THE
UNIVERSITY OF
STRATHCLYDE
IN GLASGOW

DEPARTMENT OF MECHANICAL ENGINEERING

AN ASSESSMENT OF THE STRENGTH OF ROPE SPLICES AND KNOTS IN SAILING ROPES

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April 2007

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Word Count: 4125

Abstract

The amount of research carried out on knots and splices has been limited, despite them being used everyday by thousands of sailors worldwide. As technology advances, more exotic materials are becoming ever popular in the construction of ropes. This leaves sailors with the option of purchasing either traditional ropes or more expensive performance ropes, with little known data to compare them.

This dilemma formed the basis of this project in which a more traditional rope, Polyester, was compared to a performance rope, Dyneema, in order to assess the different ropes with the aim of indicating whether the purchase of performance ropes would prove a worthwhile expenditure to sailors. Over 50 tensile tests were carried out, assessing parameters including spliced, stitched and knotted eye terminations. The results were analysed statistically to allow a comparison of the two materials to be made.

After completing the study, it was noted that both Polyester and Dyneema ropes had desirable qualities which make them suitable for different uses. The results show sailors that when looking for a rope that can be knotted easily, Polyester would be the better option, but if looking for a rope that can be easily spliced and carry higher loading then the choice would be Dyneema.

1.0 Nomenclature

$\bar{x}_k$	Average Breaking Load of Knotted Specimen (lbs)
$\bar{x}_s$	Average Breaking Load of Strength Test (lbs)
BL	Breaking Load (lbs)
$SE_{\%}$	Standard Error as a percentage of $\bar{x}_s$
Ø	Rope Diameter (mm)
ε	Knot Efficiency (%)
σ	Sample Standard Deviation (lbs)

2.0 Introduction

Every day hundreds of people across the world use and rely upon ropes for many purposes, sailing being one such example. Sailing ropes can be determined by two categories, namely the running and standing rigging. The standing rigging comprises of lines on the vessel which are fixed and are placed under high tension to keep structural components like the mast in position, whereas the running rigging comprises of lines which are used to control the vessel, including hoisting and lowering the sails.

In today's world, sailors now have the option of purchasing either traditional or exotic materials. These exotic materials provide exceptional performance, with extremely high loading being taken by very small diameters of line. The performance of these ropes comes at a price however, with Dyneema being priced at approximately £4/m, in comparison to approximately £1/m for Polyester ropes. When these prices are compared to £0.50/m for Manila rope, it can be seen that the man-made fibres can be very expensive to purchase when considering the amount of rope that is needed aboard a sailing vessel.

The aim of this project was to test two commonly used materials, Polyester and Dyneema, and compare the results with one another to identify how they perform. Two diameters of Polyester were tested, namely 8mm and 10mm, and one diameter of Dyneema was tested at 8mm. Tests were carried out on two knots, the single bowline and the figure of eight loop, but as eye terminations in Dyneema lines tend not to be formed by a knot, tests were also carried out on spliced and stitched eye terminations within Dyneema lines.

3.0 Rope definitions

Figure 1 below shows the two knots tested during the study, Figure 2 shows the two eye terminations used in Dyneema only and Figure 3 indicates what a tucked sheath looks like in comparison to a specimen without a tucked sheath.

Figure 1: Figure of eight loop (top) and bowline (bottom)

Figure 2: Stitched eye termination (top) and spliced eye termination (bottom)

Figure 3: Specimen without tucked sheath (main picture), with a tucked sheath shown in inset

4.0 Knots

- ## 4.1 Bowline

The bowline knot is commonly used in sailing, particularly in smaller craft and it is often used to fasten a halyard to the sail. The main advantages of the bowline are that it can be tied very quickly and single handed, but more importantly it can be untied after it has been loaded. The main disadvantage to the bowline is that when the rope has no load on it, it will loosen up and the knot can become undone.

- ## 4.2 Figure of eight loop

The figure of eight loop provides a very secure and reliable knot which can be put to good use in both sailing and climbing environments. Due to the high reliability of the knot, climbers will often use this knot to attach their ropes to their safety harnesses. The main disadvantage to the figure of eight loop is that the knot is very difficult to undo once the rope has been loaded. Other disadvantages include the fact that this knot is very difficult to adjust, unlike the bowline, and it also uses a lot more rope to tie the knot.

5.0 Testing apparatus

All of the testing carried out was performed using a Tinius Olsen 81000 vertical tensile testing machine, which had a load capacity of 200 000lbs. There were three different machine configurations that were used to test the ropes as different tests were carried out on the basic strength of the ropes and the strength of the knots. Due to problems with the Dyneema rope (discussed in Section 6.3), the strength of spliced and stitched eye terminations in Dyneema lines were also tested.

To hold the Polyester ropes in the tensile testing machine, the rope was held in a rig which was specifically designed for the testing of ropes (see Milne [1]). A schematic of this test rig can be seen in Figure 4 below.

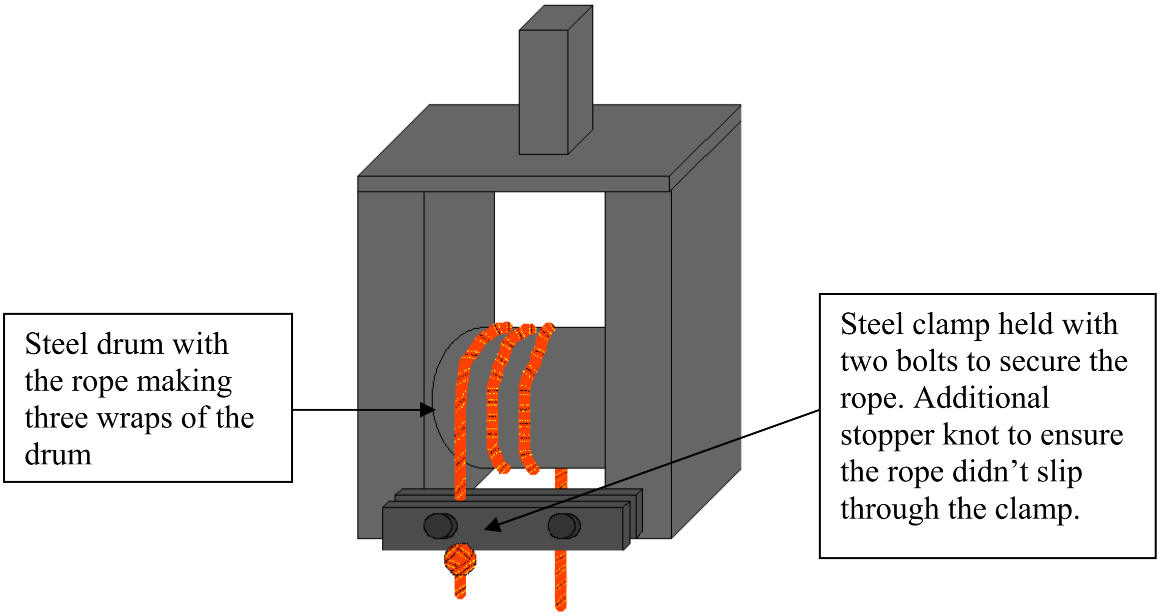

Figure 4: A schematic of the rig used to hold specimen on Tinius Olsen machine

The test apparatus used for the Dyneema ropes had to be changed due to problems which are discussed in section 6.3, and instead the Dyneema specimens were tested by creating a spliced eye termination to allow it to be held in the machine using a D-shackle.

6.0 Discussion of results

6.1 Experiment one – Basic strength tests of Polyester rope

The basic strength tests on the Polyester rope were carried out using a specimen 2.3m long with each end wrapped around each drum three times. By plotting the data from the sensor in Excel, the graph shown in Figure 5 was produced. On the graph there are two areas of importance indicated, labelled points one and two.

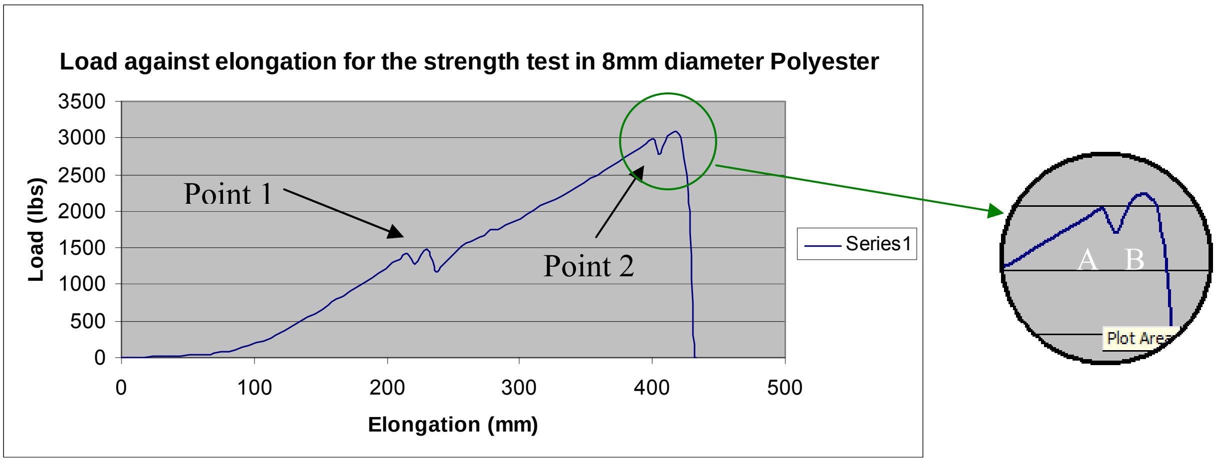

Figure 5: Identification of braid failures in Polyester strength test

The variation in the line indicated by point one is due to the slippage of the rope against the drum. As the load level was increased, friction was overcome and the rope was pulled tighter around the drum. The variation indicated at point two relates to the final failure of the specimen and has been shown in greater detail on the right of Figure 5. The failure mechanism of the rope was very fast so it was not clear which braid was the first to snap, but after closer inspection of a failed specimen, it was clear that the strands still attached are from the external braid, indicating that it was more likely that the internal braid was the first to fail at point A then the external braid failed at point B leading to complete failure of the rope.

The data recorded during testing is shown in Table 1. The average breaking load of the 8mm diameter Polyester was calculated to be 3010lbs and the test had a 3.02% standard error in the results as a percentage of the average breaking load. The 10mm diameter Polyester had a slightly higher breaking load of 4537 lbs and the test had a standard error of 1.21% as a percentage of the average breaking load.

6.2 Experiment two– Bowline and Figure of eight tests in Polyester rope

The rope length required for a bowline specimen was 1.64m, with the figure of eight loop requiring a specimen length of 1.75m. These lengths created an eye termination with an eye circumference of 200mm and a tail length of 150mm. The working end of the rope was wrapped around the drum twice and held on the rigging support whilst the eye termination was connected to a 20mm diameter D-shackle attached to the moving cross head of machine.

The results from the tests can be seen in Table 2 for the bowline and Table 3 for the figure of eight loop. By examining the average breaking loads of the knots, it shows that for both the diameters of Polyester, the figure of eight loop had both lower strength and efficiency than that of the bowline. The bowline knot provided the same knot efficiency of 73% for both diameters, whereas with the figure of eight loop, it had a higher efficiency for the 10mm diameter rope.

The failure mechanism for the knotted eye terminations was found to be the same as the results found during the basic strength tests with what appears to be the internal braid failing first, then the external braid failing finally. In Figure 6 below, point three indicates where friction is overcome as the knot tightens up on itself, and point four indicates the failure of the two braids.

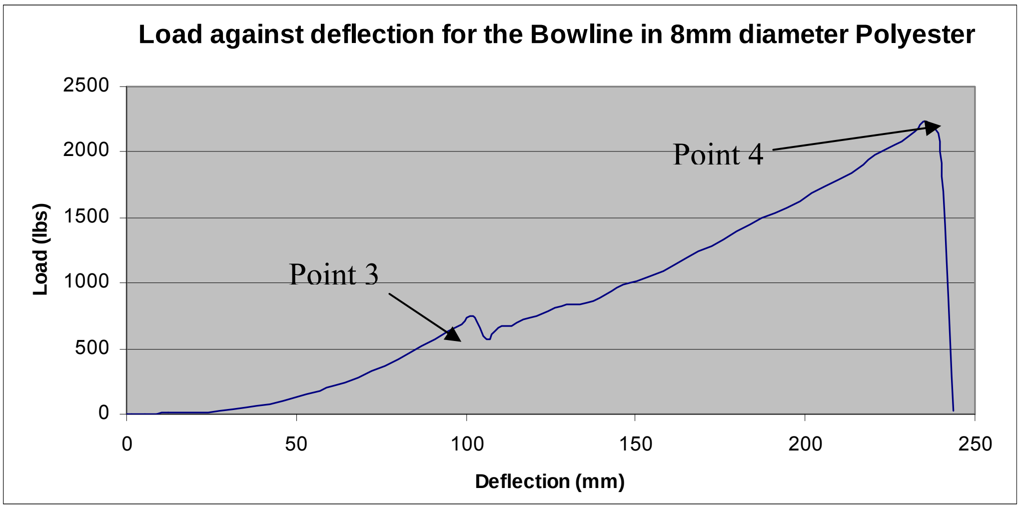

Figure 6: Identification of braid failures of a bowline specimen in 8mm Polyester

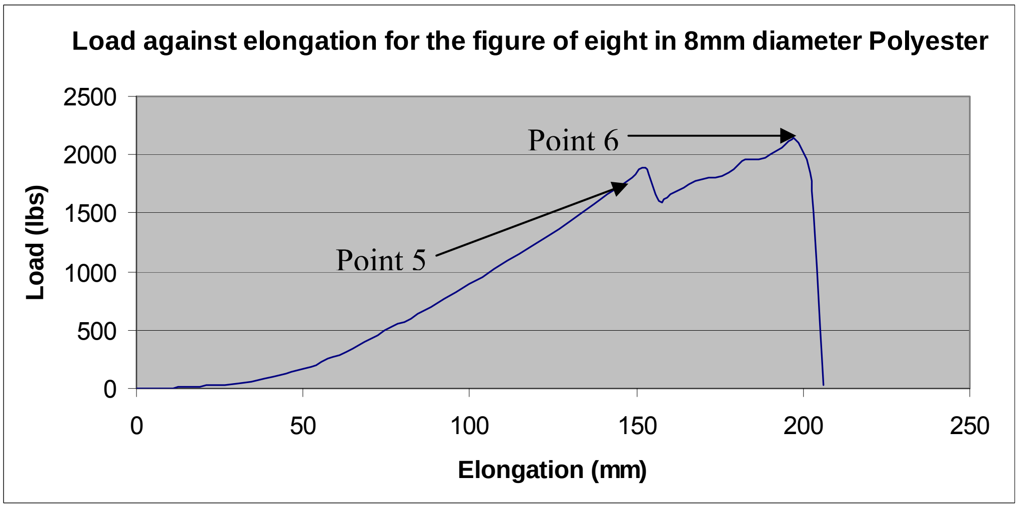

Figure 7: Identification of braid failures of a figure of eight specimen in 8mm Polyester

Two points have been indicated on Figure 7 above and those are point five which indicates the failure of the first braid (the internal braid) and point six which indicates the final failure of the specimen which was the external braid. One main difference between Figure 6 and Figure 7 is that there is no variation in results due to friction being overcome, like that observed at point three in Figure 6. The figure of eight loop has a naturally higher amount of friction present in the knot in comparison to the bowline and this was observed during testing as the bowline knot was seen to visibly move and tighten up, whereas the figure of eight loop was not. Where the friction is overcome at point three, this includes both the friction within the knot and the friction of the drum.

6.3 Experiment three – Basic strength tests in Dyneema rope

The results from the basic strength tests of the Dyneema rope can be seen in Table 4. The same procedure as used for the Polyester ropes was adopted using the same specimen size of 2.3m and wrapping around the drums three times. During the initial test, once a load level of 2200lbs was reached, the stopper knot failed against the sharp edge of the clamp, which meant that the rope simply unravelled off the drum. The second strength test carried out used a larger stopper knot as it was felt that the stopper knot of the initial test was too small and too much load was being applied to it. During this test the Polyester sheath failed first which ended the test.

To try to rectify the problem, the sheath was stripped off of the core and a third and final strength test was carried out. The Dyneema core itself is a very smooth material to the touch so during the testing it was simply slipping around the steel drums. This third test was ended when once again the stopper knot failed as the Dyneema was damaged by the steel clamp during loading.

As the three strength tests carried out did not really provide sufficient data, it was decided that the average breaking load of the rope would instead be sourced from the manufacturer [8]. The Dyneema ropes used in this study were Marlow D2 Racing and the manufacturer rated the average breaking load of the 8mm diameter rope to be 8708lbs.

6.4 Experiment four – Spliced eye terminations in Dyneema rope

The results from the tensile testing are shown in Table 5. The first splice tested used a feed length of 100mm and an eye circumference of 160mm. This specimen broke at 2950lbs which was considered to be slightly lower than expected given the efficiency of a splice is normally between 60-75% of the breaking load of the rope, so considering the average breaking load rated by the manufacturer [8] was 8708lbs, it was clear that this was not the case. When loading spliced eye terminations, there is an optimum feed length below which the splice does not break, it is instead pulled apart. This is because the tail length of the rope that has been fed inside the core is not sufficient to generate enough friction to prevent the tail end from being pulled out of the core. In order to determine what the optimum feed length was, several tests were carried out on spliced specimens with varying feed lengths from 50mm up to 200mm. The breaking loads were then plotted against the feed length to produce the graph shown in Figure 8.

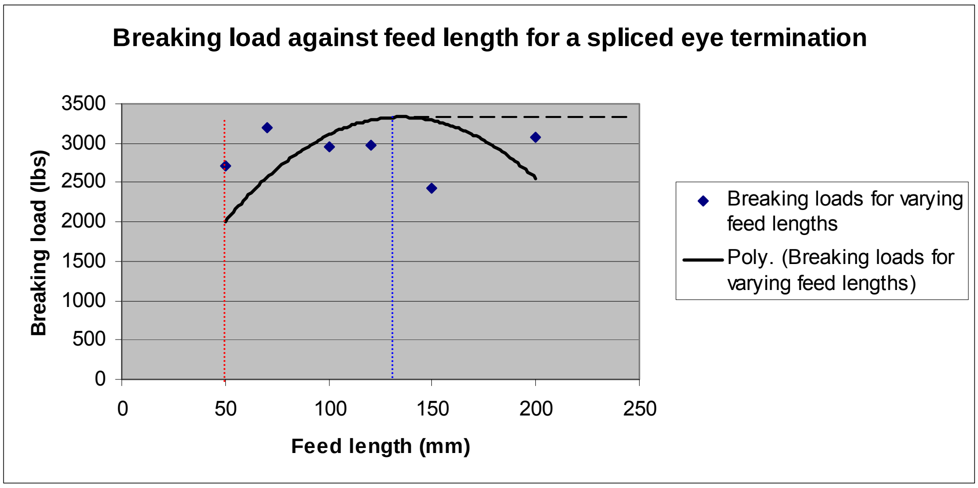

Figure 8: Variation of splice feed lengths against breaking loads

A line was fitted through the data points, which should have eventually reached a horizontal plateau if the data set had been large enough, but the dashed line on Figure 8 indicates how it should have appeared. By looking at this line and where the plateau begins, it can be seen that the feed length that appears to be the most efficient is

130mm and this is indicated by the blue dotted line. This is the most efficient feed length as it uses a minimum amount of rope and supports the optimum load. The red dotted line indicates the pull out of the spliced eyes and feed lengths to the right hand side of this line were unaffected, but feed lengths to the left of the line did suffer from the tail end being pulled out during loading.

A graph of load against elongation of the rope for a spliced eye termination with a feed length of 120mm can be seen in Figure 9 below. It can be seen from the graph that the elongation of the rope began to increase exponentially as the load approached the breaking load of the rope. This indicates that the rope failure was quite sudden and there was no noticeable indication, either visual or audible that the specimen was approaching failure.

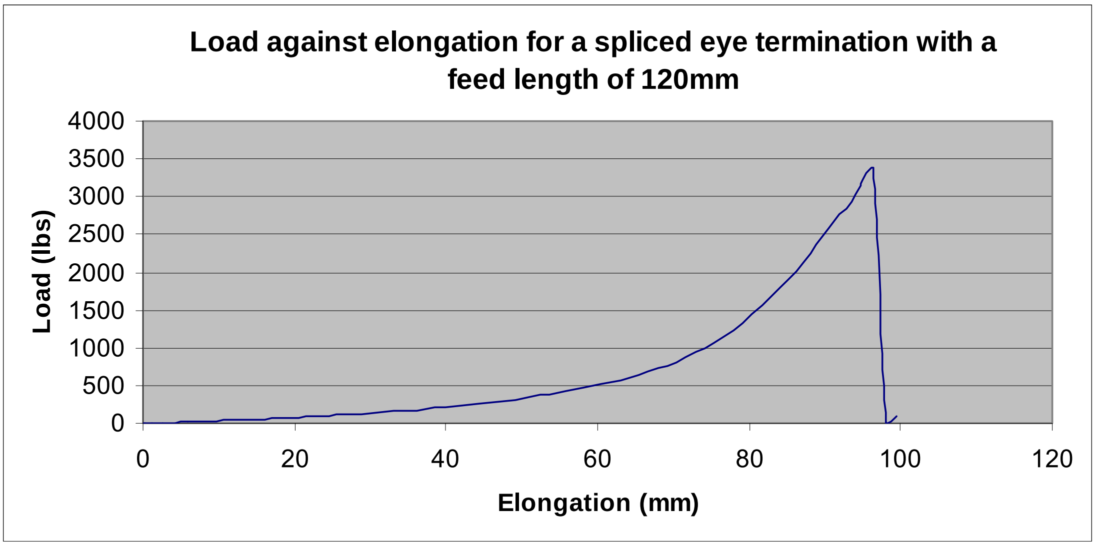

Figure 9: Load against elongation for a splice with feed length of 120mm

The efficiencies calculated for the spliced eye terminations were lower than those that were expected. The efficiency of a spliced eye would normally be between 60 and 75%, but for all of the tests carried out on, the average splice efficiency came out at around 30%. This is very low, but the reason behind it may be due to the fact that only one test was carried out for each feed length, so by carrying out further repeat tests it may be possible to increase the efficiency.

Another reason for the low efficiencies was that the working section, the distance between the ends of the feed lengths, was not long enough. A spliced specimen should have failed every time in the working section well clear of the feed length, but in some specimens this was not the case and the specimen was failing close to the end of the spliced feed length. This meant that the splice was having some effect on the end result.

Another reason for the low efficiencies could be down to the large change in cross section where the feed length ends. A schematic of this can be seen on the left of Figure 10 below. When the specimens were spliced, the rope end was simply cut and end sealed, which left a rather flat end on it. When the splice was completed, there was a noticeable change in the cross sectional area of the rope where the feed length ended. This has been highlighted on the schematic below. This sudden change in cross section will have caused a stress concentration to exist which will have reduced the load carrying abilities of the fibres, which in turn caused the rope to fail at this location as the fibres had been pre-stressed.

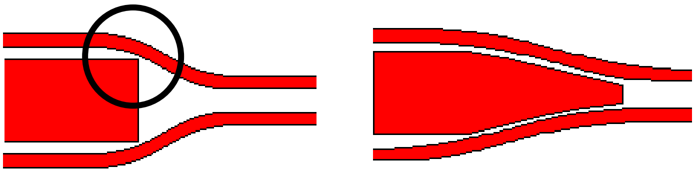

Figure 10: Schematic of cross section of the splices used in this study (on left) and splices manufactured by professionals (on right).

In practice, when splices are manufactured professionally, the end of the rope tends to be tapered in such a way that the change in cross section is more gradual and is not so sudden. In doing so, the stress concentration factor is much lower so the fibres are not as stressed, thus more load can be carried by them. This tapering is achieved by removing some of the fibres from the tail end of the rope to make it thinner, and the feed length can be made longer and fed further inside the rope to reduce the effect further. A schematic of this can be seen on the right of Figure 10 above.

6.5 Experiment five – Bowline and figure of eight tests in Dyneema rope

The data from these tests can be seen in Table 6. The initial bowline that was tested failed when the sheath was pulled off of the core. As there was nothing to constrain the movement of the sheath, the knot worked its way down the rope and tightened itself around the shackle. It was at this stage that the sheath then snapped. In the remaining knot tests, three whippings were used; two on the tail end and one where the sheath ends.

The figure of eight loop performed better in the Dyneema rope than it did in the Polyester. This knot appeared to have a lot more friction in it and whilst the bowline slipped down towards the shackle during loading, the figure of eight loop tightened up further and stayed where it was.

The graphs shown in Figure 11 and Figure 12 allow the behaviour of both knots to be examined. By comparing the two graphs, it is evident that the figure of eight loop is the more stable knot and there is no slippage.

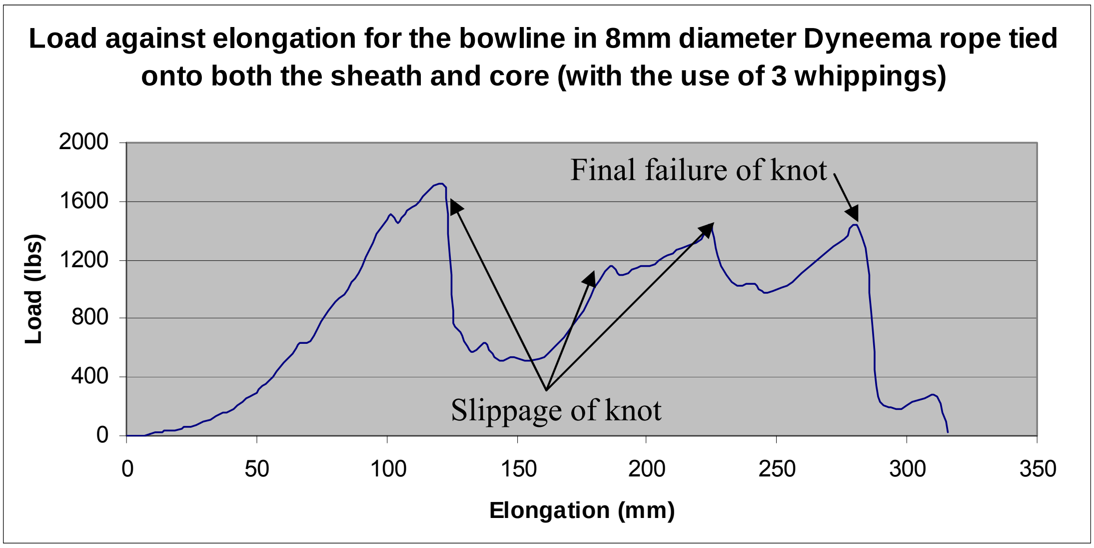

Figure 11: Behaviour of a bowline in Dyneema rope

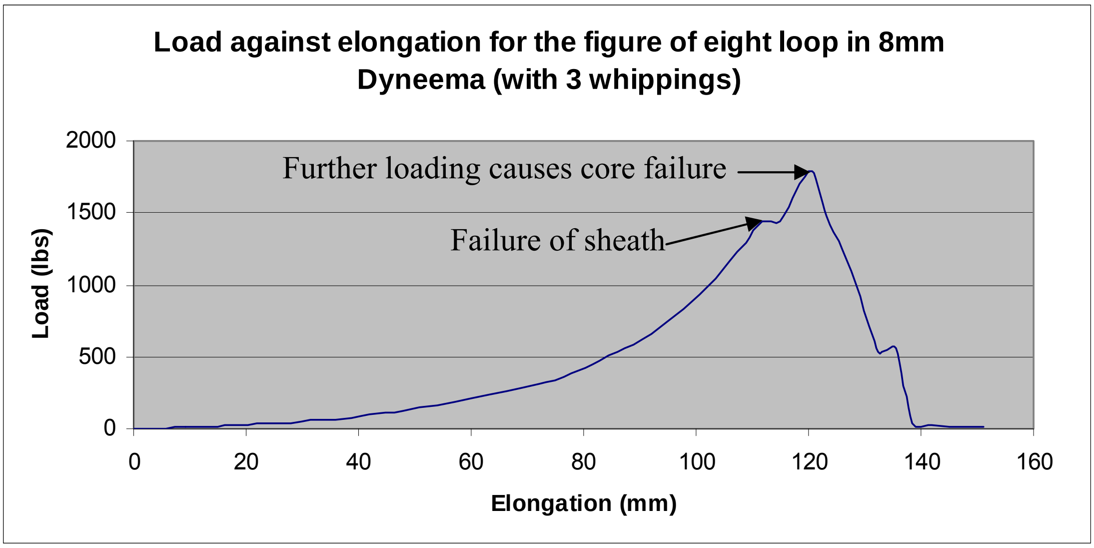

Figure 12: Behaviour of a figure of eight in Dyneema rope

The efficiencies of the knots were also relatively low with the efficiency of the bowline being 18% and the efficiency of the figure of eight being higher at 22%. The reason for these low efficiencies was because of the fact that the sheath was failing at relatively low loading which subsequently ended the test. The knotted specimen also had a splice on the other end, which although it shouldn't have made a significant difference to the breaking load, it wasn't a true result for the breaking load of the knot. It was evident that because of the material properties of Dyneema and the lack of friction in the bowline in particular, that eye terminations should be formed in other ways. This tends to be the case in a sailing environment with eye terminations in Dyneema being spliced normally.

Conditions three and four deals with the two knots tied onto the core only. The results were the same for these tests with the figure of eight taking a higher load than the bowline. What was also significant was that the test on the core only produced lower results than the tests including the sheath which would indicate that the sheath does help to increase the load capacity of the rope.

6.6 Experiment six – Bowline on core and sheath with different tuck lengths of the sheath in Dyneema rope

The results from these tests are given in Table 7. As a method of preventing the sheath from slipping off of the core, a specimen was tested with a bowline, but where the sheath ends and the core starts, the sheath was tucked inside the core, which effectively behaved like a splice, in that when the rope was loaded up, the core tightened and it clamped the sheath and prevented it from moving. In addition to this the three normal whippings were used in the same positions as before. This test resulted in a higher breaking load of 1990lbs in comparison to the average breaking load of the previous bowline tests at 1547lbs. It was evident that in preventing the sheath from slipping, the load taken by the rope was clearly a lot higher, and this may be the reason why sailors carry out the practice of tapering their lines on sailing boats.

The efficiency of the bowline knots including the tuck was significantly higher than the other bowline tests in the Dyneema, with efficiencies between 22 and 24% being calculated, whereas when there was no tuck the efficiency was only 18%.

6.7 Experiment seven – Stitched eye terminations with varying tail lengths in Dyneema rope

The results from these tests are given in Table 8. Another widely used method, along with splices, as alternatives to knotting in performance ropes are stitched and seized eyes. This method of forming an eye is not very strong as it is dependent on the strength of the whipping nylon. The theory behind this method is that when it is created, the whipping is pulled as tightly as possible so that the two parts of the sheath are held together so that when loaded up, the friction between the two parts of the sheath will prevent the eye from slipping out. This means that in theory, the larger the tail length, the more friction that will be generated, thus in turn more load can be carried. In order to assess whether this assumption is correct, three repeat tests were carried out for varying tail lengths.

During the testing the specimen kept on being loaded until eventually the friction between the two parts of the sheath was overcome and the whipping failed. Further loading beyond this lead to the eye termination pulling itself apart as it began to unravel.

7.0 Conclusions and further work

7.1 Conclusions

The main aim of this study was to compare two kinds of sailing ropes in order to assess whether the expenditure on expensive performance ropes was worthwhile. After completing the study, it was noted that both Polyester and Dyneema ropes had desirable qualities which make them suitable for different uses. The Polyester ropes performed better when being knotted than the Dyneema ropes did, although the Dyneema ropes excelled when being spliced, allowing higher loads to be absorbed.

Other conclusions that can be made are:

- When comparing the two knots, the bowline took a higher loading and had higher efficiencies than the figure of eight loop, for both diameters of Polyester.
- The figure of eight loop generates a lot more friction than the bowline so it makes for a more secure and reliable knot, both loaded and unloaded, whereas the bowline is prone to slipping as it tightens and when unloaded it is loose and free to move.
- For the Dyneema rope studied, the most efficient splice feed length was 130mm, when using an eye circumference of 160mm. This length was taken to be most efficient as it carried the highest load for the shortest feed length, therefore least amount of rope.
- It was found that whipping the sheath and core together had no effect on the loads carried by the rope, whereas by tucking the sheath into the core where it ends, a positive effect is created with higher loads being carried by the rope.

7.2 Further work

There has been very little work carried out within this field of study so there are still areas which need to be investigated further. After the results found during this study some possible areas for future study were identified and have been listed below.

- Another method for carrying out the strength tests on performance ropes like Dyneema needs to be developed as the drum method was not suitable, and by using spliced eye terminations attached to D-shackles, it led to a reduction in the breaking loads of the specimens and therefore efficiencies of the knotted eye terminations.
- The variation of eye circumference of a splice needs to be investigated to ascertain whether this has any effect on the most efficient feed length for the specimen as the testing carried out in this study focused on a single eye circumference of 160mm
- More repeat tests are required for the spliced and stitched eye terminations as only one test was carried out for the different feed/tail lengths examined. This is required to allow a larger data set to be gathered in order to determine the spread of data

8.0 Acknowledgements

The author wishes to thank his project supervisor, Dr A.J McLaren, for his constant support and guidance throughout the project.

Thanks also to Mr A. Crockett for his guidance and assistance during the tensile testing of the specimens.

9.0 References

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10.0 Tables

	Analogue Measurements		Computer Measurements	
Ø (mm)	8	10	8	10
BL (lbs)	2800	4640	3016	4556
BL (lbs)	3050	4410	2984	4380
BL (lbs)	3180	4560	3093	4568
$\bar{x}$ (lbs)	3010	4537	3031	4501
σ (lbs)	158	95	46	50
$SE_{\%}$	3.02	1.21	0.87	1.10

Table 1: Breaking loads of basic strength tests for Polyester rope

	Analogue Measurements		Computer Measurements	
Ø (mm)	8	10	8	10
BL (lbs)	2220	3230	2225	3178
BL (lbs)	2235	3400	2237	3381
BL (lbs)	2075	3130	2228	3108
BL (lbs)	2260	3480		
BL (lbs)	2150	3350		
BL (lbs)	2275	3210		
$\bar{x}_k$ (lbs)	2203	3300	2230	3222
σ (lbs)	69	120	5	116
$SE_{\%}$	0.94	1.08	0.10	1.48
ε	73	73	74	72

Table 2: Breaking loads of the bowline in Polyester rope

	Analogue Measurements		Computer Measurements	
Ø (mm)	8	10	8	10
BL (lbs)	1830	3070	1784	3074
BL (lbs)	2110	3250	2059	3237
BL (lbs)	2200	3455	2127	3431
BL (lbs)	1980	3070		
BL (lbs)	1950	3060		
BL (lbs)	1970	3100		
$\bar{x}_k$ (lbs)	2007	3168	1990	3247
σ (lbs)	119	144	148	146
$SE_{\%}$	1.61	1.30	2.82	1.87
ε	67	70	66	72

Table 3: Breaking loads of the figure of eight loop in Polyester rope

	Analogue Measurements	Computer Measurements
Ø (mm)	8	8
BL-Sheath and core (lbs)	2200	
BL-Core only (lbs)	2420	2192

Table 4: Breaking loads for the two strength tests in Dyneema rope

Feed length (mm)	Analogue Measurements	Computer Measurements	Efficiencies
50	2720	2672	31%
70	3200		37%
100	2950	2743	34%
120	3440	3357	40%
120	3160	2975	36%
120	2320	2112	27%
150	2420	2230	28%
200	3070	2925	35%

Table 5: Breaking loads of the spliced eye terminations in 8mm diameter Dyneema rope

	Analogue Measurements				Computer Measurements			
Condition	1	2	3	4	1	2	3	4
BL (lbs)	1420	1760*[1]	1300	1760	1379	1716*[1]	1243	1716
BL (lbs)	1750*[1]	1870*[1]			1722*[1]	1786*[1]		
BL (lbs)	1470*[1]	2000*[1]			1471*[1]	1970*[1]		
$\bar{x}_k$ (lbs)	1547	1877			1524	1824		
σ (lbs)	145	98			145	107		
$SE_{\%}$	0.96	0.65			0.96	0.71		
ε	18	22			18	21		

Table 6: Breaking loads of the bowline and figure of eight knots in 8mm diameter Dyneema rope

The data shown in Table 6 above comes from four different conditions that were tested. These four conditions were:

1) Bowline tied onto the sheath and core
2) Figure of eight loop tied onto the sheath and core
3) Bowline tied onto the core only
4) Figure of eight loop tied onto the core only

*[1] *This indicates that three whippings were used on this specimen to prevent the sheath from being pulled off of the core during the testing.*

	Analogue Measurements				Computer Measurements			
Tuck length (mm)	20	30	50	70	20	30	50	70
BL (lbs)	1990	1960	1920	2080	1977	1841	1899	2077
ε	23	23	22	24	23	21	22	24

Table 7: Breaking loads of bowline knots on sheath and core, with different tuck lengths of sheath in 8mm diameter Dyneema rope

	Analogue Measurements			Computer Measurements		
Tail length (mm)	20	40	60	20	40	60
BL (lbs)	1450	1480	1780	1383	1404	1708
ε	17	17	20	16	16	20

Table 8: Breaking loads for the stitched eye terminations in 8mm diameter Dyneema with varying tail lengths

To calculate the efficiency of the Dyneema specimens, the average breaking load of the rope was taken to be 8708 lbs, and this was found in data supplied by the manufacturer, Marlow [8].

The standard deviation and the standard error were not calculated for Tables 7 and 8 as there was only a single test carried out for each experiment so there was no data to calculate the average breaking load for each tuck length.