MODELING THE EFFECT OF TEMPERATURE AND FREQUENCY ON BITUMEN-COATED HELICAL CABLE ELEMENTS

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ABSTRACT

High voltage submarine cables and umbilicals are armored using galvanized steel wires. Polymer modified bitumen (PMB) is used to protect these wires from corrosion. During handling (spooling and bending) of cables at low temperatures the PMB will give rise to high shear forces between the armoring wires which reduce the cable's capacity (allowed combinations of axial tension and bending curvature) and increase the fatigue damage. It is therefore of interest to investigate the relationship of the viscoelastic properties of PMB and temperature. Material testing has included characterization of PMB by a controlled stress rheometer from -15 to +30 ^{O}C. The applied frequency was in the range 0.005 Hz to 0.5 Hz. The tests were done at strain values of 0.01%, 0.1% and 1%. Different parallels were analyzed with respect to variance/precision in the data. The results indicate that high strain and high frequency greatly affect the variance at low temperatures. The average of the parallels was used for making a regression model for the complex shear modulus, G*, as a function of temperature, frequency and softening point. This paper focuses on building a model for prediction of minimum temperature and maximum frequency for cable handling with respect to the viscoelastic behavior of polymer modified bitumen.

Keywords: Rheology, Bitumen, Cables, Umbilicals

NOMENCLATURE

Latin:

A_c	wire cross section area [mm²]
A_w	wire wetted area [mm²]
b_1	displacement of armor wire layer 1 [mm]
b_2	displacement of armor wire layer 2 [mm]
C_w	armor wire circumference [mm]
CoV	coefficient of variation (= stdev/average)
d_R	relative displacement between wires in layers 1 and 2 [mm]
F_y	yield force [N]
G	shear modulus [MPa]
G_{max}	maximum shear modulus [MPa]
$G*$	complex shear modulus [MPa]
i	index for layer 1, 2
$l_{p,i}$	pitch length in armor layer *i* [mm]
$l_{w,i}$	wetted length of armor wire in layer *i* [mm]
R	cable bending radius [m]
$r_{p,i}$	pitch radius in armor layer *i* [mm]
s	arc length [mm]
SP	softening point ("Ring & Ball") [°C]
T	temperature [°C]
V	cable (line) speed [m/min]

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Greek:

α_i	pitch angle armor layer *i* [rad]
α_T	angle between wires in layers 1 and 2 [rad]
Δy	thickness of bitumen coating [mm]
γ	shear strain [-]
Θ	element angle in the cross section [rad]
Θ_e	element end angle [rad]
Θ_s	element start angle [rad]
κ	cable curvature [m^{-1}]
σ_y	yield limit steel wire [MPa]
τ_{max}	maximum shear stress [MPa]
ω	frequency [rad/s]

INTRODUCTION

To give weight, strength and protection, submarine cables and umbilicals are equipped with several layers of armor steel wires.

Figure 1 shows a picture of an umbilical. The core consists of different elements; high pressure steel tubes, electric cables, fiber optic cables and fillers. The core is protected with several layers of steel wires and an extruded polymer sheath.

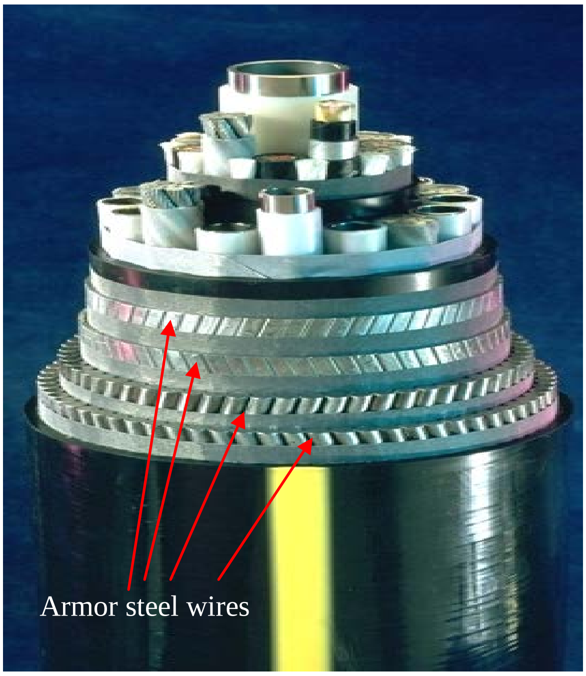

Figure 1: Example of a Nexans umbilical

To protect the steel wires from corrosion bitumen is added on to the different armoring layers.

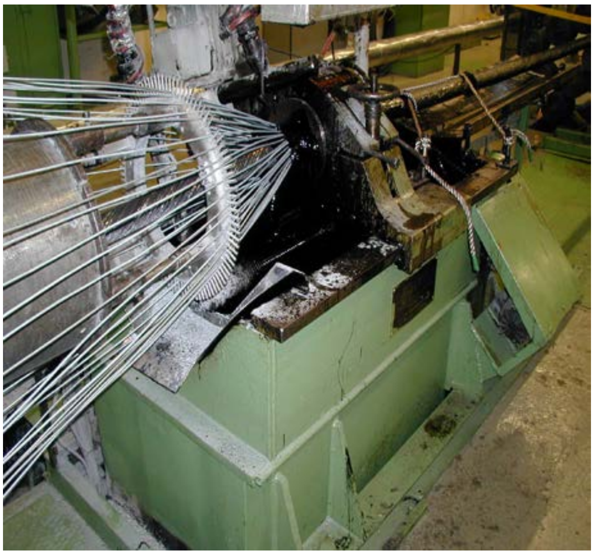

Figure 2: Wires being coated with bitumen

Adding a viscoelastic material like bitumen will give rise to shear forces between the armoring steel wires when the cable is bent. The armor wire movement is due to tensioning and bending of the cable/umbilical. In the case of high temperatures (> 10°C) this is not considered a problem. The challenge with bitumen rises when the surrounding temperature approaches 0°C and below. This is due to the nature of the (polymer modified) bitumen which behaves liquid-like at high temperatures and becomes stiff at low temperatures.

The generation of high shear forces in the armor wires will reduce the capacity (allowed combinations of axial tension and bending curvature) of the cable/umbilical, and increase the fatigue damage. Another serious problem that may arise is “bird-caging”. In this case, the armor wires become fixed due to stiff bitumen and the wires are therefore not allowed to move relative to each other. This might result in yielding and/or displacement of the wires, and formation of a “bird-cage” where the wire excess length will bulge out as shown in Figure 3.

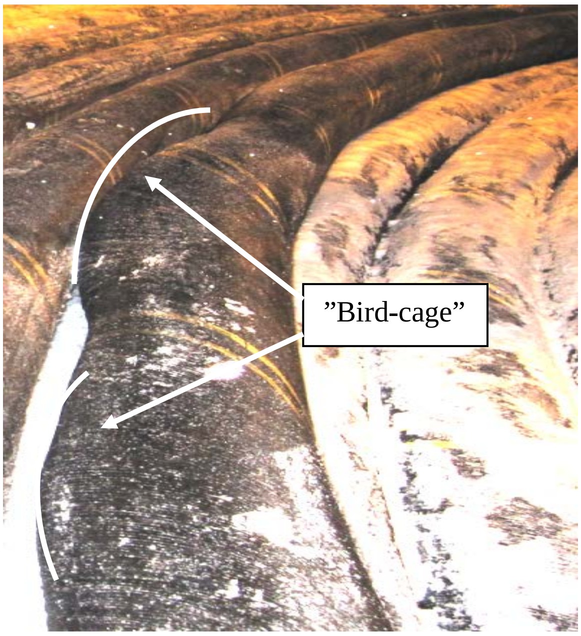

Figure 3: Cable with “bird-cage” [1]

The cross section analysis of cables and umbilicals comprises of calculation of axial-, bending- and torsion stiffnesses, capacity curves and cable/umbilical element stresses. The calculations are based mainly on numerical methods where friction between the different umbilical elements is included. The work presented in this paper aim to improve the computational handling of the effect of bitumen and the shear forces that are generated between the armoring wires while the cable/umbilical is bent.
When doing cable bending tests at Nexans Mechanical Test Centre it can be observed that the temperature has great impact on the measured bending stiffness of the cable. The reason for this is explained by the bitumen behavior.

Although there is a lot of literature to be found on the characterization of bitumen, very little is found on stresses in armor wires due to the use of bitumen in cables. Kebadze [2] and Sødahl [3] have presented work on stresses in armor wires due to friction between the wires. Also, Lutchansky [4] has reported stresses in armor wires using an elastic model (not viscoelastic).

The work presented in this paper is an attempt to combine small scale rheology tests with geometric considerations of real cables.

RHEOLOGICAL TESTING OF BITUMEN

The polymer modified bitumen (PMB) was tested on a Stress Control Rheometer with the following set-up:

Measurement system:
PP15 mm cerrated plates, 2 mm gap
Temperature: ÷ 15°C to + 30°C
Frequency sweep: 0.005 Hz - 0.5 Hz
Strain: 0.01- 0.1- 1%

MODELING STRATEGY

Testing by means of a rheometer is a fast way to characterize bitumen with respect to temperature- and frequency dependency. If the small scale results are valid for real cables, it would be beneficial with respect to both cost and time consumption.

The aim of the modeling is, for a given curvature (κ = 1/R), to be able to calculate the allowable handling temperature and cable (spooling) speed. This is based on the criterion that the shear forces generated (due to bitumen) in the armoring steel wires should not exceed the yield stress of the wires (τ_{max}).

The modeling comprises of the making of a regression model for the complex shear modulus (G*) from rheological tests on the rheometer combined with analytical calculation of shear strain in a real cable.

REGRESSION MODEL FOR THE COMPLEX SHEAR MODULUS, G*

A polymer modified bitumen (PMB), which is used for armor steel corrosion protection with 3

different softening points (SP), was investigated in the rheometer. The tests were conducted for temperatures ranging from -15°C to 30°C in 10 steps, frequencies ranging from 0.005Hz to 0.5Hz in 11 steps, and 3 different strains (0.01%, 0.10% and 1.00%).
The runs were repeated two times (3 parallels). The average from the 3 parallels giving the least coefficient of variation (CoV) for the complex modulus (G*) were used in the regression model. As can be seen in Figure 4, the temperature has a big impact on the precision (CoV) for G* for temperatures < -5°C. Also, increasing the strain or frequency tend to increase CoV. To have the most consistent result the strain and frequency should be kept low at low temperatures.

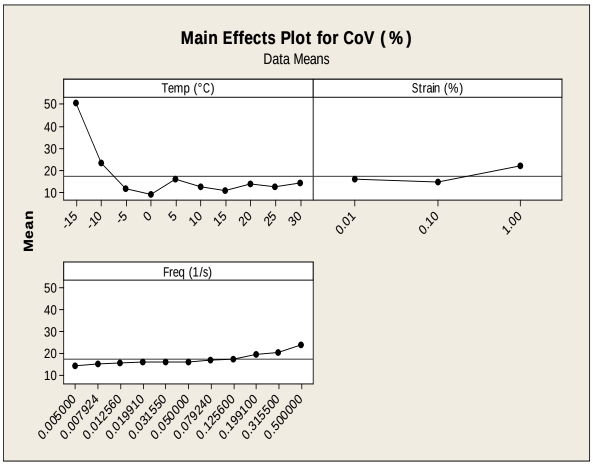

Figure 4: Main effect plot for the CoV for G* (Minitab)

The results from the rheometer tests were arranged in a Minitab Worksheet with one column for each variables; log(G*), T and log(ω). Also, the softening point (SP) was included. The rheology tests were done on 3 samples of the PMB having different softening points; 54°C, 60.5°C and 62.6°C.

"Minitab", which is the statistical software used in the present work, offers different regression model options. A linear mathematical model was chosen for representing the complex shear modulus (G*) because it is simple and gives a very high degree of statistical significance, and a high value for the coefficient of determination (R^2 = 98.3 %). That is, by this model 98.3 % of the measured variation in log(G*) is explained by the tested levels of the softening points (SP), the temperatures (T) and the frequency (log(ω)).

The following regression equation was found for the complex shear modulus, G*:

$$\log G^* = a + bSP - cT + d\log\omega \qquad (1)$$

where *a*, *b*, *c* and *d* are regression parameters.

By means of this model the complex shear modulus (G*) can be computed for different values of SP, T and ω.

Cable (line) speed and frequency

To find realistic values for the frequency input to the model the frequency can be expressed as:

$$\omega = \frac{V}{60R} \left[{}^{rad}/_{s}\right] \qquad (2)$$

ESTIMATION OF THE SHEAR FORCE IN THE ARMORING WIRE

The yield force (F_y) is calculated as:

$$F_y = \sigma_y A_c \qquad (3)$$

From [4], the arc length of a bent wire helix can be computed as a function of cable bending radius (R) and wire location (Θ) in the cable cross section. When looking into the cross section of the cable, the maximum displacement when the cable is bent, will be for the wire starting at Θ_s = 0 rad and ending at $\Theta_e = \frac{\pi}{2}$ rad. The displacement of the wire is found by calculating the difference in arc length s(Θ_s = 0, $\Theta_e = \frac{\pi}{2}$) for bent and non-bent cable.

A good approximation for the bent helix wire arc length s(Θ_s, Θ_e) is given in [4] as:

$$s_i(\theta_s, \theta_e) = a_i(\theta_e - \theta_s) - b_i(\cos\theta_e - \cos\theta_s) \quad (4)$$

The first term, $a_i(\theta_e - \theta_s)$, gives the initial arc length of non-bent helix. The second term, $b_i(\cos\theta_e - \cos\theta_s)$, gives the additional arc length when bending the helix. This term equals $-b_i$ when evaluating it for (Θ_s = 0, $\Theta_e = \frac{\pi}{2}$). The b_i's are computed and used as a measure for maximum displacement in the different wire layers.

The a_i and b_i in (4) is given as:

$$a_i = \sqrt{\left(\frac{l_{p,i}}{2\pi}\right)^2 + {r_{p,i}}^2} \quad (5)$$

$$b_i = \frac{\left(\frac{l_{p,i}}{2\pi}\right)^2 r_{p,i}}{R\sqrt{\left(\frac{l_{p,i}}{2\pi}\right)^2 + {r_{p,i}}^2}} \quad (6)$$

The relative displacement between layer 1 and 2, d_R, is calculated using the cosine rule:

$$d_R = \sqrt{b_1^2 + b_2^2 - 2b_1 b_2 \cos\alpha_T} \quad (7)$$

The pitch angle, α_i, is calculated as:

$$\alpha_i = \tan^{-1}\left(2\pi\frac{r_{p,i}}{l_{p,i}}\right) \quad (8)$$

And the angle between the wires in the first and second layer (α_T) expressed as

$$\alpha_T = \alpha_1 + \alpha_2 \quad (9)$$

The shear strain can now be calculated as

$$\gamma = \frac{d_R}{\Delta y} \quad (10)$$

where Δy (the average bitumen thickness) is given a typical value of 0.5 mm.

As wetted wire length for calculation, $l_{w,i}$, is used as a quarter of the non-bent helical wire length (Θ_s = 0, $\Theta_e = \frac{\pi}{2}$) which equals the initial wire length that is subjected to displacement. The wetted wire area (A_w) is calculated as

$$A_w = C_w l_{w,2} \quad (11)$$

In (11), $l_{w,2}$ is used since this is the wire that experiences the largest shear force (biggest displacement).
The maximum allowable shear stress in the steel wire is calculated as

$$\tau_{max} = \frac{F_y}{A_w} \quad (12)$$

This leads to the maximum value of the shear modulus

$$G_{max} = \frac{\tau_{max}}{\gamma} \quad (13)$$

The final step is to use G_{max} as the maximum value for G* in the regression model, and then solve the model with respect to temperature for different values of R, V and SP (for given σ_y, $l_{p,i}$, $r_{p,i}$, and wire geometry).

The model and results will be subject to further validation. (See "FURTHER WORK").

EXAMPLE WITH REAL CABLE DATA

Input:
- yield limit steel wire = σ_y MPa
- armour wire cross section area = A_c mm²
- pitch length in armour layer 1 = $l_{p,1}$ mm
- pitch radius in armour layer 1 = $r_{p,1}$ mm
- pitch length in armour layer 2 = $l_{p,2}$ mm
- pitch radius in armour layer 2 = $r_{p,2}$ mm
- softening point = SP°C

By changing the model input for bending radius and cable spooling speed, a contour plot was made by means of Excel spreadsheet and Minitab.

The contour plot in Figure 5 shows the acceptable combinations of bending radius and line speed for given temperatures. Calculations shows that increasing the softening point from 54°C to 60°C will affect the acceptable temperature by +0.3°C per 1°C increase in softening point.

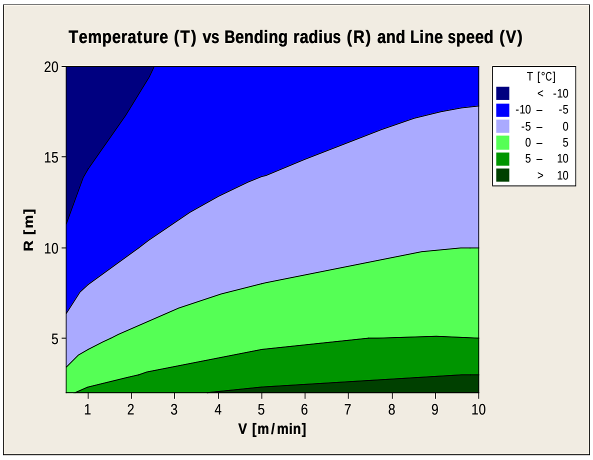

Figure 5: Contour plot of T vs R and V (Minitab)

Example: Using the contour plot

The cable temperature is 0°C.

The cable is subjected to a bending radius of 5 m.

From the contour plot: The cable line speed should be equal to or less than 1.5 m/min.

To increase the cable speed to 5 m/min (still at T = 0°C) the bending radius has to be increased from 5 m to 8 m.

FURTHER WORK

Even though the model presented here seems to function well, giving apparently realistic results, there are a couple of issues that should be discussed: The rheometer analysis is restricted to low strains (< 1 %), while strains up to 500 % have been estimated in real cable armoring. Also, the model is restricted to just one kind of PMB (although with different SP's).

So, prior to further implementation, the model has to be verified through cable spooling and bending tests. Also, the model will be compared to bigger scale tests that will be performed on bitumen samples using larger strains and amplitudes [5].

CONCLUSIONS

From the wire geometry, the maximum shear force on the armoring steel wires is estimated. This serves as a criterion for computation of the acceptable combination of bending radius, cable spooling speed and temperature by the use of the regression model for the complex shear modulus found from analyses of the polymer modified bitumen on the rheometer. An example with real cable data indicates that to increase cable spooling speed from 1.5 m/min to 5 m/min at T = 0°C, the bending radius (R) has to be increased from 5 m to 8 m.

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