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IN-SITU ESTIMATES OF THE TENSILE STRENGTH OF SNOW UTILIZING LARGE SAMPLE SIZES

By David M. McClung*

(Norwegian Geotechnical Institute, Oslo 8, Norway)

Abstract. Experimental procedure and measured estimates of the tensile strength of snow are given by a new method utilizing large sample sizes of naturally deposited snow. Data are presented as a function of average sample density, temperature, loading rate, and snow type. The results show less scatter in the data than previous *in-situ* estimates and lower mean strength values as a function of density. The relevance of the data to tensile fracture as observed in slab avalanche release is discussed.

Résumé. *Estimation* in situ *des efforts de traction dans la neige sur des échantillons de grande dimension.* On donne un procédé expérimental et des estimations des efforts de traction dans la neige par une nouvelle méthode utilisant des échantillons de grande dimension de neige déposée naturellement. Les résultats sont présentés en fonction de la densité moyenne de l'échantillon, de la température, de la surcharge et du type de neige. Les résultats montrent une dispersion moindre que les estimations anciennes et des moindres valeurs moyennes des efforts en fonction de la densité. On discute le rapport entre les résultats et les ruptures à la traction observées dans les déclenchements d'avalanches de plaques.

Zusammenfassung. In-situ-*Abschätzungen der Zugfestigkeit von Schnee an grossformatigen Proben.* Das experimentelle Verfahren und die Abschätzungsergebnisse einer neuen Methode zur Bestimmung der Zugfestigkeit von Schnee, bei der grossformatige Proben natürlich abgelagerten Schnees benutzt werden, werden mitgeteilt. Die Werte stellen sich in Abhängigkeit von der mittleren Probendichte, der Temperatur, der Belastungsrate und der Schneeart dar. Die Ergebnisse zeigen geringere Streuung als frühere Abschätzungen und kleinere mittlere Festigkeit in Abhängigkeit von der Dichte. Die Bedeutung der Daten für Zugbrüche, wie sie in Brettlawinen zu beobachten sind, wird diskutiert.

Introduction

The tensile strength of snow is an important quantity in snow mechanics. Destructive tensile fractures are habitually observed on the line where snow slabs break away from their anchoring zones (Haefeli, 1967; Perla, [1975]).

The tensile strength of snow is a function of many variables including density, temperature, and snow type. In addition, any test introduces additional variables which must be considered including loading rate, sample size, boundary conditions at the places where the sample and testing equipment are in contact, and sample disturbance in mounting the specimens.

Experiments with small sample sizes using centrifugal tensile testers consistently show large scatter in the strength values and high mean strength values (Sommerfeld, 1974). In addition, centrifugal testers cannot be used *in situ* and therefore may subject the sample to damage upon insertion of the sample tubes. Jarring of the samples against the walls of the tester at fast acceleration rates is also possible in centrifugal tests.

The procedure used in the present paper to estimate the tensile strength of snow is intended to provide estimates for larger sample sizes closer to the expected sample size in natural slab avalanches. In addition, the tests were made *in situ* and the loads were applied slowly to prevent effects of jarring and sample damage. The boundary conditions at the places where the snow specimen and the testing equipment were in contact were such that the conditions expected prior to destructive tensile fracture observed in snow-slab release were approximately simulated.

Experimental procedure

The experiments were done during the winters of 1971–72 and 1972–73 in the Cascade Mountains, U.S.A. The apparatus consisted of a series of large tables set out on a horizontal snow surface to collect samples of snow. The tables had removable, wooden sides such that the

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* Present address: Environment Canada, Canmore, Alberta ToL oMo, Canada.

samples were collected in a box on top of the tables. Following collection of a sample, the top was carefully trimmed off and the wooden sides were removed to provide uniformly shaped and sized samples. The surface of the tables was partly rough and partly smooth. It was hoped that destructive tensile fracture would occur on the line between the rough and smooth sections as the table was slowly tilted by lifting one end resulting in slow loading by body forces. This proved to be the case for each test. The fracture surfaces were, in general, smooth and perpendicular to the table surface.

The stress field in the samples in the present tests is not homogeneous. The tests were designed to simulate conditions of tensile failure in slabs whose resistance to sustaining basal shear stress is diminished. There will, therefore, be small differences when the present data are compared to uniaxial test results. However, a smaller effect is to be expected when comparing the results to field estimates.

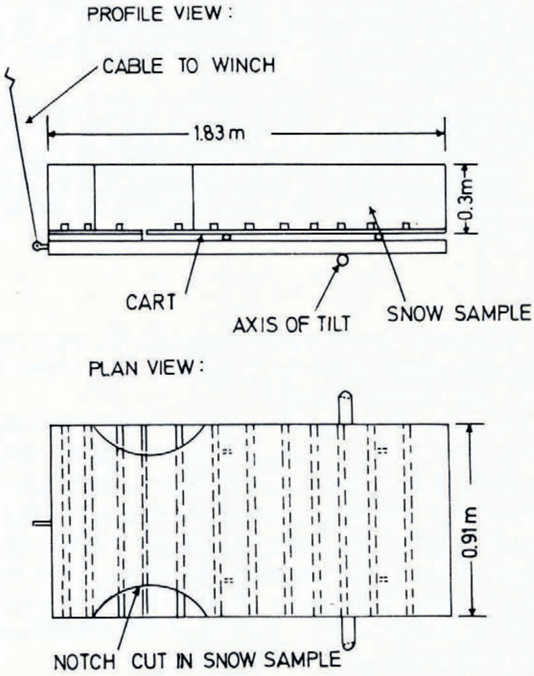

Fig. 1. Schematic drawing of tilting-table apparatus used in tensile tests.

Figure 1 shows a schematic drawing of the tilting table. The rough portion of the table surface was made by nailing wooden strips to the table surface near the end of the table that was to be tilted. The smooth portion of the table surface was achieved by constructing a cart on wheels with a rough surface on the top of the cart. Friction experiments with zero tensile force showed that this arrangement produced a coefficient of friction that was very small in comparison with other errors.

The dimensions of the samples were 0.91 m wide by 1.83 m long with sample heights on the order of 0.3 m. The samples were shaped (notched) in the vicinity of the interface between the rough and smooth sections of the table (Fig. 1). Typical fracture areas were on the order of 0.12 m^2 in cross-section.

Parameters recorded included average density, average temperature, snow type, age, and time to failure. The greatest source of measurement error in these experiments was in the

TABLE I. TENSILE STRENGTH OF SNOW VERSUS MEASURED FIELD PARAMETERS

Tensile strength $\mathrm{N/m^2}$	*Density* $\mathrm{kg/m^3}$	*Temperature* °C	*Duration of loading* s	*Age* d	*Crystal type and sample stratigraphy*
6 500	250	0.0	240	7	Fine-grained old snow; 0.05 m loose ice layer near top; water-soaked
8 200	250	0.0	240	7	Fine-grained old snow; thin ice layer on bottom
1 400	140	−6.0	60	3	Stellar dendrites; light to moderate riming; light wind-packed snow on top
1 700	140	−4.8	60	3	Stellar dendrites; light to moderate riming; light wind-packed snow on top
1 500	170	0.0	85	1	Mostly needles; moderate wind packing; fairly homogeneous sample
1 200	170	0.0	60	1	Needles, rimed stellar, graupel; wet, heavy, rain-soaked sample
2 300	170	0.0	165	2–3	Graupel, flakes, heavily rimed; wet layer on bottom
2 700	190	−0.5	147	2–3	Graupel, flakes, heavily rimed; fine-grained wet layer on bottom
2 400	170	−0.2	125	2–3	Graupel, flakes, heavily rimed; wet layer on bottom
3 900	210	−4.0	65	1	0.08 m rimed stellar over 0.25 m wind-packed, broken crystals
2 500	200	−3.0	95	1	Stellar dendrites with wind-packed layer in the middle
1 300	200	−3.0	90	1	Broken dendritic—fairly homogeneous wind-packed sample
3 100	180	−4.0	180	2	0.05–0.10 m rimed stellar dendrites over wind-packed layer
1 800	190	−4.0	75	3	0.10 m wind-packed snow over 0.25 m lighter rimed dendrites
6 100	290	−2.5	240	1	Graupel and broken crystals; homogeneous wind-packed sample
3 800	230	−2.5	240	1	Graupel and broken rimed fragments; lighter snow overlain by 0.10 m wind-packed layer
8 200	270	−5.5	240	1	Graupel and broken rimed fragments; homogeneous wind-packed sample
400	120	−3.0	145	1	Lightly rimed and unrimed dendrites; homogeneous, non-wind-packed sample
1 700	170	−3.5	140	3	Lightly rimed and unrimed dendrites; 0.15 m wind-packed snow over loose, unconsolidated snow
800	120	−3.0	60	1	Lightly rimed and unrimed dendrites; homogeneous, non-wind packed sample
3 600	200	−1.7	250	9	Fine-grained old snow; 0.15 m newer snow over fine-grained old
3 500	210	−3.0	150	9	Fine-grained old snow; layer of newer snow over older
3 500	230	0.0	140	11	Lightly rimed stellar, needles; 0.20 m new snow over 0.15 m hard, crusty snow
7 900	320	0.0	145	10	0.18 m coarse-grained old snow over 0.18 m fine-grained old snow; rain-soaked, subject to melting
6 200	350	0.0	70	11	Top 0.10 m fine-grained old snow; 0.25 m coarse-grained old with 0.08–0.10 m icy layer on bottom, water-soaked sample
4 200	330	0.0	60	11	0.12 m fine-grained, old over 0.25 m coarse-grained, old snow, water-soaked sample
1 600	180	−2.2	60	3	Stellar dendrites and needles; fairly homogeneous sample
1 600	180	−1.5	80	3	Needles and stellar dendrites; fairly homogeneous sample
2 000	170	−1.8	108	5	Very fine grained; needles, stellar dendrites; fairly homogeneous sample
2 600	210	−2.5	105	1	Fragments, stellar dendrites, needles; moderately wind-packed; fairly homogeneous
2 400	250	−1.0	92	12	Fine-grained old snow covered by radiation crust
2 700	240	−0.5	142	12	Fine-grained old snow with some graupel; fairly homogeneous sample
1 900	250	−0.5	60	12	Fine-grained old snow; homogeneous sample
2 000	170	0.0	60	1	Needles; moderately wind-packed, homogeneous sample
1 100	150	−0.8	60	1	Graupel; spatial dendrites, stellars; loose, wet snow
2 900	180	0.0	495	4	Stellar dendrites with 0.08 m layer of graupel on bottom
1 200	170	0.0	180	4	Stellar dendrites with 0.08 m layer of graupel mixed with stellar crystals on bottom
2 900	170	0.0	485	4	Stellar dendrites with 0.08 m layer of graupel mixed with stellar crystals on bottom

estimation of the average snow density on the tables. In order to minimize this error a large number of density samples were taken with a cylindrical sample cutter 0.15 m in diameter through the depth of the sample and with a small sample cutter with a volume of 200 cm^3 (0.2×10^{-3} m^3).

The angle of tilt of the table when fracture was achieved was measured with an inclinometer to an accuracy much greater than required in relation to other errors. Angles of tilt at failure ranged from 10° for snow with the lowest density to 45° for higher-density snow. The tables were tilted slowly to avoid jarring and disturbance from *in-situ* conditions.

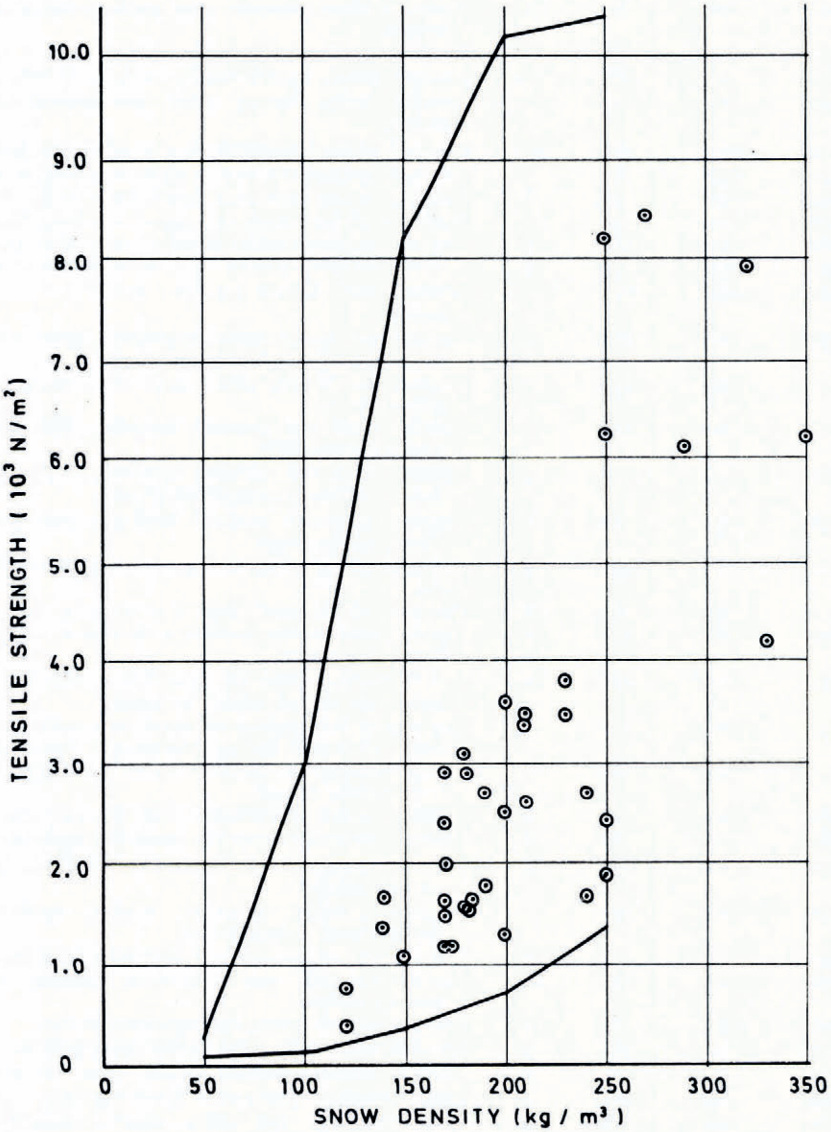

Fig. 2. Comparison of tensile-strength estimates from present experiments with the limits of the in-situ *data given by Perla (1969).* ⊙ *denotes data point from present experiments. The solid lines bound the limits of the data given by Perla (1969) for cantilever beam experiments with smaller sample sizes.*

Several experiments were conducted to test the effect of notch geometry at the interface between the smooth and rough parts of the table on the results. The results showed no discernible notch sensitivity for notch shapes ranging from very thin slits to rounded circular forms.

Table I summarizes the tensile strength estimates as functions of the measured field parameters.

Discussion of tensile-strength results

The most important easily measurable parameter to relate to tensile strength of snow is snow density (Sommerfeld, 1973). Figure 2 shows a comparison of the present estimates with the scatter band of the only other *in-situ* estimates which were given by Perla (1969). Perla's experiments were made by rapidly undercutting cantilever beams of snow in pit walls, presuming tensile failure in the top fibre. Perla's experiments differ from the present experiments in some important ways: (1) the fracture patterns observed in the beam tests indicate that fracture was not always in tension and may have included shear and bending effects, (2) the beam tests were done at faster rates than the present experiments and the possibility of jarring and sample disturbance is higher, (3) the effective sample fracture area in the cantilever beam experiments was on the order of 10% of that for the present tests.

If one accepts the definition of brittle fracture as fracture without significant prior plastic deformation (Erdogan, 1968), then it is not possible, strictly speaking, to classify the present experiments as brittle or ductile since no deformation measurements were made prior to fracture. Since the experiments were all done at temperatures near the melting point, some ductility is expected. In addition, the samples were loaded for periods of time on the order of minutes prior to fracture will most likely have given time for plastic deformation.

If one ignores, for the moment, effects of ductility and inhomogeneity of stress conditions, comparison of the present data with the *in-situ* data of Perla and the non-*in-situ* data from centrifugal tests (Keeler and Weeks, 1968; Sommerfeld, 1974) leads to the conclusion that increased sample size results in lower mean values of strength and less scatter as a function of density. These results are consistent with the predictions of Weibull-like statistics (Freudenthal, 1968) as proposed by Sommerfeld (1973) for application to brittle fracture of snow. In fact, the minimum strength values obtained in the present experiments lie close to the values for large sample sizes predicted by Sommerfeld (1974) by applying Weibull statistics to centrifugal-test data. This is shown in Figure 5.

However, use of Weibull statistics presumes brittle fracture by a specific mechanism. Size effects are expected in both brittle fracture and ductile fracture (Freudenthal, 1968). For the present experiments not enough tests are available to warrant use of such statistics and, in addition, the mechanism of fracture is not known, so that Weibull statistics, properly speaking, cannot be applied in this case.

Attempts to measure shear strength *in situ* utilizing large sample sizes

Estimates for shear strength were attempted during the winter 1972–73 in the Cascade Mountains. The basic method of sample collection was similar to that for the tensile tests. Figure 3 depicts the apparatus. The central portion of the sample consisted of a cart on wheels. The cart was flanked by two fixed portions of the sample. All three portions where the sample contacted the apparatus had rough surfaces.

The basic procedure consisted of slowly pulling the cart by a hand-cranked winch until failure. The table was in a horizontal position during the entire experiment. A maximum recording dynamometer was attached into the cable connected to the winch. Parameters studied during these tests were the same as described for the tensile tests, including sensitivity

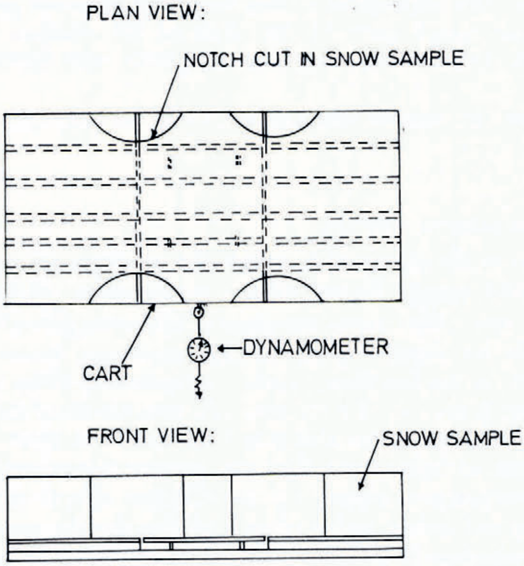

Fig. 3. Schematic drawing of the apparatus used in the experiments attempting shear-strength estimates.

to notch geometry, which was found to have little effect. The loading was applied over a time scale of one to two minutes.

Figure 4 depicts a typical fracture pattern. The four cracks were measured to be near 45° to the direction of pull in each case. These fracture patterns indicate that the samples failed in tension. It is difficult to define failure strengths in such experiments and perhaps it is not worthwhile in view of the complicated stress conditions expected to be associated with such tests.

INTERPRETATION OF OBSERVED FRACTURE PATTERNS

The fracture observed in the tilting-table tensile tests were all relatively smooth and perpendicular to the plane of the tilting table. The stress conditions in such a test would be expected to produce maximum principal tensile stresses approximately parallel to the table. Fracture in a direction perpendicular to the important tensile stress is often observed in geologic materials (Jaeger, 1962) and is observed in the release of snow-slab avalanches where a catastrophic tensile fracture perpendicular to the shear failure plane is observed (Perla and LaChapelle, 1970).

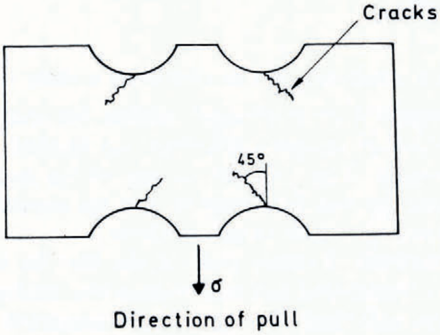

Fig. 4. Pattern of cracks observed in experiments attempting shear-strength estimates. The pattern indicates tensile fracture.

It is more difficult to analyse the tensile fracture patterns observed in the attempted shear tests. However, it is perhaps not surprising that the fractures were in tension in view of the general difficulty of generating shear fractures in isotropic, homogeneous samples of materials.

MAGNITUDE OF TENSILE STRENGTH MEASUREMENTS WITH RESPECT TO AVALANCHE RELEASE

Mellor ([1975]) pointed out that approximate values of the shear strength of snow might be made by analysis of depth and density profiles at avalanche fracture lines. Perla (1977) used this procedure to estimate shear-stress failure levels versus snow density at the weak shear failure plane for 69 slab avalanches. These are the only easily obtainable data in regard to avalanche-release failure levels. It is not possible to relate the shear strength to the tensile strength of snow at present, because the failure surface is unknown. Common failure theories for metals predict that the shear strength is one-half to two-thirds of the tensile strength.

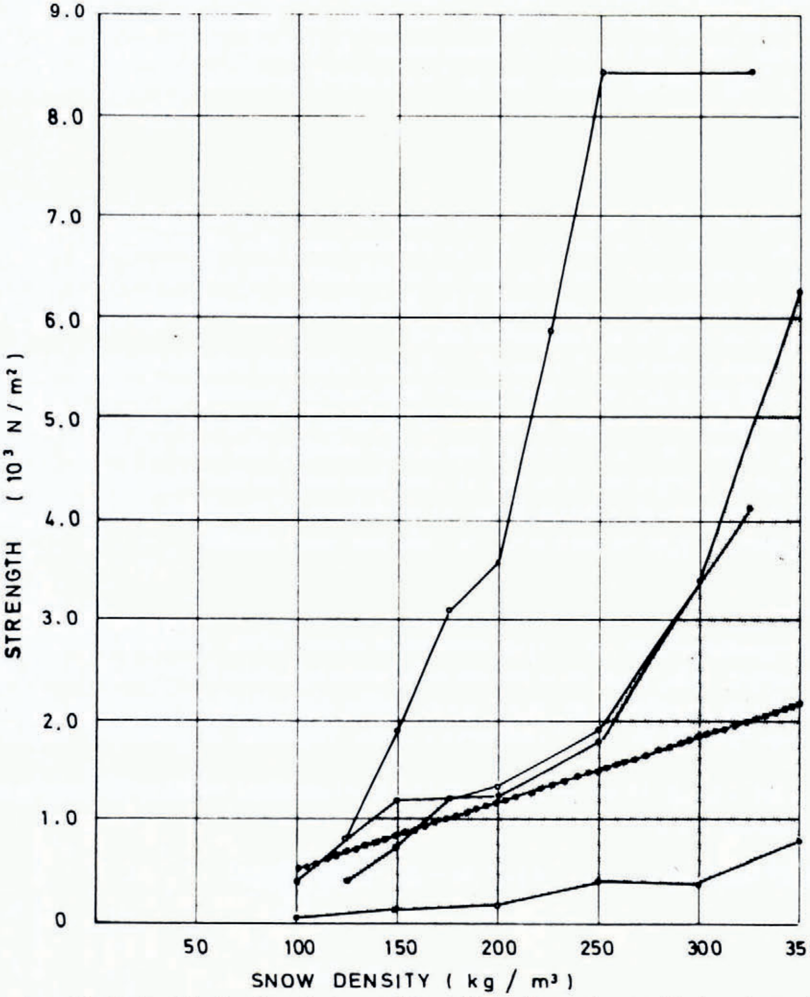

Fig. 5. Comparison of the limits of the data from the present tilting-table tensile experiments with the estimates of tensile strength for large sample sizes by Sommerfeld (1974) and with estimates of shear strength from avalanche fracture lines compiled by Perla (1977). The solid lines denote the limits of the present experiments. The shaded portion denotes the shear-strength estimates by Perla (1977). The heavy line (–●–●–●–●–) denotes the estimates by Sommerfeld (1974).

Granular materials such as snow, being much stronger in compression than in tension, might, however, be expected to have a shear strength which approaches the tensile strength due to possible widening of the failure envelope.

Figure 5 shows a comparison of the limits of the estimates from the present tensile experiments with the limits of the shear-strength estimates from fracture-line profiles as a function of density. Most of the estimates of shear strength from fracture-line profiles represent failures in planes which are especially weak in shear due to recrystallization under strong temperature gradients or other effects. Therefore, Figure 5 may indicate some aspects of the importance of strength anisotropy in the avalanche failure-strength problem. If failure strengths could be compared for homogeneous samples, presumably the tensile strength would be approximately equal to the shear strength. On the other hand, the comparison in Figure 5 indicates values of tensile strength somewhat in excess of estimated shear strength values for field conditions, perhaps indicating that the anisotropy observed at avalanche fracture lines (i.e. a noticeably weak shear failure plane under the slab) is important. However, the very approximate nature of the comparison must be kept in mind since there are differences in sample size, rate of strain, and other factors in the above comparisons. It is likely, for example, that the present tests are not of large enough sample size to be regarded as minimum estimates (Sommerfeld, 1974).

SUMMARY

In-situ estimates of the tensile strength of snow have been given by a new method utilizing large sample sizes. The data from the experiments show the effect of large sample sizes on tensile strength of snow indicating less scatter in the results as a function of density and lower mean values than previous *in-situ* tests. The data support (but do not prove) the idea that Weibull-like statistics apply to fracture of snow.

Since the samples were loaded slowly and the measured sample temperatures were near 0°C, the tests will probably have had plastic deformation associated with them. Most avalanche fractures occur in snow packs with bed surfaces of temperatures greater than -10°C (Perla, 1977). From the standpoint of avalanche release, the rate at which tensile loading occurs near fracture lines is not presently known, however, so that it cannot be stated whether the slow loading employed detracts from the usefulness of the data. The advantage of slow loading in preventing jarring may well override any such details.

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