking)} \\
\mu K_n u_n & \text{if } \sqrt{F_{sy}^2 + F_{sz}^2} - \mu F_n = 0 \text{ (sliding)} 
\end{cases}
\]

Where:

\( K_s = \) tangential contact stiffness (input as FKS on R command)

\( U_y = \) contact slip distance in \( y \) direction

\( \mu = \) coefficient of friction (input as MU on TB or MP command)

The default key option for contact algorithm is the Augmented Lagrange method. This method is the same as the Pure Penalty method but has an additional penetration control. This penetration control is used to establish whether contact is being made between two nodes or not. It requires additional information about contact stiffness (FKN), maximum allowable penetration (TOLN) and maximum allowable slip (SLTOL). The FKN and TOLN parameters are to be chosen carefully, otherwise convergence problems may occur, or too much penetration can occur.

However, since the rope windings are considered to be in contact throughout the analysis, no penetration control is required. This will both increase computing time and increase the risk of penetration problems.

(3) Weak spring, = 0. Not used (default)

No weak spring is used in this model because no separation contact behaviour is used. The weak spring should NEVER be used in conjunction with either the no-separation or bonded contact options.

(4) Gap size, = 1. Gap size based on real constant GAP.

As mentioned before, the FEM model shows gaps between rope windings. In reality, however, there is none. Therefore is the gap size of the contact elements based on a GAP of zero instead of based on the initial node location, which is the default option.

(10) Behaviour of contact surface, = 4. No separation (always).

Models no separation contact, in which two gap nodes are always tied (sliding is permitted) throughout the analysis. The default option is standard unilateral contact, where normal pressure becomes zero if separation occurs. However, no separation should be allowed during the analysis.