Carbon Fiber Rigging, Yesterday, Today and the lessons learned along the way

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Summary

Advances in materials technology allow for the exploration of new structural forms and systems. In recent years carbon fibre reinforced poymers have emerged as a candidate for rigging systems for sailing boats. The key materials used and the history of similar applications outside the marine industry are presented.

Constituents of Fibre rigging systems

The primary function of a rigging system is to transfer tensile forces between a number of points in space to prevent excessive deformation between those. As a result, continuous fibres are generally placed next to each other in mainly longitudinal orientation.
The initial performance of a rigging system depends mainly on the reinforcement fibre used in the system, the packaging density and degree of orientation. The properties of such fibres can be directly related to the atomic arrangement and the defect content of the fibre. Typically the matrices used are of Polymer type which are chosen based on property requirements, method of manufacture and intended application. Certain properties such as the durability or the fatigue life are sensitive to the interface between reinforcement material and matrix.

Fibres used

A considerable number of commercially availlable fibres can be used in a modern rigging system. Typical properties of such fibres are given in Table 1 in comparison to Nitronic 50, a standard material used for steel rod rigging applications. The values are given as material properties and cannot be compared directly to evaluate different solutions due to fibre volume fraction issues which are related to the processing route employed in the manufacturing process.

The key requirement is generally the obtainable stiffnes of a system, only very few applications are strength driven. This is certainly the case for the current commercially availlable systems.

Table 1: Typical fibres used for rigging applications

material	tensile modulus E [GPa]	tensile strength σ [GPa]	strain to failure ε [%]	density ρ [g/cm^3]
PIPD M5®	330	5.5	1.7	1.7
PBO Zylon®	270	5.8	2.5	1.56
UHMW PE Dyneema® SK76	116	3.6	3.8	0.97
PPTA Kevlar® 49	113	3.0	2.5	1.44
Carbon fibres	230 - 960	3 - 7	0.3 - 2.1	1.7 – 1.8
Stainless steel NI50	180	1.4	~ 10	7.9

Some of the materials mentioned in table 1 would have a tremendous potential for cross sectional reductions to fulfil stiffness requirements but the result may be insufficient strenth. Current trends for windage reduction and the availability of very stiff fibre types may therefore result in certain concerns regarding the strength of a system.

An important issue is the durability of the fibre used in a rigging system. The residual strength of PBO for example is about 35% after 6 months exposure to daylight according to the manufacturer datasheet. This shortcoming requires packaging which protects the fibre from environmental influences completely and questions the place of such rigging systems outside the racing market with the associated replacement schedule despite the track record the material has in the industry.

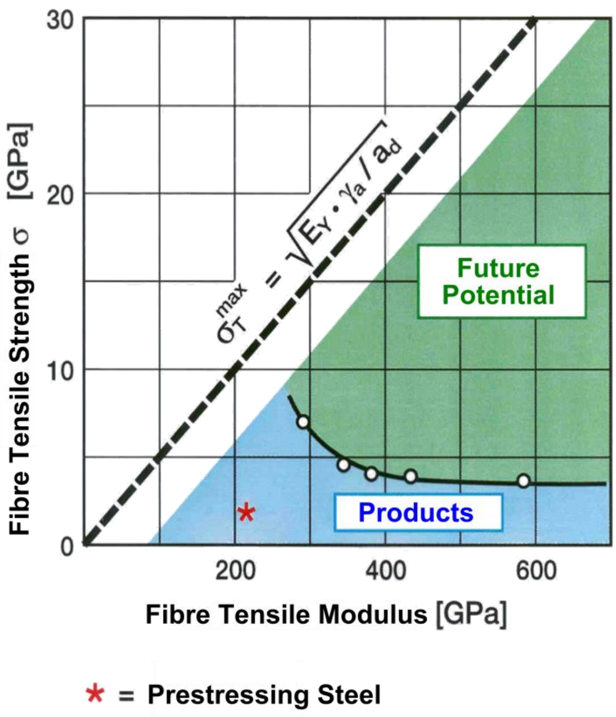

Fig 1: Future potential of carbon fibres

Carbon fibres are, according to the author and many suppliers which have followed Carbo-Links original material selection, offer by far the best properties for a modern rigging system. The combination of mechanical properties, fatigue and creep resistance with the associated environmental resistance make it an obvious choice as a preferred material for rigging systems. Figure 1 shows the fibre tensile strength versus the tensile modulus of carbon fibres. The blue area indicates the range of commercially availlable products and the green area above shows the future potential of the material if superior alignment of the graphite basal planes can be obtained in the future. The red star indicates where we are with prestressing steel in comparison. Such steel alloys have up to about 50% higher tensile strength properties than Nitronic 50. The graph in figure 1 also indicates the maximum theoretical limit based on an ideal crystalline structure.

The role of the resin system

The role of the matrix system becomes eminent when looking at figure 2. All the fibres listed in table 1 are essentially very brittle materials and exhibit very little plastic deformation, because of this, fibre breakages due to processing or handling issues or local failures due to fatigue loading occure regularly along the length of a rigging element. Figure 2 shows a stress and strength distribution along an individual fibre F surrounded by a group of randomly fractured fibres in a unidiretional composite. The stress curve indicates an increase in the longitudinal stress in the vicinity of cracks in the adjacent fibres..

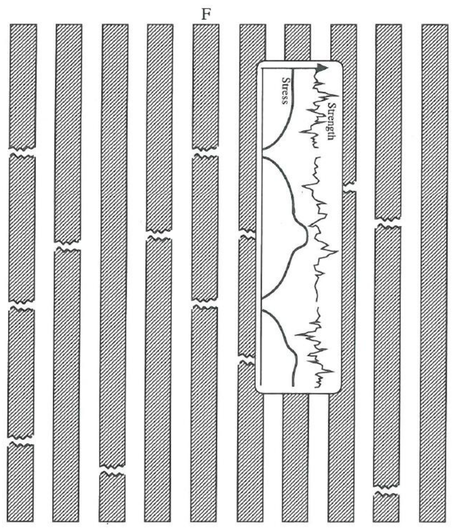

Fig 2: Schematic depiction of fractured fibres in a composite material. *(Source: An Introduction to Composite Materials, D. Hull, T. W. Clyne)*

It also shows the strength distribution along the length of the fibre which is driven by the distribution of defects in the crystalline structure. The matrix which surrounds the individual fibres ensures a load sharing effect between individual fibres and prevents an individual fibre to become obsolete over the entire length to the end fitting

The history of Carbon Fibre tensile members

The use of carbon fibre for tensile members for civil engineering structures has allready been proposed 1977, at a time where the material cost for the fibre was preventing such a use but the prospect for the future in combination with the potential from a technical and durability point of view made the scientific community decide to invest in the application of terminations systems for such cables. Pioneering work has been done in this field by Prof. Urs Meier at EMPA, the Swiss Federal Institute for Materials Testing and Research. He used the technology in the suspension road bridge shown in figure 3 where 2 carbon fibre cables with a length of 35 m have been installed. The cables have a cross section as shown in figure 4 consisting of a bundle with 241 parallel wires with a total breaking strength of 1200 t. The cable is terminated in a potted, wedge shaped cone.

Fig. 3: First road bridge in the world with bundled carbon fibre cables built in 1996.

The cables shown in figure 3 and 4 allready had incorporated load sensing features with fibre optical sensors as described in this report. This allowed to verify the true working loads during a long period of time since the installation in 1996.

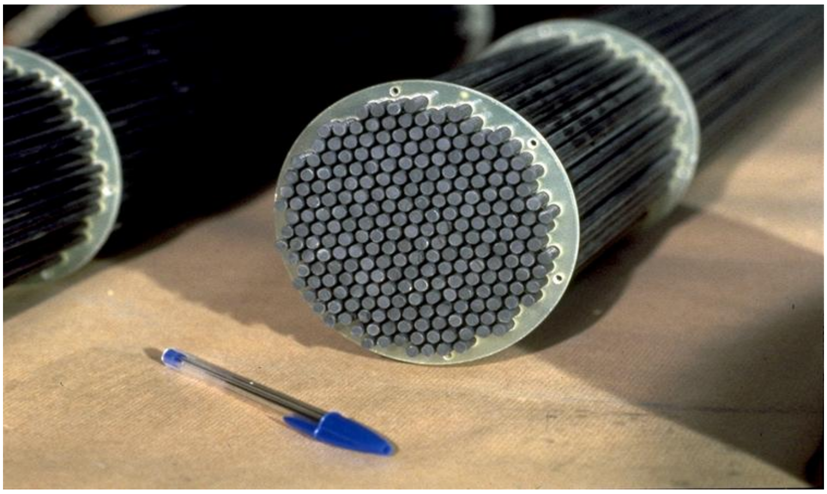

Fig 4: cross sectional view of a large bundled carbon fibre bridge cable.

Another category of tensile members are being used in the civil engineering world for passively bonded as well as pretensioned cables in the form of flat ribbons as shown in figure 5 where such cables are used for seismic strengthening applications. Such flat ribbon cables have been used with thermoplastic and thermosetting matrix systems.

Fig 5: Shear strengthening of an existing masonry wall with externally bonded carbon fibre ribbon cables.

The development of Solid Carbon Cables

The original development of the cables described above has led to the development of a different termination based on a continuous loop of fibres around metal end fittings as shown in figure 6. The major reason was the requirement of a compact and reliable end fitting which is not susceptible to premature failure due to surface contamination of the parallel rods used in the above described cables. The main application which was foreseen at the time when EMPA developed these cables was the shear enhancement of existing concrete structures.

Fig 6: Consolidated composite tendon for shear strengthening purposes of concrete.

At present the key applications of the technology are structural repair or rettrofitting projects such as the historical timbre structure shown in figure 7 and pendant cables for big crawler cranes shown in figure 8. In such applications steel is replaced for weight saving, strength improvement or fatigue life reasons.

Fig 6: Repair of a 400 year old timber structure using Carbo-Link cables with load sensing devices

Fig 7: Crawler crane with Carbo-Link pendant cables with superior handling and fatigue life.

Solid Carbon Cables as a Rigging Solution in the Marine Industry

Carbo Link started to collaborate with Alinghi, the Swiss America's Cup team, in 2001 during the preparation for the 2003 cup in Auckland. The first rigging cables built where continuous loops made from thermoplastic matrix materials. In 2003 Carbo-Link equiped an ORMA 60 trimaran with carbon lateral and platform rigging. Particularly the potential of shaped rigging cables as shown in figure 8 for drag reduction purposes has led to replacing the thermoplastic matrix materials with epoxy based thermosets. The major reason being the lower processing temperatures in the consolidation process.

The requirements of the spine platform of Alinghi V and the lateral rigging on the Groupama VOR 70 boat (see figures 9 and 10) to optimise connection details in order to minimise weight and windage has led to the spreader end solution shown in figure 11 where the continuous vertical is split locally to create space for the attachement of the diagonal. This solution ensures minimum bending moments in the vertical rigging cable because the diagonal attachement is in the centre of the vertical. It also allows diagonals to be replaced for example due to a change in specification for tuning purposes or due to accidental damage. Another key feature is the use of a spherical ball type end fitting for the diagonal attachement at the spreader end. Lateral movement of the cable, particularly when going slack, can cause considerable bending moments in the termination region when this is of moment resisiting type. This effect is independent of the cable material and also known from rod rigging systems. It is critical to allow for sufficient rotation capacity in the termination region of a rigging cable to prevent such bending moments.

Fig 8: Twin, shaped carbon fibre runner cable on a V5 AC rig

Fig 9: Alinghi V with high modulus carbon fibre spine rigging.

Fig 10: Groupama, the Volvo 70 boat which won the 2012 VOR.

Fig 11: Spreader end detail with mimimum bending moments in the cables and replaceable Diagonal.

Monitoring and Sensors of rigging

Using composite materials for rigging cables offers a unique opportunity to gather load history data for one of the yachts critical structures under real operating conditions. Not only would this enable improvements to be made in performance and safety of future designs but it also has the potential for providing real-time information to the crews of the yachts, alerting them if the design limits are being approached or exceeded.

One particular technology which has been making an increasingly important contribution to load monitoring of composite structures is fibre-optic sensing. This technology grew out of the telecoms industry where Fibre Bragg Gratings (FBGs) are used as wavelength filters for multiplexing hundreds of signals down a single optical fibre. But they are also sensitive to strain and temperature and so have found widespread application as fibre optic sensors. The basic principle is outlined in figure 12.

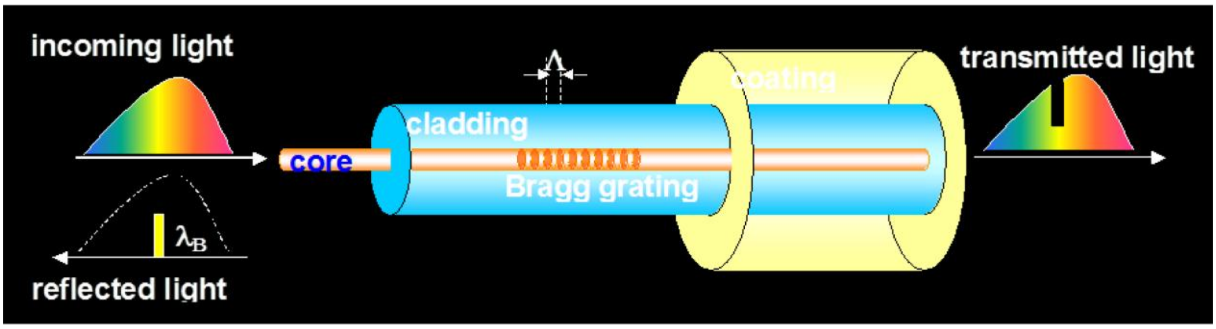

Fig 12: Schematic principle of optical fibre bragg grating strain sensors.

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