Presented to the International Technical Rescue Symposium, November 2001

Presented by: Chuck Weber, PMI Quality Manager

Abstract

This paper presents the results of 162 individual drop tests performed at PMI and slow-pull elongation data for five different life safety ropes. It was confirmed from this line of testing that the static and low stretch ropes exhibit a trend of increasing impact forces generated as the length of drop and rope are increased for any given fall factor. While this trend may be considered minimal at FF 0.25, the trend of increasing forces for FF 0.5 and greater was in fact significant.

While this report may prove useful as educational and reference material for professional rope users, it is NOT intended to be a "user's guide" at this point in time. Rather, the purpose of this report is primarily to report these initial findings of the larger effort to more accurately model the performance and limitations of life safety ropes.

Background

Last year's ITRS attendees should recall an interesting report on Fall Factors presented by Jim Kovach. The test data from that report suggested that static rescue ropes, unlike dynamic climbing ropes, did not always follow the universally accepted model of Fall Factors at high load and fall factors. It was observed through testing that measured impact forces for any given Fall Factor would in fact increase versus stay the same as the length of drop/rope was increased. This was especially noticeable in Fall Factors of 0.5 to 2.0.

This new report is our effort to validate the prior testing and further this line of study. We feel this effort is very important for all of climbing and rescue communities so that we can all know for certain that we are in fact applying the concept of Fall Factors appropriately for all types of life safety ropes: static, low-stretch, and dynamic.

Definitions

- **Low Stretch Rope.** A rope with an elongation greater than 6% and less than 10% at 10% of is minimum breaking strength. (ref. CI 1801-98)
- **Static Rope.** A rope with a maximum elongation of 6% at 10% of its minimum breaking strength. (ref. CI 1801-98)
- **Dynamic mountaineering rope.** Rope, which is capable of arresting the free fall of a person engaged in mountaineering or climbing with a limited impact force. (EN 892:97)
- **Fall Factor.** A measure of fall severity calculated by dividing the distance fallen by the length of rope used to arrest the fall. (NFPA 1983:2001)

Test rig and basic drop testing sequence and setups

PMI's in-house drop tower was used to perform all the drop tests mentioned in this report. Each test rope was tied to a rigid two-chain anchor atop the 30-ft. tall drop tower and the other end was tied to a steel basket, a.k.a. the "test weight." Follow-through Figure 8 knots were used for both rope end connections. All the drop tests were performed in an identical manner.

The tower was designed in part to meet the specifications of various EN standards for rope testing. The basket had a 10,000 # load cell connected via cable to a portable handheld meter, with sampling rate of 1000 times per second. The calibration of this testing setup was verified by 3rd party services. The rig is also known to produce accurate results when compared to official CE laboratory reports for the same product. An especially useful design aspect was custom fit steel plates that can be added as needed to adjust the weight between an "empty basket" weight of 155# and a "full basket" weight of 500#.

The basket was easily lowered and raised to any position along its vertical path by a mechanical pick-up device and electric winch. The basket traveled freely between two steel I-beams, which were set in the concrete floor below and affixed to the roof framework of the building. There was no appreciable drag in this system. A quick-release mechanism efficiently released the test weight for free fall at the desired moment.

The test weight was applied to the knotted rope of every test for ~1 min. before the drop test was performed. During that time the exact rope length was measured to ensure that it was +/- 2 inches of the desired total length. Often the rope length had to be adjusted 2 or 3 times to ensure the proper length was achieved. We felt it was important for every test rope to be preloaded with the test weight prior to the drop to minimize the knots' effect on the resulting data and be as consistent as possible. Knot lengths were kept to 8" or less.

162 individual drop tests were performed on 5 different rope diameters and types. Both 176 and 500# test weights were used in Fall Factors of 0.25, 0.5, 1.0, and 2.0. Ropes tested were:

- PMI Classic EZ-Bend, 12.5 & 11mm, Static Rope (also some limited 10mm)
- PMI Impact, 13mm, Low Stretch Rope
- Blue Water II+Plus, Low Stretch Rope
- PMI 10.6mm Dynamic Rope

The basic progression and focus of this study was to start with a single rope, test weight, and FF; then perform a series of drop tests of different rope lengths while maintaining the desired FF. To make the test data as consistent as possible each rope was cut from long continuous lengths and each drop test was performed on a brand new and unused section of rope.

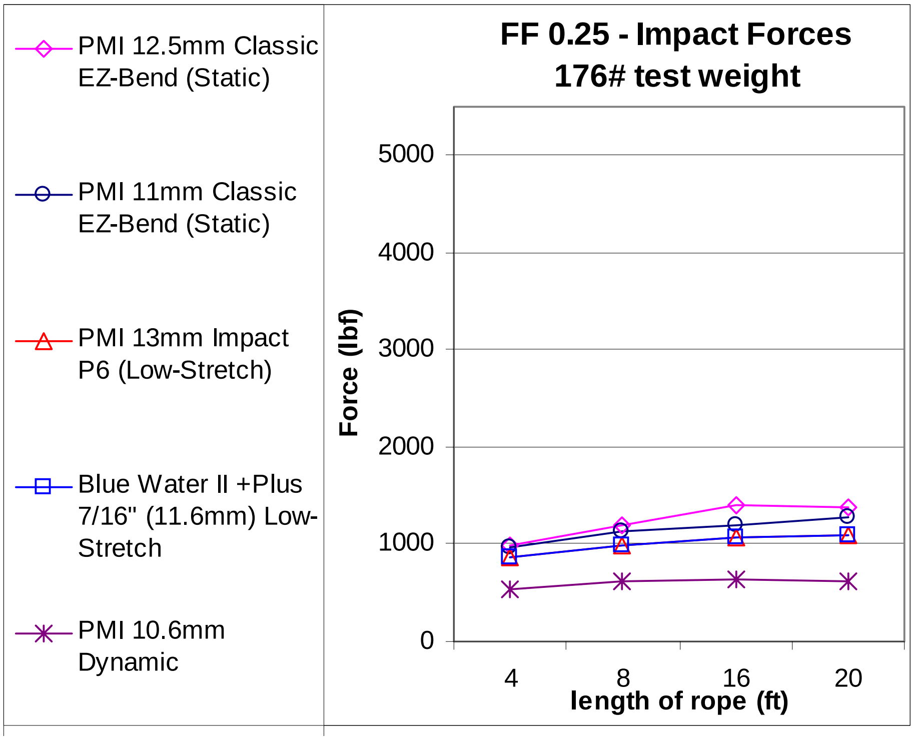
During each drop test the following were recorded:

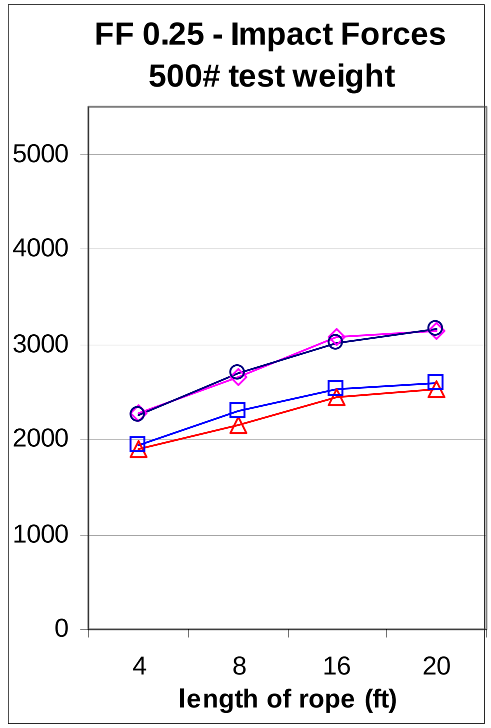
- pre and post test resting positions (holding test weight)
- Peak Impact Force (measured during drop)
- maximum elongation (on selected longer rope lengths only)

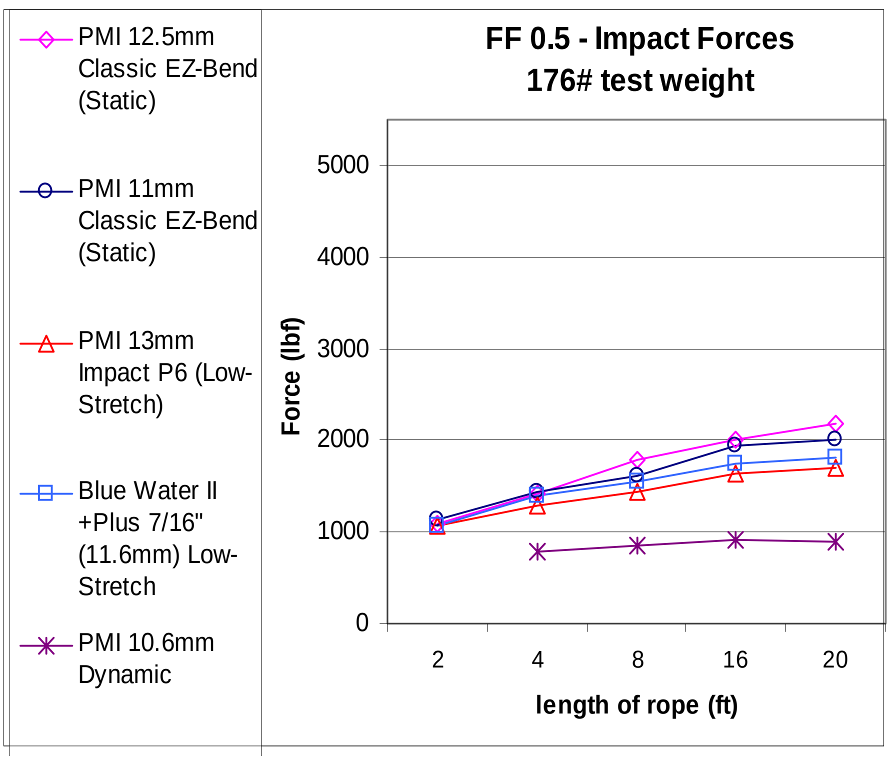
The next two pages of graphs represent the majority of the data.

Impact Forces for all ropes grouped by FF

Note: 1) graphs all scaled 0 to 5500 #, except for the last two 500# test weight graphs
2) tests with total rope failure not shown here

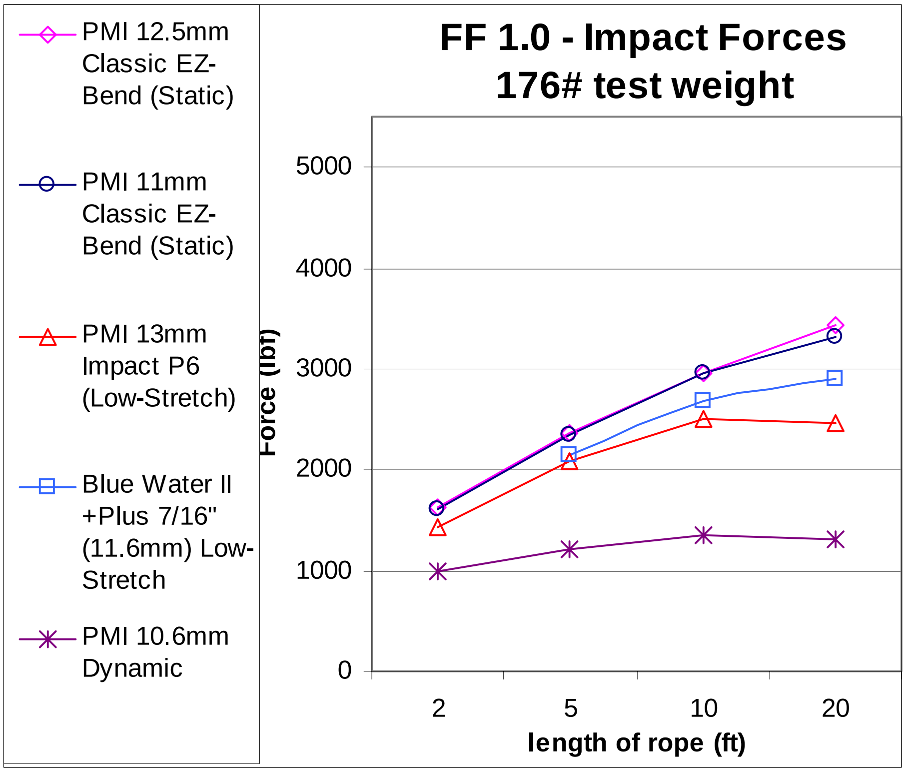


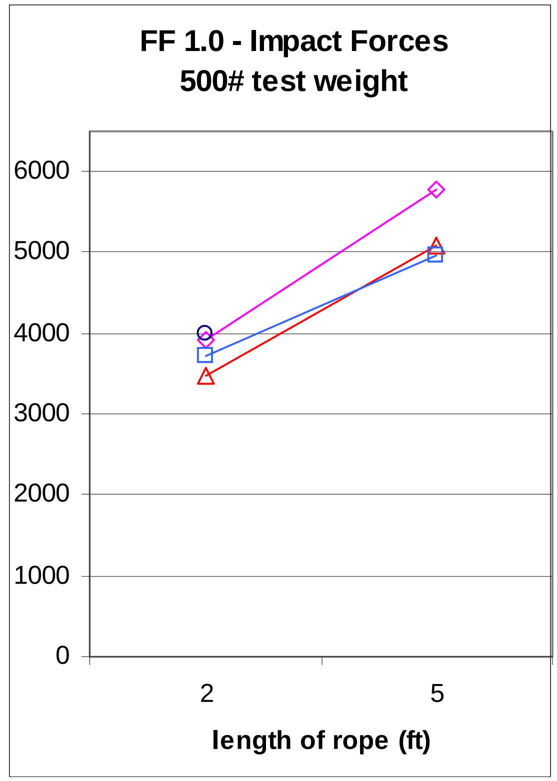


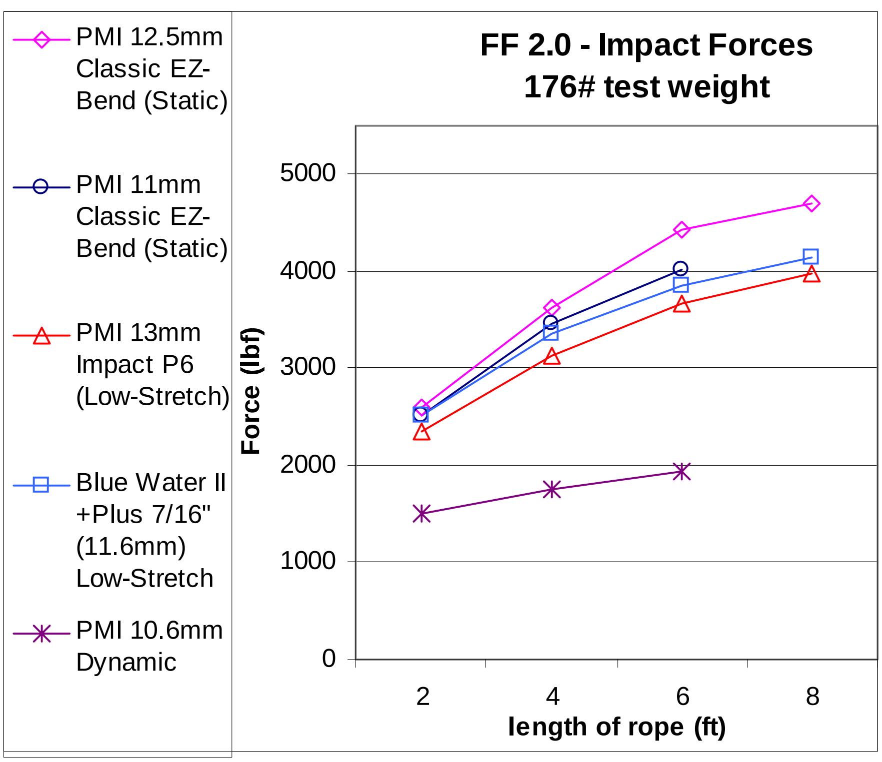


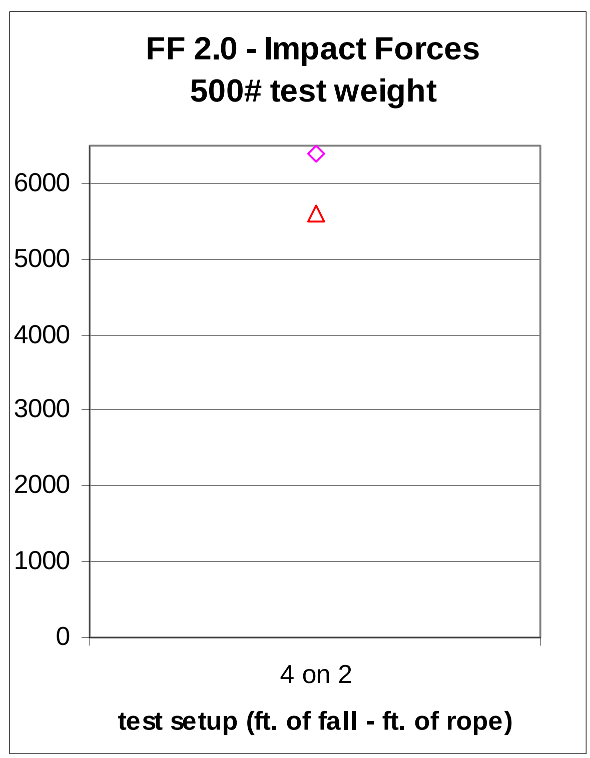
Impact Forces for all ropes grouped by FF

Note: 1) graphs all scaled 0 to 5500 #, except for the last two 500# test weight graphs
2) tests with total rope failure not shown here







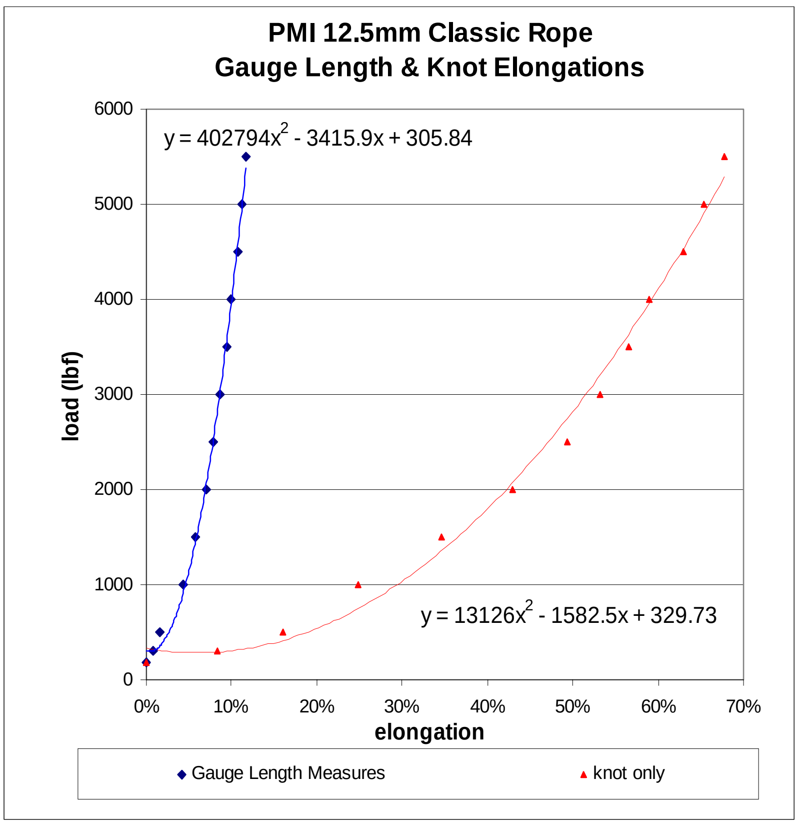


Slow-pull Tests

Most users would certainly agree that a knotted rope elongates when loaded more than the rope itself does for the same load. To better quantify that fact, we performed slow pull tests to measure both the elongation of a) the knotted end of a rope and b) a gauge length marked on the straight section of loaded rope. All the test ropes were tied into about 3 ft. test lengths with a follow-through figure 8 knot at both ends and gauge mark (200-250mm) was applied under 10# dead weight. Then dead weights of 176, 300, and 500# were applied and the measures recorded. The remainder of the elongation testing was performed by slow-pull testing on PMI's Dillon Tensile Tester equipped with a 10,000 # Dynamometer (50# increment scale).

The following graph is an example to show the typical difference between the elongation of the rope and a knotted end of the rope under the same forces. All other ropes tested exhibited the same basic result. The best-fit 2nd order polynomial equations shown were used in the rope+knot slow pull model used (see explanation and data table later in report) to estimate total rope length for a given impact force.

The next two pages give the actual data tables and show the resulting graphs for all ropes tested.



Note: Equations shown are flawed at the very low end; x=0 gives inaccurate loads, but the formulas are reasonably accurate for the purpose of an elongation model.

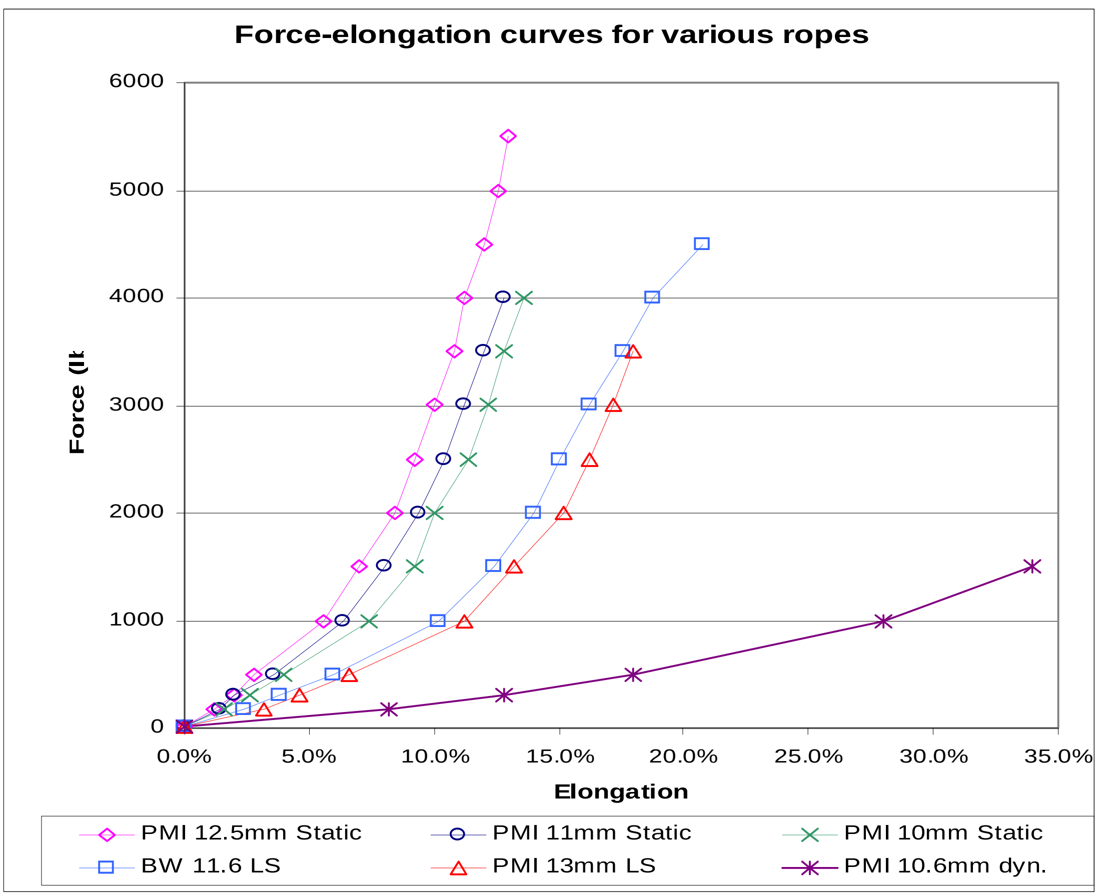
Rope Gauge Length Elongation Measures

Force (lbf)	Static Ropes: PMI 12.5mm elong.	Modulus	PMI 11mm elong.	Modulus	PMI 10mm elong.	Modulus	Low-Stretch Ropes: PMI 13mm elong.	Modulus	BW 11.6 elong.	Modulus	Dynamic Rope: PMI 10.6mm elong.	Modulus
10	0.0%	n/a	0.0%	n/a	0.0%	n/a	0.0%	n/a	0.0%	n/a	0.0%	n/a
176	1.2%	14667	1.4%	12571	1.6%	11000	3.2%	5500	2.4%	7333	8.2%	2146
300	2.0%	15000	2.0%	15000	2.6%	11538	4.6%	6522	3.8%	7895	12.8%	2344
500	2.8%	17857	3.6%	13889	4.0%	12500	6.6%	7576	6.0%	8333	18.0%	2778
1000	5.6%	17857	6.4%	15625	7.4%	13514	11.2%	8929	10.2%	9804	28.0%	3571
1500	7.0%	21429	8.0%	18750	9.2%	16304	13.2%	11364	12.4%	12097	34.0%	4412
2000	8.4%	23810	9.4%	21277	10.0%	20000	15.2%	13158	14.0%	14286		
2500	9.2%	27174	10.4%	24038	11.4%	21930	16.2%	15432	15.0%	16667		
3000	10.0%	30000	11.2%	26786	12.2%	24590	17.2%	17442	16.2%	18519		
3500	10.8%	32407	12.0%	29167	12.8%	27344	18.0%	19444	17.6%	19886		
4000	11.2%	35714	12.8%	31250	13.6%	29412			18.8%	21277		
4500	12.0%	37500							20.8%	21635		
5000	12.6%	39683										
5500	13.0%	42308										
6000												
Failure	*6800*		*5200*		*4500*		*n/a*		*4900*		*n/a*	

Note: 10-500# measures made with dead weights, then same sect. of rope transferred to Dillon 10K# Tensile Tester for 1000# and up measures

Modulus Details

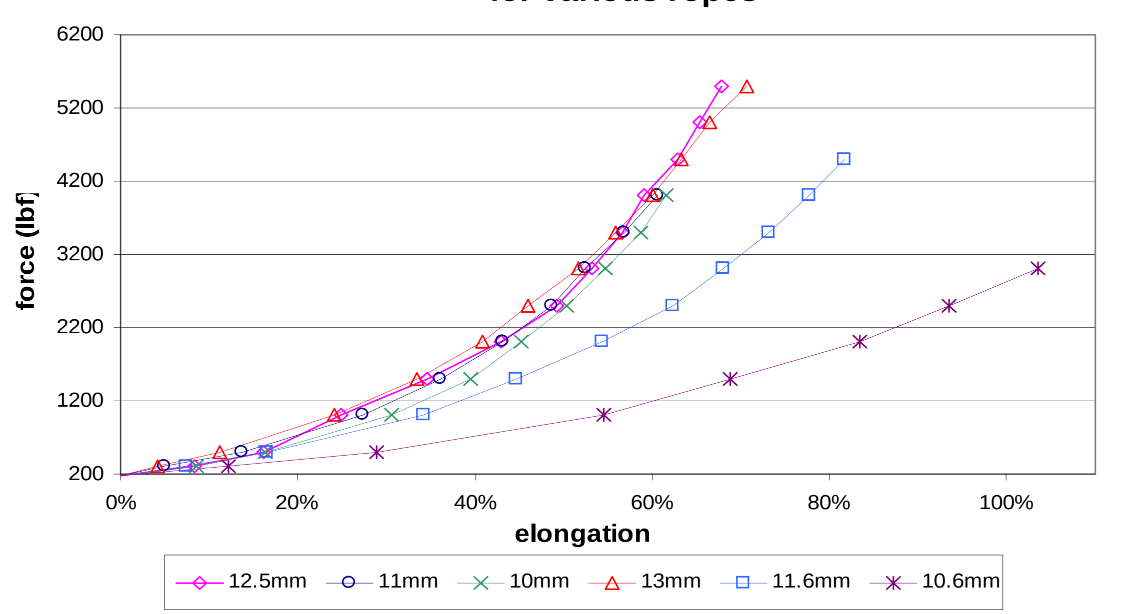
	PMI 12.5mm	PMI 11mm	PMI 10mm	PMI 13mm	BW 11.6	PMI 10.6mm
Avg.:	27339	20835	18813	11707	14339	3050
High:	42308	31250	29412	19444	21635	4412
Low:	14667	12571	11000	5500	7333	2146



	Rope Knot Elongation Measures (mm) and Elongations											
	Static Ropes						**Low Stretch Ropes**				**Dynamic Rope**	
Load	PMI 12.5mm		PMI 11mm		PMI 10mm		PMI 13mm Impact		BW II+Plus 11.6mm		10.6mmPMI	
(lbf)	meas (mm)	% inc.(1)	meas (mm)	% inc.(1)	meas (mm)	% inc.(1)	meas (mm)	% inc.(1)	meas (mm)	% inc.(1)	meas (mm)	% inc.(1)
176	205	0	183	0	177	0	215	0	175	0	198	0
300	222	8.3%	192	4.9%	192	8.5%	224	4.2%	188	7.4%	222	12.1%
500	238	16.1%	208	13.7%	206	16.4%	239	11.2%	204	16.6%	255	28.8%
1000	256	24.9%	233	27.3%	231	30.5%	267	24.2%	235	34.3%	306	54.5%
1500	276	34.6%	249	36.1%	247	39.5%	287	33.5%	253	44.6%	334	68.7%
2000	293	42.9%	262	43.2%	257	45.2%	303	40.9%	270	54.3%	363	83.3%
2500	306	49.3%	272	48.6%	266	50.3%	314	46.0%	284	62.3%	383	93.4%
3000	314	53.2%	279	52.5%	274	54.8%	326	51.6%	294	68.0%	403	103.5%
3500	321	56.6%	287	56.8%	281	58.8%	335	55.8%	303	73.1%		
4000	326	59.0%	294	60.7%	286	61.6%	344	60.0%	311	77.7%		
4500	334	62.9%					351	63.3%	318	81.7%		
5000	339	65.4%					358	66.5%				
5500	344	67.8%					367	70.7%				
6000	n/a											
Failure	*7200*		*5200*		*4200*		*5700*		*5000*		*3500*	

Notes: (1) 10-500# measures made with dead weights, then same sect. of rope transferred to Dillon 10K# Tensile Tester for 1000# and up measures, (2) 0 measure assigned to 176#

Fig. 8 Knot Force-Elongation Curves for various ropes



Rope+Knot Slow Pull Model

The purpose of the model was to insert the maximum impact forces from actual drop tests and calculate a theoretical maximum elongation value for comparison. The next page is the complete comparison table.

The model used a simple equation in which the length of the knots and exact length of rope (w/o knots) were each increased by their respective slow-pull elongation percentages (corresponding to the force recorded in the actual drop test). These two values were then added together to give the model's estimated new maximum rope (with knots) elongation.

The following general trends were noted when comparing the measured drop test forces and corresponding elongation values to both the measured slow-pull testing value and the calculated estimate from the rope+knot elongation model:

- 176# test weight
  - In the 0.25 FF tests, the actual measured total rope (w/ knots) elongation values were ALWAYS ABOUT EQUAL TO OR LESS THAN the slow-pull measured GAUGE LENGTH elongation values.
  - This is an interesting point, as one might normally expect a drop tested rope length with knots at each end, which knowingly extend a great deal, to have greater elongation than just the gauge length from a slow-pull.
  - However, in the 0.5, 1.0, and 2.0 FF tests, the combined knot and rope slow-pull elongation model was usually more accurate.

- 500# test weight
  - Essentially ALL drop tests of any FF had total rope (w/ knots) elongation values GREATER than the rope gauge length slow-pull values. The predicted elongation values of the rope+knots slow-pull model were more accurate in virtually all cases.

Total Rope Failure Test Results

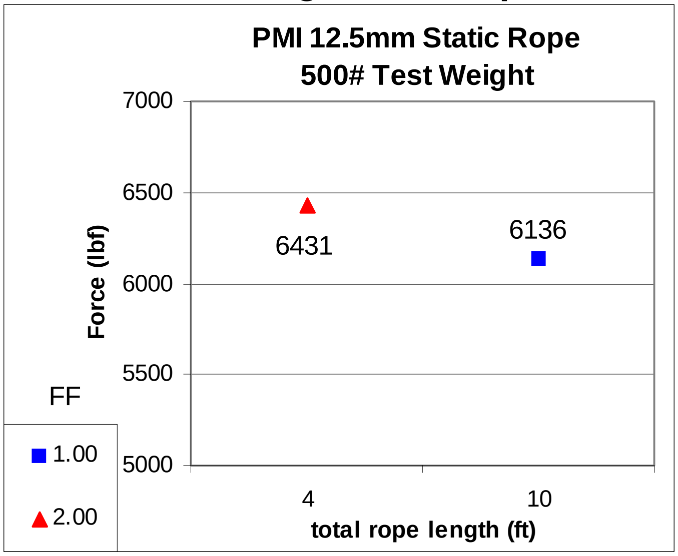
11 of the 162 tests resulted in total rope failure (see graphs on following pages). It is interesting to note that the recorded breaking strengths are in fact within 10% or less of the expected breaking strength of the knotted ropes as determined in the slow-pull tests. The good news is that the failure loads under the "dynamic conditions" of a drop test did not produce any surprisingly low force failures.

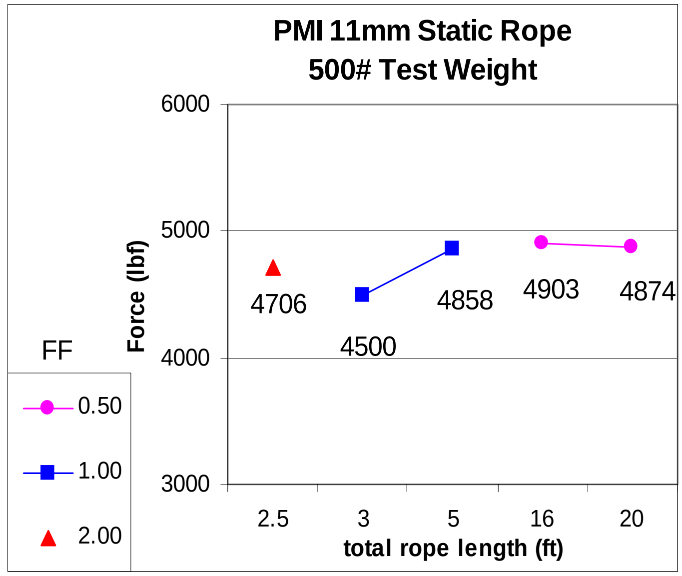
It was also noted that some of the test ropes that did NOT FAIL were in fact very close to the knotted rope's expected breaking strength. (Ref. to earlier slow-pull data table)

Note: PMI 10mm Static and 10.6mm Dynamic Ropes were not tested to failure.

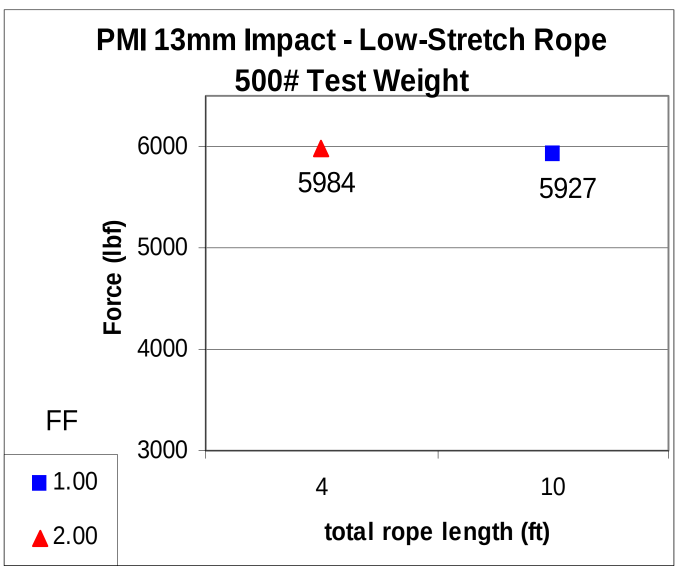
Max. Elong. Comparisons between Actual Drop Tests and Slow Pull Model											
						Actual Measures.		**Compared to Slow-pull model Elong. Values for same load**			
rope	test wt. (lb.)	**FF**	drop (ft)	rope (ft)	test #	Impact (lbf)	Max. Elong.	rope w/ fig. 8 knots	ratio to actual	*rope only*	*ratio to actual*
PMI 12.5mm Static	176	**0.25**	5	20	92	1383	4.9%	7.8%	1.59	*5.2%*	*1.06*
		0.25	5	20	131	1292	4.2%	7.6%	1.81	*5.0%*	*1.19*
		0.50	10	20	97	2180	7.5%	9.4%	1.25	*6.9%*	*0.92*
		0.50	10	20	132	2046	8.3%	9.9%	1.19	*6.7%*	*0.81*
		1.00	10	10	100	2961	11.0%	13.9%	1.26	*8.2%*	*0.75*
		1.00	20	20	101	3426	n/a	12.6%	n/a	*9.6%*	*n/a*
		1.00	20	20	133	3176	12.4%	11.4%	0.92	*8.5%*	*0.69*
PMI 11mm Static	176	**0.25**	5	20	134	1096	5.7%	6.4%	1.12	*4.7%*	*0.82*
		0.50	10	20	135	1979	8.5%	9.4%	1.11	*7.1%*	*0.84*
		1.00	20	20	14	3314	13.0%	12.8%	0.98	*9.7%*	*0.75*
		1.00	20	20	136	3106	11.4%	12.2%	1.07	*9.3%*	*0.82*
PMI 13mm Low-Stretch	176	**0.25**	5	20	143	1067	7.9%	8.2%	1.04	*6.9%*	*0.87*
		0.50	10	20	114	1695	10.2%	11.0%	1.08	*9.2%*	*0.90*
		0.50	10	20	144	1593	10.6%	10.7%	1.01	*8.9%*	*0.84*
		1.00	20	20	119	2695	13.9%	14.7%	1.06	*12.0%*	*0.86*
		1.00	20	20	145	2434	13.6%	13.6%	1.00	*11.3%*	*0.83*
		2.00	16	8	123	3982	20.6%	22.2%	1.08	*14.8%*	*0.72*
BW 11.6mm Low-Stretch	176	**0.25**	5	20	75	1090	6.8%	10.8%	1.59	*9.1%*	*1.34*
		0.25	5	20	140	1067	7.5%	10.6%	1.41	*9.0%*	*1.20*
		0.50	10	20	80	1819	10.4%	11.9%	1.14	*9.4%*	*0.90*
		0.50	10	20	141	1646	9.9%	11.2%	1.13	*8.8%*	*0.89*
		1.00	10	10	83	2682	14.0%	18.4%	1.31	*12.1%*	*0.86*
		1.00	20	20	84	2901	13.3%	16.3%	1.23	*12.8%*	*0.96*
		1.00	20	20	142	2605	13.9%	15.1%	1.09	*11.9%*	*0.86*
		2.00	16	8	88	4138	16.4%	25.6%	1.56	*15.9%*	*0.97*
PMI 10.6mm Dynamic	176	**0.25**	5	20	137	623	11.0%	13.6%	1.24	*11.9%*	*1.08*
		0.50	10	20	138	893	16.2%	18.5%	1.14	*16.3%*	*1.01*
		1.00	19	19	139	1312	24.1%	24.8%	1.03	*21.9%*	*0.91*
PMI 12.5mm Static	500	**0.25**	5	20	34	3131	9.1%	8.4%	0.92	*6.7%*	*0.74*
		0.25	5	20	146	2917	7.8%	8.0%	1.03	*6.4%*	*0.82*
		0.50	10	20	39	5126	9.6%	11.4%	1.19	*9.1%*	*0.95*
		0.50	10	20	152	5045	10.5%	11.2%	1.07	*9.0%*	*0.86*
PMI 11mm Static	500	**0.25**	5	20	147	2957	8.8%	8.4%	0.95	*6.6%*	*0.75*
PMI 10.6mm Dynamic	500	**0.25**	5	20	150	1443	n/a	23.9%	n/a	*23.4%*	*n/a*
PMI 13mm Low-Stretch	500	**0.25**	5	20	57	2534	8.2%	8.8%	1.07	*7.1%*	*0.87*
		0.25	5	20	148	2514	9.5%	8.7%	0.92	*7.1%*	*0.75*
BW 11.6mm Low-Stretch	500	**0.25**	5	20	48	2595	11.7%	9.7%	0.83	*7.6%*	*0.65*
		0.25	5	20	149	2612	9.1%	9.7%	1.07	*7.6%*	*0.84*
		0.50	10	20	53	4197	11.0%	14.5%	1.32	*11.7%*	*1.06*
		0.50	10	20	151	4173	13.3%	14.4%	1.08	*11.6%*	*0.87*

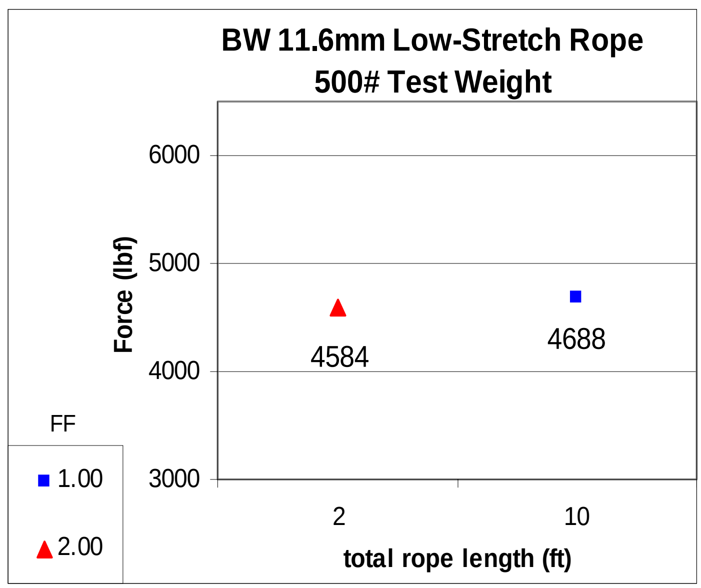
Tests resulting in total rope failure





Tests resulting in total rope failure





Notes about interpreting this report

CAUTION - “Fall Factor,” without a doubt, remains a significant and useful tool for all rope users and this report does not dispute its usefulness.

Minimizing Fall Factors remains an essential responsibility to all Rope-Use Professionals.

The 0.5, 1.0, and 2.0 drop tests conducted in this study may be unrealistic scenarios to everyday use, but they are in fact important to help model and better understand the rope’s performance over its entire range before failure occurs.

A margin of error of approx. +2/-0 inch did exist in our ability to accurately measure the maximum elongation. Method used was a simple array of horizontal fishing lines, tied on one side and lightly held on the other with Velcro, spaced every 2 inches, and repeatedly positioned across the anticipated lowest area that the falling basket would cross. The lowest displaced line was measured and used to determine the point of maximum elongation. This margin of error made it difficult to derive any highly accurate conclusions from the energy study of data collected (not detailed in this report).

Summary

- For all static and low-stretch ropes tested, the results indicate that impact forces do increase as the length of rope & fall increase for any given Fall Factor.
- The reassuring news for Rope-Use Professionals is that this “trend” is much smaller and arguably insignificant in FF 0.25, which is a much more realistic FF that could be experienced in the field.
- Also worthy of note is that this trend appears to be “leveling off” so to speak after 20 ft rope lengths, but further testing is need to verify the actual trend.
- Dynamic rope in comparison only showed minimal increased impact forces when rope lengths and FF were increased.
- Knots are significant energy absorbers compared to rope itself.
- The length of knots in many of the “short rope length” (<4ft) drop tests is a considerable % of total test rope length. This makes those data points less applicable to any real-life applications.
- The entire report data set is available in a MS Excel spreadsheet if interested.

Future testing considerations

- Further drop testing of rope lengths >20 ft following a similar sequence of various fall factors would make this line of study more comprehensive.
- Further analysis of this test data using conservation of energy principles (potential, kinetic, and strain energy relationships) and rope modulus and stiffness factors was investigated but not completed for this report. It is believed that special attention given to the ropes’ energy absorbing ability in both the elastic (low forces, <10% total strength) and plastic regions (higher forces) of the rope’s force-elongation curve will prove most useful in better understanding rope performance.

Special thanks to **Jim Kovach, Ron James,** and **Steve Bellamy**, for their significant help in conducting most of the drop tests at PMI and **Steve Hudson** for allowing me to pursue this research while on PMI’s payroll.