Friday 2-5

Effect of Twisting on the Tensile Properties of Small-Diameter Nylon Braided Rope

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Abstract

Twist decreases both strength and elastic modulus in large-diameter braided synthetic fiber ropes, but little is known about how twist affects smaller ropes, which may also be used in strength-critical applications. For example, in tire swings or other home projects where ropes are prone to twisting, understanding how twist affects strength is essential for safe operation. To measure the effect of twist on small braided fiber rope tensile strength and elastic modulus, samples of 3/16” diamond braided nylon rope were twisted and tension-tested to failure using an Instron. Results show twisting decreases tensile strength linearly by (0.51 ± 0.14) % per twist$\cdot$m^{-1}, and also decreases elastic modulus quadratically, by $(4.75 \pm 0.79) \times 10^{-3}$ % per twist$^2\cdot$m^{-2}. Small diameter braided synthetic fiber ropes are resilient to low levels of twist, but can still lose tensile strength and elastic modulus by close to 50 percent under extreme twisting (100 twist/m).

1. Introduction

Braided synthetic fiber ropes are often used for mooring boats, sport climbing, and miscellaneous home crafts. For many of these applications, ropes must be carefully selected, handled, and maintained to support the appropriate load, since they are safety-critical and/or mission-critical. Therefore, it is important for users of rope to know how different factors affect rope breaking strength and tensile properties.

Twist is one of many factors that can significantly decrease the breaking strength and elastic modulus of synthetic fiber braided rope [1-5]. Models relating twist to breaking strength and elastic modulus can guide the design and operation of any rope-dependent system. However, most prior investigations about the effect of twist on rope tensile properties were done on large (>20mm diameter) ropes for marine applications such as offshore drilling [2-5]. Less is known about the effects of twist on smaller-diameter ropes, which are more readily available to typical consumers and more commonly used in home, student, and DIY projects.

The effect of twist on small braided rope tensile strength and elastic modulus was measured. Samples of 3/16” diamond braided nylon rope were twisted and tension-tested to failure on an Instron. The measurements were compared to prior literature on larger synthetic braided ropes to verify their plausibility. Quantitative relationships between twist level and change in tensile strength and elastic modulus were determined.

2. Background

2.1 Why twist affects braided rope strength

Braided ropes are comprised of multiple strands that are interwoven [4,6]. Half of the strands are wrapped right-handed and the other half are wrapped left-handed. When in untwisted and in tension, these strands share the load equally, resulting in maximum rope strength. However, as shown in Figure 1, once twisted, strands in the direction of the twist tighten and strands opposing the twist loosen. Therefore, the strands in the direction of the twist take more load when the rope is in tension, and break sooner, decreasing the overall strength of the rope. As the amount of twist increases, the load imbalance increases, resulting in decreased overall rope strength [2-5]. This is a geometric explanation of the loss in strength experimentally found in large braided ropes.

Figure 1: A braided rope where the right-handed and left-handed strands are color-differentiated, showing the interweaving of the two types of strands. When the rope is twisted, strands wrapped in the same direction of the twist (white) become longer and thinner, while strands opposite the direction of the twist (blue) become shorter and thicker.

Another explanation for why twist can decrease the strength of braided ropes it that twist introduces torsion into the rope when it is under load. Equation 1 relates axial torque (τ), to tension in the rope (F), rotation of the rope (ϕ), rope length (z), rope diameter (d), shear modulus (G), and some constants that depend on rope construction (c_1, c_2, c_3) [7].

$$\tau = c_1 F d + c_2 F d^2 \frac{d\phi}{dz} + c_3 G d^4 \frac{d\phi}{dz} \ldots\ldots [7] \qquad (1)$$

It can be seen from Equation 1 that the torque component in the rope increases as diameter, shear modulus, rotation, and tension in the rope increases. This supports the idea that twist (rotation) may decrease the effective tensile strength of rope. The additional torsion in the rope due to twisting could cause additional stress in the strands comprising the rope, resulting in breakage at lower tensile loads.

2.2 Previous studies on the effect of twist on synthetic fiber braided ropes

Previous studies relating twist to rope strength have focused on large HMPE (high modulus polyethylene) ropes for marine applications, and show that twisting decreases the breaking strength for those ropes [2-5]. Regardless of diameter, HMPE ropes ranging 22 mm to 30 mm in diameter lose about 4-7 percent of the untwisted breaking strength per twist per meter [2,3,5]. Twist also significantly decreases the elastic modulus of rope by up to 79% at a twist level of 11.2 twists/m [5]. Another study found the breaking strength of 24 mm marine braided rope decreases by 40 percent as twist level increases to 9 twists/m [4]. Overall, previous work supports that twist decreases the tensile strength and elastic modulus of rope.

3. Experimental Design

To measure the tensile strength and the elastic modulus of rope under different twist levels, samples of 3/16” diamond braided nylon rope were twisted and then tension-tested to failure on a Model 1125 UTM Instron. In total, 20 samples of rope were tested, with 4 trials under each of 5 different twist conditions ranging from 0 twist/m to 100 twists/m.

3.1 Setup

Rope samples were prepared with 150 ± 2 cm total length. Figure 8 knots were tied at the each end of the sample, about 60. ± 2 cm apart. A diagram of the physical setup is shown, in Figure 2.

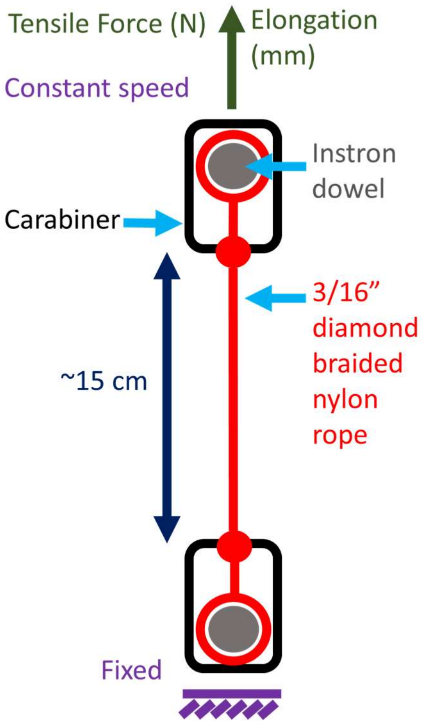

Figure 2: Experimental setup for tensile rope testing on a Model 1125 UTM Instron. The rope (red) is attached to the two dowels (gray) on the Instron and wrapped around each carabiner (black) 2-3 times. The Instron slowly pulls the rope apart until it is broken, recording both elongation of the rope (mm) and tensile force (N) during the test.

For both the bottom and top attachments, the dowel pin (attached to the Instron) went through both a figure 8 knot on the end of the rope, and the carabiner. Then, the rope was wrapped around the end of the carabiner farthest from the dowel pin 2-3 times to ensure the rope did not break at the knot. The untwisted length of rope between the two carabiners was 15 ± 1 cm at the start of the tests. While initially attaching the rope to the Instron, it was always untwisted. Then, if the test was for a twisted condition, the rope was twisted by rotating the top dowel while the rope was attached. This made it easy to accurately rotate the rope for a given number of twists, down to an estimated ± 0.1 twist uncertainty. Attaching the dowel to the Instron pins both ends of the rope, preventing untwisting during the experiment.

3.2 Measurements

Once the rope was attached and twisted if necessary, the Instron was zeroed while there was a small amount of slack in the rope, such that the rope was approximately straight, but not tight. Then, the program started and the Instron pulled the rope apart at a constant rate of 50 mm/min. The Instron recorded the elongation (mm) and the tensile load (N) between the two attachment points at a rate of 2 Hz. The resolution for load was 1 N, and the resolution for elongation was 0.1 µm. The sample rate was 2 Hz. The experiment was stopped once the rope passed its maximum load point, which was also after the rope broke. The tensile strength of the rope was taken as the maximum tensile load recorded over the entire experiment.

4. Results and Discussion

The effect of twist on rope breaking strength and elastic modulus were analyzed. Increasing twist generally results in greater elongation under a given load. This is consistent with results previously found for large-diameter HMPE ropes, where it was similarly observed that greater twist levels increased strain for a given stress [1]. This may be due to bunching of the rope that occurs naturally when rope is twisted, making the rope spring-like (see Figure 1). Figure 2 shows a comparison of the load-elongation curves under different levels of twist for a single run from each condition.

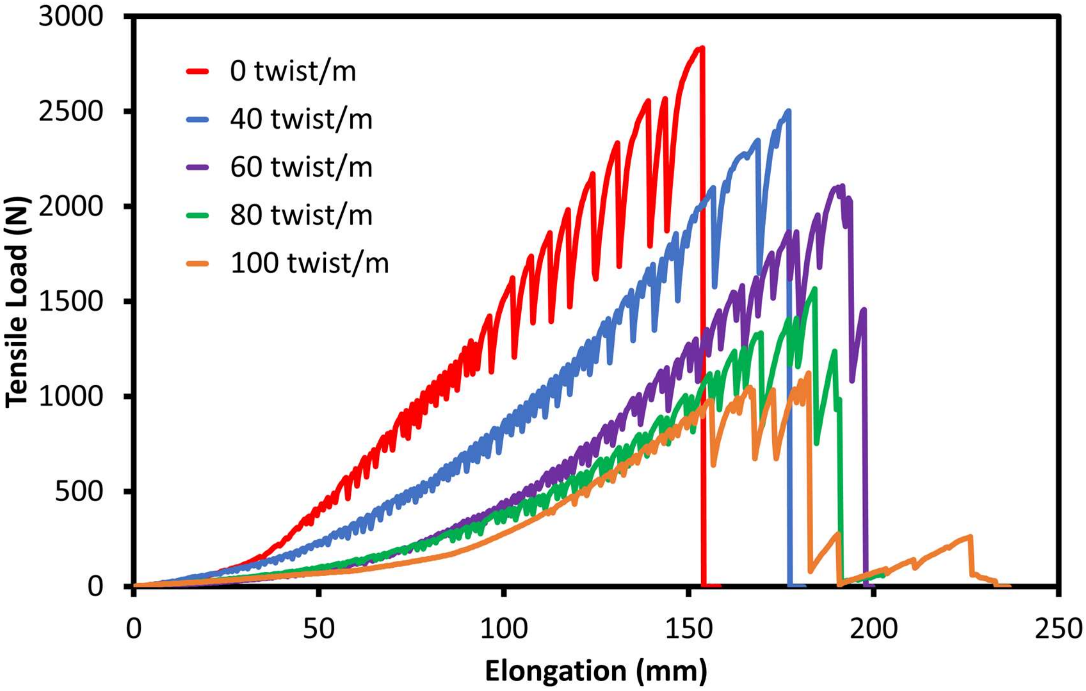

Figure 3: Raw load-elongation curves for a single sample of rope under each twist condition tested. The greater the twist level, the lower the breaking strength and the greater the elongation under a given tensile load. The repeated reductions (oscillatory-like behavior) in tensile load are due to rope slippage.

Figure 3 qualitatively shows that greater elongation occurs under any given load as twist increases, which is quantitatively confirmed by examining the elastic modulus, described later in this section. However, Figure 3 also shows how rope slippage introduced some error into the experiments. The reason for the "bumpiness" or oscillatory-like behavior of the load-elongation curves shown in Figure 3 is that the rope slipped across the carabiner as the tensile force increased. This resulted in repeated loosening of the rope over the course of the test. Because of the slippage, an uncertainty in twist level of ±1.7 twist/m was estimated.

Like in large HMPE ropes, twist decreases tensile strength linearly in the small braided ropes tested [2]. Figure 4 shows a linear fit to the average measured tensile strengths of the rope samples for each twist condition.

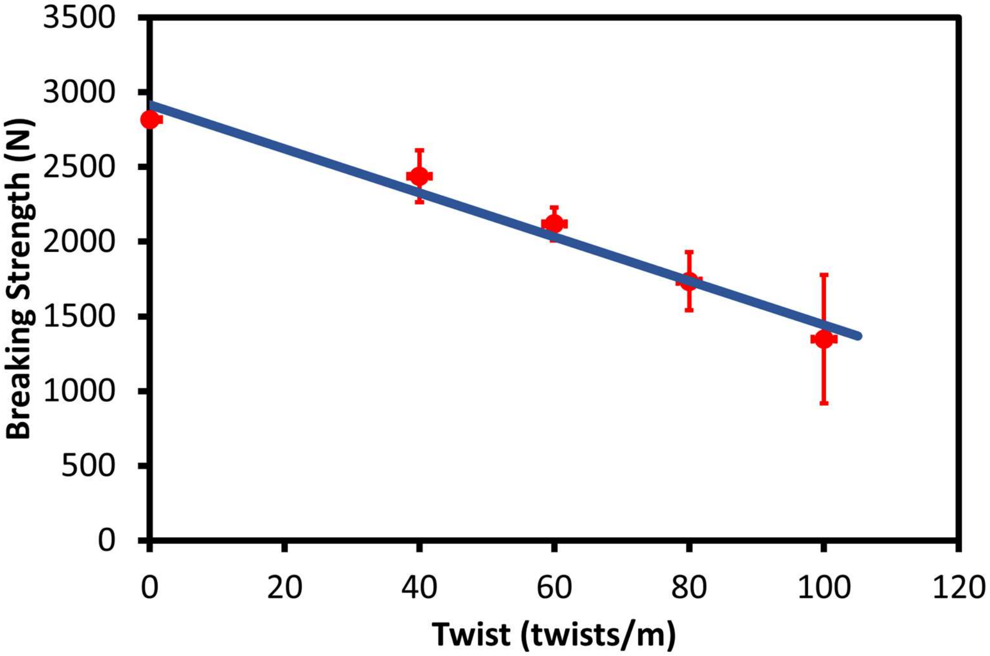

Figure 4: Linear fit to the tensile strength of rope across different levels of twist. The linear fit equation is y = Ax + B, where A = (14.75 ± 4.1) N·m/twist and B = (2920 ± 270) N. The vertical error bars reflect the 95% uncertainty in breaking strength calculated from the four trials at each twist level (for 0 twist/m, the uncertainty is too small to be seen on the graph). The horizontal error bars reflect an uncertainty in twist/m in rope of ±1.7 twist/m, estimated from setup and rope slip error.

The loss in tensile strength correlated to twist is much smaller in small-diameter nylon ropes than large-diameter HMPE ropes. The linear fit equation found for 3/16" diamond-braided nylon rope is y = Ax + B, where A = 14.75 ± 4.1 Nm/twist and B = 2920 ± 270 N. This is equivalent to a loss of (0.51 ± 0.14) % per twist·m^{-1}. In contrast, large-diameter HMPE ropes, lose 4-7 % tensile strength per twist·m^{-1} [2,5], a much greater loss. Therefore, it seems that smaller fiber ropes may be much more resilient to twist than larger ropes. This is supported by Equation 1, since the amount of torsion in a rope due to twist increases with the diameter of the rope by a high order.

The rope samples tested show a similar stress-strain profile to those found from testing large HMPE ropes, featuring a nonlinear region at low stresses, and a linear region at higher stresses [2,5]. The stress-strain curves were calculated from the load-elongation curves, and decreases in stress due to rope slipping were removed such that the curve was monotonically increasing. Then, the linear portion of the stress-strain curves were fit. An example stress-strain curve with a linear fit portion is shown in Figure 5.

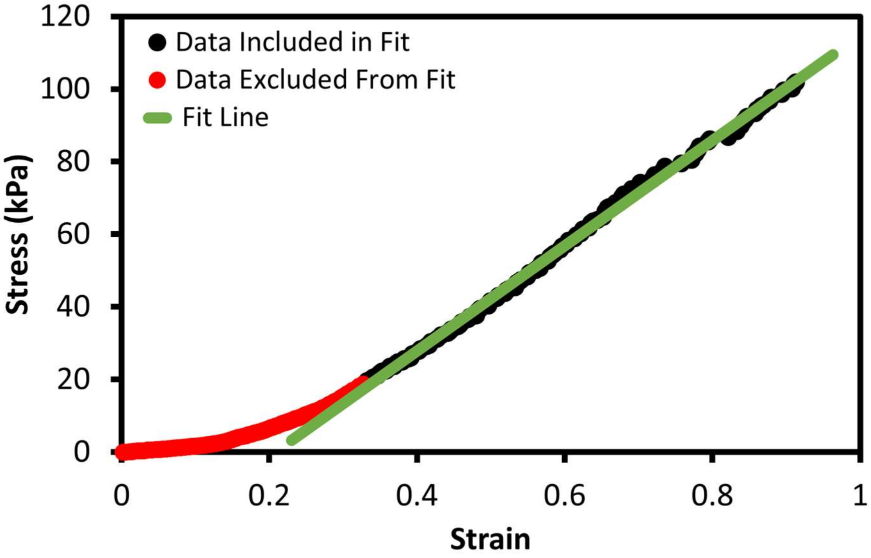

Figure 5: Example linear fit to the linear region of a stress-strain curve after decreases in stress due to rope slipping were removed. The slope of the linear fit is taken as the elastic modulus. In this case, the slope was (145.1 ± 1.2) kPa for a trial with 0 twists/m.

The linear region for each stress-strain curve was determined visually, and the slope of the linear fit was taken as the elastic modulus. For example, in Figure 5, the linear region was defined as the portion of the curve with strain > 0.33. The linear fit calculated an elastic modulus of (145.1 ± 1.2) kPa, for a twist level of 0 twist/m.

Examination of elastic moduli across all tested twist conditions reveals that twist decreases elastic modulus quadratically, shown in Figure 6. The quadratic fit shown resulted in better fit than both linear fitting and full quadratic fitting, which would have included a linear term.

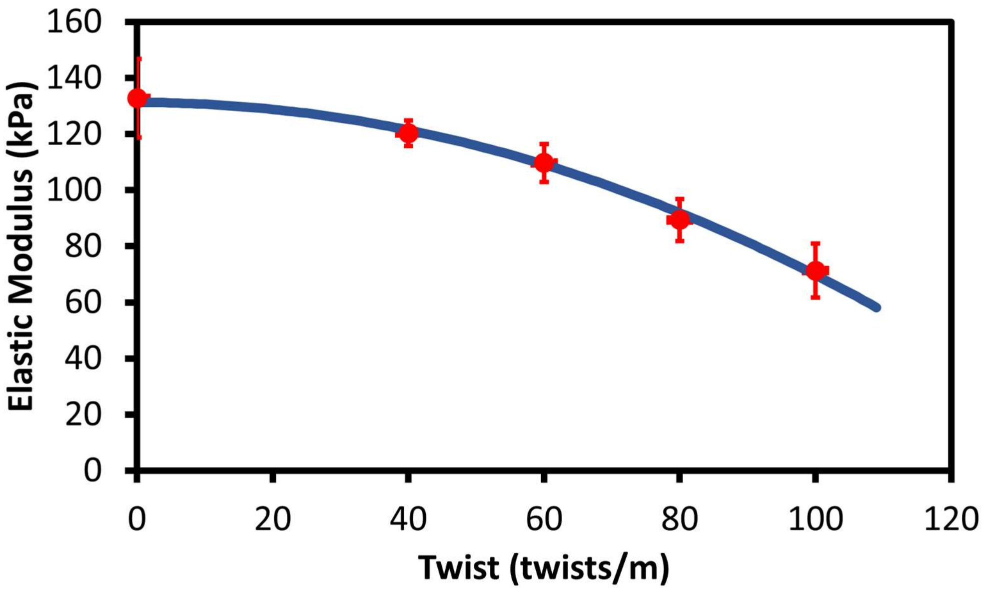

Figure 6: Quadratic fit to the elastic moduli across different twist levels, which were obtained from linear fitting each tension-elongation curve as shown in Figure 5. The quadratic fit equation is $y = Ax^2 + B$, where y is the elastic modulus (Pa), x is the twist level (twists/m), A= (-6.16 ± 0.83) $\text{Pa}\cdot\text{m}^2\cdot\text{twists}^{-2}$, and B = (131.3 ± 4.6) kPa.

The decrease in elastic modulus in Figure 6 both agrees with previous findings for large HMPE braided ropes [2,5], and partially explains why greater elongation is observed for the same load when twist level is increased (shown in Figure 2). Elastic modulus decreases quadratically according to the equation $y = Ax^2 + B$, where y is the elastic modulus (Pa), x is the twist level (twists/m), A= (-6.16 ± 0.83) $\text{Pa}\cdot\text{m}^2\cdot\text{twists}^{-2}$, and B = (131.3 ± 4.6) kPa. This is equivalent to a loss of $(4.75 \pm 0.79) \times 10^{-3}$ % per $\text{twist}^2\cdot\text{m}^{-2}$. Like loss in tensile strength, the loss in elastic modulus for the small nylon ropes tested in this experiment is much less than for large HMPE braided ropes, which lose 79% in elastic modulus with a twist level of only 11.2 twist/m [5].

The greatest limitation of this experiment is the errors due to rope slippage and inaccurate knot-tying. If the ends of the rope were spliced into eyelets as is done in other studies involving tension-testing of rope [2,5], the rope-slipping problem would be avoided and the uncertainties on the level of twist would be much lower.

5. Conclusions

Increased amount of twist decreases both tensile strength and elastic modulus in small-diameter nylon braided ropes. This is expected because twisting is known to decrease tensile strength and elastic modulus in larger ropes of similar construction [2-5]. However, the effect of twist is much lower in smaller ropes with lower elastic modulus: for the ropes tested in this project, twisting decreases tensile strength linearly by (0.51 ± 0.14) % per $\text{twist}\cdot\text{m}^{-1}$, and decreases elastic modulus quadratically, by $(4.75 \pm 0.79) \times 10^{-3}$ % per $\text{twist}^2\cdot\text{m}^{-2}$. It takes extreme twisting (100 twist/m) to reduce tensile strength and elastic modulus by close to 50 percent for the rope samples tested in this experiment. By contrast, large-diameter (> 20mm) HMPE ropes lose 4-7% strength per $\text{twist}\cdot\text{m}^{-1}$, and can lose up to 79% elastic modulus at just 11.2 $\text{twist}\cdot\text{m}^{-1}$ [2-5]. However, the decrease in effect of twisting on smaller-diameter ropes may be expected, because the torsion induced by twist in a rope under tension scales with diameter of the rope to a high order, as shown in Equation 1 [7].

Although it takes high levels of twisting to reduce small-diameter nylon rope strength, users of small diameter-rope projects should be aware of twisting as a potential strength loss mechanism for projects in which significant amounts of twist may be introduced, such as swing sets or hanging interactive objects from a ceiling, for example. For other applications where only low levels of twist will be introduced, such as a rope ladder or a tow line for carts, the effect of twist on rope tensile properties is negligible.

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References

[1] 2017, "Rope Strength & Usage", JB Rope Supply [Online]. [Accessed: 28- Sep- 2017].

[2] Davies, Peter and O'Hear, Nick. "Reduction in braided rope strength due to twist." *Oceans 2007 - Europe*. 9796389: pp 1-6. Aberdeen, UK, June 18-21, 2007. DOI *10.1109/OCEANSE.2007.4302381.*

[3] Davies, Peter and O'Hear, Nick. "How twist can affect braided marine ropes." *Sea Technology.* Vol 49 No. 7 (2008) pp 25-32.

[4] "The Effect of Twist on Braided Ropes." *Samson Technical Bulletin*. March (2012). pp 1-2.

[5] Davies, Peter, Durville, Damien, and Do Vu, Thanh. "The influence of torsion on braided rope performance, modelling and tests." *Applied Ocean Research*. Vol. 59 (2016) pp. 417–423. DOI 10.1016/j.apor.2016.07.003.

[6] H. A. McKenna, J. W. S. Hearle, and N. O' Hear, *Handbook of Fibre Rope Technology*. Boca Raton, FL: CRC, 2004.

[7] Chaplin, C.R., Rebel, G., and Ridge, I.M.L, "Tensions/Torsion Interactions in Multicomponent Mooring Lines." *Offshore Technology Conference 2000*: pp 1-8. Houston, TX, May 1-4, 2000. DOI 10.4043/12173-MS.