PREVENTING FAILURE IN MOORING SYSTEMS

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ABSTRACT

Studies of failures of mooring systems in Hurricanes Gloria (1987) and Bob (1992) made it painfully obvious that very little is known about the forces on a mooring caused by a sailboat subjected to wind and waves. Almost no quantitative data exist. Our studies have led us to some hypotheses and questions which we are addressing by a program of field measurements and laboratory tests. Failure of rodes at or near a chock in roughly half the damaged boats suggested internal and external abrasion is important. After Hurricane Gloria, we recommended polyester over nylon, because of the superior abrasion resistance of (wet) polyester (see the companion paper [2]). Because this recommendation was controversial and because many practitioners felt the compliance of nylon was a necessary element of a mooring system, we had DeSimone carry out additional comparisons between abrasion resistance of nylon and polyester. Also, DeSimone suggested joining nylon and polyester so that existing nylon rodes could be used with an extension of polyester passing from just out board of the chock to the cleat. Doelling proposed a method of joining nylon and polyester which DeCouto has been testing to assure it is as strong in tension as the nylon component while also having superior abrasion resistance. Experimental data on the issues above will be presented.

The advent of new anchoring systems means we cannot continue to use old rules of thumb that have been developed for sizing a mushroom or concrete block to hold a boat of a certain size. We (Zala and Doelling) therefore have developed a system for measuring actual forces on a mooring caused by a sailboat while simultaneously measuring some significant environmental variables. Preliminary data give good insights into the range of forces involved and the system dynamics. A brief experiment with a very old idea, the riding sail, suggests it is a very effective way to reduce forces on a mooring rode.

The measurement system, its software, and typical results are presented.

INTRODUCTION

Following Hurricane Bob, one of the authors (Doelling) wrote a letter to a boat yard operator [1] with some recommendations concerning ways to reduce damage in future hurricanes. This letter became broadly disseminated. In the letter, we recommended using polyester instead of nylon for rodes because of polyester's superior abrasion resistance when wet (surely its condition in major storms). We have retested that hypothesis and still feel it is appropriate [2, 3]. Since many persons objected to losing the compliance of the nylon, we designed and tested a simple method of joining an (existing) nylon rode with a short polyester line, so that one could enjoy the compliance of a nylon rode and the abrasion resistance of polyester at the chock. In addition we found almost no useful, quantitative, measured data concerning the magnitude of forces during a storm and no insightful analyses of motions of a boat at a mooring. We therefore undertook development of an automated system to measure the forces and motion.

ABRASION TESTS

DeSimone [3] provides a very good summary of the issues involved in failures of 3-strand lines subject to alternating stresses, reviews important relevant literature, and provides a very useful, qualitative discussion of boat motions, mooring systems, and chocks. We summarize his tests and the results here.

The test apparatus and forces were selected to test the lines at realistic loads, but subject to the constraint that the tests had to be completed in a reasonable amount of time. About 120 hours were devoted to sample preparation time and about 150 hours of testing time on an Instron servo-hydraulic testing machine. Tests encompassed 3-strand, 1/2 inch ropes from two different manufacturers: continuous filament nylon rope from Wall Ropes and New England Ropes, and polyester ropes, both continuous filament and "staple" fiber rope, from New England Ropes.

The abrasion device is designed to keep the load on the Instron grips vertical while presenting a stationary abrasive radius to the rope samples. A view of the abrasion device from the side and front of the Instron machine is shown in Fig. 1. The 1" diameter pins at 1 and 3 are polished copper, and the bar at 2 is copper that has been "scored" lightly. The abrading pins are rough enough so that the tests end in a reasonable time, but not so rough that the samples failed before 100 cycles at medium load.

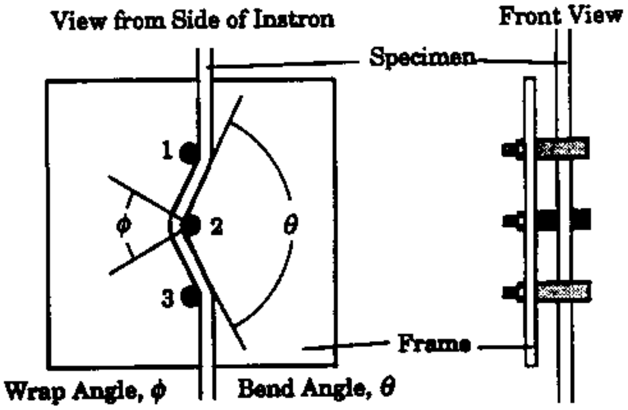

Figure 1. Abrasion device

Initial determination of the abrasiveness of the scoring on pin 2 was highly experimental. First the pin was knurled lightly, and when a representative sample failed too soon, the knurl was filed down on the lathe, and the test repeated. After several cycles the "knurl" looked more like a light score from a razor blade, forming a criss-crossing helix pattern. This condition created an abrasive environment that caused failure in a medium-loaded, average sample in under 750 cycles.

The objective of these tests was to determine the relative abrasion resistance of 4 different ropes in simulated hurricane conditions. Tests were conducted by specifying an input load on the Instron machine and noting the number of cycles to a failure of a single strand. Tests results are shown in Fig. 2.

To appear as a point on this graph at least 5 tests have been conducted per rope, per load level. A statistical mean and standard deviation were calculated to determine whether more tests were required per point. The spread of the data per point (the standard deviation) scaled upwards as a function of increasing load, remaining a constant percentage of the mean load.

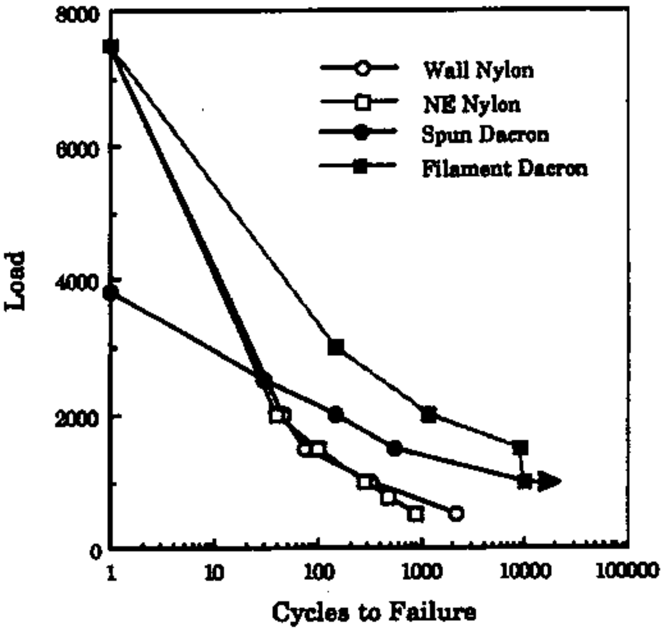

Figure 2. Results of abrasion resistance tests on 4 different ropes

For the polyester ropes, there seemed to be some threshold under which very little, if any, abrasion took place. For example, for the "spun" polyester ropes, 1,000 pound tests were stopped at 1,000 and 10,000 cycles, and the ropes compared. No significant abrasion could be seen. The filament polyester showed even better resistance to low load abrasion. DeSimone concludes, "An arrangement which could prove very beneficial would be a larger nylon mooring line that is spliced into 2 smaller polyester lines equipped with chafing gear. The energy absorption and stretch of the nylon, combined with the abrasion resistance of the polyester and the neoprene, combine to form a mooring arrangement that would be tough to break, in the worst conditions."

TESTS OF JOINED NYLON AND POLYESTER LINES

DeSimone's ideas of joining nylon and polyester lines to combine the compliance of nylon in the mooring system with the abrasion resistance of a polyester line and the smaller motion in the chock and on deck seems to be an excellent one, but the idea of splicing two polyester lines into a nylon one seemed undesirable. Instead we propose adding a short polyester line with an eye splice at one end to connect to a nylon eye on a mooring pennant. We connect them together as shown in Fig. 3. The polyester line is passed through the chock and to the cleat of the vessel to be moored.

The resulting system will have slightly more compliance than the original mooring system and would have the superior abrasion resistance to guard against failure at the chock.

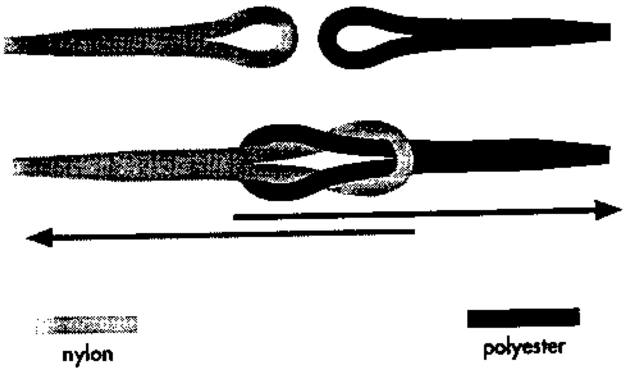

Figure 3. Eye-to-eye joint

Thus we combine the advantages of both kinds of line. A bridle could be made by using two polyester lines in the nylon eye, but we did not test such a configuration.

We did test to see if the eye-to-eye joint weakened the system. Testing was extremely difficult, primarily because it was difficult to control the system at very high strain levels and because the eye-to-eye splice proved to be very strong indeed.

The samples that were used for testing were comprised of two identical pieces, one spliced out of 1/2" polyester, and one out of 1/2" nylon. Each piece has an eye-splice at each end, consisting of at least 6 tucks (tests using 4 or 5 tucks routinely failed due to the splices pulling out where the sample was attached to the Instron machine).

The pieces of polyester and nylon are joined together using the larger loop, as shown in Fig. 3. After soaking in water until fully wet, the entire sample is mounted on the Instron machine via the smaller eyes, using steel pins.

The samples were tested by cycling between 10 and 50 percent of breaking strength, as we are primarily conducting a fatigue test. The manufacturer's breaking strength for the line is 7500 pounds force (lbf.) for both the nylon and polyester, thus the above percentages correspond to a minimum load of 750 lbf. and a maximum load of 3750 lbf. with a sinusoidal variation between these limits. The period was about 6 seconds.

Soaked fully before being installed on the machine, the line was kept wet with an apparatus that drips water on it continuously. The test was stopped when any strand failed, and the number of cycles was recorded.

Out of 11 samples, only 3 have actually failed at the nylon/polyester joint. Two of these samples were tested at a doubled frequency and the other sample was discovered to not be wet enough. Of the other 8 samples, 4 failed when the splice holding the nylon to the bottom pin pulled out, 3 failed due to strand failure near the bottom (nylon) pin. One test was stopped before failure.

The two samples tested at about 3 seconds per cycle reveal that frequency is an important factor. Both failed quickly at the joint owing to heating which weakens the nylon.

The third sample that failed at the knot also was hotter than normal, due to lack of adequate water; the water played a key role in cooling for all of the samples.

It is known that water also has an effect on the strength and abrasion resistance of the nylon, but hardly any effect on the polyester. Thus the water should accelerate the abrasion of the nylon upon the polyester; however, the water also helps to slow the abrasion of the nylon by cooling it. All the samples shared a common pattern of abrasion. Where the nylon came into contact with itself in the knot, it abraded itself.

The polyester elongated so little in comparison to the nylon that it was as if only the nylon were rubbing around stationary polyester in the knot, as the nylon extended. Indeed, the polyester hardly seemed to suffer any damage from the test, except for some polishing where it passed around the steel pin connecting to the Instron machine.

After a long time in a test, the knot pulled so tight, and the nylon stretched so much that there was hardly any incremental movement by the nylon within the knot, and abrasion slowed down in the knot.

Thus the tests while not totally conclusive suggest that such a joint between nylon and polyester is extremely strong, and suitable for a mooring line.

Finally, note that these tests were carried out with 0.5" diameter line. Any sort of decent mooring line will be of a large enough diameter that it should not experience forces of the same magnitude in relation to its breaking strength. Thus a large mooring line would experience less extension of nylon through the knot, and thus less abrasion would occur. All in all, the tests suggest that this seemingly reliable connection is, in fact, reliable.

A SYSTEM FOR MEASURING FORCES ON MOORINGS

Modern sailboat instrumentation systems are relatively easy to interface to a personal computer. Each instrument typically has its own small microprocessor, allowing the various instruments to communicate with one another via a serial "computer bus." Our experimental system uses Raytheon's Autohelm ST-50 instruments. Taken together, wind speed, wind direction with respect to the boat, compass heading, depth, and GPS or LORAN define the environment in which the boat is located. These instruments are all connected to a serial port (COM2) on a personal computer.

A load cell measures the static and dynamic tension in the mooring line. We use a DGH-1000 analog to digital converter and power supply. This unit provides a well-regulated 10-volt power supply for the strain gauges in the load cell. The DGH box, when interrogated, provides a 12-bit digital representation of the voltage output of the load cell, which is then converted to load (in pounds). This system is operated from another serial port in the personal computer (COM1). This system was tested on the boat and was found to provide useful environmental and mooring force data. The obvious limitation was that an operator had to be on the sailboat to turn the system on and off. We added a cellular telephone, not for remote data acquisition, but simply to turn the system on and off. As currently designed, the system is activated by a call to the cellular telephone, which turns on all of the instruments and the personal computer. The computer runs for a preprogrammed length of time (currently 20 minutes) and then shuts itself and all instruments off.

The system is under the control of the harbormaster, who simply calls the cellular telephone and turns the system on whenever he feels the weather conditions are interesting. Software bugs limited the amount of data we acquired last fall, and major boat maladies prevented us from getting data in the early spring. However, some representative results are shown in Fig. 4 (at end of paper), which plots load and relative wind direction over a time period of about 270 seconds (4.5 minutes).

During this experiment the wind was varying between 12 and 22 knots with an average value of almost 18 knots. The first thing that becomes obvious is that there is no simple relation between load and wind direction. The period as the boat sails back and forth on its mooring is approximately 2.0-2.5 minutes. Notice the very significant drop in load just before the boat changes directions at either end of its excursion. Observant sailors will note that boats sometimes literally sail forward on their moorings before being pulled to the opposite side. These data very clearly demonstrate this phenomenon. The mean load was about 320 pounds for this sample. Another data set showed a mean load of about 650 pounds for an average wind of 21.5 knots.

Another way of describing the load history is a histogram, which shows the number of occurrences of load in successive 25-pound load intervals. The data in Fig. 5 (at end of paper) indicate the range of data we have to deal with in order to describe the environment and the response. Longer data sets are needed to get better insight.

Finally, we designed a small riding sail, which was mounted on the backstay and pulled tightly toward the bow. We are not 100 percent satisfied with the data, but our observations on board were consistent with the data we obtained. Specifically, the boat stood directly into the wind with only a 10- or 20-degree variation in compass heading, which was comparable to the 10- or 20-degree change in wind direction. In other words, tacking back and forth on the mooring was very much reduced. A concomitant result was that the tension was very substantially reduced. The rode tension was a factor of 3 or a factor of 10 lower at the same wind speed. Confirmation of this result will be discussed at the presentation of this paper.

Finally, it should be recognized that safety of a boat on a mooring in a storm depends on four elements of the mooring system. The first is the strength and design of the deck hardware (cleats, chocks, etc.); second is the strength and abrasion resistance of the mooring lines (rodes); third is the integrity of chains, shackles leading to the anchoring system; and fourth is the resistance of the anchoring system to being pulled out. All of these elements should be of balanced design so they last "one hundred years and a day," like the Deacon's One-Hoss Shay [4]--and ride out a 100-year hurricane.

ACKNOWLEDGMENTS

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[4] Oliver Wendell Holmes, "The Deacon's Masterpiece or the Wonderful 'One-Hoss Shay'" in *The Autocrat of the Breakfast Table*, Chapter 11, Houghton-Mifflin, Boston, 1899.

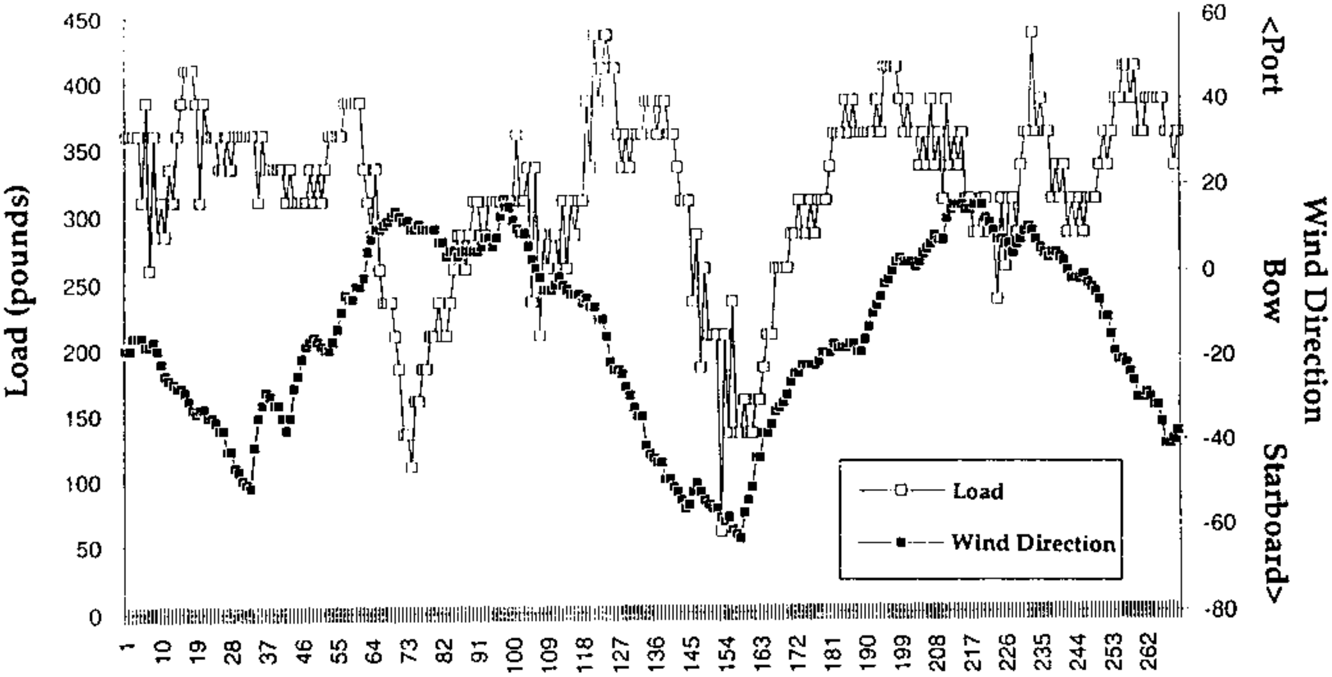

Figure 4. Load and relative wind direction in period of ~270 seconds

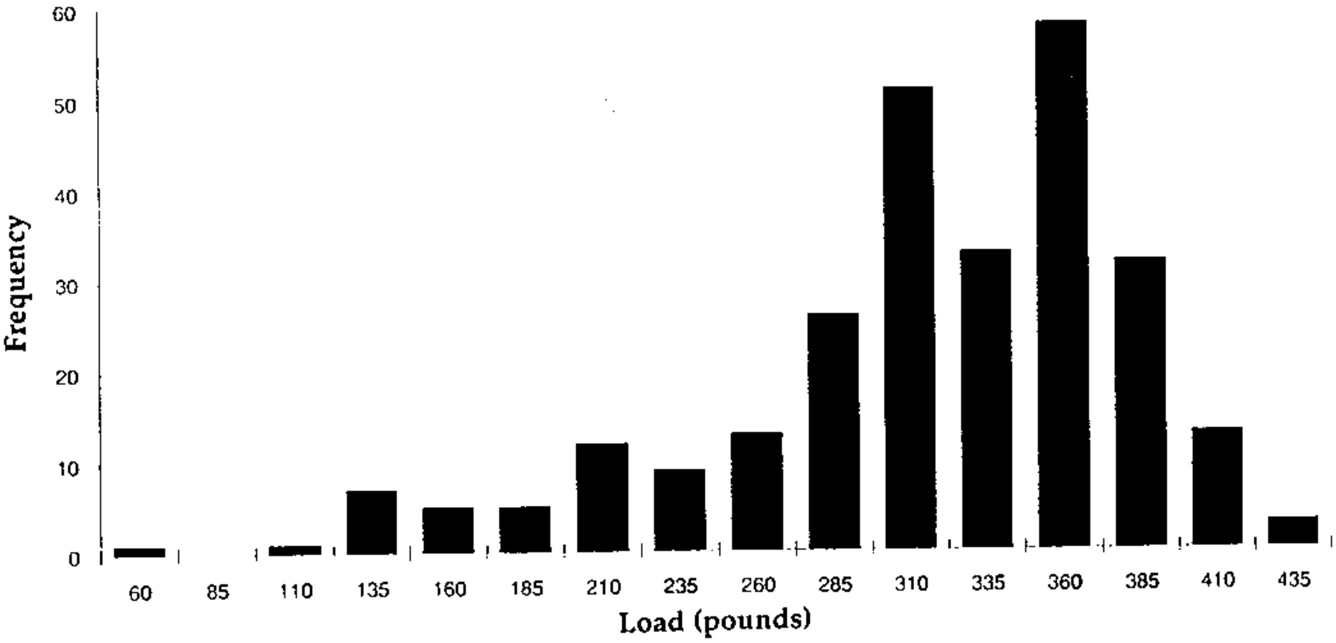

Figure 5. Load histogram

THE DEACON'S MASTERPIECE:

OR THE WONDERFUL "ONE-HOSS-SHAY."

A LOGICAL STORY.

Have you heard of the wonderful one-hoss-shay,
That was built in such a logical way
It ran a hundred years to a day,
And then, of a sudden, it -- ah but stay,
I'll tell you what happened without delay,
Scaring the parson into fits,
Frightening people out of their wits, --
Have you ever heard of that, I say?

Seventeen hundred and fifty-five,
Georgius Secundus was then alive, --
Snuffy old drone from the German hive;
That was the year when Lisbon-town
Saw the earth open and gulp her down,
And Braddock's army was done so brown,
Left without a scalp to its crown.
It was on the terrible earthquake-day
That the Deacon finished the one-hoss shay.

Now in building of chaises, I tell you what,
There is always *somewhere* a weakest spot, --
In hub, tire, fellow, in spring or thill,
In panel, or crossbar, or floor, or sill,
In screw, bolt, throughbrace, -- lurking still,
Find it somewhere you must and will, --
Above or below, or within or without, --
And that's the reason, beyond a doubt,
A chaise *breaks down,* but does n't *wear out.*

But the Deacon swore (as Deacons do,
With an "I dew vum," or an "I tell *yeou,*")
He would build one shay to beat the taown
'n' the keounty 'n' all the kentry raoun';
It should be so built that it *couldn'* break daown,
--"Fur," said the Deacon, "'t's mighty plain
That the weakes' place mus' stan' the strain;
'n' the way t' fix it, uz I maintain,
Is only jest
T' make that place uz strong uz the rest."

So the Deacon inquired of the village folk
Where he could find the strongest oak,
That could n't be split nor bent nor broke, --
That was for spokes and floor and sills;
He sent for lancewood to make the thills;
The crossbars were ash, from the straightest trees,
The panels of white-wood, that cuts like cheese,
But lasts like iron for things like these;
The hubs of logs from the "Settler's ellum,"--
Last of its timber, -- they could n't sell 'em,
Never an axe has seen their chips,
And the wedges flew from between their lips,
Their blunt ends frizzled like celery-tips;
Step and prop-iron, bolt and screw,
Spring, tire, axle, and linchpin too,
Steel of the finest, bright and blue;
Thoroughbrace bison-skin, thick and wide;
Boot, top, dasher, from tough old hide
Found in the pit when the tanner died.
That was the way he "put her through." --
"There!" said the Deacon, "now she'll dew."

Do! I tell you, I rather guess
She was a wonder, and nothing less!
Colts grew horses, beards turned gray,
Deacon and deaconess dropped away,
Children and grand-children -- where were they?
But there stood the stout old one-hoss-shay
As fresh as on Lisbon-earthquake-day!

EIGHTEEN HUNDRED; -- it came and found
The Deacon's Masterpiece strong and sound,
Eighteen hundred increased by ten; --
"Hahnsum kerridge" they called it then.
Eighteen hundred and twenty came; --
Running as usual; much the same.
Thirty and forty at last arrive,
And then came fifty, and FIFTY-FIVE.

Little of all we value here
Wakes on the morn of its hundredth year
Without both feeling and looking queer.
In fact, there's nothing that keeps its youth,
So far as I know, but a tree and truth.
(This is a moral that runs at large;
Take it. -- You're welcome. -- No extra charge.)

FIRST OF NOVEMBER, -- the Earthquake-day. --
There are traces of age in the one-hoss-shay,
A general flavor of mild decay,
But nothing local, as one may say.
There could n't be, -- for the Deacon's art
Had made it so like in every part
That there was n't a chance for one to start.
For the wheels were just as strong as the thills,
And the floor was just as strong as the sills,
And the panels just as strong as the floor,
And the whippletree neither less nor more,
And the back-crossbar as strong as the fore,
And spring and axle and hub *encore*.
And yet, *as a whole*, it is past a doubt
In another hour it will be *worn out*!

First of November, 'Fifty-five!
This morning the parson takes a drive.
Now, small boys, get out of the way!
Here comes the wonderful one-hoss shay,
Drawn by a rat-tailed, ewe-necked bay.
"Huddup!" said the parson. -- Off went they.

The parson was working on his Sunday's text, --
Had got to *fifthly*, and stopped perplexed
At what the -- Moses -- was coming next.
All at once the horse stood still,
Close by the meet'n-house on the hill.
-- First a shiver, and then a thrill,
Then something decidedly like a spill, --
And the parson was sitting upon a rock,
At half-past nine by the meet'n'-house clock, --
Just the hour of the Earthquake shock!
-- What do you think the parson found,
When he got up and stared around?

The poor old chaise in a heap or mound,
As if it had been to the mill and ground.
You see, of course, if you're not a dunce,
How it went to pieces all at once, --
All at once, and nothing first, --
Just as bubbles do when they burst.

End of the wonderful one-hoss shay.
Logic is logic. That's all I say.

Oliver Wendell Holmes, "The Deacon's Masterpiece or the Wonderful 'One-Hoss Shay' " in *The Autocrat of the Breakfast Table,* Chapter 11, Houghton-Mifflin, Boston, 1899.