Testing submarine cables for combined axial compression and bending loads

Andreas TYRBERG, Erik ERIKSSON; ABB AB, High Voltage Cables, Karlshkona, Sweden, andreas.tyberg@se.abb.com, erik.x.eksson@se.abb.com
Frank KLEBO, Jorgen GRØNSUND; MARINTEK, Trondheim, Norway, frank.klaebo@marintek.sintef.no, jorgen.gronsund@marintek.sintef.no

ABSTRACT
To verify that a dynamic power cable can sustain combined compression and cyclic bending loads, a test program has been performed in a new built full-scale rig specially designed for testing combined compression and bending loads. The loads used in the test program where established based on the extreme loads from the dynamic analyses.

This paper describes the new rig and the test program performed. The paper also gives background to the loads used in the test program and discusses the potential failure modes associated with axial compression.

KEYWORDS
Compression, Bending, Full-scale testing, Dynamic cables

INTRODUCTION
Background
Dynamic analyses are performed to verify that the structural integrity of a submarine power cable is maintained during an installation campaign. The analysis can be performed for different weather conditions with the purpose to establish the weather restriction of an installation operation.

For dynamic cables, a global analysis is performed to establish the extreme and fatigue loads that will be applied to the cable during its service life. Since the dynamic cable is a permanent installation it is important to verify that the integrity of the cable is maintained even during the worst storm conditions. In the analysis, the curvature, torsion and tension of the cable is evaluated and the results are compared to the cable integrity criteria.

In the case of large vertical movements of the vessel or host platform, the cable can be subjected to axial compression, i.e. negative tension. There are currently no standards or recommendations which give guidance with regards to acceptable levels of axial compression in power cables, nor how to verify that the cable can sustain axial compression. Due to lacking knowledge, common industry practice is therefore to not allow axial compression. For cable laying “zero compression” will often be the limiting criteria, thereby restricting the weather window of the installation operation. For a dynamic installation a zero compression integrity criteria can have a large impact on the feasibility of the configuration.

To verify that a dynamic power cable can sustain combined compression and cyclic bending loads, a test program has been performed in a new built full-scale rig specially designed for testing combined compression and bending loads. The dynamic cable will be used to energize a Floating Storage and Offloading (FSO) vessel, where the cable will be suspended from the floating vessel in a tethered wave configuration and enter the vessel through a turret together with several flexible flow lines.

This paper describes the new rig and the test program performed on the power cable. The paper also discusses the potential failure modes associated with axial compression.

Failure modes from axial compression
Very little data has been published on axial compression of submarine power cables. In [1] an axial compression test on the power cores of a deep water umbilical is reported. The axial compression was the result of temperature differences inside the umbilical and the test was performed without bending. For flexible pipes, which are used in the offshore production of oil and gas, experimental studies regarding axial compression have been reported in [2] and [3], where two different failure modes of the helical armour wires were studied.

Numerical and analytical studies of armour wire buckling and birddaging in flexible pipes has also been reported in [4], [5] and [6].

Based on these studies it can be concluded that excessive axial compression can result in birddaging or buckling of the helical armour wires. For a power cable the same failure modes of the armour wires can be expected.

When a cable is exposed to axial compression a negative tension is created in the load bearing components, primarily the armour wires and conductor(s). The compressive force onto the cable will be distributed between the different components based on their relative axial stiffness in compression. A second effect of negative tension in the helical elements is that a radial force outwards will be created. Radial deflection of the armour wires is prevented by the outer covering. Since the radial stiffness of the inner central core(s) is larger compared to the radial stiffness of the outer covering the axial stiffness of the cable in compression will be significantly lower compared to the axial stiffness in tension.

The process of buckling/birddaging of armour wires can be divided into three main failure modes [6]:

- Birddaging – Due to negative tension the armour wires move radially, lifting from the supporting inner layers. If the radial force becomes too large this can result in failure of the outer covering and a sudden radial expansion of the armour wires occurs – a birddage is created, as showed in figure 1. This failure mode is related to the strength of the outer covering and is not
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a buckling phenomenon. In flexible pipes, so called anti-birdcage tapes, are often used to increase the strength of the outer support. The tapes are reinforced with aramid or glass fibre to provide a high breaking strength. For special purpose applications, anti-birdcage tapes could also be considered in submarine cables.

Figure 1: Example of birdcaging of submarine cable.

- Radial buckling – If the outer covering is sufficiently strong but the armour wires are allowed to deflect radially, radial buckling can occur. The outer covering is intact at the same time as the armour wires buckle in the radial direction. The radial stiffness of the layers surrounding the armour wires are important; buckling occurs at a lower compressive force if the stiffness of the supporting layers is low since the wires can deflect radially more easily. This failure mode would lead to the creation of radial protrusions on the cable while the outer cover is still intact.

- Lateral buckling – If the strength and stiffness of the outer cover is strong/stiff enough to prevent birdcaging and radial buckling the armour wires might instead move sideways; resulting in a so called lateral or transverse buckling. Figure 2 shows an example of an armour wire layer that has buckled laterally. The capacity will depend on available friction forces which prevents the wires from moving lateral.

Figure 2: Example of lateral buckling or armour wires. Testing on flexible pipes [3], has shown that compression

and cyclic bending, can trigger lateral buckling of the armour wires over time. The combination of compression and bending will therefore reduce the compressive capacity of the cable. It is therefore important to take both effects into account simultaneously during testing.

Local buckling and instability may potentially also occur in the other helix components of the submarine cable, for instance the cores or the conductor strands.

TEST CABLE

This paper describes the testing that was performed to qualify a dynamic power cable for the maximum axial compression loads that it can experience during its service life.

Cable design

The cable is a three phase, 11 kV, AC cable with 300 mm² compacted copper conductors. Figure 3 shows an illustration of the tested dynamic cable.

Figure 3: Tested dynamic cable.

A combination of a substantial vessel length and harsh environmental conditions implies challenging dynamic loads onto the cable system. The following cable design requirements were derived from the dynamic analysis:

- Large weight to diameter ratio in order to avoid over bending, interference with neighbouring risers and enable an overall suitable behaviour of the system. In total four layers of armouring were therefore incorporated in the cable design.

- High bend stiffness in order to avoid over bending during operation of the system. Additional layers of outer extruded PE jackets were applied in order to increase the bend stiffness of the cable. This design feature did in addition provide the cable with a supplementary corrosion and abrasion protection.
• Ability to withstand cyclic axial compression. Antibirdcaging tapes, comprising a layer of HDPE with integrated aramid fibres, were applied over the outermost armour layer to increase the strength of the outer support and thereby reduce the risk for birdcaging.

**Global loads onto cable during operation**

A dynamic analysis, based on regular waves, was performed on the configuration which showed that the cable would experience axial compression during extreme weather conditions. A maximum compressive load of approximately 10 kN occurred during design wave conditions representing a maximum wave with 100 year return period. The cable undergoes simultaneously bending and the minimum bending radius at the location of maximum compression was 15.5 m. The tension during a load cycle will vary and the cable will be in both positive and negative tension (compression).

The analysis showed that the cable would experience some axial compression also for wave conditions representative of 1 and 10 year return period. Based on this it was concluded that during a 3 hour irregular sea state, representative of 300 years return period, the cable will undergo several bending cycles and for some of these the cable will experience axial compression.

A test program was established to qualify the cable for the loads expected during operation. The purpose of the test program was to show that the cable could sustain:

- Axial compression of 10 kN while simultaneously being bent to a bend radius of 15.5 m.
- Repeated bending cycles with axial compression without development of any instability in the cable.

**Load program and safety factors**

Since there are no standards or recommendations that specify safety factor to be used in conjunction with compressive testing of cables, umbilicals or flexible pipes a quite large safety factor was adopted; the test program was performed at a compressive load of 20 kN corresponding to a safety factor of 2 compared to the maximum expected compressive load.

500 bending cycles were performed to verify that repeated bending while subjected to axial compression do not result in any instability in the cable.

**Test specimen**

The length of the test specimen was 8 m with moulded end fittings in each end. A lubricated steel wire, with a minimum breaking load of 30 kN, was installed in the centre of the cable utilizing the gap between the three power cores.

**TEST SETUP**

**Rig**

The Norwegian Marine Technology Research Institute (MARINTEK) has recently increased the research related to submarine power cables subjected to compressive loads. As a part of this initiative, MARINTEK built a test rig for full-scale testing of umbilicals and power cables subjected to combined compression and bending loads in 2014, see figure 4.

![Figure 4: Full-scale test rig for combined compression and bending loads.](image)

The test rig was designed to apply a constant bending moment along the length of the test specimen to obtain a constant radius of curvature. This was achieved by running two bending actuators and one horizontal actuator simultaneously in position control, according to a predefined geometric relationship. It is important to apply the target curvature along a significant length of the test specimen to trigger lateral buckling in a realistic manner.

The purpose of a compression test is usually to verify the structural integrity of the cable components with respect to compressive loads, not to trigger global buckling of the power cable. Hence, the load control system was designed to apply compressive loads to the components, while keeping the total compressive load in the cross section close to zero. The system includes a steel wire installed in the centre of the test specimen tensioned by computer controlled actuator. By connecting the steel wire to both end fittings, and applying tension to the wire, the total axial load in the cross section (i.e. cable + steel wire) is zero. Hence, the cable will not be subjected to global buckling for any compressive load (the steel wire in tension, all cable components are in compression). The tension actuator was programmed to run in load control, at a constant load.

**Instrumentation**

The purpose of the instrumentation and measurement system installed in the full-scale test was two-fold:

- Verify the applied loads
- Measure the response in the test specimen

The principal applied loads were bending and compression. Compression was measured from the applied tension in the steel wire, but adjusted for any reaction force in the horizontal actuator.

Bending was quantified by the radius of curvature, which was measured by 8 inclinometers installed along the neutral axis of the sample. The inclinometers measure the angle of the cable at the specific location very accurately. The radius of curvature was calculated from the relative change in angle between two neighboring inclinometers, taking the distance between each inclinometer into account. This method assumes a constant radius of curvature between the inclinometers, thus several inclinometers are required to measure any variation in curvature along the sample.

To monitor any instability in the sample during testing, the cable twist was of special interest. Lateral buckling of wires in a tensile armour wire layer will reduce the torsion balance of the cable, and a significant change in twist will be observed. The rig is designed such that the test
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Sample is free to rotate at one end during dynamic testing to allow any twist. Measurement equipment is installed to monitor twist in the cable. A sudden jump in twist (range or mean value) is a possible indication of instabilities in the sample due to the combined compression and bending load.

Radial buckling or bird-caging will reduce the axial stiffness of the cable, and a change in the force-displacement curve of the tension actuator is expected. The rig includes equipment for measurements of the circumference (i.e. radius) of the sample continuously during testing.

If a failure occurs, a change in reaction force in the horizontal actuator is expected as well, and these measurements are of special interest. Tension actuator position and reaction force in the horizontal actuator are measured and carefully studied for any abnormalities as well.

Other important instrumentation included bending moment and bending angle of the rotation actuators. These were closely monitored to detect any change in the structural behaviour of the test specimen during cycling.

**Load program**

The loads used in the test program were established based on the extreme loads from the dynamic analysis, see Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of curvature</td>
<td>15.5 m</td>
</tr>
<tr>
<td>Compression</td>
<td>20 kN</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 1: Load program

The loads were converted to equivalent rig loads by performing an analysis of the rig and test specimen based on geometry, see Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max rotation (each end)</td>
<td>18.45°</td>
</tr>
<tr>
<td>Max horizontal displacement</td>
<td>265.0 mm</td>
</tr>
<tr>
<td>Steel wire tension</td>
<td>20 kN</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 2: Rig loads

The loads were applied in a cyclic sinusoidal manner, where the frequency was 0.01 Hz. The low frequency was chosen to avoid any self-heating in the sample from friction.

The 500 cycles were applied in 5 load cases.

**RESULT**

**Test phase**

The first load case included 10 cycles and was run under close observation to verify that the target loads were achieved, see figure 5.

**Figure 6: Cable subjected to combined compression and bending loads.**

The compression level in the cable is found from the tension in the steel wire and reaction force in the horizontal actuator. The position of the horizontal actuator was adjusted such that the reaction force was minimized and that maximum compression level in the cable was 20 kN or above during each cycle.

The applied steel wire tension for all cycles is shown in figure 6.

**Figure 6: Steel wire tension, all cycles.**

The curvature was measured using inclinometers installed along the neutral axis of the cable. The maximum curvature in the load program was specified to 1/15.5 m which corresponds to a curvature of 0.0645 1/m. The applied loads were specified such that the maximum curvature in the mid-section of the cable was larger than 0.0645 1/m. The measured curvature in the mid-section of the cable is shown in figure 7. The measurement shows that the curvature ranges from 0.027 to 0.067 during one cycle. This is equivalent to a bending radius ranging from 37 m to 15.0 m.
Figure 7: Measured curvature – 3 cycles.

The measured curvatures for the last 100 cycles are shown in Fig. 8 for reference.

Figure 8: Measured curvature, cycles 400 – 500.

The plots in figure 6 – figure 8, shows that the applied loads are in line with the defined load program. A set of additional plots are required to verify the response of the test specimen subjected to these loads. For the current test sample, lateral buckling was of interest. Any instabilities from lateral buckling would result in loss of torsion balance.

The twist measurements for all cycles are shown in figure 9. No sudden jumps or irregularities were observed. The twist increased gradually from -0.05 deg/m to 0.26 deg/m, a total change of 0.31 deg/m during the dynamic test, or 0.06 deg/m pr. 100 cycles. The development in twist was significantly less at the end of the test, approximately 0.02 deg/m pr. 100 cycles. This indicates a decrease in twist and that the twist eventually may stabilize at this compression and bend load.

No instabilities or abnormalities were observed in the twist measurements.

Figure 9: Measured twist.

A total of 500 cycles were applied. The minimum radius of curvature was 15.5m or below and maximum
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Compression was 20kN or above in all cycles. The test was successfully completed and no damages or abnormalities were observed.

**Dissection and visual inspection**

After the test phase was completed, the sample was removed from the rig and subjected to dissection and visual inspection. No abnormalities or damages were observed in any of the layers. Some pictures from the dissection are shown below. Figure 10 shows one of the armour layers; there are no signs of buckling or radial protrusions.

The core assembly is shown in figure 11; there are no signs of buckling or other instabilities. One of the cores was dissected down to the conductor and no signs of buckling or other damages could be seen on any of the conductor strands.

![Figure 10: Armour wire layer after completion of test program.](image)

![Figure 11: Core assembly after completion of test program.](image)

**Electrical testing**

A routine test, according to IEC 60502-2 [7], was performed on two of the phases to verify that no changes had occurred with regards to the electrical performance of the cable. The following tests were included:

- Electrical resistance of conductors
- Partial discharge test
- Voltage test

The resistance measurement and electrical tests fulfilled the acceptance criteria in IEC 60502-2 and it could be concluded that the compression test had not resulted in any degradation of the electrical performance.

**CONCLUSION**

To verify that a dynamic power cable can sustain combined compression and cyclic bending loads, a test program was performed in a new built full-scale rig specially designed for testing combined compression and bending loads. The loads used in the test program were established based on the extreme loads from the dynamic analysis.

A total of 500 load cycles with combined bending and compression were applied. The minimum bending radius during a load cycle was less than 15.5 m and the maximum compression was at least 20kN. The test was successfully completed and no damages or abnormalities were observed. After completion of the test program the cable was electrical tested, dissected and all layers were visually inspected. The cable passed the electrical tests and no abnormalities or damages were observed in any of the layers.

It can be concluded that the tested dynamic cable can withstand combined compression and cyclic bending loads representative of the loads experienced during operation.

**REFERENCES**


[7] IEC 60502-2, Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1.2 kV) up to 30 kV (Um = 36 kV) - Part 2: Cables for rated voltages from 6 kV (Um = 7.2 kV) up to 30 kV (Um = 36 kV).