IN-SITU STRENGTH MEASUREMENTS OF THE SNOWPACK[1]

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Abstract.--Two test techniques were developed, one to measure the shear strength of weak layers and another to measure the tensile strength of slab layers in the snowpack. Both tests are easily applied to measurements of the naturally occurring snowpack in the starting zones with a minimum amount of disturbance of the test sample. Complete descriptions of each test including the theory, test procedures, and evaluation techniques are presented. The results of several tests conducted using both techniques are presented and discussed. The shear strength measurements compare well with previous estimates and corroborate previously discovered relationships between shear strength and normal stress. The tensile strength measurements compare well with previous uniaxial tension tests performed on similar sample sizes and snow types. As these test techniques are perfected in the future they will be able to provide specific strength data and a better understanding of snow behavior.

INTRODUCTION

Slab avalanches result from the tensile failure of the slab layer and the shear failure of a weak snow layer under the slab layer. Several techniques have been developed and tested to measure the strength of these layers. The centrifugal tensile test (deQuervain, 1950 or Bader, et al. 1951) which spins a snow sample creating a region of tensile stress at the center of rotation, results in the tensile failure strength of the sample. Even with the improvements in design by Sommerfeld and Wolfe (1972) the small sample size and the act of removing the sample from the snowpack prior to testing makes the application of the test results to the actual strength of the snowpack questionable. Shear tests on snow have been conducted in-situ using shear frames (deQuervain, 1950). Because of the small sample sizes and high variability in the results many tests and statistical evaluations are required to yield an estimate of shear strength. In addition, most of the overburden snow must be removed above the weak layer of interest to perform the shear frame test. This alters the normal load on the weak layer and has been shown to influence the results (Roch, 1966). In-situ tensile tests have been used to measure the tensile strength of snow. The cantilever beam test, on newly fallen snow (Perla, 1969) and slab layers (Rosso, 1983), provides tensile strength measurements without removing the sample from the snowpack and can be done on quite large sample sizes. However, because of the complex stress distribution correlation of the test results to actual tensile strength of the slab layer is questionable. In-situ tensile tests performed by McClung (1979) required the preparation of large tilting tables to collect snow samples. The tests were limited to the snow that fell during a storm on the prepared tables and further testing required the deposit of more snow on the tables from the next storm.

The two tests described here are designed to alleviate many of the problems with the aforementioned test techniques and result in a more accurate estimate of the actual tensile and shear strengths of the snowpack. The trapezoid tensile test is carried out in-situ without any previous preparation at the test site. A uniaxial tensile stress is created in the sample and the test can be conducted on a wide range of sample sizes. The flatjack shear test is also done in-situ, does not require any of the snow above the weak layer to be removed and can be conducted on a wide range of sample sizes.

FLATJACK SHEAR TEST

Flatjacks have been used in experimental geology to measure changes in the earth's stress field and to apply stress for experimental purposes to large in-situ rock masses (Swolfs, et al. 1975). Their

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application to snow mechanics required a total redesign of the technique for a media where much lower stress must be applied and measured. A flatjack is a flat slender fluid-filled bladder which when inserted into a slot can be pressurized to apply stress to the material surrounding it. The pressure of the fluid in the flatjack can be related to the stress in the surrounding material. For the technique discussed here a common sphygmomanometer, of the type used by medical personnel to measure the blood pressure of a patient, was used. The rubber bladder was removed from the fabric "cuff" and a new nylon case was made. Fiberglass cards were inserted on each side of the bladder to maintain a uniform plane to apply stress to the snow and prevent the bladder from taking on the round shape of a balloon or from taking on some other shape dictated by regions of differing hardness in the snowpack. A small nylon bag was also tied around the rubber bulb hand pump to prevent snow and ice from affecting the operation of the check valve. The pressure gage, calibrated in mm-Hg was not modified but the readings do need to be interpreted to calculate the correct stress applied, as will be discussed later.

After identifying the weak layer with a shovel shear test, a block of snow must be isolated above the layer. The block should be slightly wider than the bladder and long enough to assure that the block's center of gravity is behind its front edge. With the snow removed on both sides of the block a saw cut can be made down the back of the block perpendicular to the slope and down to the weak layer. The bladder is then inserted in the slot made by the saw and positioned so the bottom edge of the bladder is just above the weak layer. The bladder is now pumped up slowly while the pressure gage is watched closely. As the pressure increases some compression of the snow will take place causing slight drops in pressure

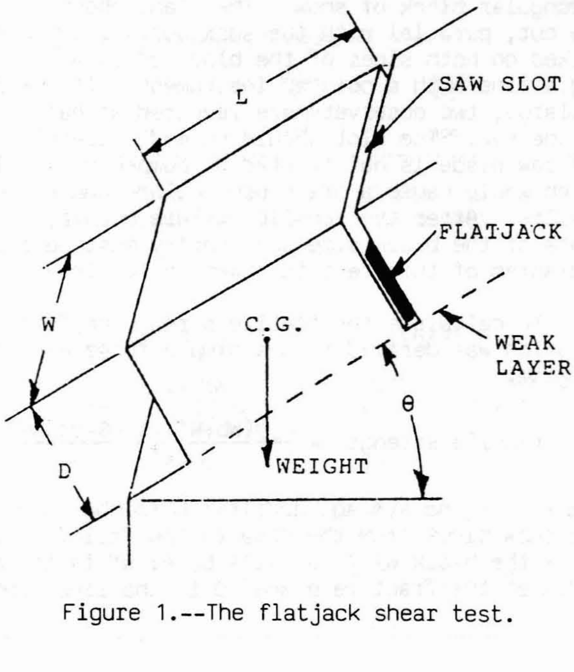

Figure 1.--The flatjack shear test.

Table 1.--Flatjack pressure correction data.

Calibration Mass (Kg)		9.85	21.65	39.95	52.12	70.37
Calculated Pressure (mmHg)		25	55	101	132	178
		Gage Pressure Readings (mmHg)				
	10	26	56	99	140	204
	12.5	31	61	107	147	212
Flatjack Thickness (mm)	16	33	64	114	152	220
	19	36	68	120	159	230
	22	38	72	124	171	---
	25	40	82	138	184	---

but eventually the pressure will increase and shear failure along the weak layer will take place. The maximum pressure reached and the bladder-slot thickness just before failure must be recorded. A diagram of this test is shown in figure 1.

CALIBRATION OF THE FLATJACK

The relationship between the pressure in the bladder and the force applied to the block of snow should depend simply on the area of the bladder; however, as the bladder expands it stretches and some of the pressure is resisted by the tension in the bladder. Also as the pressure increases the area of the bladder in contact with the snow changes. These variations need to be considered when calculating the true force applied to the snow block.

The flatjack was setup in the laboratory to lift a series of flat weights vertically off a bench. The first weight was placed on the bladder and it was pumped up until the weight raised approximately 10mm off the bench, the gage pressure was then recorded. The bladder was pumped up until the weight was 25mm off the bench and pressure readings were recorded approximately every 3mm. This procedure was carried out for five different weights (table 1).

By using the area of the deflated bladder a "calculated pressure" was determined for each weight. By subtracting this value from each gage pressure reading a "pressure correction" was calculated. These "pressure corrections" were plotted against the actual pressure readings to determine a correction formula (figure 2). An approximation using two linear equations was used for the test results reported here based on the fact that most tests were felt to have resulted in a bladder thickness of approximately 12-14mm prior to shear failure.

To calculate the shear stress the following equation was derived from a simple force equilibrium diagram:

$$\text{shear strength} = \frac{(Pg-Pc)B}{LW} + T\rho g \sin\theta$$

where Pg is the gage pressure reading; Pc is the pressure correction; B is the deflated bladder area;

L, W and T are the length, width and thickness of the snow block; ρ is the average density of the snow block; Θ is the slope angle; and g is the acceleration due to gravity.

TRAPEZOID TENSILE TEST

Trapezoid tensile tests involve undercutting a block of snow on a steep slope by sawing up the slope parallel to the snow surface until a tensile failure occurs at the leading edge of the saw slot. An attempt was made to perform this test on a block of snow between two parallel trenches; however, the block became quite long without failure occurring. By digging the trenches on either side of the block so they will converge if continued up the slope, the area supporting the tensile load decreases as the block is undercut and the stress increases more rapidly until failure and a trapezoid shaped block slides off the slope into the snow pit. To reduce any bending stresses from developing, the block of snow must be supported by pulling a foam pad up the saw slot as the saw is advanced.

The equipment developed and used to perform the tests reported here included an aluminum saw with the foam pad attached to it's back edge. Two saw/pad combinations were used. One, for ease of packing in the field with a saw approximately 0.6 meters long and a pad about one meter long. The second, to experiment with larger sample sizes had a saw about 1.2 meters long and a pad extending behind the saw for about 2 meters. Different materials were experimented with to

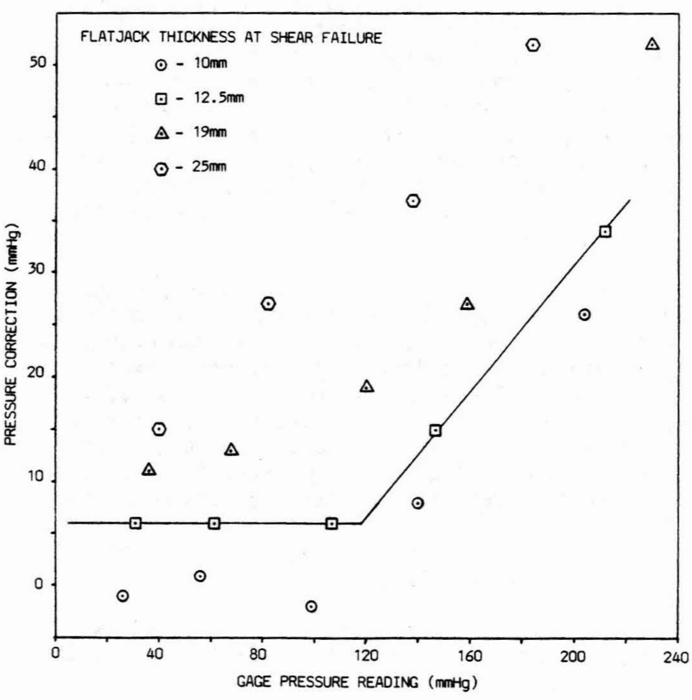

Figure 2.--Pressure correction vs. gage pressure reading for various flatjack thickness values at shear failure. Solid line shows the approximation used to correct for a 12.5mm flatjack thickness.

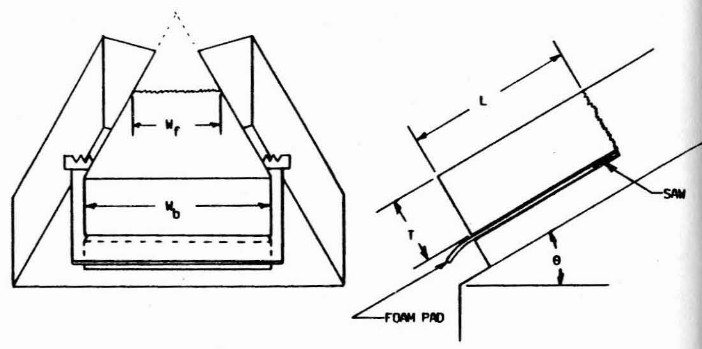

Figure 3.--The trapazoid tensile test.

provide supportive and low friction pads. The pad used for these tests had two layers of a poly-foam material about 3 or 4mm thick commonly used for packing and shipping material. These layers of foam were placed between two sheets of a fiber reinforced plastic tarp material. Experiments conducted with a tilt board found coefficients of friction that varied from 0.05 for cold dry snow to 0.35 for warm snow with free water present. A coefficient of friction of 0.1 was used for all tests reported here.

To perform a trapazoid tensile test a location with a fairly steep slope must be selected. Typical avalanche starting zones are ideal if work can be carried out safely during low risk periods. After identifying a slab layer or layers of interest, two trenches must be dug up the slope from the pit wall to a depth about 10 to 20cm below the slab layer. The trenches are dug at equal angles to the fall line so they will converge at a point up the slope from the pit wall about four times the distance between the trenches at their start. The trenches should stop before they actually converge to assure a tensile failure in the slab not a shear failure in the plane of the saw cut under the tip of the triangular block of snow. The plane chosen for the saw cut, parallel with the snow surface, should be marked on both sides of the block of snow by scribing a line with a pointed instrument. If the block is large, two observers are required at each end of the saw. The slot should be made carefully so the saw blade is not twisted or bumped vertically which would cause a premature failure and erroneous results. After the tensile failure occurs, measurements of the block size and density must be recorded. A diagram of this test is shown in figure 3.

To calculate the tensile stress the following equation was derived from a simple force equilibrium diagram:

$$\text{tensile strength} = \frac{L\rho g(Wb+Wf)(\sin\Theta-\mu\cos\Theta)}{2Wf}$$

where ρ is the average density; L is the length of the snow block from the base to the failure plane; Wb is the block width at it's base; Wf is the block width at the fracture plane; Θ is the slope angle;

Table 2.--Flatjack shear test results.

SHEAR AREA M^2	CORRECTED PRESSURE mmHg	SLAB DENSITY Kg/M^3	SHEAR STRENGTH N/M^2	NORMAL STRESS N/M^2
1-27-85	COLLINS STUDY PLOT - UNSPEC. CRUST			
0.05	64	-	4948	194
2-3-85	P. RIDGE - WIND SLAB/EARLY TG			
0.106	14	150	596	281
0.084	9	150	500	281
0.162	14	150	420	281
0.282	29	150	483	281
2-10-85	COMMA CHUTE - WIND SLAB/TG ON CRUST			
0.075	44	265	2917	1125
0.114	64	265	2910	1282
2-10-85	RACECOURSE - UNSPEC. WEAK LAYER			
0.1	24	134	1244	419
2-17-85	SUGARLOAF SHOULDER - UNSPEC. WEAK LAYER			
0.167	177	280	5168	1529
2-17-85	DEVIL'S CASTLE - UNSPEC. WEAK LAYER			
0.179	64	200	1524	530
0.103	19	200	900	700
3-4-85	HIGH RACECOURSE - UNSPEC. WEAK LAYER			
0.15	29	160	909	231
0.174	54	160	1361	231
0.144	24	180	867	318
11-24-85	JITTERBUG - UNSPEC. WEAK LAYER			
0.289	155	270	2984	1301
12-15-85	HIGH GREELY - GRAUPLE ON ICE CRUST			
0.204	184	200	4287	1233
0.12	54	200	2455	1102
1-26-86	HIGH ARMPIT - ET/OLD STELLARS			
0.124	34	220	1278	540
0.126	49	220	1721	540
3-23-86	COLLINS STUDY PLOT - EARLY ET/GRAUPLE ON CRUST			
0.122	127	220	4024	431
0.092	113	220	4748	431
0.115	155	220	5210	1035
0.076	84	220	4272	992
0.119	127	220	4132	992
0.158	226	220	5515	2416
4-6-86	N. FACING CATHERIN'S - ET/GRAUPLE ON CRUST			
0.112	177	300	6565	789
0.109	163	300	6422	1019
0.125	148	300	4959	662
0.122	134	300	4540	509

Table 3.--Comparison of shear frame test results and flatjack test results on a weak snow layer.

SHEAR STRENGTH N/M^2

SHEAR FRAME		FLATJACK	
SMALL (.01 M^2)	LARGE (.025 M^2)	AREA (M^2)	STRENGTH (N/M^2)
1020	890	.106	596
890	850	.084	500
		.162	420
		.282	483

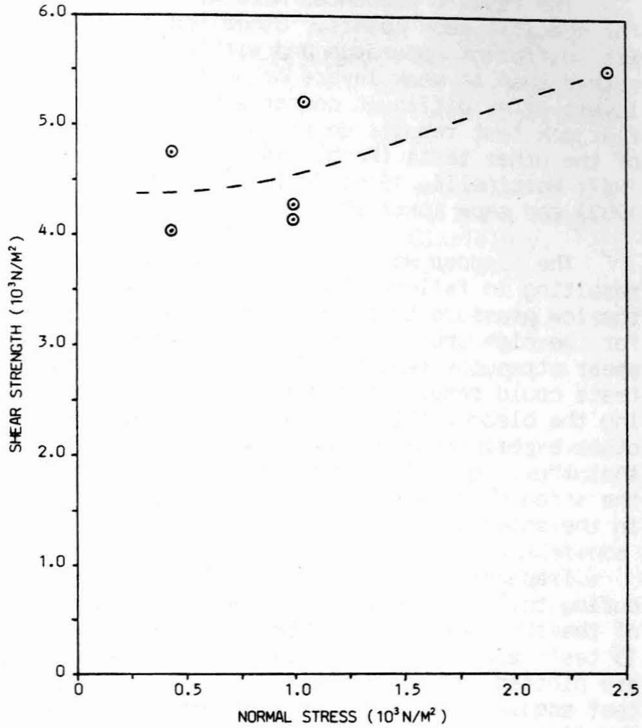

Figure 4.--Shear strength vs. normal stress for a grauple weak layer.

μ is the coefficient of friction between the snow and the foam pad; and g is the acceleration due to gravity.

RESULTS

Flatjack shear tests were conducted during the 1984-85 and 1985-86 winter seasons in the mountains of the ski area at Alta, Utah. The results of 29 tests are presented in Table 2. Four of the tests were conducted on a weak layer which was also tested with a shear frame. Both a 100 sq.cm frame and a 250 sq.cm frame were used and the results are presented in Table 3. The flatjack test results compare well with the shear frame tests if the lower shear strengths measured with the flatjack are the result of the larger sample size. By using a factor of .65 on the results of the large shear frame tests, as suggested by Sommerfeld (1984), to account for the sample size effect, the flatjack results show only slightly lower strengths.

For one group of flatjack tests conducted on a weak layer of grauple at a depth of 1.1 meters different amounts of the slab above the weak layer were removed prior to testing. The resulting shear strengths are plotted versus the different normal stress conditions (fig. 4). An increase in shear strength with increasing normal stress is demonstrated as suggested by tests conducted previously (Roch 1966).

The results presented here are shear strengths for specific weak layers. Other tests, conducted with different apparatus and within snow layers rather than at weak layers or weak regions between layers offer difficult comparisons. However, the flatjack test results do fit within the limits of the other tests (Roch, 1966; Keeler and Weeks, 1967; Martinelli, 1971; Perla, 1969; Perla, et al. 1982) and show lower shear strengths in general.

The bladder was inflated at an even rate resulting in failure after about 30 seconds for the low pressure tests to approximately 90 seconds for the high pressure tests. The scatter in the shear strengths reported for a single group of tests could result from the difficulty in estimating the bladder thickness prior to failure or other experimental errors. However, it is felt that the largest influence on the variations in the strength measurements is the natural variation in the snowpack.

Trapezoid tensile test results were conducted during the 1985-86 winter season in the mountains of the ski area at Alta, Utah. The results of 13 tests are presented in table 4. These results are plotted versus the average density in the test sample (fig. 5). For purposes of comparison, the limits of the tensile strengths measured by McClung (1979) are shown on this graph. McClung's data were chosen because the sample sizes were similar to these tests. The test technique used by McClung also resulted in a tensile loading similar to that in the trapezoid tensile test. The results presented here show some lower tensile strengths but in general compare well with McClung's data.

Table 4.--Trapezoid tensile test results.

	FRACTURE AREA M^2	AVERAGE DENSITY Kg/M^3	TENSILE STRENGTH N/M^2
1-12-86	EAST BALDY - FINE GRAINED ET		
	0.078	265	6337
1-19-86	HIGH SUNSPOT - EARLY TG		
	0.235	244	3220
	0.1	244	1568
	0.12	244	2085
2-2-86	BALLROOM TREES - EARLY ET		
	0.126	145	605
	0.159	145	244
	0.126	145	187
	0.066	145	524
3-23-86	BALLROOM - EARLY ET		
	0.136	140	694
	0.04	140	920
	0.168	140	423
	0.04	140	1482
3-30-86	NORTH FACING CATHERIN'S - ET		
	0.088	250	2654

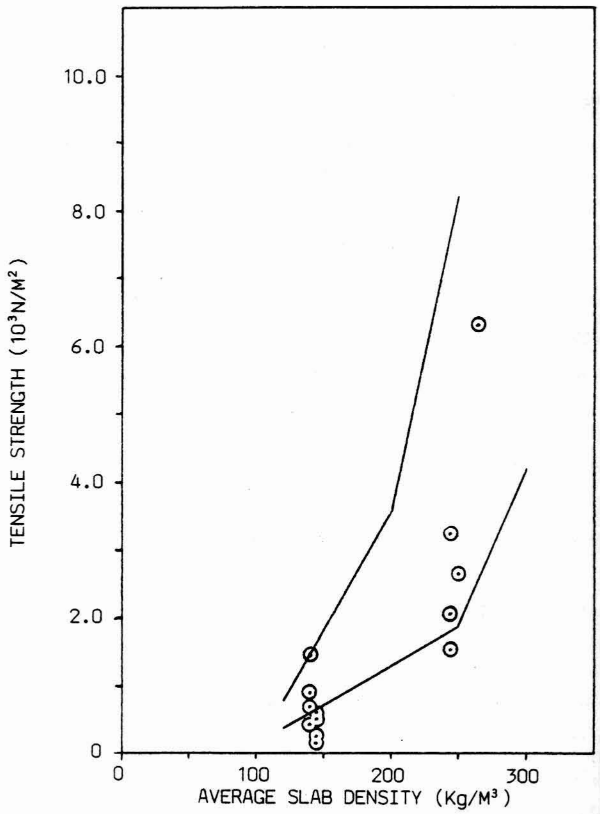

Figure 5.--Tensile strength vs. average slab density. Solid lines show the limits of other in-situ data collected by McClung (1979).

The rate of loading in the trapezoid tensile test is considered to be very short. Although the test procedure requires several minutes between the initial saw strokes and failure, the failure region (at the front edge of the advancing saw slot) has been loaded only for a few seconds prior to failure. In all of these tests failure occurred at the front edge of the saw slot or a short distance ahead (up slope) of it. When failure occurred ahead of the slot, the fracture showed a short region of shear failure between the edge of the saw slot and the tensile failure surface. The length of this shear region was always less than 5% of the total length of the test block and it's affect was ignored when calculating the tensile strength. The tensile failure surface was always approximately perpendicular to the slope.

CONCLUSIONS

The flatjack shear test can be easily applied to strength tests on thin weak layers under thicker slab layers. However, the stiffness of the slab above the weak layer will affect the shear stress distribution and the test results. Because the test can be conducted without removing any of the snow above the weak layer and can be conducted on various sample sizes the results can be a more accurate estimate of the actual shear strength than estimates made by using other techniques, like the shear frame.

The trapezoid tensile test can be applied to any snow layer or layers, but must be conducted on a fairly steep slope. This technique is susceptible to jarring of the sample as the saw undercuts the snow block and requires careful experimental technique for good results. Other questions which need to be answered as this test is used and further evaluated include; whether the foam support pad behind the saw adequately prevents bending stresses and whether there is any affect due to the possible stress concentrations at the leading edge of the saw slot.

Both test techniques have been used for only a small number of tests and much more experience is required before a complete understanding of their application to the measurement of snow strength is gained. The test results presented here lack complete records of the snow temperatures, crystal types, and other parameters which affect snow strength. These test procedures do form the background for a larger more complete study of snow strength.

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