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## CFRP Mooring Lines for MODU Applications

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### Abstract

Precise station keeping is a requirement of mobile offshore drilling units (MODUs) and production vessels operating in ultra-deepwater. DeepSea Engineering and Management in co-operation with Petrobras is undertaking a concept, feasibility development study and scale prototype testing of pultruded Carbon Fibre Reinforced Plastic (CFRP) rod for ultra-deepwater mooring line applications. For a given capacity this paper illustrates the potential the technology has to compete with polyester lines on weight per unit length and with steel lines on diameter.

This paper presents a Carbon Fibre mooring line for MODU applications as part of the PROCAP 3000 Program. It describes the suitability of CFRP as a reliable mooring system, presents a design approach and analysis process. One of the key aims is to use existing vessels, equipped to handle steel lines, for ultra-deepwater deployment of CFRP lines with no or minimal modification. The product undergoing testing was designed for 200 Te breaking load with a cross section identical to its steel equivalent and circa 1/4 the weight. DeepSea Engineering working with Reading University in the UK successfully tested CFRP terminations to circa 80% efficiency using conventional rope open spelter sockets with a proprietary potting compound.

### Introduction

CFRP is being considered for ultra-deepwater MODU mooring lines because of its potential for substantial weight reduction and increasing payload for the same diameter as an equivalent steel wire. In addition, existing polyester mooring line systems for ultra-deepwater are significantly larger in diameter for a given load capacity when compared to steel lines. Dedicated handling vessels are required to facilitate

synthetic mooring installation, increasing deployment costs. CFRP has the potential to utilize existing fleets equipped to handle steel lines with little or no modification. Figure 1 below illustrates the potential benefits of CFRP lines over steel and polyester lines by comparing specific strength and modulus.

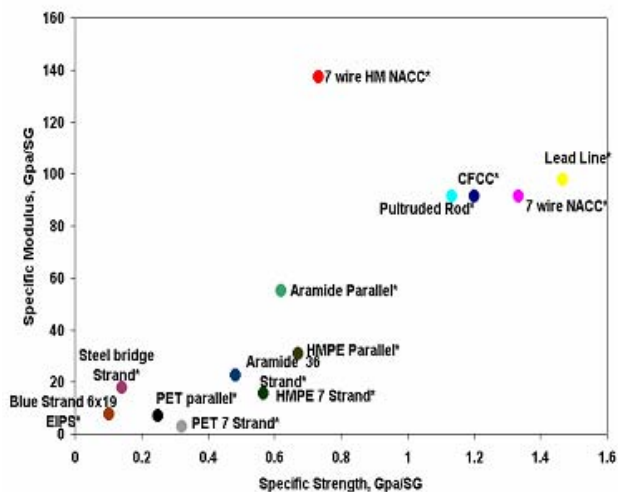


Figure 1 Comparison of specific strength and modulus of existing rod, cable and tendon technologies<sup>1</sup>

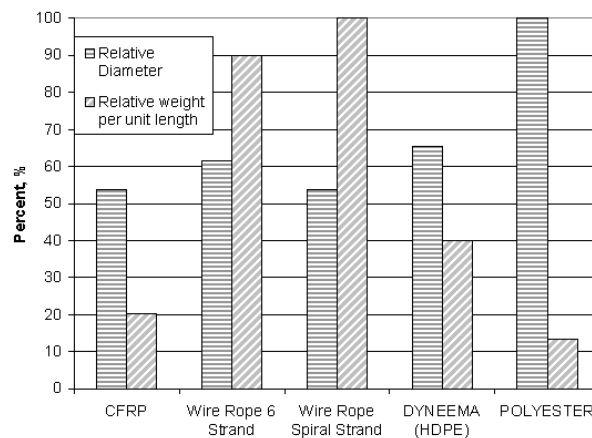


Figure 2 Comparison between the relative diameter and weight/unit length between the technologies for a 200 tonne line

<sup>1</sup> Data obtained from appropriate sources such as company literature and web sites (1)

Figure 2 illustrates the relative diameters and weight per unit length between the competing technologies for a 200 Te line. CFRP shows a competing diameter with spiral strand steel and roughly half the diameter of polyester. CFRP is 20% of the weight per unit length of spiral strand wire rope and competes with polyester.

### State of the Art Review of CFRP Line Technology

Current CFRP line technology is largely centered around stressed members; rods, tendons and stranded cables, for civil engineering applications such as pre and post-stressing concrete and cable stayed bridges. The majority of the products have been developed by the Japanese. Carbon Fibre Composite Cable (CFCC) was developed by Tokyo Rope, Nippon Steel Advanced Carbon Fibre Cable (NACC) developed by Nippon Steel in Figure 3 below. These products have been deployed in numerous civil applications throughout the world (1).



Figure 3 Left to right, CFCC & NACC, Examples of CFRP rope

Other technologies using carbon fibre for reinforcing elements in civil engineering structural applications include Leadline rods and Tendons developed by Mitsubishi Chemical Company. Leadline reinforcing elements are circular rods that are pultruded using unidirectional carbon fibres at 65% fibre volume fraction with an epoxy resin.

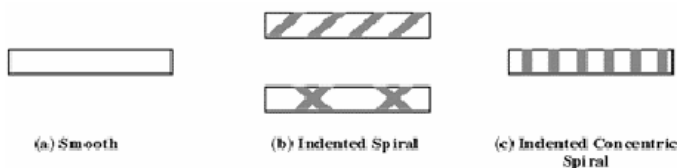


Figure 4 Surface Treatment of Leadline (Left), Typical Anchorage System (Right)

Figure 4 left, shows the surface types used in the rod to assist the transfer of load from the rod to the surrounding structural material and Figure 4 right shows a typical anchorage system. Mitsubishi Chemical manufacture leadline rod from carbon fibre. Mitsubishi Chemical's Leadline tendons were used to construct Southfield's composite reinforced bridge. See Figure 5 left. Examples of Cable Stayed bridges using CFRP tendons can be seen in Figure 5 right. The novelty of the Storchen Bridge in Winterthur Switzerland is the use of cables made of carbon-fiber-reinforced polymer wires.



Figure 5 Left Southfield Bridge, Michigan, Right, Storchen Bridge

In the offshore Oil and Gas (O&G) industry two separate company consortia involving Aker Kvaerner/ConocoPhillips and Freyssinet/Soficar/Doris Engineering have undertaken some development of the civil tendon technology and applied it to the taut mooring requirements of Tension Leg Platforms. Kvaerner/Conoco has a product called 'Comptether' marketed under a joint venture (2) & (3). This technology is dedicated to the tethering of TLPs and has not been designed for either taut leg mooring or catenary mooring systems. The tether consists of 781 off 6 mm diameter rods fabricated by pultrusion and bundled into 13 strands. Each strand contains either 31 or 85 rods and is wound with a slight helix to form the tether. The tether is spoolable onto a 4.5 to 5.0 m drum. Design code DNV OS501 "Composites Components" was being used as the basis for qualification. A PVC profile is used to separate the strands and a PE outer jacket is used to protect the tether. The proposed termination was a potted system using an epoxy resin. The paper describes a number of technical challenges were left uncompleted; the end termination technology was a proposal and the tendon test matrix for reeling, bending, fatigue had not been completed.

Freyssinet, Soficar and Doris Engineering have proposed carbon fibre composite tendons for deepwater mooring of TLPs (4). The tendons comprise of 19 off 6 mm diameter carbon fibre (T700) epoxy resin impregnated rods fabricated by pultrusion. The rods were protected by a HMPE sheath and the voids between the rods were filled with an 'incompressible' polymer. The paper describes a system in principle that could be adapted from existing cable stayed bridge tendons but at the time of writing had yet to be adapted, manufactured and tested for offshore use. There are currently no CFRP products developed for Catenary, Taut or Semi-Taut deepwater moorings. This paper describes such a system and the analytical techniques developed to model the product.

### Review of Polymer Line Technologies

This section shall provide a brief summary of technologies such as polyester, aramide and HMPE, these technologies have been identified as the main synthetic fibres for deepwater and ultra-deepwater applications. They have been used in the marine mooring line industry for many years. However, their application to deepwater mooring systems for the offshore industry is a recent introduction and has been limited. Materials such as nylon and polypropylene while used as mooring line in the marine industry do not exhibit sufficient

mechanical and physical properties to be considered for deepwater applications.

There have been a number of JIP fibre tether technology development programs over the past 15 years borne out of a recognition that there was need to better understand tether and cable technology for deepwater exploration and exploitation (5). Fibre Tethers 2000 concentrated on synthetic fibres and concluded that synthetic rope for deepwater mooring was desirable because of their low weight, high strength and range of suitable stiffnesses – the most likely candidate material was considered to be polyester. Polyester exhibits good resistance to fatigue and abrasion, has good strength and stiffness properties and had a track record of marine application.

However, further studies undertaken under a ‘Testing and Optimization’ JIP showed that polyester rope loses strength during high-cycle fatigue. This degradation has led to additional studies in to the durability of polyester. Recent studies have shown that the fatigue life of polyester is superior to that of steel wire (6).

Alternatives to polyester include HMPE (High Modulus Polyethylene or High Molecular Weight Polyethylene, HMWPE) their principal advantage being superior strength to polyester, high abrasion resistance and smaller size for a given load requirement. HMPE is significantly more costly and not available in the quantities necessary for ultra-deepwater mooring systems. There are also concerns over its long term creep properties for permanent mooring systems. A number of issues were identified during a trial of HMPE on Scarabeo III MODU (7).

- contact between steel and HMPE during deployment when under tension can damage the line
- modification may be required to standard equipment such as Shark’s Jaws grippers and J chain chasers.
- line insertion increased the mooring time by up to three times, this was not considered practical
- the importance of training personnel in the deployment, recovery, benefits and limitations of the synthetic lines was identified

Other candidates with potential are high performance thermoplastic polyethylene (HMPE) such as:

- Spectra – Allied Signal (Now Honeywell)
- Dyneema – Dyneema Japan Ltd, Japan.
- Tekmilon – Mitsui Petrochemicals, Japan

And, aromatic Polyester fibres such as;

- PBO – polybenzoxazole - The Dow Chemical Company in the US or Toyobo in Japan under the trade name Zylon.
- Vectran HS – Hoechst Celanese Corporation in the US.

And, aramide fibres such as

- Kevlar – Du Pont, US
- Twaron – Akzo Fibers US
- Technora – Teijin Limited, Japan

Synthetic fibre rope has a typical construction of low twist cores laid parallel with a braided cover to improve the handling and abrasion characteristics of the rope. The analysis of synthetic rope is complicated by its visco-elastic behaviour such that the extension and modulus are a function of time and loading history. Upon removing the load, some but not all of the strain is recovered as elastic deformation, the residual strain remains as viscous flow. High molecular weight fibres such as HMPE are more prone to this type of behaviour than PET (Polyethylene terephthalate – Thermoplastic polyester). Maxwell, Voigt and Zener elements are often used in polymer processing to model this type visco-elasticity (8) & (9).

In practical applications synthetic fibre ropes for catenary mooring systems will require the use of heavy steel chain or wire on the sea bed because the nature of a catenary and drag anchor system that relies on weight of the mooring line to ensure that the force on the anchor remains tangential to the sea bed. Even on a taut leg system it is likely to be the case that chains or wire will be required near the sea bed and the vessel to mitigate the effects of abrasion & wear at these locations as well as for periodic tension adjustments at the vessel end.

Figure 6 and Figure 7 compare the properties of fibres and their derived products. A key observation supports the use of CFRP material since it maintains its advantage thorough out the comparison. The material strength and modulus of non-fabricated CFRPs compares favorably to its derived products such as CFCC and NACC. These products also display good characteristics when compared to their specific strengths and specific modulus.

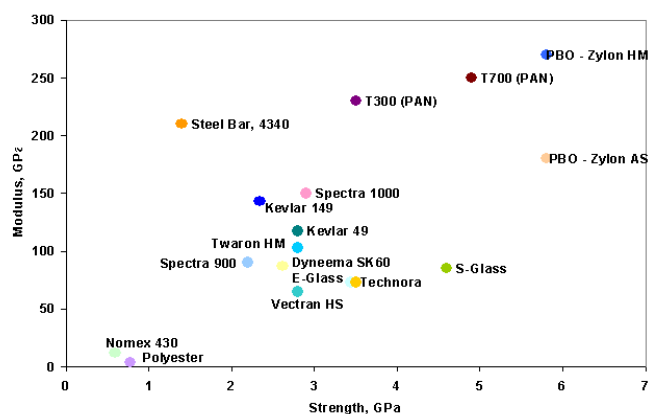
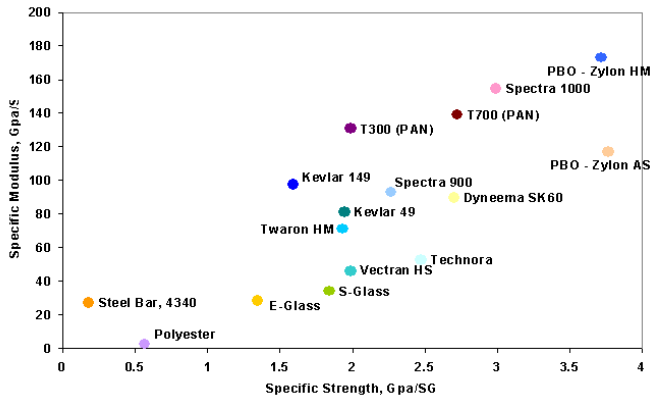


Figure 6 Comparison of Strength and Modulus of a Variety of Fibres<sup>2</sup>

<sup>2</sup> Data obtained from a variety of reference sources that includes vendor web sites as well as text books (10)



**Figure 7 Comparison of Specific Strength and Modulus of a Variety of Fibres**

### General Description and Configuration

The design objectives were to use existing pultruded carbon fibre rods fabricated to form a cable capable of matching the diameter of existing steel lines for a given payload with the ability to be reeled. In addition, the rods were to be terminated in conventional rope open spelter sockets using a proprietary potting compound. It was assumed that some minor modifications would be acceptable in order to better optimize the design. The CFRP design should also be torque balanced. Wear resistance is considered beyond the initial proof of concept stage since any wear protection would ancillary to the core objectives.

In order to prove the concept for MODU applications, scale prototype mooring line would be manufactured to satisfy the main objectives by performing a tensile rupture test, fatigue test and bend test.

After a concept selection process a spiral strand approach was considered to provide the most appropriate solution. While steel line spiral strand is not considered reelable, CFRP is half the stiffness and as such a spiral strand approach can be reeled. However, pultruded CFRP rod is rigid and should be considered as a structure for analytical purposes, therefore without post assembly treatment the ability of the rods to be reeled was restricted by the helix strain. Figure 8 below shows the general configuration of the chosen CFRP design and the end termination.



**Figure 8 General Configuration; Left to right, Rope Cross Section, Conventional Socket Modified End Termination**

Figure 8 left shows spiral strand cross section consisting of a load bearing core of spiral wrapped rods and an over wrap of

two layers of non load bearing small diameter rods. The outer layer was designed with a higher helix angle than the load bearing core and was to act as mechanical restraint to prevent bird-caging under reeled conditions. In addition, since the outer layers are non-load bearing they can be traded for more suitable wear resistant layers further along the development programme. Between the core layers is a tape wrap layer to assist with manufacturing process and the ability of the rods to slide over one another.

A key design issue for CFRP rope is how to harness all of the available tensile strength. The end termination design can be used to illustrate the problem. Steel line potted using spelter sockets and a potting compound relies on the tensile force on the line pulling the potted plug in to the socket. The combination of the wire brush and the compressive force exerted on the steel strands provides a mechanical lock and prevents the steel wire being pulled out. The bond strength between the brush and the potting compound is not a significant factor to the operation of the socket. Never the less, there does need to be sufficient friction and mechanical locking between the brush and the plug during the initial loading period to ensure the plug is pulled into the socket so that a compressive force in the plug develops.

This approach works for steel, in part, because steel can be considered to exhibit the same properties in all directions. For a composite cable adoption of the same approach is problematic because CFRP rods possess orthotropic properties such that their transverse properties are poor compared to their tensile properties. The transverse strength of CFRP is roughly 10% of its tensile property. This implies that the rods could crush laterally under load before they reach their tensile capability. In addition, CFRP rods not being ductile do not possess a 'brush' in the termination so the bond strength between the rods and potting compound becomes important as does the requirement to supplement the bond strength with a suitable mechanism for applying a mechanical lock.

Figure 8 centre and right images show the socket configuration. Standard open spelter sockets were used along with a proprietary potting compound. The end termination design was subject to detailed numerical analysis by DeepSea Engineering and sub element testing at Reading University in the UK. While there is a requirement to retrofit a 'widget' in to the rod ends testing showed that conventional sockets with a specific proprietary potting compound achieved highly successful termination efficiencies of circa 80% of the rod strength. It is beyond the remit of this paper to detail the approach, failure mechanism and results.

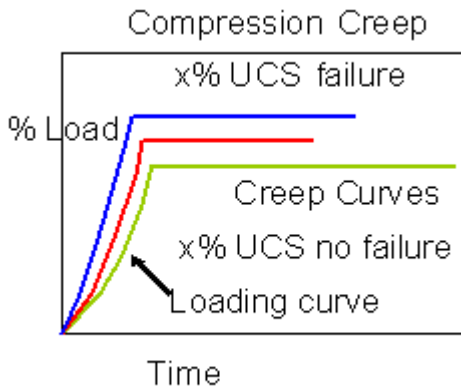
### Addressing the Life Cycle Issues

For design and analysis of a CFRP mooring system there was a requirement for numerous tests to determine essential mechanical properties. These are listed Table 1 below.

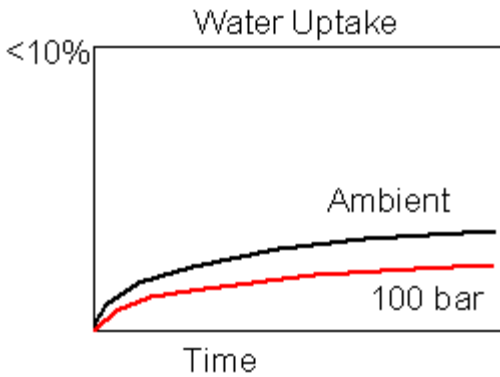
UD Axial Tension	F1t
	E1
	$\nu_{12}$
UD Transverse Tension	F2c
	E2
	$\nu_{21}$
UD Axial Compression	F1c
	E1
	$\nu_{12}$
UD Transverse Compression	F2c
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**Table 1 Basic Static Mechanicals**

In addition to the basic static mechanicals water uptake rates were determined to obtain saturated mechanicals, saturated creep, saturated fatigue and impact data for designers to understand how the material performance may degrade over its life.



**Figure 9 Representation Compressive Creep**



**Figure 10 Water Uptake Data**

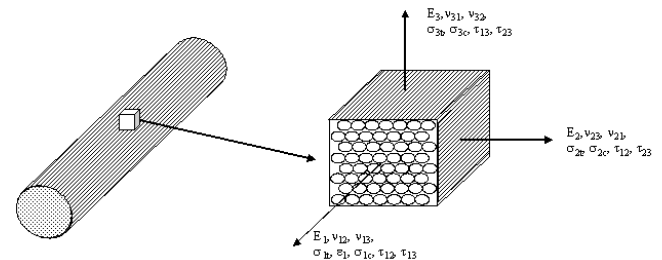
Figure 9 illustrates typical creep data obtained for epoxy based CFRP. The graph shows compressive creep and it was seen during testing that there was an apparent threshold for creep failure below which no failure was demonstrated. This threshold generally co-incided with the bottom end of the scatter for mechanical strength. Figure 10 shows some comparative water uptake data. Interestingly the water uptake rate was shown to be less when the material was subject to 100 bar water pressure.

**Analytical Design Model**

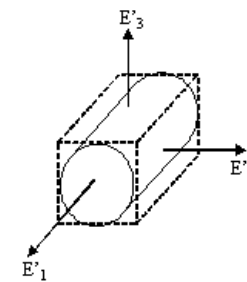
DeepSea Engineering developed a bespoke analytical model to investigate the CFRP rope design and configuration. The modeling approach is similar to that used for flexible pipe and umbilical analyses. The model assumes that each layer is orthotropic and homogeneous. The analytical steps can be described as follows. Each orthotropic layer comprises of individual rods with properties described in Figure 11 below. These properties were determined from a combination of testing and micro-mechanical laminate theory.

From the individual rod properties the homogeneous orthotropic properties of each individual layer were determined based on a given rod diameter. There was a central core of seven parallel rods on which the helical load-bearing core was wound. Figure 12 below shows the determination of the longitudinal and transverse modulus for each layer. Two transverse properties are determined based on a Hertzian contact theory of cylindrical bodies (11) & (12).

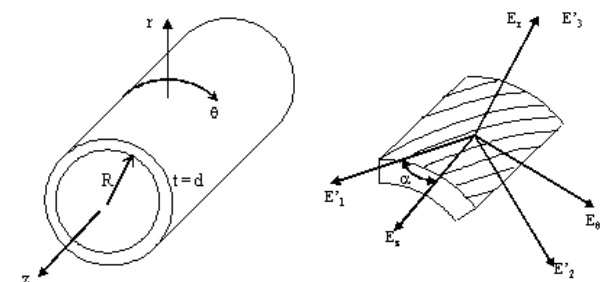
Each orthotropic layer or sheath was then converted using a cylindrical co-ordinate matrix to obtain the properties with respect to the helix as shown in Figure 13 below.



**Figure 11 Description of CFRP rod Properties**



**Figure 12 Determination of Longitudinal and Transverse Modulus**



**Figure 13 Left, Definitions, Right, Properties with Respect to the Helix**

Equation 1 shows the stiffness equations and matrix used for each layer which were summed up for all layers in a rope.  $p_i$  and  $p_o$  are the contact pressures between the layers (13). There are radial compatibility equations which enforce the layers to be in contact.

$$\begin{bmatrix} k_{11} & k_{12} & k_{13} & 0 \\ k_{21} & k_{22} & k_{23} & 0 \\ k_{31} & k_{32} & k_{33} & 0 \\ 0 & 0 & 0 & k_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \gamma_x \\ \varepsilon_\theta \\ \varepsilon_r \end{bmatrix} = \begin{bmatrix} N_x \\ M_x \\ p_i 2\pi R \left( R - \frac{t}{2} \right) - p_o 2\pi R \left( R + \frac{t}{2} \right) \\ - p_i \pi \left( R - \frac{t}{2} \right) - p_o \pi \left( R + \frac{t}{2} \right) \end{bmatrix} \quad (1)$$

The output consisted of axial strain,  $\varepsilon_z$ , degree of twist,  $\lambda_z$ , circumferential,  $\varepsilon_\theta$ , radial,  $\varepsilon_r$  and through thickness strains and interlayer contact pressures. The output was then used to determine the rope axial stiffness. From the global deformations a backwards procedure was used to determine the axial and transverse strains and stresses in the rods for each layer. The stresses and strains were assumed to be the same in all rods of a single layer.

Axial strain and applied force determined the rope axial stiffness. Twist output enabled the rope to be torque balanced. Torque balance of the layers was achieved by varying the lay angles and direction of rods in different layers. The objective was to minimize or eliminate twist at the applied load.

## Conclusions and Discussion

This paper sought to highlight the potential of CFRP pultruded rod for MODU mooring line applications. The paper used comparisons with existing CFRP line technology used in civil engineering, see Figure 1, and provided a summary review of these technologies. In addition the paper compared alternative synthetic line systems, see Figure 6 and Figure 7. From these comparisons CFRP is shown to provide a technically viable alternative for ultra-deepwater mooring systems.

A summary of the analytical technique used to develop a CFRP mooring line was described. The technique was not dissimilar to that adopted for analysing flexible armour layers in umbilicals. The approach differs from that used in rope design because CFRP rods should be considered structures.

This paper reports the reasons for selecting CFRP and the analytical techniques used to design a system. A design has been proposed that will form the basis for pultruded CFRP rods to be fabricated in to a spiral bundle for use as a MODU mooring system. Creep failure appeared to occur when the tested samples were loaded greater than the lowest static mechanical test value, although this observation would need more validation. Water uptake rates for samples at 100 bar pressure was lower than for those at ambient. It was beyond the scope of this paper to report the end termination design and prototype test results. It is expected that these will be reported in due course.

## Acknowledgements

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