

The Study of Knot Performance and Knot Failure

Exploring the Secrets of Knotted Cordage to Understand How Knots Work

The Breaking Point of Natural-Fiber Knots

Why Knots Break at Predictable Places

I have found no description of a break actually occurring at the point of greatest curvature or nip within a knot tied in rope. ... There seems to be no consistent explanation of where the break occurs at a knot.

– Charles Warner
"Studies in the Behaviour of Knots" 194

The break in material almost invariably occurred at a point just outside the entrance to the knot, which is usual in all tests. . . . A rope practically never breaks within a knot. ... It appears to be true that a rope is weakest just outside the entrance to a knot. ... On testing [the Bowline Bend] I could find no tendency to break at the point of crossing. The material broke each time at a point just outside one of the Bowline Knots.

– Clifford Ashley, 17, 30

Few people have any precise notions regarding the ... breaking strength of knots. Indeed, the subject has been so systematically neglected by scientific investigators that little precise information about how knots work is presently available. ... Little is known about the mechanics of knots, and friction itself is still a scientific mystery. Under the circumstances, it behooves the layman to speak skeptically rather than dogmatically about why knots behave the way they do.

– Cyrus L. Day
15–16

The main reason of the weakening of a knotted string is the curvature of the string.

– Pieranski et. al, 10.2

The normal break in any knotted strand when put under tension, is at the knot. This general rule applies to rope or string, gut or nylon. ... In Chaytor's blood-knot, it is always inside the knot that the break occurs. ... It is at X [the centre of the knot] that the break always occurs in this form of blood-knot.

– Stanley Barnes, 42, 24, 48

... When a knot breaks, "it does so immediately outside the offending knot. ... The sharper the curved parts of the knot, the tighter the nip, the greater the chance the rope will break."

– Geoffrey Budworth
Knots in Crime, 28

Key Words. Knot breaking point, entry point, first curve, collar, Bowline, Blood Knot, core-and-wrap structure, straight-line knots, slide-and-block device, natural fiber, artificial fiber

Summary

Tests conducted more than half a century ago by Ashley, Day, and Barnes show that knots of the Bowline type tied in manila rope usually break just outside the nub. In most knots, this is the point where the standing part begins to curve as it enters the nub or knotted part. Analysis shows that these knots break at the entry point for two reasons. First, the rope at this entry point bears virtually 100% of the load. Second, the curve at that point compresses some fibers and stretches others, so that the load is unevenly distributed and the rope is weakened. This point, which is also where the rope first curves, is the only place where both of these stresses occur simultaneously. A few knots that use the core-and-wrap structure, such as the Blood Knot and the Double Fisherman's Knot, also break at the first curve, but in these knots, this point is well within the nub. The general rule, which pertains to all knots tied in natural-fiber rope, is that a break occurs where the segment of rope that enters the knot first begins to curve, that is, at the first curve in the most heavily-loaded segment of rope. Curves in other parts of a knot, however severe they may be, do not affect the place where it breaks. Some knot specialists hold a contrary view. These conclusions cannot be applied simply or directly to knots tied in ropes made of artificial fibers, but some of the same concepts may well apply.

Since the 1940s, when the three writers published their findings, few writers have systematically investigated the breaking point of knots. Other than these early tests, which appear to have been largely informal, the only scientific studies of the breaking point of knots I have found are those by Pieranski *et al.* and Long, *et al.* The study of why a knot breaks where it does has remained difficult and puzzling, and a good deal of traditional lore continues to be passed on uncritically.

This paper can be read alone, but it is easier to understand if you've read the previous ones on knot security and knot stability.

If your analysis is different from mine, or if you have found a better way of stating things, let me hear from you on the knotblog or via email. [Click here to send an email message.](#)

Introduction to the Study of the Breaking Point of Knots

This study of the breaking point of knots pertains to any practical knot tied in rope made of natural fibers. It is part of a series of studies that examine how a knot is built, how it works, and what structures make it perform better or worse.

Considering how long mankind has been using knotted cordage and how disastrous a break can be, it is surprising how little is generally known about the way knots break. While it is agreed that most knots reduce the strength of a rope, numerous interviews I have conducted with experienced mountaineers, rescue personnel, and sailors, some of whom are also engineers, show that they have no idea where knots usually break, and even less why they break at that place. Few of them have thought about the forces and structures that weaken a knotted rope and that determine its breaking point. In addition, few studies have been conducted to determine where a knotted rope usually breaks or why it breaks there.

In this presentation, I review the studies that have been made of the breaking point of knots, then apply the concepts of structural analysis to attempt to determine their usual breaking point.

Because so few tests have been conducted on the breaking point of knots and so few data are available, as well as the complexity of knot behavior, the returns are not in, even on the preliminary question of where knots break. Whatever may be finally determined about this matter, an analysis of the problem increases understanding of knots and how they work.

This study of the breaking point of knots uses the same concepts and follows the same step-by-step organization as those that guided the previous studies on knot security and stability.

The breaking point of knots is one more aspect of knot lore that writers have neglected. What Cyrus Day noted about the neglect of knot performance in general applies with special force to the breaking point of knots: "The subject has been so systematically neglected by scientific investigators that little precise information about how knots work is presently available" (1947, 1986 15).

Discussion of the causes of the curve in the stem and analysis of the extremely severe curve in the Overhand Bend are to be found in the study titled "Knot Strength."

The Aims and Method of this Study

The central aim of this study is to determine where a knot tied in natural-fiber rope usually breaks and why it breaks at that point. The breaking point is different in two types of knots, one represented by a Bowline and the other represented by a Double Fisherman's Knot. Applying elementary principles of mechanics, I examine how the structures of these two kinds of knots affect their breaking point.

More general aims are to bring together what has been said about the breaking point of knots, to raise awareness of the principles that determine the performance of knotted ropes, and to suggest useful concepts and procedures for further analysis and laboratory tests.

Assumptions, Qualifications, and Limitations of this Study

Any thorough understanding of the performance of a knot would have to take into account numerous complexities. In this study, many of these are laid aside or held constant.

Several Assumptions Limit the Scope of this Study

- Except for Stanley Barnes' tests on nylon leader, the publications that I have consulted about the breaking point of knots pertain to cordage made of natural fibers. For this reason, this study pertains to the breaking point of knots tied in natural-fiber ropes. I have made no attempt to apply them to other types of cordage.
- As is well known, other kinds of cordage, including rope made of nylon, has very different properties of surface friction and compression which makes it impossible simply to extrapolate the results of experiments conducted in other kinds of materials. The breaking point of these kinds of cordage is beyond the scope of this study. However, it seems likely that some of the concepts developed here for natural-fiber rope would apply to other types of cordage, however different the results would be.
- Following the findings of Ashley, Day, Barnes, and others, I assume that a Bowline and most other knots usually break just outside the knot, where the standing part enters the nub. Their conclusions are confirmed by more recent investigations by Long, *et al.*, and Pieranski *et al.* The evidence on the breaking point is not abundant, and some knot specialists hold a contrary view, but in the absence of definitive tests, I have tentatively accepted the conclusions of the early investigators.
- Following Barnes, I assume that a Blood Knot does not break at the entry point but in the center of the knot. I make the same assumption about a Double Fisherman's Knot.
- This study does not take into consideration the variability of rope. To develop general principles that would apply to knots tied in any length of natural-fiber rope, I assume that the knots are tied in ideal uniform cordage that does not exhibit the variation and imperfections of actual rope.
- The performance of hitches, which are tied to objects such as rails and bundles, presents problems that are beyond the scope of this study.

Other Limitations Narrow the Scope of this Study

- As in my other studies of knot performance, this study of the breaking points of knots is limited to what can be known through observation and analysis. I have conducted no bench or laboratory experiments. I have applied only elementary concepts of mechanics such as load and friction and have described knot performance in ordinary terms, using no equations, graphs, or diagrams.
- The effect of other variables that influence knot performance is beyond the scope of this study. Except as otherwise noted, I assume that the knots, materials, conditions of loading, and use of knotted rope are standard and uniform. I exclude from this study the effect of backup knots because they would obscure the very properties of knots that I want to examine.

I have verified this analysis by reviewing reports of various tests, as well as by conducting interviews with knot users and through correspondence with knotting specialists. Yet many

assertions have not been confirmed by tests and remain unproved. And although experiments on knots tied in nylon filament (Barnes) or cooked spaghetti (Pieranski *et al.*) were conducted with care, it seems reasonable to question whether the results of these tests can be applied directly to the performance of knots tied in ordinary rope. These are matters for further investigation.

Throughout this discussion, I have tried to keep in mind Cyrus Day's admonition about making dogmatic statements on knot performance: "Little is known about the mechanics of knots," he says, "and friction itself is still a scientific mystery. Under the circumstances, it behooves the layman to speak skeptically rather than dogmatically about why knots behave the way they do" (16).

Terms and Concepts for Studying the Breaking Point of Knots

Several terms are essential for analyzing the breaking point of knots. Some of these terms are in current usage, some are redefined or limited for the special requirements of this study, and some are newly coined. These and other terms are discussed in the study of knot strength that follows and in "Terminology of Knot Performance."

The *load* is the pull exerted on a knot, for example, by a weight suspended from the loop of a Bowline. *Fibers* are the individual threads of a rope. The *nub* is the knotted part of a knot, as distinguished, for example, from the standing part, the tail, and the loop of a Bowline. A *segment* is a particular section of rope in a knot, for example, the loop of a Bowline. The *standing part* is the straight segment of rope that enters the nub of a knot. The *entry point* is the place where the standing part enters the nub. Knots that join two ropes have two standing parts and two entry points.

The *stem* of a knot is the segment of rope that connects the standing part to the nub. In knots of the Bowline type the stem is a short segment that terminates at the entry point. In knots of the core-and-wrap type, the stem extends deep into the knot. The *collar* is the structure that wraps around the standing part at the entry point; in knots of the Bowline type, the collar helps to create the first curve in the stem.

As a noun, *wrap* refers to a segment of rope that passes around another segment. An example of a wrap is the helix of a core-and-wrap knot that circles around the stem, as in a Double Fisherman's Knot. Warner uses the word *wrap* in this sense (*A Fresh Approach* 30).

Several other terms pertain only to the small group of knots of the core-and-wrap type, which includes the Double Fisherman's Knot and the Blood Knot. In these knots, several wraps enclose a central core. Knots of this type use the *slide-and-block* device, a construction in which the wraps of each half of the knot are pulled along the core of the other half so that the two halves meet in the middle of the knot and prevent each other from moving further.

In all knots, the *first curve* is the place where the segment that enters the knot is forced out of a straight line into a curve. In a Bowline and most other knots, the first curve is at the point where the standing part enters the nub, just as it crosses over the collar. Core-and-wrap knots are *straight-line knots*. In these knots, the standing part enters the nub without curving. The core remains straight in line with the main longitudinal pull of the knot until it makes its first curve well inside the knot.

Part 1. The Breaking Point of a Bowline

The following section examines the breaking point of a Bowline. The procedures and concepts used here apply to knots of the Bowline type, which includes most knots. A later section examines the breaking point of a core-and-wrap knots such as the Double Fisherman's Knot. The Bowline and the Double Fisherman's Knot provide typical examples of two kinds of knots that follow the same general laws but break in different places. A final section proposes a general principle that applies to both kinds of knots.

The figure on the next page identifies the parts of a Bowline and indicates three places that many people think it would break under excessive loading, as well as the actual breaking point, as determined by several tests.

The Breaking Point of a Bowline

SP The Standing Part, the straight segment of rope outside the nub, bears 100% of the load. In this part of the knot, the load is distributed evenly on all the fibers. As the standing part merges with the stem, it curves around the arc of the bight.

X The Entry Point, where the standing part merges with the stem, is the place where a Bowline usually breaks under excessive load. The rope curves here first, and virtually 100% of the load falls on this point.

Parts of the Nub

The nub is the knotted part of the knot. In a Bowline, it is composed of the stem, the bight, and the hitch.

S The Stem (between the dotted lines) crosses over the collar created by the arc of the bight and creates the first curve. This curve distributes the heavy load unevenly, causing the knotted rope to fail at the entry point.

B The Bight is the curved segment that forms a collar around the standing part as it enters the knot. The apex of the bight is sometimes mistakenly thought to be the breaking point of a Bowline.

C The Crossover of the Hitch The nip of the knot, where the arms of the hitch cross each other, is often mistakenly thought to be the place where a Bowline usually breaks.

H The Hitch The arc of the hitch (opposite its crossed arms) is also mistakenly thought to be the usual breaking point.

T The Tail bears no load except its own weight.

L The Loop The loop bears the entire load, but each leg bears only about 50% of the load.



Structures that Determine the Breaking Point of a Bowline

As shown in the figure, a Bowline is a fixed-loop knot tied in a single length of rope. It is made up of the standing part, the loop, the tail, and the nub. The nub, or the knotted part, is composed of the stem, a hitch, and a bight. All of the load on a Bowline falls on the standing part, and about half the load falls on each leg of the loop.

Where does an overloaded Bowline usually break? The apex of the bight, the crossover of the hitch, and the arc of the hitch are often mistakenly selected as the place. But most breaks occur at the entry point, the junction where the standing part makes the first curve as it enters the nub and merges with the stem. For determining the breaking point of a Bowline, the critical aspect of this structure is the location of the first curve, which bears virtually 100% of the load. The text explains why a Bowline and other knots of its type usually break at that point.

A Bowline Breaks “Just Outside the Knot Itself”

From the interviews that I have conducted with knot tyers, it appears that most people assume that knotted cordage that is loaded too heavily will break somewhere inside the knot. Some think that a Bowline, for example, would break in the apex of the bight, where the stem crosses over it at the top of the knot. Others point to the place where the two arms of the hitch cross, and still others to the arc of the hitch, that is, the place where the hitch wraps around the legs of the bight. These choices may seem quite reasonable. They are places where the bight and the hitch create curves, and more or less severe ones. A load would pull them tight and create a lot of pressure. If not at one of those places, where else could the knot break? And why would it break there?

As Clifford Ashley put it, the actual location of the breaking point of most knots is “quite different from what is generally accepted” (17). In tests conducted more than half a century ago, Ashley as well as Cyrus Day and Stanley Barnes observed that a knotted rope usually breaks just outside the knot itself. This is at the point where the standing part merges with the stem and begins to curve as it enters the nub. Despite different conclusions by some writers and correspondents, I assume that breakage usually occurs in that first curve at the entry point, at X in the Figure.

Ashley and Day make few further observations about the breaking point of knots, and most other writers I have consulted, with the exceptions of Barnes, Long, *et al.*, and Pieranski *et al.*, either disregard the matter or mention it only briefly. Except for those who are acquainted with the works of these writers, everyone seems to be surprised that most knots would break at the entry point. Perhaps just as surprising is the line of reasoning that helps us understand why knotted ropes usually break at that point.

Why an Overloaded Bowline Usually Breaks Just Outside the Knot

The following sequence of observations explains why a Bowline usually breaks just outside the knot and why it breaks there. The first five points apply to all knots while the other points apply to a Bowline and to most other knots—all except knots that use the core-and-wrap device such as the Blood Knot and the Double Fisherman’s Knot. These concepts, which are derived by the same method used in the studies of knot security and knot stability, are crucial for understanding the breaking point of knots.

Some Segments are Loaded Fully and Some Partially

The breaking point of a knot depends first of all on the portion of the load borne by various segments of rope.

1. A full load falls on the standing part of a knot.

Observation of a Bowline shows that the full load comes to bear on the standing part of the knot, the segment of rope that leads to and merges with the knotted part. This elementary

concept is fundamental in locating where a knot usually breaks and understanding why it breaks there.

2. Contact between segments of rope reduces the load on the segments inside the knot.

What may not be so immediately obvious is that when the fully-loaded standing part enters the knot and crosses another segment of rope, some of its load is converted to pressure and friction, and the load on it is reduced. This reduction of load takes place at all points of contact between surfaces in the knot, that is, all crossovers and parallel segments. This basic principle of physics—that contact between surfaces reduces the load on a segment of rope—must not be overlooked.

3. The load on segments of rope inside the knot is always less than 100%.

A full load falls only on the standing part of the knot and not on either arm of the loop or on any segment of rope within the knotted part of a knot. This is because the load is diminished at every crossover in the nub, that is, at every place where the surface of a loaded segment of rope comes into contact with another surface.

Straight Segments and Curved Segments Distribute the Load Unevenly

The breaking point depends on whether the load on the fibers in a rope is distributed evenly. Loads on straight-line segments and on curved-line segments affect the individual fibers of the loaded rope in contrasting ways.

4. In a straight-line segment, all of the fibers bear the load equally.

As we conceive of the behavior of our ideally uniform rope, the load in a straight-line segment of a knot is transmitted straight along the length of the rope. Because the standing part falls in a direct line with the longitudinal forces in the knot, the load is distributed evenly on all the fibers of the rope. Measurement of the load falling on the fibers at any cross section of the standing part of a knot would demonstrate that each of the fibers bears the same proportion of the load.

5. A curve in a segment of rope redistributes the load unevenly on the fibers.

While a straight-line segment of rope, conceived ideally, distributes the load evenly on the fibers, a curved-line segment stretches the outside fibers and compresses the inner ones. This stretching and compression redistribute the load unevenly. The fibers on the inside of the curve bear less load, while the fibers on the outside of the curve bear more load.

Vines and Hudson (1992) noted that "in any sharp bend of a rope, . . . the rope fibers on the outside of the bend carry the majority of the load on the rope" (54). The Alpine Club committee (1864) made a similar observation (Kennedy, 325). Their statements must be modified to say that any curve, whether it is severe or gradual, causes the load to be redistributed.

6. The stem curves as it enters the knot.

At the top of a Bowline, the bight forms a collar around the stem, and the stem curves as it crosses over the collar and enters the nub of the knot. This means that the lower end of the

stem lies somewhat out of a direct line with the standing part and at an angle to the main line of longitudinal forces in the knot.

The structures of the knot that cause the stem to curve at the entry point and that hold the rope in this misalignment are the standing part, the collar, and the structures that anchor the stem at its lower end. These structures are described in detail in the next study, "Knot Strength."

Ashley and Day appear to have been following this line of thought when they associate the weak point of a knot with rigidity. "It appears to be true," Ashley says, "that a rope is weakest just outside the entrance to a knot, and this would seem to be due to the rigidity of the knot" (17). Day surmises that the rope breaks there "perhaps because the complex stresses and strains that operate on the rope where it enters the knot are amplified by the rigidity with which the rope is held in place at that point by the knot itself" (15–16).

These writers did not, however, follow up what their observations imply or make it clear why rigidity would have that effect. My observation shows that it is not only that the collar is rigid but that it holds the standing part rigidly at an angle.

The First Curve in the Stem Weakens a Knot

7. The uneven distribution of load in a curved segment weakens a knot.

In a Bowline, the standing part makes its first curve at the entry point. The uneven distribution of load in a Bowline at the entry point, caused by the curve in the stem, weakens the knot at that point. The outside fibers, carrying more of the load than the inside fibers, are placed under greater stress. Under an excessive load, these outer fibers are stretched until they break, just as they are in a green stick if you bend it to the breaking point. The inner fibers, unable to support the increasing load, break soon after. In this way, the curve of the stem creates a weak point that leads to failure of the knot in an overloaded rope.

8. A gradual curve in the stem is sufficient to weaken a knot.

Few knots, in fact, are severely curved at the stem. But observation of knots such as a Bowline, which are known to break outside the knotted portion, shows that even a slight curve reduces their strength sufficiently to cause them to break at the entry point.

9. A Bowline Breaks where a Full Load falls on the First Curve

The location of the breaking point of a Bowline depends finally on the effect of a full load on the first curve. At the point in a Bowline where the standing part merges with the stem and enters the knotted part, virtually a full load falls on fewer than all the fibers of the rope. More severe curves may appear further inside the knot, but because contact with other segments reduces the load everywhere else within the nub, a full load and uneven distribution of load occur simultaneously only at the entry point. A Bowline usually breaks at the first curve because at that point only, virtually a full load falls on a segment weakened by a curve. Most other knots break at the same point.

Part 2. The Breaking Point of Core-and-Wrap Knots

In agreement with Ashley and Day, Stanley Barnes comments that in the case of most knots "it was always at the knot that a break occurred" (15). He notes the exception of the

Blood Knot, which has a very different structure from the Bowline and most other knots. His personal experience as an angler, confirmed by bench experiments, convinced him that a Blood Knot does not break just outside the knot but at the point where the core "forms its first sharp coil ... deep inside the knot" (43, 50–51). This is at "the centre of the knot," the place he marks with an "x" in several drawings of this unusual knot.

As with the statements by Vines and Hudson (1992) and by Kennedy (1864), Barnes's comment that the breaking point of a Blood Knot is at the "first sharp coil" must be modified to say that it is at the first curve, whether severe or gradual.

Identification of The Blood Knot

Barnes identifies this Blood Knot as the "three-fold, outward coil, Chaytor type" (124). This is the knot that Day calls a Barrel Knot (110), and it is similar to the one that Ashley calls a Barrel Knot (#295). Although this or a similar knot is illustrated in several knot books, both its structure and its performance have been overlooked; neither Ashley nor Day made a special note of its unusual structure, and apparently they did not test it. It is neglected despite the fact that it is remarkably secure, stable, and strong and the fact that it continues to be used by anglers for these qualities as well as the fact that its slender profile creates little wake in the water. The Double Fisherman's Knot, which has a similar structure, works in a similar way, and exhibits many of the outstanding properties of the Blood Knot, is part of the usual knot-tyers repertory and the preferred bend for many high-performance uses. For these reasons, the extended comments that Barnes made about the Blood Knot are particularly useful.



The Blood Knot, tied loosely

The Relevance of Barnes's Studies to Knots Tied in Rope

Most to the point here is Barnes' statement that in the Blood Knot he tested, "it is always inside the knot that the break occurs," always at the center of the knot. (42, 24)

The knots that Barnes tested were tied in the thin, smooth, and slippery filaments of nylon or gut that are used by anglers to attach a line to a hook. "Paradox breaks," the term he uses for breaks at some other place than the usual, occurred most often in gut and are caused by uneven thickness of the material or damage during tying the knot (45–46), not by a weakness of the knot itself. For this reason, these paradox breaks at unanticipated places are not relevant to analysis of knots tied in the ideally uniform rope. The results of Barnes' tests on sound nylon filaments, however, jibe with this analysis of knots tied in ordinary rope, and I find nothing in his work to contradict the conclusions here about the breaking point of knots of either the Blood Knot type or the Bowline type.

While the Blood Knot is an exception to the rule that knots break at the entry point, it is not an anomaly and it does not contradict the general rule. But to account for its behavior, we need to broaden the concept of the breaking point suggested by Day and Ashley.

The breaking point of a Blood Knot is to be explained by its unusual core-and-wrap structure. The *core* is the central segment of rope that runs from the place where the standing part enters the nub to the center of the knot. (The core in this type of knot is the segment that Barnes (47, 83) calls the "standing part extension" or "continued part.") Encircling this core is a series of *wraps* that squeeze it tight.

Most relevant to the breaking point of a Blood Knot is that core-and-wrap knots are also *straight-line* knots. As the standing part enters the nub, it is kept in line with the main longitudinal pull of the rope. For this reason, it does not curve as it enters the knot but passes deep into the nub in virtually a straight line. The core curves only when it reaches the center. This curve in the core weakens the knot at its center in the same way that the first curve weakens a Bowline at the entry point.

A Blood Knot breaks well within the interior of the nub, then, because the standing part does not curve at the entry point but further inside the knot. It appears that this principle applies also to hitches. Warner noted that "An early test of fastenings to a standard pin showed that ordinary hitches, with a sliding knot on the standing part, broke where the standing part met the pin." ("Behaviour" 193). It seems likely that other knots built with the core-and-wrap structure, such as a Double Fisherman's Knot, would also break deep inside the knot.

Where a Knot Breaks: The General Rule

The general rule, which pertains to all knots tied in natural-fiber rope, is that a break occurs where the section of rope that enters the knot begins to curve, that is, at the first curve in the most heavily-loaded segment of rope. The reason for this is that the curve redistributes the load unevenly so that some of the fibers are weakened by being over-stretched. In a Bowline and most other knots, that first curve is located at the entry point, just outside the nub. In a Double Fisherman's Knot, the first curve of the most heavily-loaded segment is at the center of the knot. For other core-and-wrap knots, it is also well inside the nub.

Curves in other parts of a knot, however abrupt or severe they may be, do not affect the place where it breaks.

If this analysis provides some lines of thinking that help us understand the breaking point of knots and suggests paths for the further study, it will have fulfilled its purpose. This study leaves us with the question that everybody seems to ask, "How strong is this knot?" That is the subject of the next study, titled "Knot Strength."