Measurement of flexural rigidity of submarine cables

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CABLE BENDING MACHINE
ANALYTICAL FORMULA FOR BENDING STIFFNESS (BS) COMPUTATION

Bending Stiffness: 

$$BS = \frac{1}{48} \cdot \frac{F_{\text{max}} \cdot L^3}{D_{\text{max}}}$$

where:
Load $F_{\text{max}}$ is measured in kilograms [kg];
Deflection $D_{\text{max}}$ is measured in meters [m];
Separation $L$ between supports is measured in meters [m].

Bending Stiffness BS is computed in kilograms*square meters [kg*m$^2$].

The solution of the differential equation of a thin beam supported by two rollers at extremities has a shape close to a parabola.

The separation between the supports has to be more than 20 times greater than the outside diameter of the cable.

The measure starts with the cable in straight configuration at no load.
SHAPE OF THE CURVED CABLE

\[ Y = f(X) \quad \frac{M(X)}{BS(\rho)} = \frac{1}{\rho} = \frac{f(X)''}{[1 + (f(X)')^2]^{3/2}} \]

Superposition of the cable and a parabola \( Y = 0.6 \times X^2 \) (in metres).
MODELING OF NONLINEAR HYSTERESYS

Superposition of the hysteresis loop with an ellipse of same area and same BS.

Submarine 3x800 mm² cable: measured loop and fitting ellipse
MODELING OF NONLINEAR Hysteresys

The force “F” is the results of the Displacement “D” multiplied by the Bending Stiffness

\[ F = D \cdot BS \quad \quad D(t) = D \cdot \sin(\omega t) \]

The deformation can be approximated by a sinusoidal function, where \( \omega \) is the loop frequency (pulsation) and \( \delta \) is the phase shift between the Force and the Deformation.

\[ F(t) = D \cdot BS_{eff} \cdot \sin(\omega t - \delta) \quad \quad BS = BS_{eff} \cdot e^{-i\delta} \]

\[ W = \int F \cdot dD = 2\pi \cdot F_{rms} \cdot D_{rms} \cdot \tan (\delta) \]

where “W” are the losses computed over a closed hysteresis loop and \( F_{rms} \) and \( D_{rms} \) are the mean average values of force and displacement.
STANDARD PROCEDURE FOR BENDING STIFFNESS AND TAN δ MEASUREMENT

Cable extreme position during bending cycles
DEFLECTION LOOP MEASUREMENTS

EPR1 1x800 mm² cable bending cycles: for different bending radii at slide speed 10 mm/sec

XLPE1 1x800 mm² cable bending cycles: for different bending radii at slide speed 10 mm/sec

EPR1

XLPE1
CHARACTERISTICS OF STUDIED CABLES

The cables are identified as:

3x800 Al 66 kV EPR Wet design Complete Submarine cable (shortly EPR3 cable);
3x800 Al 33 kV XLPE Semi-Wet design Complete Submarine cable (shortly XLPE3 cable);

Single core samples have been extracted from three cores:
1x800 Al 66 kV EPR Wet design Single Core cable (shortly EPR1 cable);
1x800 Al 33 kV XLPE Semi-Wet design Single Core cable (shortly XLPE1 cable).

Synthetic conclusions are:

EPR1 cable is more flexible than XLPE1 cable, thanks to softer polymer;
XLPE3 cable is more flexible than EPR3 cable, thanks to yarn compositions of fillers and armoring;

Bending Stiffness largely depends on bending radius and weakly on slide speed.

Aluminum conductor greatly reduces BS of the single core cable, useful for handling at connections.
DEFLECTION LOOP MEASUREMENTS

MV 1x800 mm² cable bending cycles:
slide speed 10 mm/sec, supports separation 2 m.

Concentric loops for various maximum slide displacement (bending radii)
REDUCTION OF BS WITH DEFLECTION

MV 1x800 mm2 cable bending cycles: bending stiffness module at various deflections

Variation of BS with deflection
CABLE INTERNAL FRICTION

MV 1x800 mm² cable bending cycles:
bending stiffness module at various deflections

Variation of friction coefficient $\delta$ with deflection
SPEED LOOP MEASUREMENTS

Concentric loops for five slide speeds (cycle frequencies) at constant maximum deflection

MV 1x800 mm² cable bending cycles: variable cycle frequency, max deflection 536 mm.
BS VARIES WEAKLY WITH SPEED

MV 1x800 mm² cable bending cycles:
bending stiffness module at various slide speeds

Variation of BS with slide speed
CABLE INTERNAL FRICTION

MV 1x800 mm² cable bending cycles: tan delta angle at various slide speeds

Variation of δ with slide speed
BENDING STIFFNESS COMPARISON

The cable has been prepared in straight configuration with no transversal load.
BENDING STIFFNESS COMPARISON

EPR3 cable with shaped fillers

XLPE3 cable with yarns
BS VARIES WITH CABLE INSULATION

Bending stiffness of XLPE1 & EPR1 1x800 Al, at slide speed of 10 mm/sec, for different bending radii

XLPE1 cable is stiffer than EPR1 cable
Bending Stiffness of XLPE3 is lower than EPR3 cables, due to different overall cable construction.
CONCLUSIONS

• Specific test equipment has been presented to provide accurate measurement of the flexural characteristics of MV to HV submarine power cables.

• Various types of single core and three cores cables have been tested, with different types of construction and armoring.

• Knowledge on the mechanical performance can be derived from the complete bending pattern, defining a hysteretic friction coefficient: mean value of the Bending Stiffness and friction coefficient can be calculated, despite the nonlinear behavior of the composite structure of the cable.

• The Force vs. Deformation cycle is fitted with an ellipse that has the major axis inclined as the diagonal of the loop, in order to obtain the average Bending Stiffness. The area of the ellipse is tuned to be equivalent to the area of the loop, through the tan δ parameter: the energy dissipated in one cycle is the same for the loop and the ellipse.

• The experimental results showed that power core polymeric insulation influences the bending stiffness of the whole cable, but greater influence is due to the overall cable construction, such as shaped fillers, friction between adjacent layers and armoring.
Thank you