An Assessment of the Strength of Splices in Sailing Ropes

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Abstract

The techniques used to create eye terminations in braid-on-braid sailing ropes by splicing are governed by convention and 'rules of thumb', and have no industry standards. Spliced eye terminations are widely used. The aim of this investigation was to determine the effects on the rope strength after changing dimensions in the splice, and the effect of fatigue on a spliced rope.

Repeated break tests on different splice geometries we carried out using an existing tensile test apparatus to measure the breaking strength of rope containing splices of varying geometries. Splice efficiencies were found and conclusions taken from these results. To investigate the effect of fatigue, a support for an existing tensile test machine was designed and a spliced rope fatigued over a number of cycles.

It was found that although there is no critical length for a splice, ease of manufacture affects the choice of certain geometry. Future work was identified for fatigue testing, as the initial tests were inconclusive.

1. Introduction

Ropes are a key part of any sailing vessel, and have been for centuries. In reefing, mooring and controlling sails, ropes are necessary to the function of the craft. As with many other aspects of yachts and sailing vessels, ropes have developed as new technology allows for higher speeds, improved handling and reduced weight. While traditional wooden ships would have used twisted hemp, modern craft will often be found rigged with polymer braided ropes, or wire **[1]**.

Ropes on board will often require a looped end (or eye), created with a termination. Knots and splices are common terminations. Some ropes are used in what is known as *running rigging* – these are ropes often in motion – to adjust the sails when tacking, for example. When a termination is required, knots are most commonly used in running rigging due to their ability to be tied and untied quickly to adapt to the changing sailing conditions. *Standing rigging* is the term used for ropes that will not need to be altered while on course, such as stays. Terminations in these ropes are commonly splices, which are not undone easily.

Methods of splice manufacture are generally based on 'rules of thumb' and tradition. There are no industry standards and little research has gone into determining the optimum size for a splice to achieving the highest splice efficiency **[2]**. This study has investigated the effect of changing the established splice geometry for braid-on-braid splices in 8mm diameter polyester sailing rope.

2. Manufacture of Samples

2.1 Rope Structure

Ropes have been used throughout millennia for a wide variety of applications. Rudimentary rope-making is a skill still taught in survival courses today. A basic rope is created by twisting plant fibres together – these fibres form yarns, yarns together form strands and the strands are twisted together to create the rope.

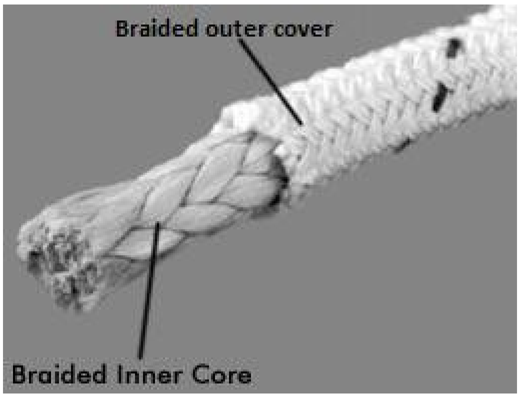

Figure 1: Construction of a braid-on-braid rope ***[4]***

A braided rope is fashioned differently, and often from man-made materials (such as polyester, polypropylene). Instead of twisting the strands together, they are braided (hence the name) into, most often, a tube **[3]**. Braid-on-braid (or 'double braid') ropes consist of two tubes – a braided core and a braided cover or sheath. The benefits of this construction are numerous – as well as the visual identification made possible by adding coloured strands to the sheath, sometimes a rope that is difficult to handle can be covered in a sheath of a different material to alleviate difficulties in use. A material such as Dyneema has a very high strength but is difficult and uncomfortable for a user to handle. A polyester cover can be added (along the whole rope, or sometimes the cover tapers to an end leaving the rest of the core free, if only part of the rope is to be handled) to increase comfort and ease of use.

As a rope is pulled, the fibres elongate and the diameter contracts in tension (a property governed by Poisson's ratio). Due to this, the rope 'clamps' itself internally, generating friction. A splice is held in place both by this constriction and by friction between the strands of the braid.

2.2 Comparison of a Climbing Rope and a Sailing Rope

Much investigation has been made into the properties of climbing ropes **[5]**, which are far more elastic than sailing ropes (often made from nylon, as opposed to polyester, which allows them to absorb shock loads if a climber falls). Many of those involved in this investigation had experience with climbing ropes, and so initially it was helpful to test both a climbing rope and a sailing rope in the same manner, to observe the differences between them. It was seen that the climbing rope extended nearly the full available distance, while the sailing rope deflected a significantly smaller distance.

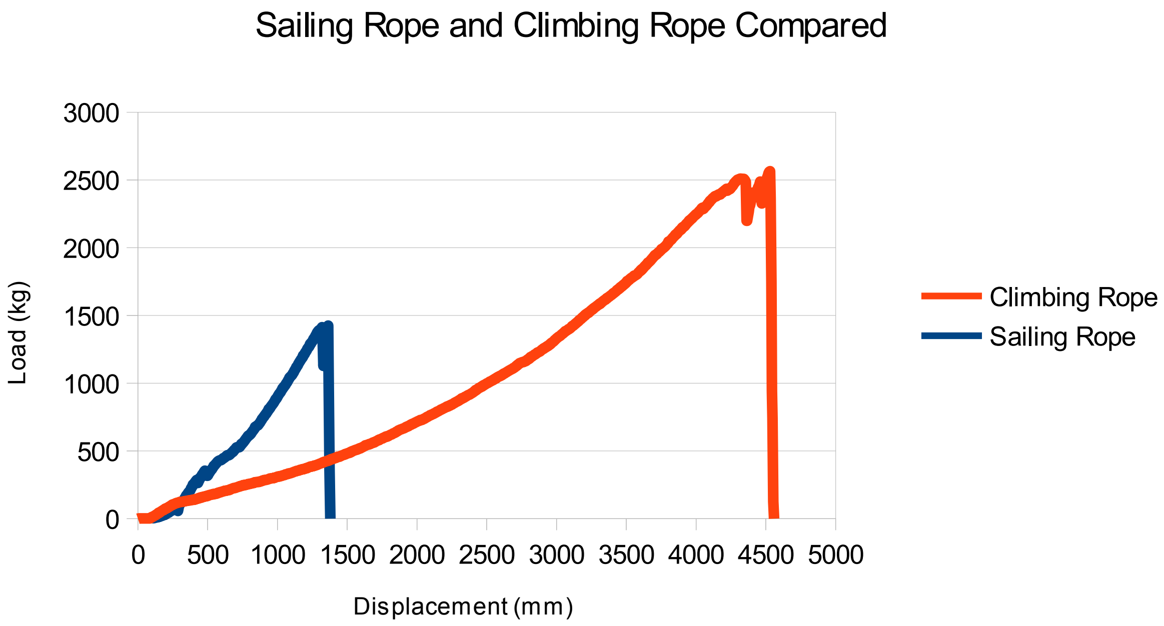

Figure 2: Sailing rope and climbing rope plotted on the same graph. It can be seen that the climbing rope extended more than twice the distance of the sailing rope

Sailing ropes, in comparison with climbing ropes, generally do not come under shock loads and are therefore manufactured from materials with a relatively high elastic modulus (high stiffness) such as polyester and polypropylene. The material can reflect the intended purpose of the rope – for example, polypropylene floats, and ropes of this material are often used for lifesaving, so a rope can be thrown to a person in the water and it will be clearly visible and accessible.

2.3 Splicing

Figure 3: Swedish fids and 8mm rope. Two relative sizes of fids are generally used - the smaller for use with the rope core, the larger fid for the cover.

Required for splicing are hollow needle-like tools called *Swedish fids*.

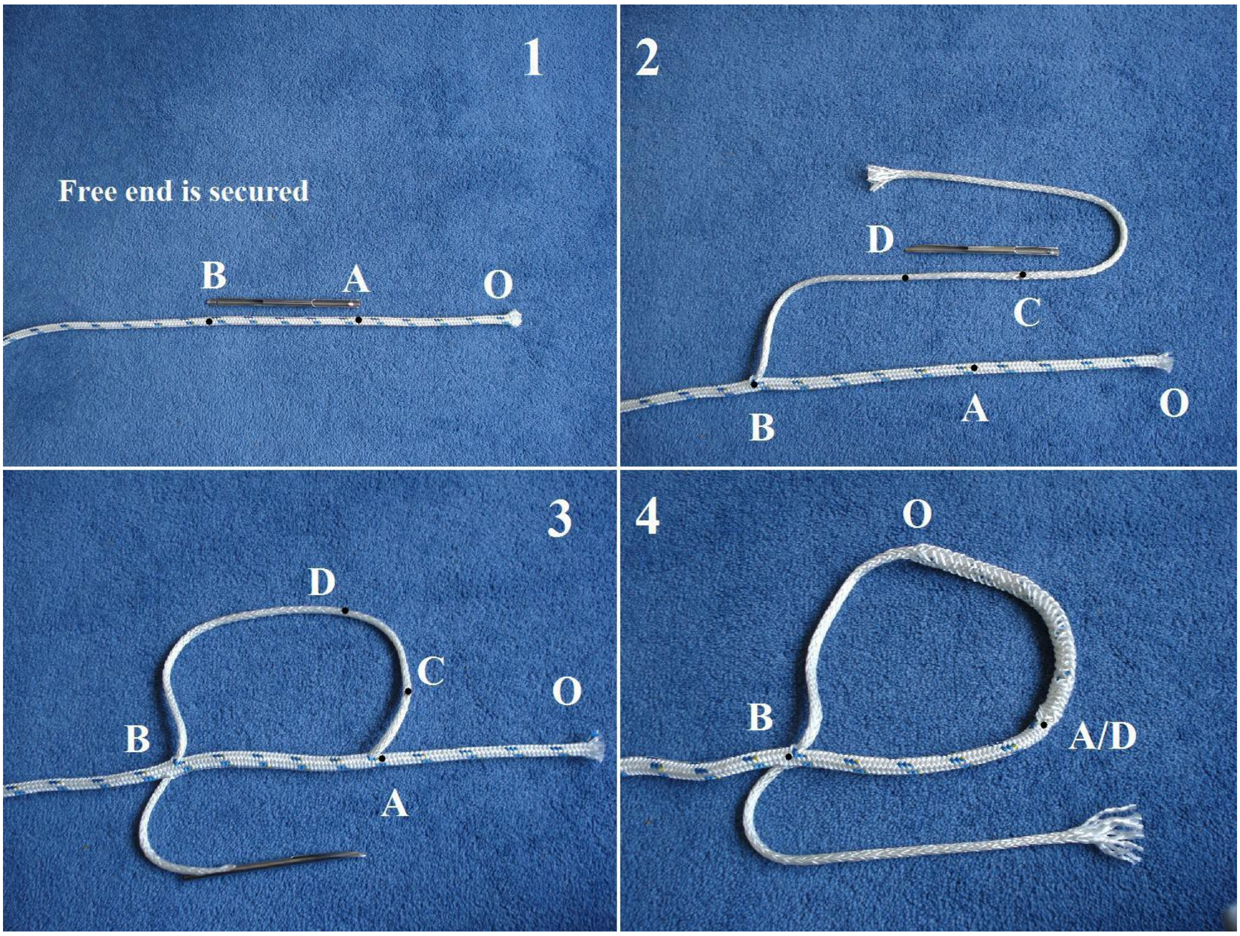

Figure 4: Manufacture of a double braid splice. Method from that published by Marlow Ropes ***[6]***

Using the large fid, a point is measured 1 fid length from the end of the rope (**O**). A mark is made at the end of this length, point **A**. The eye size is determined next (by marking point **B**), which was taken to be another full fid length (length **AB** was kept constant for every test). The smaller fid is then inserted at **B** and the core removed from within the sheath. The core is marked where it leaves the cover (**C**) and the core pulled out further. A final point, **D** is made at a distance two-thirds of a large fid length from point **C**.

Using the small fid, the core is inserted into the cover at **A** and taken out at **B**. The cover (using the large fid) is inserted into point **D** and worked through so that the core completely covers the sheath from **O** to **A**. The core is pulled from the free end to tighten the splice, and, using the rest of the rope, the splice is *milked* until the core-covered-sheath slips into the remaining rope. A tug on the eye is made to settle the splice, and the remaining core cut off.

While the splicing method itself was straightforward, some difficulties were encountered. Removing the core from the sheath carried a high risk of pulling strands of fibres – in a tensile test, the shortest fibres bear the load until they break and the load is redistributed to the next shortest fibres, and so it is preferable to have all fibres at an even length. It was difficult to avoid twisting the rope while inserting the needles in the correct points. Often, the twists or pulled fibres would cause difficulties when milking the splice, as some bunching or twisting would stop the sheath sliding easily over the splice.

To simplify the splicing, it was recommended to leave as long a free end beyond the splice as possible, as during the process the core is pulled out further than the length of the sheath, and the sheath is pushed over the splice more easily when there is more of it to 'milk'. The test called for a two-metre length for the samples[1], which was deemed too short for the manufacture of a splice. Instead, the rope was divided into four-metre lengths, a splice was made at each end, and the rope was cut with a hot knife in the centre. This ensured that every specimen consisted of a splice made *from* a two-metre length (as opposed to a two-metre length *after* splice manufacture).

2.4 Variation of Splice Length

To investigate the effects of changing the splice geometry, it was decided to systematically reduce the measured lengths when creating the splice.

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[1] As ropes stretch (deflect) when they are pulled, the length will extend as the test goes on. A 2m length was deemed sufficient to fit into the existing machine.

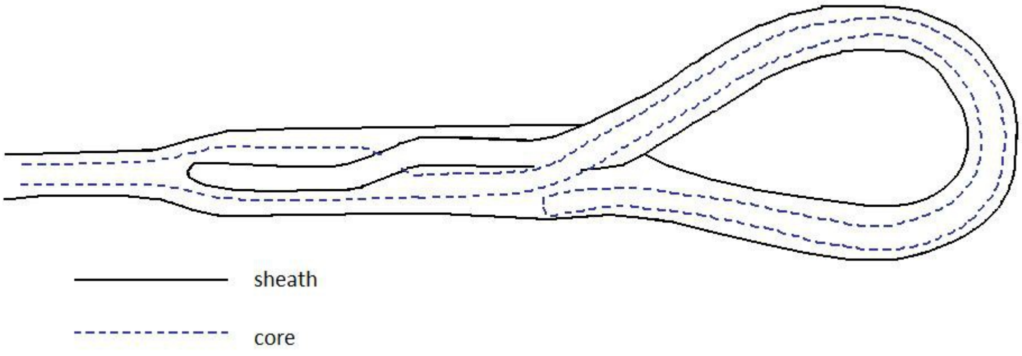

Figure 5: Internal construction of a splice. After Milne ***[2]***

The eye size was kept constant at 1 fid (174mm)[2]. Four different geometries were tested[3].

Measured length in splice (mm)	**Fraction of standard geometry**			
	1	1/2	1/3	1/5
O-A	174	87	58	35
A-B	174	174	174	174
C-D	120	60	40	24

Table 1: Geometry of tested splices. A full splice, half of the original length, a third, and a fifth.

Figure 6: Completed splices with four different internal geometries. The end of each splice is indicated by a dot.

As the splice geometry decreased, it was found that manufacture of the splice became more difficult. The very short lengths require extra care to be taken to avoid unravelling the braid or excessive twisting.

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[2] Length **AB**. When changes in geometry are referred to, e.g. “all geometry reduced by a half”, the eye size is not included

[3] Here, 'length' does not refer to the length of the finished splice, but to the measured dimensions in manufacture, which are constant relative to one another. A '1 fid length' splice's finished length is significantly longer than the fid.

3. Experimental Procedure

3.1 Apparatus

Figure 7: Setup of the Tinius Olsen tensile test machine.

The break tests were carried out on the Tinius Olsen, a screw driven tensile testing machine[4]. This setup allows the free end(s) of the rope to be wrapped around a drum before testing, which minimises stress concentration.

A set of baseline rope tests was carried out first. A two-metre length of rope[5] was attached to the Tinius Olsen, by wrapping each end around a drum and increasing the load until the rope snapped. This same test was carried out on each rope with a different eye splice, with the adjustment of one drum on the machine being replaced by a shackle, which allowed the splice to be pulled by its eye (as shown in **Figure 7**). Each test was repeated several times.

Test	No. of samples tested
2m rope	6
2m rope with 1 fid splice	6
2m rope with ½ fid splice	6
2m rope with 1/3 fid splice	6
2m rope with 1/5 fid splice	3

Table 2: Number of tests carried out on differing geometry. A further 3 1/5 length splices were used for fatigue testing.

In each test, catastrophic failure of the rope was preceded by initial snaps and a drop in the applied load. These drops could be plotted on a graph, and indicate failure of the core.

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[4] For a full description of the equipment and setup, see **Milne [2]**

[5] LIROS Top-Cruising 8mm

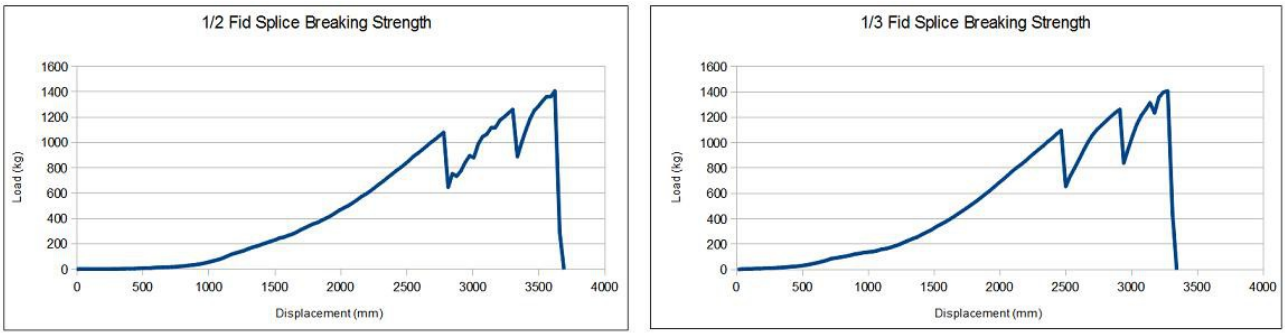

Figure 8: Typical output for tensile testing of a splice. There is internal failure in the core at two points, followed by failure of the whole rope. The initial failures were deemed to be entirely internal, as on inspection, the cover appeared unchanged in all other areas.

3.2 Fatigue Testing

While a full investigation was not possible, some initial fatigue testing was carried out. The Tinius Olsen machine was not suitable for these tests, and so the Instron 8802 was used in its stead. To minimise stress concentrations in the free end of the rope, a new support was built for the Instron – an adaptation of the drum and clamp support present on the Tinius Olsen.

A shorter length of rope was used to allow for the smaller stroke of the Instron.The splice was attached to the supports in the same manner as in previous tests. The rope was pre-loaded to 75% of the breaking strength of the rope before fatigue commenced. A pre-load of 7kN was set manually, and the test run for 6000 cycles at a frequency of 1Hz, with an amplitude of approximately 0.9kN.

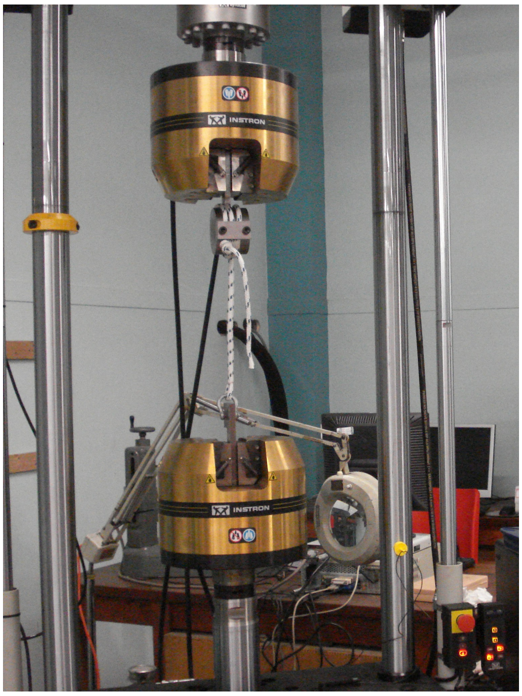

Figure 9: Setup of the Instron fatigue testing

4. Results

4.1 Varying Splice Dimensions

Test	Breaking load at each repetition (kg)						Mean breaking load (kg)	Standard Deviation
	1	*2*	*3*	*4*	*5*	*6*		
2m	1413	1471	1352	1373	1494	1383	1414	56.81
2m, 1 fid	1412	1385	1398	1410	1356	1419	1396	23.26
2m, ½ fid	1345	1448	1361	1407	1383	1413	1393	37.55
2m, 1/3 fid	1366	1457	1408	1452	1443	1402	1421	35.49
2m, 1/5 fid	1417	1486	1433	/	/	/	1445	36.12

Table 3: Results of static break tests. The standard deviation indicates that the results are mostly consistent.

The manufacturer's reported breaking strength (in kg) was 1650kg – however, the highest load withstood by the rope was around 1480kg. The ropes failed within a 150kg margin.

When testing the spliced rope (with standard geometry) it was found that failure did not occur at the splice, but further up the rope, and therefore had a similar breaking strength to the unspliced rope. This result was also encountered for each different splice geometry.

It had been expected that a splice with each measurement (excluding the eye size) reduced to a third of the standard geometry would begin to pull out of itself, and failure would occur in that way rather than the rope snapping. However, this geometry failed in the same way as before. It was then decided to reduce the geometry to a fifth of the original dimensions, in the expectation that this splice would pull out instead of failing catastrophically, but again the rope failed nearer to the drum. The only visible difference in the third- and fifth-of measurements was that the core noticeably failed or weakened at the top of the splice before the whole rope failed in a different position further up, in a similar manner to all previous tests.

4.2 Splice Efficiency

The splice efficiency is calculated as:

$$\text{splice efficiency} = \frac{\text{breaking load with splice}}{\text{baseline breaking load}}$$

	Mean breaking load (kg)	**Mean baseline breaking load (kg)**	**Splice efficiency**
1 fid	1426	1416	1.007
½ fid	1377	1416	0.972
1/3 fid	1430	1416	1.010
1/5 fid	1443	1416	1.019

Table 4: Splice efficiencies for each mean breaking load

4.3 Fatigue Testing

From the test described in **3.2**, there was no noticeable effect on the splice. Graphical data is unavailable, however it was observed on an output monitor that the position of each clamp relative to the other (data which indicates stretching of the rope) levelled off and remained constant after approximately 1000 cycles.

5. Discussion

5.1 Baseline Tests

The average breaking strength of the rope used was found to be lower than the manufacturer's reported load. This could suggest that different results are obtained by different test procedures. It was discussed at the beginning of this investigation **[7]** that the breaking strength changes with the diameter of the drum (or wheel) used, and that a different result can be obtained with a different drum. Time constraints did not permit investigation into this suggestion, and further study would be needed to verify this. However, as each rope tested in this investigation failed within a fairly consistent margin, it seems possible that a higher breaking strength could be reported by using a larger diameter on the drum, which could be the reason for this discrepancy between the tested specimens and the manufacturer's report. The implications of this are not fully clear, as it is unlikely that a sailing rope (particularly one used in the rigging, as opposed to a mooring line) would be operating so close to its breaking load that a 100kg discrepancy would make a difference.

5.2 Shortened Splices

It was expected that the shorter splice geometry would weaken the strength of the splice, and that instead of breaking the rope, failure would occur by the splice pulling out. This was not the case, as the only splices to show any 'pulling' were the shortest tested (with 1/5th of the original dimensions), and produced only very slight changes. The rope failed nearer the drum, away from the splice, as in all other tests. This suggests that even though the splice was put under strain, the stress concentration required to break the rope was found elsewhere.

These results would suggest that in braid-on-braid splicing, the length of the splice has no effect on the breaking strength of the rope. The accepted standard geometry is preferable only when considering ease of manufacture, as the smaller the dimensions, the longer it takes to ensure a neat splice with no pulled or uneven fibres. There appears to be no critical length for a braid-on-braid splice, as opposed to a three-strand splice **[2]** where it was found that below a certain number of tucks, the splice unravelled itself. A three-strand splice is held together by friction generated from the material in contact – the more tucks, the more contact. The strength of a braid-on-braid splice comes from both friction and internal constriction, as discussed in section **2.1**, and it is apparent that constriction occurs regardless of the length of the splice. It is noted that this investigation was carried out with only one type of rope, and for larger diameters, the shorter lengths of splices may have a different effect. More research would be required to establish if these results are valid for all braid-on-braid ropes.

5.3 Fatigue Tests

Time restrictions did not permit a full investigation to be carried out, but the expectation is that where a splice may not fail in a static tensile test, under dynamic loading the splice could weaken and perhaps pull out. In static tests there appear to be no differences between a standard splice and one with geometry 1/5th of the standard length, however, when under repeated cyclic loading for an extended period of time[6] the shorter splice could fail and show that while there is no difference in *breaking strength*, under commonly encountered conditions a standard splice is preferable,.

The variation in measured difference of position between the two clamps (as viewed on an output graph) indicated that the rope still stretched during fatigue. However, as this levelled off, it would suggest that the rope stiffens over time. Further work could investigate this 'bedding in' and determine how a stiffer rope is affected by fatigue.

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[6] A situation more common in real life. A splice in a rope attached to a sail (a spinnaker, for example) could be loaded irregularly and tugged over a long time as the wind catches or leaves the sail and causes it to billow or relax.

6. Conclusions

The desired tests were carried out successfully, and the key variable of splice length was assessed thoroughly. Due to resource and time restrictions, the conclusions drawn apply to a certain type of rope, and so to fully understand the effects on splice strength, similar tests should be run with different diameters of rope.

It can be seen that there is no critical splice length when using braid-on-braid rope – a rope containing a splice will fail at some point in the free end, and therefore the breaking strength for different splice lengths are equal to the baseline strength of the rope.

Under the conditions of this investigation, there was no noticeable effect on splices through fatigue. Further work is required to determine the behaviour of ropes under dynamic loads.

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