



ENGINEERING REPORT

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High-Level Study on the Potential Impact of Rollers on Subsea Power Cables

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Executive Summary

A high-level numerical analysis has been undertaken to indicate the impact of rollers on subsea power cables passing over quadrants or sheaves while under tension. The objective was to predict the potential impact that rollers might have on the subsea power cable.

The impact of various quadrant and sheave designs was evaluated, primarily for a typical single-armoured 132kV cable and for a representative range of tensions. The results of the study indicate that there is potential for this type of cable to sustain damage at tensions above approximately 20kN. Tension levels of 80kN or more resulted in predictable damage to the lead sheath.

Evaluation of the different quadrant configurations (excluding those with the widest roller spacing of 22.5° and tightest quadrant radius of 3.5m) indicate that for installation tensions of 20kN, a high voltage cable will probably not sustain damage if it is kept moving over the quadrant. However, predicted stress levels in the screen-sheath material is high enough that creep damage would occur if the cable was held on the quadrant under tension for extended periods of time.

A typical 33kV cable was also subjected to the roller impact analysis for comparison with the 132kV design. The 33kV cable was found to be less susceptible to roller damage. This is because the 33kV cable example did not include a lead screen-sheath, handling tensions were lower, allowable bend radius was smaller and the diameter of the rollers relative to the cable was larger than for the 132kV example. This may extend the acceptable range of application of roller sheaves without subjecting the cable to non-conformances.

The analysis presented in this document focussed on a single design of 132 kV cable. It should be noted that alternative cable constructions to those considered in this study are likely to have different levels of robustness against the impact of rollers. We would recommend that cable installers should perform analysis on the specific cables to be installed to confirm acceptable handling parameters and review the impacts of cable handling equipment to be used.

1 Introduction

This report documents a numerical analysis to approximate the impact of passing a subsea power cable over the rollers of quadrants and sheaves under tension. The objective was to determine whether damage may be inflicted on critical cable components due to localised, radial pressure exerted by the rollers. The analysis considers a dynamic operation as would be experienced during an installation campaign, and a static operation as would be expected during a repair campaign.

Two cable types were evaluated; a 33kV design and a 132kV design. The following sections focus on analysis of the 132kV cable since its size and construction make it more vulnerable to roller induced damage.

A software model of the cable was initially generated. This was used to approximate the component loads and deflections when passed over different quadrant geometries over a range of tensions. Corresponding material stress levels experienced by the more vulnerable cable components including the screen-sheaths and serving layers were then estimated with the use of Hertzian contact stress calculations. The construction and response characteristics of the example cables were defined based on existing designs of the type typically deployed at offshore wind farms.

Figure 1-1 below illustrates a high voltage subsea cable passing over a quadrant.

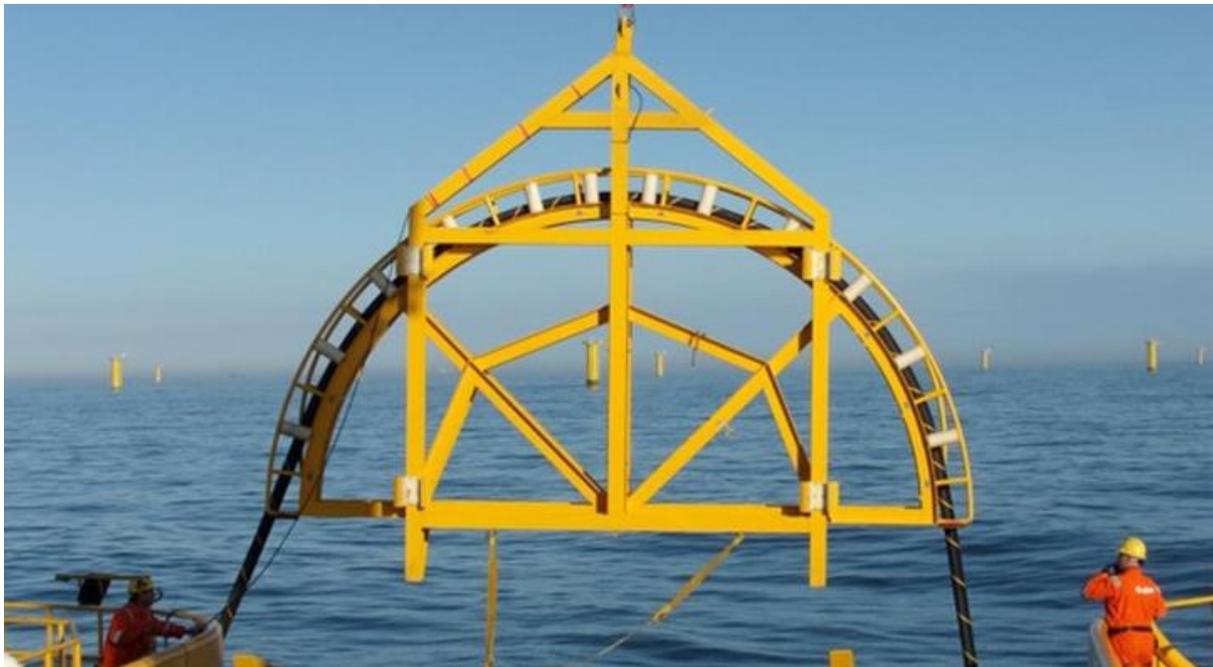


Figure 1-1: Subsea Cable passing over a quadrant structure¹

¹ <http://www.subenesol.co.uk/Rental/Offshore-Wind-Farm-Cable-Lifting-Quadrant>

2 Cable properties

The example 132kV cable's physical and mechanical properties are given in Table 2-1 below.

Cable property	Value	Units
Outer diameter	232	mm
Weight in air	91	kg/m
Cable weight in water	48	kg/m
Bending stiffness (EI)	52.8	kNm ²
Radial modulus, E	3.04	GPa
Axial stiffness	863	MN
Torsional stiffness	1076	kNm ²
Cable Poisson's ratio, ν	0.6	
Depth of lead sheath beneath cable surface	15	mm
Min. allowed bending radius during laying	3.5	m

Table 2-1: Physical and mechanical properties of the example cable

The bending, axial and torsional stiffness characteristics as well as the radial modulus of the cable were estimated with the use of BPP's cable design and analysis software tool known as BPP-Softcore. BPP-Softcore utilises a hybrid analytic/finite element computational method which is capable of correctly accounting for the structural behaviour of helical and cylindrical layers and of interlayer forces and friction in umbilical structures.

Having been developed in-house and extensively validated through cable testing programmes, BPP Softcore is capable of accurately predicting the mechanical properties of a cable or umbilical construction as well as the torsional stability, inter-layer forces and load sharing characteristics of the component parts. BPP-Softcore accounts for the radial distortion of the cable's soft components and translates axial tensions, bending moments, internal and external pressures into stresses and strains in all components.

The example cable incorporates 3 x 1,200mm² conductors and XLPE insulation. The conductor cores are encapsulated by lead screen-sheaths and high density polyethylene outer jackets. The cable features a single layer of bitumen soaked armour wires with an outer layer and armour bedding, both comprising of polypropylene roving. The armour package consists of 107 x 6mm grade 34 galvanised steel wires. The Poisson's ratio of the cable structure has been estimated based on its predicted lateral expansion when compressed vertically along its cross-section.

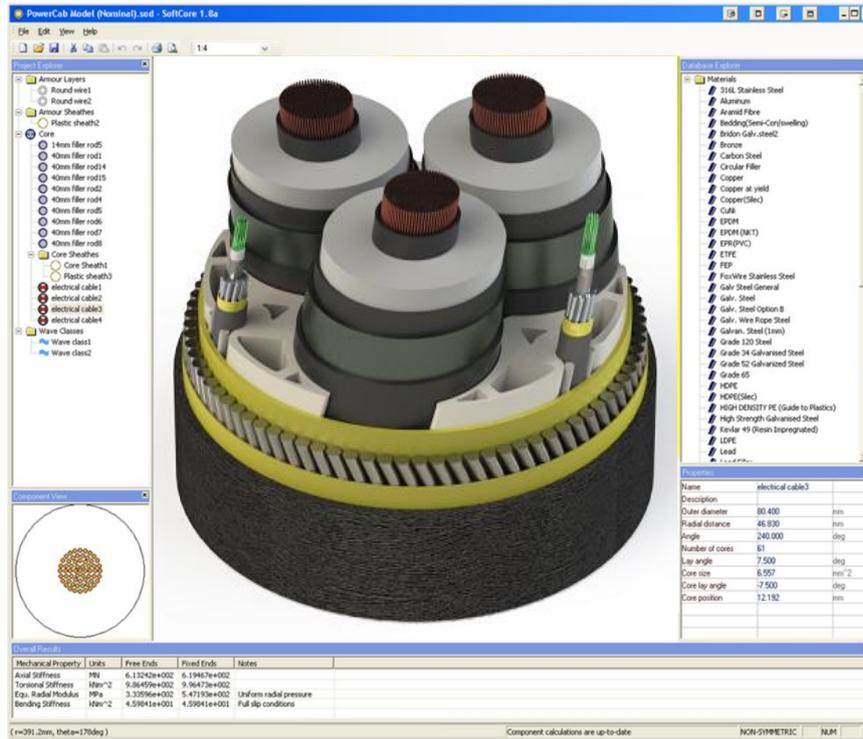


Figure 2-1: Idealised 132 kV cable model represented by BPP Software

3 Quadrant properties

In this report, the term ‘quadrant’ is used to describe all quadrants, roller sheaves and overboarding chutes where the cable is supported by rollers with diameters significantly smaller than the minimum allowable bend radius of the cable.

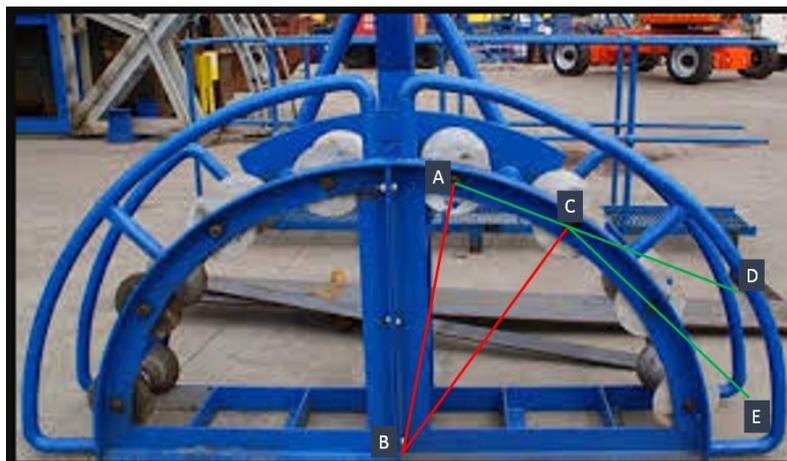


Figure 3-1: Quadrant geometry²

A variety of properties for the geometry of the quadrant were used as input for the analysis. The main parameters are given in Table 3-1 overleaf. The rollers are assumed to be made of steel with

² Original quadrant image from <http://www.briggsmarine.com/services/equipment-hire/subsea-cable-equipment/>

a Young’s modulus of 196 GPa and a Poisson’s ratio of 0.4. The cable is unsupported between the rollers. The calculations are based on the following assumptions with respect to the quadrant under consideration:

- Angle between rollers - $\angle ABC = \angle ECD$ in Figure 3-1
- Radius of roller centres - line BA or BC in Figure 3-1
- Diameter of rollers
- Material properties of rollers

Angle between rollers [degrees]	Radius of roller centres [m]	Roller diameter [m]
5	4.0	0.09
10	4.0	0.09
15	4.0	0.09
18	3.5	0.09
	3.5	0.18
	4.0	0.09
	4.0	0.18
	8.0	0.09
	8.0	0.18
22.5	4.0	0.09

Table 3-1: Properties of the quadrant/roller assemblies under consideration

4 Methodology

4.1 Calculation of roller reaction force

The bending moments experienced by the cable and the reaction forces at the rollers were calculated by treating the cable as a beam subjected to bending. Since the bending is symmetrical about the roller, this can be taken as a built-in condition (end B in Figure 4-1 overleaf). The length of the beam is equal to half the cable arc length from one roller to the next. The lateral force (W) on end A of the beam can be calculated from the cable tension. The moment (M_0) at end A can be calculated since the angular deflection at end A is known to be half of the angle between the rollers.

Results were checked by summing the vector reaction forces from all the rollers of a given 180° quadrant and the result was equal to twice the cable tension as expected.

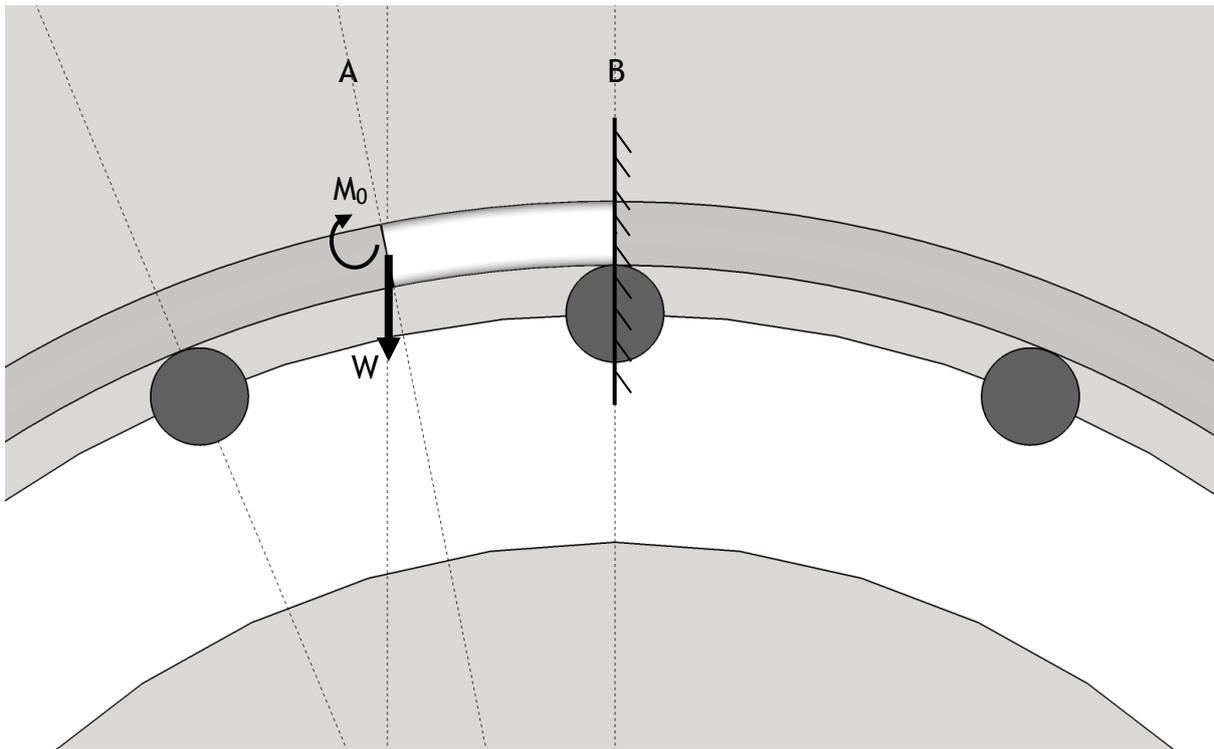


Figure 4-1: Cable treatment as a beam in bending

4.2 Hertzian contact stress calculation

The compressive stress levels in the cable components due to contact with the rollers were estimated by applying Hertzian contact calculations. E^* is a function of the material properties of the two bodies in contact.

$$E^* \equiv \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1} \quad \text{Equation 4-1}$$

Where:

ν is the Poisson's ratio of the two materials

E is the Young's modulus of the material

Subscripts $_1$ and $_2$ denote the materials for the cable and roller. The equivalent curvature radius, R_e is found by:

$$R_e = (R'R'')^{1/2} \quad \text{Equation 4-2}$$

Where R' and R'' are the major and minor relative radii of curvature equal to the radii of the two cylinders.

When two cylinders of differing diameters are in contact, the contact area forms the shape of an ellipse with major semi-axis of length a and minor semi-axis of length b . The maximum contact pressure, p_0 is equal to:

$$p_0 = \frac{3P}{2\pi ab} = \left(\frac{6PE^*}{\pi^3 R_e^2} \right)^{1/3} [F_1(R'/R'')]^{-2/3} \quad \text{Equation 4-3}$$

Where:³

P is the contact force

$F_1(R'/R'')$ is a function approximately equal to 1

The principal stresses at a given depth, z into the material are given by:⁴

$$\sigma_1 = \sigma_2 = \sigma_x = \sigma_y = -p_0 \left[(1+\nu) \left(1 - \frac{|z|}{c} \arctan \left| \frac{c}{z} \right| \right) - \frac{1}{2 \left(\frac{z^2}{c^2} + 1 \right)} \right] \quad \text{Equation 4-4}$$

and

$$\sigma_3 = \sigma_z = -p_0 \left(\frac{z^2}{c^2} + 1 \right)^{-1} \quad \text{Equation 4-5}$$

Where:

$\sigma_1, \sigma_2, \sigma_x, \sigma_y$ are the principal stresses parallel to the plane of contact

σ_3, σ_z is the principal stress normal to the plane of contact

c is the equivalent radius of the contact area such that $c = \sqrt{ab}$

When the principal stresses are known, the Von Mises yield criterion is written as:

$$\sigma_v = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \quad \text{Equation 4-6}$$

Where σ_v is the Von Mises equivalent stress. When calculating the stresses in the lead sheath of the power core, the worst-case condition is where the power core is directly adjacent to the roller.

³ Johnson, K. L. and Inc Books24x7, Contact Mechanics (Cambridge University Press, 1985)

⁴ Contact Stresses and Deformations ME EN 7960 - Precision Machine Design Topic 7, University of Utah

5 Acceptance criteria

The calculations yield results in terms of material stress levels in the cable's component layers. The polypropylene roving and the lead screen-sheaths around the cable cores were noted as being particularly vulnerable to damage. For the purposes of this study, reasonable acceptance criteria based on material stress levels are given in Table 5-1 below.

Component	Condition	Stress [MPa]
Lead sheath	Acceptable (green)	Up to 7.5
	Warning (amber)	7.5 to 12
	Unacceptable (red)	12 and above
Polypropylene roving	Acceptable (green)	Up to 31
	Warning (amber)	31 and above

Table 5-1: Material stress acceptability criteria

The stress ranges in Table 5-1 were derived as follows.

The tensile strength of lead typically varies between 12 and 17 MPa⁵; therefore, stress levels above 12MPa are considered unacceptable. While lead starts to creep under compression at approximately 2.75 MPa⁵, the lower threshold of the amber condition was set at 7.5 MPa since this produces a primary creep of strain 0.1 over a short period of time, followed by a creep strain rate of $6.34 \times 10^8 \text{ s}^{-1}$ at 20 °C⁶. The amber condition indicates that damage will accumulate over time if the cable is held over the quadrant under tension, whereas the cable passing continually over the quadrant would be acceptable.

Polypropylene properties vary considerably, but a compressive strength of 31 MPa was considered representative⁷. Values that exceed 31MPa are considered to present an amber condition since the roving is not critical to long-term cable integrity.

In addition to the material stress level estimates, any loading and quadrant combination that results in a breach of the cable's minimum allowable bend radius of 1.8m is considered unacceptable.

6 Results

Contact stresses were calculated for a variety of quadrant geometries and the range of cable tensions given in Table 6-1 overleaf were considered. For each level of tension, the equivalent water depth was calculated based on the cable's submerged weight in water. Additional tensions due to dynamic effects or on-bottom tension and layback distance would result in a higher cable tension for a given water depth.

⁵ <http://www.ila-lead.org/UserFiles/File/factbook/chapter2.pdf>

⁶ ISSN - 0261-3069; Article Title - Compressive creep properties of lead alloys; Authors - M.K Sahota, J.R Riddington; Journal Title - Materials & Design Journal Volume/Issue - Volume 21, Issue 3, Pages 159-167 Year - 1 June 2000

⁷ <http://www.polyhedronlab.com/services/plastics-testing/polypropylene-testing.html>

Cable tension		Equivalent water depth
kN	kgf	m
0	0	0.00
20.0	2038.74	42.47
40.0	4077.47	84.95
60.0	6116.21	127.42
80.0	8154.94	169.89
100.0	10193.68	212.37
120.0	12232.42	254.84
140.0	14271.15	297.32

Table 6-1: Cable tension levels

Results of the indicative bending and contact stress calculations are given for a range of quadrant sizes and designs in Table 6-2 below and overleaf. Stresses in the screen-sheath material are calculated for the worst-case condition where the power core is directly adjacent to the roller.

Table 6-2: Component stress and bending results for a range of quadrant designs and sizes

Cable tension	Quadrant dimensions			Cable bend radius at roller	Roller reaction force	Contact stress in polypropylene roving	Von Mises equivalent stress in lead sheath
	Angle between rollers	Radius of roller centres	Roller diameter				
kN	deg	m	m	m	N	MPa	MPa
0	5	4	0.09	4.16	0.00	0.00	0.00
20	5	4	0.09	4.14	1744.78	111.91	3.44
40	5	4	0.09	4.11	3489.55	141.00	6.72
60	5	4	0.09	4.08	5234.33	161.41	9.90
80	5	4	0.09	4.06	6979.10	177.65	12.98
100	5	4	0.09	4.04	8723.88	191.37	15.98
120	5	4	0.09	4.01	10468.65	203.36	18.91
140	5	4	0.09	3.99	12213.43	214.08	21.78

0	10	4	0.09	4.16	0.00	0.00	0.00
20	10	4	0.09	4.06	3486.23	140.96	6.72
40	10	4	0.09	3.96	6972.46	177.60	12.97
60	10	4	0.09	3.87	10458.69	203.30	18.90
80	10	4	0.09	3.78	13944.92	223.76	24.57
100	10	4	0.09	3.70	17431.15	241.03	30.01
120	10	4	0.09	3.62	20917.38	256.14	35.27
140	10	4	0.09	3.54	24403.61	269.64	40.35

Cable tension	Quadrant dimensions			Cable bend radius at roller	Roller reaction force	Contact stress in polypropylene roving	Von Mises equivalent stress in lead sheath
	Angle between rollers	Radius of roller centres	Roller diameter				
kN	deg	m	m	m	N	MPa	MPa
0	15	4	0.09	4.16	0.00	0.00	0.00
20	15	4	0.09	3.94	5221.05	161.27	9.87
40	15	4	0.09	3.74	10442.10	203.19	18.87
60	15	4	0.09	3.56	15663.14	232.59	27.28
80	15	4	0.09	3.40	20884.19	256.00	35.22
100	15	4	0.09	3.25	26105.24	275.77	42.77
120	15	4	0.09	3.11	31326.29	293.05	49.98
140	15	4	0.09	2.99	36547.33	308.50	56.90

0	18	3.5	0.09	3.66	0.00	0.00	0.00
20	18	3.5	0.09	3.45	6257.38	171.30	11.72
40	18	3.5	0.09	3.25	12514.76	215.83	22.27
60	18	3.5	0.09	3.08	18772.14	247.06	32.06
80	18	3.5	0.09	2.93	25029.51	271.93	41.24
100	18	3.5	0.09	2.79	31286.89	292.93	49.93
120	18	3.5	0.09	2.66	37544.27	311.28	58.19
140	18	3.5	0.09	2.55	43801.65	327.69	66.08

0	18	3.5	0.18	3.71	0.00	0.00	0.00
20	18	3.5	0.18	3.48	6257.38	135.96	11.45
40	18	3.5	0.18	3.29	12514.76	171.30	21.51
60	18	3.5	0.18	3.11	18772.14	196.09	30.68
80	18	3.5	0.18	2.95	25029.51	215.83	39.17
100	18	3.5	0.18	2.81	31286.89	232.50	47.11
120	18	3.5	0.18	2.68	37544.27	247.06	54.58
140	18	3.5	0.18	2.56	43801.65	260.09	61.64

0	18	4	0.09	4.16	0.00	0.00	0.00
20	18	4	0.09	3.85	6257.38	171.30	11.72
40	18	4	0.09	3.58	12514.76	215.83	22.27
60	18	4	0.09	3.35	18772.14	247.06	32.06
80	18	4	0.09	3.15	25029.51	271.93	41.24
100	18	4	0.09	2.97	31286.89	292.93	49.93
120	18	4	0.09	2.80	37544.27	311.28	58.19
140	18	4	0.09	2.66	43801.65	327.69	66.08

Cable tension	Quadrant dimensions			Cable bend radius at roller	Roller reaction force	Contact stress in polypropylene roving	Von Mises equivalent stress in lead sheath
	Angle between rollers	Radius of roller centres	Roller diameter				
kN	deg	m	m	m	N	MPa	MPa
0	18	4	0.18	4.21	0.00	0.00	0.00
20	18	4	0.18	3.89	6257.38	135.96	11.45
40	18	4	0.18	3.61	12514.76	171.30	21.51
60	18	4	0.18	3.37	18772.14	196.09	30.68
80	18	4	0.18	3.16	25029.51	215.83	39.17
100	18	4	0.18	2.98	31286.89	232.50	47.11
120	18	4	0.18	2.82	37544.27	247.06	54.58
140	18	4	0.18	2.67	43801.65	260.09	61.64

0	18	8	0.09	8.16	0.00	0.00	0.00
20	18	8	0.09	6.23	6257.38	171.30	11.72
40	18	8	0.09	5.04	12514.76	215.83	22.27
60	18	8	0.09	4.23	18772.14	247.06	32.06
80	18	8	0.09	3.64	25029.51	271.93	41.24
100	18	8	0.09	3.20	31286.89	292.93	49.93
120	18	8	0.09	2.85	37544.27	311.28	58.19
140	18	8	0.09	2.57	43801.65	327.69	66.08

0	18	8	0.18	8.21	0.00	0.00	0.00
20	18	8	0.18	6.25	6257.38	135.96	11.45
40	18	8	0.18	5.04	12514.76	171.30	21.51
60	18	8	0.18	4.23	18772.14	196.09	30.68
80	18	8	0.18	3.64	25029.51	215.83	39.17
100	18	8	0.18	3.20	31286.89	232.50	47.11
120	18	8	0.18	2.85	37544.27	247.06	54.58
140	18	8	0.18	2.57	43801.65	260.09	61.64

0	22.5	4	0.09	4.16	0.00	0.00	0.00
20	22.5	4	0.09	3.70	7803.61	184.39	14.41
40	22.5	4	0.09	3.33	15607.23	232.32	27.19
60	22.5	4	0.09	3.02	23410.84	265.94	38.92
80	22.5	4	0.09	2.77	31214.45	292.70	49.83
100	22.5	4	0.09	2.56	39018.06	315.30	60.08
120	22.5	4	0.09	2.37	46821.68	335.06	69.76
140	22.5	4	0.09	2.21	54625.29	352.72	78.95

7 Conclusions

- 7.1 The results for most quadrant configurations (excluding widest roller spacing of 22.5° and tightest quadrant radius of 3.5m) indicate that for typical installation tensions of 20kN, the cable will not be damaged if it is kept moving over the quadrant. However, stresses in the screen-sheath are high enough that creep damage would result if the cable was held on the quadrant under tension for long periods of time.
- 7.2 Tension levels of 80kN or more resulted in predictable damage to the lead sheath.
- 7.3 The results of the study indicate that an export cable under tension supported by rollers of a quadrant are vulnerable to damage due to the contact stresses. The results show several distinct trends:
- Increased tension results in increased susceptibility of damage;
 - Increased spacing between rollers results in increased susceptibility of damage;
 - Increased roller diameter results in reduced susceptibility of damage.
- 7.4 Stresses in the lead screen-sheaths that are sufficient to cause creep will not damage the cable immediately and would be acceptable for free laying of the cable where the rollers are only briefly in contact. However, creep damage resulting in thinning of the lead sheath where it is adjacent to the roller (and distortion of the lead sheath in cross-section) could result if the cable was held over the quadrant under tension for an extended period.
- 7.5 All results indicate that cable sections over rollers while under tension can incur damage to the fibrous polypropylene roving. This would result in compression thinning, and potential parting of the roving, exposing sections of underlying armour wires. Where roving is parted, the resistance to bird-caging of the armour wire will be reduced.
- 7.6 The minimum bend radius of the cable is breached in several of the results, especially at higher tensions and with wider roller spacing. This has potential to damage the cable's armour wires.
- 7.7 Calculations were also performed on a representative 33kV cable design. This smaller cable was found to be less susceptible to damage at the quadrant due to the following factors:
- The cable did not include a lead screen-sheath;
 - Handling tensions were lower;
 - Allowable bend radius of the cable was smaller;
 - Roller diameter was larger relative to cable diameter.

This may extend the acceptable range of application of roller sheaves with 33 kV cables without subjecting the cable to non-conformances.

- 7.8 The estimates of material stress levels predicted by the study are indicative only. It should be noted that subsea cables are complex composite structures comprising many different component parts, constructions and materials. The cable and roller are treated as

homogeneous cylinders which limits the fidelity of the results. Higher level of accuracy could be attained with the use of a finite element method.

- 7.9 The analysis presented in this document focussed on a single design of 132 kV cable. Alternative cable constructions to those considered in this study will have different levels of robustness against roller damage. We would recommend that cable installers should perform analysis on the specific cables to be installed to confirm acceptable handling parameters and review the impacts of cable handling equipment to be used.

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