Simulating and Testing Ice Screw Performance in the Laboratory

Final Design Proposal

16.621

Fall 2002

Author: Warren Bennett

Advisor: Dr. Kim Blair **Partner: Stefano Alziati**

10th December 2002

Executive Summary

Ice screws are protection devices that allow climbers to anchor themselves to ice. This project is a response to the current lack of any controlled testing procedure for ice screws, and the perceived margin for improvement of ice screw design and usage in the field. This project develops a quantitative, repeatable test methodology for ice screws.

This project is of value to the technical and the climbing community because it will create a methodology for making 'climbing ice' types in the lab. The project will provide data on current safety standards of ice climbing equipment. It is also hoped that this study will reduce the failure rate in ice climbing by being the first step towards the improvement of such protective equipment, and in educating climbers about the limits of their equipment and how to use that equipment most effectively.

This project replicates natural ice formations in the laboratory by testing a set of methodologies of ice manufacture and analyzing the ice specimens obtained through a series of prescribed measurements. The objective is to obtain two distinctly different types of ice. Once repeatable ice formation has been achieved, the variables affecting ice screw safety can be tested in the test bed. All testing will occur on the MTS machine found in TELAC (Technology Laboratory for Advanced Composites). Statistical techniques will be used in the processing and presentation of data, and in evaluating the level of success of the project.

The projected budget for the project is $2,884. The bulk of expenditure is the purchase of the ice screws themselves at $50 per screw. It is hoped that sponsorship for this aspect of the project will be found through negotiations with equipment manufacturers.

The project schedule indicates that data collection will be completed in week 9, two weeks before the end of data collection in 622. This gives 2 weeks of leeway before the final day to collect data in 16.622 for potential problems.

Table Of Contents

List Of Figures

List of Tables

1. Introduction

1.1 Background

As a sport, ice climbing has been a growth area in the last 10 years. Ever since Yvon Chouinard introduced the first rigid crampons and curved ice picks in the late 1960's, climbers have been refining techniques and developing equipment in order to push the limits of ice climbing (see Figure 1).

Figure 1: Illustrating a climber on an ice face*

One of the current limitations on ice climbing is the strength of the anchors that the climbers use. Current research into better protection is based on anecdotal evidence and lacks a controlled methodology for test or evaluation. Ice screws are the main protection type; thus, for the purposes of this investigation, the focus is solely on ice screws.

* photograph taken by Luca Marinelli, exhibited courtesy of project advisor, David Custer.

Ice screws are pieces of climbing safety gear that are used as anchors on a route. This route can be led (when the climber places his own protection on the route) or top-roped (a rope anchored at the top of the climb). The climber is then attached to the screw by a carabiner through the hanger and is thus anchored to the climbing face. Figure 2 below shows an ice screw.

Figure 2: An ice screw

The ice screw itself consists of a hollow screw that is turned into the ice by use of a ‘hanger’ on its end. The screw first ‘bites’ the ice with a set of sharp, beveled teeth; as it is turned the ice is forced out through the center of the hollow screw. In order to reduce friction, both the inside surface and outside threaded surface of the screw are machined to be smooth. The screw is usually in the range of 10-22 cm long and has a diameter of 17 mm, the hanger is typically around 8 cm long. Screws can be made from steel or titanium.

Ice screws provide effective anchoring, if placed properly, but, like all protection devices, they are subject to the changeable nature of the ice environment. Proper placement is defined as placing the screw in good ice and at an orientation that allows the loading to be held by the screw threads, so the load path runs the length of the screw.

The essence of good ice protection is speed and reliability. The gear must be placed in tens of seconds to minimize climb-time and thus fatigue. It must also sustain the forces produce in the event of a fall (around 10 kN).

Existing research is lacking in the area of ice protection technology. There a few documented tests in the public domain, but these tests have not been sufficiently controlled. The statistics from these tests, notably the Harmston, Luebben study in 1997[1] and the study commissioned by Black Diamond,[2] lead to the conclusion that there is room for improvement in ice protection performance.

There have been numerous papers into the study of ice mechanics and also into the study of the rheological nature of ice. This forms the basis of the literature review in section 3.

1.2 Summary of Project

The motivation for this project is twofold. Firstly, the poor performance of ice screws in existing tests. Secondly, the lack of repeatability of the existing tests. It is believed that with a standardized testing procedure, ice protection improvement will be possible.

The project goals are, first, to produce a realistic simulation of the ice in the lab, and, second, to test the factors that affect the safety of ice screws and their placement. In order to realize this project, the procedure is:

1) Investigate and understand ice types and their formation
2) Develop a method of repeatably replicating the ice flows
3) Develop a controlled methodology for testing the factors that affect the safety of the placement of ice screws.

Successful completion of the primary goal will permit controlled testing and evaluation of ice screws and will allow the industry to initiate standardized testing of ice protection,

1.3 Value to Technical and Climbing Community

This project is of value to the technical and the climbing community because it will create a methodology for making "climbing ice" types in the lab. There is no data available on repeatable ice formation processes for testing ice-climbing equipment in the public domain. If ice is effectively simulated in the laboratory, the industry will be closer to setting safety standards and thus providing safer protection for climbers everywhere. An inexpensive, reliable and realistic lab-based testing method for ice protection would give strong support to the development of ice protection beyond its present state.

If the first part of the experiment is fulfilled, then this project will go on to provide data on current safety standards of ice climbing equipment. It is also hoped that this study will reduce the failure rate in ice climbing by being the first step in educating climbers about the limits of their equipment and how to use that equipment most effectively.

2. Statement of Project

Primary Hypothesis:

The structure and morphology of different types of ice formations can be characterized and simulated in a lab to provide a "test bed" useful for assessment of ice screws.

Secondary Hypothesis:

If the above hypothesis is true, then using the simulated ice, the variables affecting screw placement safety can be determined.

The objectives are then, firstly, to develop a repeatable means of reproducing ice in a lab and to characterize this ice using rheological data or to understand why ice cannot be simulated in the lab, and secondly, to use this ice model to test simulated falls on ice screws in a manner closely related to climbing conditions.

The success criteria that will be used to measure the project are:

1)
   a) If hypothesis 1 is true, then success is characterizing the critical rheological properties of ice.
   b) If hypothesis 1 is false, then success is identifying why ice cannot be made successfully.

2)
   a) If hypothesis 2 is true, then success is the development of a test for ice screw safety that produces consistent data and repeatable data.
   b) If hypothesis 2 is false, then success is identifying why ice screw performance cannot be characterized.

3. Literature Review

The three topics of the literature review cover: the understanding of ice, ice testing results, and ice screw testing.

3.1 Understanding Ice

This section covers ice structure, ice formation, and the micro mechanics of ice failure

3.1.1 Ice Structure

Ice is close to melting at the temperatures at which it is encountered in climbing (around 0º, according to the Harmston and Luebben study[1]). As such, it is a 'high temperature' material that exhibits a wide variety of behavior that is dependent on a number of factors. Ice can creep with little applied stress, or it can fracture in a brittle manner. Thus, classical solutions do not work for analysis of ice; it is neither a 'simple elastic' nor an 'elastic/plastic' solid. Instead, specific methods for its characterization must be undertaken.

According to Schulson[3], ice has 12 different crystallographic structures and 2 amorphous states. The particular structure formed most commonly in nature is the I_h-type. This is formed by simply freezing water and has a hexagonal structure (see Figure 3).

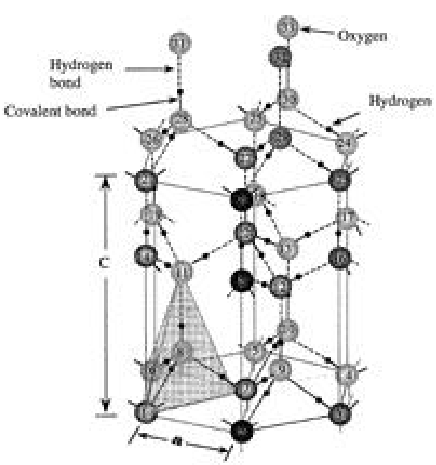

Figure 3: A schematic crystal structure of I_h ice

The oxygen atom is strongly covalenty bonded to the 2 hydrogens to form a single water molecule, but, when frozen, the water molecules themselves are bonded weakly by hydrogen-bonds. Vacancies in the structure are predominantly point defects. It is these, along with the dislocation density (the number of grain boundaries per unit volume), that determines the characteristics of the ice. The microstructure of the ice depends on its mechanical-thermal history.

3.1.2 Ice Formation (morphology)

There are 3 main ways of forming natural ice:

1. Heterogeneous nucleation at the surface of a slowly flowing water body.
2. Nucleation of frazil (Fine spicules, plates or discoids of ice suspended in water) particles that appear in a fast flowing, supercooled water masses.
3. The freeze up of snow or atmospheric ice nuclei falling into the water.

These starting points for ice formation must considered in the context of producing ice in a laboratory.

3.1.3 Micromechanics of Failure

According to Wu & Niu[4], the main reason for ice failure is due to impurities at grain boundaries disrupting the overall structure. These impurities initiate early melting and microcracks. The grain structure and orientation also affects the failure mode. This information is important to how the macroscopic ice structure is controlled (by addition of impurities for example).

3. 2 Ice Testing Results

This section of the literature review focuses on the methods used to characterize the engineering properties of ice.

3.2.1 Compressive Strength

The benchmark for compressive strength is set by uni-axial load tests on specimens in laboratories[5]. There have been numerous studies carried out on the ice *in situ* but analysis of these tests was hampered by the complex stress states set up within the ice.

Typical values for the range of compressive strength are from 0.5 – 10 Mpa.

3.2.2 Flexural Strength

Flexural strength is generally lower than the compressive strength for ice and typically ranges from 0.5–3 Mpa. It should be noted that the temperature up to –5ºC did not influence the flexural strength of the specimen.

3.2.3 Ice Rheology

The stress-strain behavior of ice is important to understand as it has relevance to any study involving ice as a working material.[5] In a general sense, ice is described as a viscoelastic material. The simple spring dashpot model for ice is shown in figure 4 below. This model attempts to simulate the 4 deformation mechanisms of ice:

1. Elastic deformation due to atomic bonds changing length.
2. Delayed elasticity due to sliding at the grain boundaries.
3. Viscous deformation due to dislocation movement within grains.
4. Deformation due to microcracks in the ice.

The total strain of the ice is usually thought of as the sum of all these components. This model allows for both the creep of the ice, and the ductile to brittle transition, as strain rates are increased. The fourth point is the most important in relation to the project as the ice screw itself initiates many microcracks, and the primary reason for ice failure is the propagation of those cracks.

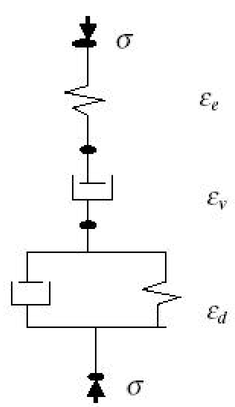

Figure 4: A spring and dashpot model of ice.[6]

The values of the spring and dashpot constants are dependent on a number of factors including the structure and temperature of the ice.

3.2.4 Temperature Dependency

It has been shown that, at temperatures up to –5ºC, the flexural strength of the specimen is not influenced by temperature.[5,7] However at temperatures near zero, it was the impurities at the grain boundaries that induced melting which meant that even the flexural strength of thick ice was zero. This change in behavior important for the project as this indicates a marked change in behavior around the temperatures of interest.

3.2.5 Impact Testing on Ice

A further study of particular relevance to the ice screw testing section of this project are a series of drop impact tests on laboratory and natural freshwater ice[7] conducted in the late 1960s by the Artic and Antarctic research Institute (AARI) and then again by the National Research Council of Canada (NRC) in the late 1980's.

Both tests consisted of dropping specially prepared 'impacters' of hemispherical surface of weights between 30 and 300kg onto the test surfaces from heights ranging from 0.02 to 1.6m metres. The measurements taken were the size of the imprint and acceleration record for the AARI tests, and the maximum pressure and penetration depth (taken using pressure transducers) in the NRC tests (from this the acceleration record could be calculated).

The results of these tests were compared to a hydrodynamic model. The model assumes that a thin layer of crushed ice develops during impact between the indenting body and the undamaged ice, and that its flow is similar to that of a thin layer of viscous fluid. The findings of this study most relevant to the project are:

1. The energy of mechanical crushing of ice depends on the ice state. This energy was up to 7 times more for cold winter ice in comparison to warm spring ice. The critical temperature was –5?C, either side of this the ice properties were significantly different. This agrees with the observation made in section 3.2.4.

2. Analysis of test data showed that, within the considered interval of impact velocities, impact crushing strength of freshwater ice decreased with increasing impact velocities linearly.

3. Theoretical predictions of maximum ice load and depth of penetration, based on the hydrodynamic model coincide closely with experimental data.

These findings indicate that a theoretical model can predict some properties of ice to a very high accuracy. However, the same model may not always predict different quantities to the same accuracy.

This impact testing is of direct relevance to our project because we expect impact results to correlate closely with ice screw performance.

This study is limited as it was carried out in an uncontrolled environment.

3.3 How to make Ice

Information on the making of the ice was gathered, via email, from a current expert in the field of ice mechanics, John Dempsey.[8] Full details on 'how to make (perfect) ice' is found in Appendix A. Appendix A gives information on test apparatus insulation, tips on repeatable crystal growth (such as the use of existing frost particles to nucleate ice grains in the specimen), and it also gives advice on how to allow for the expansion of the water on freezing. As indicated above, this will only produce one ice type, the most perfect ice that we can make. The methods for making other types of ice will be investigated in the preliminary testing stage, section 5.1.1.

3.4 Ice Screw Testing

Two studies are relevant to Stage 2 of this project:

3.4.1 The Harmston/Luebben Study

Harmston and Luebben[1] conducted tests that consist of placing ice screws into a natural ice formation and dropping a 185 lb weight from various heights, while statically attached to the protection point, giving forces of between 8 kN – 12 kN. The results from this test show that the screw ripped out of the ice 7 out of 12 times. A variety of variables were tested, including screw angle and screw length. The tests suggest that a downward angle for the screw is most effective and that a longer screw is more likely to hold than a shorter screw. The main conclusion drawn from the test was that ice conditions are so variable that it is difficult to accurately predict the holding strength of ice screw placement.

A critical examination of the test conditions suggest that many independent variables, including temperature, sun exposure and ice quality, were not controlled. Also, the uncontrolled method of dropping a weight onto the ice screw had no control over the strain rate.

3.4.2 Black Diamond internal study

Black Diamond Equipment has made its own investigations into ice screw effectiveness.[2] The tests consist of placing ice screws into an ice cell and then loading these cells in a Universal Test Machine. The ice cells are constrained by a steel container and prepared using untreated tap water. Freezing of the cells was at around –10ºC and the whole process took about 72 hours. Ice cells are regenerated 20 times, by simply filling in the damaged hole and refreezing, before being regenerated.

It was found in this study that the ice screws tested failed either by levering the hanger off the screw head, by breaking of the screw shaft, or by pulling the screw out of the ice. It was also found that the screw placement angle was a significant factor in how much load the ice screw could withstand.

The limitations on this study are the unpredictable and variable nature of the ice cells used for testing. The cell composition was not tightly controlled and regeneration of the cell is not consistent.

3.5 Summary

Ice failure occurs due to impurities initiating cracks on a microscopic level. There is a brittle–elastic behavior change as ice passes through -5ºC.

It has been found that, when subjected to loading in certain conditions, ice screws fail at loads that they are designed to hold. Current research in the area of ice screw testing lacks a controlled procedure for the repeatable testing of ice screws in ice. A study that regulates not only the ice screw testing but also the ice into which the screw is embedded would be beneficial to this area of research.

4. Technical Approach

This project adds to the knowledge base on the subject of ice screw testing by providing a controlled test environment. This study will bring quantifiable and repeatable results to the field of ice screw testing.

There are two distinct stages in the experimental setup of this project:

- The characterization of ice.
- The testing of ice screws in ice.

The main challenge is to repeatably create the structure and morphology of ice in the lab. Once the ice formations can be created in a laboratory, a realistic testing method can be devised. The major hurdle is in creating the different types of ice encountered by climbers. These ice types range from good ice (pure, transparent and crack free) which is thought to be the safest, to *hollow, layered, slushy, aerated* and *chandeliered* which are all thought to be poor ice types for screw placement. This descriptive basis for the ice is then converted to quantitative properties based on analysis. Not all the ice types can be created and tested owing to the timescale of 16.622. Therefore, two ice types were chosen (see section 5.1.1 for further details).

The first step towards a controlled methodology for ice screw testing is thus the ability to characterize the ice and make it consistently. This step entails defining a process and then being able to test the ice for certain properties and gaining repeatable results.

Once the ice test-beds have been developed so they are representative of climbing conditions, the ice screws can be tested. Initially, the screws will be tested on 'perfect' (flawless) ice. Comparisons between with results from the previous tests (Harmston and Luebben[1] and the Black Diamond study[2]) will be conducted. This is the control. When testing the ice screws, the independent variable will be the screw placement angle. The variables chosen are to be limited owing to the time-scale of the course.

5. Experimental Design

5.1 Basic Concepts

This section explains the planned experimental procedures for the project.

5.1.1 Preliminary Testing

This stage involves experimenting with different types of ice and finding the most effective method of creating repeatable ice. To this end, possible methods for making the different kinds of ice will be investigated. The factors under test will be air and impurity concentrations in the ice, the critical levels of which will be obtained. One particular issue to be addressed is the effective production of distinctly different types of ice (based on their properties).

From this preliminary testing module, two different types of ice, named ABS1, and ABS2 (Alziati & Bennett Standard #) will have been obtained. It is hoped to produce a sample of 'perfect' ice (few cracks, no aeration, no particulates), and a sample of either aerated ice, or 'dirty' ice (high particulate concentration).

The potential strategies for creating the aerated ice are as follows:

1. Drill air holes into the ice.
2. To use a mixture of crushed ice and water close to freezing point.
3. Suspend small pockets of air in the ice mix (using tethered balloons)
4. Construction of a specialized rig that constantly blows air through the ice mix.
5. The use of soda water or carbonated water.
6. A combination of these strategies.

The most effective method for creating aerating ice will be determined during the preliminary testing stage of the project. The method will be chosen based on the best combination of speed, ease of production, and quality of ice produced.

The creation of these 'bad' types of ice is not a widely documented subject. Hence, it is extremely difficult to say exactly how the specimens will be made. However, limited preliminary testing of 'bad' ice during the Fall Semester 2002 has yielded some interesting discoveries. Encouraging results have been obtained in making small-scale formations with carbonated water.

One further decision to be investigated during preliminary testing is the size of the ice specimen. The specimen must be large enough to have a screw inserted into its body and not show any visible signs of stress, and it must be small enough to carry manually.

A further option for ice production is the purchase of prefabricated ice.

5.1.2 Stage 1: The Characterization of Ice

This stage will consist of testing the mechanical properties of the two different types of ice produced, named ABS1 and ABS2. The methodology for creating these ice types effectively will have been developed in the preliminary testing. Each ice type will have properties that are measured to be significantly different. The objective of this stage is to characterize each ice type in terms of its physical and mechanical properties.

First, the physical properties of the ice produced (density, purity) will be measured. The density will be calculated by measuring the volume and the weight directly; the volume itself will be measured by recording the amount of water the specimen displaces. Purity will be measured by weighing the mass of particulate added to the water before freezing. Second, to characterize the ice specimens mechanically, specimens will be put under standard tensile and compressive tests in an MTS machine (see figures 5, 6 and 7). As shown in figure 6, the tensile test plates will be frozen into the ice specimen and then pulled. A notch will be machined into the specimen to ensure that failure does not occur at the plate/ice interface. The MTS machine will apply a gradually increasing force until the failure occurs. For the compressive test, the ice specimen will be placed between the plates of the MTS machine, and a compressive force will be applied, as shown in figure 7. For the characterization stage, the cylindrical ice specimen dimensions will be 10 cm diameter and 15 cm in length.

From these tests the material properties of tensile strength, and compressive strength will be measured directly. The Young’s Modulus will also be evaluated from the results of the tests. A computer records the displacement, load, and time data from the MTS machine.

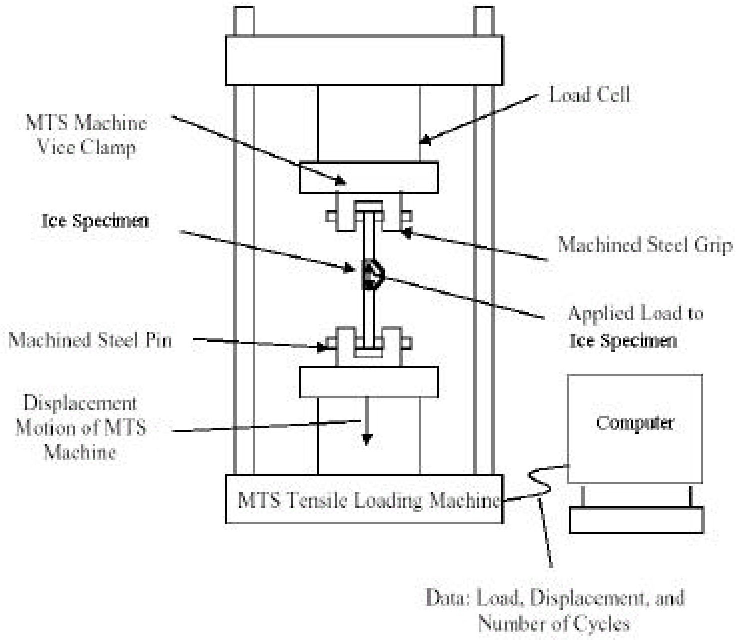

Figure 5: MST test apparatus in TELAC.[9]

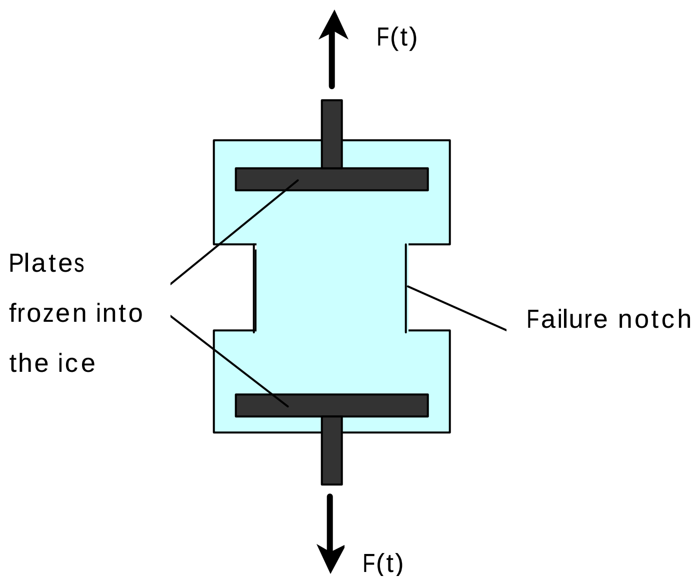

Figure 6: Schematic of tensile test

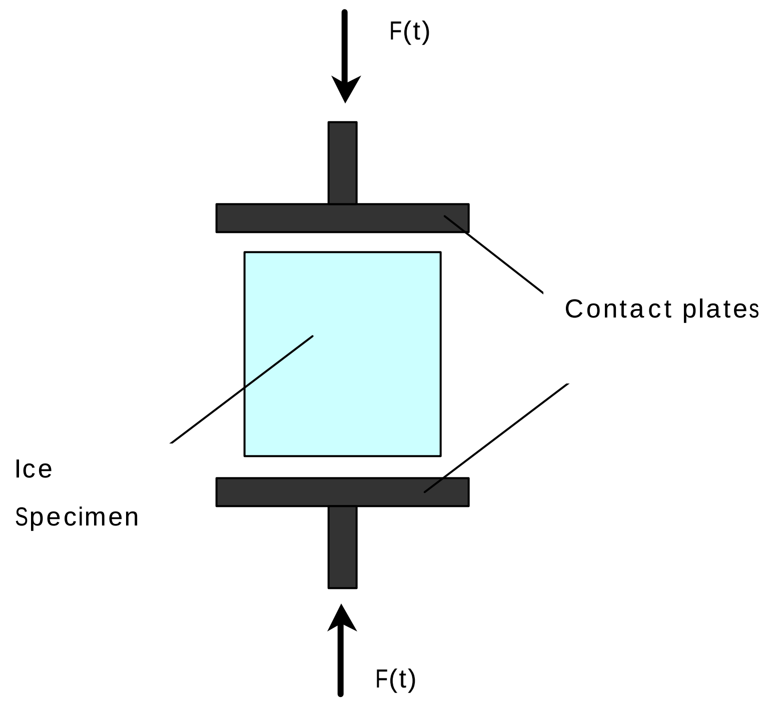

Figure 7: Schematic of compressive test

The third test that will be carried out is an impact test. For this test a heavy steel ball will be dropped from a fixed height onto the ice surface. The radius of indentation will then be measured and the impact toughness can be calculated. An illustration of this is shown in Figure 8.

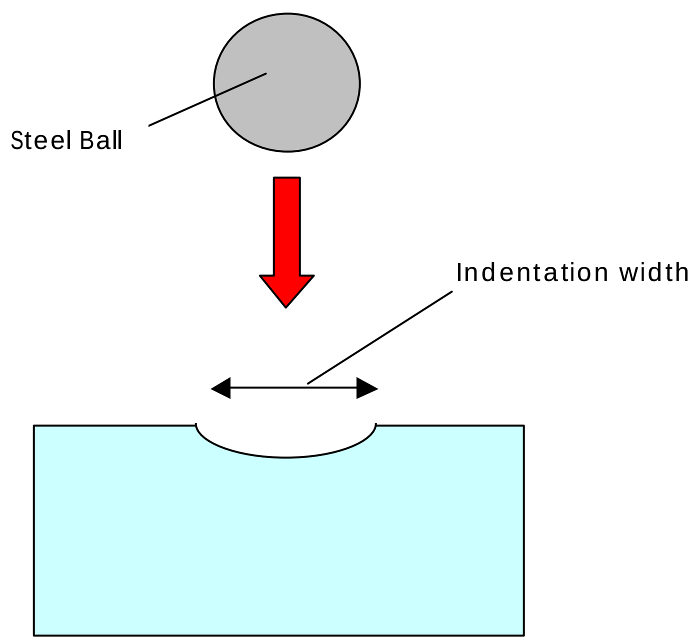

Figure 8: Impact testing

Testing of each specimen will be carried out at two different temperatures either side of the critical -5?C temperature where the ice properties change from elastic to brittle.

The making of each specimen will be carried out according to a combination of both the recipe prescribed by Dempsey[8] (please see appendix A) and of the processes examined in the preliminary experimentation.

5.1.2 Stage 2: Testing of Ice Screws in Ice

Once the ice types have been produced and mechanical characteristics measured, the effect of placement angle on ice screw safety will be tested on each ice type (see figure 8). Each of these tests will be conducted at values of –15?, 0?, and 15? of ice screw angle placement. This angle is measured relative to the perpendicular of the ice face, where positive is above and negative below (as illustrated in figure 9). The loading of the specimens in the MTS machine will be under two regimes:

?? Impact Strength

The impact strength will measured by fast loading of the screw. The load rate will be at 10kN per second, which is the approximate load rate of a falling climber. This will be increased until failure.

?? Low load rate

This regime is at a low load rate of around 0.1kN per second (a factor of 100 below the Impact Strength regime above).

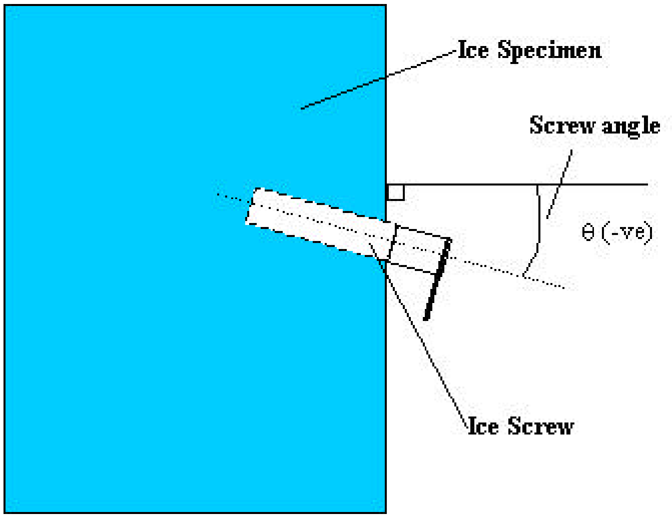

Figure 9: Ice screw placement angle

These ice screw tests will be carried out in an MTS machine (figure 5). A computer will record the displacement, load, and time data.

The rig that will hold the cylindrical ice specimen in place during testing is shown in figure 10. The rig consists of a piece of sheet steel folded into a configuration that will give maximum contact area over the ice/steel interface. For a detailed plan of the mounting apparatus please see Appendix B. The specimen will be placed inside this large angle and strapped on using canvas ties and ratchets. The ties will also support the ice against premature cracking when the ice screw is placed in the end of the specimen. Then the entire apparatus will be screwed onto the steel base plate of the MTS machine. The ice screw will be attached to the MTS ram by means of clamps (see Appendix C).

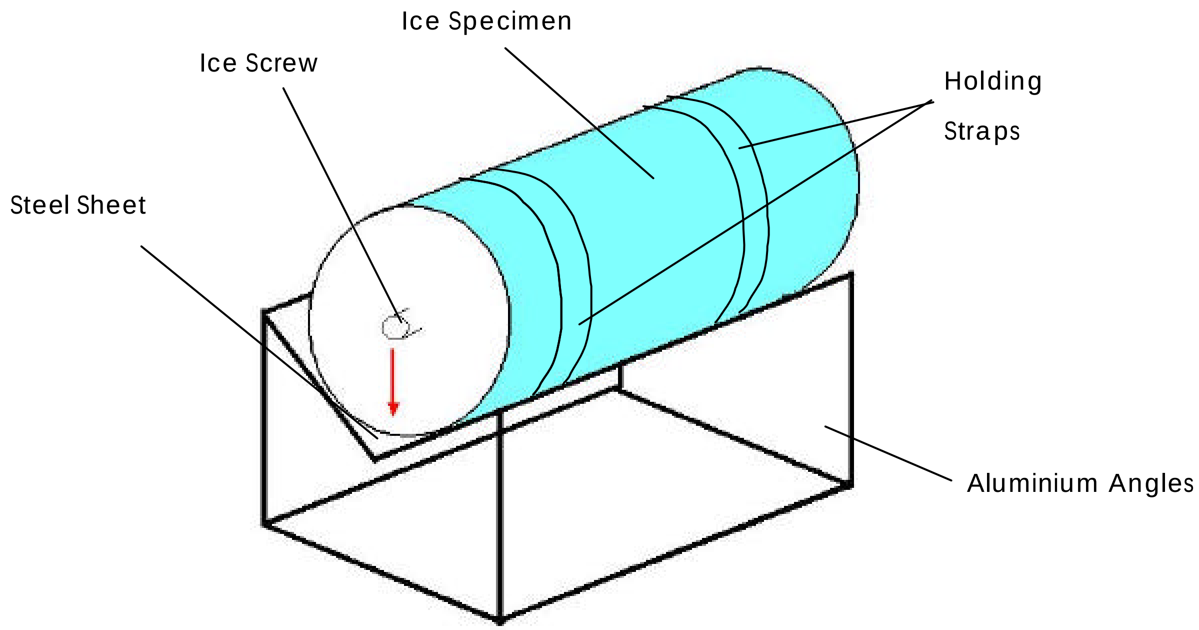

Figure 10: Showing the rig for securing the ice specimen during stage 2.

It should be noted that a new ice screw will be used for every test. Identical ice screws will be used for all experiments.

For this stage of the experimentation the dimensions of the ice specimen will be around 30 cm in diameter and 40 cm in length. However, as stated before, the exact dimensions have yet to be determined in the preliminary testing stage.

5.2 Error Analysis

The main source of error comes from the unpredictable nature of ice fracture. This will be handled with the use of statistics (see section 6.2). Before applying the statistical analysis techniques, the systematic errors must be identified. This will leave only data variation due to the unpredictable nature of ice.

The errors associated with this project are located mainly in the measurements that will be taken throughout testing. The greatest source of error lies in the MTS loading machine, which is accurate to a tolerance of ±13N. At a testing load of 2kN this represents an error of 0.65%, which is very small.

Other possible errors are associated with the measurement of length, temperature and volume and mass:

- Lengths: The MTS machine quotes measurements to an accuracy of ±0.1 mm. This equates to an error of 0. 5-1 % based on lengths of possible ice screw movement.
- Temperatures: Temperatures are measured to an accuracy of one decimal place using a thermocouple and digital readout. The errors associated with this are 0.5 – 2.5 %.
- Volume measurements will be made by recording the amount of water displaced by the ice specimen. The errors associated with this are 0.5%
- Mass will be measured using an electronic balance accurate to 3 decimal places. The errors associated with this are small enough to be neglected completely.

Therefore the total probable error in this project is around 5 %.

5.3 Test Matrices

The test matrices for the project are laid out below with details on the dependent and independent variables. Owing to the erratic behavior of ice, all characterization and ice screw tests will be repeated 4 times, and statistical techniques applied to obtain the 'true' values, thus the blocks in the test matrices represent 4 data points.

5.3.1 Stage 1: Production of Ice and Testing of its Mechanical Characteristics

The independent and dependent variables for stage 1 are listed below. These are followed by a diagram of the test matrix for this stage.

The measurements taken in this stage will occur in 2 different modes:

Firstly, the identification measurements will be taken:

1. Mass of ice formed (kg)
2. Volume of ice formed (m^3)
3. Mass of impurity dissolved in water (kg)

Secondly, the measurements taken from the tensile, compressive and impact tests will be the following:

Independent Variables

The controlled variables in this stage are:

1. Temperature of ice: initially two values will be set at -2?C and -10?C, but may be subject to change according to the refrigeration unit's capabilities.
2. Ice type will be changed: ABS1, and ABS2 will be tested at each of the above temperatures.

Dependent Variables

The values that will be measured from the tests at this stage are:

1. Stress level at tensile fracture (N m^{-2})
2. Stress level at compressive fracture (N m^{-2})
3. Extension of the ice specimen after fracture (m) [Tensile and compressive tests]
4. Depth and radius of indent (m) [Impact test]

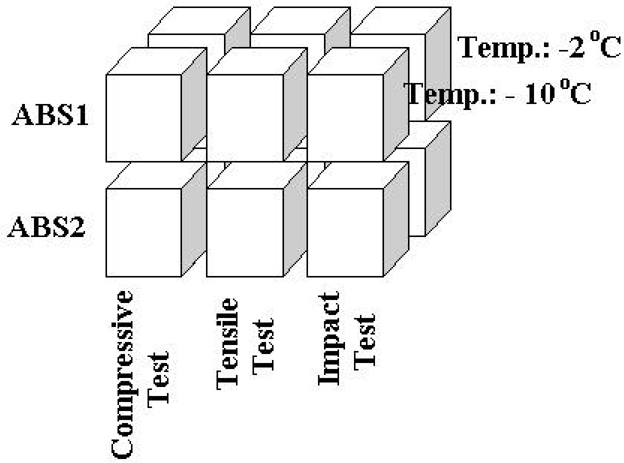

Figure 11: Test matrix for stage 1 (each block consists of 4 data points).

5.3.2 Stage 2: Testing of Ice Screws in Ice

The independent and dependent variables for stage 2 are listed below. These are followed by a diagram of the test matrix for this stage.

Independent Variables

The controlled variables in this stage are:

1. The screw angle will be varied between +15? and -15?
2. Ice type will be changed: ABS1 and ABS2 will be tested at each screw angle.

Dependent Variables

The values that will be measured at this stage are:

1. The load at which the ice screw pulls out under the high load rate regime (kN)
2. The load at which the ice screw pulls out under the low load rate regime (kN)

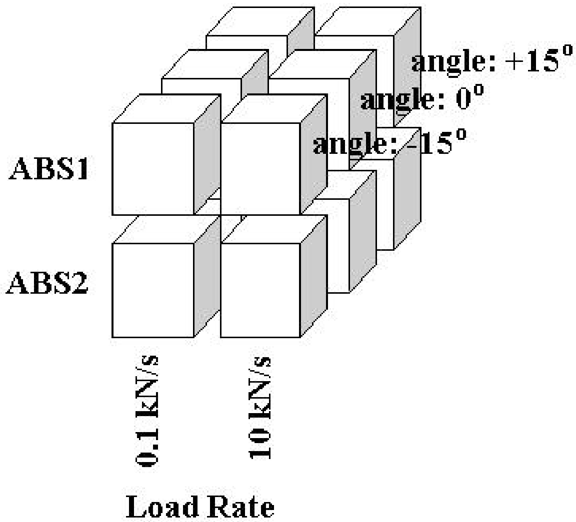

Figure 12: test matrix for stage 2 (each block consists of 4 data points).

5.4 Safety Concerns

The major safety concern connected to working with subzero materials is that prolonged exposure can lead to frostbite. To avoid this, gloves will be worn when handling ice.

It is also expected that the ice specimens will be of considerable size and weight. Hence when moving these specimens, caution must be exercised to avoid back injury.

Lastly, ice is a brittle material and will facture on impact. Thus, safety goggles should be worn when testing the ice, to protect against flying ice chips. Also, shielding will be set up around the test specimen.

During all experimentation TELAC (The MIT Technology Laboratory for Advanced Composites) safety procedures will be followed.

6. Data Analysis

6.1 Data Processing

6.1.1 Stage 1: Production of Ice and Testing of its Mechanical Characteristics

Data processing in stage 1 will involve the use of equations 1 and 2 to provide the value of the Young's Modulus, E,. The MTS computer will give the values of the force applied at failure via a digital read-out. The only processing that must be done here is dividing this force by the cross-sectional area of the plane of failure to obtain a value of the stress level, $?_x$.

$$?_x \ ? \ \frac{?l}{l} \quad [1] \qquad\qquad E \ ? \ \frac{?_x}{?_x} \quad [2]$$

6.1.2 Stage 2: Testing of Ice Screws in Ice

Data processing from stage 2 will comprise recording MTS digital read-out of forces at failure. After error analysis and accounting for offset measures, these are the values that will be quoted in the experimental results.

6.2 Data Reduction

To reduce the data, a statistical approach will be taken. Owing to the random nature of the behavior of ice, each individual test will have to be repeated a certain number of times so that statistical techniques can be used. The experiments will be repeated four times only, due to time constraints. Ideally, good results would yield a standard deviation smaller than the mean value and a skewness of the same order of magnitude as the standard deviation.

To illustrate this point, figure 13 shows some distributions that might be expected. If the scatter graph for the experiments looks like graph 1 in Figure 13, then no more experiments need to be carried out. If, however, the scatter of data is similar to graph 2, then the number of experiments should be increased in order to reduce the standard deviation. Unfortunately, as stated before, this could prove difficult owing to the time constraints. The problem is balancing the need for statistical significance with the time available.

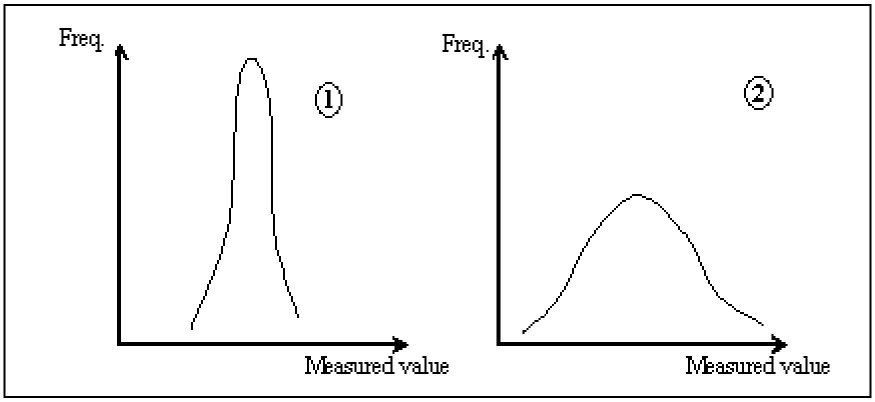

Figure 13: Graphs showing scattered normal distributions

1) Low standard deviation

2) High standard deviation

6.2.1 Stage 1:

The mean and the standard deviation of the results will be taken. The values obtained will be fitted to a normal distribution and the confidence level of the values for tensile and compressive strength, E, and impact strength will be ascertained. Further statistical measures that will be investigated are the mean square value and the t-statistic test. These tests will indicate the consistency of the data and hence the level of success in achieving repeatability in the results.

6.2.2 Stage 2:

Again the mean and the standard deviation of the data obtained will be obtained and fitted to a normal distribution to obtain a confidence level for each test. The mean squared value will be analyzed, as will the t-statistic and so the degree of confidence in the distribution will be ascertained.

6.3 Correlation

In order to prove the first hypothesis is correct the results of stage 1 will be analysed, and, if consistent, then the ice types produced have been made in a controlled repeatable fashion and therefore simulate ice effectively. Successful characterization is defined as obtaining recorded mean measurements for 'good' ice that lie within one standard deviation of the quoted values in the available literature. Successful characterization of bad ice is defined as obtaining data with a standard deviation of the same order of magnitude as that obtained for good ice. There is no data available for comparison of previously recorded values.

The second hypothesis will be proved correct if there is a definite trend of repeatable data from the various loading measurements. This will show how the placement angle affects ice screw safety. Repeatable data is defined as having a standard deviation of less than 15 % of the mean value. The data in the Black Diamond study[2] had a standard deviation of approximately 25 % of the mean value. It is believed that 15 % is a figure that would be acceptable as an industry standard test.

7. Project Planning

7.1 Budget

The most expensive part of the budget is the ice screws. At $50 per piece, they provide the bulk of the cost. To address this issue, potential sponsors, including Black Diamond, the world leaders in ice screw manufacturing, have already been contacted, as can be seen in the schedule below. It is strongly anticipated that a sponsor will be found through various contacts in the climbing community. This will bring the cost down considerably to around $150.

The budget is summarized in the table 1. All figures are based on market costs.

Table 1: The proposed budget

Item	Availability	Quantity	Real World Cost	16.62X Cost
MTS Machine use	MIT	5 days	$2,500	donated
Machine Shop	MIT	Unknown	unknown	donated
Test Rig	MIT	Unknown	unknown	donated
Refrigerator	MIT	Unknown	unknown	donated
Ice Screws	Order	54	$2,700	$2,700
Carabiners	Order	6	$30	$30
Slings	Order	4	$24	$24
Ice Boxes	Order	4	$40	$40
Building Materials	MIT/Order	1	$50	$50
		Total:	$5,344	$2,884

7. 2 Schedule

The proposed schedule for 16.622 and the remainder of 16.621 is shown in Table 2.

The preliminary testing has commenced in the 16.621 Fall semester and will proceed through most of February. The success of the preliminary experiment and discovery of sponsors will be presented in the first oral progress report on 27th of March. The ice screw testing will be run in the lab for a maximum of three weeks. The project is predicted to be finished by week 9. This gives 2 weeks leeway in terms of the 622 deadline for unforeseen circumstances. Data analysis will then proceed until the middle of April. From then on, preparations will be made for the oral final report and the written final report.

Table 2: The proposed schedule

ID	Task Name	Start	End	16.621	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	**Shop Demonstrations**	**5-Feb**	**7-Feb**																
2	**Construction**	**4-Nov**	**15-Mar**																
3	Build Test Rig	16-Feb	22-Feb																
4	Build Insulating Box	16-Feb	22-Feb																
5	Conact sponsers	4-Nov	15-Mar																
6	Order materials	4-Nov	15-Mar																
7	**Stage 1**	**22-Oct**	**15-Mar**																
8	Preliminary Testing	22-Oct	22-Feb																
9	MTS Acquaintance	9-Feb	15-Feb																
10	Ice Testing	23-Feb	15-Mar																
11	**Stage 2**	**16-Mar**	**5-Apr**																
12	Ice Screw Testing	16-Mar	5-Apr																
13	**Reports and Presentations**	**27-Feb**	**13-May**																
14	Oral Progress Reports	4-Mar	6-Mar																
15	Last day to collect data	18-Apr	18-Apr																
16	Progress Review	11-Feb	3-Apr																
17	Final Presentaion	29-Apr	1-May																
18	Final Written Report	13-May	13-May																

7.3 Facilities Required

The MIT Technology Laboratory for Advanced Composites (TELAC) will host all testing. TELAC is equipped with an MTS machine that will be used to load the ice specimens and ice screws. The necessary refrigeration unit required to freeze the ice specimen is located nearby the MTS machine. Storage space for the test equipment is also required.

Required construction materials are steel brackets, rods, plate, and miscellaneous bolts, nuts, etc. for attachment. Additionally blue foam will be used to insulate the steel case.

The MIT Gelb laboratory contains all the necessary metal tools to construct the apparatus required. Items that must be constructed are the steel plates for the tensile loading, the casing (depicted in figure 10) for holding the cylindrical ice specimen and the insulated box for making the ice specimens in.

8. Conclusion

In summary, this project will be a first step towards improvement in ice climbing safety and the education of climbers in the limitations of their equipment.

A successful project will be the simulation of the ice in the laboratory, or the understanding of why ice cannot be effectively simulated in the laboratory. If ice can be simulated in the laboratory, then the second success of the project will be the understanding of how ice screw placement angle affects safety.

9. Acknowledgements

My project partner and I would like to extend our thanks to the following people:

Our advisors, Dr Kim Blair and Dave Custer whose patient guidance and tremendous enthusiasm have been a constant source of inspiration.

Professor John Dempsey (Clarkson College) whose expert guidance on difficult issues has been invaluable.

Nemo Equipment Climbing Company whose expert insight into the sport of ice climbing has been instrumental in the development of the project.

And of course the 62X Faculty and staff with a special mention for John Kane and Dick Perdichizzi whose experience in the sphere of project testing has proven essential.

10. References

1. Luebben, Craig, 'The Cold Truth – How Strong is Ice Protection?', *Climbing Magazine*, November 1997, pp. 106 - 115

2. Harmston. C, 'Myths, Cautions and Techniques of Ice Screw Placement', Internal Report, Black Diamond Equipment, July 1998.

3. 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.

4. Wu, M. S., Niu J., "Prediction of ice failure by Micromechanics", *AMD Ice Mechanics*, Vol. 163, 1993, pp.35-49.

5. T. Nakato, R. Ettema, Issues and Directions in Hydraulics (A.A. Balkema/ Rotterdam/ Brookfield/ 1996.

6. LØset S., "Thermomechanical Properties of Materials, examintaions May 24 1997 (0900-1300) - Brief solution", Norwegian University of Science and Technology (NTNU) Faculty of Civil and Environmental Engineering Department of Structural Engineering, www.bygg.ntnu.no/~sveinulo/at204/at20497/at204s97.pdf, 10/10/02.

7. Likhomanov, V., Stepanov, I., Frederking R., Timco G. W., "Comparison of Results of Impact Tests on Laboratory and Natural Freshwater Ice with Hydrodynamic Model Predictions", *The Proceedings of the Eighth (1998) International OFFSHORE AND POLAR ENGINEERING CONFERENCE*, Vol. 2, 1998, pp. 453-459

8. Email from Ice Expert John Dempsey, Clarkson College, Putsdam, New York. Email: john@clarkson.edu, 09/30/2002

9. Okal, M., 'Carabiner Testing', *16.621 Final Report, Spring 2001*, pp. 8-10.

Appendix A – Recipe for Ice Formation

Forwarded message from John Dempsey john@clarkson.edu
Date: Mon, 30 Sep 2002 10:35:05 –0400
From: John Dempsey john@clarkson.edu
Reply-To: John Dempsey john@clarkson.edu
Subject: Re: Information on ice
To: salziati@mit.edu

Stefano and Warren,

Please give my regards to Professor Parks. I'll give it a go. What size freezer do you have? Larger blocks will produce better results.

Suppose that you make up a cube of a box (quite well made so that it does not leak)-make it out of some softwood so that it absorbs water?? Cube of dimension N cm; suppose N is something like 25. Now insulate the bottom and all sides of the box; could just use that blue styrofoam but make the wall thickness of the order of 12 cm.

This is to stop any freezing nucleation on the sides or bottom. Now fill the box with cold water and put it in the freezer-prepare for leakage because the ice will try to expand outwards---which is why you want as much surrounding insulation as possible.

If you have the patience, monitor the temperature and stir that water so that it all cools more or less uniformly; right near freezing use some of the frost in the freezer as seed crystals and float the frost on top.

This method should give you repeatable clear blocks - the slower you grow the ice the better it will be in terms of say dislocation density etc.

Oh, almost forgot, you need a pressure release under the ice as it grows-like a pipe fitted to the side at the bottom-insulated or wrapped in heat tape, so that as the ice grows down, it will push water out the pipe-angle the pipe to maintain more or less the same pressure (head). In other words, let this excess water drip into a bucket or some such.

Be careful of thermal shock-let the ice warm up slowly. You can work at 0 Celsius or very near. I have observed with warm ice, that when you turn ice screws into it, you get these very fine radial crack under the expansion-interesting.

Temperature of the ice is probably your main variable. Let me know how this goes.

John Dempsey, Prof

Appendix B – Engineering Drawings, MTS Mounting Apparatus, Stage 2 testing

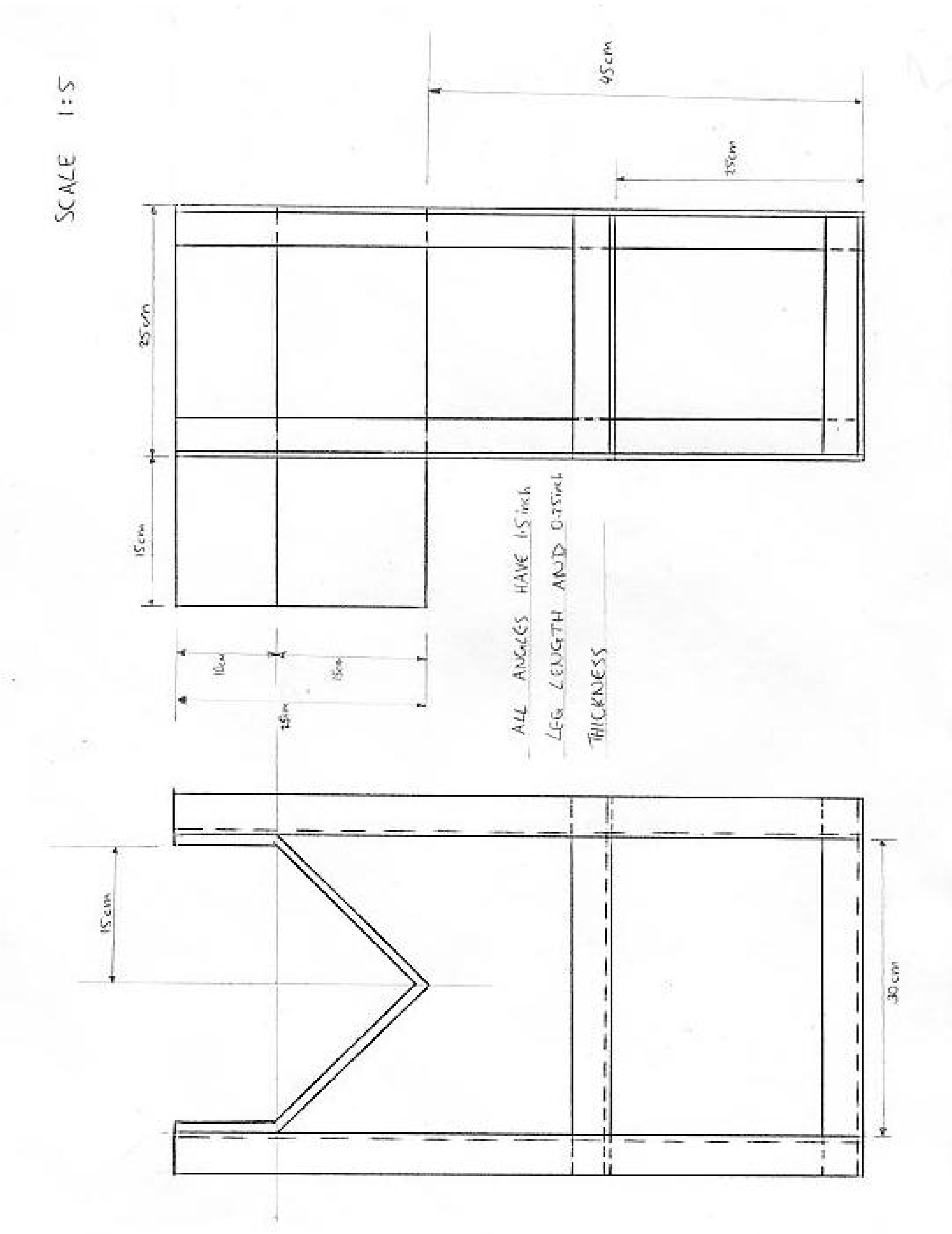

Figure 14: Front and right-hand views of stage 2 MTS mounting apparatus.

Appendix C – Engineering Drawings, ASTM Grips

The full dimensions of the four components of the total ASTM grip set-up are shown below. All dimensions are given in inches as the machinery in the Gelb Laboratory operates with English units.

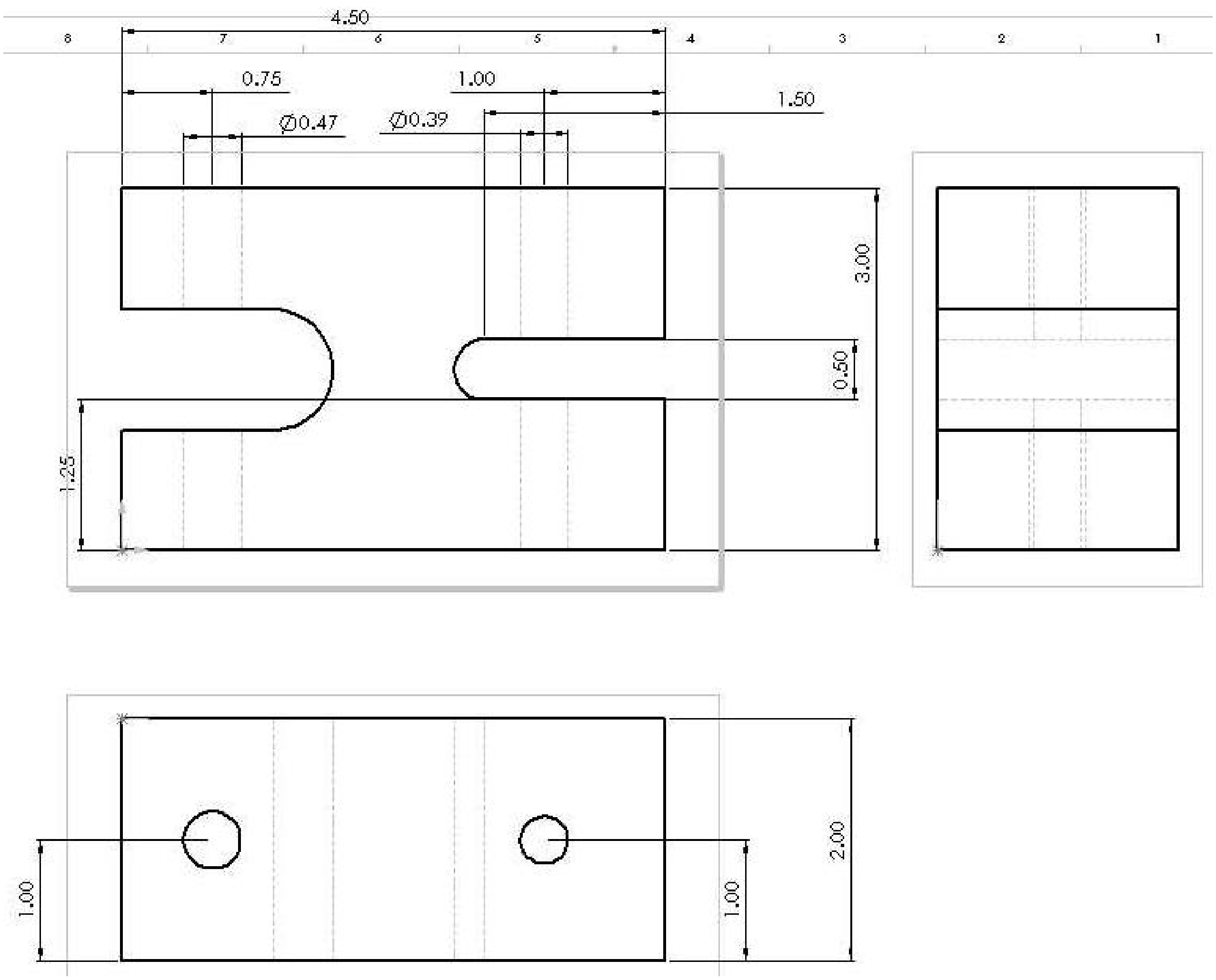

Figure 15: Third angle projection of main ASTM grips.

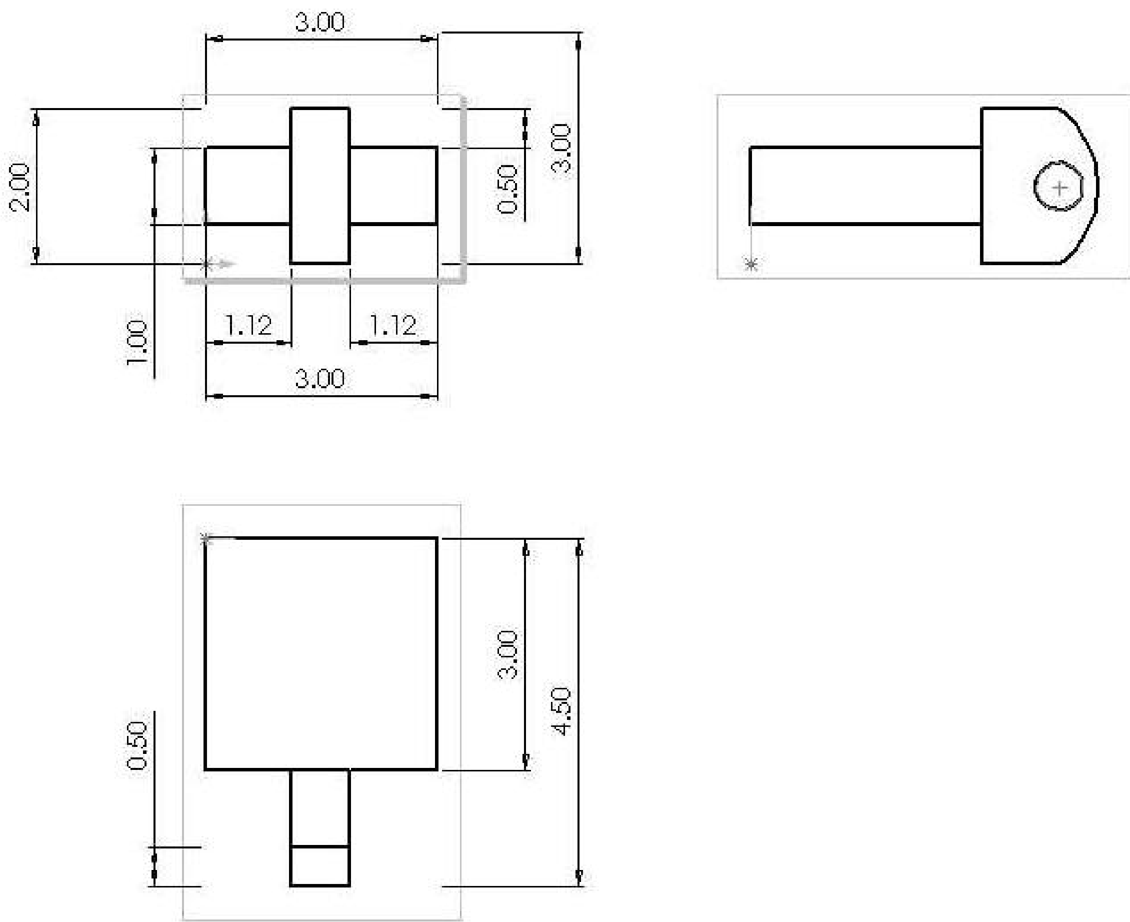

Figure 16: Third angle projection of the connectors.

Appendix D – Detailed Parts List

Parts include:

- ?? MTS Machine
- ?? Refrigerator: temperature controllable between 0°C - -20°C
- ?? Thermocouples and digital readout
- ?? Grips for MTS machine: ATSM
- ?? 54 Ice Screws: Black Diamond
- ?? Electronic Mass Balance: correct to 3 decimal places
- ?? Measuring Cylinder: 40 liter capacity
- ?? Impurities (dirt, sand, grit, etc…)
- ?? Aluminium angles: 8 ft long, leg length 1.5 inches, thickness 0.25 inches
- ?? Steel plate: 40cm x 65cm
- ?? Assorted Nuts & bolts
- ?? 10, 000lb Load Cell: As agreed with Dick Perdichizzi
- ?? Soda Siphon

[1] Luebben, Craig, 'The Cold Truth – How Strong is Ice Protection?', Climbing Magazine, November 1997, pp. 106 - 115

[2] Harmston. C, 'Myths, Cautions and Techniques of Ice Screw Placement', Internal Report, Black Diamond Equipment, July 1998.

[3] 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.

[4] Wu, M. S., Niu J., "Prediction of ice failure by Micromechanics", *AMD Ice Mechanics*, Vol. 163, 1993, pp.35-49.

[5] T. Nakato, R. Ettema, Issues and Directions in Hydraulics (A.A. Balkema/ Rotterdam/ Brookfield/ 1996.

[6] LØset S., "Thermomechanical Properties of Materials, examintaions May 24 1997 (0900-1300) - Brief solution", Norwegian University of Science and Technology (NTNU) Faculty of Civil and Environmental Engineering Department of Structural Engineering, www.bygg.ntnu.no/~sveinulo/at204/at20497/at204s97.pdf, 10/10/02.

[7] Likhomanov, V., Stepanov, I., Frederking R., Timco G. W., "Comparison of Results of Impact Tests on Laboratory and Natural Freshwater Ice with Hydrodynamic Model Predictions", *The Proceedings of the Eighth (1998) International OFFSHORE AND POLAR ENGINEERING CONFERENCE*, Vol. 2, 1998, pp. 453-459

[8] Email from Ice Expert John Dempsey, Clarkson College, Putsdam, New York. Email: john@clarkson.edu, 09/30/2002

[9] Okal, M., 'Carabiner Testing', 16.621 Final Report, Spring 2001, pp. 8-10