Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

PBO Fibres: from sailing design towards architectural performance

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Abstract

PBO fibres, also called "high-performance" polymer fibres, are a group of materials known as "rigid rods". Through this work it is pretended to make some considerations about the use of these new generation fibres. Poly (p-phenylene-2.6-benzobisoxazole)(PBO) is rigid-rod isotropic crystal polymer. PBO fibre is a high performance fibre developed by TOYOBO (Japan) PBO fibre is quite flexible and has very soft handling, in spite of its extremely high mechanical properties.

Over the past ten years Future Fibres Company has pioneered the use of PBO for yacht rigging and has proven it to provide remarkable performance and longevity. Their method of producing these PBO cables delivers the lightest, smallest cables available on the market today.

The PBO cable is formed by combining the incredible properties of PBO (poly(p-phenylene-2,6-benzobisoxazole)) fibre with the simple yet undeniably reliable process of continuous winding.

A PBO cable is dry fibre tightly compacted and does not rely on a resin matrix that, if impacted, can be compromised. The cover of the cable is a vital component and whilst PBO is an excellent material for yacht rigging purposes, due to its extreme strength, low elongation and general robustness it must be protected from sunlight and seawater. Future Fibres has perfected its cover design that comprises a consolidating film, environmental protection layer and a customizable braided cover that can be tailored to suit any specific application.

PBO has great potential to be used in construction or rehabilitation applications. At the same time the fibres, following further testing, would open up several design opportunities for high quality architectural projects.

Keywords: PBO fibres, Cable, Polymeric structural material, Plastic material

1. Introduction

The Marine industry is using carbon fibre, PBO fiber or other similar structural elements in high performance racing boats and yachts. It is possible due to the good performance of these fibres, high mechanical benefits, stability at high temperatures and above all lightweight. This technology has also been tested on Formula 1 Teams, as an active safety element in case of collision, preventing uncontrolled projection of tires. These experiences lead us to an initial question: If these materials respond optimally to a dynamic action, why not initiate research for its use in structural elements on buildings?

Through this work it is pretended to make some consideration about the use of these new generation fibres. This reflection should be based on tests, studies or results of experiences more or less unique, which make from it a step forward towards a massive use, that we consider feasible, given the experiences in other fields.

2. Fibres employed in naval engineering

2.1. Historical review about fibres employment in navigation

Phoenician, Greek, Roman and Muslim navigators exploited the properties of esparto grass in commercial and military boats construction. During the MiddleAge, hemp would be introduced, and, during XVII Century, it would be improved by tar, to seal the fibres.

Along the second half of XX Century, inox steel-wire braided cable would appear. It performed good against oxidation, but it was a heavy and not very elastic material. In the '80, it is developed the Nitronic 50 (rod ridding, a high grade stainless steel), with the purpose of increasing the efficiency and the performance of rigid cables. Within this research line, other rod rigging would use cobalt, carbon and Kevlar.

From the '90 a lot of innovative synthetic fibres come out. Examples should be done by dyneema, vectran y technora fibres, employed in racing boats and yatchs.

In 1998 Future Fibres build the first PBO cables in the world, becoming pioneers in Composite rigging. This is a mile stone in the sailing history due to the properties of PBO, an 80% lighter than Nitronic 50, and a 50% more resistant.

2.2. Fibres used now a day in naval engineering

2.2.1. PBO

Poly (p-phenylene-2.6-benzobisoxazole)(PBO) is rigid-rod isotropic crystal polymer. PBO fibre is a high performance fibre developed by TOYOBO (Japan) and has superior tensile strength and modulus to Aramid fibres, such as Kevlar, Technora and Twaron. It also has outstanding high flame resistance and thermal stability among organic fibres. PBO fibre shows excellent performance, in such properties as creep, chemical resistance, cut/abrasion resistance, and high temperature abrasion resistance, far exceeding other Aramid fibres, PBO fibre's moisture regain is low (0.6%) and it is dimensionally stable against humidity.

PBO fibre is quite flexible and has very soft hand, in spite of its extremely high mechanical properties.

Over the past last ten years Future Fibres has pioneered the use of PBO for yacht rigging and has emproved it to provide remarkable performance and longevity. PBO's properties deliver the lightest, smallest cables available on the market today.

2.2.2. Dyneema

Dyneema is a high-performance polyethylene (HPPE) which is a subset of the thermoplastic polyethylene. It has extremely long molecular chains that can transfer load more effectively to the polymer backbone by strengthening intermolecular interactions. The result is a very tough material, with the highest impact strength of any thermoplastic presently made. It is highly resistant to corrosive chemicals, with exception of oxidizing acids. It has extremely lox moisture absorption, has a very lox coefficient of friction, is a self-lubricating, and is highly resistant abrasion (15 times more resistant to abrasion than carbon or steel).

In relation to PBO, a Dyneema cable is around 10 percent heavier and 22 percent larger in diameter for the same level of stretch. It does suffer from creep which rules it out for side shrouds, however, its durability around corners makes it an ideal fibre for certain applications e.g. strops.

2.2.3. Kevlar

Kevlar was introduced by DuPont in the 1970's. It was the first organic fibre with sufficient tensile strength and modulus to be used in advance composites.

Kevlar is an aramid, a term invented as an abbreviation for aromatic polyamide. The chemical composition of Kevlar is poly para-phenyleneterephthalamide, and it is more properly know as a para-aramid. Aramids belong to the family of nylons. Common nylons, such as nylon 6.6, do not have very good structural properties, so the para-aramid distinction is important. The "aramid "ting gives Kevlar thermal stability, while the "para" structure gives it high strength and modulus.

Kevlar was the fore-runner to PBO and shares many of the same properties but cannot compete with PBO in terms or strength and stretch.

2.2.4. Carbon

Carbon fibre consists of extremely thin fibres about 0.0002-0.0004 inches in diameter and composed mostly of carbon atoms. The carbon atoms are bonded together in microscopic crystal alignment makes the fibre incredibly strong but requires a resin matrix to support the fibres. The resin matrix makes carbon fibre cables a relatively brittle solid, which brings with it certain problems, such as increased weight and the risk of impact.

2.2.5. Comparative table of values

PBO is inherently stronger than other composite fibres: 5.6 percent stronger than carbon and approximately twice the strength of Dyneema and Kevlar. PBO is also 50 percent stronger than Nitronic 50 Rod for the equivalent level of stretch.

	PBO	**Dyneema**	**Kevlar**	**T800 carbon**
Tensile strength (Gpa)	5.8	3.0	2.8	5.49
Weight (kg/m)*	0.162*	0.179*	0.254*	--

*Cable with Nominal break load of 21.950 kg

Figure 1: Comparative table of values: PBO- Dyneema – Kevlar - T800 carbon fibers. (Future Fibres Company)

2.3. About PBO use experience

Over the last 10 years Future Fibres has established itself as the one of the world's leading composite cable supplier with clients from America's Cup and F1 teams to the UK Ministry of Defense.

It is the only composite rigging company to have Germanisher Lloyd accreditation. It is also the only Motorsport tether supplier, to date, to provide the full range of safety tethers for the Motorsport Industry with homologation from both the FIA and SFI. Its success has been built on a precise, patented loop construction process.

With over 65 trained staff at its 5,000 m² purpose-built facility in Valencia, Spain, Future Fibres is 100% focused on the design and manufacturer of composite cables. This is achieved by continued researching of new materials and constant in house testing to refine the best method of production for individual materials so as obtain the maximum benefit from said materials.

2.3.1. PBO cable description

The cable is formed by combining the incredible properties of PBO (poly(p-phenylene-2,6-benzobisoxazole)) fibre with the simple, yet undeniably reliable, process of continuous winding.

It is normal when designing composite standing rigging that the cable stiffness (EA) is matched to the equivalent Nitronic rod in order to maintain the original design specification. Generally Nitronic 50 is specified with a 2.5 times factor of safety over the working load. The strength versus modulus ratio of the PBO fibre gives approximately 50% extra strength over the stretch equivalent Nitronic 50 rod resulting in an increased factor of safety.

Future Fibres is able to build cables to any given stretch equivalent, break strength or diameter. This bespoke construction method serves as an invaluable tool for designers freeing them from the standard rod sizing constraints.

A PBO cable is dry fibre tightly compacted and does not rely on a resin matrix that, if impacted, can be compromised. The cover of the cable is a vital component and whilst PBO is an excellent material for yacht rigging purposes, due to its extreme strength, low elongation and general robustness it must be protected from sunlight and seawater. Future Fibres has perfected its cover design that comprises a consolidating film, environmental protection layer and a customizable braided cover that can be tailored to suit any specific application.

The role of the Future Fibres end fitting is simply to interface the cable with mast or deck terminations. The structural integrity, however, rests solely in the continuously wound fibre. Other composite solutions rely on end terminals to transfer the load to the cable, adding an extra link in the chain, more complexity and additional weight. The working life of these cables is also limited by the serviceable life of the end terminals.

Spools are generally used in the design of standing rigging to optimize weight and aerodynamic drag, alternatively adjustment can be achieved by using custom threaded adjusters.

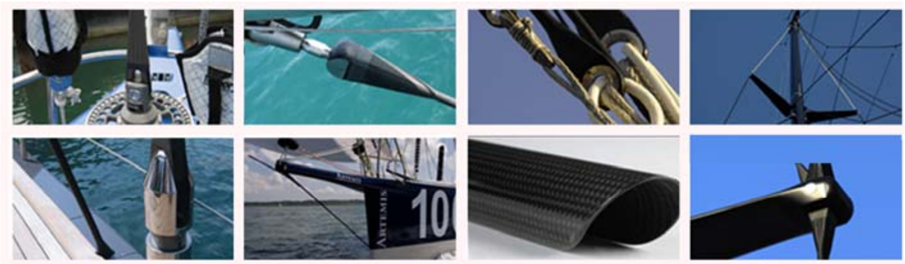

Figure 2: Some PBO Cables Details (Future Fibres Company).

2.3.2. Cable life

Future Fibres prides itself on its quality control process. Each stay is rigorously tested throughout its various stages of construction, in accordance with the Germanischer Lloyd standard. When dealing with America’s Cup, the Volvo Ocean Race it is absolutely vital that this level of quality is maintained. Having dealt with these customers for nearly a decade, quality is second nature at Future Fibres.

As a direct result of this rigorous QC, Future Fibres PBO is setting the standard for reliability with in excess of 150 complete sets of standing rigging, 6,000 individual cables supplied and over 20,000 Safety tethers to date.

Future Fibres rigging has been tested in extreme conditions including over 30 circumnavigations in world record attempts and races. Many yachts have sailed in excess of 50,000 miles on a single set of Future Fibres PBO standing rigging.

In addition we have amassed data from laboratory test situations with fatigue testing to over 1 million cycles; combined with extensive testing of used cables. This has given our design team invaluable knowledge of the real world behavior of our cables. A combination of these test results has allowed Future Fibres to produce quantified cable life recommendations.

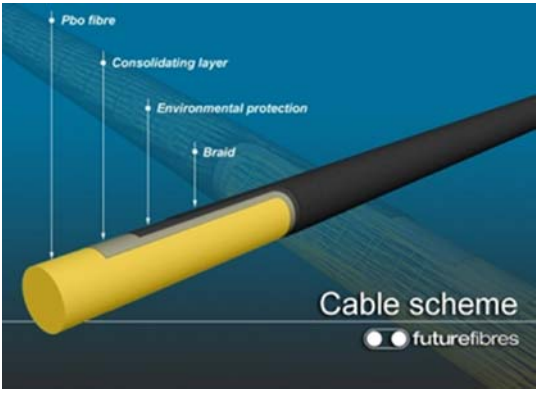

Figure 3: PBO Cable scheme (Future Fibres Company).

Due to the different load cases for each rigging element, Future Fibres recommends a replacement interval of 6 years (or 60,000 miles) for vertical stays, 3 years (or 30,000 miles) for diagonals and forestays and 2 years (or 20,000 miles) for running backstays, provided that the standard service schedule is maintained throughout this period.

Part of the inherent design of a Future Fibres cable is its covering, great emphasis has been placed on life expectancy and the covers play an essential role in this. The three layer protection system is not only designed to compact the fibres to minimize diameter, it also serves to keep out light, moisture and resist chafe.

3. Role of plastic materials in construction

We must point out certain reservations to be taken into account, as with most plastic materials in its possible use: lifetime, prolonged weathering behaviour (UV, high temperatures), maintenance or replacement and cost. These should be analyzed, as indicated, very accurately in future works.

Nevertheless, we mustn't stop our reflexion on their use, being able to start testing them for example on temporary buildings, emergency buildings, auxiliary structural elements or, personal and collective protection equipments for health and safety in construction. This route is being followed by lots of plastic materials in the building industry, from a job "humble" use or without structural function, making their way day by day into the world of structural materials.

Listing the plastics used now in construction could be a virtually endless. Polyolefin, polymerized styrene, halogenated polymers, polyvinyl esters, phenoplasts, aminoplasts, reactive resins, polyurethanes, silicones, and caoutchoucs might be some of the polimer groups which, together with their corresponding subdivisions of other polymers, would extend infinitely.

In most cases, their good properties can, respond to the requirements included in the lifetime of a building: normal use temperature from -10º C to 60ºC; range of expansion coefficients that could be between 60 and 200 x 10^{-6} / ºC (between 15 x 10^{-6} /ºC on reinforced plastics and 12 x 10^{-6} /ºC on concrete with synthetic resins, close to the values on steel or reinforced concrete). As indicated above, bad behavior against UV or high temperatures in plastics must be taken into account. It should be insisted upon the behavior, especially of all the natural exposure to the environment, making attention to the values of laboratory testing, about physical alteration and the consequences on their mechanical behavior. In addition, it will be also interesting, from the viewpoint of the characterization of any plastic material, its compatibility with different chemicals to be used. Saechtling, H. [8].

On one hand the different types of plastics and on the other hand its constructive purpose, form a lattice manifold. If we limit ourselves the use of these plastics as load-bearing structural element, the range is substantially smaller, like the number of proposals through the just over 140 years of history of this material. The use of plastic as a structural system has often been through its combination with other materials, such as reinforced plastics (FRP), or combined with materials such as wood-based materials as binders synthetic resin (urea resin (UF), melamine urea resins, phenolic resins (PF). Some plastics can enable response to requests such as: lighting by means of light elements, easy to put in place, reducing weights, easy to assembly, all of them linked to the structural design of the building. An example of this is the USA Pavilion at Expo 1967 in Montreal, with the use of acrylic glass, or more recently in the Olympic pool of the Olympic Games Beijing 2008 with the use of ETFE or the use of GRC (strengthening concrete with pieces of fiberglass) in prefabricated systems. The use of plastic as a purely structural material has been developed in various structural systems: domes, hyperbolic paraboloids, precast-based shell elements (small buildings), membrane structures, air craft and folded surfaces. Each system developed with different types of plastics:

Polyurethane in sandwich elements, rigid polyurethane foam in emergency igloos, polyhedra based on GF-UP, GFK precast, high-strength synthetic fibers coated with plastic to build membrane structures.

4. Tensile architecture and plastic raw materials

A cable is a tensile stress transmitter, that can be the role element of an unilinear (one-dimensional) supporting system, it's larger in one dimension than in the other two.

Focusing the study field on the cable as a structural element, from the initial study of tensile structures by Frei Otto, plastic materials were considered essential for the design and rapid development of these structures. Therefore the relationship between early studies of pneumatic structures and plastics has been clear, naming in his splendid analysis of structures the caoutchouc, polymers such as nylon in the group of polyamides, polyvinylchloride, fiberglass with teflon, polyester or acrylic fabrics, being used from the lighter membranes to membranes used in the containment of reservoirs.

Figure 4: Model of German Pavilion for Expo 1967. Gutbrod, Otto, Leonhardt, Kendel Medlin (Frei Otto).

Farthest references in the use of meshes like tensile structures based on cables and knots have been related with fishing nets and nautical references, specifically support systems for the Viking ships sails in southern Sweden. Other historical references are suspension bridges based on natural fiber cables. Frei Otto gave order and criteria to the use of these structural systems, producing outstanding examples of suspended tensile systems, as the Yale Hockey Stadium (New Haven); Dulles Airport (Washington), the suspended ceiling of the Baxter laboratories (Chicago) and the Olympic ring in Munich, 1972.

Since tensors in tents until bridges with the biggest bearing distances in the world have relied on the use of loads transmission capacity by cable systems. The use of the cable in its many provisions had already been studied and classified in a detailed manner by Frei Otto, in the shape of a cable, cable mesh or cable membranes, Otto F.[7]:

Spatial suspended structures

Prestessed tension-loaded structures: prestressed individual cables, structures with individual cables forming surfaces, prestressed cable under load, plane systems subjected to stresses in the surface,.

Cable Systems and Nets Forming vertical Surfaces

Freely suspended cables that form surfaces

Single Cables arranged radially

Nets of cables and struts

Nets of cables and elements rigid in bending, etc…

Figure 5: Tokyo Olympic Swimming Pool, 1967 of Tsuboi & Kawaguchi (Irvine).

Obviously all of these structural systems have relied on the use of steel for its realization, being the only one capable of transmitting tensile stress joined with natural fibers, reducing the durability problem of these.

The cables typology starts form those made of metal filaments. The placement of these yarns generates different types of steel cables commonly used: stranded, braided or bundled cables.

As well as its typology in terms of the placement of filaments, it will be needed to determine non-structural considerations like protecting the cables from moisture, ultraviolet rays, friction between fibers, etc...

PBO used in yacht as a composite cable, makes thinking about their structural use. But this experience comes with proposals on the environmental protection of the cables and the different linking systems developed: knots, joints, edge knots, knots deviation, terminals that can logically support the development of a technology in the field of architectural structures.

Figure 6: Walls examples and some details realized by GIG. PBO Cables, Austria (Future Fibres Company).

4. Conclusion

Future Fibres company (Museros – Valencia) has got and experience of over 10 years using PBO fibre Poly (p-phenylene-2.6-benzobisoxazole). It is being used in high demanding markets such us high level racing boats and superyachts (America's Cup, Volvo Ocean Race..) o Formula 1 Teams.

Carbon fibre, Kevlar or Dyneema, have been developed and tested on a starting point in fields like yatching, and afterwards they have been started to be used in architecture; or in both fields at the same time.

All range of tensile structures developed during the '60 and '70 from Frei Otto studies, invite us to investigate and use new materials from a typological point of view, more than from a structural point, PBO fibre could be used in temporary emergency structures, auxiliary structural elements or protection equipments for health and safety in construction.

Like carbon fibres, PBO could be also used in structural reinforcements in rehabilitation.

Backwarding this fibre, there is a well developed technology, reinforced with laboratory tests, extensive testing of used cables and real world behavior in extreme conditions.

Additional benefits come from the range of terminals, connectors and cable protections designed. In conclusion, a great opportunity to study the use of PBO in the field of spatial structures.

Acknowledgement

Valentina Cristini, Architect.

Eduardo Fernández Moscoso, Architect.

Antonio Trimboli, Civil Engineer.

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