OPTIMIZING DESIGN OF A DYNAMIC FIBER OPTIC RISER CABLE USING CROSS SECTION ANALYSIS

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Abstract: There is a growth in utilizing fiber optics for offshore infrastructure for both telecom and permanent reservoir monitoring (PRM) systems used for seismic data acquisition. In case the application requires a large number of fibers (PRM), or no fibers are available in the existing infrastructure, it is relevant to install a separate fiber optic riser cable. This paper presents how computer tools used for cross section analysis, combined with analytical and empirical knowledge, was used to improve the mechanical properties of a new fiber optic riser cable.

1. INTRODUCTION

To meet the growth in utilizing fiber optics in offshore infrastructure, a separate dynamic fiber optic riser cable has been developed. The riser cable contains 288 fiber optic elements, can be installed at up to 3000 m water depth, and is designed for having long fatigue life even in harsh environments. Figure 1 shows the cross section of the riser cable. The cable core consists of 18 steel tubes for carrying the fiber optic elements, a HDPE sheath (black), 4 layers of steel wire armoring, and an outer HDPE sheath (yellow).

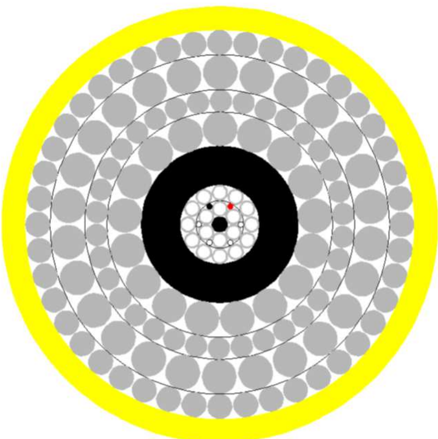

Figure 1: Cross section of the newly developed dynamic FO riser cable.

The development has been accomplished by combining knowledge and experience of the fiber optic cable industry with that from the offshore oil and gas industry. Throughout its entire operational lifetime, the cable will be exposed to tensile and bend loads which depend on actual weather conditions and sea state. This results in a large number of cyclic loads in terms of tensile and bending, and consequently effort in avoiding long term fatigue is a key issue. The different phases for the design of a dynamic fiber optic riser cable are well described in reference [1].

Cross section analysis is a terminology used in the offshore oil and gas industry. It refers to mechanical analyses of subsea power cables, umbilicals, and power umbilicals. A cross section analysis typically includes the cable's or umbilical's axial stiffness, bending stiffness, torsion stiffness, and capacity. The capacity represents the allowed combinations of axial cable tension and cable bending curvature for which all cable elements are within their respective capacity criteria. A cross section analysis may also include results to be used as inputs for dynamic analyses.

The theoretical foundation for cross section analyses are widely covered in the scientific literature. References [4] and [5] present models of traction in cable elements at cable bending due to friction. Reference [6] derives a stiffness matrix for axisymmetric analysis of cable and umbilicals. The axial stiffness and the torsion stiffness can be derived from this stiffness matrix as shown in reference [7]. References [8] and [9] each covers a range of topics within cross section analysis.

This paper presents the cross section analysis of the cable, where the axial-, bending-, and torsion stiffness are calculated together with the capacity curve. Also, the cross section element stresses are calculated for dynamic analysis. The cable stiffnesses are used for handling, installation and operational purposes. Calculation of cable element stresses due to tension, bending, and friction, form the basis for the cable's capacity.

2. NOMENCLATURE

A	Cross section area [m^2]
d_L	Pitch diameter [m]
E	Young's modulus [MPa]
EA	Axial stiffness [MN]
EI	Bending stiffness [kNm^2]
f	Friction force [N/m]
GI_p	Torsion stiffness [kNm^2]
I	Moment of inertia [m^4]
I_p	Polar moment of inertia [m^4]
L	Layer number [-]
l_P	Pitch length [m]
M_b	Bending moment [kNm]
M_t	Torsion moment [kNm]
MBR	Minimum bending radius [m]
MHT	Maximum handling tension [kN]
p_L	Radial load in layer L [N]
s	Length of wire [m]
T	Cable tension [kN]
Z_L	Tension in wire in layer L [N]
α_L	Armor wire pitch angle in layer L [deg]
β_t	Torsion moment to tension coupling factor [m]
ε	Strain [-]
κ	Cable bending curvature [m^{-1}]
μ	Friction coefficient [-]
ρ_L	Curvature radius of wire helix in layer L [m]
σ_f	Stress due to friction [MPa]
φ	Torsion twist angle [deg/m]

3. SOFTWARE

The calculation of cable axial-, bending-, and torsion- stiffnesses, the capacity curve, and the element friction stresses, has been performed using the UFLEX2D software. The UFLEX2D is a finite element (FEM) based program. The UFLEX program system originates from a joint Marintek and Nexans effort kicked off in 1999, resulting in a 2D software module (UFLEX2D) for structural analysis of complex umbilical cross-sections. The first version of the tool was launched in 2001. From 2005 and onwards further development of the 2D module as well as the development of a 3D module (UFLEX3D) has taken place within a Joint Industry Project (JIP). The JIP is still running, and is financed by a group of 10 sponsors covering the following oil and gas industry segments; operators, suppliers, technical service providers.

4. DEFINITIONS

Pitch radius, r_L: the distance from the center of the cable to the centre of the helical element as illustrated in Figure 2. ($r_L = d_L/2$).

Pitch length, l_P: the distance along the cable's length axis for one revolution of the helical element. See Figure 3.

Pitch angle, α_L: the angle between the cables axis to the axis of the helical element. See Figure 3.

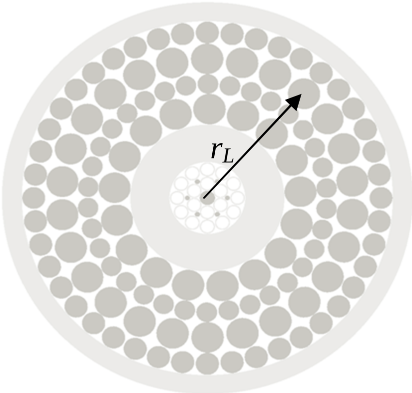

Figure 2: Definition of r_L.

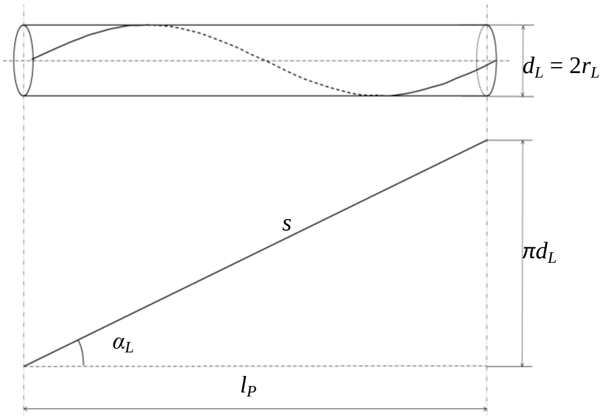

Figure 3: Geometry of a wire belonging to layer L of a helically twisted cable

5. TENSION AND FRICTION IN ARMOR WIRES

When the cable (or umbilical) is axially tensioned, the tensile forces in the individual helical steel armor wires create a radial force on the layers underneath, corresponding to a radially oriented distributed load. This load can be expressed as in reference [2]:

$$p_L = \frac{Z_L}{\rho_L} \quad (1)$$

where Z_L is the tensile force in wires in layer L, and ρ_L is the curvature radius of the wire helix in layer L. The curvature radius ρ_L and the helical wire pitch radius r_L are related as follows [2]:

$$\rho_L = \frac{r_L}{\sin^2 \alpha_L} \quad (2)$$

where α_L is the armor wire pitch angle in layer L.

Combining Eq. (1) and Eq. (2) gives the dependency of the radial load as a function of the layer pitch radius (r_L) and the armor wire pitch angle (α_L):

$$p_L = \frac{Z_L \sin^2 \alpha_L}{r_L} \quad (3)$$

From Eq. (3) the most obvious way to reduce the radial load (p_L) is to decrease the lay angle (α_L), since the wire pitch radius (r_L) is determined by the cable design, and therefore not so easy to change.

In addition to the tensile force in the wire when the cable is in tension, the wires also have to overcome the frictional forces that is directly proportional to the radial load p_L by a constant; the friction coefficient that relates the friction force, f, to the radial load:

$$f = \mu \cdot p_L \quad (4)$$

where μ is the coefficient of friction. The latter is important when the cable is bent, because bending the cable will cause tension and compression stresses in the armor wires if the friction is restricting the natural displacement of the wires.

In order to calculate the global bending stiffness of the cable or umbilical we have to account for the friction that arises in the cable elements when the cable is subjected to bending. The friction therefore has a large impact on the cable's capacity, that is, the combination of axial tension and bending.

By combining Eq. (3) and Eq. (4) the friction force can be expressed as:

$$f = \mu \frac{Z_L \sin^2 \alpha_L}{r_L} \quad (5)$$

To improve the cable's or umbilical's capacity and fatigue life, it is favorable to reduce the friction forces between the cable elements. By considering Eq. (5) this can be achieved by either (i) reduce the coefficient of friction (μ) by use of low friction materials, and/or (ii) decrease the armor wire pitch angle (α_L), meaning using a longer wire pitch length (l_P).

6. CROSS SECTION ANALYSIS

The first step in the cross section analysis is to build a 2D cross section model of the cable or umbilical in UFLEX2D as shown in Figure 4.

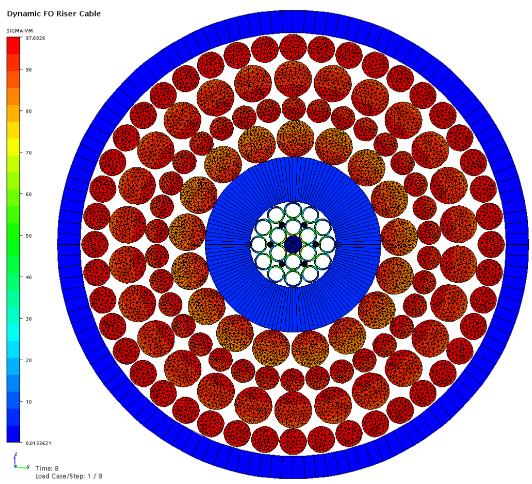

Figure 4: UFLEX2D model of the newly developed dynamic FO riser cable.

Based on the cable elements geometries and material properties, the cross section analysis of cables and umbilicals consist of calculating the following:

- the axial-, bending- and torsion stiffness
- the capacity curve
- the friction stresses in cable elements (to be used in dynamic analysis)

The axial stiffness (EA) relates the cable tension to the cable strain. For a given tension the UFLEX2D simulates the resulting cable strain. By plotting the cable tension (T) versus the cable strain (ε), the slope of the resulting curve will give the axial stiffness, as shown in Figure 5. The labels "No rotation" and "Free rotation" refer to if the cable is fixed or free to rotate, respectively. The two curves lying on top of each other indicate a well torsion balanced design, which means that the cable does not rotate when tensioned.

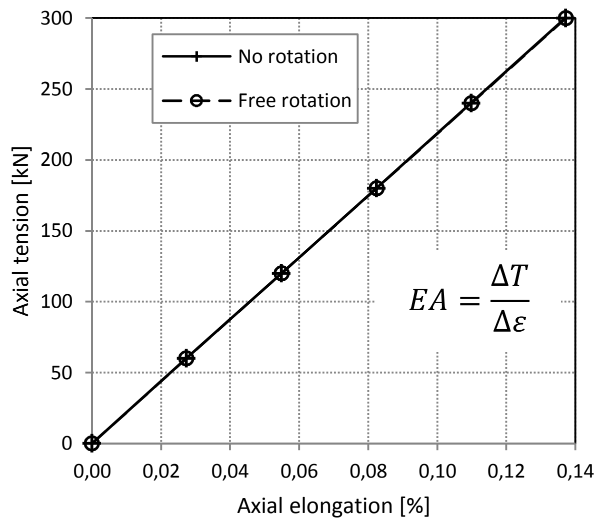

Figure 5: Axial tension versus axial elongation.

Bending stiffness (EI) is defined as the ratio between the bending moment (M_b) and the bending curvature (κ). The bending stiffness is described by a hysteresis loop due to internal stick-slip effects. These effects are modeled by UFLEX2D. Figure 6 shows the bending moment versus bending curvature graph. This curve is constructed by simulating the bending moment for different settings of curvature.

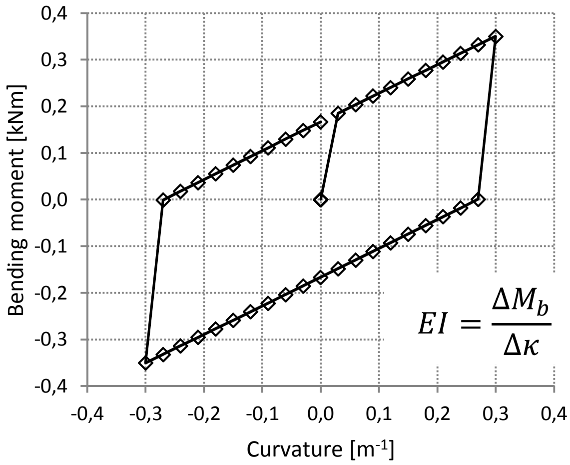

Figure 6: Bending moment versus curvature.

When plotting the torsion moment (M_t) versus the torsion (φ), the slope of the resulting curve will give the torsion stiffness as shown in Figure 7. As for the bending stiffness curve, the torsion moment is simulated for different settings of torsion.

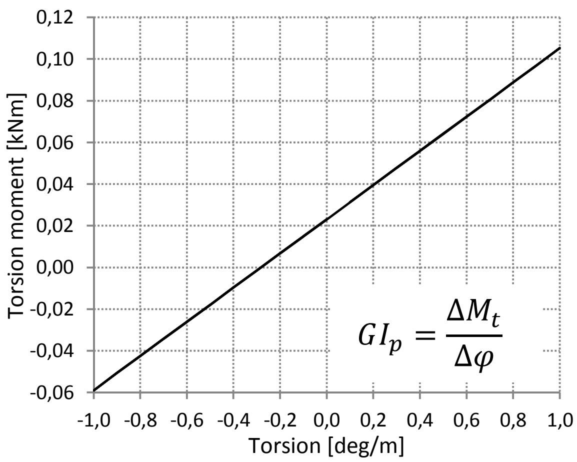

Figure 7: Torsion moment versus torsion.

Reference [10] introduces the cable's torsion moment to axial tension coupling factor, β_t, as a measure of how well the cable is torsion balanced. The β_t is the slope of the curve when plotting torsion moment versus axial tension while the cable is locked from twisting. This is shown in Figure 8.

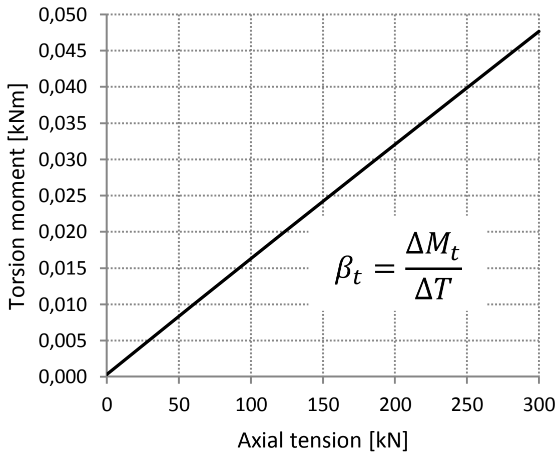

Figure 8: Torsion moment versus axial tension.

The total stress in a cable element is the sum of stress due to tension, bending, and friction. So, in addition to the tension and the bending stresses, the different cable element stress due to friction (σ_f) is calculated. This is important input to the dynamic fatigue analysis in reference [3].

7. ANALYSIS RESULT

To illustrate the effect of changing the friction coefficient (μ) and the pitch length (l_P), the following four combinations of high and low pitch length versus high and low friction coefficient for the model of Figure 4 were analyzed:

- Low pitch length and low friction
- Low pitch length and high friction
- High pitch length and low friction
- High pitch length and high friction

Figure 9 shows the capacity curves for the four different combinations of pitch factor and friction. At zero tension, all curves show approximately the same maximum curvature, κ, of 0.87 m^{-1}, which corresponds to a minimum bending radius (MBR) of 1.14 m. At zero curvature there is a substantial difference in the axial tension of the four curves. The axial tension at zero curvature represents the maximum (allowable) handling tension (MHT) of the cable. The low friction curves give the best capacities. Increasing the pitch factor gives a further improvement in the allowable axial tension.

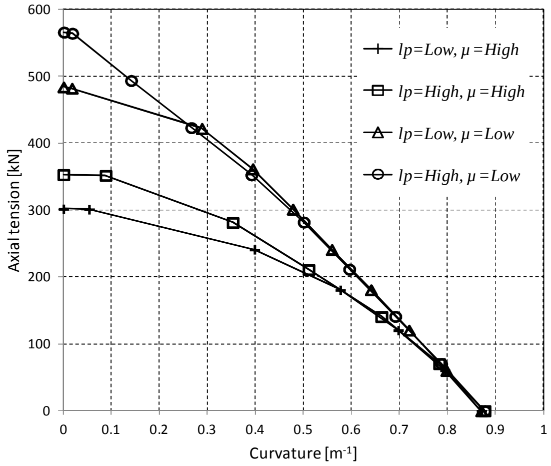

Figure 9: Capacity curves for four different designs of the new dynamic FO riser cable.

A summary of the result from the cross section analysis of the new developed dynamic FO riser cable for four different combinations of pitch length (l_P) and coefficient of friction (μ) is given in Table 1.

l_P [m]	μ [-]	*EA* [MN]	*EI* [kNm^2]	GI_p [kNm^2]
Low	Low	147	0.61	7.2
Low	High	147	0.61	7.2
High	Low	218	0.62	4.7
High	High	218	0.62	4.7

l_P [m]	μ [-]	MHT [kN]	MBR [m]
Low	Low	480	1.15
Low	High	300	1.15
High	Low	560	1.14
High	High	350	1.14

l_P [m]	μ [-]	σ_f [%]	β_t [m]
Low	Low	44.7	4.5 x 10^{-4}
Low	High	100	4.5 x 10^{-4}
High	Low	33.2	1.6 x 10^{-4}
High	High	84.5	1.6 x 10^{-4}

Table 1: Results from the cross section analysis. Due to confidentiality, the σ_f figures are scaled so that the highest value corresponds to 100 %.

Axial stiffness (EA) is not affected by the coefficient of friction, but significantly increased by the pitch length (l_P). This means that the strain of the cable is lower for same tension. The bending stiffness (EI) is marginally influenced by the change in pitch length, while the torsion stiffness (GI_p) decreases with increased pitch length. The latter means that the necessary torsion moment for a certain twist of the cable is reduced. Both the pitch length (l_P) and the coefficient of friction (μ) greatly influence the maximum handling tension (MHT). The combination of high pitch length together with low coefficient of friction is giving the highest MHT of 560 kN. The same combination is giving the lowest armor wire friction stress (σ_f); approximately 33 % of the combination of low pitch length and high coefficient of friction. The stated value of σ_f in Table 1 refers to the maximum friction stress value acting in the armor layers for each combination of pitch length and coefficient of friction. The last column states the torsion moment to tension coupling factor which shows that the increase in pitch length does reduce the coupling factor, meaning a better torsion balanced design.

8. CONCLUSION

The cable design of a new developed dynamic FO riser cable was optimized by use of cross section analysis. In the original design a low pitch length and a high coefficient of friction between the armor layers were used. This design resulted in high armor wire friction stresses, and low handling tension. Changing the design by introducing low friction materials between the armor layers, and increasing the pitch length, the wire stresses and the cable capacity were significantly improved. Also, the dynamic fatigue life analysis showed good results [3].

9. REFERENCES

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