HOW COMPOSITE MATERIALS COULD MAKE LIGHT WORK OF SUBMARINE SYSTEM CONSTRUCTION.

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ABSTRACT: With perhaps 90% of cable interconnecting wet plant on a typical trans-oceanic system being of lightweight construction it raises the question of why cable to repeater mechanical interface components, often known as a 'bend limiters', capable of armour cable loads are often unnecessarily used for deep-water 'lower load' deployment situations.

In an effort to answer this question, this paper will describe the work carried out to design, manufacture and test a 'low load' carbon fibre repeater 'bend limiter' in order to better understand if this idea could potentially be implemented without compromising the necessary deployment, reliability and functionality of deep-water submarine cable systems normally met by metal similar components.

1. INTRODUCTION

At the interface between typical submarine wet plant and the transmission cable is a mechanical connection that allows articulation between the two components and, at the same time, withstands the tensile loading during deployment and recovery operations.

These conditions are particularly arduous when these components are passing over ships' sheaves where both tensile and bending loads combine to stress the components in a complex way.

Typically, these mechanical components are of a common 'high load' design for various cable strengths. This 'common design' approach minimises component diversity but is potentially wasteful in terms of material and hence cost. To design a 'low load' metallic interface to complement an existing 'high load' universal solution would seem to be an obvious route to take for the (low load) deep water and (high load) shallow water applications. However, to have two (or more) different designs for different cable strengths has potential drawbacks in that it is likely to need different interface and ancillary elements to fulfil the different requirements of each version.

An alternative approach is to consider developing a single coupling design that uses a "high strength to weight ratio" composite material for low load lightweight cable and Titanium (or another suitably strong corrosion - resistant metal) for high load armoured applications.

Using composite materials as an alternative to metal presents its own challenges. To replicate exactly a metallic design in a composite material is not always viable as, for example, features machined in metal might not be directly transferable to a composite. Further challenges include understanding material supply, manufacturing and subsea behaviour of such high performance materials.

Considering the potential uses of composite materials, it seemed desirable to investigate if using a 'common design' but 'different material' approach could offer the advantages of both material cost and rationalised components over the approach of using different designs in metal for different situations.

2. PERFORMANCE REQUIREMENTS

With some new ‘Light weight’ cables having a NTTS of 80kN, a linear tensile safety factor of 2:1 and an articulation angle of 66^0 were chosen as the minimum requirements for this design.

Although the proposed bend angle is typical for current solutions, the safety factor for lightweight cable is significantly higher than that typically allowed for armour applications. Because composite materials demonstrate different properties to metal equivalents, it was deemed necessary to have the 2:1 safety factor to give confidence in the solution if manufactured from this type of material.

3. MATERIAL CHOICE

Considering composite based product for this kind of application is not restricted to carbon fibre based material. Glass reinforced composites also offer suitable characteristics of a good strength to weight ratio and advantageous manufacturing processes.

However, early analysis quickly established that size – for - size carbon composites offer superior strength and lighter weight, the two key parameters, for a marginal increase in cost over glass-reinforced materials.

With the highest specific modulus of any commercial yarn, a Tensile Modulus around 230GPa and ultimate Tensile Strength of around 3.5GPa (Range is approx. 230-400 GPa and 3.5-5.0 GPa depending on specific yarn type) carbon fibre composites appeared to be the material of choice.

In addition to the great compressive and flexural strength, carbon fibre composite products also show excellent inter-laminar Shear Strength, Fatigue Resistance and a Low Thermal Expansion coefficient.

Along with the fundamental yarn, choosing the correct Resin System is of vital importance. Key attributes needed are good mechanical properties, low degradation, good resistance to thermal stress, excellent resistance to corrosion, and low water absorption.

The yarn ‘Impregnation Method’ is also fundamental to obtaining the best composite performance. Key to this is full saturation of the carbon fiber matting (the pre preg) with resin with good ‘fiber wet out’ specific to the Carbon Tow Size.

Therefore, with optimised production processes it is possible to manufacture products from carbon fire composites with excellent strength to weight ratios that offer performance suitable to replace metal solutions.

4. DESIGN & ASSEMBLY CONSIDERATIONS

From discussions with the material suppliers and during the early material investigations, it became apparent that directly transferring features that are possible to machine in metal to a composite component could present difficulties in terms of the practicalities of machining and/or the cost of doing so. To alleviate this issue, keeping the design as ‘simple’ as possible by eliminating complex features was key to progressing the idea.

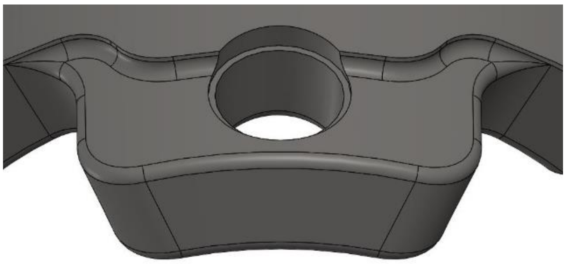


Figure 1: Existing Yoke

For example, shown in Fig 1, is a typical bend limiter feature, as currently used in an existing product, which contains a number of complex internal and external ‘features’ that require many machining operations.

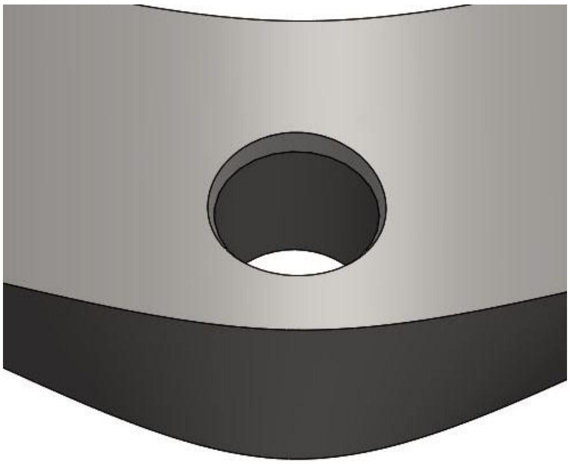


Figure 2: Simplified Yoke

In comparison, the equivalent CF proposal, shown in Fig 2, is much simplified reducing the number and complexity of machining operations.

A secondary but key design aim was the ease of assembly and (when required) dis-assembly of the bend limiter by the integration engineers.

Although the inherent lightweight nature of carbon fibre aids with handling, the design needs to consider how easy or difficult it is for the engineer to assemble or disassemble the parts.

To assist in this process, the removal of threaded components (threads directly cut in carbon fibre are often avoided) combined with the use of 'low force' push-in parts became a key feature to the solution.

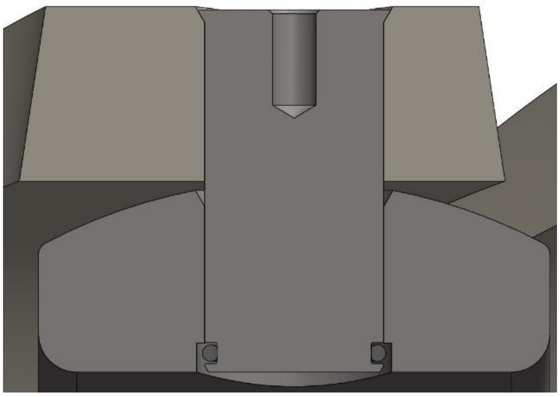


Figure 3: Swivel Pin

To achieve this 'ease of assembly', a simple but effective 'push in' design of the 'yoke' to 'inner ring' swivel pin with retention achieved with a O-Ring was designed. The low force required to insert the pin allows assembly 'by hand' without the need for special tools. The design, shown in Fig 3, maintains effective 'in service' retention and allows removal of the swivel pin without damage to the main parts with the use of a special tool.

5. MANUFACTURING CONSIDERATIONS

The supply of carbon fibre composites is typically in sheet or tube form when not moulded to a specific shape for a particular solution.

An early understanding of the design requirements meant that manufacturing the components from the composite material in 'raw' tube form was the obvious early choice.

Choosing to machine the components from a single tube gives maximum material uniformity and the most efficient method in terms of material wastage.

However, manufacturing in this way (different tubes for inner and outer components) has a significant impact on the design in that all features have to be within the dimensions of the 'tube' therefore restricting design features within that envelope.

Typically, many readily available carbon fibre composite products are in the range of 5 to 10mm section thickness. However, in the early stages of this product development, it was quickly realised that in order to achieve the necessary strength for a proposed coupling, the component section thickness would need to be in the order of 30mm.

To produce a carbon fibre tube with a section thickness of 30mm presents particular difficulties. The main concern is ensuring the 'voids' caused by poor interlayer adhesion are eliminated.

Tube manufactures understand that the two main factors causing these interlayer adhesion voids are 1):- the trapping of outgassing vapours of the curing resin and 2):- the limit of the manufacturing process to maintain pressure on the materials during the tube winding process.

Eliminating these issues is important in order to ensure the structural integrity and therefore 'quality' of the components.

However, this type of 'material flaw' could be located within the structure of the tube and may or may not become apparent until machining operations have been completed.

To demonstrate how this problem can manifest itself, Fig 4 shows an example of poor inter-layer adhesion as observed from the machined surface. The fact that these features might occur within the material and therefore remain hidden raises the issue of detecting them during inspection.

As the Sub Sea industry is very familiar with the use of X-ray to assess 'flaws' in subsea PE over moulded joints, the use of X-ray's as a non-destructive method was considered applicable for the carbon fibre parts.

To demonstrate this Fig 5 displays an X-ray image of the 'external visible flaw' shown in Fig 4. This clearly shows the extent to which poor interlayer adhesion, not quantifiable from external examination, has occurred deep into this part.

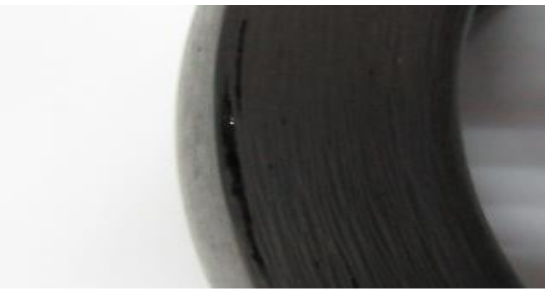


Figure 4: Interlayer Defect

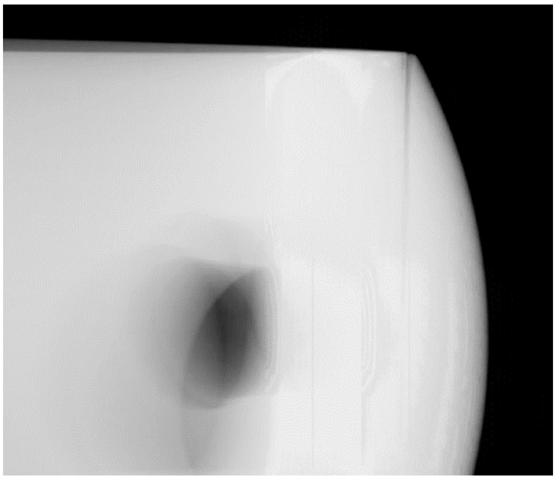


Figure 5: X-ray image of Interlayer Defect

With the use of non-destructive testing and careful optimisation in the manufacturing process, it is possible to achieve confidence in the quality of the component prior to use.

A supplementary benefit of the design is the ability to achieve lower material wastage during machining. The yoke contact faces have identical geometry designed in which allows them to be machined by removing a small amount of material in-between the adjacent active faces of two consecutive yokes. This reduces the length of the prefabricate tube by approximately 30%. Fig 6 shows.

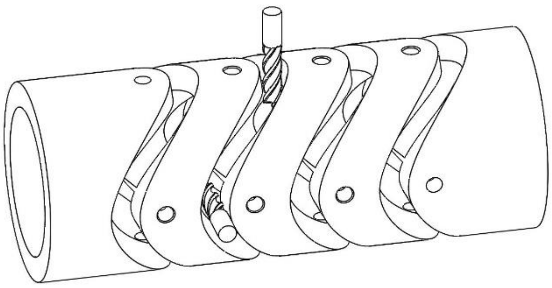


Figure 6: Tube Machining

6. MATERIAL EVALUATION TESTING

Conducting material evaluation testing to assess the fundamental level of performance required with this type of material was essential prior to the production of prototype 'bend limiter' parts. Choosing to test representative samples of the inner ring and outer yoke was a way of answering the question of material performance. These test used three sets of samples, two of the inner ring, one wet & one dry, and one 'dry' sample for the outer yoke. The purpose of exposing one inner ring sample to 83MPa for 72hrs whilst retaining one dry sample was to allow a comparative test of the two parts to ascertain if the exposure to high-pressure water would have any detrimental effect on the material's tensile performance. Although not a definitive water absorption test, the change in weight from 3.797kg to 3.799kg was not seen as significant enough to warrant serous concerns being raised.

Basing the tensile testing program upon a reduced set of 'typical' cable qualifications parameters seemed sufficient to establish the initial material performance. These parameters were set at the NTTS level of 80kN for straight tensile and 30 -50kN for fatigue cycling, typical for a high load lightweight cable.

To test the individual carbon components, the manufacture of metal jigs, to act as the corresponding carbon parts, allowed fixing them in the test rig for tensile testing.

Figures 7 and 8 show the 'metal jig' set up for testing the inner and outer ring samples.

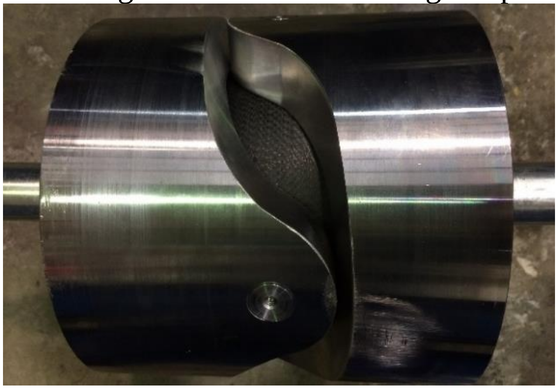


Figure 7: Tensile test of Inner Yoke

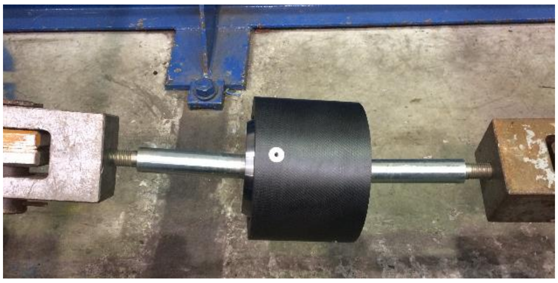
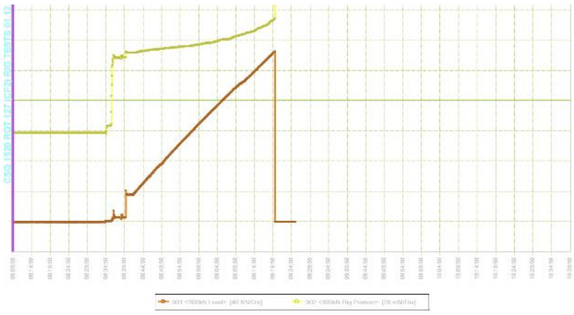


Figure 8 Tensile test of Outer Yoke

7. MATERIAL EVALUATION RESULTS

Results of the relatively low load NTTS and Fatigue material evaluation tests showed no degradation to the parts. The tensile to failure results shown in Graphs 1 & 2 show no significant difference between the 'wet' and 'dry' samples with the dry sample failing at 224.4 kN and the wet sample failing at 231.4 kN. For an 80kN working load, these results indicated that it would be possible, with this material, to achieve a 2:1 safety factor with confidence that exposure to deep-water deployment will not detrimentally affect performance.



Graph 1: Tensile test of Inner Yoke

Graph 2: Tensile test of Outer Yoke

8. PROTOTYPE DESIGN

The composite bend limiter (Fig. 9) is similar to existing metal bend limiter(s) (Fig. 10), in that it uses a combination of outer yokes and inner rings that are connected to each other by swivel pins enabling both resistance to tensile loading and bend angle between the cable and wet plant.

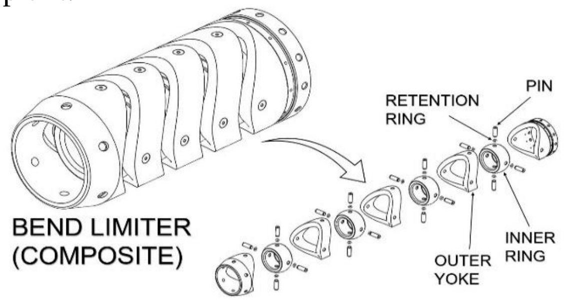


Figure 9: Composite Bend Limiter

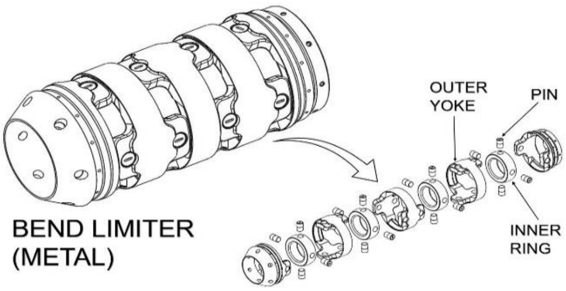


Figure 10: Metal Bend Limiter

The yokes at the 'cable' end of the bend limiter connect to the wet plant /cable termination using radial pins. The use of specialized adaptors allows the sea case yoke to connect to various terminations of different wet plant equipment.

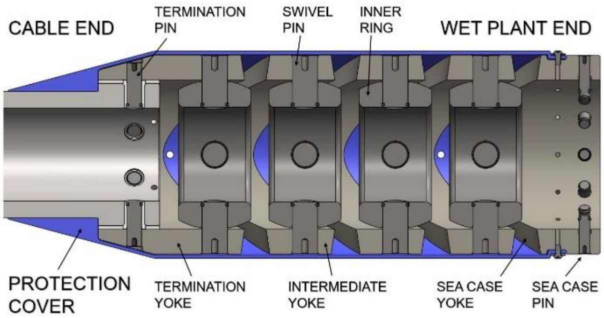


Figure 11: Composite Bend Limiter Section

The main input parameter of the bend limiter is the total maximum bend angle; this angle results from wet plant functionality requirements and must be the same for the metal and composite bend limiters. Fig 12 shows.

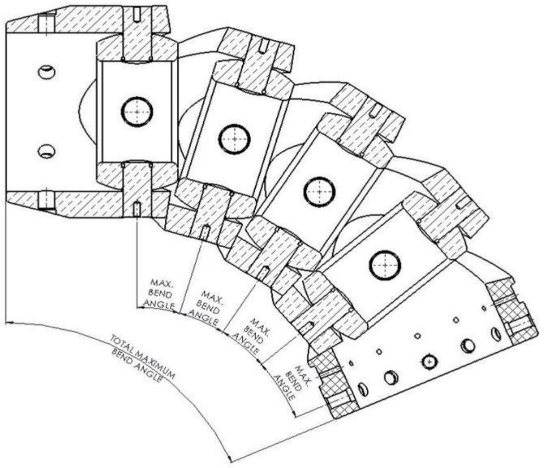


Figure 12: Composite Bend Limiter Max Bend Angle

While the inner rings of the composite bend limiter are functionally identical to the metal bend limiter's version, achieving the bend restriction of the outer yokes is different for the composite version. During the design phase, an opportunity arose to modify the bend restriction method in order to ensure continuous contact between the adjacent yokes at full bend for any given direction. This design feature avoids high load small contact patches taking the material beyond its fundamental parameters.

Manufacturing the yokes from a composite tube of predefined diameters and length, allows the removal of material from both ends creating the bend restricting "contact faces" as seen below.

In the case of the intermediate yokes the 'recesses' on each end of the intermediate yoke are offset by 90º to each other. The pinhole position and the depth of recess cut control the maximum bend angle of the bend limiter.

9. ACTIVE CONTACT FACES DEFINITION

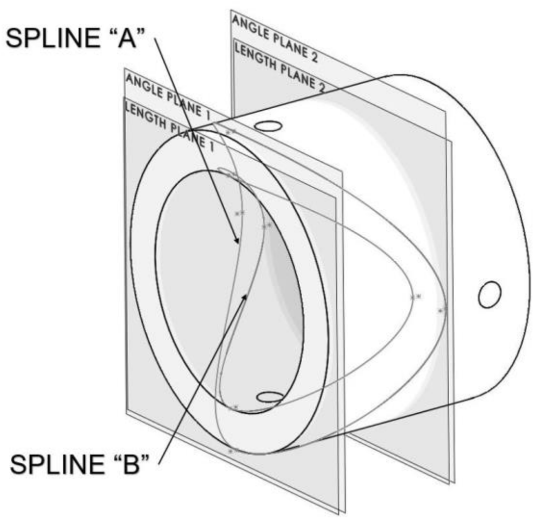


Figure 13: Split Line Definition

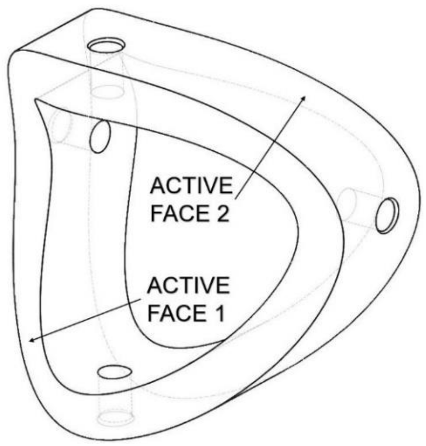


Figure 14: Active Contact Faces

Each active contact face is built in the 3D model starting from two spline curves. Spline curve A is located on the outer diameter of the yoke and Spline curve B is located on the inner diameter of the yoke. The two-spline curves are used to create a surface; the surface is used to intersect – cut the square tube profile and remove the material between the tube's frontal face and the cutting surface thus creating the desired "lobes" and "dwellings" geometry.

The splines are "constructed" using pre-defined points; the points are equally spaced at 90º around the yoke circumference.

Each point of Spline curve A has a corresponding point on Spline curve B, located at the same angular position. All the Spline curve B's points are offset with the same distance in relation to the Spline curve A's points – this distance is called "Bend Angle Distance" and is an input parameter of the total bend angle; the bend angle distance controls the bend angle and is the same for all the yokes within a Bend Limiter.

In order to control and adjust the position of the points, parallel planes are used perpendicular to the yoke's revolution axis. Two pairs of planes are required to define an active contact face; the distance between each two planes in a pair is the bend angle distance. The first plane in the pair, called the "Length plane #", controls the length/depth of the "dwelling"/ "lobe" geometry. The second plane in the pair, called "Angle plane #", controls the angle.

Two design features are used to retain the swivel pins that connect the outer yokes to the inner rings, whilst allowing them to rotate during articulation, but avoids accidental displacement when the bend limiter is in use.

Inwards stop position uses a tapered geometry at the top of the pin matching the chamfer on the outside of the yoke pinhole. This restricts the pin from moving inwards and leaves the front face of the pin flush with the outer diameter of the yoke.

Outwards retention uses the combination of a groove at the bottom of the pin and a corresponding recess at the bottom of the inner ring's pinhole with an O-ring located in the corresponding groove. With the retention ring installed on the pin and the yoke and inner ring aligned, the pin is then 'pushed' into the yoke's pinholes which compresses the O-ring with the chamfer machined into the yoke. Once the pin is fully inserted, the frontal faces of the pin's groove and of the inner ring's recess become aligned allowing the retention ring to expand in its "resting" position. The frontal face of the inner ring's recess acts as a stopper against the retention ring preventing the pin from coming out under 'normal' operating conditions.

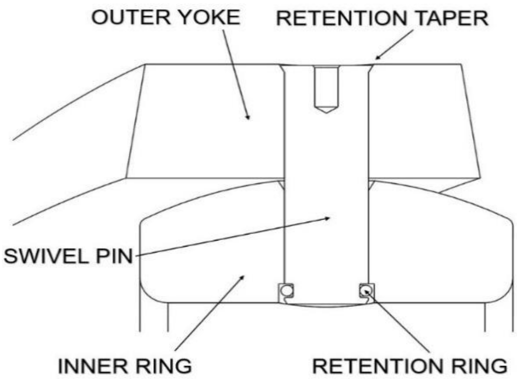


Figure 15: Pin Retention

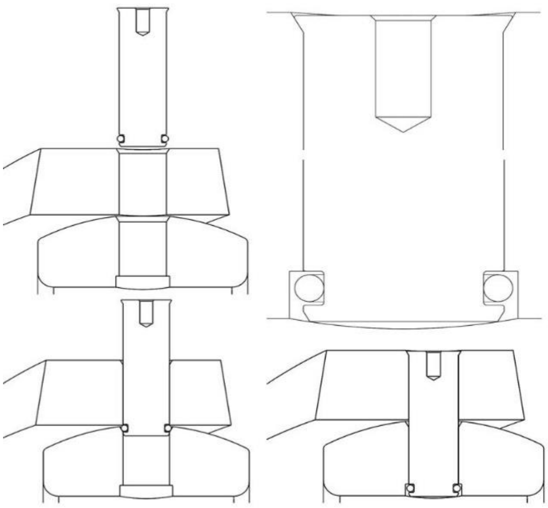


Figure 16: Pin Installation

The yoke and inner ring geometry, described above, was subject to stress analysis during the early design phase. Using Finite Element Analysis (FEA) software, mechanical strength evaluation of the main parts was able to provide detailed information about stress, displacement and strain in the component. Confirming the FEA results by means of secondary calculations ensured that the maximum stress within the tube wall in proximity of the pinholes - which act as stress raisers – was below the material's admissible limit. For the analysis, a force of 120kN was applied along the bend limiter's axis, equivalent to the cable break load of the heaviest lightweight currently available, Shear stress calculations on the swivel and retention pins,, showed that they were capable of withstanding the 120kN load.
Performing further calculations and FEA analysis of a Titanium version of the Composite Bend Limiter design, showed that by applying the cable-breaking load of the heaviest double armour cable (currently in excess of 550 kN) confirmed that that a withstanding the load without the material going into yield. This early indication is however to be confirmed by experimental testing before the metal bend limiter can be approved for wet plant use.

10. SHEAVE PERFORMANCE OF FIRST EXPERIMENTAL SAMPLE

Following the successful straight tensile test, it was critical to establish whether the bend limiters would survive representative deployment and recovery situations. To evaluate how the bend limiter would perform in these situations a repeater sample, using 'pair' of bend limiters with associated cable was constructed and subjected to the very severe 'Round The Sheave' (RTS) test.
This test represents both the deployment and recovery condition all subsea equipment are likely to face and is often the test that reveals any weakness in the components.
Fig 17 shows the sample passing around the 3m sheave at Global Marines' test facility.
Figure 18 shows the recorded load for the sample passing around the sheave, which

reached a one off peak of 93kN with a minimum test value of 80kN achieved.

Figure 17: Sheave Test

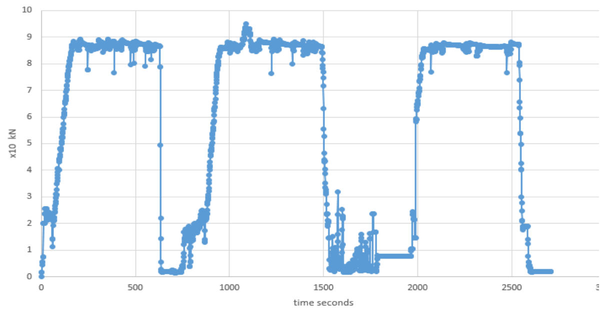


Figure 18: Sheave Test Result

11. SUMMARY OF KEY RESULTS AND CONCLUSIONS

The expectation that the requirement for lighter subsea components has a great importance in the design of equipment and is likely to become more and more critical for the next generation of telecommunication submerged plant. The constant demand for higher fibre count and more capacity is driving an increase in size and weight, both of which have a detrimental impact on deployment and recovery depth. Connecting the heavier and larger equipment by cable of limited load capacity, increasing the cable load limit and thus weight and cost per km has a significant impact on overall system cost; this is an option to be used when other options are not available.

A bespoke lightweight bend limiter design that accrues the advantages of weight reduction and cost effectiveness may bring significant advantages to the next generation of fibre optic amplifiers.

The uncomplicated design of the component parts makes them suitable for various materials and manufacturing methods to suit lightweight or armoured cable load requirements.

Results have shown that for lightweight cables with an NTTS of 80kN the carbon Fibre bend limiter, constructed from components previously subjected to 83MPa hydrostatic pressure, perform well within the material's safety limit and can support loads in excess of the lightweight cables UTS without failing.

This evaluation has indicated that the use of composite material (carbon fibre in this case) is a viable alternative to metal for subsea components utilising the inherent characteristics of lightweight and lower cost to the operator's advantage.

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