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A WORKMAN'S GUIDE TO IN SITU SEA ICE FRACTURE TESTING

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ABSTRACT
In situ sea ice fracture testing can be hard work and invariably expensive, hence tips on creating blocks and rectangles, coring, harvesting beams, or making thin slabs may be profitable on both counts.

INTRODUCTION
Cracks occur in ice in a great many ways, some starting out from an uncracked surface, some nucleating from within, some propagating from the tip of an existing crack tip. The fracture mechanics that is finally developed for any ice should be able to analyse the following, as stated by Arne Hillerborg for concrete (Hillerborg, 1983):

1. The formation of a crack in a specimen which is not notched or precracked.
2. The growth of a crack to a size of the same order as that of the specimen.
3. The influence of imposed deformations on crack formation and crack growth.

The fictitious crack model developed by Hillerborg has been extended to include viscoelastic deformations (Mulmule and Dempsey, 1998) and an extensive series of in situ field tests have been undertaken, both in the Arctic and the Antarctic (Adamson et al., 1995, Dempsey et al., 1999a&b, 2003, 2004). In this paper, a brief list of the topics that one should consider before undertaking such tests are listed, followed by a rather pragmatic discussion of the issues one confronts in the field. It is meant to be useful to any group planning an in situ sea ice fracture test program.

IMPORTANT TOPICS
The following topics are important (and will be discussed during the presentation):
1. Notch acuity (DeFranco et al., 1991, Wei et al., 1991)
2. Notch sensitivity (Dempsey, 1991, Dempsey et al., 1992)
3. Crack growth stability (DeFranco and Dempsey, 1994)
4. Crack path stability (Sumi et al., 1985)
5. Specimen size
6. Positive geometry (Bazant and Planas, 1998)
7. Keyhole (KH) tension test (Figure 2)
8. Doubly-Edge-Notched-Doubly-Slotted (DENDS) tension test (Figure 3)
9. Stable fracture and the stress-separation-law

The reader is reminded that if one is to assess the crack growth stability characteristics, then the compliance of the loading device must be measured (the so-called machine compliance). If flatjacks are used, calibration of the flatjacks is necessary (Pennington and Dempsey, 2011).

The fracture toughness quantity K_{Ic} is a common target of ice fracture studies. It implies a specimen size, rate, geometry independence at a certain temperature for a certain ice and cracking orientation. This K_{Ic} is typically determined via the unstable fracture of a macrocrack. This one parameter fracture mechanics cannot be used to meet any of the three objectives stated above. Rather sophisticated in situ fracture and tension tests are required, wherein stable fracture is obtained, and the true fracture characteristics can be determined.

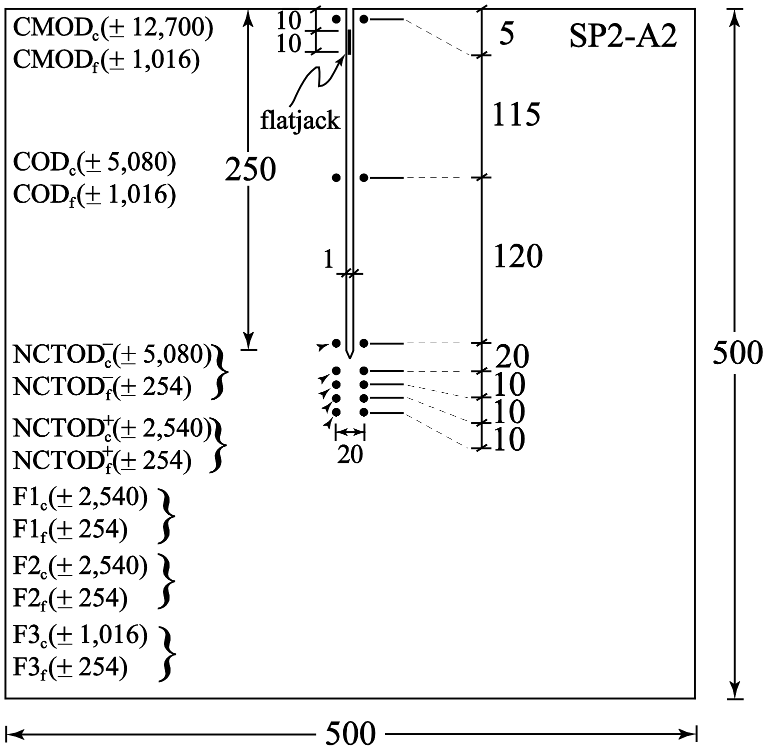

Figure 1. The edge-notched-square-plate (ENSP) in situ fracture test configuration. Length dimensions are in cm, while LVDT gauge ranges are in µm.

SAFETY

The risk of hypothermia is always a possibility; however, overheating may also be a problem. Use layers of clothing to control body temperature. If the weather closes in, shelter will be needed: tents, sleeping bags? Insulation rolls for under the sleeping bags? Food such as snacks and dehydrated food. Cooker and fuel, pots (at least to melt). First aid, tea/coffee, milk? Spare extreme cold weather (ECW) gear and communication tools. Try to ensure there is some form of shock stop on the power supply. Earth (ground) the generators (earthing rods). Word of advice: secure some sort of disk on the earthing rod so it cannot fall through). A Kovacs ice corer can be used to make the hole. While working, chainsaws are designed to cut…anything! It has to be a priority: chainsaw chaps and good boots are essential.

Special care is needed while removing gauging after the fracturing takes place. One is on the edge of a block and in a potential mouse trap position. The block is also half of its original size, which dramatically reduces its floatation. This is also compounded if the ice is warm. Get someone to counter balance your weight if there is any concern and rope if necessary. Old experiment sites melt the quickest as things warm up so consider them dangerous and flag them off.

SPECIMEN SIZE
How small is too small? This comes down to safety: a small plate can be dangerous like a mousetrap. If it seems safer to do the starter crack and gauging before you cut free for stability purposes please remember you will have only half of the floatation and weight on the block as you try to retrieve the gauges from what is now the edge. Half of the specimen will flood under your weight and possibly the whole specimen should flood due to the use a counter weight. Perhaps wear a rope? Remember, larger is easier, much easier.

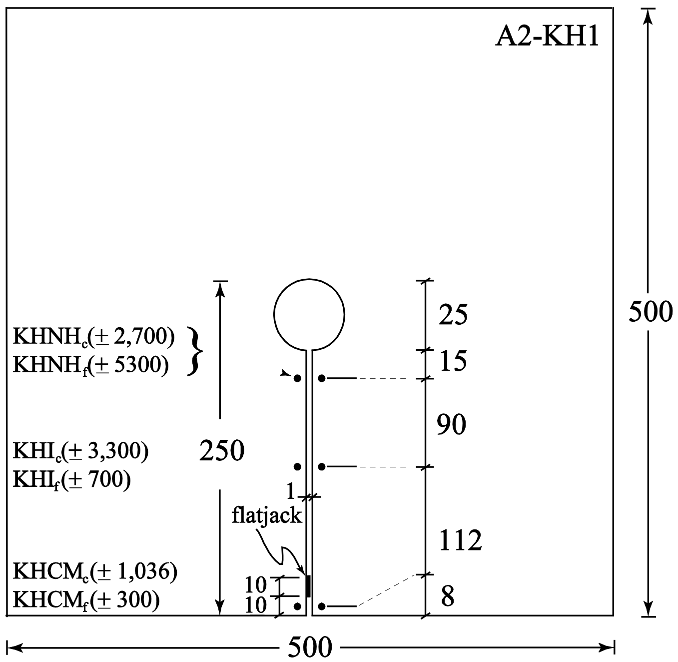

Figure 2. The keyhole (KH) in situ tension test configuration. Length dimensions are in cm, while LVDT gauge ranges are in µm.

POWER
You will want, at least, two generators (and a spare is not a silly idea).

1. Your computer needs steady power. Big generators are good. Although heavier, you get to park and leave it; it has a bigger tank of fuel and will run for extended periods without attention. Run power through an "uninterrupted power supply". History has smooth power as a big challenge, as it tends to be "moody" the colder it is. The Uninterruptible Power Supply (UPS) is put in the warm hut with the computers , the Data Acquisition Hut (DAH). You'll need multiplugs. A very long cable from the generator to the hut is recommended. This means no risk of vibration around the specimen but most of all this removes a constant drumming noise from the ambient noise.
2. Coring. Use an easy carry generator and a decent sized drill with a 13mm chuck. Do not underestimate the drill size.

CHARACTERIZATION & ORIENTATION OF ICE PLATES
Characterization of the ice and c-axes orientations is a job that needs to happen ahead of creating blocks as it involves time and skill. Allow a few weeks for this task (ahead of test date). After coring, options include: cutting to length in the field and transporting in plastic

jars or stored in a plastic sock which is placed in a core tube. Remember to mark for orientation (e.g. North) immediately before returning to labs or field facilities, to thin section, microtome, and view on a Rigsby stage. Having selected the cutout-crack orientation, a helpful hint in the field is to place two flags apart from each other and well off to one side that is perpendicular to your orientation. Sighting the two flags, such as having one flag disappear behind the other, will automatically give the line for the back (or front) of your specimen. This makes for a quicker marking out and allows the team to shuffle sideways with each new experiment.

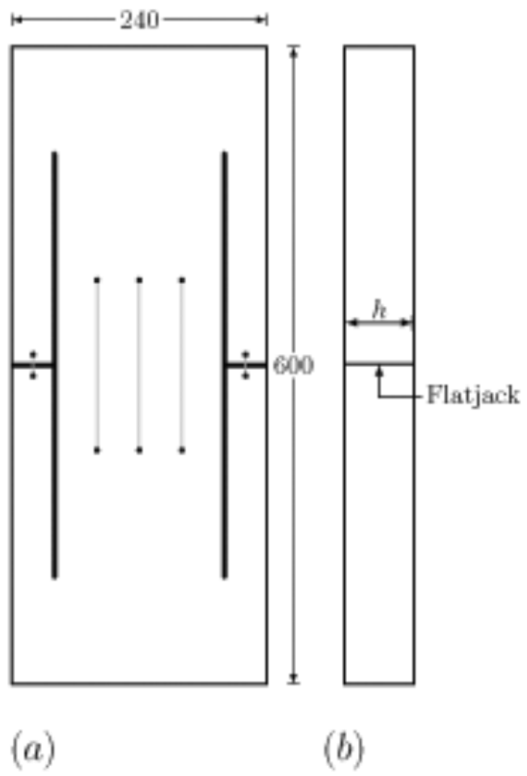

Figure 3. The doubly-edge-notched-doubly-slotted (DENDS) in situ tension test configuration; h is the ice thickness, length dimensions are in cm: (a) plan view, (b) side view.

BLOCK PREPARATION

This is for a specimen “landlocked” inside the parent shelf of ice. The fracture test may involve an edge-notched-square-plate (ENSP) configuration (Figure 1), or an edge-notched-rectangular-plate (ENRP). The tension test (the tensile strength is determined by a separate test program on the same ice on the same day) may involve the keyhole (KH) geometry (Figure 2) or the doubly-edge-notched-doubly slotted (DENDS geometry (Figure 3).

1. Leave the snow on the specimen: this is desirable; it stops or slows down any changes, especially the temperature profile, and is a great labor saver.
2. Measure out as you please; commonly square or rectangular.
    a. Check your diagonals to ensure square corners.
    b. Use chalk lines to ping a line in the snow. Take several chalk lines, as the string and chalk gets wet.
    c. On thick ice, certainly for ice over 1 meter (or even 700 mm) an ice saw on tracks or a Ditch Witch is recommended. On thinner or warm ice a chainsaw comes into its own. If there is a lot of slurry forming, consider scooping it off

with a square mouth shovel to avoid it freezing in the kerf, in colder weather something must be used to keep the kerf open. A strip of steel with the thickness of a chainsaw bar works well to slip along the kerf occasionally to clear possible freezing ice. It needs to be reasonably heavy or the ice will resist it. It is also handy as a tool to confirm that the cut is fully through.

DITCH WITCH

If cutting with a Ditch Witch, never complete the cuts to the ends.

1. Firstly, for safety, as the specimen will break free, risking vehicle and driver.
2. Secondly, to avoid damaging the ice by stressing it, as the ice plate struggles to support the Ditch Witch. The corners should be finished with a chainsaw.

Once the block is fully cut away clear most of the rubbish and slurry off the specimen. Slurry and broken bits in the water can be left until the next day; it will have floated to the surface and frozen together allowing for an easy cut with the chainsaw and easy removal with tongs. The result should be good black water, proof there was no contact between specimen and parent ice.

Figure 4. The Ice Saw

CHAIN SAWING (Chain saw or Ice Saw)
Cut along two adjoining sides twice to create approximately 25 cm wide slabs. If using an ice saw (which runs on tracks) consider the pattern so as not to have to track over another cut…movement may occur. Cut slabs to manageable lengths and weight by plunging the chainsaw tip down into it (if dealing with very thick ice, park the ice saw on the specimen and lower the blade down through parent ice and into the slab). Use extreme caution as the chainsaw is around one’s feet. Wear the safety gear, and it is not a job to do when fatigued. Remove the blocks with ice tongs. Try bouncing them up and down and it will figuratively pop them out for you to grab with said tongs. On very thick ice (meter or more) it is recommended that a plate be created that you can attach to the ice with ice screws. Use a set of H frame scaffolding with wheels and a good beam across the top with an endless chain (chain hand wench) that can be attached to the plate so the ice can be hoisted and wheeled away. At this point, problems will occur if the parallel cuts are not perfectly vertical: an upside down wedge will not come out. Do not be afraid to bias the cut on the parent ice to create a wedge in easily slides out.

Figure 5. Notch acuity: fine tuning the crack-tip sharpness.

CUTTING THE REMAINDER
If the ice is thick and an Ice Saw is being used, consider marking and cutting your starter crack first (for stability). Be sure to stop short and finish the last bit with a hand saw to create a sharp crack tip. If warm, clear the least amount of snow whilst removing the slurry created along the starter crack to help maintain its character. Then cut the remaining two sides (with the saw on the parent ice!). If cutting with the chainsaw cut the remaining two sides, then the starter crack. Stop short of your crack tip and finish with a hand saw. A good, clean, sharp, accurate crack tip is required. When the block breaks free, glide it to the middle with the greatest of ease creating a 12 cm kerf all-round the plate.
During construction, please avoid walking on the specimen…once it is free it has less stress.

KEYHOLE EXPERIMENT
If a KH experiment (to independently determine the tensile strength) is being conducted, expect to find it easier to drill the hole first with a corer and then cut the starter crack to it.

GAUGING
Choose the gauging in relation to what crack opening displacements are expected. Here are some tips:

1. Make sure gauges along the starter crack have plenty of travel. Especially down near the crack mouth. If the ice warms the ice will be more flexibility in the ice. Not to be paranoid, but it is advisable to place a “coarse” and “fine” LVDT at each location, “coarse” being very much an overestimate of the range needed, “fine” being close to the estimated range needed. It is highly reassuring when the fine matches the coarse until it goes out of range.
2. A major challenge is keeping the salt out of everything, take care and plan for it. Electrical contact spray on plugs at the end of day is a must. Caps on the end of the cables is recommended (the snow can drift over the test specimen, and completely cover the cables and connectors, unlike lab conditions, and bad contacts will ruin your data and the day).

Figure 6. The drill chuck used to drill holes for the dowels.

3. *Marking out the starter crack*. Clear enough snow on both sides of the crack so that it is possible to write on the ice (approximately 250 mm each side). Ping a chalk line on each side (approximately 100 mm from starter crack). Pick the lengths down one side and mark. It is recommended that a large wooden set square be used (a corner of some thin ply works well) to mark the points on the parallel chalk line. This will ensure that the gauges line up as accurately as possible with the targets.
4. *Attaching to the ice*. As a general rule: metal on ice is not good. Freezing wooden dowels into the ice works well. Drill the hole through a perpendicular guide, then wet the dowel with fresh (not salt) water and press it into the hole and let it set. If you have to hit it, it is not acceptable.
5. *Linking the cables to acquisition hut*. When making the data acquisition cables, remember to add extra length. This is to avoid having the cables in amongst your

gauges, and the data acquisition hut will not have to be right at the kerf. Extra length simplifies things. It is wise to run all the cables in a flexible tube: to protect from salt damage, for faster layout and faster packing up, all round easier handling.

6. Dialing gauges to zero manually obviously takes a steady hand: radio communication with the data acquisition hut is a must.
7. Retrieving gauges undamaged after the test may be difficult if the crack goes through the dowel's hole, but if you are using flatjacks the greater risk is the pressure transducers going into the water after the crack opens and having the flatjack roll over. Put in some high dowels and attach the transducers by string. Do not be afraid to take a spare transducer. Again, be careful on smaller specimens.

At the end of the season with warm days and warm ice, and brine channels opening, freezing dowels in can be difficult. Try creating shadows over the dowels and hoping. Experiments generally have to be quick because gauges will be creeping as the dowels move. Desperation only: if the holes become slack, try a rubber band between the dowels. Re-zero and go for it immediately. Playing with a specimen for an extended period before starting the breaking cycle, changes/influences the ice.

DATA ACQUISITION HUT

The DAH needs to be insulated, as light as possible, and on a sled of some sort to keep it mobile. It needs a thermostatically controlled heater and generator of its own (so as not to degrade the smooth power to the computers). The warmth is essential to the computers, the UPS, gas servos, data acquisition system and the Principal Investigators. A shelter for staff is recommended as well, it can be tough in the cold wind. Somewhere sane for smoko and lunch is needed, as lives and science are at risk. Allow for short periods to recuperate, check that everyone is on the same page, and discuss suggestions or point out problems…mechanical, scientific, environmental and health.

CORING – VERTICAL AND HORIZONTAL

1. Vertical coring is standard and as the top 50 mm is often rejected, chipping the surface to create a cavity will greatly enhance the starting of the corer (they are inclined to skip around otherwise). Handling is improved by adapting your corer to take a swiveling disk on its drive shaft. A second person can hang onto it to help guide. There are many stories of corers breaking through while the chuck has come loose, sending the corer to the bottom. The disk being wider than the corer defends against that. Do not forget to mark the orientation on the top of the core before you core (e.g., North).
2. Horizontal. Rather than lifting the slab or block out, cut it to length and roll it on its side (a sturdy board is a simple instrument that helps complete the roll). Now core it in situ using the vertical core technique. Do not forget to mark the orientation on the top of the core before you core (e.g., East-West).
3. If using cores for salinity: rather than packing it as a whole, do your temperature profile immediately, cut it into desired lengths, and put them in plastic jars. It helps to catch the brine otherwise lost between site and lab.

Figure 7. Coring with a drill: disk that stops the corer plunging down is visible.

BEAMS

Some investigators harvest beams from the block, or the parent material beside the block, for further work. Clearly, orientation of this material in relation to the master experiment is important. Bobbing the slabs out and laying them without damage is important. Try making them a bit longer so that ice tongs can grab the ends without damaging the beam's ice and cut the excess length off once it is lying down. Handling it afterwards is equally important. Having cut your beams to the desired thickness try cling wrapping them and place them in a box with Styrofoam lining (similar to a coffin). It truly helps in transporting the blocks without stressing them and keeps them out of the sun once harvested.

MULTIPLE EXPERIMENTS FROM A SINGLE BLOCK

Math allows for variations, so when a large block breaks – invariable biasing one way or the other – complete the cutting of the existing starter crack to the other side forming another block. And even possibly (please remember small specimen advice) again into a third block.
On completing an experiment the kerf can be reused by forcing the broken specimen to one side holding it in place with a couple of scraps of ice and let it freeze there overnight. It is a simple process to clean that kerf the next time.

THIN SLABS OF ICE

Thin slabs of ice are created by harvesting sheets of ice to the tune of an inch thick to view its microstructural profile. Cutting in situ: an Ice Saw on tracks allows best control of the thickness and when it breaks free it floats safely. However, one can get flexing in the saw bar and a bias in the form of an upside-down wedge. Clearly the thin slab cannot take force, so is recommended that you cut it from the parent ice beside the kerf you created when preparing the specimen. This saves one cut and gives the advantage of a little space but good support for the thin slab when it floats free. Thin slabs tend to roll over when there is open space beside them. Smaller thin slabs can be readily created on a harvested block or beam, using a steady hand. Put a planar piece of ice against it to help support it (this normally takes assistance).

Plan it so no fingers are in danger. To view or photograph the profiles, place a black sheet or blanket behind the slab. This greatly enhances the profile.

SUNDRIES

1. Fuel. It is one of those commodities that can easily run short. After all how much fuel can generators and snowmobiles take? Plenty! Oil for the skidoos is a must, and a little sump oil can be the great savior for a generator with a fussy oil level kill-switch.
2. Maintenance. Respect the gear. If you have the ability, wash liberally with fresh water and dry. Either way, spray everything with WD-40 or CRC. If it is a chainsaw, run it to get what you can out of the clutch, with a bit of luck get some WD-40 in there. *Side Note:* Expect to take several days to clean and return gear. Especially clean, oil and pack the gear. Be thorough.
3. Rubber gloves for sawing ice. As a small hint, take plenty. Once wet inside they take a long time to dry out.
4. Measuring tapes; metal tapes (classically the shorter tapes); take spares! The salt water is murder on them. Do not forget longer tapes and pins (e.g. 100mm+ screws) for they are essential for marking the block before the chalk lines are made.
5. A minor point – the noise of saws will draw the interest of surrounding wild life. This is fine if it is just the penguins.

CONCLUSIONS

This paper summarizes the important theoretical topics that should be considered prior to an in-situ sea ice fracture testing program. The remainder of the paper is a (hopefully useful) workman's guide to the practicalities of in situ fracture testing.

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