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ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Strength Tests on Newly Fallen Snow[1]

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In situ strength tests previously applied to metamorphosed snow were modified to measure the mechanical properties of newly fallen snow during storms. A large drop cone penetrometer, protected from the wind by an aluminum shell, was used to determine snow "hardness." A lightweight model of the Haefeli ram penetrometer measured "Ram Numbers." Shear strengths were obtained from large, lightweight frames. Some preliminary tests were made with a shear vane driven by a torque wrench. A new technique was devised for measuring tensile strength: a cantilever beam of snow is undercut until it fails under its own weight.

In many regions affected by avalanches, the most dangerous conditions arise during storms. This is partially due to the structural instability of the newly fallen snow (LaChapelle 1967). Mechanical characteristics of fresh snow pertinent to avalanche formation must be measured during and immediately after storms.

Because of their fragility, samples of newly fallen or weakly metamorphosed snow usually are disturbed in transit despite careful handling. The alternative is to test the snow **in situ**. Although the literature contains many references to **in situ** testing of metamorphosed snow, reports confined to such measurements of newly fallen snow are scarce. Roch (1966) performed systematic **in situ** tests on alpine snow profiles. His techniques were designed to test snow in various stages of metamorphism; consequently, his fresh snow measurements did not discriminate among the many possible varieties of newly fallen snow. Keeler and Weeks (1968) explored the consistency of various **in situ** test schemes. Like Roch, however, they were primarily interested in the entire profile of the alpine snowpack. Martinelli[3] measured the properties of freshly deposited snow in the starting zone of several avalanches, and suggested several of the modifications reported in this Note.

Many difficulties are encountered in setting up consistent experiments on fresh snow. An important problem is the structure and property variation in the Z direction (fig. 1) which necessitates sampling the entire profile of newly fallen snow at closely spaced intervals. For most tests, a practical interval is **5 cm**. The problem of variation in the X and Y directions can be minimized by the choice of a suitable study area, free from wind and precipitation anomalies. Because of rapid metamorphism, measurements must be taken at 8-hour intervals during the storm period. Finally, the tests must be performable during blizzard conditions, and must cover a strength range of at least two orders of magnitude.

[1]*Research reported here was financed through a cooperative agreement between the Wasatch National Forest, Salt Lake City, Utah, and the Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo. The drop cone and lightweight ram penetrometers were designed by E. R. LaChapelle, Wasatch National Forest.*

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[3]*Martinelli, M., Jr. The physical and mechanical properties of freshly deposited snow in alpine area. (In preparation for publication, Rocky Mountain Forest and Range Exp. Sta., USDA Forest Serv., Fort Collins, Colo.)*

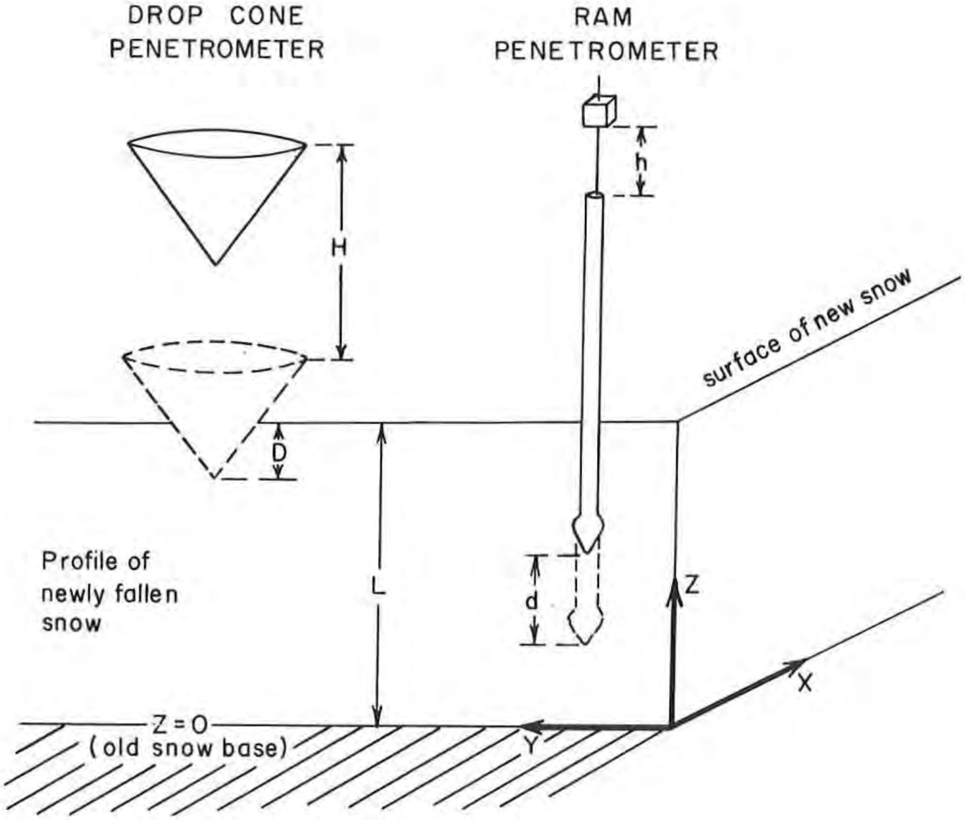


Figure 1.--Coordinate system and symbols used in this study for testing strength of newly fallen snow.

This report summarizes the development of four **in situ** tests which overcome the above difficulties. The drop cone penetrometer, the ram penetrometer, and the shear frame are modified versions of devices previously applied to metamorphosed snow. A cantilever test is introduced for measuring tensile strength.

Drop Cone Penetrometer

Drop cone penetrometers have provided self-consistent values for hardness of snow. Takahashi and Kudo (1941) performed drop cone experiments on snow in the density range of 250 to 420 kgm^{-3}. Their data led to the following relationship:

$$U = mgH = qD^p \qquad [1]$$

where U = energy of impact
m = mass of the drop cone
g = acceleration due to gravity
H = distance of fall (fig. 1)
D = depth of penetration (fig.1)
q and p are constants related to the snow structure.

They defined hardness of the snow, P, as simply:

$$P = \frac{U}{\text{Volume of depression}} \qquad [2]$$

Inaho (1941) applied the drop cone to a variety of snow types. In his experiments, p ranged from 1.6 to 5.2. This showed the limitation of the hardness definition given by equation [2], which assumes p = 3. Other drop cone experiments have been reported (Bader et al. 1951, Yosida et al. 1957, Anisimov 1958). Drop cone hardness of clay has been related to shear strength (Hansbo 1957).

At the Alta Avalanche Study Center, a drop cone penetrometer (table 1) was developed for testing freshly fallen snow. Its operation (fig. 2) is as follows: the instrument rests on the snow, supported by its flange in a level position. The cone assembly is held up by the clamp. The operator looks through the observation window, loosens the clamp, gently lowers the cone assembly until it touches the snow, and notes the meter stick reading Z_r. The cone assembly is then lifted to an initial reading on the meter stick (Z_1), released and allowed to fall, penetrate the snow, and come to rest at position Z_2.

Table 1.--Results of drop cone penetrometer experiment conducted at the Alta Avalanche Study Center, spring, 1967

Date	Time of day	Number of samples	Density (ρ)	Constants related to snow structure		Hardness number ($\overline{P}$)[1]
				q	p	
			kg m^{-3}			
February 26	1300	10	100	[2]0.54	3.75	[2]6
March 14	1500	25	120	.14	4.40	9
March 15	1100	10	180	1.18	3.70	11
March 16	1500	11	310	.38	4.40	24
March 19	0800	17	120	.30	3.89	5
March 19	1500	25	110	1.91	3.36	7
March 29	1500	20	170	2.56	3.40	10
March 30	1100	15	100	.75	3.52	4
March 30	1700	28	210	[3]34.80	2.56	20
April 1	1500	15	70	1.23	3.40	5
April 13	1100	20	210	.33	4.42	22
May 6	1700	20	390	.55	4.30	26
May 11	1500	15	110	1.57	3.26	5
May 13	1700	10	100	.27	3.84	4

[1] $\overline{P}$ based on L = 15 cm.
[2] All values in this column are to be multiplied by 10^{-4}.
[3] Ice crust on the surface.

The distance of fall and depth of penetration are, respectively

$$H = Z_2 - Z_1$$
$$D = Z_2 - Z_r$$

U can be increased by decreasing Z_1 (that is, raising the cone assembly) or by adding weights to the cone assembly.

With previous drop cone models, the diameter of the cone impression had to be measured. This was a time-consuming operation, and restricted the experimenters to two or three drops per determination of U. Using the procedure described above, the operator can make quickly 5 to 10 drops for each determination. The aluminum frame provides ample protection from the wind during blizzard conditions.

Provision was made for using 120°, 90°, 60°, and 45° cones. After comparative studies 60° cones, with base diameters 15, 25, and 40 cm, were selected as most suitable. Though 120° and 90° cones gave consistent results, the base diameter of these cones would have to be large to allow for deep slab penetration. The 45° cone was disqualified because of a peculiar inconsistency; certain snow types would fracture around the impact point of this narrow-angle cone.

On a log-log diagram, U is approximated to be a linear function of D (fig. 3); in most cases this is an excellent approximation. From the log-log diagram it is possible to determine the p and q of equation [1].

Because penetration is a complex process, it is difficult to uncover intrinsic values of strength or

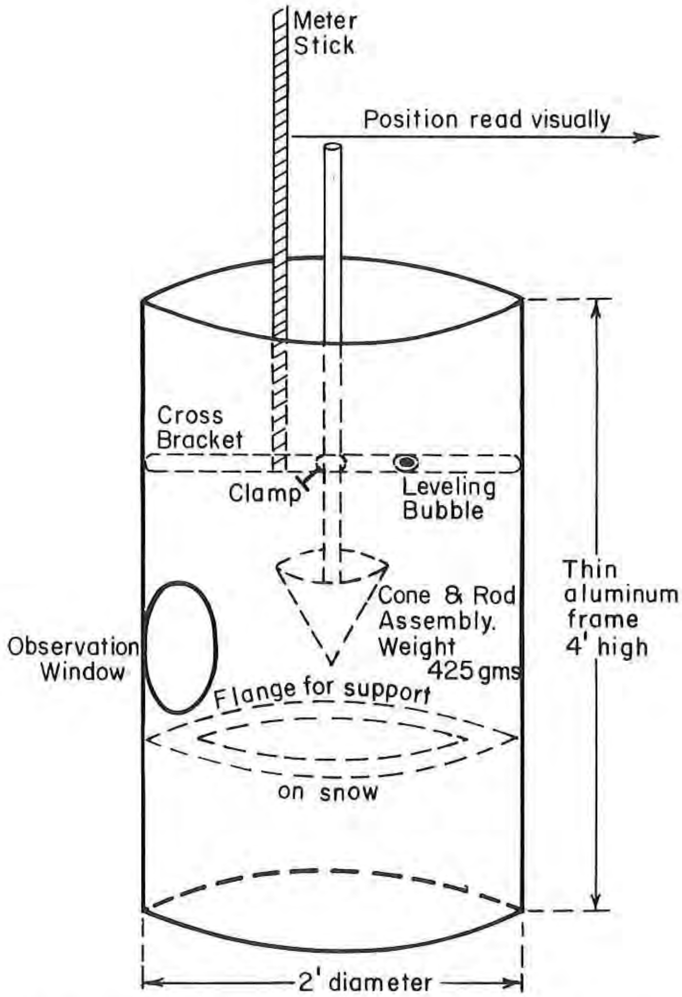


Figure 2.--Drop cone penetrometer developed at Alta Avalanche Study Center, Utah.

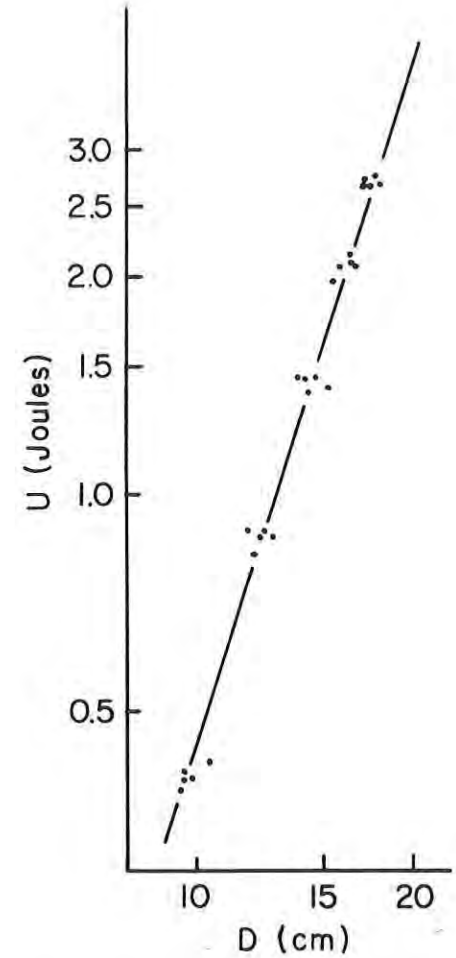


Figure 3.--Impact energy (U) as a linear function of penetration (D) on a log-log diagram. Density of newly fallen snow tested was 110 kgm^{-3}, Alta Avalanche Study Center, March 19, 1967.

resistive pressure from equation [1]. Mellor (1964) summarizes some of the power relationships that have been used, and Kinosita (1967), making a distinction between brittle and plastic failure, reports power relationships for the force which resists the intrusion of a cone. In newly fallen snow, it is useful to derive power relationships for resistive pressure directly from equation [1] by lumping all of the mechanisms that resist penetration into a single conservative force.

$$\vec{F} = - \nabla U \qquad [3]$$

Then, from equation [1]

$$F = p \; qD^{p-1}$$

and

$$dF = q \; (p-1) \; p \; D^{p-2} \; dD$$

For a 60° cone, an incremental band of area is

$$dS = \frac{4}{3} \pi \; D \; dD \qquad [4]$$

The resistive pressure, P, is

$$P = \frac{dF}{dS} = \frac{3}{4\pi} q \; (p-1) \; p \; D^{p-3} \qquad [5]$$

Finally, the "Hardness Number," $\overline{P}$, of a layer is defined as an average of the resistive pressure taken over the thickness of the layer, L

$$\overline{P} = \frac{1}{L}\int_0^L P\,dD = \frac{3q}{4\pi}\,\frac{p\,(p-1)}{(p-2)}\,L^{\,p-3} \qquad [6]$$

Clearly, the thicker the layer, the more resistance it offers to conical penetration. For comparison of snow types, all values of $\overline{P}$ should be based on the same value of L.

Ram Penetrometer

A ram penetrometer for measuring the relative mechanical strength of snow was designed by Haefeli (1939). Each winter this instrument is used in many alpine regions to determine the strength changes of the snow profile in relation to the avalanche hazard. Correlations have been established between this well-known instrument and intrinsic snow properties (Keeler and Weeks 1968).

The Haefeli penetrometer is too heavy (about 1 kg per section) to be used on newly fallen snow. On a suggestion by M. Martinelli, a lightweight ram was designed at Alta (fig. 4) and applied to newly fallen snow during the season 1967-68.

Haefeli (1939) recommended a "Ram Number" defined by

$$W_1 = \frac{Rh}{d} + R + Q \qquad [7]$$

where R = mass of driving hammer (kg)
h = height of fall of driving hammer (cm) (fig. 1)
d = depth of penetration (cm) (fig. 1)
Q = mass of penetrometer, not including hammer (kg)
W_1 = Ram Number (kg)

Equation [7] is based on a coefficient of restitution, η = 1. Haefeli demonstrated that a ram number, W_η could be derivedin terms of a general η

$$W_\eta = \left(\frac{\frac{h}{d}\,\frac{(1+\eta^2)}{2} + 2}{\frac{h}{d} + 2}\right) W_1 \qquad [8]$$

He chose equation [7], however, partially because of its simplicity and partially because he felt η would have a high value because of the low ratio of strain energy of the penetrometer to total impact energy. This last argument was not clear, and Waterhouse (1966) discussed a corrected form of equation [7] which in principle is equation [8].

Based on data compiled by Chellis (1961), a reasonable value of η for the Alta Ram is η = 0.5. The equation [8] becomes

$$W_\eta = \left(\frac{0.63\,\frac{h}{d} + 2}{\frac{h}{d} + 2}\right) W_1 \qquad [9]$$

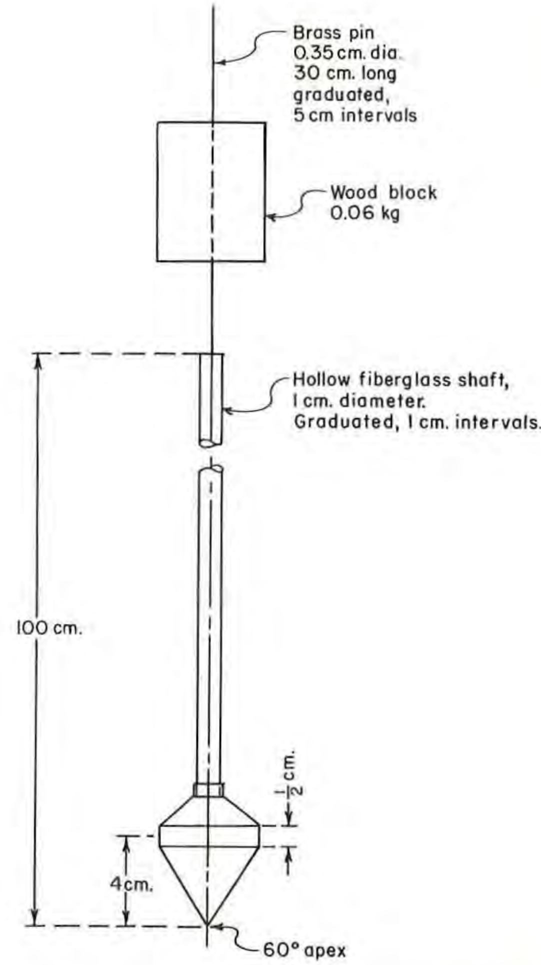


Figure 4.--Light-weight ram penetrometer designed at Alta Avalanche Study Center, Utah. Mass of penetrometer, (not including wood block) is 0.06 kg.

When the Alta Ram is applied to a moderately strong layer of newly fallen snow, h/d may be 10 or larger and, from equation [9],

$$\frac{W_\eta}{W_1} \simeq 0.70$$

Thus, the corrections are important and equation [9] should be used when a consistent comparison is desired between the Ram and other tests.

Olson and Flaate (1967) summarized various formulas that could possibly replace equation [9] and avoid the use of η . On the other hand, equation [9] is in convenient form for correcting W_1 , the Ram Number used in most previous studies.

In contrast to metamorphosed snows which typically have Ram Numbers of the order of 10^1 to 10^2 kg, the Ram Numbers of newly fallen snows are of the order of 10^{-1} to 10^0 kg.

The main advantage of the Ram is its ease and speed of use. A 3-meter-thick layer of newly fallen snow can be tested in about 2 minutes. Other tests which depend on digging snowpits and slicing out samples are far more time consuming.

From some preliminary experiments, the Alta Ram appears suitable for strength tests at the fracture zone of avalanche slopes during periods of soft slab formation.

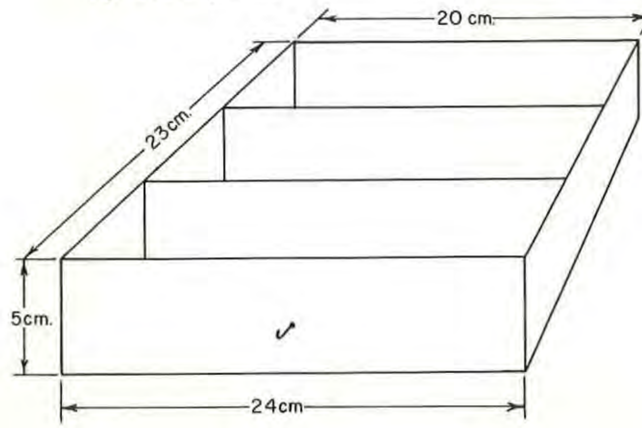
Unfortunately, the Ram Number is related to the complex mechanism of penetration rather than direct shear or tensile strength. Difficulties can be expected when attempts are made to correlate the Ram Number with intrinsic snow properties despite the careful selection of a relationship such as equation [9].

Shear Frame

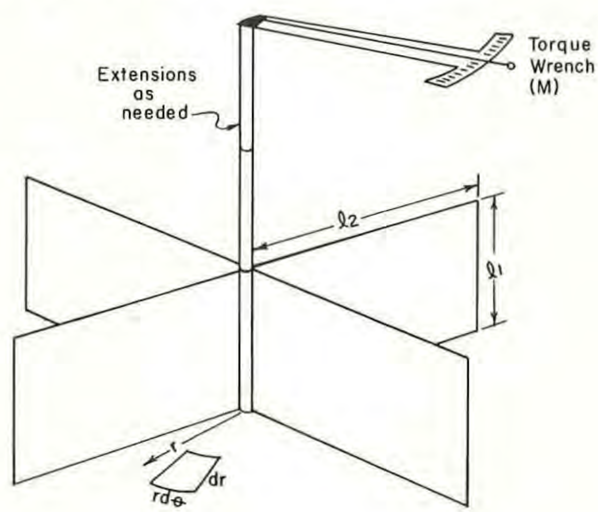
The Alta Shear Frame (fig. 5a) is a modification of a shearing apparatus introduced by Roch (de Quervain 1950). Since strength of new snow varies widely, two separate frames are necessary. Both frames have the same dimensions; but one frame is fabricated from very thin gage aluminum (about 0.75 mm) so that it is easily supported by weak, low-density snow; the second frame is fabricated from thicker aluminum (about 1.5 mm) and can be used on stronger snows. A low-range spring scale (O - 10 N) is used to pull the light frame; a higher range scale (0 - 100 N) is used on the heavier frame. The scales are equipped with memory attachments. Readings are taken at 5 cm intervals in the wall of a snowpit.

Figure 5.--Snow-testing instruments as modified by Alta Avalanche Study Center, Utah:

A, Shear frame.



B, Shear vane.



Roch (1966) reported consistent measurements with a rate of loading that induced failure between 1 and 2 seconds after the initial application of the force. This rate is facilitated by a rapid but smooth pull on the spring scale. All of the tests reported in this paper presume brittle-type failure which can be achieved by the rapid application of stress (Kinosita 1967).

Table 2.--Comparison of shear frame strength (τ) and beam number (B) for newly fallen snow, Alta Avalanche Study Center, 1968

Depth (Z) in cm	Snow density (ρ)	Shear frame		Cantilever beam	
		Maximum force (F)	Shear strength (τ)	Beam length (λ)	Beam number (B)
	kg m^{-3}	N	N m^{-2}	cm	N m^{-2}
37-32	103	6.9	138	8	389
31-26	130	14.7	294	11	925
25-20	133	19.6	392	14	1530
19-14	146	34.3	696	21	3840
13-8	165	40.2	804	24	5520
7-2	225	51.0	1020	--	--

The shear strength of the snow, τ, is maximum force F divided by area of frame, which for the Alta unit is

$$\tau = 20\ F\ (N\ m^{-2}) \qquad [10]$$

Some typical values of shear strength calculated according to equation [10] are shown in table 2.

Roch (1966) determined the Coulomb-Mohr envelopes of his samples by placing various weights on a glass plate. He verified Haefeli's prediction with respect to fresh snow, that a small normal load on the shear frame tends to break the dendritic branches and cause a slight reduction in strength (Haefeli 1939). Roch also observed an increase in strength with an increase in normal loading, but he judged that the increased loading caused the fresh snow to densify by successive failures, which resulted in a major alteration in the structure of the original test specimen. It is anticipated that Roch's technique of normal loading can be applied to freshly fallen snow; further investigations are planned.

Closely related to the shear frame is the shear vane (fig. 5b). The moment, M, applied by the torque wrench at the instant of failure is balanced by the shear strength, τ, according to

$$M = 2 \int_0^{2\pi} \int_0^{\ell_2} \tau r^2\, d\, r\, d\theta + 2\pi\, \ell_1\, \ell_2^2\, \tau \qquad [11]$$

Suggested dimensions for use on newly fallen snow are ℓ_1= 5 cm and ℓ_2 = 10 cm. Because a snowpit is not required for its operation, the shear vane is a faster test than the shear frame.

Cantilever Beam

Tensile strength of alpine snow has heretofore been determined by a centrifugal test (fig. 6) (de Quervain 1950), and calculated from

$$\sigma = \frac{1}{S} \int_0^{\ell} \frac{V^2}{r}\, dm \qquad [12]$$

where σ = tensile strength
S = cross section area of cylinder
2ℓ= length of cylinder
dm = mass of infinitesimal disc
r = distance of disc from axis of rotation
v = linear speed of disc at failure

This test appears to be reliable and may offer a true indication of the actual tensile strengths of small cylindrical samples. Unfortunately, cylindrical samples of newly fallen snow are not easily collected; an alternative for measuring tensile strength is needed.

The following **in situ** test has been developed: A snowpit is excavated, according to figure 7a. A flat aluminum plate, graduated in centimeters, is inserted into the pit wall (fig. 7b), and then with-

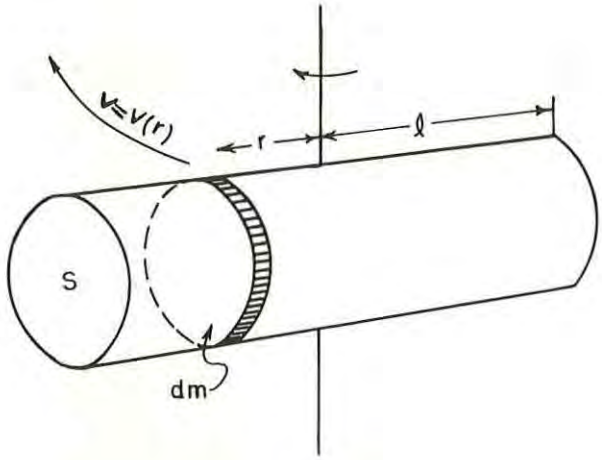


Figure 6.--Centrifugal test.

drawn quickly with a downward pressure. These two steps are repeated, with a deeper insertion of the plate each time, until the cantilever beam fails (fig. 7c). After removing the 1 or 2 centimeters of snow which were compressed by the downward pressure of the plate, the sequence can be repeated for the next 5 cm interval and so on down through the snow profile.

This test must be accompanied by a density profile taken at about 5 cm intervals. For newly fallen snow, it is most convenient to collect density samples in cylindrical cans (1,000 cm^3 in volume or about 5 cm high and 8 cm in radius).

In situ beam tests have been applied to investigate the flexural properties of fresh ice and sea ice (Tabata et al. 1967), but a search of the literature has not revealed any previous application of beam testing to low-density snow. The precise interpretation of snow beam data in terms of tensile strength is an open question.

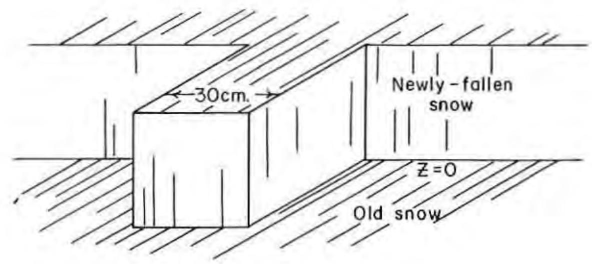
A reasonable approximation[4] to the tensile strength σ, sustained by the top fiber of the beam, may be

$$\sigma = \frac{Mc}{I} \qquad [13]$$

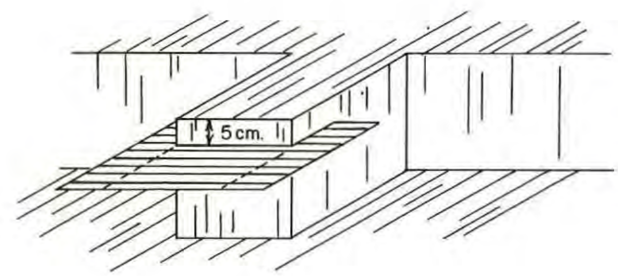
[4]*Personal correspondence with Zyungo Yosida, Inst. Low Temp. Sci., Hokkaido Univ., Sapporo, Japan.*

Figure 7.--Cantilever beam test:

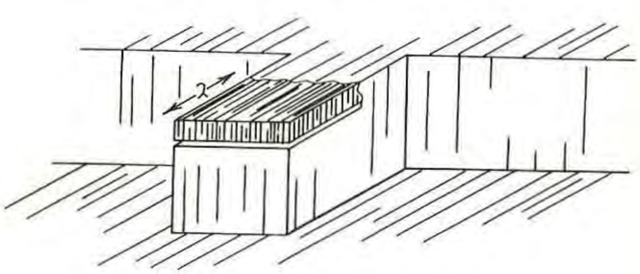
A, Excavation of snow pit.



B, Insertion of plate into pit wall.



C, Failure at a length, λ.



where M = the moment of the beam
c = the distance from the neutral axis to the top fiber
I = the cross-sectional moment of inertia of the beam

For a beam of length λ, thickness L, and density ρ, equation [13] becomes

$$\sigma = \frac{3g\,\rho\lambda^2}{L} \quad (N\ m^{-2}) \qquad [14]$$

Equation [14] is based on the symmetric stress distribution shown in figure 8a. For other stress distributions, such as the unsymmetric case shown in figure 8b, σ is still of the order of $g\rho\lambda^2/L$. Following the analogy of the "Ram Number," a "Beam Number" (B) can be defined as

$$B = \frac{3g\ \rho\lambda^2}{L} \quad (N\ m^{-2}) \qquad [15]$$

Values of B are shown in table 2. It is expected that B can be related to the tensile strength perhaps as suggested by the above study, simply

$$\sigma = k\ B \qquad [16]$$

where k makes an adjustment appropriate to the stress distribution of the beam.

The foregoing analysis presupposes tensile failure. Observations of the beam fracture patterns (fig. 9) do not verify that this is necessarily the case. In consideration of the possible role that shear failure plays, it is preferable to assert

$$\sigma \geq k\ B \qquad [17]$$

Three sequential profiles of newly fallen snow are shown in figure 10. For each layer, the "Ram Number" is plotted as a solid line and the "Beam Number" as a dashed line. The first profile (a) was taken at the beginning of the storm, 1700 hours, February 12, 1968; (b) was taken at 0900, February 13, 1968; and (c) at 1600 February 13, 1968.

In table 2, a comparison of τ and B indicates that newly fallen snow is considerably stronger in tension than in shear. It is of interest that Keeler and Weeks (1967) show 10:1 for the ratio of tensile to shear strength, while Roch (1966) shows up to 8:1. These high ratios are not easily reconciled with the standard theory of strength of materials which predicts

$$\frac{\sigma}{\tau} \leq 2 \qquad [18]$$

Martinelli[5] has also obtained relatively high ratios for tensile to shear strength, but feels that these ratios reflect the peculiarities of the tests rather than the intrinsic strengths of the snow. In fact, Sommerfeld[6] associates the reported high ratios with the stress concentrations that are introduced by vanes in the shear-testing devices and the lack of the same in the tensile tests.

The distribution of B with density is shown on a semi-log diagram (fig. 11). Further investigations will be needed to determine if the order of magnitude variation in B at all densities is a real variation in tensile strength as opposed to a peculiarity of the cantilever test.

[5] *See footnote 3, p. 1.*
[6] *Personal communication with R. A. Sommerfeld, Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo.*

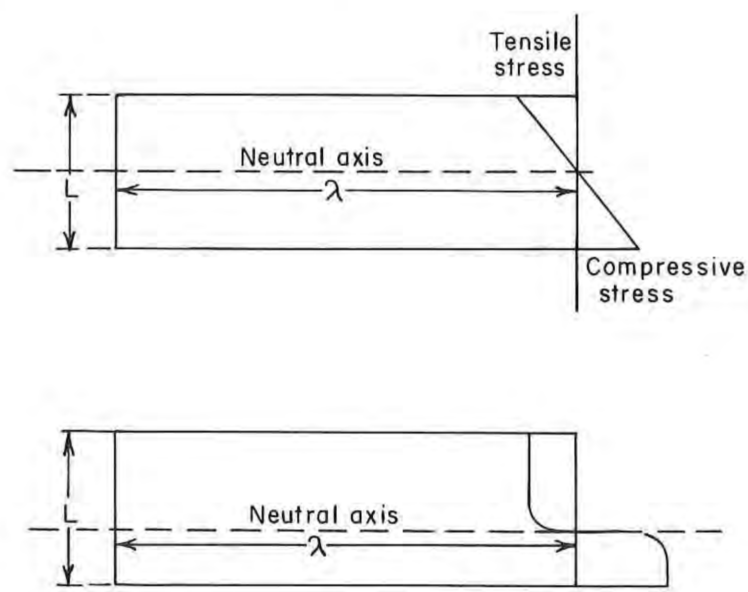


Figure 8.--Stress distribution of a cantilever beam:

A, Symmetric.

B, Unsymmetric.

Conclusions

Preliminary studies at Alta have demonstrated that mechanical properties of newly fallen snow can be determined by a variety of simple **in situ** tests, most of which are well known and are at least self consistent. These tests can all be performed during the most severe alpine weather. Future experiments are needed to establish the mutual consistency of these tests, as well as their relationship to the intrinsic properties of the snow.

Generally speaking, penetration experiments are easy to perform but difficult to interpret. From drop cone data, the "Hardness Number" can be calculated, as

$$\overline{P} = \frac{3q}{4\pi} \frac{p\,(p-1)}{(p-2)} L^{p-3} \qquad [6]$$

and corrected "Ram Numbers" can be obtained from

$$W_n = \left(\frac{0.63\,\frac{h}{d} + 2}{\frac{h}{d} + 2} \right) W_1 \qquad [9]$$

It may be possible to relate these numbers theoretically or experimentally to shear and tensile strengths.

Shear and tensile experiments, although more difficult to perform, are feasible if the apparatus is made light and large in comparison to the similar apparatus used on metamorphosed snow. Further development of the shear frame test is needed to determine the Coulomb-Mohr behavior of newly fallen snow.

The cantilever test, despite problems of interpretation, gives an indication of the tensile strength in terms of a "Beam Number"

$$B = \frac{3g\ \rho\lambda^2}{L} \qquad [15]$$

The high ratio of tensile to shear strength reported here and in previous studies should receive more attention. It may be possible to either discover the mechanism in the crystal structure which permits this high ratio, or alternatively show that peculiarities in the tests are responsible for this unexpected behavior.

When relationships between these tests are established, the more expedient tests can be conducted at the fracture zone of avalanche paths.

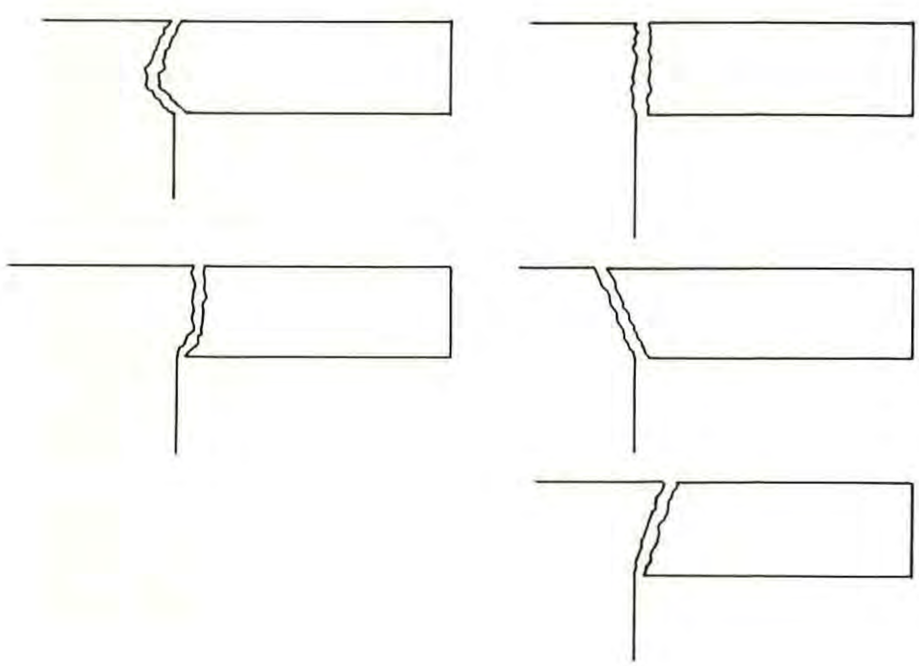


Figure 9.--

Typical fracture patterns observed in the cantilever beam test.

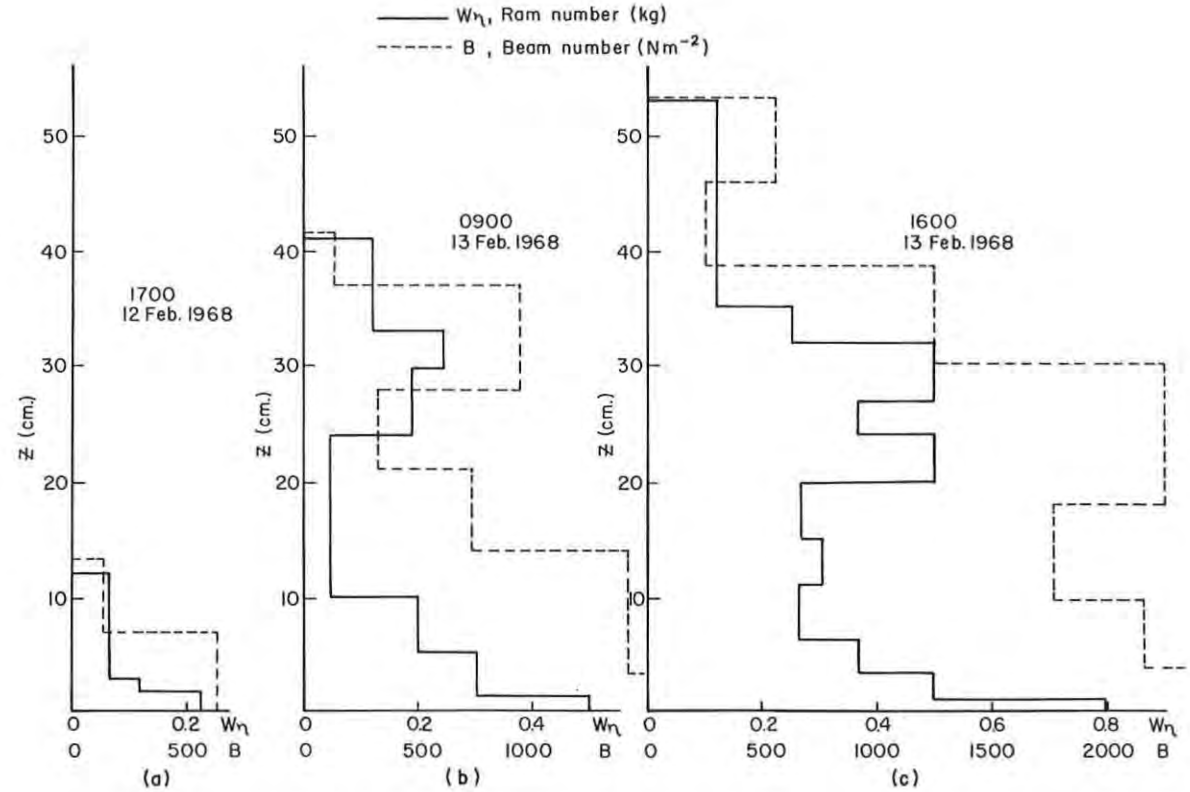


Figure 10.--Comparison of Ram number (solid line) and Beam number (dashed line). Newly fallen snow February 1968, at Alta Avalanche Study Center, Utah.

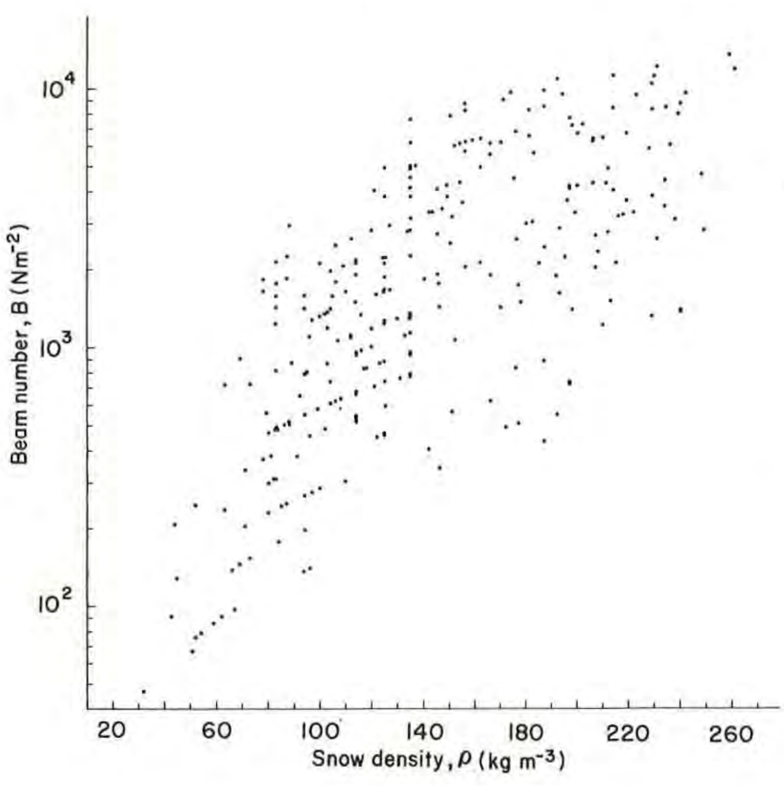


Figure 11.--Beam number (B) plotted against snow density on a semi-log diagram. Data from 1967-68 winter, Alta Avalanche Study Center, Utah.

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