

The effect of load rate, placement angle, and ice type on ice screw failure

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ABSTRACT: Accident reports and previous research show that ice screws often fail to remain anchored in ice when subjected to the typical loads produced by climbing falls. This research characterized the failure of ice screws placed in ice and pulled to failure in a tensile tester. The test matrix is comprised of two ice types (water ice and aerated ice), two loading rates (125 N/s and 12,500 N/s), and three placement angles (-30° , 0° , 30°). High-speed video provided a qualitative record of the failure. Four results were worthy of note. The failure loads were significantly below those reported in the literature. Load rate significantly affects failure load. Angle, load rate, and ice type show a complex relationship with failure load. Two failure modes were observed, a sudden “popping out” and a “slicing out.” These results suggest that climbers should minimize loading rate and place ice screws where the ice is in compression.

INTRODUCTION

Climber lore suggests that ice is a fickle medium for anchors. This reputation is primarily due to the nature of ice, whose properties change dramatically with both temperature and morphology. At low temperatures (below -20°C) ice exhibits brittle behavior, and above -5°C its behavior is plastic (Schulson, 1999). This behavior is further complicated by the many different factors that contribute to ice formation; temperature history, water flow, sun exposure, snow entrainment, and glacial processes can all combine to produce the myriad of formations that climbers climb. Although the variable nature of the medium is one of the aspects that draws ice-climbers to the sport, this variability presents a challenge to the design, testing, and use of ice screws.

The seminal ice screw studies, conducted by the German and Austrian Alpine Clubs (DAV/ÖAV) in the early 1980s, show a wide variability in test results and an alarming number of ice screw models (22 of the 33 tested) that could not sustain an impact force of 10 kN (Schubert & Mägdefrau, 1985; Damisch, 1985). These tests are conducted in the field on glacier ice and in the lab on ice made by wetting and refreezing crushed ice to mimic glacier ice. Several comparable loading methods are used, including dynamic drop tests with a falling weight, “static” pulls by 6 climbers loading a dynamic rope as swiftly

and as heavily as possible, and pulls from a mechanical tester at a pull rate of 20 to 30 mm/min. Loading rates for all tests are on the order of 100 N/sec. An “optimal” placement angle is determined based on balancing the pull from both the up and down direction – important for glacier work but less relevant to modern waterfall climbing. These findings have prompted improvements in the manufacture of ice screws and led to the Union Internationale des Associations d’Alpinisme (UIAA) Standard 151, which has been recently subsumed by the European Standard, EN 568. The standard requires ice screws to sustain a load of 10 kN at a 100 mm/sec tensioning rate in a refrozen, crushed ice slurry at -18°C with a 0° placement angle. The DAV/ÖAV studies and the resultant EN standard have improved ice screw safety by defining a standard testing methodology and setting a 10 kN threshold for minimum failure load.

Despite the intervening 20 years of improvements, recent climbing literature suggests that ice screws continue to make fickle anchors; they fail in both the lab and the field, and the failure sometimes comes as a surprise or occurs at a surprisingly low force. Ice screw “pulling out” makes a regular appearance as a contributing cause of climbing accidents. Climbers who experience ice screw failure often express consternation at the failure of ostensibly solid placements. Research shows a wide variation in the failure force (Harmston, 1997; Luebben, 1997). Typical standard deviations are on the order of 25% of the average (~ 20 kN, 5 kN std) implying that 1 in 10 ice screws fail at less than half the average and about 1 time out of 100 an ice screw will fail below 5 kN, well within the range of nominal forces produced during a climbing fall (Pavier, 1998) These recent results continue to emphasize the degree of variability in ice screw performance.

The variability exhibited, even in controlled lab situations, is further exacerbated by conditions in the field and the choices faced by climbers who must decide how and how often to place anchors. The Harmston and Luebben studies address the relationship between failure load and two variables that climbers can control: ice screw length and placement angle. The results for both variables run counter to conventional climbing practice; ice screw length has little effect on failure load and a positive placement angle correlates with higher failure load. Further elements that a climber might take into consideration are: the size of the ice feature in which the screw is placed, the structure and morphology of the ice, the internal stress state of the ice, the temperature, and the magnitude and duration of a potential fall. To our knowledge, conventional wisdom for all these situations has not been verified experimentally.

Our work repeated previous studies of placement angle and investigated the effect of two additional variables: ice type and strain rate. Placement angle was addressed because of the discrepancy between the previous studies and conventional climber practice. Ice type was addressed because of the discrepancy between the many types of ice found in the field and the few types that have been used in previous tests. Strain rate was deemed important because of the expected relationship between temperature and strain rate for materials like ice in which fracture is mediated by defect mobility; thus correlating the effects of fast loading rate are expected to correlate with low temperature.

Two further departures from previous work were introduced to perform the experiments in a safe and timely fashion. We have used 13 cm ice screws. The use of a short screw allows us to focus on the failure of the ice; the ice screw is not damaged in the test. Additionally, the 13 cm screw permitted a test on both ends of an ice cylinder whose dimensions were limited by the size of the tensile tester and the strength of the

experimenters' lower spines. Concern for our backs also drove our decision to make our ice cylinders in PVC tubes rather than in the steel containers used in previous works.

METHODS

This research characterized the failure of forty-three, 13 cm ice screws placed in ice and pulled to failure in a tensile tester. The test matrix is comprised of two ice types (water ice and aerated ice), two loading rates (125 N/s to 12500 N/s), and three placement angles (-30° , 0° , 30°). A positive angle indicates the ice screw is being tensioned along its length; a negative angle indicates compression.

ICE RECIPE

In order to test two types of ice, we needed to be able to make two types of ice in a timely and repeatable manner. We chose a "water" ice, frozen tap water, and an "aerated" ice, made by freezing a 3:1 mixture of tap water and carbonated water (seltzer water). The water ice was chosen because it closely mimics both field conditions and the ice in previous studies. The aerated ice proved simple to make and closely mimicked aerated ice found in the field; its appearance and "feel" when placing an ice screw were similar to ice that has either been formed during a snow event or been exposed to solar radiation for several days at temperatures low enough to preclude melting. The two ice types were characterized by measuring the density and compressive strength of cylindrical "puck" samples 16 cm in diameter. Density was determined by measuring volume and weight, and compressive strength was determined by crushing the samples between steel plates in an MTS testing machine at a fixed displacement rate of 0.508 mm/s. For ice screw testing, both ice types were produced in PVC pipe "buckets," cylindrical containers 30 cm in diameter (internal) and 40 cm in height; the PVC wall thickness was 15 mm. Filled PVC cylinders were placed in a freezer at -18°C ; a thin, flexible tube allowed water from the center to vent as the ice formed. Fig. 1 shows both a "puck" sample of aerated ice that has been dyed with food coloring to identify the air pockets and a PVC cylinder of water ice with vent tube.

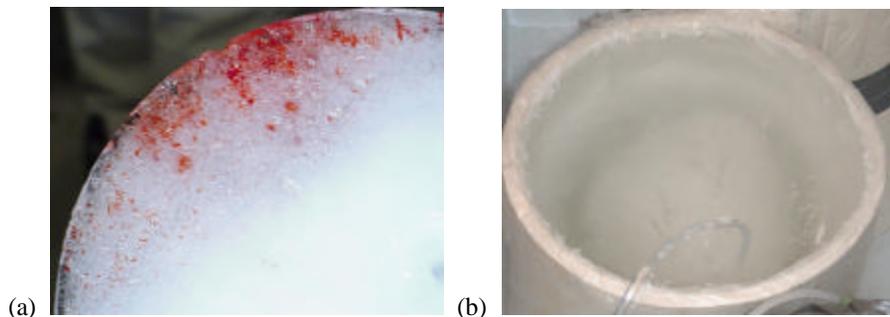


Fig. 1 A "puck" sample of aerated ice that has been dyed with food coloring identifying the air pockets (a), and a PVC cylinder of water ice with vent tube (b).

ICE SCREW TESTING

We used a 13 cm long version of a popular brand of ice screw. Ice screws were kept in the freezer with the ice samples (-18°C), screwed into ice cylinders within minutes of testing, and pulled to failure in an MTS tensile tester. Data were recorded at 500 Hz at an accuracy of ± 5 N. Our two pull rates were 25 mm/s (fast) and 0.25 mm/sec (slow), which translated to loading rates of 125 N/s to 12500 N/s respectively, rates that are representative of the fastest and slowest loading rates expected in field. Eight tensile tests were recorded on high-speed video to provide a qualitative, visual record of the failure. One of the high-speed video test cases was run with 22 cm ice screw to determine whether these longer ice screws fail in a fashion similar to the failure mode of the 13 cm version.

RESULTS

ICE CHARACTERIZATION

Our water ice pucks had a mean density of 0.913 g/cm^3 with a standard deviation of 0.0008 g/cm^3 ; aerated ice pucks had a mean density of 0.804 g/cm^3 with a standard deviation of 0.03 g/cm^3 . Compression tests showed similar mean compressive strengths for both water ice, 0.487 MN/m^2 , and aerated ice, 0.398 MN/m^2 ; large standard deviations ($\pm 30\%$) and insignificant F-test results from this measurement suggest that these compressive strengths did not differ statistically. The similarity between the compressive behaviors of these two ice types is shown in Fig. 2. A difference was apparent when observing the compression; after the tests were performed on water ice, the specimens froze to both the metal plates in the MTS machine and the fingers of the experimenters, whereas aerated ice was wet to the touch.

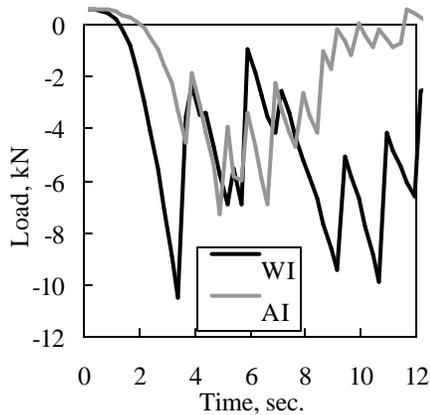


Fig. 2 Typical compressive failure results for water ice (WI) and aerated (AI) ice.

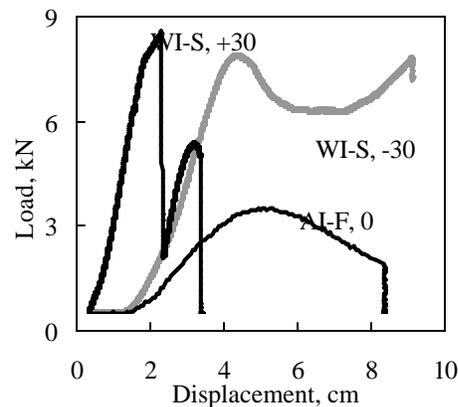


Fig. 3 Typical load/displacement curves. The peak values taken from graphs like this one are used to produce Fig. 4.

ICE SCREW LOADING

Typical load vs. displacement results are shown in Fig. 3. Once the initial slack has been taken out of the system, loading proceeded at constant rate. The failure load was taken as the first peak and the resulting data points are displayed in Fig. 4. In Fig. 4(a), lines are added to illustrate trends. The same data is shown again in Fig. 4(b) along with the data from Harmsten, Luebben and DAV/ÖAV for comparison.

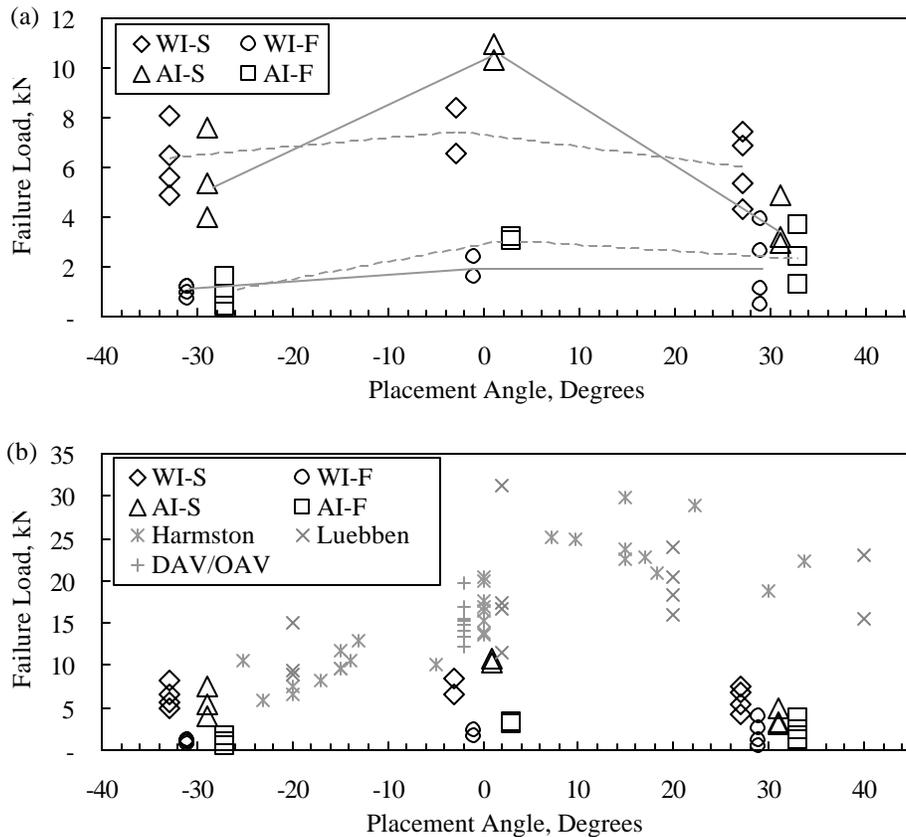


Fig. 4 (a) Failure load vs. placement angle data points for the 4 pairings of water/aerated and fast/slow load rate. WI is water ice, AI is aerated ice. F and S are fast and slow load rate. (b) Data from the Harmsten, Luebben and DAV/ÖAV tests are shown for comparison. Note that data points at -30° , 0° and $+30^\circ$ are expanded $\pm 2^\circ$ for clarity.

High-speed video footage provided evidence of a qualitative difference between the failure modes of the fast and slow load rates. Single frame images that portray fast and slow load rate behavior are shown in Fig. 5 along the same time line. Fast loading rates caused the ice screw to swiftly “slice” its way out of the ice. The failure mode at slow rates was characterized by the ice screw suddenly “popping” out of the ice. These failure

modes are reminiscent of failure modes in wood fasteners: axial pullout of screws and shearing failure in wood connectors.

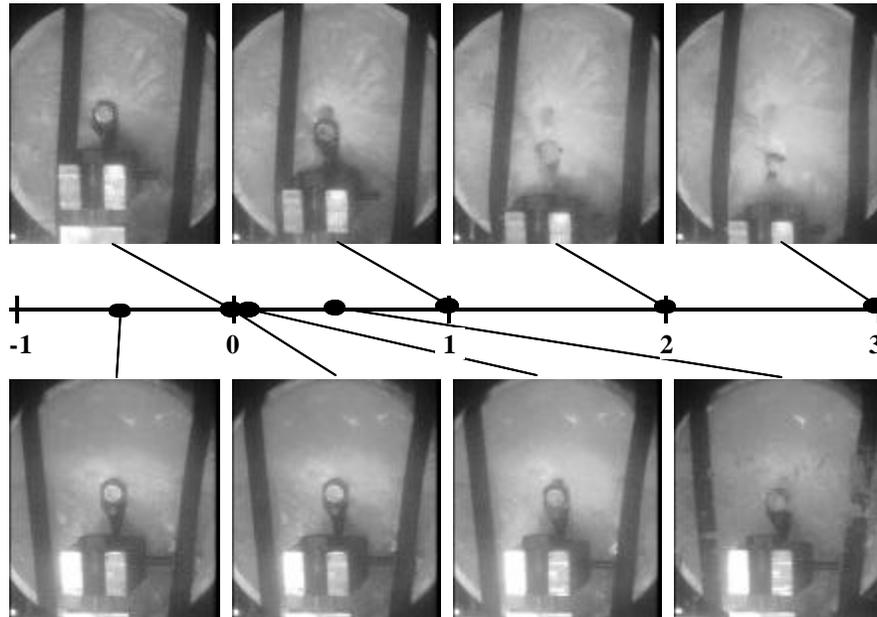


Fig. 5 Failure images from high-speed video. The timeline shown is in seconds. Failure initiates at $t = 0$. Fast load rate is shown on the top, slow load rate on the bottom.

DISCUSSION/CONCLUSION

We have further characterized the performance of ice screws by investigating how placement angle, loading rate, and ice type affect failure load and failure mode. Four trends are worthy of analysis: our low failure loads, the effect of loading rate, the complex relationship between angle, ice type, loading rate, and failure load, and the two failure modes observed in the high-speed video recordings.

The most significant result is our low failure loads. One possible reason for these low loads is our use of PVC rather than steel housing. Our first concern was that the ice screws were propagating cracks to the outer edge of the cylinder, but our spent cylinders exhibited no such fractures (with the exception of surface spaulding). Nor were such fractures visible in the high-speed video recordings. Because cracks do not extend to the edges, we hypothesize that the size of our ice cylinders is sufficient; this suspicion is supported by the 5 diameters rule of thumb for the cone of influence for fastening screws. Our explanation for the low failure loads is that two aspects of our procedure affected the stress condition of the ice: we used a venting tube to allow water to escape as the freezing progressed and the PVC allowed substantial expansion. In contrast, the ice constrained in the steel containers used in previous works cannot expand or escape, resulting in an internal stress condition absent in our tests. If this hypothesis is valid, then ice screw strength depends on the internal stress condition of the ice. Further research is needed to

confirm the dependence of failure load on the compressive state of the ice. In the meantime, climbers should consider preferentially placing ice screws in places where compression is likely, such as at the bases of columns, rather than at the top of curtains.

Our second most significant result is that a faster loading rate reduces failure load. A two order of magnitude difference in load rate results in a three-fold decrease in failure load. Loading rate is a factor that climbers can control through the use of skinny ropes, soft belays, and closely spaced ice screws. We suspect these precautions become more relevant as temperature decreases, effectively raising the strain rate. Further work should be done to determine the relationship between temperature and failure load.

Our third result is the complex relationship between placement angle, ice type, loading rate, and failure load. While all of our tests of negative placement angle were in agreement with the previous study results showing reduced failure load, our results for positive placement angles showed a complicated dependency on loading rate and ice type. Our data suggests a positive placement angle in aerated ice at a slow loading rate may result in a very low failure load. Climbers might consider 0° placement angles.

Finally, high-speed video shows two failure modes, which are previously unreported. At the slow load rate, the ice screw simply “pops out” of the ice, displacing only a little ice in the immediate vicinity of the ice screw. At the fast load rate, the ice screw “slices” a slot in the ice as it pulls out. These failure modes are very similar to those reported for wood fasteners (American Forest). Further refinements of ice screw design might increase the failure load under these distinct failure modes.

Overall, our research suggests that ice screw behavior is complicated, that it is sensitive to load rate, placement angle, temperature, internal ice stress state, and ice type, and that it is subject to two failure modes that correlate closely with load rate. Further study should address the relationship between failure load and both internal stress and temperature of the ice.

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