Dynamic Shock Load Evaluation of Ice Screws:
A Real-World Look

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Abstract:
Background: It is unknown how many climbers take lead falls on ice screws placed in waterfall ice. Generally, what is reported are accidents that occur when ice screws fail or are pulled from the ice. To date, there is very little information regarding ice screw testing.

Methods: Over the period of eight days of drop testing, we conducted a randomized placement of short ice screws in real-world vertical waterfall ice. Different fall factors, including the UIAA standard, were evaluated to determine what a climber might expect from dynamic shock loading of an ice screw in real climbing conditions. Sixty-one drops were performed on ice screws in real world ice.

Conclusions: We show that while ice is a variable medium, a predictable and surprisingly strong normogram can be produced in the conditions we performed our testing in. However, because the methods of judging ice conditions are based solely on experience, it may be difficult for novices to discriminate these conditions. The perception that ice screws are weak protection is unfounded when "good" ice is utilized.

A definition of terms have been created that may help provide a nomenclature for discerning ice conditions.

I. INTRODUCTION:

The main objective was to gain an understanding of the behavior of ice screws under dynamic shock loading and peak forces needed to hold a falling ice climber in a real world setting. There is little information regarding real-world testing. Rather, most testing is done in laboratories and the tests performed there only evaluate the tensile strength of the materials and not necessarily the application for which they were intended to be used in the first place. Climbers rely on word of mouth, books, periodicals, and training from others to gain insight on the equipment used. Good data is not only hard to find but is difficult to acquire outside in real world conditions. This was an attempt to find scientific-based data that might help climbers think more critically about their ice screw placements.

II. HYPOTHESES:

1) There is a significant difference in impact force between failing and non-failing ice screws. The null hypothesis is there is no significant difference in impact force between failing and non-failing ice screws.

2) Short ("stubbie") screws when placed in good ice do not provide a significant amount of protection and are not as good as typical rock climbing anchors.

3) Peak forces seen in dynamic shock loading of ice screws are equivalent to those seen in rock climbing, and ice screws in the positive orientation of $\geq+10º$ but $\leq+30º$ are capable of holding these forces in fair to good ice and may surpass rock gear in strength in this orientation.
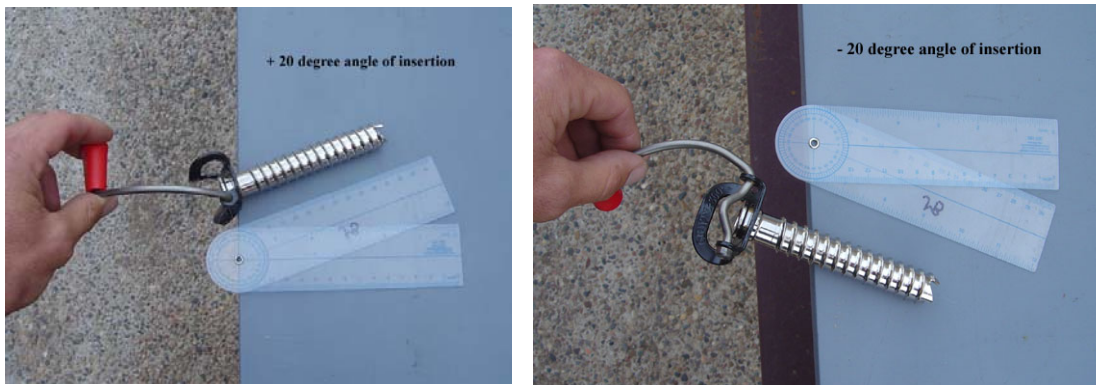
Figure 1: **Defining the angles:** *left:* **a positive 20°;** *right:* **a negative 20°. These angles are relative to vertical ice from the horizontal/perpendicular line relative to the ice face.**

> 3) Drop testing on real world ice is completely different from lab ice. A large spread of results has been reported on ice screw strengths, and the CE tests ice screws in a non-ice medium for approval. The tests that abound are at different forces and time durations. Can drop testing in a natural forum on actual ice climbs produce more realistic and repeatable results? Our hypothesis is that there is a significant difference between real-world and lab ice testing.

III. BACKGROUND:

To date, there is very little information regarding ice screw testing. One of the major factors for this is the lack of consistency of ice quality. This makes the science of testing anything in ice obscure at best. Volumes of research have been performed on oceanic and glacial ice, but there is sparse information of anything regarding waterfall ice especially in application to ice climbing. The general thought has been that "climbers essentially take their lives in their own hands should they take a fall onto an ice screw." Their only protection, aside from luck, has been experience. The rule of thumb has been that the "leader must not fall."

Craig Luebben[1] and Chris Harmston did some drop testing on ice screws and found poor results in aerated ice. Using a solid mass of 185 pounds of iron, Luebben reports having "pulled out entire lengths of ice screws" in some tests resulting in a ground fall from the top of the climb. "The ice had lots of aeration and bubbles in it; the way the ice was made was different back then," in a conversation I had with Luebben. The drops were from 16-28 feet, with corresponding fall factors of 1 to 1.7. A total of twelve drops on screws were performed: the top screw failed in seven tests, ice hooks failed three out of three times, and a pound-in screw with a stitched load limiting device failed under a fall factor of one using a 16 foot fall. The 10.5 mm dynamic rope ran from the iron, down through the protection and was clipped into an equalized anchor. A single dynamometer was used to record peak forces. However, how many tests were performed in each configuration or what the exact data was from those falls is unavailable and unclear. Perhaps the most confounding variable is that the same rope was used repeatedly.

Luebben went on to perform more tests, this time using a dynamic belay with an ATC and "back weighted the rope with 75 pounds (not a mechanical hand)." The fall factor was reduced to somewhere between 0.9 and 1.2 and no failures were reported. An Abolakov (treaded tunnel) held a 0.8 fall factor and again, three of three ice hooks failed. No configurations were reported to ascertain how the fall factors were obtained and the forces produced from these tests is unknown, but the results were clearly separated into fail or no fail.

Further testing on the strength of varying lengths of ice screws in ice, what angle of ice screw placement is better, and if tying off a foreshortened screw was a good idea or not, was also performed. These tests were done using a come-along. Chris Harmston, then the quality assurance manager at Black Diamond, performed similar tests:

Harmston's methods were as follows[2]:

"The top few inches of really bad ice is chopped off and a new layer of water is added and allowed to Freeze. A screw is placed in one half of the cell and pulled to failure at 12 cm per minute. The screw generally fails by cratering the top 5-8 centimeters of ice away from the screw, bending of the screw and finally, either levering the hanger off the head of the screw, breaking the tube of the screw, or pulling the screw out of the ice. A second screw is placed in the other half of the cell near the first screw's hole and similarly pulled to failure (yes, the ice is shattered and broken from the first test). After the tests are completed any broken-off screws are removed by chopping them out with an ice axe. The cell is placed back into the freezer and water is added to the old test holes and allowed to freeze onto the remaining ice. The cells are used repeatedly in this fashion up to 20 times before the entire cell is allowed to thaw and be 'regenerated". As can be inferred, this technique of ice preparation is highly variable and unpredictable (not unlike real world ice), yet has yielded conclusive and supportable results."

The trends that Luebben observed followed those of Harmston's in regards to strength of ice screw material in slow pull testing where force is applied for a relatively longer period of time and at sustained high forces. The results are interesting and may be extrapolated to similar real world uses, but only Luebben has reported actual drop test data.

Luebben's results have prompted some significant changes. Perhaps the most important one is in the way ice screws should be placed. Placing the screw at a +10 to +20 degrees has shown a significant increase in strength from the -10 to -20 degrees, as the positive angle does not compress and thereby fail the ice under the screw, and relies on the friction of the threads for holding strength.

Most recently, testing at three placement angles (-30º, 0º, and +30º) was evaluated[3]. Their conclusions were in agreement with both Luebben and Harmston reports in that negative placement angles showed reduced failure load. However, their data also suggest that positive angle placement had a dependency on loading rates of 125 N/s and 12,500 N/s and two manufactured ice types. Unfortunately, a third loading rate was not performed to provide for a graphical representation of what the scale of the difference might be, linear, logarithmic, or otherwise. They also report that a faster loading rate reduces failure load, but they did not do actual drop tests to validate what force reached upper threshold limits.

"If a metal screw was placed in a similar metal material, the thread surface area equaling at least 1.5 times the diameter of the screw is significant in strength to hold the screw in the material. However, all bets are off when two materials of differing characteristics are used, such as metal and ice," according to Frank Zanner, a PhD in metallurgy retired from Sandia National Laboratories in Albuquerque, New Mexico. Therefore, an assumption of how an ice screw might behave based solely on its physical characteristics is unreliable. Drop testing must be performed.

In drop testing, the UIAA[4] uses an 80 kg load on a single rope and 55kg on a half rope as a test mass for dynamic falls. The reasoning behind the lower test mass on the half rope is that a half rope should ideally see only 70% of an 80kg dynamic fall factor of 1.74. In the UIAA test this is a solid mass, not a human form such as the Rescue Randy, and represents an ideal worst-case scenario for placing loads on the protection seeing the load. The UIAA test insults the rope further in that the anchoring system is a bollard and backed up by a non-slipping mechanical hand.

Dynamic loads on this medium may vary from static loads in the way that moving a body through water slowly such as a swimmer is different than a body hitting the water with a velocity of 100 m/sec. The behavior of ice on screws may be different with different velocities of force applied.

Joe Josephson showed that Ice Threads (a.k.a., an Abolakov), were shown to be substantially strong[5] and today they are standard practice in use for retreat off of an ice climb. Abolakovs are also used as protection points while climbing, but were not evaluated by our testing in Ouray.

IV. LOCATION:

The Uncompahgre Gorge is the setting of the Ouray Ice Park in Ouray, Colorado. It was selected as the site for the drop tests for several reasons. The gorge is a slot canyon with greater than a one hundred foot vertical to overhanging drop and is the site of over 180

established popular ice climbing routes. The sun does not hit the bottom of the route on any day but does reach the retro-base formation[6] for a brief period between noon and 14:00 hrs. This is like many natural ice climbs in other areas. Ouray is known for having many different types of ice during a season.

Figure 2: **Configuring the data collection node and preparing the test weight on the "Rhythm Method"WI5 in Ouray, Colorado.**

The ice route used was the "Rhythm Method," WI5, located on the northwest side of the lower bridge and represents undulating vertical and overhanging ice to assure free fall in the vertical axis. Testing occurred throughout the two months of January and February over a total of seven days.

V. TESTING METHODS:
a. Data
The testing system used was a wireless Microstrain V-link data logging system that was modified to meet the needs of data acquisition while on the ice climb. The V-link stores the data and then it is downloaded through a wireless transceiver into the laptop for later analysis. We used a Pelican case to house the V-link and made quick disconnects from the case that attach up to four load cells and one manual triggering device. An automatic triggering system that allowed a single user the capability to run tests quickly and efficiently was also engineered.

Figure 3: **Typical S-type load cell attached with quick disconnect to wireless v-link data logging system.**

b. Ice Type
Although one can consider that ice is an ever-changing medium with varying properties, "it is neither a 'simple elastic' nor an 'elastic/plastic' solid[7]." Furthermore, "ice has at least twelve different crystallographic structures and two amorphous states. The particular structure formed most commonly in nature is the Ih-type. This is formed by simply freezing water and has a hexagonal structure[8]," and is likely the structural form most often found in the Ice Park as well as abroad. Further analysis should be done in this area to confirm consistency where other waterfall ice forms and is climbed.

Density measurements were taken by chipping a sample from where the top piece ice screws were placed. On site, the sample was weighed, then was melted in a beaker and allowed to reach 47ºC and the volume measured. The ice densities measured were $\bar{x} = 0.97, \ n = 8$. The density of the Ouray Ice is equivalent to that of the ice made by the Ready Ice Company in Albuquerque, NM: $d = 0.97$, $n = 4$ for comparison.

Figure 4: **Typical placement and typical ice conditions throughout the Ouray Ice Park.**

Ambient air temperature varied from 20F°/-7°C to 33 F°/1°C, and the ice temperature diurnal variation was -6.6°C at 08:00 hours to -1.9 ºC at 13:00 hours, but was fairly consistent on a daily evaluation . Temporal variability could not be accounted for due to the slow and tedious process of doing drop testing in real world conditions.

What will not be described here is the form or quality of the ice. Instead, *Appendix A* provides a descriptive vernacular used in an effort to make an attempt to better portray the quality of the ice as seen by a lead climber placing an ice screw.
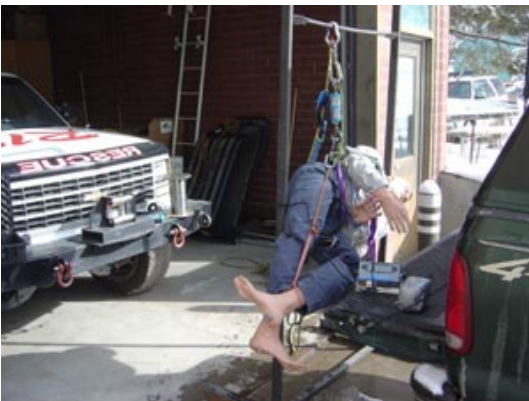

Figure 5(left) weighing the test mass, & 6 (right) displaying the results of why a stopper knot is necessary – note the over camming of the Grigri that allowed no slip.

c. Configurations
Several lead climbing orientations were performed using a (172 pound = 78.0178876 kilogram (two pounds of clothes and gear))[9] Rescue Randy for the simulation of a fallen lead climber. The Randy had a seat harness and a chest harness.

For all tests:
Grigris were used at both the test mass side and the anchor side. Stopper knots were placed behind each device to prevent and control for slip. For the appropriate tests, the rope ran freely through the top piece carabiner as in lead climbing orientation. Otherwise the rope hung freely and without obstruction.

Stopper knots allow for all belays to be equivocal and non-dynamic for consistency of the experiment as it would be nearly impossible to account for a dynamic belay's variability. This method is similar to the UIAA test where a bollard wrap is used and creates a non-dynamic belay condition. The Grigri retains full strength of the rope[10] by using a bollard. It was important to consider having no knot at the anchor as it absorbs energy.
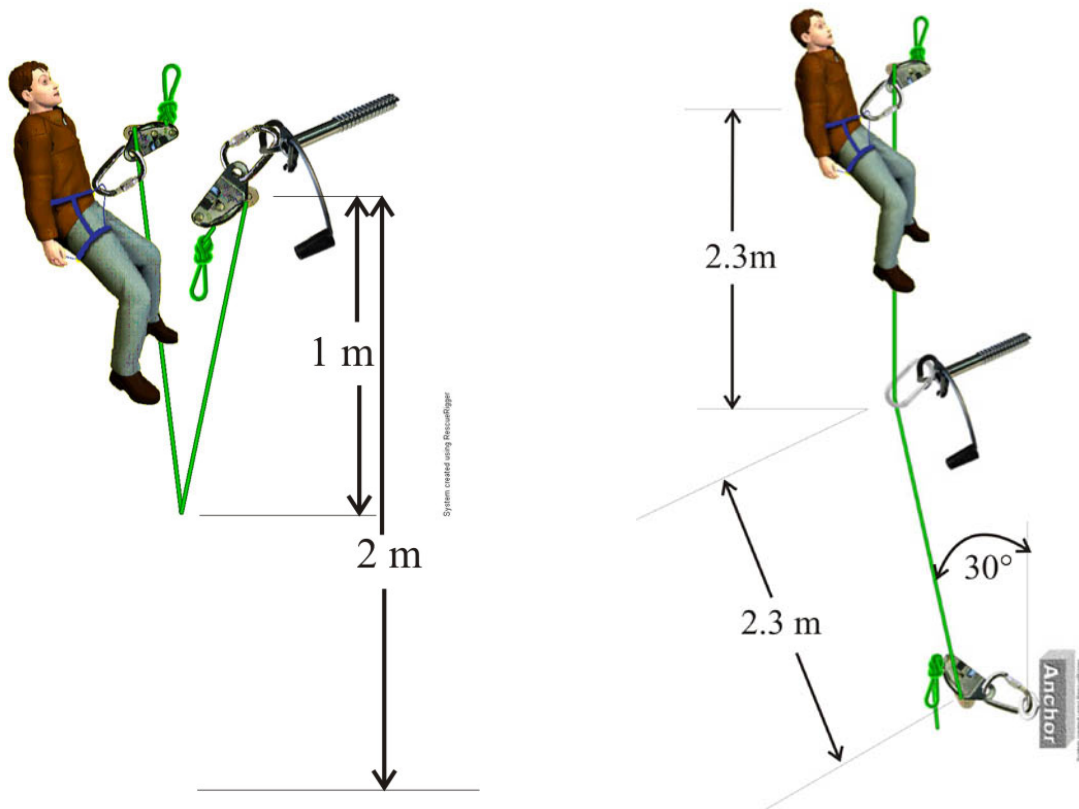

VI. FALL ORIENTATION

a. Orientation #1 Fall Factor 1- Anchor (Figure 7)
The test weight is placed at the same level of the ice screw acted upon. The test weight is dropped 2m on 2m of rope. This would replicate a slip from the belay stance.

b. Orientation #2 Fall Factor 1 – UIAA Variant. (Figure 8)
The test piece was placed at 2.3m above the anchor and at a 30° angle. The test weight was raised to 2.3m above the test piece (straight up) and released. This test was also a fall factor of one. However, it is also a likely scenario. *Understand that it places more force on the ice screw test piece than Orientation #1.*


Left to right: Figure 7, fall factor 1 from an anchor; Figure 8, fall factor 1 in lead climbing formation UIAA-variant.

c. Orientation #3 fall Factor 2 (Figure 9)
The test weight was placed at 2m above the ice screw test piece and released.

d. Orientation #4 Fall Factor 1.71 - UIAA drop test (Figure 10)
From the anchor point to the ice screw test piece was a distance of 300mm (30 cm) and at a 30 degree angle to the anchor. The test weight was lowered to 2.5m from the test piece. The weight was then raised up to 2.3m above the test piece (that allows for slack) and released.
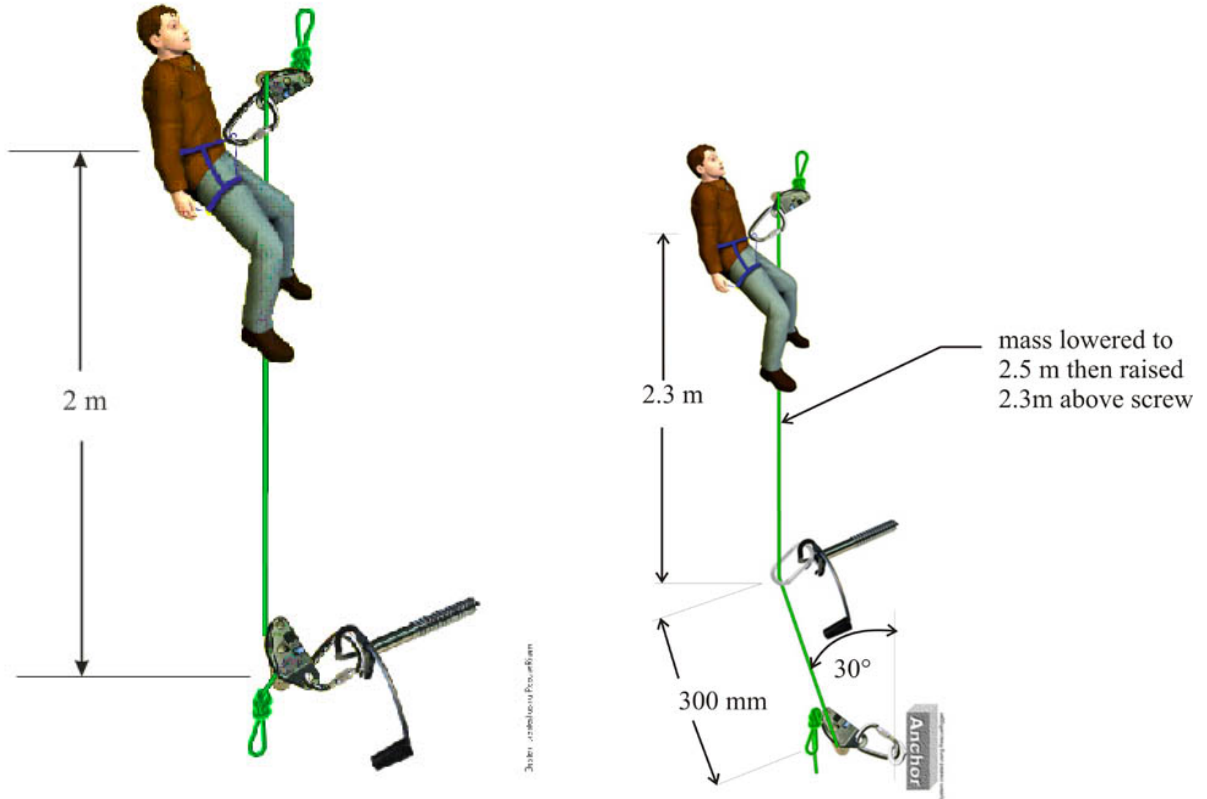
Left to right: Figure 9, fall factor 2; Figure 10, fall factor 1.71 (the UIAA test)

VII. LIMITATIONS - Several confounding factors are evident:

a. Choice of protection placement
Not everyone will be able to perceive ice quality in the same way. There is simply no substitute for experience. Sometimes that experience comes in the face of grave danger while leading, and it seems to exhibit operantly conditioned responses from seasoned ice climbers as can be seen from the choice of tool and protection placement.

b. Ice screw manufacturer
Each manufacturer has its own style of production. Only three styles were tested: the Grivel 360°, Petzl Laser, and Petzl Laser Sonic, all of which were the shortest of their make.

c. Ice / environment

 Certainly, ice is an ever-changing medium. Conditions were generally what one might expect to climb in, but there was no way to control for environmental variation. This might best be done in a facility capable of producing waterfall ice and maintaining stable conditions, day or night.

d. Test mass

An area of continuing debate is the rigid mass that is often used in drop testing. We used a test dummy, not a rigid mass. This issue is not covered in this paper. More research in this area should be investigated.

RESULTS

We looked at the data in several different ways and asked several questions that were pertinent to ice climbers and those interested in ice screw placements. Other questions arise as one was answered. We used statistical analysis to verify our hypothesis.

Table 1: **Descriptive Analysis, pass, fail and all-inclusive.**

passing screws		failing screws		total all	
Mean	8.294	Mean	10.1	Mean	8.63
Standard Error	0.348	Standard Error	0.88	Standard Error	0.34
Median	7.93	Median	10.8	Median	8.17
Mode	6.07	Mode	#N/A	Mode	6.07
Standard Deviation	2.464	Standard Deviation	2.91	Standard Deviation	2.62
Sample Variance	6.072	Sample Variance	8.49	Sample Variance	6.88
Kurtosis	1.003	Kurtosis	1.04	Kurtosis	0.05
Skewness	1.178	Skewness	-0.67	Skewness	0.78
Range	9.95	Range	10.6	Range	10.9
Minimum	4.93	Minimum	3.98	Minimum	3.98
Maximum	14.88	Maximum	14.6	Maximum	14.9
Sum	414.7	Sum	112	Sum	526
Count	50	Count	11	Count	61

First, we looked at pass verses fail. What could someone expect if a mass was exerted on an ice screw protection point while using a single rope and a static belay?

To show breakdown of variance of impact force by fall factor we tabulated Figure 11. Higher fall factors produced a higher impact force, but note that ff2 did not get above 10kN, nor did any ff2 fail on a single screw. Figure 12 shows a complete breakdown of peak impact forces by individual test.
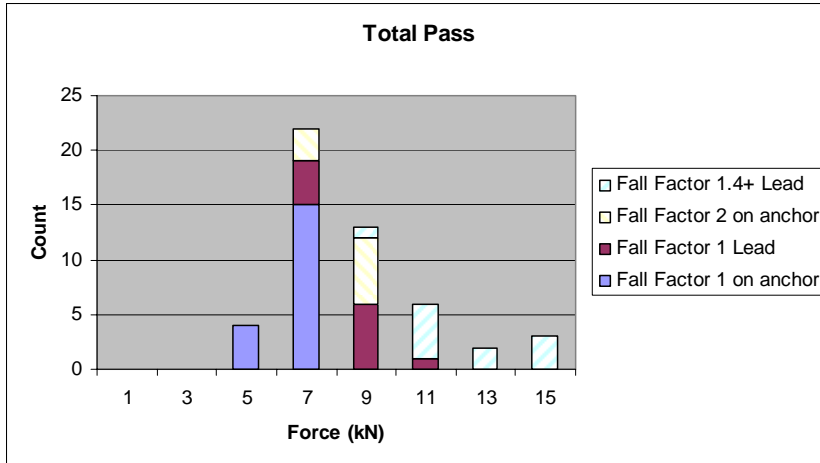
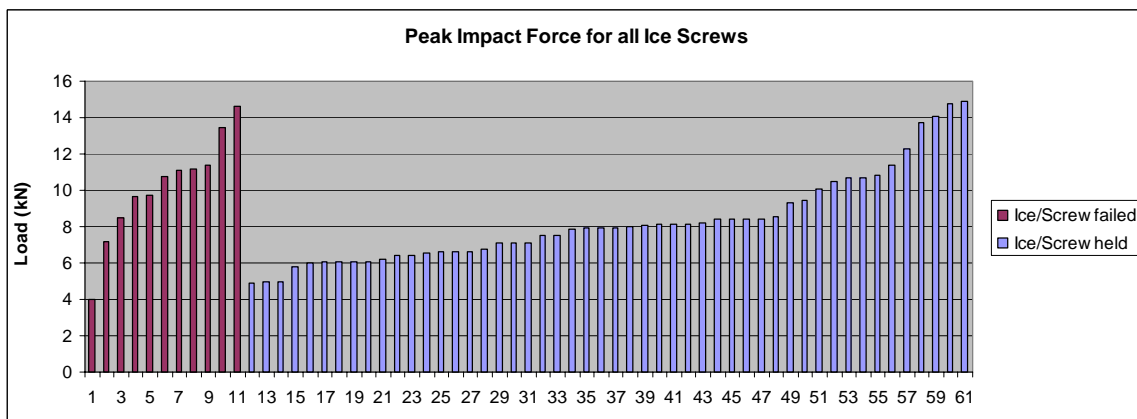*Figure 11:* **Total Number of Pass Drops Relevant to Peak Impact Force.**

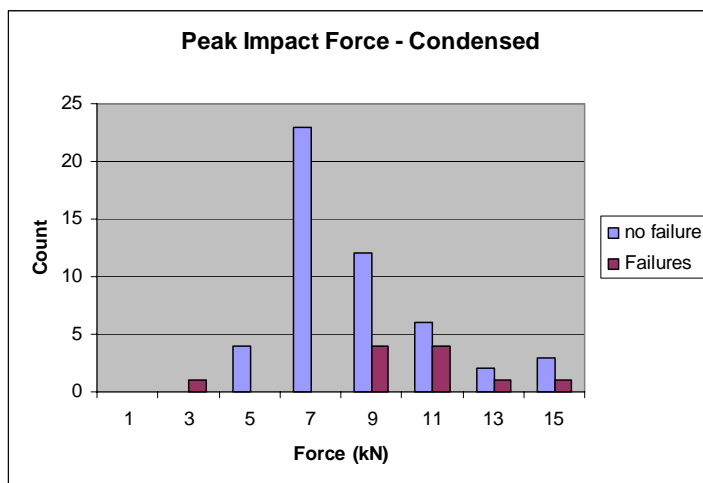*Figure 12***: Results of all tests**

Figure 13: **Condensed count of all tests separated out in no failure (pass) and failures vs. Force (kN).**

The results of our tests were surprising. At first glance it appears that there is no significant difference in impact force between passing and failing screws, and that it looks like a 50/50 shot at failing a screw. Both categories of pass/fail fall into the same relative bins.

In evaluation of the statistical analysis we use the standard formula for the one-sample t confidence interval of 95%,

$$CI_{95} = \overline{X} \pm t \frac{s}{\sqrt{n}}$$

Where, $\overline{X}$ =mean, t =how far $\overline{X}$ is from μ in standard deviation units, $s/\sqrt{n}$ =standard error (estimation of standard deviation). This is making the assumption that one puts ice screws into what appears to be "good" waterfall ice as outlined earlier.

For the normal distribution in our experiment:

Pass (held)	Failed (pulled)
$8.63kN \pm 2\sigma = 7.29 < \overline{X} < 9.97$	$10.14kN \pm 2\sigma = 6.24 < \overline{X} < 14.04$
$8.63kN \pm 3\sigma = 6.62 < \overline{X} < 10.64$	$10.14kN \pm 3\sigma = 4.29 < \overline{X} < 15.99$

A t-test for the normal distribution curve shows:

$$t = \frac{\overline{X} - \mu_o}{\dfrac{s}{\sqrt{n}}}$$

Using a 95% confidence interval, where α=0.05, we find p = 0.0365. The statistics show that there is a significant difference and that out of 100 samples, there is less than a 3.65% chance that the samples we obtained were due to sampling error. Therefore, we can support the hypothesis that there is a significant difference in impact force between failing and non-failing ice screws in real-world ice. What is attributed to this difference? Likely, it is the ability of the individual placing the screw to discriminate the ice conditions where the screw is placed.

The failure of 3.98 kN is close to the 3 standard error (standard deviation) from the mean. This was indeed an outlier in the fact that I was able to make the statement that it was "psychological pro" and would likely not hold a high impact force when I placed the screw. This explains the lower-end of the failures.

Evaluation of High Fall Factors >1.0

Looking at fall factors of 1.4-1.7, there was no significant difference in pass or fail.

t-Test: Two-Sample Assuming Equal and Unequal Variances:
Setting α=0.05 we find that p=0.017 and 0.037 respectively.

What was observed is that the stubby screws saw high impact forces of nearly 15kN without failure. This fact only supports the reasoning that *ice placement selection ability becomes the important factor.*

COMPARISON OF PREVIOUS TESTING AND AVAILABLE DATA

We used the Black Diamond data to look at relevant comparison to our own.

For 13cm length ice screws in lab ice at Black Diamond:
N = 63
x̄ = 4279/19.0
Std. Dev (s) (IbF/kN) 1275/5.7
High (lbF/kN) 8269/36.8
Low (lbF/kN) 2387/10.6

Calculating the Black Diamond's 2 and 3 sigma, we see that it is much greater than our results:
$$19kN \pm 2\sigma = 16.1 < \overline{X} < 21.9$$
$$19kN \pm 3\sigma = 14.7 < \overline{X} < 23.3$$

Calculating our results with those of Black Diamond's with a two-sample t-test:
$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}}} = 10.99$$

We find that *t=10.99.* When *p=0.05, t>p, which did not show a significant difference and could be due to chance alone,* and therefore it could be said loosely that, the type of testing that Black Diamond did in the lab can not be compared to our testing in Ouray on real-world ice because of failure to reject the null hypothesis. A larger sample and further testing should be done to confirm these results.

Perhaps overdriving our system either using static rope or increasing the mass to force-fail all screws would be indicated to obtain failure in all tests to produce a higher number from which to draw our samples for a better comparison analysis.

Addressing fall factor 2:

A total of nine drops of ff 2 were performed before discovering futility.
$$7.8kN \pm 2\sigma = 6.8 < \overline{X} < 8.8$$

The maximum impact force reached was only 8.6kN with no failures. This opens the door to a large debate that could be justified in several ways of, "when should I put in my first ice screw when leaving a belay stance on a multi-pitch ice route?"

Certainly, the classic thought process has long been to either clip the master point if the anchor points are potentially weak, and/or place a screw immediately to avoid a ff 2.

Research needs to be done to establish if a rope becomes stiffer after a first impact due to non-elastic deformation. If indeed, on second impact the rope is stiffer, then the potential exist for a "double whammy phenomena." Using our data, the average ice screw might likely pull out somewhere between 3.98-14.6 kN in good ice. The question becomes, once the rope has just been stretched, possibly to near its UIAA limit, what is the behavior of the rope if it does not have time for the elastic properties to recoil and provide for more shock load absorption? If the belay is not "bomber," the possibilities could be grim. Could a "double whammy" generate more force than a direct ff2 fall? We do not know. This is an area in need of further research.

DISCUSSION
Nothing substitutes for good training, experience, and expertise, and our investigation supports that notion. We have made an effort to help those who use ice screws to stack the odds in their favor by performing real-world application to an enigmatic topic. This exercise has shown many things of importance in addition to the use of good judgment:

1) Higher impact forces above 10 kN are more than likely to cause ice screw failures. At this load, a narrow margin appears to exist between passing and failing. High impact forces can be created by simply overdriving a system with a large mass and can lead to anchor point failure (no heavy ice lead climbers allowed). There are other ways at achieving this same end result such as, using an old rope, clipping two double ropes together when only one should have been, or increasing friction in the system by any modality are several of those ways.

2) Short ("stubbie") screws when placed in good ice provide a significant amount of protection that was quite unexpected and equivalent to that of rock gear when placed at $\geq+10°$ but $\leq+30°$. By showing this, we have validated the concept of what angle ice screws should be placed in vertical waterfall ice as previously studied by Luebben and Harmston. While poor screw placement is always a possibility, poor ice screw placement is as weak as "rattly" rock gear. The analogy can be made that poor ice screw placement is similar to just throwing your rock climbing rack on top of the rock, clipping your rope to it and jumping off the cliff, only to hope that the gear somehow miraculously catches on something and holds your fall. Proper protection placement is crucial.

3) Ice gear is good if placed in zones of compression or areas devoid of large air pockets within 15-30 cm of the screw placement. Anecdotally, small air bubbles within the ice do not seem to matter on vertical waterfall ice.

4) Our tests were inconclusive regarding the hypothesis that real world ice is different from lab ice even though there was a significant difference between lab ice and real-world ice in our statistical analysis. Lab tests and lab ice may not

reflect real-world ice, but further testing and investigation into this topic should be performed before drawing any conclusions.

5) Ice density does not appear to play a major role in waterfall ice strength capacity.

6) Temperature varies greatly in waterfall ice. It has been shown that ice becomes brittle below -5°C. We did see more failures in the morning than in the afternoon hours. However, the ice did not get above -1.9°C. The density of the ice itself does not appear to be a significant factor, but temperature may be. Colder ice (less than -5°C) should be studied.

7) During the course of our ice screw testing, we were able to test three ice hooks, all three failed, did not slow the test mass down at all, and became a sharp flying projectile heading towards the test mass (climber).

Certainly, many other inferences about these results can be made. More discussion about application is in order and testing in some of the aforementioned areas is appropriate. Hiring an experienced climbing guide to gain knowledge about ice climbing is prudent.

Appendix A
ICE TYPES
This glossary of terms is by no means extensive or definitive. It was gathered from an interview of over 50 ice climbers at the Ice Park during the days of testing. Terms may also vary according to any given changes on any given day. This is only to help for sake of discussion.

EXCELLENT
Goo, Block of Cheese, blue, solid, vertical hockey rink, sinker, thunker, stonker, hero, bomber, thick, windshield ice, blue, green, glowing, iridescent.
Cold yesterday, warm (perhaps humid today)

GOOD
Opaque, rivulet surface, good screw placement, small occasional dinner plating (tension release fracture), minimal fracturing on tool and screw placements, psychologically encouraging, "a little colder out or less humid than *Fair* ice conditions."

FAIR
Large dinner plating, exfoliating surface (radial cracking), beginning to chandelier, small cauliflowers.

POOR
Large Cauliflowers, deep and extensive chadeliering, sublimated surface, brittle, gray, sun bleached, baked out, back warmed, hollow, low gonging, air pockets upon insertion of screw, baby heads, loose bobbles.

PITIFUL

Verglass, very warm, extremely cold, crap, shit, crumbly, full raking, 8-10 swing ice, slush, porridge, rotten, falling apart, falling, crashing

Appendix B
Ropes used:
UIAA drop testing:
Brand new Sterling Evolution Kosmos Dry 10.2 mm rope. Lot # R1-092704DPC/DJC

FF0.3 and 1.0 (free fall from anchor) drop testing:
Brand new Sterling 8.8 half rope Lot #R47-082404
Brand new Sterling 10.4 single rope Lot #04-110504

UIAA variant drop testing FF1.0:
Brand new Sterling 10.4 single rope Lot #04-110504

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[1] Luebben, Craig. How to Ice Climb (pp.143-158). Connecticut: The Globe Pequot Press, 1999.

[2] Harmston, Chris. Climbing no 172 (Nov 97), pp106-115; or http://www.needlesports.com/advice/placing screws.htm

[3] K. Blair, D. Custer, S. Alziati, W. Bennett (2004) "The Effect of Load Rate, Placement Angle, and Ice Type on Ice Screw Failure." 5th International Engineering of Sport Conference.

[4] UIAA EN-892, dynamic mountaineering ropes, UIAA-101.

[5] Joe Josephson. "Ice Anchor Review", The Canadian Alpine Journal, 76, 1993, pp66-67

[6] Retro-base – large formation of ice made by the sprinkler system that serves as the source reservoir during the day preserving the ice route.

[7] Bennett, Warren. 10/2002. Simulating and Testing Ice Screw Performance in the Laboratory, Final Design Proposal.

[8] Schulson, Erland M., "The Structure and Mechanical Behavior of ice", The Minerals, Metals and Materials Society, http://www.tms.org/pubs/journals/JOM/9902/Schulson-9902.html. 09/30/02.

[9] http://www.onlineconversion.com/weight_common.htm

[10] Beverly, M., Attaway, S. "Hang 'Em High: How Good Are Belay Devices?" ITRS 2005.