New large diameter synthetic rope testing yields high strength and performance efficiencies

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I. Introduction

The utilization of lightweight and flexible large diameter (up to 96mm diameter and larger) high modulus synthetic fiber ropes in traditional marine and industrial wire rope applications has gathered momentum over the last several years. While the performance handling value proposition of using synthetics makes sense to end-users, until recently there has been a combined lack of technical support material and understanding of large diameter synthetics; e.g. rope strength efficiencies, shape retention, diameter concerns, abrasion and cut resistance, elongation properties, and bending efficiency. By comparison, the wire rope industry has effectively compiled a vast store of performance and engineering data on its products, which is essential for use in the design of systems requiring performance guarantees and a high degree of accuracy.

Recent testing on braided High Modulus Polyethylene (HMPE) Plasma® ropes by Cortland Puget Sound Rope (Cortland) has provided valuable new technical information on the design and performance of large diameter high performance synthetic fiber ropes that should provide valuable insight into the use of such ropes in high strength applications. Tensile testing conducted in May of 2011 not only supplied "real-life" terminated tensile strengths for large diameter ropes but also confirmed design theories that braided synthetic constructions, such as Cortland's patented 12 x 12 design, provide excellent load-sharing efficiency in large constructions.

II. High Modulus Synthetic Fiber Ropes

High modulus synthetic fibers have been commercially available for over (40+) years, starting with Kevlar® aramid. In addition to Kevlar and other aramids such as Technora®, HMPE (Spectra® and Dyneema®) and Vectran® Liquid Crystal Polymer (LCP) fibers are now also utilized in high performance ropes, with HMPE constructions proving to be the most versatile across a broad range of applications. Synthetic fiber rope constructions made with these materials can equal or exceed the tensile strengths of steel wire ropes of equal size and HMPE fibers in particular offer significant weight savings (up to 1/7th the weight of steel for comparable strengths).

The most prevalent construction used with high performance fibers is the 12-strand design. This torque-balanced construction offers good strength characteristics, as well as ease of handling and spliceability. Until relatively recently, 12-strand braids were essentially limited to under 15-in. circ. (120mm diameter) due to a lack of large braiding equipment. In addition, as with most rope designs, conventional 12-strand ropes experienced a rather significant drop-off in strength translation as the size of the rope increased. This was due primarily to the increased twist required to make the strands and give them a degree of structural integrity when braided into final rope form. Consequently, the replacement of wire rope was initially limited to smaller sizes in a variety of applications, where weight savings and safety were paramount issues and creep, such as that exhibited by HMPE fiber, and comparative cost were not issues.

The fiber rope industry's "challenge" to wire rope in larger sizes and high strength applications has faced three primary issues. First, as mentioned above, the design of the rope needs to maintain a high level of translational efficiency as sizes increased without sacrificing other performance properties such as structural integrity, spliceability and resistance to abrasion damage. The rope construction must be optimized in order to take advantage of the performance properties inherent in these high modulus synthetic fibers while obtaining maximum strength translation.

Second was the ability to actually make large ropes that could achieve the required strengths while not having limitations imposed by the design of the rope itself. As an example, ropes as large as 30-in. circ. (240mm) have been manufactured using specialized parallel core designs. However, this type of design is not necessarily considered suitable for the types of lifting applications envisioned in conjunction with high modulus synthetic fibers. As mentioned above, existing 12-strand braiding equipment was limited in size to ropes of about 120mm and the lengths that could be produced on these machines was very short for that size.

Finally, applications such as lifting and deployment, positioning and mooring require detailed performance data to facilitate the design and implementation of the systems that carry out these operations. The wire rope industry has a wealth of test data and application information to support engineering requirements-the fiber rope industry is just beginning to develop this type of information.

III. ROPE CONSTRUCTION

Figure 1. Example of typical 12 x 1 design HMPE rope; each strand with "singles" twisted yarns

The issue of strength translation has been addressed by Cortland with its patented unique 12-strand construction known as the 12 x 12. In the 12 x 12 design, each of the 12 strands in the finished rope is, in itself, a 12-strand braid.

Figure 2. 12 x 12 design Plasma® HMPE rope

This construction maximizes fiber efficiency by reducing the amount of twist required to combine yarns together to build large ropes. Instead of doing multiple twisting operations to make the large strands needed to produce a big 12-strand finished rope, the 12 x 12 design divides the required mass of fiber into much smaller components, using a single twist to produce each element and then braiding them together to form one "braided strand" of the finished rope. Minimizing the amount of twist used in the production process provides higher strength translational efficiencies in the finished product.

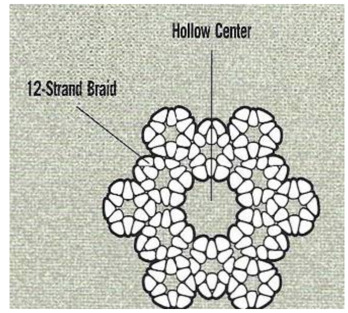

Figure 3. Cross section view of 12 x 12 design rope

In addition to excellent strength translation, the 12 x 12 design offers the following advantages:

1. Firmer or "rounder" rope profile than a conventional 12-strand rope
2. Better internal abrasion resistance between strands
3. Greater dimensional stability
4. Ease of handling, especially when disassembling the rope to install splices
5. The ability to make long continuous lengths by splicing individual braided strands together to form a secure, locked connection

IV. ROPE MANUFACTURING

Figure 4. Nominal 168mm diameter Plasma® 12 x 12 coming off Herzog braider

Early on Cortland identified the need for larger ropes. Initially, the focus was on applications such as the deep water installation of subsea equipment, which required long lengths of medium sized ropes. In 2006, Cortland purchased the world's first large 12-strand braider capable of making ropes up to approximately 200mm in diameter. Initial production runs included 3000 meters of 80 and 88mm ropes for offshore deployment systems. However, as interest in lightweight alternatives to ultra-large wire rope sling assemblies grew, the capabilities of this machine were utilized to make increasingly larger sizes of the Plasma® 12 x 12 construction.

Figures 5 & 6. Herzog 2000 braider in Anacortes, WA. rope mill

V. ROPE TESTING

The rope industry in general, and Cortland in particular, has carried out extensive tensile testing, tension-tension cycling and cyclic bend over sheave (CBOS) testing on smaller sized ropes; however, basic performance data on large sized ropes has been lacking. Even with the ability to make big ropes, the availability of large test machines capable of breaking these ropes was somewhat limited.

Unlike wire rope test equipment, synthetic fiber rope test beds need to have a sufficiently long length and stroke to handle splice lengths and initial constructional compaction. Virtually all synthetic fiber ropes compact down when first loaded, which translates into a one-time increase in the length of the test sample. The test machine must have sufficient stroke to accommodate this increase in length. In addition, synthetic ropes are also typically tested with eye splices that are fairly long and subject to the same initial compaction. Fortunately, test beds designed specifically for testing large, high strength fiber rope assemblies have been established in various locations in the U.S. and Europe in recent years.

VI. DESIGN PROGRAM

In late 2010, Cortland was tasked with building large Plasma® 12 x 12 assemblies for use as heavy lift slings for an offshore wind farm installation in Europe. Three different strengths were needed, two of which greatly exceeded the largest ropes previously made by Cortland. The largest Plasma® 12 x 12 size made to date had achieved a breaking strength of approximately 1140 tonnes. The breaking strengths required for the two largest new slings were over 50% greater. Consequently, the design of these new ropes would be a real test of the 12 x 12 construction and the translational strength efficiency of the design.

The required linear density (mass / unit length) needed to produce the target strength for each sling was calculated using historical test data and 12 x 12 construction parameters. This information was then used to predict the size of each rope, although size was not a critical issue in this particular application. Existing 12 x 12 construction parameters were scaled up for the new sizes in order to produce a finished rope that had the same handling characteristics and performance properties as smaller sizes of the same construction. No special manufacturing techniques, such as reduced twist levels or increased braid angles, were used to try and achieve the required strengths.

The diameter of the different slings was not an issue in this job. However, one of the difficulties in designing these large diameter ropes is that the target nominal diameter of the rope can only be achieved by pre-loading the new rope to compact the construction. Unlike steel wire ropes, braided ropes have some void areas within the structure. When first loaded, the rope will compact down, causing the diameter to reduce; however, this also causes the rope to lengthen by a corresponding amount. Since length is very often a critical dimension when producing finished assemblies, this compaction must be thoroughly understood by the rope manufacturer and incorporated into the design fabrication processes. For example, the diameter of the first test specimen reduced by almost 15% during the initial cycling process, while the overall length increased by a corresponding amount.

VII. TEST PROTOCOL

Cortland tested the large Plasma® assemblies at Holloway Houston Inc. using their 5,000-tonne fully instrumented test bed. The test protocol followed the procedures set forth in Cordage Institute CI 1500-02 "Test Methods for Fiber Rope" with specific reference to the section of the test standard pertaining to the determination of cycled strength.

Figure 7. O.D. measurement of 168mm diameter Plasma® 12 x 12

Key provisions of the testing process included the following:

1. Fabricate a rope sample with appropriate splice terminations on each end and load it to a predetermined reference tension (load). The splice technique used was Cortland's standard Moran 5-4-3 tuck splice. A sufficient "free area" between splices was included.
2. While under the initial reference tension, take measurements of:
    a. Overall sample length
    b. Splice length
    c. Diameter measurements
    d. Measurement of braid "picks"
3. Cycle the rope ten times from the reference load to 50% of the established or estimated ultimate break load.
4. Upon completion of the 10th cycle, re-measure the rope while under the reference tension.
5. Load the sample to destruction at a prescribed rate of speed.

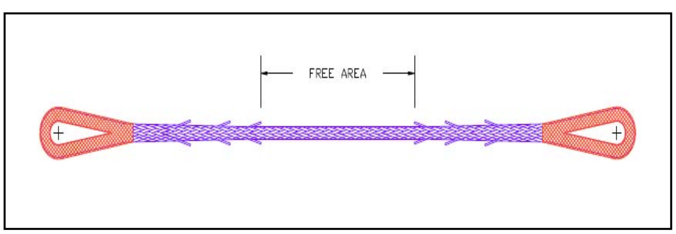

Figure 8. Drawing of Plasma® 12 x 12 eye-and-eye sling with Moran 5/4/3 spice and "free area" between bases of the splices

As described above, conventional hand-spliced eyes were used in this test, as they are in the majority of synthetic fiber rope tensile testing. Typically, spliced synthetic fiber rope loses up to 10% of its projected ultimate break strength due to the splices. However, in the U.S. published strengths are derived from tests on spliced ropes, so any strength loss associated with a spliced termination has been taken into account. It should be pointed out that, in the global market, many rope makers publish ISO/BS rope strengths, which are strengths calculated for un-spliced ropes.

The pins used for the testing provided a D:d ratio of approximately 3:1 with respect to the rope diameter. However, testing has also been conducted on smaller D:d ratios with excellent strength results. It should be noted that when using D:d ratios approaching 1:1, the pin typically fails well before the rope reaches its breaking strength.

As with wire rope, the higher the bending ratio, the greater the strength efficiency rating, especially when utilizing high modulus synthetic fiber ropes such as Plasma®. This is particularly important with respect to working ropes such as those that are running through sheaves or are utilized in dynamic heave compensation systems. In these types of dynamic applications, D:d ratios in excess of 20:1 are needed to promote effective rope life.

VIII. TEST RESULTS

The first large Plasma® test was witnessed by Cortland personnel and invited guests from a variety of companies. The rope achieved a breaking strength of 1892 tonnes. At the time, this value represented the highest strength ever achieved by a 12-strand braided rope construction and has important implications for future synthetic fiber rope strength member applications. A second test the following week on a slightly larger rope yielded an even higher breaking strength of 1912 tonnes, while a smaller rope broke at a load of 1288 tonnes. All three tests met or exceeded design expectations.

Figure 9. 168mm diameter Plasma® 12 x 12 tensioned on test bed

The first rope broke within 1% of the design spliced breaking strength. Just as importantly, the actual diameter after cycling was 167mm while the calculated diameter had been 168mm.

Figure 10. 168mm diameter Plasma® 12 x 12 rope sample after destructive test. Note at bottom left of photo that two of original 12 strands are still intact.

The rope broke at the base of the splice, which is the point at which it should normally fail. The rope compaction and elongation were, for all practical purposes, equivalent to the design assumptions, which is an important factor to take into consideration when fabricating assemblies with a precise length tolerance.

IX. Conclusion

With these test results, lightweight synthetic Plasma® 12 x 12 rope has now proven its performance capabilities in large sizes suitable for use in the most demanding of operations. The "real-size data" created is significant in positioning high modulus synthetic ropes as a viable alternative to steel wire rope and chain in ultra-high strength applications. The tests conducted in May essentially validated the Cortland design and manufacturing processes, thereby enabling Cortland to publish a finalized product strength chart with confidence. Given the high modulus rope application success in smaller diameter applications, combined with the new interpretative knowledge gained during this testing, it is anticipated that a more rapid conversion from wire rope to synthetics in several critical lifting applications may be viewed in a more favorable light. Furthermore, Cortland has not reached the upper limit of the sizes that can be produced and will continue to test new sizes and materials.

TABLE I.

Plasma 12 x 12 strand Rope Specifications

Dia.	Size	Weight		Minimum Tensile Strength	
mm	(Circ.)	lbs./100'	Kg/100m	Pounds	Te (tonnes)
104	13	458	682	1,697,000	770
108	13 1/2	473	704	1,827,000	829
112	14	486	723	1,880,000	853
116	14 1/2	518	771	1,927,000	874
120	15	535	796	2,069,500	939
124	15 1/2	574	854	2,212,000	1004
128	16	614	914	2,355,000	1069
132	16 1/2	654	973	2,497,500	1133
136	17	703	1046	2,640,000	1198
140	17 1/2	754	1122	2,782,500	1262
144	18	798	1188	2,925,000	1327
148	18 1/2	844	1256	3,068,000	1392
152	19	890	1325	3,210,500	1457
156	19 1/2	937	1394	3,353,000	1521
160	20	984	1464	3,496,000	1586
164	20 1/2	1032	1536	3,638,500	1651
168	21	1080	1607	3,781,000	1716
172	21 1/2	1122	1670	3,963,500	1798
176	22	1160	1726	4,066,000	1845
180	22 1/2	1210	1801	4,209,000	1910
184	23	1261	1877	4,351,500	1974
188	23 1/2	1312	1953	4,494,000	2039
192	24	1365	2031	4,637,000	2104
196	24 1/2	1417	2109	4,779,000	2168
200	25	1471	2189	4,922,000	2233

Notes:

1. Tensile strengths determined in accordance with Cordage Institute 1500-02 "Test Methods for Fiber Rope" using spliced test samples.
2. Sizes and weights are nominal and are based on measurements made after loading rope ten times to 50% of minimum tensile strength.

References

[1] Cordage Institute, "International Standard, Test Methods for Fiber Rope, CI 1500-02," Wayne, PA 19087-1866: pp. 1-17, May 2006.