DYNAMIC DEEP WATER POWER CABLES

Stian KARLSEN (Nexans Norway AS), Roger SLORA, Kristian HEIDE, Sjur LUND, Fredrik EGGERTSEN, Per Arne OSBORG

As an increasing amount of electric power is required sub sea at oil- and gas fields in deeper waters, there is a growing demand for Dynamic Deep Water Power Cables (DDWPC) in the offshore industry. Electrical power is mainly required for sub sea pumps and direct electrical heating of pipelines. Power cables provide electrical power transmission to sub sea pumps or processing equipment with a potential to increase and accelerate the production, especially from those fields associated with heavy crude oil or particularly deep water.

Power cable conductors are made of pure Electrolytic Tough Pitch (ETP) copper. This material has excellent conductivity but poor mechanical properties. Calculating the mechanical load carrying capacity of a copper conductor is also difficult as the stress-elongation relation deviates from linearity well below the defined yield limit of 0.2% plastic strain. Moreover, copper has poor creep properties at common conductor design temperatures.

A project was therefore initiated to qualify DDPWC for a minimum of 3000 m water depth taking into account the above mentioned challenges. Full scale cables with different characteristics were produced and tested. To examine the effect of creep and non-linear stress-elongation relation in copper, long-time stress relaxation tests were employed to measure the level of stress the conductor will be exposed to over time, given the presence of proper load carrying elements in the cross section. Deformation controlled fatigue testing was employed on conductors with representative mean stress to establish fatigue properties for deep waters.

The study has shown that careful design with special emphasis on controlling the lay angles of the copper phases and armouring layers, in addition to control the friction forces between the conductors and the load carrying elements, is crucial to achieve the desired stress distribution in the cable cross sections and preventing mechanical over-loading of the conductors.

1. Introduction

As an increasing amount of electric power is required sub sea at oil- and gas fields in deeper waters, there is a growing demand for Dynamic Deep Water Power Cables (DDWPC) in the offshore industry. Electrical power is mainly required for sub sea pumps and direct electrical heating of pipelines. Power cables provide electrical power transmission to sub sea pumps or processing equipment with a potential to increase and accelerate the production, especially from those fields associated with heavy crude oil or particularly deep water.

Today the majority of sub sea processing equipment is installed at water depths down to about 1000 meters. Up-coming deep water projects are located e.g. in the Gulf of Mexico and offshore Brazil. The typical water depths at these locations are reported to be in the range from 1500 meters to 2600 meters.

Hereby a development project following the DNV's Technology Qualification Management plan [1] was initiated to qualify a dynamic deep water power cable with copper conductors down to 3000 m water depth with environmental conditions similar to the Gulf of Mexico. During the concept selection phase, failure mode identification and risk ranking evaluation identified mechanical failure of the copper conductors as one of the failure modes. Hence, as part of the qualification program, a study was initiated to investigate the mechanical properties of power conductors in different design solutions in order to qualify a dynamic deep water power cable for 3000 meters water depth.

Power cable conductors are made of pure Electrolytic Tough Pitch (ETP) copper. This material has excellent conductivity but poor mechanical properties. Calculating the mechanical load carrying capacity of a copper conductor is difficult since the stress-elongation relation deviates from linearity well below the defined yield limit of 0.2% plastic strain. In addition, copper has poor creep properties at common conductor design temperatures. Consequently it is imperative that the cable design itself relieves the stress in the copper at particularly deep waters.

With special attention to the necessity of relieving the stress in the copper conductors a battery of tests were employed to investigate the relevant properties of the copper conductors. The experiments have involved tensile tests, stress-relaxation and fatigue testing on the power phases as well as full-scale tensile tests on manufactured test cables.

All analyses have been carried out with UFLEX2D, which is a finite element computer program for stress analysis of cables and umbilicals exposed to pressure, tension, torsion, bending and external contact loads. UFLEX2D is certified by DNV formally expressed in 'Certificate of Fitness for Service – UFLEX2D Cross-sectional Analysis Software. Det Norske Veritas, 2008.'

The test results have been carefully examined and compared with the UFLEX2D analysis results to ensure that this calculation tool handles and calculates the properties in a dynamic deep water power cable properly.

Finally, a prototype cross section including capacity curve is presented for a cable capable of operating at 3000 m water depth. The design is based on experience gained throughout the presented study, i.e. with optimised combination of lay-angles of conductors and armour and by Nexans' earlier experience with flexible centre fillers.

2. Conductor Properties

Stranded conductors consist of several layers of copper wires. Dependant on the conductor cross section and application the wires will have defined sizes and shapes. The thermo-mechanical treatments of the wires represented by wire drawing, annealing and conductor stranding have a great impact on the mechanical property of each individual wire. Therefore, as the thermo-mechanical treatment will vary between different conductor sizes and layers within each individual conductor, mechanical engineering of stranded conductors is challenging, e.g. engineering for dynamic deep water power cables.

The electrical properties of the wires are less dependent on thermo-mechanical treatment. The difference in conductivity between a soft annealed and hard drawn material is only about 3% while the difference in yield strength is more than a factor of two [2].

The power phase made as basis for this study is shown in Figure 1 and manufactured at Nexans' plant in Halden, Norway. The conductor is made of 19 stranded ETP copper wires designed in accordance with the requirements in IEC 60228 [2]. The conductor is filled with a semi-conductive compound to prevent longitudinal water ingress. This compound also affects friction between the individual wires. Mechanical test results of the conductor presented in this paper may therefore not necessarily be regarded as valid for other conductor constructions.

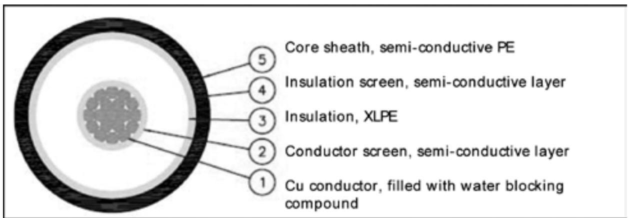

Figure 1: 36 kV, 95 mm² insulated conductor from Nexans Norway AS

2.1 Copper theory

The most commonly used material for power cable conductors is ETP copper, designated by the UNS C11000 series. ETP copper is one of the copper alloys with a purity of at least 99.95% and is as such characterized by high electrical conductivity. The electrical resistivity of ETP copper is less than 17.07 Ω/km [4].

Stress-elongation relations

For pure copper the stress-elongation relation deviates from linearity well below the defined yield limit of 0.2% plastic strain, which is the common definition of yield strength for metallic materials designated as R_{p02}. As for the above mentioned mechanical properties, the degree of non-linearity is dependant on thermo-mechanical history. For a soft annealed ETP copper wire with R_{p02} tested to be 147 MPa, the R_{p001} (stress at 0.01% plastic strain) was found to be 89 MPa, whereas for a «1/8 hard drawn» ETP wire the same parameters were found to be 245 MPa and 120 MPa [5].

Stress-relaxation

Pure copper is also characterised by poor creep properties. There exists limited amount of creep data for most alloys. Soft annealed 2.5 mm thick strip of ETP copper are found to have a creep rate of 1.2×10^{-3} %/h when exposed to 100 MPa at 130°C [2]. This means that that the length will be doubled after 10 years exposure. For temperatures below 90°C which is Nexans design limit temperature for power cables, no useful data are found.

It is theoretically possible to calculate the creep rates for different temperatures and stresses by use of mathematical models for the different creep mechanisms often illustrated in deformation-mechanism maps [6]. However, the uncertainties of such calculations will be too high for engineering purposes in a dynamic power cable due to the changes in stress and temperatures which would initiate changes in creep mechanisms during the design life. Anyway, from the data found it is obvious that an elongation process of the conductor will continue throughout its service life if not prevented by a stress relieving component.

If it can be assumed that the conductor is stuck to a load carrying component, such as an armour layer, stress-relaxation tests are more useful for engineering purposes than conventional creep tests. Tests have shown that stress relaxation of copper follows the Arrhenius behaviour over the temperature range from 23-150°C [5]. For a given temperature stress relaxation is found to follow the empirical law in Eq. 1. After 10 000 hours (1.14 years) annealed ETP copper initially exposed to 45 and 89 MPa was found to have lost over 60% of its initial stress when exposed to temperatures above 60°C. The same test at room temperature resulted in 40% stress reduction. Work hardening was found to reduce stress relaxation to some degree, but even for a «1/8 hard» wire only 35% of an initial stress of 69 MPa was remaining after 10 000 hours at 93°C [5].

Eq. 1 $$\frac{\Delta\sigma}{\sigma_0} = K \cdot \ln(1 - \gamma \cdot t)$$

$\Delta\sigma/\sigma_0$: Fraction of stress remaining of initial.

t : Time.

K and γ : Empirical constants fitted to test data.

Fatigue

The fatigue properties of construction metals are often expressed as S-N curves (stress versus number of cycles to failure), which are linear when plotted in log-log coordinates, sometimes described by the Basquin's equation which may be expressed as in Eq. 2 [7]:

Eq. 2 $$\Delta S = \left(\frac{N}{a}\right)^{\frac{1}{m}}$$

S [MPa] : Stress range.

N : Number of cycles to fracture.

m and a : Empirical constants fitted to test data.

The above mentioned non-linear stress-strain behaviour and also the creep/stress relaxation properties indicate that the effect of plastic straining should be considered in the fatigue analysis of the conductor.

Fatigue curves may also be presented as strain (ε) versus number of cycles (*N*). The ε-*N* curve may be represented by mathematical expressions for both elastic (ε_e) and plastic strain (ε_p) which both are linear when plotted in log-log coordinates. Plastic strain range (ε_p) may be expressed by the Coffin Manson relation and the elastic curve reformulated from stress by dividing stress with the E-modulus. The total strain range (Δ ε) may then be expressed as follows [7]:

Eq. 3 $$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p = \frac{\Delta S}{E} + \Delta\varepsilon_p$$

Fatigue test results of various pure copper qualities are collected from NIST Monograph 177 [8]. 126 plastic strain controlled tests and 150 stress controlled tests were done at room temperature. All stress controlled tests were done with annealed material, whereas the strain controlled tests were done on both annealed and cold worked material. The stress controlled test data may be converted to elastic strain values according by Eq. 3 and the E-modulus of 115 GPa [2].

Linear regression analysis of the $\Delta\ \varepsilon_p$ and converted $\Delta\ \varepsilon_e$ data points are represented by Eq. 4 and Eq. 5, including best fit and best fit minus 2 standard deviations (-2STD). Figure 4 shows the results as strain data in a log-log diagram. The curved line represents total strain range (Δ ε) as calculated according to Eq. 3.

Eq. 4 $$\Delta\varepsilon_e = \left(\frac{N}{a_e}\right)^{\frac{1}{m_e}}$$

Where a_e = 3.06E-10 for best fit (5.96E-12 for -2STD), m_e = -5.730.

Eq. 5 $$\Delta\varepsilon_p = \left(\frac{N}{a_p}\right)^{\frac{1}{m_p}}$$

Where a_p = 0.64 for best fit (0.11 for -2STD), m_p = -1.701.

The fatigue curve in Figure 4, represented by Eq. 3, Eq. 4 and Eq. 5 takes into account the elastic-plastic behaviour of pure copper with various degree of cold deformation. Hence, it is a good basis for testing and evaluation of fatigue performance of ETP copper conductors in power cables.

2.2 Conductor testing

Conductor tensile properties

Several wires and complete conductor cross sections are tested. For the centre wire, which is the softest wire in the conductor cross section R_{p02} was measured to 255 MPa, whereas yielding actually started approximately at 100 MPa.

Yield strength (R_{p02}) and tensile strength (R_m) of Nexans conductors are found to decrease with increasing cross section size as shown in Figure 2. The main contribution to the differences in tensile properties was found to be the size of the individual wires. Smaller conductor cross sections are made of smaller wires that achieve more hardening due to a finer grain structure from wire drawing. Including for measurement uncertainties, 224 MPa is found to be a safe R_{p02} limit for a 95 mm² conductor.

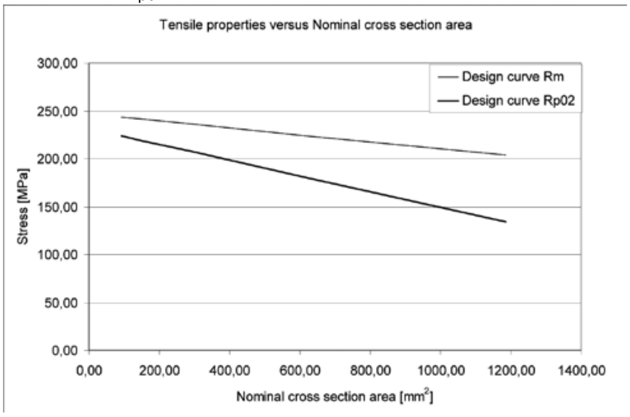

Figure 2: Tensile properties versus conductor area for Nexans copper conductors

Conductor stress relaxation

Stress relaxation testing was done at Det Norske Veritas. Testing was done on individual wires and whole conductor cross sections at 20, 60 and 90°C. All test specimens were stressed to between 102-103 MPa, i.e. within the linear part of the stress-strain curve and held at constant strain for several days while the stress was logged. After 105 days the testing was stopped and showed that the stress in the cables had been reduced to 90, 75 and 60 MPa for the three test temperatures respectively.

The test results are plotted as stress versus logarithmic time in Figure 3. Iteration of the test data was done to estimate the constants in Eq. 1 and to calculate expected remaining stress after 20 years (175 200 hours) which is a typical minimum design life of a dynamic deep water cable (Table 1). Stress relaxation curves based on the estimated constants are shown as dotted lines in Figure 3.

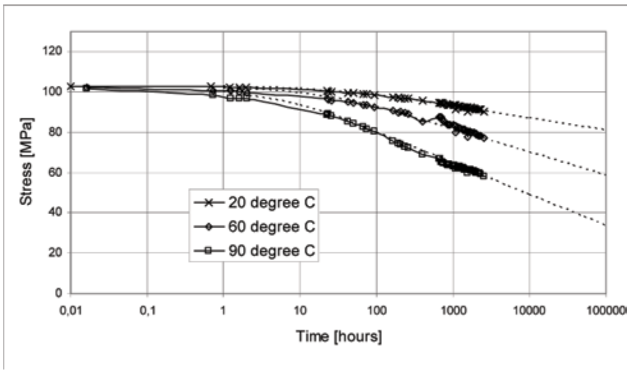

Figure 3: Stress relaxation test of 95 mm² copper conductor with 102-103 MPa initial stress

Due to uncertainties, both test data and extrapolated values should be used with much care. However, it is safe to conclude that creep is a potential failure mode in dynamic deep water cables and that that the initial stress in a dynamic deep water copper conductor protected from creep will be considerably reduced after only a few years in service.

Table 1: Stress relaxation calculations for a 95 mm² copper conductor

Temp [°C]	Initial stress [MPa]	Calculated constants (Eq. 1)		Extrapolated stress after 20 years (175 200 hours)
		γ	K	
20	103	0.0563	0.0246	80 MPa
60	102	0.0574	0.0489	56 MPa
90	102	0.227	0.0668	30 MPa

Conductor fatigue

Power phases (Figure 1) were tested by rotational bend testing. The strain range levels were assumed to be a function of the curvature in the test rigs and the diameter in a single wire without considering any contribution from strain increase due to internal friction between the wires.

Increasing mean stress is known to reduce the fatigue life [7]. The mean stress applied was 90 MPa. The test results are therefore considered to be conservative for conductors that are protected from creep (Figure 3). As the test results include effects from friction and mean stress they are applicable for calculating the fatigue life without adjustment for friction factors or mean stress.

In addition to contributing to conservatism in the test results, the high mean stress helped identify the number of cycles to fracture in the conductors. As tension, elongation and number of cycles were logged throughout the test and tension was kept constant, the possible moment of fracture could be identified as a sudden increase in elongation. The test samples tested by rotational bending were stopped after fracture and dissected.

In Figure 4 all test results are plotted together with the results from linear regression of NIST 177 data. The lower line represents average NIST 177 test results minus 2 standard deviations. The test results indicate that the lower line might be proposed as a fatigue design curve for the conductor. However more tests are being performed to generate more data for lower strain values.

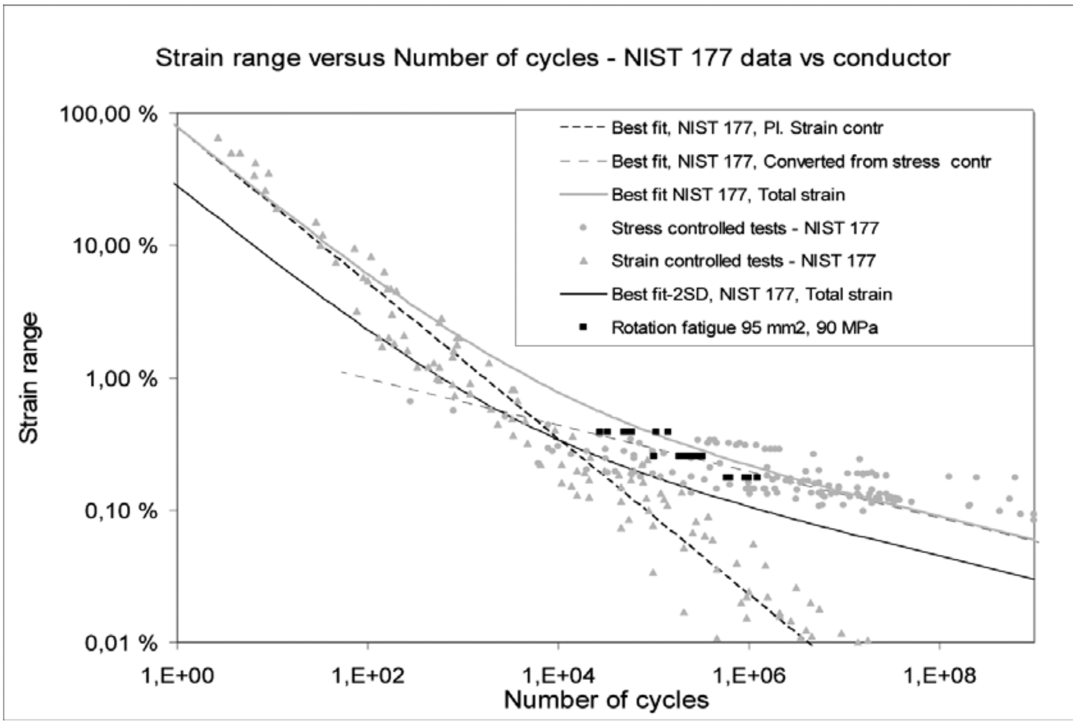

Figure 4: Fatigue properties in Nexans 95 mm² copper conductor

2.3 Discussion of maximum water depth for a copper conductor

A simple way to calculate the maximum water depth for an element hanging in water is presented in the equations below. Static equilibrium requires the following relation:

Eq. 6 $$F = A \cdot h \cdot \rho \cdot g\left(1 - \frac{\rho_w}{\rho}\right)$$

F [N] : Axial tension in the rod (top tension)

h [m] : Water depth

A [m^2] : Area of the rod

ρ [kg/m^3] : Density of the rod (Cu: 8900)

g [m/s^2] : The gravitational constant (9.81)

ρ_w [kg/m^3] : Density of seawater (1025)

The axial tension in the rod at maximum allowable stress in the copper is given as:

Eq. 7 $$F_{max} = 10^6 \cdot A \cdot \sigma_{max}$$

F_{max} [N] : Axial tension at maximum allowable copper stress.

σ_{max} [MPa]: Maximum allowable stress in copper.

Combination of Eq. 6 and Eq. 7 and gives ($F=F_{max}$):

Eq. 8 $$h(\rho, \sigma_{max}) = 10^6 \cdot \frac{\sigma_{max}}{\rho g}\left(1 - \frac{\rho_w}{\rho}\right)^{-1}$$

As seen from Eq. 8, maximum allowable copper stress has to be determined in order to calculate maximum water depth. Calculated water depth with input data from stress-elongation tests are shown in Table 2. The water depth from Eq. 8 is divided with a dynamic factor of 1.5.

Table 2: Water depth based on Eq. 8

Max stress [MPa]	Comment	Max water depth [m]
100	Max stress to non linear behaviour	863
224	R_{p02} (Figure 2)	1934

It is important to emphasise that the approach above is only meant as a simple method for roughly estimation of maximum water depth based on maximum allowed conductor stress. Maximum allowed conductor stress is subject to large uncertainties due to lack of precise creep data at different operating temperature. The stress relaxation test shows that creep occurs at 100 MPa. The conductor should therefore be protected from creep even at 863 m water depth.

Further, a dynamic cable will always be exposed to bending and consequently the diameter of the cable elements can not be neglected as in Eq. 8. Neither can the induced friction stresses in the cable elements be neglected at deep water. Anyway, the simple calculation above clearly shows that a dynamic power cable containing copper must contain additional strength element at deep water. Based on this conclusion, it was decided to qualify a prototype with a cross section concept as presented in Figure 5.

3 Test cables

The Failure Mode Identification and Risk Ranking [1] evaluation identified creep and fatigue as potential failure modes for the copper conductor. Creep is an obvious failure mode since deep water naturally results in increased stress in the copper compared to shallower water depth.

Increased conductor stress results in increased friction stress between the conductor strands and increased R-ratio in the ε-N curves. Both of these mechanisms have a potential for reducing the fatigue lifetime at deep water, whereas the bending curvature at deep water is normally not different than for shallower water. The probability of both failure modes, creep and fatigue, will therefore be considerably reduced by relieving the stress in the conductor.

Figure 5 presents a dynamic power cable design from Nexans with three power phases as presented in Figure 1 surrounded by two steel armour layers. This concept was chosen as analyses showed that the steel armour has a potential to release stress in the copper conductors.

Analyses were performed by means of UFLEX2D which is a FEM-based cross-sectional analysis software developed for Nexans by Marintek in Norway. UFLEX2D received Certificate of Fitness for Service from Det Norske Veritas (DNV) as cross-sectional analysis software in 2008 [9]. UFLEX2D is specially suited for analysis of complex riser/cable cross-sections handling non-trivial issues such as non-linear behaviour and frictional effects. Six cables were manufactured, analysed and tested in order to investigate to which extent different combination of lay-angels influenced the power conductor stress.

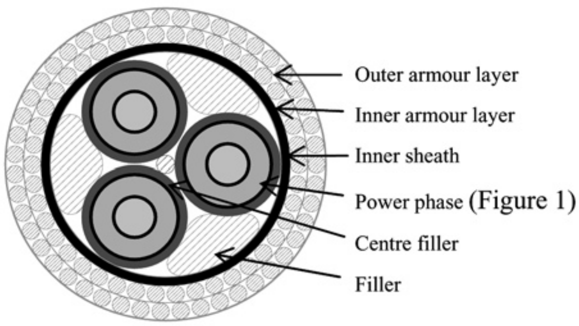

Figure 5: Test cable concept

3.1 Manufactured test cables

The objectives with the manufactured test cables were to confirm the analysis from UFLEX2D for a typical dynamic power cable and establish increased knowledge prior the engineering of the final prototype. Totally six cables with different combinations of lay-angles were manufactured and tested in order to verify the conductor stress versus axial tension relation analysed by UFLEX2D. Name and combination of lay-angels are shown in Table 3.

Table 3: Combination of lay-angels in the test cables

Cable name	Lay-angle	
	Power phase	Armour layers
Cable 1-0	Low	N/A
Cable 1-1	Low	High
Cable 2-0	Medium	N/A
Cable 2-1	Medium	Medium
Cable 3-0	High	N/A
Cable 3-1	High	Low

Cable 1-1, Cable 2-1 and Cable 3-1 are based on the concept illustrated in Figure 5. These cables are further referred to as the armoured power cables. Further, cable 1-0, 2-0 and 3-0 are identical to 1-1, 2-1 and 3-1 respectively, but without armouring. These cables are further referred to as the non-armoured power cables.

3.2 Tension versus elongation test

A principle sketch for the test arrangement is shown in Figure 6.

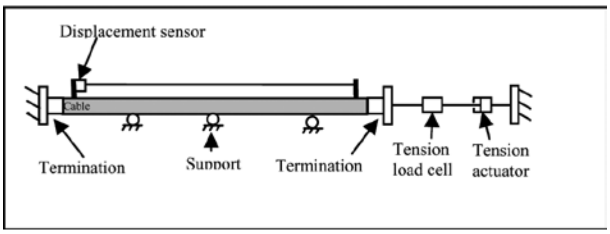

Figure 6: Principle sketch for the test arrangement

The tests were controlled by the tension, i.e. the load was set by a set point and a controller secured that the load followed the set point. The loads were increased stepwise with 10 minutes holding times. The cables were tensioned in 3 cycles, where the next cycle was tensioned equal or higher then the previous cycle. Two identical tests were performed per cable, which means that totally twelve cable object were tested. The test results for the non-armoured power cables are shown in Figure 7.

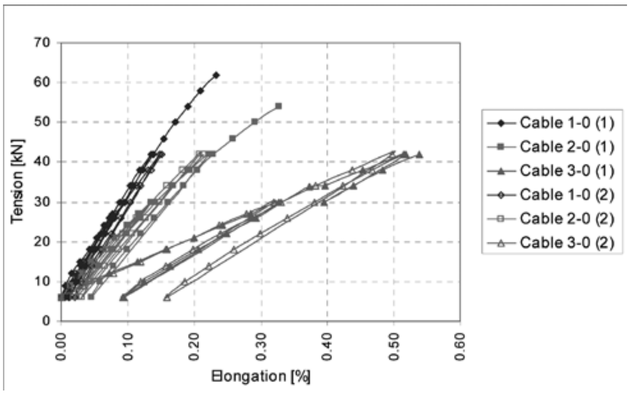

Figure 7: Tension versus elongation for non-armoured power cables

The parentheses (1) and (2) in the legends represents test object 1 and 2 for each cable. The test results for the armoured cables are shown in Figure 8.

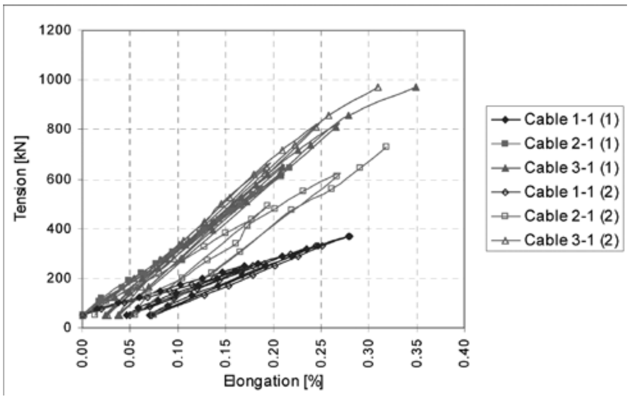

Figure 8: Tension versus elongation for armoured cables

The divergent test results (test 1 and 2) for Cable 2-1 are probably caused by inaccurate resetting of the displacement sensors. However, the average axial stiffness is within expected value compared to the other cables and compared to the UFLEX2D analysis.

The results from the non-armoured power cables in Figure 7 clearly shows that the axial stiffness decreases with increased lay-angles, which means that the tension, and thereby the conductor stress, is reduced for a given elongation. The result also shows that the axial stiffness in some extent increases with number of cycles. This is probably caused by hardening of the annealed copper and by geometrical setting.

The results from the armoured power cables shows that the axial stiffness is highest for cable 3-1 which has the lowest lay-angles in the armouring, even though the conductor part of the cable has the lowest axial stiffness (see Cable 3-0 in Figure 7). Consequently, it seems that Cable 3-1 has the most favourable geometry in respect of releasing the conductor stress.

3.3 Analysis and test results

Conductor stress versus water depth

One of the objectives with the manufactured test cables was to confirm the UFLEX2D analysis regarding conductor stress at different lay-angles. The power conductor stress from the tension-elongation tests presented in Figure 7 may be derived as follows:

Eq. 9 $$\sigma = \frac{EA_n}{A \cdot \cos(\alpha)} \varepsilon$$

σ [N/mm^2] Average power conductor stress.

EA_n [N] Derived axial stiffness (from test data) for the : non-armoured power cables based on data presented in Figure 7.

A [mm^2] Total power conductor area.

α [deg] Lay-angle for the non-armoured power cables.

ε [-] Elongation in cable.

As shown later in section 0, there are no relative displacement between the power phases and the armouring. Consequently, the elongation for the power phases inside the armoured power cables is identical to cable elongation. The elongation for the armoured power cables is given as:

Eq. 10 $$\varepsilon = \frac{T}{EA}$$

T [N] Total axial tension in the armoured power cable

EA [N] Derived axial stiffness (from test data) for the armoured power cables presented in Figure 8

By combining Eq. 10 and Eq. 11 , the average conductor stress in armoured cables may be derived as follows:

Eq. 11 $$\sigma = \frac{EA_n}{A \cdot \cos(\alpha)} \cdot \frac{T}{EA}$$

Eq. 11 is only valid for the linear part of the tension elongation curves for both the non-armoured and armoured power cables. Calculated conductor stress by Eq. 11, which is based on derived axial stiffnesses from test data for all three test cycles, and results from the UFLEX2D analysis for the armoured test cables are shown in Figure 9 - Figure 11.

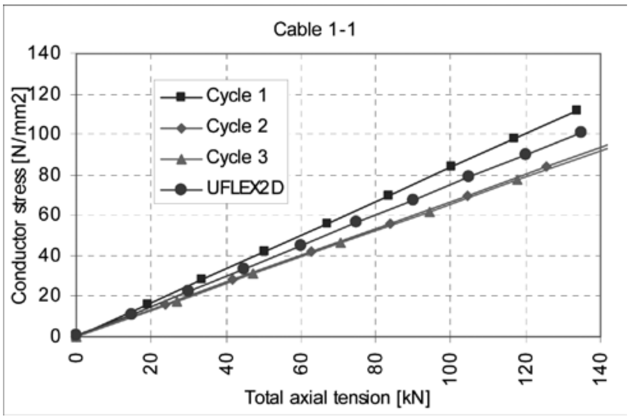

Figure 9: Axial tension versus conductor stress, Cable 1-1

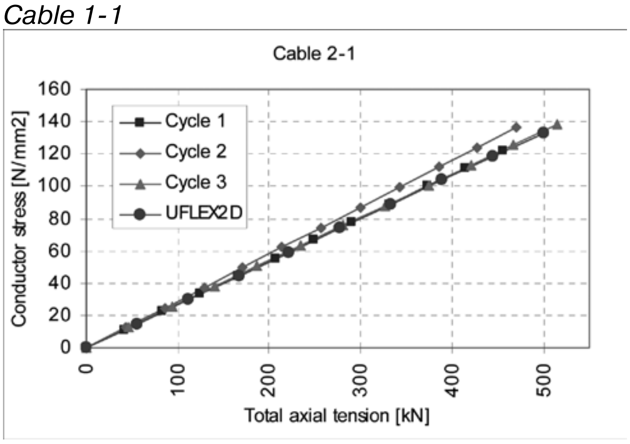

Figure 10: Axial tension versus conductor stress, Cable 2-1

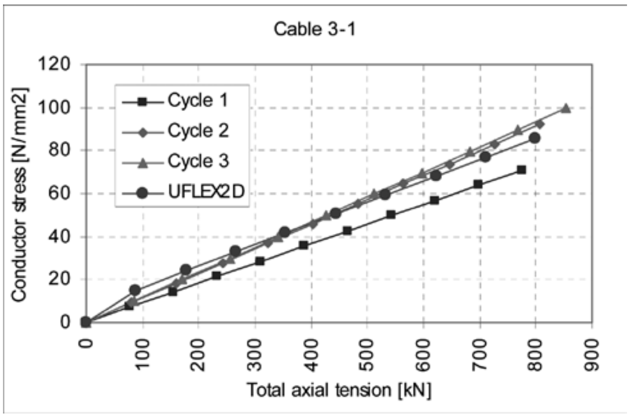

Figure 11: Axial tension versus conductor stress, Cable 3-1

Only the derived axial stiffnesses for each cycle are incorporated in the plots, i.e. the plastic deformation after the previous cycle is not included in the results and the axial stiffnesses are only derived for the linear part of the tension-elongation curves. There are no typical patterns within the tests for the different load cycles, but the UFLEX2D analysis lies within the load cycles.

By studying the results from the different cables, one notice that the conductor stress are considerably lower for Cable 3-1 compared to especially Cable 1-1 for a given axial tension. Maximum tension within each plot is limited by maximum allowable elongation for use of EA_n and EA. The static submerged cable weight at 3000 m water dept is just below 500 kN. That means, only Cable 3-1 stays within linear utilisation for the power conductors. For this cable the conductor stress is below 60 MPa, i.e well below both the R_{p02} limit (225 MPa) and the limit to non-linear behaviour (100 MPa).

Generated friction from the armouring

In order to verify that the power phases are stuck to the armouring, the friction force between the power phases and the sheath and between the sheath and the inner armour layer were analysed. The friction force per meter cable is calculated as:

Eq. 12 $$F_{fr} = 1000 \cdot \mu \cdot d \cdot \sigma_c$$

Where:

F_{fr} [N/m] Friction force (shear force) per meter cable.

μ [-] Friction factor between the contact surfaces.

d [mm] Total contact distance (in cross section plan).

σ_c [N/mm²] Contact stress from UFLEX2D (FEM-analysis).

The friction force versus submerged weight of the power phases for the two contact surfaces as function of water depth are shown in Figure 12.

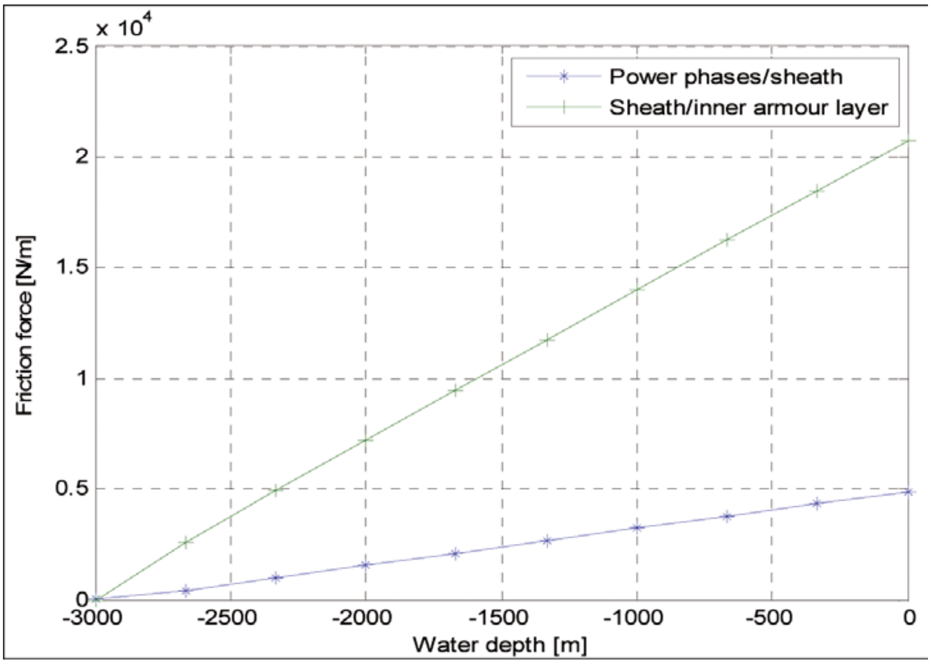

Figure 12: Friction forces versus water depth

Total submerged weight of the power phases are 23 N/m. Even at 2500 m water depth, the friction force between the power phase and the sheath is 31 times larger than the submerged weight of the power phases. The friction contribution from the fillers is not included in the calculations above, which means that the ratio for the power phases/sheath is even higher. However, the result clearly shows that the power phases are stuck to the armouring. Both simple analytical calculations and a friction test support the conclusion above.

4 PROTOTYPE CABLE

Based on the testing, analysis and previous company experience a prototype cable (Figure 13) is engineered and ready for production. The cross section is optimised with regards to lay angles, armour grade and use of a Nexans patented flexible centre filler.

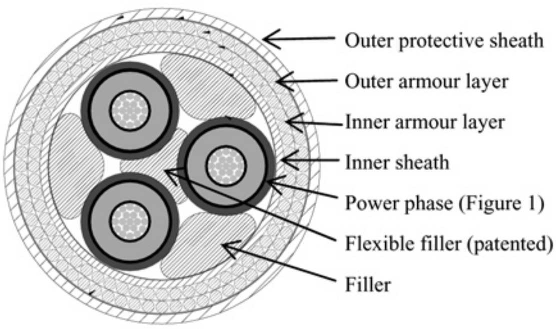

Figure 13: Prototype cable cross section

4.1 Cable capacity of prototype cable

The cable capacity is defined by the combination of axial tension and bending curvature which gives the allowable utilisation of the cross section elements. The Von Mises equation is used to establish allowable utilisation in the cable elements at different utilisation factors of material yield stress. The results reported are so-called first onset values, i.e. the point at which the first node reaches the specified stress limit. The friction factors are incorporated into the UFLEX2D analysis by using contact elements. The contact element is defined between each body inside the umbilical that may be in contact. This means that each contact between two bodies can be described by a specific coefficient of friction. The capacity curves for the prototype are shown in Figure 14.

The capacity curve is used during dynamic analysis in order to verify that the combination of cable tension and curvature at the vessel induces tension in the cable elements within the given utilisation of yield strength.

The «100 % utilisation» curve is applicable for installation and Accidental Limit State (ALS) whilst the «80 % utilisation» curve is applicable for a 100 year extreme condition. The limit at zero tension for the «100 % utilisation» curve defines the Minimum Bending Radius (MBR), while the limit at zero bending defines the Maximum Handling Tension during installation (MHT).

The static cable weight at hang off (3000 m water dept) is 470 kN. The ratio maximum allowable tension for operation (80 % utilisation at zero curvature) versus static cable weight is 2.3. As a rule of thumbs, a ratio of approximately 1.5 will be sufficient for the 100 year extreme analysis. The copper stress is below 50 MPa at 470 kN axial tension i.e. well below the non-linear limit of 100 MPa for the conductor strands.

The limiting element in the prototype is the armour wires which have a yield limit of 750 MPa.

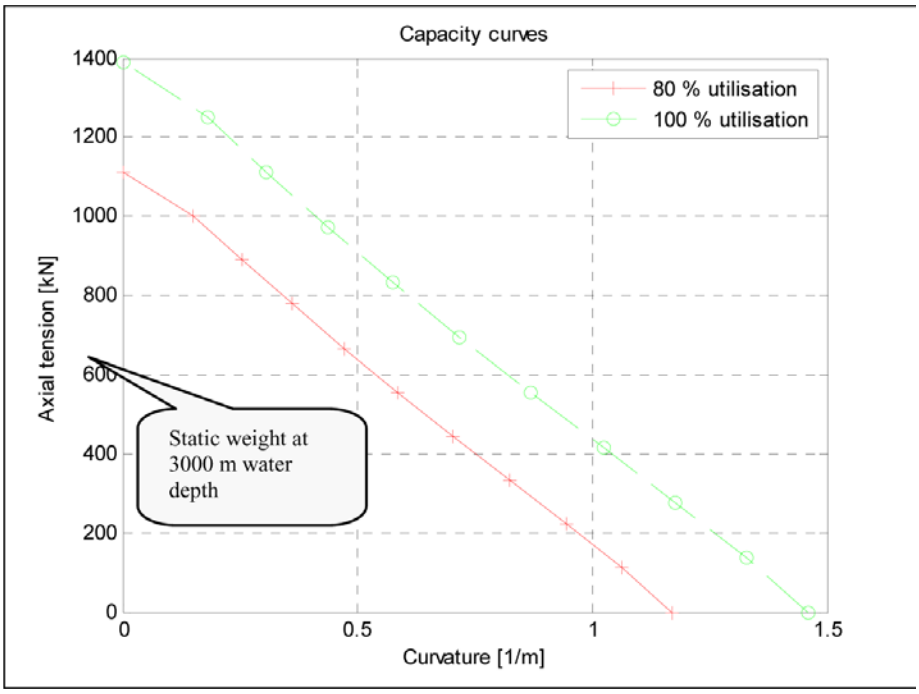

Figure 14: Capacity curves for Cable 3-1

The ductility of the armour decreases with increasing tensile strength, hence also the risk for embrittlement. It is therefore not a good design philosophy to use much higher grade armour than actually needed. For very high strength steel this risk becomes significant. Nexans is therefore reluctant to use armour with higher yield limit than 750 MPa, e.g. due to the risk for hydrogen embrittlement. For armour with yield strength above 750 MPa, the hardness will increase above 350 HV which is a common limit to avoid the risk for hydrogen embrittlement [10]. Use of higher grade armour should therefore not be used without precautions to avoid the effect of cathodic protection, e.g. by sheathing individual wires. The above capacity curve indicates that the cable weight may be significantly increased without having to increase the armour yield limit for this water depth.

5 Discussion, Results and Further Work

The mechanical properties of a copper wire vary by the thermo-mechanical treatment it undergoes, whereas the electrical properties of the wires are less dependent of this treatment. Hence understanding and defining the mechanical properties of copper under varying conditions has been of essential concern.

For pure copper the stress-elongation relation deviates from linearity well below the defined yield limit of 0.2% plastic strain. Also, the creep rates for copper vary by temperature and inflicted stress. By assuming that the conductor retains its shape during the service life, stress-relaxation tests are more useful than for engineering purposes than conventional creep tests. Tests have shown that stress relaxation of copper follows the Arrhenius behaviour over the temperature range from 23-150°C.

Because of the non-linear stress-strain behaviour of copper a traditional S-N curve for copper conductors in a dynamic power cable will have limited application. It is therefore suggested to present the fatigue curves of copper as ε-N curves. Hence the fatigue curve presented in Figure 4 served as basis for testing and evaluation of fatigue performance of copper in power cables.

Several wires and complete conductor cross sections have been tested. R_{p02} for the copper conductor was found to be 225 MPa (Figure 2), whereas the yielding starts already at 100 MPa for the softest centre wire.

Regarding conductor stress relaxation it was found safe to conclude that initial stress level in a typical dynamic power cable protected from creep would be considerably reduced after only a few years in service (Figure 3).

The conductor fatigue testing was performed by way of rotational bend testing with a mean stress of 90 MPa to the conductors. Tension, elongation and the number of cycles were logged throughout all the tests, and the time of fracture was identified as a sudden increase in elongation without any tension increase. The results of the fatigue testing are plotted in Figure 4, and were found to be within the expected results from NIST 177.

A simplified calculation verified that a dynamic deep water power cable with copper inside had to contain additional strength elements to relieve the copper stress. Based on this conclusion a test cable design as shown in Figure 5 was chosen. Following the testing of the pure copper conductors, a variety of tests were employed on this particular cable design. Six cables with this cross section, 3 cables with armouring and 3 without, with varying lay-angles in the copper phases and the armouring layers, were manufactured and tested. UFLEX2D, Nexans FEM-based cross-sectional analysis software, was used to aid us in the process of choosing the cable cross section as well as the different lay-angles. The test results were in return used to very that Uflex2D calculated these designs accurately within a small margin of error.

The tension-elongation test set-up is shown in Figure 6 and the test results for the non-armoured and the armoured cables are shown in Figure 7 and Figure 8 respectively. The tests and calculations showed that the cable design with the lowest lay-angles in the armouring and the highest lay-angles in the power phases was the most favourable with respect to stress relief in the copper conductors.

In Figure 9, Figure 10 and Figure 11 the results of the axial tension versus conductor stress are plotted for the three different cases of the armoured cables. For the most favourable design, the induced conductor stress is below 60 MPa, i.e. well below both the R_{p02} limit (225 MPa) and the limit to non-linear behaviour (100 MPa) at 3000 m water depth.

In this type of construction, where the copper conductors are stuck to the inner armour layer, creep is not an issue. On the contrary, the presented stress-relaxing tests show that the stress will decline over time. Consequently, the copper may be utilised to higher stress for this type of construction compared to a construction where the copper has to carry its own weight and where creep limits the maximum allowable stress utilisation.

Based on the testing, analysis and previous company experience, a prototype cable (Figure 13) is engineered and ready for production. The cross section is optimised with regards to lay angles, armour grade and use of a Nexans patented flexible centre filler. For this design the copper stress is reduced to below 50 MPa at 3000 m water depth, i.e. well below the non-linear limit for the conductor strands. The ratio of maximum allowable tension for operation (80 % utilisation at zero curvature) to static cable weight at 3000 m water depth is 2.3. As a rule of thumbs, a ratio of approximately 1.5 will be sufficient for the 100 year extreme analysis.

This study has documented that a deep water power cable probably will withstand the 100 year extreme loads inflicted by tension and curvature at these water depths. However, a dynamic analysis supported by a flex test plays a decisive role in completely qualifying a power cable down to 3000 meters during normal operation (fatigue) and extreme conditions for a given design life.

The next phase of this project is therefore to manufacture the prototype cable and perform a dynamic analysis with a flex test. In addition, before installation, a battery of tests need to be performed to verify that the cable can be installed at the given water depth without damaging the inside elements.

6 Conclusion

This study has shown that careful design with special emphasis on controlling the lay-angles of the copper phases and armouring layers, in addition to control the friction forces between the conductors and the load carrying elements, is crucial to achieve the desired stress distribution in the cable cross sections and preventing mechanical over-loading of the conductors.

Careful examination and comparison of the results from the testing and the analyses performed by the UFLEX2D program has verified that the properties in a dynamic deep water copper cable can be properly determined. The conclusion can be summarized as follows:

- In a dynamic deep water power cable the copper needs stress relief to prevent creep.
- An ingenious combination of lay-up angles in the copper phases and the armouring layers will relieve the stress in the copper phases to such an extent that the power cable can be safely operated in deep waters down to 3000 meter.
- The frictional forces between the copper phases and the nearby armouring layer are more than sufficient to prevent the copper from slipping inside the cable due to gravitational forces.

7 References

1. DNV-OSS-401, Offshore Service Specification, Technology Qualification Management, Det Norske Veritas, July 2006
2. ASM Handbook vol. 2, Properties of Wrought Copper and Copper Alloys –C1100
3. IEC 60228, Conductors of insulated cables, Issue 3, 2004
4. ASM Handbook vol. 2, Introduction to Copper and its alloys
5. A. Fox, Stress-Relaxation Characteristics in Tension of High-Strength, High Conductivity Copper and high Copper Alloy Wires, J. Test. Eval., Vol 2(No. 1), Jan 1974, p 32-39
6. Georg E. Dieter, Mechanical Metallurgy, ISBN 0-07-100406-8, p 445-449
7. Georg E. Dieter, Mechanical Metallurgy, ISBN 0-07-100406-8, p 375-431
8. NIST Monograph 177, Properties of copper and copper alloys at cryogenic temperatures, by N J. Simon, E. S. Drexler and R. P. Reed, National Institute of Standards and Technology, 1992
9. Certificate of Fitness for Service – UFLEX2D Cross-sectional Analysis Software. Det Norske Veritas, 2008
10. DNV RPB401 Recommended practice Cathodic Protection Design. Det Norske Veritas, January 2005