Metallic and composite cables: a brief review

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Abstract: For cable-moored offshore tension-lag platforms in ultra-deep waters (2000 m), the usage of metallic cables is impractical, making carbon fibre reinforced polymer (CFRP) natural substitutes. CFRP cables have been applied in different situations, such as in cable-stayed bridges, in order to take advantage of its outstanding fatigue behaviour, higher specific stiffness and strength, and good corrosion resistance. However, there are not much experimental data available in the literature for these cables and theoretical solutions still need to be further developed. On the other hand, several theoretical approaches have already been developed for isotropic (metallic) cables, some of them with many simplifications nonetheless still showing good agreement compared to experimental data. On this context, this paper aims to report recent advances on composite cables, comparing previous research results on both composite and isotropic cables on the experimental, analytical and numerical fields.

Keywords: carbon-fibre reinforced polymer; mechanical behaviour; wire rope.

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1 Introduction

It is not completely clear where wire ropes were first used, but according to Verreet (2002), some mural paints showing ropes were found in Egypt, as early as 4,000 years ago. As time went by, the need for more flexible ropes appeared, so in the 19th century stranded ropes started being produced. This rope structure is still used in many applications, as for the oil and gas industry, civil engineering, aerospace and telecommunication.
According to Hollaway (1994), the modern composite materials industry was born in 1909, with the appearance of phenolic resins, but this sector only started growing up after 1940. According to Meier (2012), composite cables are much more recent for industrial applications, and in order to encourage their use in structural applications, it is necessary to fully study and understand their behaviour, which could be translated as evaluating analytical solutions, constructing numerical models and executing experimental tests. This paper goal is to report recent advances on composite cables, comparing previous research results on both composite and isotropic cables on the experimental, analytical and numerical field.

2 Isotropic cables

Costello (1990) investigated isotropic (identical properties in all orientations) cables developing analytical models, and unlike most of the previous analytical solutions, he treated the wires as rods, allowing bending and torsion stiffness analysis. He proposed a very simple, but still accurate approach, based on classical beam theory in order to analyse bending and tensile stress behaviour on single-layered and multi-layered strands, shown in Figures 1 and 2, respectively. However, he neglected friction and slippage between rods and core, and between adjacent rods, and considered that the rods did not rotate around the core when the force or bending moment was applied. Costello (1990) also proposed an easy way to evaluate fatigue life of a rope running around a sheave and submitted to normal stresses.

Figure 1  Single-layered strand

Source:  Costello (1990)
Usabiaga and Pagaldy (2008), also using beam theory, developed an analytical solution for regular and lang lay cables (Figure 3) submitted to tensile stress allowing for rod rotation, neglecting, however, the Poisson effect. They compared their model with Costello (1990) analytical solution for Poisson ratio of 0.0 and 0.3 and verified a small difference. However, the cable behaviour was greatly influenced by rod rotation when the cable was submitted to torque. They also showed that the resulting torque at the cable ends is higher in the lang lay architecture, i.e., when both wires and strands have the same lay direction.

Experimental results were reported by Utting and Jones (1987a, 1987b) and compared with analytical predictions. They presented a new approach, considering slippage in the case of a cable subjected to tensile stress. They concluded that the load-torque relation in a strand was linear, and the torque increased as the helix angle was reduced. Rotations and extension were also higher for cables with small helix angles.
Relative to friction, Utting and Jones (1987a, 1987b) stated that plastic yielding occurred, with the contact point moving along the cable surface without slip, following the axial force direction. However, in an actual situation, the wire flattens as load is applied, with changes in contact area, so their analytical solution cannot be realistically used.

Concerning stress distribution, three strain gauges per rod were used, and they observed that, when a torsional restraint at the rods is applied, the external load supported by the helical rods increased. This torsional restraint followed a linear relation with the applied axial load, being higher for small helix angles. Relative to the extension, they concluded that the rods with less torsional restraint would experience higher extensions. In fact, rods with small pitch (low helix angles) are submitted to a lower strain under axial conditions. Utting and Jones (1987a, 1987b) also noticed, with parallel positioned strain gauges, that stresses at the helical rods were higher near the strand grips.

Elatia et al. (2004) developed another analytical model for multi-layered strand cables using the reciprocity theorem of Betti. They also executed experimental tensile tests, fixing the cable and measuring the torsion resistance at one end, and putting a bearing on the opposite end to create a free-end condition. They showed that in the multi-layered strand, unlike the single-layered case, the strain on an outer rod is not constant along the cable length, but follows a harmonic function, with upper bound close to the core and lower bound far from the core along its twist. In their numerical and analytical solutions, they neglected Poisson effect and studied two extreme cases with the aid of an imaginary sieve:

1. the sieves were locked, constraining wires slippage between them (infinite friction between wires)
2. the sieves were unlocked (well-lubricated rope, with no friction).

They reported only a slightly difference in cable response, however, on the external rods the evaluated stress was considerably different.

Custódio and Vaz (2002) summarised the main simplifications and assumptions made by analytical solutions, which includes linear elastic isotropy, wires as homogeneous cylindrical helices equally spaced and perfectly wound, end effects, friction between wires, and self-weight neglected, and the pitch variation is traditionally assumed as linear and small. The authors focused their work in elaborating a nonlinear model, aiming to solve the problems generated by this last assumption relative to the pitch variance. A model to avoid frictionless hypothesis was elaborated by Argatov (2011), which considered the interwire contact in his model by attempting for the Poisson effect and flattening due to contact deformation.

Even with a collection of available analytical solutions for isotropic cable, with different degrees of complexity between them, a review made by Cardou and Jolicoeur (1997), whose author analysed the main analytical models until this time, pointed for a lack of solutions that could accurately predict the behaviour of individual wires under tensile stress. Relative to the bending behaviour, the authors stated that the models could not even predict the global response.

On the numerical field, Erdemnez and Imrak (2011a) analysed multi-layered cables through finite element method (FEM). They started investigating the minimum length to be modelled that could still give a trustable result for any cable length, saving
computational time and guaranteeing that the contact between wires effectively occurs. They compared an elastic frictionless FEM model with Costello (1990) solution, however, they could only obtain good agreement between FEM and Utting and Jones (1987a, 1987b) experimental data after adding plastic strains and normal contact, showing that the tangential contact play a small role. They also extended their FEM model to multi-layered cables and stated that it could be applied to a bending condition instead of only tensile stress. In fact, Jiang (2012) analysed isotropic cables in pure bending considering plastic strain and friction and also achieved good agreement with Costello (1990) analytical solution on the elastic region. He analysed only single-layered strands, but suggested that his work could be extended to multi-layered strand cables.

Relative to contact pressure measurements, Jiang et al. (2008) plotted the values arisen from the contact between adjacent wires and between external wires and core from wire ropes submitted to tensile stress. The authors concluded that, for elastic and plastic models, the pressure between core and wires is greater than between wires, even with the low friction coefficient applied (0.12), and in the 1 × 7 cable tested by the author, the two contacts occur at the same time. When comparing the change in helix angle, a great difference between its FE solution and Costello (1990) was achieved. Labrosse et al. (2000) analytically measured, through a hysteretic model, the frictional dissipation on an axially loaded wire rope, achieving small values and stating that friction could be neglected, and linear models are able to predict the cable behaviour under tensile stress conditions, but the author tested only a single layer cable.

Ghoreishi et al. (2007) compared their finite element model results with experimental data from Utting and Jones for a 1 × 7 single-layered cable under axial loading, varying the helix angle, and obtained small variations. They also analysed the same cable through nine different analytical models, including Costello (1990), Hruska (1952), Machida and Durelli (1973), McConnell and Zemeke (1982), Kumar and Cochran (1987), Ramsey (1988), Sathikh et al. (1996) and Labrosse (1998), each of them with different considerations and assumptions. Ghoreishi et al. (2007) constructed a stiffness matrix with four elements: axial stiffness and torsion in the main diagonal and coupling terms in the secondary diagonal. They plotted the four elements of the cable stiffness matrix in order to compare each of them with his numerical data, varying the helix angle from 60° to 90°. All models that did not underestimate torsional stiffness provided good results for helix angles above 75°, or 70° for the models that considered the Poisson’s effect. As the helix angle decreased, only the FEM remained accurate, with a trustable solution. Lately, Argatov (2011) compared his asymptotic interwire model with Ghoreishi et al. (2007) numerical model. The difference in tensile stress behaviour was lower than the analytical models tested by Ghoreishi et al. (2007).

Another concern when designing wire ropes is the bend over sheave problem, since they must be bend repeatedly without damage (Davies et al., 2011). Witz and Tan (1992), who proposed two failure modes for flexible pipes and umbilical marine cables, analytically investigated this problem. The first mode stands for deformation without sliding, and the other after the wires starts sliding one relative to each other. Erdonmez and Imam (2011b) could numerically model a multi-layered cable, which was not possible by the analytical solutions mentioned above for flexure loadings, being bend over a rigid sheave. The authors modelled the problem by superposition, firstly applying loading on longitudinal direction, and then, at the free end, a loading in the transversal
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direction to bend the cable over the sheave. The authors noticed that, instead of what was achieved by Jiang (2012) for pure flexure, in this case the core strand is loaded more than the outer are. Cutler and Knapp (2010) proposed a new methodology for experimentally test the bend over sheave problem. The authors design a variable diameter sheave, instrumenting the wires with strain-gauges, so they could validate their FE numerical model by comparing it with their experimental data.

3 Composite cables

3.1 Advantages of a carbon fibre cable

Carbon-fibre reinforced polymer (CFRP) cables are traditionally manufactured by pultrusion using epoxy resin, allowing for the use of long fibres and high fibre volume fraction. The reasons for choosing epoxy, despite of its high cost, are mentioned by Kaw (2006), and include high strength, low viscosity, which prevent fibres misalignment, low volatility, and low shrink rates, improving compatibility between matrix and fibre.

The importance of CFRP cables is verified nowadays mainly on the civil engineering sector. Meier (2012) investigated the advantages of using CFRP cables for structural applications in suspended structures. Due to CFRP cables properties, like corrosion resistance and high specific strength, he decided to evaluate the maximum bridge span allowed by both, steel cables and CFRP cables. He found that, for classical suspension bridges, steel cables could support a span up to 7.7 km, while CFRP cables up to 37.5 km. Meier (2012) also pointed out two drawbacks in using CFRP cables. The first is related to their weak wind erosion and ultraviolet attack resistance, which could be easily solved by using polyethylene layer as shielding. The second is their higher initial design cost compared to steel. Xie et al. (2014) also pointed for the superiority of CFRP cables relative to steel in creep and relaxation.

Motoyama et al. (2002) highlighted the lightweight, high strength, no-magnetism and corrosion resistance of the CFRP cable, extending its usage for the aerospace industry as stowage of satellite for transportation, and as a viable way to reduce weight in deployable structures. Also focusing on the aerospace industry, Maji and Qiu (2014) investigated the cable damping coefficients. By executing numerical and experimental tests, the authors stated that by increasing the pitch and tensile load they could also improve the cable damping coefficient, reducing vibrations that may lead to malfunction on deployable structures.

Regarding the petroleum industry, composite materials are not new in this sector, as cited by Eckold (1994). Glass reinforced materials have already been used in pipelines, salt water disposal, casing, surface injection, flow and gathering lines, mainly because they offer both design and operational advantages, such as lightweight and corrosion resistance. Jackson et al. (2005) analysed the use of carbon fibre composite cable (CFCC) a commercial CFRP cable developed by Tokyo Rope for mobile offshore drilling units, and compared existing cable technologies, shown in Figure 4. In this figure, CFCC, Nippon Steel Carbon Fiber Cable (NACC) and Leadline (commercial product developed by Mitsubishi Plastics) are carbon fibre derivatives. They also showed the superiority in mechanical properties of carbon fibres relatively to many synthetic materials, stating that CFCC are an excellent solution for the oil and gas industry.
Figure 4 Comparison of specific modulus and strength of different cable materials (see online version for colours)

Source: Jackson et al. (2005)

Odru and Geffroy (2002) studied the use of CFRP cables in the offshore industry, more specifically in tension leg platforms (TLP) used to extract oil in ultra-deep waters. The advantages reported by them include good fatigue resistance, high level of flexibility, safety due to the non-propagation of defects, as found in bulk materials, and unlimited size for mooring. They also mention that the tested characteristics of one sample were able to represent the behaviour of the entire cable.

3.2 Experimental data

Since such cables are new for industry, and some properties like relaxation creep, aging and fatigue are difficult to be numerical or analytical predicted, it is very important to execute experimental tests in CFRP cables that could be used to validate numerical and analytical models. Longitudinal properties of a common CFRP with T700S fibres were reported by Meier (2012) and are listed here in Table 1 together with low carbon steel properties reported by Iron and Steel Society (1999).

As can be seen in Table 1, strength of CFRP is much higher than steel. Nevertheless, Meier (2012) warns that the transversal properties of CFRF cables are relatively poor, while steel cables are isotropic materials.
In the case of civil engineering, the cables can be straight to take full advantage of the axial properties of the rods. Meier et al. (2015) monitored different bridges where CFRP cables were applied since 1991, and until 2015 none of the bridges needed any kind of repair on the CFRP cables, not even visible defects were detected.

Anchorage of the composite cables is not an easy task. Jung and Park (2011) measured the ultimate strength of CFRP cables with common anchorage methods for higher bonding area at the cable ends. They found that ultimate stress, with an untreated surface, increased from 349 MPa to 1,022 MPa, showing the important role played by the anchorage on cable performance.

Motoyama et al. (2002) analysed CFRP cables with 68% fibre volume fraction, consisting of six rods spirally twisted around a straight rod (core), each rod having 3 mm diameter. For the quasi-static tensile test, failure occurred in all rods simultaneously, at a strain of 1.35% and a load of 114.5 kN. The longitudinal Young modulus measured was 134 GPa. They also performed high-speed tests in order to analyse dynamic tensile properties, and again, all rods failed simultaneously, but the fractures occurred preferentially close to the ends, unlike quasi-static tests. The load vs. strain curve lost its linearity as the test speed increased from 0.1 to 4.0 m/s. Based on an acoustic emission technique, they found that, for CFRP, it takes 9 $\mu$s for the stress wave to propagate between two strain gauges, so differences of localised strain could be neglected. They also measured ultimate strain and energy absorption as a function of the strain rate, and these values increased for higher strain rate.

A fatigue study was performed by Odru and Geffroy (2002) using pultruded carbon fibre rods submitted to 2.1 million cycles at 45% of breaking load under tensile stress, and they did not find detectable defects after the tests. Sparks et al. (2003) performed fatigue and ageing tests on unprotected CFRP cables and concluded that there was no strength loss due to those effects on the material. Ali et al. (2015) also investigated the CFRP cable aging on sea water, executing tensile stress test before and after the aging. After 7,000 hours underwater, a loss of only 7% on the tensile strength was achieved.

Santos et al. (2015) investigated the application of CFRP cables in the electrical sector. Since these cables are lighter, they allow for higher spacing between towers, reducing cable sag. Three resins were tested to identify galvanic corrosion between aluminium and the composite material. Epoxy and polyester successfully protected the material, whereas phenol formaldehyde did not pass. They also stated that, for high demand periods, the wire temperature could reach 200°C, so only the epoxy resin should be used.
Focusing on the aerospace industry, Maji and Qiu (2014) investigated the cable damping coefficients. By executing experimental tests, the authors stated that by increasing the pitch and tensile load they could also improve the cable damping coefficient, reducing vibrations that may lead to malfunction on deployable structures.

3.3 Analytical and numerical solutions

Currently, as far as this review has reached, there is no available analytical solution for composite cables under tensile stress, since all solutions mentioned before apply only for isotropic materials, which is not the case for composites. Nevertheless, Pan (1992) developed an analytical solution for short fibre yarns, considering them as transversally isotropic. His work is a good start in order to achieve an analytical solution, since the consideration of short fibres could be neglected when applied for cables, simplifying his equations. Pan (1992) disregarded friction, but Luz et al. (2014a) measured the static friction coefficient between carbon-epoxy pultruded rods, finding the value of 0.6. The latter showed that neglecting friction will result in less than 1% difference for tensile and bending conditions. On the bending behaviour, Crossley et al. (2003) proposed an analytical solution for elastic transversally isotropic cables. The cable wires were considered frictionless or bonded, assuming the displacement field as a four-degree polynomial.

Luz et al. (2014b) compared a CFRP cable FEM numerical solution with the previous mentioned analytical solution of Costello (1990). Although this analytical solution applies only for isotropic materials, they found that, for large pitches, the difference in tensile stress between the analytical and the numerical solutions of a transversally isotropic cable was lower than 5%. The similarities in the response of isotropic and transversally isotropic cables were not confirmed for bending behaviour as reported by Menezes et al. (2014). They modelled CFRP cables and analysed the influence of parameters such as pitch and rod radius, showing that by reducing their pitch, CFRP cables greatly improve their bending behaviour. Indeed, for the anchorage of oil platforms the cable must show some flexibility in order to be able to be bent around small spools, which may be achieved by reducing cable pitch.

4 Concluding remarks

Concerning isotropic cables, despite of the many assumptions made by analytical models, they can accurately predict the torsion, tensile and bending behaviour of simple cable geometries. In the case of small pitch cables, approaches that attempt for the friction between wires and between wires and core should be applied. On the numerical field, the literature provides experimentally validated models for cables with plastic strain, friction and complex geometries.

Regarding orthotropic cables, the advantages showed by CFRP demands the usage of such cables in different areas. This composite cable has already been tested under tensile stress and bending behaviour, fatigue, relaxation and aging in corrosion environment, showing an outstanding behaviour and a clear superiority relative to steel. However, a cyclic bending fatigue test still needs to be performed for its fully characterisation and usage in offshore structures. Analytical solutions for isotropic materials could not be applied for CFRP cables, and as far as this review has reached, there are only analytical solutions for bending behaviour without numerical or experimental comparison. Numerical model with experimental validation are still necessary.
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References


