QUANTIFIED LOADED COLUMN STABILITY TEST: MECHANICS, METHODOLOGY, & PRELIMINARY TRIALS

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Abstract: Avalanche forecasters have employed ad-hoc "collapse" (loaded column) stability tests for decades, stacking blocks of snow on top of an isolated column until the column collapses and/or fractures in shear. This study presents a more rigorous "quantified loaded column test" methodology, and preliminary analyses of the test method.

An isolated vertical column of snow is cut, on a slope, using a plywood load plate of 0.04 m^2 or 0.08 m^2 as a template. One of two test modes is employed, depending on the depth of the weak layer. Vertical load is applied to the column at the areal center of the load plate using a mechanical force gauge. Each load increment of 2.0 kg over 0.08 m^2, or of 1.0 kg over 0.04 m^2, is equivalent to 25 mm of water. Loading is "rapid" in order to generate brittle shear fracture at the weakest slab/weak layer boundary. Net shear stress (N/m^2) at fracture is computed and a stability ratio is calculated, dividing shear stress at fracture by in-situ shear stress at the base of the slab.

Test variability and plate-size effect were investigated in trials during the 1999/2000 season. Side-by-side trials were performed where the quantified loaded column test was compared to the shear frame.

KEYWORDS: avalanche forecasting, stability test

1. Introduction

Stability has been defined as "the ratio of the resistance to failure versus the forces acting toward a failure" (McClung & Schaerer, 1993, p. 124). Shear fracture, associated with still poorly understood "deficit zones", is now accepted as the primary mechanism in natural slab avalanche release (Conway & Abrahamson, 1988; Schweizer, 1998). Researchers and practitioners have developed many methods for in-situ shear tests of the weakest slab/weak layer interface within the snowpack including the shear frame, Rutschblock, stuffblock, shovel shear (arguably a weak layer identification test only), and the "collapse" (loaded column) test. Of those, the shear frame has been the only test that directly produces a quantified, ratio-scale measurement of shear strength. A stability ratio, relating measured shear strength with shear stress introduced by gravitational load, is computed.

Researchers have refined the shear frame test by evaluating the effects of loading rates and normal load, developing correction factors for the effect of shear-frame size, and developing sophisticated stability indices (Perla and Beck, 1983; Föhn, 1987; Jamieson, 1995). At the same time, shortcomings of the test, including difficulties in testing very weak layers buried under relatively hard layers, caused Perla and Beck (1983, p. 490) to advocate that, "the shear frame be replaced by a device that measures a more fundamental index of *Gleitschcict* [potential zone of shear fracture within the snowpack] strength".

Sommerfeld (1980) concluded from his research into the processes of snow failure and fracture, and the findings of others, that, "failure of snow in large volumes can be predicted from tests on small volumes at high stress rates" (p. 222). Accordingly, the QLCT measures the rapid, vertical load required to induce brittle shear fracture at the weakest slab/weak layer boundary within an isolated column of snow. The surface area tested has been calibrated to provide insight to the observer about the magnitude of precipitation loading required for shear fracture. Test results (in N/m^2) are used to compute a stability index ratio. This article describes the mechanics of the QLCT, the methodology and equipment, and the results of trials conducted during the 1999/2000 season in the Bridger Range of Southwest Montana and at Rogers Pass, British Columbia.

2. QLCT Mechanics

In this section we present the mechanics involved with the stresses applied to a weak layer/interface by both the natural overburden and

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the QLCT test. We also provide a rationale for some simplifying assumptions used in the analysis. Consider a column of snow that is under only gravity loading, with no variation down slope, and the stresses that would exist on the layer located a depth h below the snow surface.

From equilibrium, the stresses τ_{slab} and σ_{slab} on the bottom surface can be found to be:

$$\tau_{slab} = \rho gh \, Sin\Psi \, Cos\Psi$$
$$\sigma_{slab} = \rho gh \, Cos^2\Psi \tag{1}$$

The subscript "slab" is used to denote stresses resulting only from the snowcover overburden. In the above ρ, τ_{slab}, σ_{slab}, g and h are respectively the average snow density, shear stress, slope-normal stress, gravity, and depth. The terms w and x are the mean width and downslope dimension of the snow column. The additional failure load that is applied during the QLCT then determines the strength of the snow at the bottom surface.

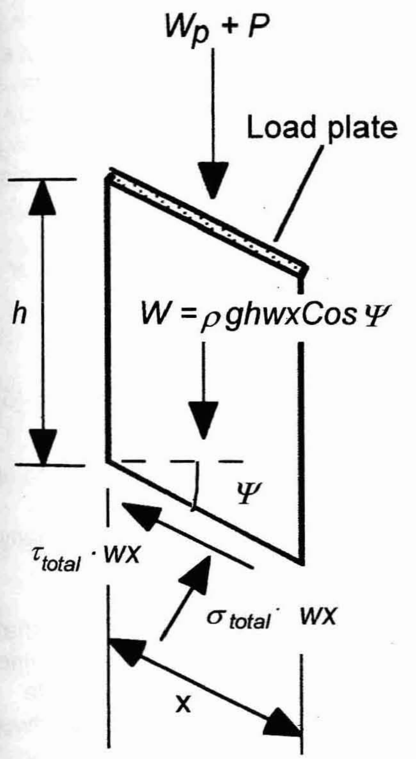

Figure 1. Schematic of quantified loaded column test.

Figure 1 illustrates the stress state in the QLCT for the surface mode test. This involves the loading of the column to test a weak layer that is close to the surface (this is discussed in more detail in the next section). In this case, a plate is laid on the top surface, and a vertical load P is applied to the plate through the centroid of the column to minimize variation of stress across the bottom surface of the column.

The term W_p is the load applied by the plate weight, and P is the force that is applied to the plate itself. In the above figure, the subscripts "total" imply that the stresses result from all of the loads (slab, plate and applied vertical load). The total shear and normal stress due to this combined loading is given by:

$$\tau_{total} = \rho gh Cos\Psi \, Sin\Psi + \frac{W_p + P}{wx} Sin\Psi$$
$$\sigma_{total} = \rho gh Cos^2\Psi + \frac{W_p + P}{wx} Cos\,\Psi \tag{2}$$

In the above equation, the downslope length x and mean width w appear as factors, since the plate load W_p and applied load P must be divided by the column dimensions to obtain stress values. These factors can be eliminated by replacing W_p and P by the water equivalent of snow needed to produce the total stresses. This is in fact done, as explained in Section 4.

The ratio of the failure stress τ_{Total} and the in-situ stress τ_{Slab} determines the stability of the slope. The procedure for determining this index is described in detail in Section 4.

The stresses calculated in equation (2) are the stresses acting on the slope-parallel surface shown in Figure 1. However, these are not the largest stresses acting on this layer. The largest stresses, normally termed the *principal stresses*, act on a surface cutting though the bed surface at an angle θ relative to the bed surface.

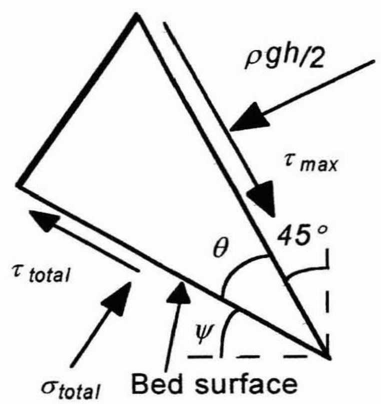

Figure 2. Principal stresses acting on plane at an angle θ relative to bed surface. The normal stress on this has the value of $\rho gh/2$.

These principal stresses act at the bed surface and may cause failure sooner than the stresses τ_{Total} and τ_{Total}. Figure 2 illustrates the plane upon which the principal shear stress acts.

The maximum shear stress τ_{Max} acts on a plane making a 45° angle with the vertical. These principal stresses have the forms:

$$\sigma_{max} = \frac{\sigma_{total}}{2} + \sqrt{\left(\frac{\sigma_{total}}{2}\right)^2 + \tau_{total}^2}$$

$$\tau_{max} = \sqrt{\left(\frac{\sigma_{total}}{2}\right)^2 + \tau_{total}^2} \qquad (3)$$

The principal shear stress τ_{Max}, which cuts through the bed surface, can fail the snow more readily than τ_{Total} and σ_{Total}. The maximum shear stress makes an angle of 45° with the vertical direction. It does not normally line up with the bed surface unless the slope is also 45°. Therefore, rather than calculating the principal shear stress, it has been decided to work strictly with the stress τ_{Total} and σ_{Total} acting in the bed surface.

In the following sections, the failure stresses calculated with the quantified loaded column test are described. As will be seen, two sizes of loaded columns will be used, and this will in turn be compared with the failure stresses determined with the shear frame. The cross-sectional areas of many shear frames differ from the areas of both loaded column tests. Therefore, some means of correcting for these size differences must be made to provide an objective evaluation of these tests.

Sommerfeld (1980), Perla (1983) and Föhn (1987) have made studies of the size effect for determining snow strength. The results are summarized in Figure 3. This figure shows the correction factor that is needed to obtain the failure stress on an infinite area, given the cross sectional area of the sample being tested.

The curve denoted by "data fit" is the curve adopted by Föhn (1987) as determined by his experiments. A least squares fit to this would yield:

$$C = 15.95A^3 - 13.25A^2 + 4.029A + 0.526 \qquad (4)$$

In this equation C is the correction factor, and A is the cross-sectional area of the test apparatus.

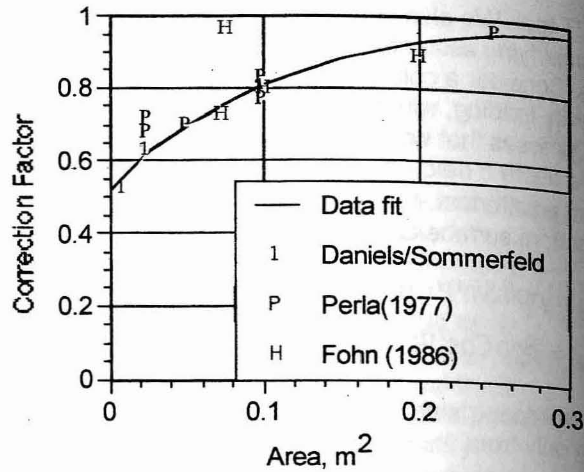

Figure 3. Correction factors required to scale measured failure stresses (after Föhn, 1987).

Finally, the QLCT and the shear frame will later be compared in this paper. These two tests differ in one important way. In the shear frame test, no slope-normal load is applied to the material, and therefore it measures just the shear strength of the snow layer being tested. However, in the QLCT, the shear strength of the weak layer is tested while it is under overburden caused by the snow (ρgh), the weight of the load plate (W_p) and the vertically applied load (P). Normally this would be taken into account by utilizing some theory, such as the Coulomb-Mohr failure criterion, which calculates the increase in shear strength due to a normal stress σ_n. The relationship for this criterion is given by:

$$\tau_{Failure} = \tau + \phi\sigma \qquad (5)$$

The term ϕ is the adjustment factor reflecting the effect that the normal stress σ has on the shear stress $\tau_{Failure}$ required for failure. For many materials, ϕ may be a function of the normal stress.

Results by Perla and Beck (1983) found that, for large rounded grains, facets, depth hoar, fine grained snow, and even fresh snow, a definite nontrivial relationship (nonzero ϕ) existed between $\tau_{Failure}$ and σ. However, Jamieson (1995) found that, for persistent weak layers such as surface hoar, the value of ϕ was so small that its effect was negated by experimental scatter. Consequently he assumed a value of $\phi = 0$ for such persistent weak layers. This result is rather surprising, but until new experimental results indicate otherwise, we assume there is no nontrivial relationship between τ and σ and assume that $\phi = 0$ in the following analysis. More research is needed to determine if a value of zero for ϕ is indeed correct for persistent weak layers.

3. QLCT Design, Equipment & Methodology

Development of the QLCT began with the assumption that, for avalanche forecasting purposes, stability tests of snowpacks under the influence of down-slope creep forces are superior to tests of snowpacks subject only to vertical settlement. The challenge has been to develop a test apparatus for use on sloping study sites and capable of testing weak layers at any depth.

3.1 Test design and equipment

One of two nominal column surface areas are used, based on the snowpack strength: 0.08 m^2 (where 2.0 kg = 25 mm of H_2O over 0.08 m^2) and 0.04 m^2 (1.0 kg = 25 mm of H_2O over 0.04 m^2). Plywood 'load plates', 9 mm thick, with a tapered shape (toward the back of the column, to prevent binding at the column sides), and a recessed "dimple" at the areal center, are used to define the sides of a vertical column. The 0.08 m^2 load plate weighs 0.50 kg and the 0.04 m^2 load plate weighs 0.25 kg.

Compact Wagner-brand model FDK-10 and FDK-40 mechanical force gauges, with ranges of 0.5 to 5 kg and 2.0 to 20 kg respectively, are used to measure the vertical loads applied to the isolated snow columns at the areal center of the load plates. This combination of gauges and load plates provides adequate overlap to cover most test conditions.

Candidate weak layers are identified in the course of normal snowpit procedures. Then, one or two preliminary QLCTs are conducted to confirm the weakest weak layer and the appropriate mode, plate, and gauge configuration for subsequent tests. These preliminary test results are not used to compute final results.

3.2 Surface mode test procedure

Surface mode is used for tests of weak layers within ≈30 cm of the snowpack surface. A load plate is placed on the snowpack surface and, to prevent it from sliding downslope, the plate is tethered by a roller bearing assembly to a 90 cm mountaineering 'snow picket' installed, vertically, immediately uphill of the load plate. The load plate itself provides a template for the vertical saw cuts used to isolate the snow column. First the column sides are cut, then the front face, and the back-cut is made last. With practice, a skilled observer can assure that the surface area of the slab/weak layer boundary being tested within the column is equal to the surface area of the load plate. Generally, the 0.08 m^2 load plate is employed in surface mode.

In surface mode the observer uses the appropriate force gauge to manually apply vertical force at the areal center of the load plate. During the test the load plate compresses low-density snow near the surface but is held over the column by its roller-bearing tether to the snow picket behind the column. Load-time to shear fracture is, nominally, 1-2 seconds. Although observer skill may be significant in surface mode tests, consistent results are possible (see Trials and Discussion sections).

3.3 Bench mode QLCT procedure

"Bench mode" is utilized for more deeply buried and/or stronger weak layers. (Figure 4). A 50 cm wide horizontal shelf is prepared removing surface, lower-density snow, the load plate is placed on this level surface, and the sequence of vertical saw-cuts are made to isolate the column.

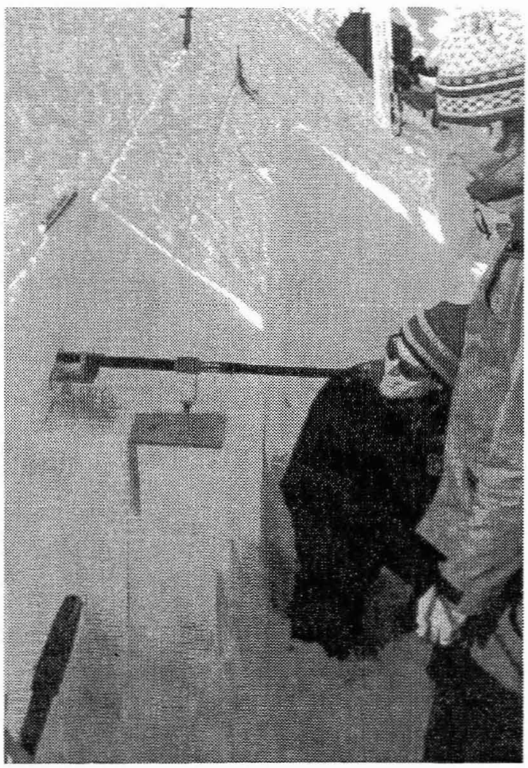

Figure 4. Bench mode test following shear fracture. The 0.04 m^2 load plate is shown.

In bench mode the surface area of the slab/weak layer boundary being tested is larger than the load plate surface area. That difference in surface areas is a function of slope angle and is accounted for in the calculation of the test result. The height of the bench above the weak layer, measured on the vertical pit face, is held constant in each test, as is the position of the load plate behind the front edge of the bench.

In bench mode, the force gauge is installed in a PVC bracket that slides freely along the round tubing handle of a specially designed flat-bladed "shovel". With the tool handle parallel to the snow bench, and the force gauge placed vertically above the areal center of the load plate, the flat blade is inserted into the snow wall behind the bench. With the tool blade thus "anchored", the tool handle provides the observer with extra control and leverage during loading. If all "4-finger" or softer snow is removed above the bench, minimal column distortion or destruction occurs. Load-time to shear fracture is, nominally, 1-2 seconds. Variability of the bench mode procedure has been evaluated and compared with shear frame variability in side-by-side trials (Section 5.2).

Calculating bench mode test results requires measuring mmH_2O_{Col}, the water equivalence of the column remaining between the weak layer and the load plate. This is performed in a two-step procedure using a snow sampling tube to measure $mm\alpha$, the water contained in the parallelogram-shaped volume bisected by the load plate, and $mm\beta$, the water contained in the remaining parallelogram-shaped volume lying above the weak layer, as follows:

$$mmH_2O_{Col} = \frac{mm\alpha}{2} + mm\beta \qquad (6)$$

3.4 Sample number & quality

Currently, for routine sessions, ten QLCTs are performed in a grid of two cross-slope rows of five tests each. A 4m cord is used to mark, perpendicular to the slope's fall-line, the location of the pit (bench) face and back wall (and column center-line for surface mode tests) on the snow surface before excavation. Within each row, tests are spaced 50 cm from column-center to column-center, and the center-line of the second row of tests is set 100 cm (as measured horizontally) directly uphill of the center-line of the first row. Thus, the sixth test is performed directly uphill of the first test.

Tests resulting in "Q1" (unusually clean and smooth shear) or "Q2" ("average" shear, mostly smooth) planar shears are deemed valid. Non-planar "Q3" (uneven, irregular, or rough) results are typically logged as "no shear" (Johnson & Birkeland, 1998). In cases of very low-density "slabs" over a weak layer (such as a density change within a new layer), "collapse" results are common and, if consistent in location, are considered valid tests.

4. Stability Index Calculations

Test result calculation procedures differ according to the test mode employed. However, both procedures generate the same end-product, expressed as the stability index:

$$S_{QLCT} = \frac{\tau_\infty}{\tau_{Slab}} \qquad (7)$$

where τ_∞ is the C adjusted (equation 4) total shear stress at shear fracture and τ_{Slab} is the shear stress at the boundary between the in-situ slab and weak layer (equation 1).

4.1 Surface mode τ_∞ calculations

Calculating τ_∞ for surface mode tests begins by converting the sum of the mean maximum vertical force applied through the force gauge P_{Mean} and the load plate weight W_p into its water equivalent. For example, using the 0.08 m^2 load plate, where 2.0 kg of vertical force is equivalent to 25 mm of H_2O, and the load plate weighs 0.5 kg:

$$\text{Ex: } H_2O_{Test} = \left(\left(\overline{P} + 0.5\right) \div 2.0\right) \times 0.025 \qquad (8)$$

The vertical measurement H_2O_{Test}, with a density of 1,000 kg m^{-3}, is used to determine the increment of shear stress, τ_{Test}, producing shear fracture:

$$\tau_{Test} = \left(1000 \times H_2O_{Test}\right) g \, Sin\Psi \, Cos\Psi \qquad (9)$$

Next, the in-situ shear stress created by the slab itself is added to obtain total shear stress τ_{Total}:

$$\tau_{Total} = \tau_{Test} + \tau_{Slab} \qquad (10)$$

In surface mode the weak layer surface area being tested is the same as the load plate area.

Applying equation (4) correction factors applied to τ_{Total} ($C = 0.667$ and $C = 0.771$ for the 0.04 m^2 and 0.08 m^2 load plates respectively), yields:

$$\tau_{\infty} = C(\tau_{Total}) \tag{11}$$

The S_{QLCT} index can be calculated using equation (7).

4.2 Bench mode τ_{∞} calculations

Because the horizontal load plate's shape is projected vertically onto a sloping stratigraphy, the surface area of the slab/weak layer boundary being tested is larger than the surface area of the load plate and loading is diffused in proportion to slope angle. QLCT reference tables provide "angle factor" $\angle_{Factor}$ multipliers for the ratio of mm H_2O per kilogram force P at a given slope angle. The mean vertical force P measured at shear fracture plus the weight of the load plate W_p are converted to mm H_2O by this factor, the measured water equivalence in the snow in the column, H_2O_{Col}, is added, and their total is converted to meters to find H_2O_{Test}:

$$H_2O_{Test} = \frac{\left(\left(\bar{P} + W_p\right) \times \measuredangle_{Factor}\right) + mmH_2O_{Col}}{1000} \tag{12}$$

The vertical measurement, H_2O_{Test}, with a density of 1,000 kg m^{-3}, is used in equation (9) to determine the increment of shear stress τ_{Test} producing shear fracture. Because τ_{Test} for bench mode tests incorporates the shear stress produced by the snow within the column under the load plate, $\tau_{Test} = \tau_{Total}$.

Slope-adjusted correction factors C are listed by plate size A and test site slope angle ψ in the QLCT reference tables. To find τ_{∞}, τ_{Total} is adjusted using equation (11) with the appropriate, slope/plate-specific value for C. The S_{QLCT} index can then be calculated using equation (7).

5. QLCT Trials Analysis

Two types of trials were conducted during the winter of 1999/2000, one comparing results between QLCT load plate sizes and the other comparing the QLCT to 0.025 m^2 shear frame tests. Table 1 shows the 4 row by 11 cell layout (44 test locations) used in the trials. For the plate-size trials, plate size is shown as "4" (0.04 m^2) or "8" (0.08 m^2). For the QLCT vs. shear frame trials, QLCT cells are shown as "LC" and shear frame cells as "SF". All results, whether from QLCT tests or shear frame tests, were adjusted for test-size A differences using the corresponding correction factor C derived from equation (4).

5.1 Plate-Size Comparison Trials

Surface mode trials were performed on 2/16/00 at the Bradley Meadows study plot (BM) in the Bridger Range of southwest Montana and near the Illiecillewaet Campground (IC) at Rogers Pass, British Columbia, on 3/14/00. Tests were 40 cm apart within rows, centered within a cell, with 80 cm (horizontal distance) between rows.

Because numerous pairs of data were collected at replicated fixed distances, this design allows for variogram estimation for both plate sizes. If the variograms indicate spatial dependence, then the spatial dependence could be modeled.

If, on the other hand, the variograms do not indicate strong spatial correlation patterns, then we treat the variation in responses as random at distances at this local level. Then, a simpler analysis can be conducted to compare the strengths associated with the two plate sizes. Note that the layout produces 22 vertical pairs (eleven 4/8 or 8/4 pairs in both the first two and last two rows). These pairs yield 22 differences (0.04 plate minus 0.08 plate strength). A paired t-test or a signed-rank test can be performed using these 22 differences.

Using the Proc Variogram procedure of the SAS statistical software package (SAS, 1996), the variograms indicated no strong spatial correlation pattern at such a local level. Thus, the simpler analysis was performed yielding the results shown in Table 2 where $\bar{x}_d$ and s_d are the mean and standard deviations of the n_d differences and t_d and p_d are the t-statistic and its p-value. Due to missing data, only 21 complete pairs occurred. The value in parentheses is the p-value for the signed-rank test for paired data. Based on these results we fail to reject the null hypothesis of no difference in strength between the two plate sizes.

Table 2. Plate-size comparison results

	BM	IC
n_d	21	21
$\bar{x}_d$	-9.047 N/m^2	0.143 N/m^2
s_d	48.333 N/m^2	129.782 N/m^2
t_d	-0.858	0.005
p_d	0.4011 (0.5397)	0.9960 (0.7500)

Table 1. QLCT trials test cell layout.

Row	Cell 1	2	3	4	5	6	7	8	9	10	11
4	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)
3	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)
2	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)
1	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)	4 (LC)	4 (LC)	8 (SF)	8 (SF)	8 (SF)	4 (LC)

This result provides evidence supporting the application of the correction factor *C* to convert test area to an infinitely large area for the purpose of computing a stability ratio S_{QLCT}. These analyses were performed using the Proc Univariate procedure of *SAS* (SAS, 1991).

5.2 QLCT vs. Shear Frame Trials

Bench-mode trials were performed at the Rogers Pass Fidelity (FI) and Cheops (CH) study sites, operated by the University of Calgary's ASARG program, on 3/16/00 and 3/13/00 respectively. Darkness curtailed the trials at Cheops before a complete set of data could be collected.

Because of the analogous layout of methods, the same approach to data analysis that applied to the plate size analysis also applies to the comparison of the QLCT and shear frame methods.

For both the QLCT and shear frame data, the variograms indicated no strong spatial correlation patterns. Thus, the simpler t-test and signed-rank test analyses, using QLCT minus SF strength differences, were performed yielding the results presented in Table 3.

Table 3. QLCT vs. shear frame results

	FI	CH
n_d	22	9
$\bar{x}_d$	-498.45 N/m^2	628.89 N/m^2
s_d	364.93 N/m^2	330.94 N/m^2
t_d	-6.41	5.70
p_d	< 0.0001 (<0.0001)	0.0005 (0.0078)

Based on these results we reject the null hypothesis of no difference in strength between the QLCT and SF methods, and conclude that statistically significant differences exist. The significant differences, however, are inconsistent across the two study areas. At the Fidelity site the shear frame strengths were larger than the QLCT strengths, while at the Cheops site the converse held. A possible physical explanation for these results is discussed below.

6. Discussion

As with other stability tests, operator skill and consistency represent a potential source of error in the QLCT, particularly with the surface mode. Ongoing trials, and development of the surface mode test apparatus, are needed to evaluate and reduce that potential error.

Additionally, given that test result variability increases/decreases with increasing/decreasing mean strength, a sequential sampling procedure designed to achieve a specified level of test precision with a minimum number of tests is currently under development.

The QLCT vs. shear frame trials results presented in Section 5.2 are difficult to interpret. The same surface hoar layer deposited on 2/21/00, and buried under a slab of some 70-80 cm, was tested at both sites. Operator variation is probably not responsible for the contradictory results. Rather, we hypothesize a mechanical explanation.

In surface hoar, depending on the effects of creep and settlement on the orientation of the grains to the slope and the thickness of the weak layer, vertical loads may exploit a moment arm over the length of the grains which a purely shear-oriented force is unable to replicate. At Fidelity the test site was significantly flatter ($\angle$ 15°) than at Cheops ($\angle$ 25°), reducing the creep effects at Fidelity on the buried surface hoar and leaving the grains somewhat more "upright".

In thinner, more granular weak layers, or in very thin layers of "laid down" surface hoar such as that tested at the Cheops site, the vertical load of the QLCT may produce a normal-force effect increasing shear strength. The shear frame technique, on the other hand, effectively eliminates such normal forces and, rather, tests the minimum shear strength of the weak layer in the absence of normal forces. It might be argued, then, that the QLCT, with its vertical loading, more realistically replicated the combined shear and normal forces acting on weak layers in the snowpack during those trials at both the Fidelity and Cheops sites. Further side-by-side trials and analyses are needed.

The QLCT will be utilized during the winters of 2000/2001 and 2001/2002 to investigate the objective extrapolation of study plot stability onto nearby and distant avalanche starting zones, and the uncertainties inherent in that process.

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