GLACIER SNOW BRIDGE MECHANICS

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ABSTRACT: The vocabulary of avalanche mechanics is useful in describing the mechanics of glacier snow bridges. We calculate the forces involved in isotropic snow bridges and present theoretical considerations for anisotropic bridges. We also discuss travel decisions (hike, crawl, snowshoe, ski, or do not cross). Slab avalanches have a large ratio of shear plane area to that exposed to tension, such is not the case with snow bridges. Scientists accustomed to avalanche mechanics must turn their models ninety degrees to consider shear failure across layers (mode II) and tensile failures initiating underneath the bridge (mode I). Calculated snow pressures for various flotation devices are used for calculations of shear and moment. The potential types of failure are (1) shear at the footwear—snow bridge interface (punching failure), (2) shear at the ends of bridges, and (3) flexure (tensile failure). Type (1) falls tend to be the shortest and type (3) falls the longest. Results show that wearing boots creates seven times as much shear stress (at the edge of the footwear) as skiing, making punching failure more likely. But this type of failure is primarily important for short, thin bridges. On bridges longer than skis, the skis only reduce end-of-bridge shear and moment modestly. Maximum moment, which is probably the most critical measure, is roughly proportional to the square of the bridge aspect ratio. Since injury potential, self-arrest distance, and rescue complexity increase with skis, knowing how forces vary with bridge geometry will help glacier travelers in their cost-benefit analyses. Probe poles convey information about resistance to penetration, which is directly related to shear strength, tensile strength, and fracture toughness. Anisotropic concerns such as ice lenses and penetration of load pressure are discussed. Finally, mnemonics and heuristics are proposed to assist the glacier-traveling community in analyzing snow bridges.

Keywords: Snow bridge, Glacier, Shear, Tension, Flexure, Toughness

1. OBJECTIVES

Crossing a long, narrow snow bridge over a gaping, blue crevasse may be at once the most exciting and hazardous part of glacier travel. Teaching novices how to analyze snow bridges can be challenging, in part because the mechanics of snow bridges have not been well described.

In the spirit of merging theory and practice, this paper has three goals:

1) Elucidate snow bridge mechanics at the educator level. Hopefully this will demystify for our students how we use probes on snow bridges.

2) Calculate representative forces generated by various modes of locomotion including hiking, crawling, snowshoeing and skiing.

3) Provide a class outline and mnemonic for teaching snow bridge analysis. Hopefully, this will stimulate discussion of heuristics for snow bridge go/no-go decisions.

For context, the class outline, "Snow Bridge Analysis" is part of broader topic, "Glacier Route-finding," so an outline for that is included as well.

2. INTRODUCTION

2.1 *Epidemiology*

Two hundred significant falls into a crevasse/moat were reported to the American Alpine Club from 1951-2003 (Williamson 2005). Many more went unreported. At the National Outdoor Leadership School (NOLS) we track the epidemiology of injuries, illnesses, and near misses. Near misses are defined as a close call in a dangerous situation that did not result in an injury. Over the period 1999-2002, 3.8% of near misses school-wide occurred while on glacier—16 of 418 (Leemon and

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Schimelpfenig 2003). Eleven of those 16 were crevasse falls. For context, these occurred over 630,937 program days, where a program day is defined as a student or instructor being in the field for one day.

At NOLS Alaska the criteria for crevasse near misses are (1) any un-roped step or fall into a crevasse, (2) roped falls to head depth or deeper, or (3) the rope system does not work as planned. On NOLS Alaska mountaineering courses from 2004-2006 the most common type of near miss (43%) was crevasse falls due to snow bridge failure (not (1) or (3) above). Table 1 shows 12 near misses as well as 2 (shoulder) injuries occurred during the period due to snow bridge failures. For comparison there were 2 avalanche near misses (climber-triggered, but no one caught) at NOLS Alaska during that period. These incidents occurred over 18,176 program-days.

Of the 16 crevasse fall incidents, 12 were attributable to inaccurately assessing the snow bridge strength. (Four of the near misses were attributable to inattentive students who stepped on well-marked snow bridges previously deemed to weak to cross.) To reduce injury and near miss rates while glacial mountaineering, we must understand snow bridge mechanics.

	# falls due to bridge failure	% of total at NOLS Alaska	Minimum fall distance (m)	Median (m)	Maximum (m)
Near Miss	12	43	1.3	9.0	15.0
Injury	2	9	chest	3.8	7.5
Total	14	28	chest	6.0	15.0

Table 1. Crevasse falls due to snow bridge failure were a plurality of near misses reported on NOLS Alaska mountaineering courses from 2004-2006.

2.2 <u>Case study</u>

The impetus for this study was a particular incident wherein an instructor-in-training fell 15 m into a crevasse. Though he was uninjured, we analyzed this near miss closely for lessons learned. In this case, the climber was being coached on how to route-find and lead in glaciated terrain. This occurred on 21 May 2004 in the Chugach Mountains, Alaska. There had been significant warming according to the course log: “Sunny in the AM, cloudy in the PM, +5°C—significantly more melting today than in previous days.”

At 1330, the instructor-in-training had just taken over the lead. He was uphill and out of view of an instructor, who was leading a second rope team, when the instructor-in-training came upon a snow bridge that was 4.5 m long. (We define length as the distance to span the crevasse). The snow bridge was 2 m thick and 6 m wide (*i.e.* open to each side). He noted it was sagging a little and made the decision to have everyone put on skis, “to spread out the weight.”

When he reached the middle of the bridge it collapsed catastrophically. Due to the skis, the second climber on his rope team had difficulty arresting and was dragged ~5 m uphill. They made several mistakes but the thing that intrigued us was the perception that skis would provide a significant advantage—enough so that they felt it worth the time to put them on. In fact, skis did not prevent the fall and probably lengthened it.

This bridge failed in flexure due to the climber inducing a bending moment, which was at its maximum when he briefly reached the center of the bridge. The moment was only slightly smaller due to the skis than it would have been on foot. Thus the skis gave him a false sense of security and reduced his partner’s ability to self-arrest. A lack of understanding of the types of failures and the mechanics involved skewed this climber’s cost-benefit analysis towards wearing skis, which may have contributed to his decision to attempt to cross a long, sagging bridge late on a warm day.

2.3 <u>Snow Bridge Failure Types</u>

Bridge failures, whether made of concrete and steel or of snow fall into two primary categories—shear failure or flexure failure. Shear failures can be sub-divided into two sub-categories by location. One is punching failure, which in a highway bridge involves failure at the top of a pile-supported pier or of the deck (road) surface. Picture a small portion of the concrete and re-bar collapsing under an overweight truck tire. The other type of shear failure is at the end of a bridge, where loads are transferred from one structural member to another (I-beam to abutment). Flexure failure is due to an applied bending moment. On a highway bridge that could be from an overweight vehicle in the middle of a long span which causes tensile stress underneath the span in excess of the tensile strength.

In the discussion, we revisit the details of these three failure types in the medium of snow. But here is a non-scientific way to explain the three types to students using old cartoon characters:

1. Shear (punching) failure: Picture Wile E. Coyote. In his haste to catch Road Runner, he steps on an otherwise reasonable looking bridge. But this bridge is only thick enough to hold Road Runner, not a coyote. He falls through, leaving a perfect outline of his body in an otherwise intact bridge.
2. Shear (end-of-bridge) failure: Wile E. Coyote works his way back to the top only to follow Road Runner's tracks across another bridge. This time he makes sure it is thick enough that his foot will not poke through it. But he fails to notice a crack in one end and as soon as he steps on the bridge the whole thing falls out from under him.
3. Flexure failure: Now poor Wile E. Coyote is walking at the bottom of the crevasse, trying to understand these bridges. He hears Road Runner and looks up to see him speeding across a very long bridge. He sees the bridge flexing and then the underside of it cracking. Before he can move, the span breaks in half and falls right on him. Beep beep!

In reviewing the literature, we were unable to find descriptions of the mechanics of snow bridges and their failures. Further, decisions about whether to walk, crawl, snowshoe, or ski when crossing bridges have not been described with respect to all of the stresses created by each mode of locomotion.

3. METHODS

We used a software package to calculate end-of-bridge shear forces and moments on simply supported beams (Jayswal 2002). Simply supported beams are those that are fixed at one end and supported by a roller or pin at the other (free to rotate or translate). Though snow bridges do not strictly fit this definition, the software provided a first-order approximation of additional forces generated by loading a snow bridge. Further, the software allowed for simulation of distributed loads, such as skis.

We calculated pressures exerted on the surface of the snowpack when hiking, crawling, snowshoeing and skiing. In each case, the weight was assumed to be on only one leg, except in the case of crawling. For that we assumed the weight was split evenly between one hand and a knee to mid-shin. These assumptions provided a maximum pressure to use as input to the software model.

We calculated punching shear (edge-of-footwear), by dividing the climber's weight by the circumference of each type of footwear and assumed a bridge thickness of 1 m (for punching shear). All calculations of end-of-bridge shears and moments assumed these surface areas:

Hiking:
$0.027 \text{ m}^2 = 0.30 \text{ m} \times 0.09 \text{ m}$

Crawling
$0.018 \text{ m}^2 = 0.10 \text{ m} \times 0.18 \text{ m}$ (hand) and
$0.063 \text{ m}^2 = 0.18 \text{ m} \times 0.35 \text{ m}$ (knee & half-shin)
We assumed 0.70 m between one's hands and half-shins when crawling.

Snowshoeing:
$0.160 \text{ m}^2 = 0.75 \text{ m} \times 0.21 \text{ m}$

Skiing:
$0.160 \text{ m}^2 = 1.60 \text{ m} \times 0.10 \text{ m}$

We positioned the hypothetical climbers in worst-case scenario locations. For end-of-bridge sheer, this meant having full weight on the bridge, but all the way at one end of the bridge. In the case of crawling, this meant with the hand closer to the end of the bridge than the half-shin because the hand has a greater pressure than the half-shin. For moments, we placed the climbers in the center of the bridge. For crawling moment, we put the hand in the middle of the bridge.

Further, we assumed the climber was not creating an impact on the bridge by moving. We assumed the climbers weight was evenly distributed over the foot, hand, half-shin, snowshoe or ski. We ignored the effect of the dissipating pressures within the snowpack as described by Föhn (1987) as well as snowshoe or ski flex. Calculations assumed weightless bridges. Thus, the calculated stresses represent the *added* stress on a bridge due to a climber. Finally, we also assumed the snowpack was isotropic in all dimensions.

After obtaining results from the above, we incorporated them into a class outline—"Snow Bridge Analysis". We shared multiple drafts of this with NOLS instructors and students via courses, the *NOLS Staff Newsletter* (Rochelle 2006), instructor seminars, briefings, and debriefings. Feedback improved the outline iteratively.

4. RESULTS

Below are calculations for a 70 kg climber on 1 m- and 4 m-long bridges (Table 2). We added a couple of lighter animals for comparison with snowshoers and skiers. We calculated pressures with and without a 30 kg pack.

	Pressure (kPa)		Shear (Pa)—punching Edge-of-footwear		Shear (Pa)—End-of-bridge		Maximum Moment (N-m)	
	70 kg climber	with 30 kg pack	1 m long	4 m long	1 m long	4 m long	1 m long	4 m long
Hiking	25.4	36.3	880	880	583	661	146	661
Crawling	8.5	12.0	424	424	384	611	78	562
Snowshoeing	4.3	6.2	358	358	429	622	107	622
Skiing	4.3	6.2	126	126	215	549	54	549
Lynx (Halfpenny & Ozanne 1989)	3.1	injured	43	43	108	108	35	197
Snowshoe hare	1.1	dead	17	17	13	13	6	25

Table 2: Calculations of pressures, shear forces and moments on snow bridges varied with bridge length.

We intuitively know that snowshoes or skis reduce pressure on the snow (*e.g.* ski penetration *vs.* boot penetration). In fact, skis reduced pressure by 83% (25.4 Pa to 4.3 Pa) and punching shear by 86% (880 Pa to 126 Pa) relative to hiking.

Skis reduced end-of-bridge shear stress by 63% (583 Pa to 215 Pa) for a 1 m-long bridge because they *fully* spanned the bridge. The effect was a more modest 17% (661 Pa to 549 Pa) for the 4 m-long bridge. Skis reduced the bending moment by 58% (146 Pa to 62 Pa) on a 1 m-long bridge, but only reduced it by 17% (661 Pa to 549 Pa). This is a key finding of this paper.

We further investigated the relationship between bridge length and maximum moment for the hiking and skiing cases (Figure 1). Once the bridge length is longer than the footwear or flotation device, the relationship between bridge length and moment is linear. The absolute difference in moment between hiking and skiing for bridges longer than skis is 111 N-m, thus the proportional difference decreases from 45% (1.6 m-long bridge) to 13% (5.0 m-long bridge).

Snowshoes had similar results to skis. They also reduced pressure 83% and reduced punching shear by 59% relative to hiking. Snowshoes reduced the end-of-bridge shear stress 6% on the 1 m bridge and 26% on the 4 m bridge. The moment was reduced by 27% on the 1 m bridge and 6% for the 4 m bridge relative to hiking.

Crawling reduced pressure by 67% and punching shear by 52%. Crawling reduced end-of-bridge shear by 34% on the 1 m bridge and 8% on the 4 m bridge. Crawling lessened moment 47% on the 1 m bridge and 15% on the 4 m bridge.

Moments created by snowshoeing and crawling are linear with respect to bridge length. Snowshoeing and crawling fall between the curves in figure 1.

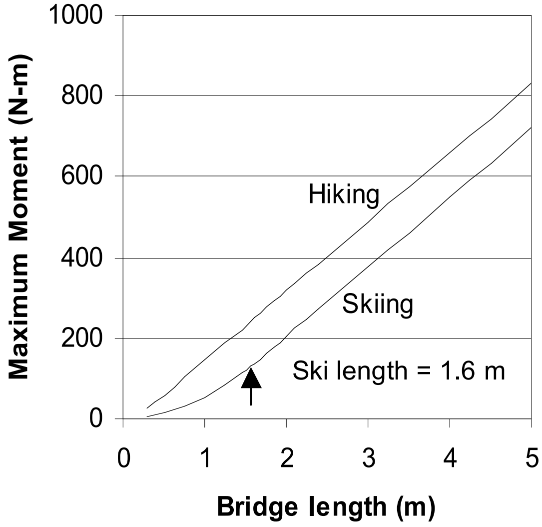

Figure 1. Maximum moment (mid-bridge) increased linearly with bridge length if bridge length>ski length.

5. DISCUSSION

5.1 Revisiting the 15 m crevasse fall

In the case study, the bridge was 4.5 m long and the climber put skis on "to spread out the weight." This person's was intuitively correct that skis would reduce the pressure on the snow surface significantly. Indeed he reduced the pressure by 83% and therefore the punching shear stress by 86%. The bridge failed in flexure, because he was halfway across when it failed. Wearing skis only reduced the moment by 15%. In exchange he had partners ill-equipped to self-arrest and had skis on while plunging into the crevasse.

We believe that tensile failure due to induced moment is more likely to be responsible for large snow bridges failing than is end-of-bridge shear failure. There are two lines of evidence for this. Anecdotally, when climbers take long crevasse falls, we have heard more stories than not that they were out in the middle of the bridge (where moment is maximized and shear is minimized). The second line of evidence is bridge geometry, which tends to look like an arch. When this is true, the cross-sectional area in shear is larger than the area in tension (under the mid-point).

5.2 *Structural theory of snow bridges*

To understand the three types of failures students need to understand the two locations for shear (edge-of-footwear and end-of-bridge) and how bending moment induces tension. For completeness, we included compression in the discussion.

Shear is the critical strength on which we focus our avalanche stability tests because nearly all of the surface area that fails in an avalanche is in shear. (Tensile strength is more important on big bridges, though). The crown fracture is a tensile failure, not a shear failure. For example, for a 50 m wide x 100 m long x 1 m deep avalanche, only the crown (50 m x 1 m = 50 m^2) was a tensile failure. The entire bed surface-slab interface (50 m x 100 m = 5000 m^2) and both flanks (2 x 100 m x 1 m = 200 m^2) failed in shear. Finally, the stauchwall (50 m x 1 m) failed in compression. Thus, >98% (5200 m^2/5300 m^2) of the failure was in shear. Approximately 1% of the surface area was tensile failure and 1% compression failure.

The tricky thing with snow bridges is that everything is turned 90º from our standard avalanche viewpoint. So shear failures happen in a vertical plane. For punching failure, the force is one's weight, and for end-of-bridge failure the force is the weight of the bridge plus the climber. On a 1 m wide x 5 m long x 2 m thick bridge, 2 m^2 on each end of the bridge are subject to shear failure. But on a bridge this long, the most likely failure is a tensile failure in the bottom half ($1m^2$) of the bridge at the center induced by a bending moment.

Moment is created by a force pushing on a lever arm like a wrench. It has units of force times distance. Moment is something we don't worry about much in avalanche science (though it might be interesting to calculate the moment created by a skier compressing a stiff slab when turning. This moment could translate to a shear force at the bed surface.) Picture a diving board with a diver out on the end of it. He weighs 700 N (71 kg of mass acted on by gravity) and the board is 2 m long. Therefore the moment is 1400 N-m. One can demonstrate these forces to students by bending a pencil. A snow bridge is like a pencil held at both ends pressing down on the middle of it with one's thumbs. When pressed hard enough, it will fail under a bending moment in flexure—with a snap! The wood fibers in the bottom of the demonstration pencil released acoustic energy when they failed in tension.

Similarly, when a climber stands in the middle of a snow bridge, it puts a bending moment on the bridge, which causes the bottom of the bridge directly beneath the climber to be in tension (Figure 2). Since a snow bridge is actually a beam fixed at each end, both of those ends are also in tension, but on top! If you look at the diver on the diving board, the upper half of the board is in tension and the bottom half is in compression. Snow bridges have the same types of forces, only upside down and attached on *both* sides. The longer the diving board is, the greater the tension will be at the attachment point of the diving board. The longer the snow bridge is, the more critical will be the role of moment relative to shear.

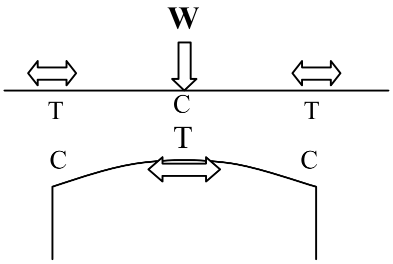

Figure 2. This illustrates the location of tensile (T) and compression (C) forces in a longitudinal cross-section of a crevasse. W is the climber's weight The arrows represent the direction of pull in the snow bridge.

5.3 *Focus on tensile strength and stress*

We can calculate the theoretical tensile stress based on moment, which in turn can be calculated from the load. The calculations below are for a simply supported beam with a uniform load pressure (like the weight of the snow). For a fixed beam, the denominator in equation (2) would be 24. For a point load fixed or simply supported, the length (L) in equation (2) would not be squared.

The maximum tensile stress is related to the moment:

$$\sigma_{t\max} = \frac{6M_{\max}}{WT^2} \qquad (1)$$

Where $\sigma_{t\max}$ is maximum tensile stress
$M_{\max}$ is the maximum bending moment
W is the width of the snow bridge and
T is the thickness of the snow bridge.

Note that for a simply supported beam

$$M_{\max} = \frac{PL^2}{8} \qquad (2)$$

Where P is the pressure (uniformly distributed)
L is the length of the bridge

So $$\sigma_{t\max} = \frac{3PL^2}{4WT^2} \qquad (3)$$

What this tells us is that the length and thickness are more important than the width. In fact a good way to think about this is by considering the aspect ratio, L:T. The tensile stress on a the snow at the bottom of the middle of a snow bridge is directly proportional to the square of its aspect ratio $(L/T)^2$. Thus we propose a heuristic: Be wary of snow bridges that are significantly longer than they are thick.

Overall, the role of tensile strength is far greater in maintaining snow bridge integrity than it is in stability for avalanche paths. Thus it is important for the climber to estimate. The tensile strength of snow is a power function of the density with an exponent between 1.5 and 2.1 (Kirchner *et al.* 2001, Conway and Wilbour 1999, Schweizer and Jamieson 2003). So if it is twice as dense, it'll be 50-115% stronger. The tensile strength of 10% powder is less than 0.001 kPa, whereas for ice it is about 1 kPa. Luckily, density is something we can get a feel for when using a snow probe.

The resistance felt when probing continuous full depth snow (as opposed to reaching air or an ice lens) gives the same information as doing a hand hardness test deep in the bridge. With a 0.015 m diameter probe pushing with 98 N of force (5 kg-force, the pressure on the snow is 555 kPa—equivalent to a pencil hardness. Hardness is a good proxy for density and thus tensile strength of the snow. See Figure 3 for pressure generated while probing, the equivalent hardness and a note on what kind of snow might be present.

Another potential tool for assessing tensile strength for snow bridges in the field is the cantilever beam test (Perla 1969, Mears 1998, Sterbenz 1998). To perform this test one isolates a 30 cm wide by 30 cm *tall* "column" (actually a cantilever) of snow. Then one makes that cantilever as long horizontally as one can, isolating the bottom of the column with a saw, which induces tensile stress in the top of the cantilever. This would simulate snow bridge forces well. A challenge is that the layer one would want to test would be deep in the snowpack next to the bridge and the snow at the base of the bridge would be exposed to air and thus under a different metamorphism regime. Since this is a new idea, we'd have to work out correlation to bridge strength for various bridge geometries.

Probing force used while on glacier	Force (N)	Pressure (kPa)	Hardness	Typical Snow
Hardness test AAA & USDA 2004	10-15	1.0-1.5	F+	Fresh
Hardness test Colbeck *et al.* 1990	49	5.0	P	Early spring
Typical glacier probing force	100	9.8	P	Dense spring
Bare hand slips on probe	180	18.4	I	Ice lens

Table 3. Probing force/pressure for a typical probe (d=0.015 m) are related to hardness and density.

5.4 <u>Snow bridge fracture mechanics</u>

Scientific research is sparse on snow bridges, but we suspect that:

- Falls up to armpit deep tend to be punching failures (a hole in the bridge) and tend to be through thin, short bridges.
- Long falls tend to be flexure failures (the whole bridge) and tend to involve longer, somewhat thicker bridges.
- Because of the arched geometry of most bridges, we don't think that end-of-bridge shear is a prominent cause of crevasse falls (though it may be for natural bridge failures in warm temperatures).

Anecdotally, this seems to be true. When someone falls a long distance, they tend to take the whole bridge with them.

Kirchner and others used variations of the cantilever beam test in the field and lab to develop estimates of fracture toughness for snow samples (Kirchner *et al.* 2002a, 2002b). Fracture toughness is defined as "a material's resistance to brittle failure when a crack is present" (Cullister 1994). In other words, once the snow has a small crack, how resistant is it to crack propagation?

Snow is one of the most brittle common substances, meaning it doesn't stretch much before it breaks. Fracture toughness of snow is directly proportional to the square of the density—twice as dense, four times as tough. Not surprisingly, the fracture toughness in shear of 10% powder is less than 0.1 kPa-$m^{1/2}$ whereas for ice it can exceed 100 kPa-$m^{1/2}$ (Kirchner *et al.*

2000). Steel can reach 50,000 kPa-m$^{1/2}$! The fracture toughness of snow in tension is about 1.4 times that in shear (Schweizer *et al.* 2004). But tensile stresses far exceed shear stresses in bridges with high aspect ratios.

There are three modes of failure with respect to fracture toughness, which are defined by how the surfaces move relative to each other:
Mode I (opening)—The surfaces are moving directly apart under tension, normal to the plane of the crack, like tearing open a Ziploc bag. This one is most important at the bottom center of the bridge where the tensile stresses are greatest.
Mode II (sliding)—The surfaces are sliding on each other, parallel to the plane of the crack as on the bed surface of an avalanche (edge-of-footwear and edge-of-bridge). This could occur across layers in a snow bridge.
Mode III (tearing)—These are surfaces ripping, parallel to the plane of the crack but perpendicular to the face of the crack, as one would tear a piece of paper. This happens when a wide snow bridge fails at both ends, but for only part of its width and the weight of the bridge pulls more of it into the crevasse. We have seen a hundred meters of a kilometer-wide bridge fail this way.

The fracture toughness in different modes can differ. Kirchner et al. (2002a) investigated mixed modes, which are possible in snow bridges and avalanches. They found that in long cantilevers fracture toughness in tension (K_{IC}) dominated fracture toughness in shear (K_{IIC}), On the other hand, $K_{IC}<K_{IIC}$ for short cantilevers. This supports our statements about the importance of tensile strength in bridges with high aspect ratios.

5.5 *Method of locomotion*

On a 4 m-long bridge, skis reduced moment by 17% and crawling by 8% (As opposed to 58% and 34% respectively on a 1 m bridge). But skis have disadvantages. Most importantly, they make self-arrest more difficult. In the case study 15 m fall, we estimated a third of the fall distance was due to a difficult 5 m arrest (Rochelle 2004). Further, skis could cause more of an injury during the fall and complicate crevasse rescue. Skis and snowshoes certainly have a place in glacier travel, particularly in firn zone where there are numerous small crevasses bridged by thin snow. But when it comes to crossing big crevasses, we believe their worth is overestimated. We are more willing to crawl across bridges than most climbers (placing the rope over a shoulder to avoid dislocation).

5.6 *Future research*

There are a number of assumptions made in this research. Relaxing any of these would provide fodder for future research.

The first area of interest would be calculating the stresses induced by the weight of the bridge itself. We focused on the added weight of a climber. A 4 m long x 2 m thick x 5 m wide bridge with 40% density snow weighs 16 tons. Incorporating the weight of the snow would make the differences between skiing and crawling even less important than we calculated.

Second, it would be fruitful to repeat this analysis of snow bridges as fixed beams. Also note that we did a two-dimensional analysis of a three-dimensional world.

Third, it would be interesting to relax the assumption that the pressure of a climber on snow does not dissipate in the snow. We know the opposite is true (Föhn 1987), which is why we typically only dig a couple of meters down when looking for weak layers in the snowpack. If the snowpack is anisotropic it can help dissipate forces. An ice lens would spread downward forces further to the sides, decreasing the tension on the bottom of the bridge (Gleason 2006). This is a critical consideration in the field. There was a recent debate about whether to call this bridging. When there are meters of air under the bridge, rather than a weak layer, the answer is clearly "yes."

Fourth, we assumed that the climber is not moving. Having a live load increases the forces significantly. Highway engineers include a 30% safety margin above the specifications required for a dead load to account for rolling loads (AAHSTO 2002). Racewalkers increase impact by a factor of ten or more (Rochelle 1992).

One of the author's biggest crevasse falls occurred trying to get a rappel rope unstuck. He had the brilliant idea of repeatedly flicking a loop of slack upwards, inadvertently bouncing on a snow bridge over a bergschrund. Dynamic forces matter! Skiing is an advantage in this regard, but walking or crawling gently can make up for that. When a climbing partner says, "Think light!" she means, "Place your boots down gently (slowly) and flat to reduce the impact," not "Meditate on helium balloons." The latter may encourage the former, however.

6.2 Snow Bridge Analysis

One who doesn't analyze snow bridges—WHIPS! This mnemonic refers to the vernacular term for taking a long fall as in "taking a whipper."

Weather:
- Climate
  - Continental (shallower, less dense, drier snow; colder winter temperatures)—weaker bridges per unit length
  - Maritime (deeper, denser, wetter snow; warmer winter temperatures)—stronger bridges per unit length
- Latitude
  - High latitude—colder, more brittle glaciers, bigger crevasses
  - Low latitude—warmer, more ductile glaciers, smaller crevasses
- Elevation—For instance in Himalayas it mimics a maritime regime down low and continental up high (Sharma 2000)
- Zone on glacier
  - In firn zone, the bridges are barely strong enough bear their own weight.
  - *Heuristic: When traveling in firn zone be especially careful.*
  - *Heuristic: In accumulation zone, be wary of bridge strength in the first tension zone you cross.*
- Temperature/radiation
  - Sun and significant warming weakens bridges. What time of day is it? Are you on night schedule?
  - *Heuristic: If there's been significant warming or you're hearing snow bridges collapsing, it's a bad time to be traveling.*
- Precipitation
  - Recent snow, precipitated or wind-borne, adds stress (weight) without strength.
- Visibility
  - If it is flat light or a whiteout, it will be harder to recognize cracks. Low, direct sunlight is best.
  - Recent snow or wind obscures details of the crevasse.

Human Factor
- Decision-making traps:
  - FACETS— Familiarity, Acceptance, Commitment, Expert halo, Tracks, Social proof (McCammon 2002)
  - These decision-making traps apply in slightly different ways than in winter, but still pertain.

Ice
- Ice is critical to snow bridge strength.
  - Can you see an ice lens or lenses from the side? Investigating from the sides is a great technique.
  - Can you feel ice lenses when probing?
  - *Heuristic: An impenetrable, continuous ice lens makes for stronger bridges.*

Pressure
- Pressure=Weight/Surface Area
  - Weight = Body weight + pack weight
  - Surface Area = Area of bottoms of boots, hands and shins, snowshoes, or skis
    - Skis help if the snow bridge is not longer than the skis, but don't help as much on long bridges.
    - Analogous to a snowshoe hare vs. moose comparison used in teaching winter ecology

Size/shape
- Is it cracked or sagging?
  - *Heuristic: Bridges with significant cracking or sagging should not be used.*
- Thickness (depth)
  - Thickness is perhaps more important than length, which is more important than width.
  - *Heuristic: If you can feel air with your probe, at least hesitate. Probes should be 2-3 m long on high latitude glaciers.*
- Length (distance *across* crevasse)
  - Introduce the concept of a bending moment. Going further out on a bridge multiplies the bending moment (similar to the lay concept of leverage).
  - *Heuristic: If a bridge is significantly longer than it is thick, be wary.(Aspect ratio=Length:Thick)*
  - *Heuristic: If a bridge is too long to reach across with a ski pole before stepping on the bridge, use a probe >2.5 m long to probe for full-depth snow.*
- Width of bridge
  - *Heuristic: If holes are present, use caution.*

Explain "Size/shape" to your students with diagrams showing several crevasse/snow bridge side views. Explain forces and moments involved. Give examples to highlight the importance of thickness—like bending a ruler with thumbs pressing on the flat part *vs.* on edge. Once most of your class understands the forces, then draw lines simulating probes going into the snow bridges to show what clues they will actually get. Tell them that hitting glacial ice will feel sticky (best case scenario), an ice lens will be harder and more brittle (next best), continuous full depth snow will feel consistent, and air will feel like a nearly complete loss of resistance.

6.1 Glacier Route-finding

This class is the context for the previous outline, "Snow Bridge Analysis," which is the subject of this article. This class is organized chronologically, after *Snow Sense* (Fredston and Fesler 1994).

Recognize
- Look for linear features, depressions, changes in color, texture
- Look sideways, back and forth
- Be wary especially in zones of tension. Refer to glaciology class taught earlier in the course.

Avoid
- Think big picture (compression zones). Reference glaciology class
- Give respect to crevasses
- When going between two crevasses, split the distance between them

Reduce
- *Analyze the snow bridge* carefully as described in the above outline.
- Prepare
    - Notify your partners to be ready to self-arrest
    - Use good rope management—no slack!
    - *Consider* removing pack and/or adding flotation (*i.e.* snowshoes or skis)
    - Consider placing protection (especially useful when the approach angle is not perpendicular)
    - Consider a 5th class belay for first climber and two 5th class belays for subsequent climbers
    - Consider setting up a fixed line for the rest of the expedition
- Go earlier in the day
- Turn back

Mitigate

The details are covered in multiple other classes, but repeating the big picture for context is key!
- ABC, rescue and regroup
- If unconscious,
    - Get patient upright using cordalette from chest harness to rope—this is a breathing issue!
    - Perform first aid
    - Perform crevasse rescue (multi-team haul, 2:1, 3:1, or 6:1)
- If conscious,
    - Have fallen climber ascend rope
    - If not possible, do crevasse rescue (multi-team haul, 2:1, 3:1, or 6:1)

7. CONCLUSION

By investigating snow bridge mechanics, we increased our understanding of the forces involved and can help others make good decisions about whether or not to cross bridges and how and when to cross them. Hopefully the long diving board analogy will help climbers understand how forces multiply with bridge length. On short snow bridges, we only worry if they are really thin. Then they might fail in shear. But on long snow bridges, we are standing on a long lever arm.

It would be interesting to obtain high-speed footage of snow bridges failing under loads. We suspect it would show a tensile failure on the bottom first, followed almost instantaneously by tensile failures on top at the sides. Then the whole bridge would collapse. Hopefully the climber would be watching and not feeling like Wile E. Coyote at that point.

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