IN-SITU TENSILE STRENGTH MEASUREMENTS OF ALPINE SNOW

J.B. Jamieson[1] and C.D. Johnston[2]

ABSTRACT

During the winter of 1987-88, over 450 in-situ tests of tensile strength were made in the Alberta Rockies. An average of 7 tests was made for each of 66 snow layers. Snow with a faceted microstructure was half as strong as new, partly settled or rounded snow of the same density. The precision of 7 tests is 15% with 90% confidence. Notch sensitivity, rate effects and critical strain, are used to show that the test fractures were brittle. Measurements of tensile strength and slab thickness made at crown fractures support the hypothesis that stronger, thicker slabs results in wider crown fractures.

INTRODUCTION

In-situ tests provide estimates of snow strength based on cross sections generally larger than those feasible in the laboratory. In addition, the snow specimens can be tested without being disturbed by extraction from the snowcover or by transportation to the testing device. Typically, in-situ tests do not allow control over variables such as snow or air temperature. Also, present in-situ test methods do not facilitate good control over the stress or strain rate.

Previous In-Situ Studies

Four in-situ studies of tensile strength precede the present work. Perla (1969) made approximately 250 cantilever beam tests on newly fallen snow. In 38 rolling cart tests, McClung (1979) loaded larger specimens to failure in 1 to 8 minutes. The results showed less scatter and the fractures likely involved ductility since the shape of the notches did not affect the results. Conway and Abrahamson (1984) developed the slip plate test method (Figure 1) used in the present study. They made thirty-three tensile tests of snow slabs on avalanche slopes with loading times to failure of up to 15 seconds. Rosso (1986) measured the strength of 13 large trapezoidal portions of snow slabs by undercutting them with a snow saw until they failed in tension.

The present study includes over 450 slip plate tests, most of which were made in and near the Skiing Louise Resort in the Canadian Rockies during the winter of 1987-88.

---

[1] Graduate Student, Dept. of Civil Engineering, University of Calgary, Calgary, Alberta.

[2] Professor, Dept. of Civil Engineering, University of Calgary, Calgary, Alberta.

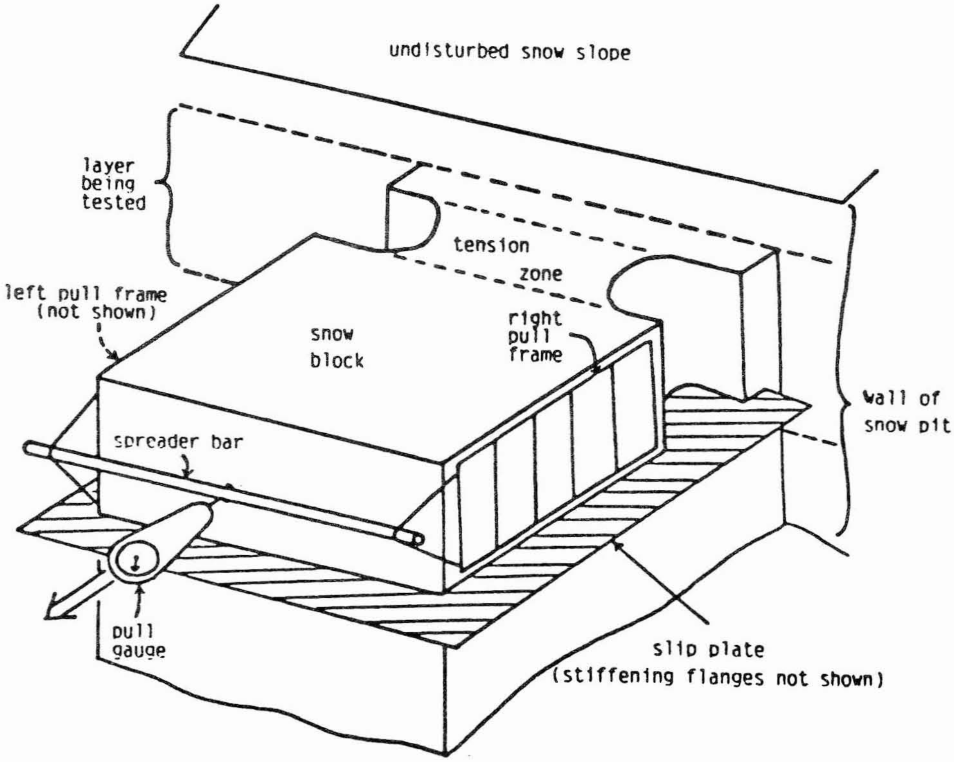

Figure 1. Tensile Test Using Slip Plate

TEST METHOD

From a pit wall facing downslope, a column of snow approximately 40 cm by 40 cm was isolated as shown in Figure 1. A homogeneous layer thicker than 10 cm was selected. Snow over this layer was carefully removed, exposing the top surface of the snow to be tested.

One pull frame was gently pushed into each side of the column parallel to, and close to, the exposed surface. Slightly below and parallel to the snow layer to be tested, a low friction slip plate was inserted. The two notches each with a 50 mm radius were cut with a downward stroke of a notching tool. After the notches were cut, the resulting width of the tensile zone was approximately 20 cm. Thus, a block of snow was isolated on top of the slip plate, between the two pull frames and remained attached to the snowpack only by the notched tensile zone.

A spreader bar was attached between the two pull frames and increasing downslope pull was manually applied with a pull gauge until fracture occurred. For the tensile strength measurements presented in Figure 3, loading times ranged from 0.5 to 5 seconds with a mean of 2.2 seconds.

Friction between the snow and the slip plate was measured by tilting the plate and noting the angle at which a snow block on the plate began to slide. Friction angles for the snow blocks on the waxed slip plate ranged from 2° to 9.5° with a mean of 3.6°.

EQUIPMENT

Slip Plate

Plates of 0.6 mm stainless steel were sufficiently stiff to resist denting and bending under normal handling and were observed to undercut the snow blocks cleanly. The preferred size of plate was 45 cm across, 40 cm in the downslope direction and had 2.5 cm stiffening flanges on three sides at right angles to the surface of the plate. The cutting edge without the flange was sharpened to facilitate gentle insertion under the snow block.

Pull Frames

Frames soldered from 25 mm wide strips of 0.45 mm stainless steel proved adequately sturdy for testing snow up to 350 kg/m^3. Given the dimensions of the plate and tensile zone, 28 cm was the maximum and the preferred length of the frames. Four equally spaced cross pieces were soldered in place. To ensure that the width of the frames approximately spanned the depth of the snow layer being tested, frames with widths of 10, 20 and 30 cm were used. The cutting edges of the frames were sharpened to permit gentle penetration of the sides of the snow block.

Notching Tool

The blade of this tool consisted of 0.6 mm stainless steel sheet metal bent into a semicircle with a 50 mm radius. During the study of notch sensitivity, two other notching tools with tip-radii of 10 mm and 1 mm were used.

STRENGTH CALCULATION

The following measurements were taken: maximum pull force (P), loading time (t), downslope length of the block (l), cross-slope width of the block (w), depth of the block (d), the corresponding dimensions of the tensile zone (l_t, w_t, d_t), slope angle (β), friction angle (γ) for the snow block on the plate, snow density (ρ) and the mass of the frames (m_f).

From statics, the average stress in the cross section at fracture is:

$$\sigma = (W \cdot \sin \beta + P - W \cdot (\tan \gamma) \cdot \cos \beta) / (w_t \cdot d_t) \qquad (1)$$

in which the weight of the block and frames is:

$$W = (l \cdot w \cdot d \cdot \rho + m_f) \cdot g \qquad (2)$$

FACTORS AFFECTING RESULTS

Rate Effects

To study the effect of the manual pull rate on the results, the test method was repeated approximately 10 times at each of three study plots. By deliberately slowing down the rate of pull, loading times ranging up to 65 seconds were obtained. Approximate stress rates were calculated from the stress at failure σ and the loading time t:

$$\sigma \simeq \sigma / t \qquad (3)$$

Using the set of 11 tests made on a layer of rounded grains at Wolverine Study Plot on March 24, 1988 as an example, a decrease in strength for an increase in the approximate stress rate is shown in Figure 2. The other two rate experiments show a similar trend but with more scatter.

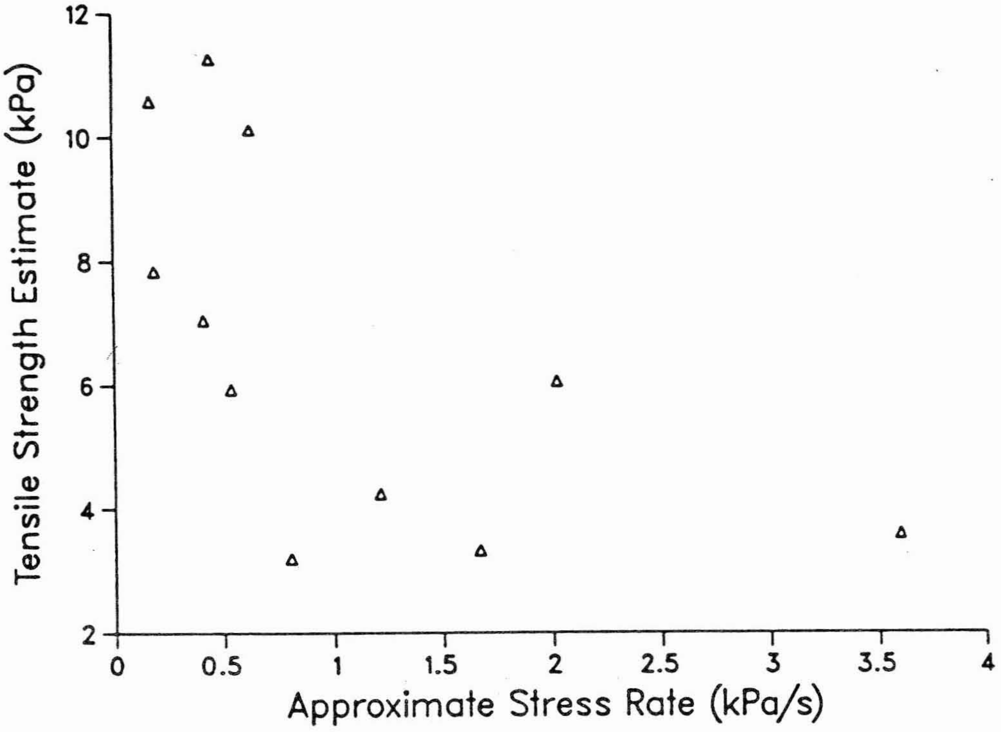

Figure 2. Effect of Stress Rate on the Strength Of a Layer of Rounded Grains with a Density of 302 kg/m^3

Notch Shape

The effect of notch radius was studied by comparing the results of tests made with various notching tools. Adjacent tests on the same snow layer were paired: one test made with standard notches (50 mm radius) and one test with low radius notches (1 mm or 10 mm radius). Strength determined by tests made with 10 mm radius notches was not susbtantially reduced from tests made with standard notches. However, the strength of tests made with 1 mm radius notches was reduced an average of 22% from tests made with standard notches. Further, the difference between these paired test results was detected at the 99% confidence level (Jamieson, 1988).

Screening of Data

During the winter of 1987-88, 555 tests were made. The effect of fourteen test conditions and ten fracture characteristics on the results was analyzed by a multivariate regression to determine which factors were associated with systematic increases or decreases in strength (Jamieson, 1988). From the factors that were detected at the 99% confidence level, the following were considered to be unrelated to the study of strength in terms of material properties:

- notch radii of 1 mm (25 tests),
- loading times greater than 5 seconds (38 tests),
- fracture at the back of the notched zone (28 tests), and
- fracture at the front of the notched zone (7 tests).

The first two factors have already been discussed. The latter two factors (fractures at the front or back of the notched zone) were associated with a decrease in strength. The tests associated with these four factors were rejected, giving a refined set of 457 tests for studying the tensile strength in terms of material properties. The following sections of this paper are based on the refined data set. The results of 21 tests on moist snow (NRCC/CAA, 1986) are included since the moisture factor was not associated with an increase or decrease in strength.

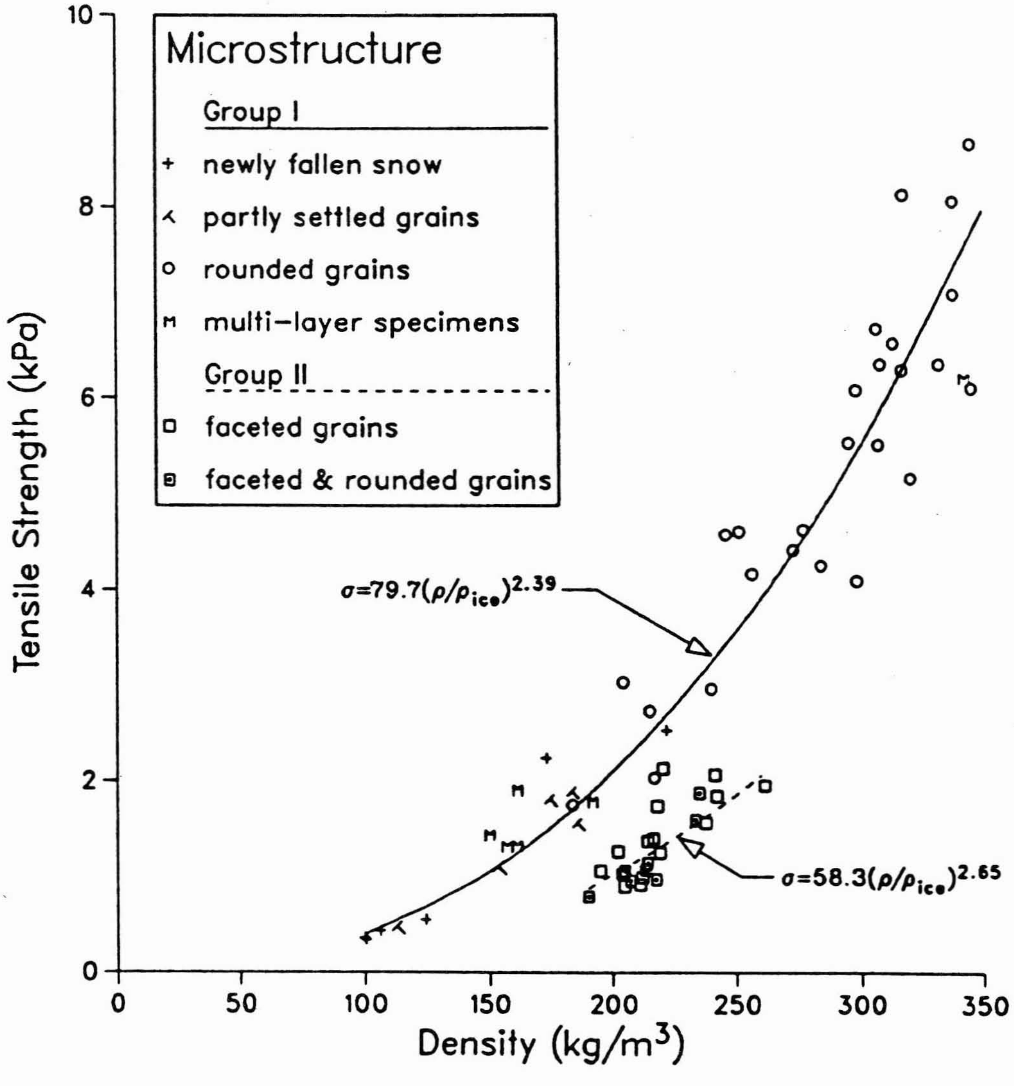

Figure 3. Dependence of Strength on Density and Microstructure

RESULTS

Dependence of Tensile Strength on Density and Microstructure

At a particular study site on a given day, a snow layer was tested an average of 7 times. The means of the 66 sets of repeated tests are plotted in Figure 3. Two regression lines determined by least squares are also presented: one line for layers of grains which showed faceting (Group II), and one line for the other tested layers (Group I). The layers of grains which showed faceting (Group II) were approximately half as strong as the layers in Group I.

Comparison with the Results of Previous In-Situ Studies

Faceted snow, wet snow and moist snow are excluded from this comparison since there are only 3 tests on faceted snow (Rosso, 1986) and 9 tests on wet snow (McClung, 1979) with which to compare the present results. Below a density of 200 kg/m^3, the present tensile strengths are consistent with previous studies (Figure 4). Above 200 kg/m^3, the present results appear lower than the few previously reported data. Such a reduction in strength may be due to the rapid loading used in the present study. Nevertheless, there is a clear need for further in-situ studies of tensile strength.

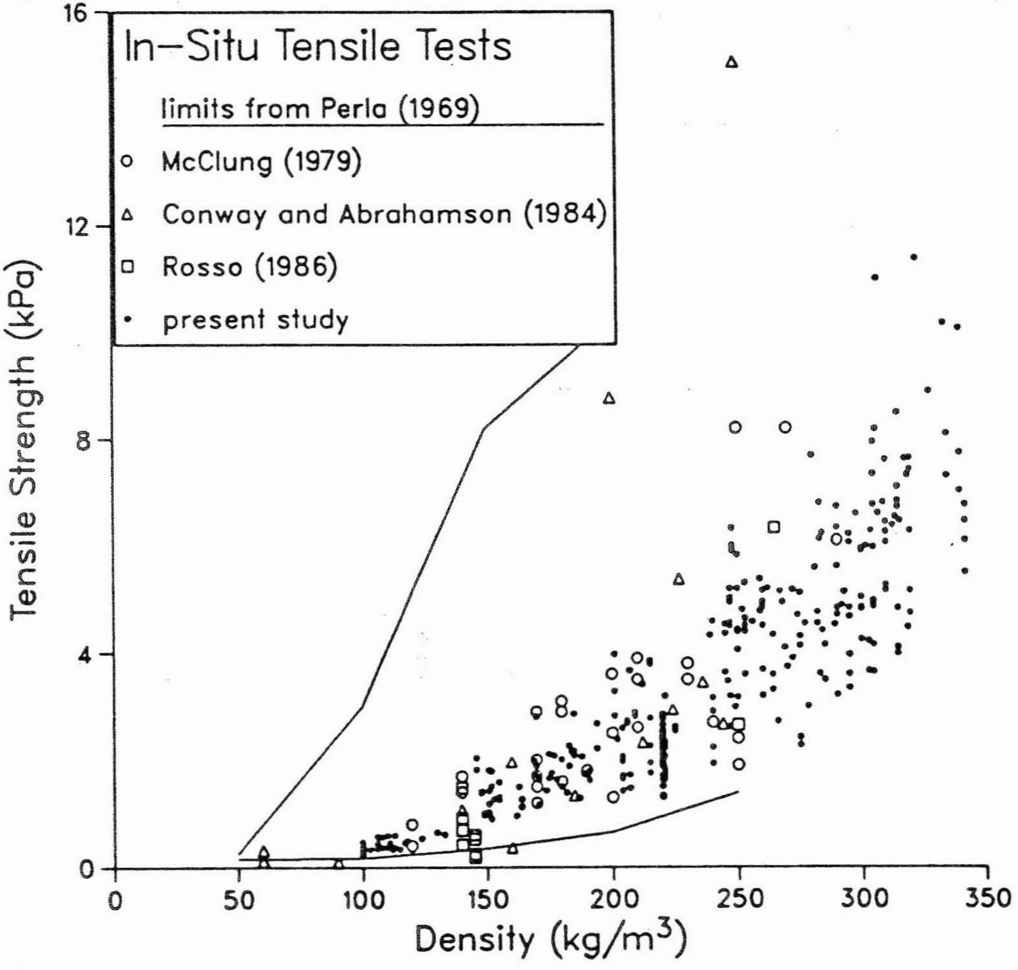

Figure 4. Comparison with Previous In-Situ Studies

Precision

Appropriate sample sizes can be estimated, for required levels of precision, from the coefficient of variation (v) of repeated tests on a particular layer of snow. For the two largest sets (30 and 42 replicates), the coefficients of variation were both 0.20. Using this value for v, the number of tests (n) which must be averaged to obtain precision p at the $1-2\alpha$ confidence level is given by:

$$n=(t_{\alpha,n-1}v/p)^2 \tag{4}$$

in which $t_{\alpha,n-1}$ is the tabulated value from a Students t-distribution with n-1 degrees of freedom which has a probability of α associated with each tail. Equation 4 is solved iteratively and the results are given in Table 1.

Table 1. Number of Tests for Required Precision

Required Precision of Mean (%)	Confidence Level (%)	Estimated Number of Tests
10	90	13
10	95	18
15	90	7
15	95	10

There were an average of 7 tests in a set of replicates in this study. With 90% confidence, the mean strength determined from 7 replicates will have a precision of 15%.

Critical Strain

Approximate values for the strain just before failure were obtained from a photographic technique which was applied to 15 tests. Rulers were placed across one of the two notches. During the few seconds for which the load was manually increased, photographs of this notch were taken up to 5 times per second.

The deformation of the tensile zone before failure as shown by the ruler in the photographs ranged from 0 to 1 mm with an average of 0.5 mm. Although the accuracy is ∓0.5 mm, the technique is useful for establishing the order of magnitude of the deformation. Since the length of the tensile zone is 10 mm, a deformation of 0.5 mm corresponds to a strain of 0.5%. These critical strains are in agreement with the critical strains for brittle fractures due to constant strain rates (Narita, 1980, 1983).

This argument is based on the assumption that the critical strain from constant strain rate tests can be compared with the approximate values measured in-situ by manually increasing the stress. However, the stress-strain curves reported by Narita are essentially linear for loading times up to 40 seconds. Similarly, the constant strain rate experiments of Singh (1980) which were made in the field, show stress to be proportional to strain for loading times up to 80 seconds. Since the loading times in the present study are well within the range of linear stress-strain behaviour, comparable critical strains are expected.

Failure Mode

In a laboratory study of tensile fractures, Narita (1980, 1983) identifies the following three characteristics of brittle tensile fractures:

1. Sharp fractures perpendicular to the axial load.
2. Sudden failure with no microcracking at strains of 0.8% or less.
3. A decrease in strength with an increase in strain (or stress) rate.

In the present study:

1. The fracture surfaces were sharp and averaged 91.5° from the slope which was approximately parallel to the direction of loading.
2. The critical strain was < 1%.
3. The strength decreased with an increase in loading rate.

The agreement between brittle results in the laboratory and the present in-situ results, combined with the notch sensitivity of the present results, indicates that the fractures in the present study were essentially brittle.

CROWN WIDTH OF SLAB AVALANCHES

Avalanche workers have often reported that stronger, thicker slabs propogate wider crown fractures which result in larger slab avalanches.

To assess this hypothesis, measurements of tensile strength and slab thickness were made at the crown fractures of 13 unconfined slab avalanches. For eleven of these avalanches, the measurements were made within two days of the occurrence. Of these eleven, four avalanches were triggered by explosives and seven were released by skiers. The remaining two avalanches occurred naturally and the measurements were made 5 days after the occurrences during which the temperature ranged from -13°C to -31°C.

For each of these unconfined avalanches, measurements were made at a site along the crown fracture at which the slab was average in thickness and where there were no unusual features in the crown fracture such as rock outcrops or trees. At these crown fractures, an average of four measurements of the tensile strength and of the thickness (perpendicular to the slope) were made.

Correlations of crown width with mean strength, mean thickness and with the product of mean strength and mean thickness are reported in Table 2. Although strong conclusions are not possible based on 13 data points, the r-values presented in Table 2 are consistent with the hypothesis.

Table 2. Correlations With Crown Width

	Min.	Max.	r-value
Thickness, D (m)	0.10	0.47	0.84
Tensile Strength, σ (kPa)	0.36	6.2	0.70
Thickness x Tensile Strength, $D\sigma$ (kN/m)	36.	2.92	0.82

The correlation of crown width (B) with the product of tensile strength (σ) and thickness (D) is of particular interest since it best represents the reports of field workers. By regressing crown width (in metres) on this product (in kN/m) the following ratio is obtained:

$$B/D\sigma \simeq 40 \qquad (5)$$

The crown width is plotted against the product of thickness and tensile strength in Figure 5.

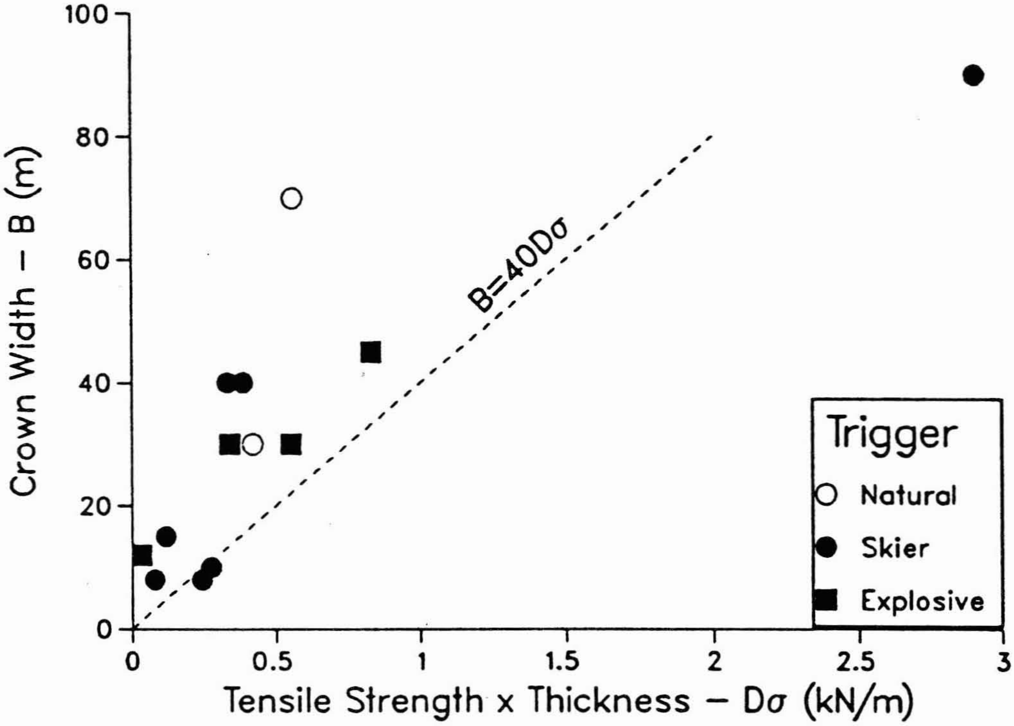

Figure 5. Crown Width vs Slab Thickness x Strength

Although the number of data points is very limited, there is no apparent effect of different triggers on the results.

Brown et al. (1972) report that there is no known theoretical upper limit to the width of slab avalanches. However, the trend apparent in Figure 5 suggests that the width of a crown fracture may be a property of the slab and independent of the triggering mechanism. Further research is necessary to investigate mechanisms which may limit the width of slab avalanches.

ACKNOWLEDGEMENTS

During this project, important advice was received from Clair Israelson of Parks Canada and from P.A. Schaerer and D.M. McClung of the National Research Council of Canada. Dave Norcross of Parks Canada and the staff of the Temple Research Station helped with the collection of fracture line data. John Worrall of Skiing Louise Ltd. provided lift access. Alan Evenchick of Fernie Snow Valley Ski Resort assisted with the two large sets of repeated tests. Chris Stethem of Chris Stethem and Associates and R.I. Perla of the National Hydrology Research Institute loaned the pull gauges. Many thanks.

We are grateful to the Alberta Recreation, Parks and Wildlife Foundation for financial support throughout the field work and analysis of results and to the Natural Sciences and Engineering Research Council for financial support during the preparation of this paper.

REFERENCES

Brown, C.B., R.J. Evans and E.R. LaChapelle, 1972. "Slab Avalanching and the State of Stress in Fallen Snow", Journal of Geophysical Research, Vol. 77, No. 24, p. 4570-4580.

Conway, H. and J. Abrahamson, 1984. "Snow Stability Index", Journal of Glaciology, Vol. 30, No. 106, p. 321-327.

Jamieson, J.B., 1988. M.Sc. Thesis, in preparation, Dept. of Civil Engineering, University of Calgary, Calgary, Alberta.

McClung, D.M., 1979. "In-Situ Estimates of the Tensile Strength of Snow Utilizing Large Sample Sizes", Journal of Glaciology, Vol. 22, No. 87, p. 321-329.

Narita, H., 1980. "Mechanical Behaviour and Structure of Snow Under Uniaxial Tensile Stress", Journal of Glaciology, Vol. 26, No. 94, p. 275-282.

Narita, H., 1983. "An Experimental Study on Tensile Fracture of Snow", Contributions from the Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, Series A, No. 32, p. 1-37.

National Research Council of Canada and Canadian Avalanche Association, 1986. "Guidelines for Weather, Snowpack, and Avalanche Observations", NRCC Technical Memorandum No. 132, p. 53.

Perla, R.I., 1969. "Strength Tests on Newly Fallen Snow", USDA Forest Service, Research Note Rm-150, 12 p.

Rosso, R.S., 1986. "In-Situ Strength Measurements of the Snowpack", Proceedings of the International Snow Science Workshop at Lake Tahoe, ISSW Workshop Committee, Homewood, California, p. 210-215.

Singh, H., 1980. "A Finite Element Model for the Prediction of Dry Slab Avalanches", PhD. Thesis, Colorado State University, Fort Collins, Colorado, 183 p.