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The Structural Expertise of Steel Cables

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Summary

Considering the fact, that steel cables are structural elements forming statically determinated systems, their rupture can lead to catastrophe. In this context, the structural assessment of steel cables represents a primary necessity, generated by the requirement to assure security and safety in use.

Generally the main causes which induce degradation/deterioration of cables are: fatigue and corrosion.

The effects of corrosion and fatigue are displayed usually through fiber laceration sequent to a certain service time, after which the number of ruptures and lacerations increases exponentially.

This paper covers some problems of structural expertise along with numerical simulation aspects of corrosion and fatigue, as well as a methodology for the deduction of the presumed service life of steel cables.

KEYWORDS: steel cable, structural expertise, corrosion, fatigue.

1. INTRODUCTION

The irrefutable qualities of bearing cable structures justify, from one part the extension of their application area, from another part the remarkable effort for world-over research concerning a better insight and knowledge about their behavior under corrosion and fatigue, envisioning a safer and more judicious design.

The aim of the authors through the submission of this paper is to present some aspects of their research done by the Faculty of Civil Engineering and Building equipments from the Technical University of Cluj-Napoca.

Since the middle of 70' the pursuit of this kind of research was focused in the following directions:

- Tests carried out in situ (generally considering only statical behaviour, just infrequently considering dynamical too), including the exact quantification of cable structure geometry based on survey techniques. Due to the fact that

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those kinds of structures are located usually at considerable heights, the applicable survey techniques have a dynamic character, recording also the swing and vibration of the structure and the movements induced by dynamic loads (wind, functioning equipment, traffic).

- Laboratory tests, in order to identify the structural materials through physico-mechanical and chemical analysis.
- Statical and dynamical analysis and calculus, including the evaluation of the service time for every structural component considering possible future loads and actions over the operative period.

It has to be pointed out the complex and time consuming character of any credible structural expertise in this field, considering the vastity of involved factors which are combined with the unstationary character of the loads (wind, temperature, vibrations from equipment and traffic etc.) [9], [10], [11].

Figure 1. The Agigea Bridge from Romania

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2. CABLES AND TIE-BACKS IN MEMBRANOUS CABLE STRUCTURES

Common materials used in cable fabrication during history were: papyrus, camel hair, flax and hemp, until in 1834 when the first cables and ropes from steel wires were made. This new building material soon became indispensable in many fields, due to its special properties – high breaking strain compared to its self weight, great flexibility and durability [17]. In the field of construction, cables were used initially as bearing parts for suspended bridges, and much more lately for covering large areas without intermediate holders [18].

In the last period, in highly corrosive environments, cables made from polypropylene (specific cable weight / specific water weight = 0.91), polyester and nylon (specific cable weight / specific water weight = 1.14) are used.

2.1. Steel qualities and brands for cables and tie-backs [19], [20]

Cables and tie-backs are made from high- and very high-grade steel, with an average carbon content of 0.5% and a breaking strain around 60 daN/mm^2. Considerable growth of mechanical strength can be obtained through repeated deformations applied on steel rods during the fabrication process of wires. Thus, a cylindrical steel bar is transformed on the drawbench in wire, while its breaking strain rises up to 120 – 200 daN/mm^2. After that, the wire is subdued to a thermal treatment and hereby the material regains its plastic properties. The wire yarns are entwisted on a central wire, in one or more layers, composing strands. At their turn, the strands are coiled around a central core, forming the cable.

Nowadays in Romania two types of steel are used in the fabrication of wires which can be embodied in cables:
- carbon steel with 0.6 – 0.9% C and 0.3 – 0.7% Mn,
- thin alloyed steel, usually with manganese and silicon.

From carbon steel are wires with smooth (SBP) or marked (SBPA) surface made, each type in two qualities (I and II). From thin alloyed steel, high strength rods (PC90) are produced, with geometrical, chemical, mechanical and technological properties prescribed by the STAS438/1-74 standard.

The semi-product which is used in the fabrication of strands and cables is the proprietary carbon steel wire (through initial thermal treatment the steel is heated up to 880 – 930 °C, followed by a quick cooling to 450 – 500 °C in a lead bath after which the cooling continues slowly in the air) and drawn SBP type wire (the laminated wires are forced on a drawbench through a smaller hole than the actual diameter of the wire) without final annealing treatment.

The cables can be classified upon several criteria:

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- Classification based on shape: The cables can be flat or round shaped. At their turn, round shaped cables can be simple (made from a single strand), double (composed from several strands) or coupled (formed by wrapping double cables around a central core).
- Classification according to the number of strands: Cables can be made from 1, 6, 8, 18 or 36 strands.
- Classification upon the core material: The cable core can be manufactured from vegetal, mineral, metallic or synthetic wires.
- Classification after the quality of fibers: Steel cables can be produced from uncoated (mat) or zinc coated wires.
- Classification upon the laying of strands: The wire yarns can be coiled in a strand towards right (Z) or left (S). At their turn, the strands can be wrapped within a cable towards right (Z) or left (S).

2.2. Bearing structures with cables

From the point of view of structural analysis, bearing structures with cables can be divided in the following two categories:

- isolated cables,
- cable nets and suspended structures.

Considering these structures, cables can be:

- isolated parallel or twisted wires,
- fascicles of stranded wires,
- ropes,
- thin steel rods,
- ribbons,
- chains,

arranged in one direction or in different directions (Fig. 2).

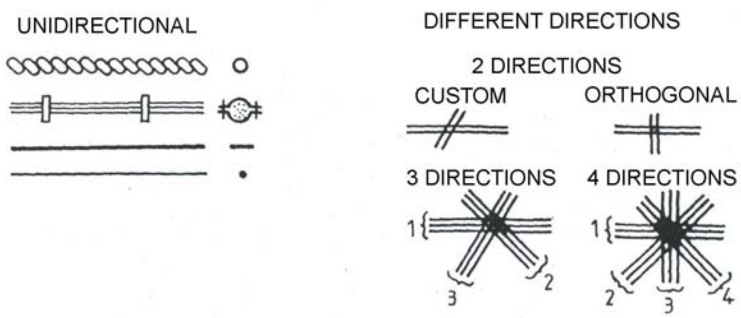

Figure 2. Different cable types

A synthetically exhibition of bearing structures with cables is presented in fig. 3.

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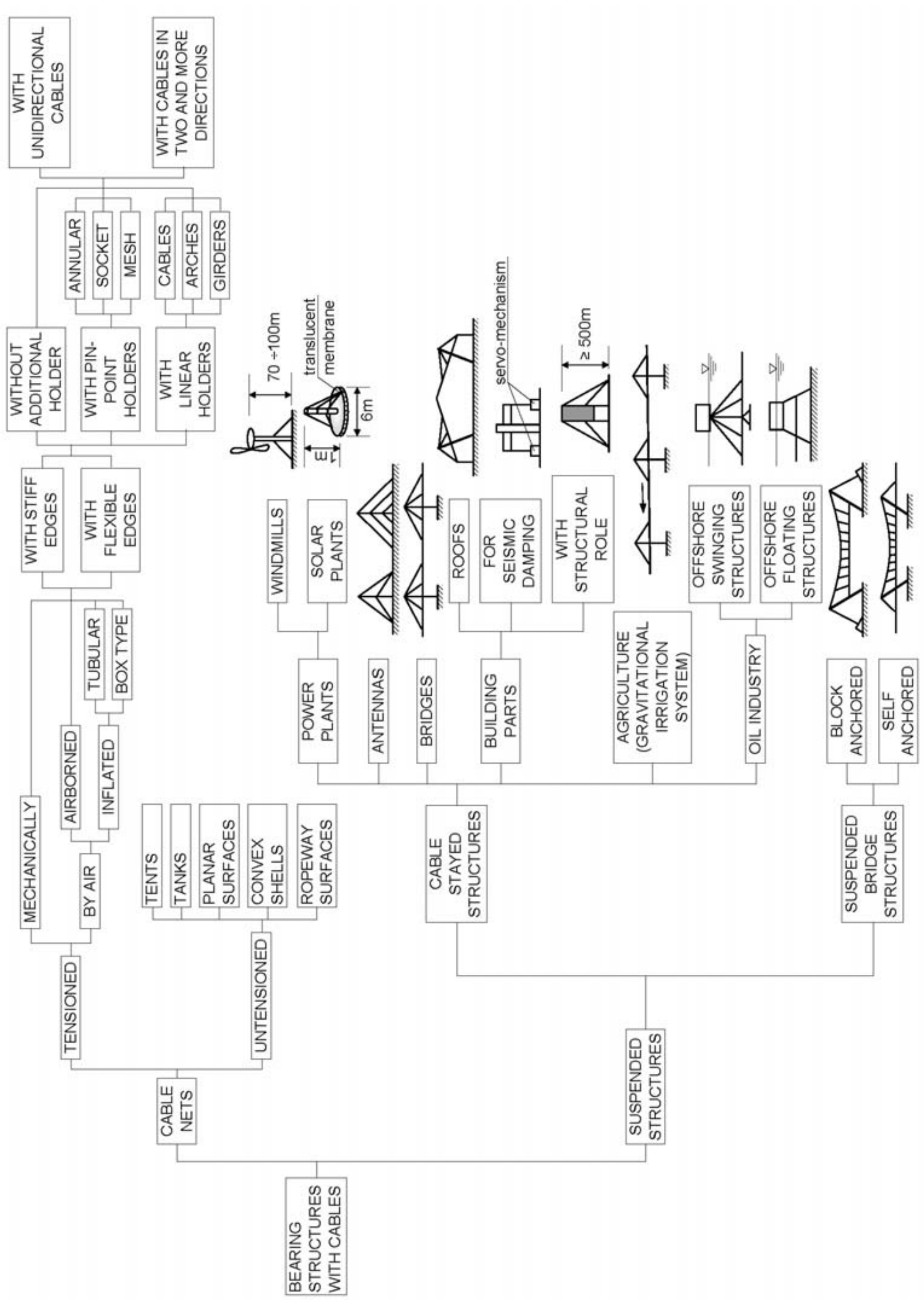

Figure 3. A classification of bearing structures with cables.

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3. EXAMINATION FACETS FOR STRUCTURAL CABLES

In case of structural cables the problems which are generating noticeable modifications of the structural safety can be grouped in the following classes:

- Problems concerning the quality of the constitutive material (cold flow, brittle or breaking in different manners etc.).
- Fatigue problems due to repeated stress.
- The problem of considerable displacements caused by static and dynamic loads.
- Corrosion and erosion problems.

Bearing structures with cables are characterized by loads which are strongly depending from the basic geometry of the structure, namely by the initial balanced state (including also the geometrical and physical imperfections) induced by the steady and working loads and by eventual pre-stressing.

The expertise and checking of these structures must be done by studying the nonlinear geometrical (eventually physical) behavior and all the factors upon which relies the structural safety. As a decisive element rises in this context the occurrence of corrosion and endurance to oligocyclic fatigue. The resistance to oligocyclic fatigue will be studied from secondary stresses (from vibrations or from daily thermal expansion – contraction) considering the intensity of the stress range.

3.1. Loads on structures with cables

The main loads applied on bearing structures with cables are arising from self weight, wind pressure, temperature, working loads with connected dynamic effects and support displacements.

3.1.1. The influence of weight

The following effects will be considered from dead load, combined also with other loads and forces from different causes:

- active loads, containing self weight and snow build-up, ice (frost);
- inactive loads, containing the self weight of the structural element and other permanent loads.

3.1.2. The influence of wind

This action will be considered in the context of KÁRMÁN vortices, combined from case to case with the phenomena of galloping and fluttering.

3.1.3. The influence of temperature

The low environmental temperature must be considered in any cases. Structural elements with lower working temperature than 0 °C will be additionally loaded with ice (frost) through the condensation of the moisture from the atmosphere.

In case of cable sustaining tubular structures with closed ends, through the cooling of the built-in gas or steam the inner pressure can drop enough to create vacuum inside the tube. In such case these tubular structural parts must bear up to the external pressure at low temperature.

3.1.4. The influence of dynamic effects

Buildings with structural cables are checked against the detrimal effects of vibrations that can arise from several sources, such as:
- impact forces;
- resonance developing from the operation of equipments (including air conditioning and ventilation appliances, loud musical gears, traffic etc.);
- seismic actions and wind.

3.1.5. The influence of thermal effects (expansion, contraction)

Thermal effects should be considered in combination with loads and forces from other causes:
- thermal actions through constraints and restraints;
- effects due to different coefficients of thermal expansion in case of structures with mixed materials (like steel and aluminum).

3.2. Case of laboratory-tests

The minimal bench tests which are carried out in a laboratory in order to identify the compounding materials of bearing structures with cables are:
- axial extension test, at different velocities;
- repeated bending test;
- torsion test;
- chemical test of the base material;
- simulation of corrosion and fatigue.

3.3. Site investigations [21]

Examining the behavior in time (ageing property) of steel cables is a special assay, imposed primary by the necessity to insure operational safety. In situ tests will pursue:
- Diminution of cable section, namely *loss of metallic cross sectional area* (LMA) due to corrosion, plastic deformation (afterflow) etc. [22].

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- Modification of the shape (geometry).
- Broken wires, laceration and other *local faults* (LF) due to fatigue [22].

In principle the following methods are used for site investigations:
- visual inspection,
- electrochemical (potential, electrochemical sounds, magnetic etc.) methods,
- other nondestructive testing (microscopical examination, gravimetry, infrared thermography, gammagraphy, radiography and radar processing) [23], [24], [25].

For structural cables only a few of these methods give adequate results.

For visual inspection carried out in site, the authors are advising a new method: MOV_CAM (currently under patenting), using sliding digital cameras in order to view and process the image of the cable (fig. 4).

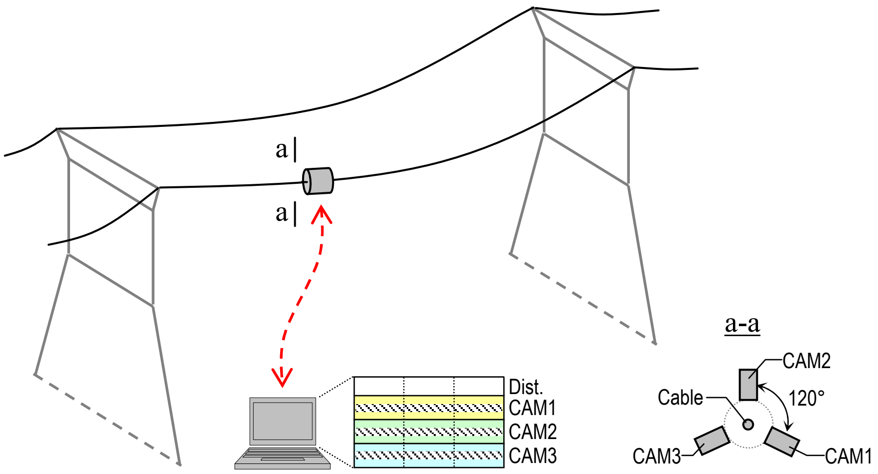

Figure 4. Visual investigation with digital cameras (currently under patenting).

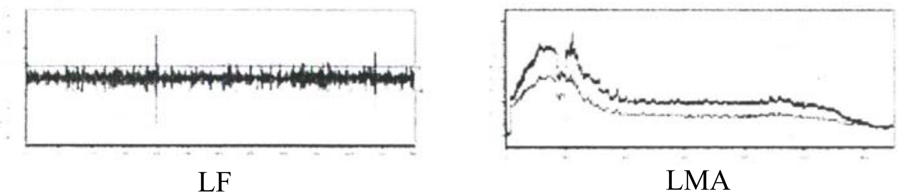

Figure 5. Sample results from LF and LMA testing.

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For LMA and LF type investigations electromagnetic processes are successfully used lately, based on a magnetic head equipped with strong permanent magnets and sensors with distance meter. The software enables to inspect and to display the local faults (LF) and the sectional area diminishments (LMA) in a synthetically manner (fig. 5).

The investigation of the occurrence of corrosion in situ has a peculiar meaning, on one side due to the increasing intensity of the polluting agents in the environment, on the other side due to the requirement regarding the prolongation of the operational service time of cables.

Cables are highly sensitive to corrosion because their self constructional embodiment enables the penetration and stagnation of moisture.

One of the most delicate problems of structural engineering is to track and to keep under control the evolution of degradations caused by corrosion, because this aspect entail in time changes in the physico-mechanical properties and therefore in the strength of materials, leading also to stress redistribution in the structural elements. That is the reason why in the following part a method for monitoring the corrosion of steel cables and the principle of numerical simulation for this process will be described.

The acquisition of primary data about corrosion, in the case of cables, can be done with the method of electric resistance, which is easily applicable in situ. The method of electric resistance is based on the principle that cable corrosion is accompanied by cross sectional reduction. In this way, if there is no intercrystalline corrosion, the raising of electric resistance is produced by the diminution of the cross section.

In case of intercrystalline corrosion, the area of the cross section is not modified significantly, but the specific resistance increases. Thereby, measuring the electric resistance on different portions of a steel cable, considering 500 – 1000 mm long segments, the commencement of corrosion can be promptly recorded. Monitoring the corrosion of steel cables by the means of the electric resistance method enables the undelayed signaling of the occurrence of corrosion, including intercrystalline corrosion. This method is simple, safe and relatively cheap, implying low costs.

4. NUMERICAL SIMULATION OF CABLE CORROSION

The numerical simulation of corrosion can be done in order to study the phenomena in time, using probabilistic degradation functions or data acquired through monitoring. Some of the most frequently encountered fault types are presented in table 1.

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Table 1. Typical patterns of wire rope degradation and failure [25]

Illustration	Short explanation
	A "bird cage" caused by sudden release of tension and resultant rebound of rope from overloaded condition. These strands and wires will not return to their original positions.
	A close-up of a rope subjected to drum crushing. The distortion of the individual wires and displacement from their normal position is noticeable. This is usually caused by the rope scrubbing on itself.
	A wire rope jumped from a sheave. The rope itself is deformed into a "curl" as if bent around a round shaft. Close examination of the wires show two types of breaks – normal tensile "cup and cone" breaks and shear breaks which give the appearance of having been cut on an angle with a cold chisel.
	Localized wear over an equalizing sheave. The danger of this type wear is that it is not visible during operation of the rope. This emphasizes the need of regular inspection of this portion of an operating rope.
	A wire which has broken under tensile load in excess of its strength. It is typically recognized by the "cup and cone" appearance at the point of the fracture. The necking down of the wire at the point of failure to form the cup and cone indicates that failure occurred while the wire retained its ductility.
	An illustration of a wire which shows a fatigue break. It is recognized by the squared off ends perpendicular to the wire. This break was produced by a torsion machine which is used to measure the ductility. This break is similar to wire failures in the field caused by excessive bending.
	A wire rope which has been subjected to repeated bending over sheaves, under normal loads. This results in "fatigue" breaks in individual wires, these breaks being square and usually in the crown of the strands.
	An example of "fatigue" failure of a wire rope which has been subjected to heavy loads over small sheaves. The usual crown breaks are accompanied by breaks in the valleys of the strands, caused by "strand nicking" resulting from the heavy loads.
	A single strand removed from a wire rope subjected to "strand nicking". This condition is the result of adjacent strands rubbing against one another and is usually caused by core failure due to continued operation of a rope under high tensile load. The ultimate result will be individual wire breaks in the valleys of the strands.

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The SACOC (*Structural Analysis of Corrosion for Cables*) software package is based on the finite element method and it proved to be very useful in the study of the corrosion of structural cables. A schematic block diagram of this program is presented in figure 6 [21].

The user can take advantage of several available degradation functions simulating cable corrosion in time, or he can use quantifications from site investigations gathered in a data base.

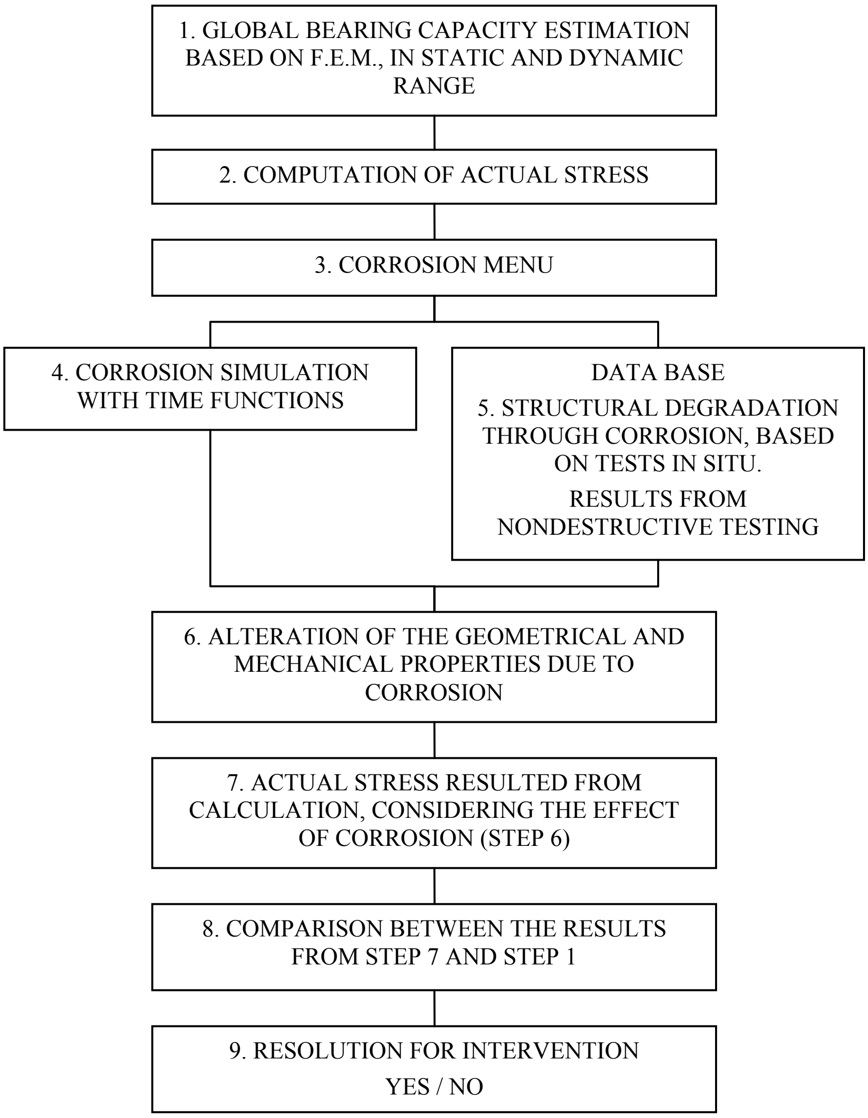

Figure 6. The schematic block diagram of the SACOC software.

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5. CABLE QUALITY CERTIFICATION

The quality of cables is guaranteed by the manufacturer through quality assurance certificates, released for each product range. Deviations in dimensions, properties and shape shall not exceed the prescribed limits from the relevant Romanian technical regulations, nor those stated by the manufacturer. The list of standards for wires and steel cables is presented in table 2.

Table 2. The list of Romanian standards (STAS) in use

Pos.	Title	STAS code
1	Materials	880-66
2	Cold-drawn steel wires for drag ropes	1298-80
3	Steel cables. Concept and classification.	1710-79
4	Steel cables. Simple structure cables. Shapes and dimensions.	1513-80
5	Steel cables. Technical requirements.	1352-78
6	Steel cables. Double cables. Combined structure. Shapes and dimensions	1689-80
7	Steel cables. Combined cables. Double cables. Ordinary structure. Shapes and dimensions	1535-71
8	Steel cables. Combined cables. Triple structure. Shapes and dimensions	2693-80
9	Steel cables. Combined flexible double cables. Shapes and dimensions	1353-80
10	Steel cables. Flat cables. Shapes and dimensions	1559-80
11	Alternate bending test for steel wires	1177-74
12	Testing of metals. Torsion test for wires	1750-80
13	Testing of metals. Coiling test for wires	6622-70
14	Testing of metals. Tensile test for wires	6951-76
15	Testing of metals. Tensile test for steel cables	2172-74
16	Combined double concentric cables	2590-80
17	Steel wire for prestressed concrete	6484-77

6. CONCLUSIONS

Bearing structures with cables are liable to generate unappointed phenomena in comparison with conventional structures. Thus, beside the great displacements originated from their custom designed structural shapes, displacements arise due to the $\sigma_{breaking} / E$ ratio. While this ratio in case of conventional structures, considering OL37 steel is $3700 / 2100000 = 1 / 568$, in case of using cables becomes $15000 / 1650000 = 1 / 110$, namely five times bigger.

Zinc coated cables are able to withstand to corrosion approx. 10 – 15 years. For this reason, in case of highly corrosive environment should be remembered that high quality ropes and cables made from synthetic materials with outstanding endurance are available too.

The required anchoring of cables must be done by wrapping their end with cast zinc inside threaded pipes instead of using clamps, because the cable may slip out from the clamp at high dynamical stress.

Cables should be prestressed in a jointly manner with their anchors (thus the anchoring is tested) before installation, with a force equal to approx. 1.10 times the computed actual stress, in order to consume the significant remnant elongations and to avoid subsequent loosening and relaxation.

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