Interpreting fracture character in stability tests

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Abstract: For at least a decade or two, some avalanche safety programs have recorded and interpreted the character of fractures in stability tests. It has been reported but not previously verified that stability tests resulting in "clean" or "fast" fractures or "pops" or "drops" are more likely to correlate with avalanche occurrence than other types of fractures.

Starting in 1997, a study in the Columbia Mountains of western Canada classified the fractures in rutschblock and compression tests as Progressive Compression, Thin Planar, Sudden Collapse, or Non-Planar Breaks. Over 2800 stability tests were conducted at study slopes and study plots as well as over 450 stability tests near recent dry slab avalanches, resulting in a total of over 6000 fractures with classified characters.

Some snowpack characteristics including weak layer grain type associated with the different fracture characters were identified. Critical weak layers or interfaces for dry slab avalanches were more often associated with Thin Planar fractures than with Progressive Compressions or Breaks in rutschblock and compression tests. Fracture propagation on low angle terrain was most commonly associated with Sudden Compression fractures in compression tests.

Keywords: snow stability tests, snow fracture, snow layer, avalanche forecasting

1. Introduction

For decades avalanche workers have noted the character of fractures in stability tests, with a goal of better interpreting the test results. Systems for classifying fractures or "shears" were proposed in the late 1990s.

Using a system proposed for the compression test (Jamieson, 1999), this paper analyzes over 6000 fractures observed during rutschblock and compression tests in the Columbia Mountains of western Canada over five winters. The objective is to determine if the proposed system for characterizing fractures can improve the interpretation of rutschblock and compression test results, which are sometimes used as inputs for avalanche forecasting. After associating the various fracture characters with weak layer and snowpack characteristics, the results of compression and rutschblock tests beside recent avalanches are summarized.

All fracture characters are assumed to involve a component of shear for fracture propagation in weak layers.

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2. Literature review

Since 1981, the Canadian Avalanche Association's Guidelines for Weather, Snowpack and Avalanche Observations (NRCC, 1981, 1989; CAA, 1995, 2002) have assigned a special code (STC) to shovel tests that resulted in noticeable collapsing of a layer and "settlement" of the overlying block when the shovel is inserted. The persistence of this code over 20 years suggests that field workers found it useful to distinguish fractures involving collapse from fractures that did not.

With reference to the compression test, the 1995 and 2002 editions of the Observation Guidelines note that sudden failures that result in distinct lines ("pops") on the column walls are more often associated with avalanches than test results with rough or indistinct fractures.

For the rutschblock test, Schweizer and others (1995) proposed a rating system for the type of release and quality of the fracture plane. Schweizer and Wiesinger (2001) refined the descriptions for type of release (whole block, below the skis, only an edge) and fracture quality (clean, partly clean, rough). This system is now in use in Switzerland.

In 1999, Karl Birkeland and Ron Johnson proposed three levels of "shear quality" (Q1, Q2 and Q3) for the Stuffblock test. This system can also be used for other tests (Tremper, 2001, p. 160). Johnson and Birkeland (2002) summarize six winters of

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Table 1: Descriptive classification of fracture character in tests of snowpack columns

Fracture character	Code	Other descriptors	Fracture characteristics[1]		
			Sudden	Compression	Planar
			Fracture crosses column with a single loading step	Noticeable displacement of slab perpendicular to slope	Fracture is confined to an interface, or thin layer, typically < 1 cm thick
Progressive Compression	PC	Indistinct, rough, slow	Inconsistent	**Yes, initial compression of layer *not* greater than any subsequent compression with additional loading steps**	Usually not
Thin Planar	TP	Shear, pop, clean	**Yes**	**No**	**Yes**
Sudden Collapse	SC	Collapse, drop	**Yes**	**Yes, initial compression (collapse) of layer greater than any subsequent compression with additional loading steps**	Usually not
Non-Planar Break	B	Break, rough	Inconsistent	**No**	**No, or not planar across column**
No Fracture (across column with maximum loading steps)	NF	-	**No**	**No**	**No**

[1] **Defining characteristics in bold type.**

using this system for the stuffblock, compression and rutschblock test. Using data mostly from southwest Montana and northwest Wyoming, they report improved interpretation of stuffblock, rutschblock and compression tests, particularly those tests with high scores using the three-level classification system.

In a 1999 article on the compression test, Jamieson outlined a four-level description of fracture character (Progressive Compression, Thin Planar, Sudden Collapse, non-planar Break), but presented no data on the utility of the classification system. Some field workers in Canada, many of whom had been informally describing fracture character, began to use the classification system. This four-level scheme has been slightly refined and is the focus of this paper.

3. Methods

Since the beginning of 1997, the University of Calgary's ASARC avalanche research group has recorded the character for over 6000 fractures from 2974 compression tests and 282 rutschblock tests according to Table 1. Since 1999, four percent of the fractures in the compression tests and four percent of those in the rutschblock tests were not classified, partly because observers had difficulty classifying a small percentage of fractures into the four classes.

In the winters of 1996-97 to 2001-02, we have done compression tests on avalanche slopes where 217 dry slabs were skier-tested. Including whumpfs (Johnson, 2000; Johnson and others, 2001) and remotely triggered avalanches, 131 of these slabs were triggered. In addition, compression tests were done next to 15 natural avalanches. We did compression tests on each of these slopes on a site that appeared typical of the start zone. If time permitted it, we did one or two rutschblock tests. In total, 640 compression tests were performed next to skier-tested slopes, and 37 next to natural avalanches. We made 119 rutschblock tests next to skier-tested slabs and six next to natural avalanches. The tests at avalanche sites were done within three days of dry slab avalanches. Had we only used tests done on the day of the avalanche or within one day, the number of data would have been limited for analysis.

At each compression test site a snow profile was made, giving us information about hand hardness, crystal type, layer thickness and so on. This information enabled us to relate the observed fracture character to different snow pack properties.

4. Snowpack characteristics associated with fracture character in compression tests

Thin Planar (TP) fractures were observed in 55% of the classified fractures in compression tests. The second most common fracture character was No Failure (20%); however, this is a consequence of our practice of monitoring persistent weak layers long after they are likely to release avalanches. A Break was recorded in only 2% of our classified fractures. Sudden Collapse (SC) and Progressive Compression (PC) make up 12% and 11% of the fractures, respectively.

4.1 Grain type and grain size

Figure 1 shows the percentage of each fracture character (described in Table 1) observed in compression tests for several grain types. The number of compression tests for each grain type is also given.

The percentage of Progressive Compression fractures is greatest (39%) in recently deposited layers of new snow (precipitation particles). Sudden Collapse is mostly associated with depth hoar (76%) and faceted grains (27%). Thin Planar fractures are the most common character for all grain types except depth hoar.

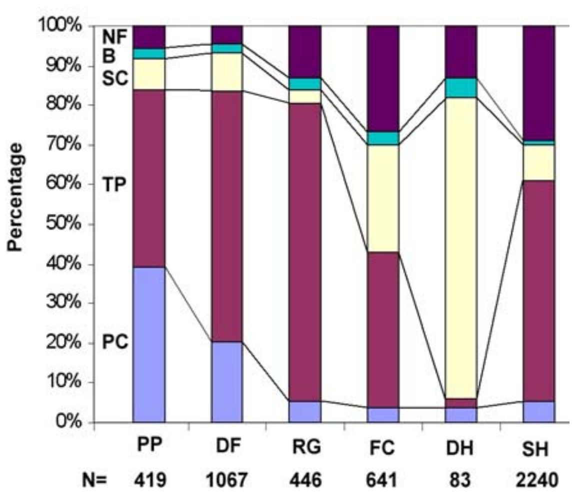

Figure 1: Percentage of fracture characters in compression tests by grain type for precipitation particles (PP), decomposed fragments (DF), rounded grains (RG), faceted grains (FC), depth hoar (DH) and surface hoar (SH). The number of fractures with the specified character is shown below the bar for each grain type.

The mechanism that causes different fracture types is relevant. A Thin Planar fracture is usually associated with a fracture at the top or the bottom of a weak layer. Sudden Collapse and Progressive Compression on the other hand, involve a substantial thickness of a weak layer. In the case of a Progressive Compression fracture, the crystals in the weak layer are rearranged after each tap. For a Sudden Collapse, the critical loading step results in an obvious displacement of the overlying slab perpendicular to the slope caused by a sudden and extensive rearrangement of the crystals.

Fractures in layers of rounded grains (RG) and decomposed or fragmented particles (DF) exhibit a high percentage of TP fractures, suggesting fracture at the upper or lower interface is common. Surface hoar (SH) layers also exhibit a high percentage of TP fractures either because the fracture occurs at the upper, or more likely, the lower interface (Jamieson and Schweizer, 2000), or because the layers are often too thin for noticeable collapse (SC). Layers of depth hoar are usually fairly thick, the crystals and pore spaces are relatively large, enabling dramatic rearrangement of the crystals when critical loading is applied.

Layers of faceted crystals cover a wide range of layer thickness and grain size. The median thickness of the layers with Thin Planar fractures was 1.1 cm, whereas the faceted layers with SC fractures had a median thickness of 15.0 cm.

For Thin Planar fractures and Sudden Collapses, we found a median grain size of 1 and 2 mm, respectively.

4.2 Layer thickness

In Table 2, the lower quartile, the median and the upper quartile of the layer thickness for each fracture character is given.

The median layer thickness for layers that did

Table 2: Layer thickness by fracture character

Fracture type	Layer thickness (cm)		
	Lower Quartile	Median	Upper Quartile
PC	1.0	7.0	11.0
TP	0.5	1.0	6.0
SC	1.0	5.0	14.0
B	1.0	4.0	14.7
NF	0.3	0.5	1.0

Table 3: Layer thickness by fracture character for persistent weak layers

Fracture type	Layer thickness (cm)		
	Lower Quartile	Median	Upper Quartile
PC	0.4	0.6	1.0
TP	0.4	0.8	1.0
SC	1.1	3.0	15
B	0.6	1.0	1.5
NF	0.3	0.5	1.0

not fracture in the compression test is 0.5 cm, lower than the median for other fracture characters. This is because we only record a No Fracture for a persistent weak layer that we are monitoring over time, often for a month or more after burial. Therefore our data set for No Fracture is biased towards layers of surface hoar and faceted crystals (66% and 17%, respectively), the median thickness of which is 0.7 cm and 2.0 cm, respectively.

The median layer thickness for Thin Planar fractures is also less than for PC, SC and B fractures, probably because many fractures of surface hoar layers are Thin Planar (44%).

If we limit layer thickness by fracture character to persistent weak layers, the results change dramatically (Table 3), except for layers that did not fracture. In this case, the median weak layer thickness is roughly similar for PC, TP, B and NF results. For SC fractures, many of which involve depth hoar and facet layers, the median layer thickness is substantially greater.

4.3 Fracture depth

The average depth of the fracture for PC, TP, SC, B, and NF is 19 cm, 52 cm, 58 cm, 61 cm and 83 cm, respectively. Figure 2 suggests that as some weak layers of PP/DF particles age and are buried more deeply, their fracture character may evolve from PC to TP to B. Weak layers of facets or surface hoar, which exhibit less PC fractures, are more likely to evolve from TP to NF with occasional B fractures at intermediate depths (Figure 2). For these persistent weak layers the median age for PC, TP, B and NF was 3, 20, 16 and 33 days.

4.4 Compression test score

The median compression tests score, as well as the lower and upper quartile for each fracture type are shown in Table 4. The median compression test

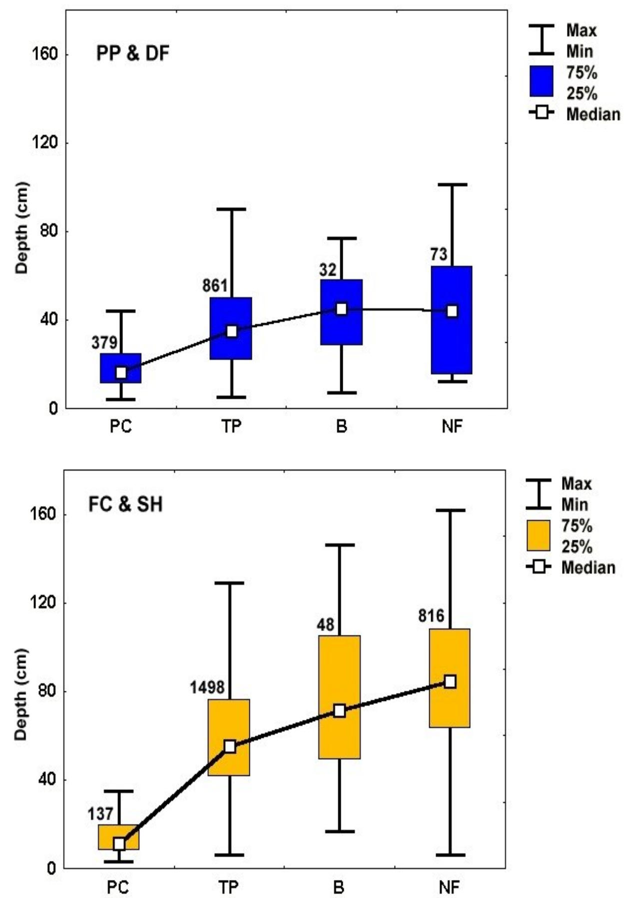

Figure 2: Weak layer depth by fracture character for PP and DF and for FC and SH layers

score for Progressive Compressions, Thin Planar fractures and Breaks are in the easy, moderate to hard and hard range, respectively.

The median compression test score for Sudden Collapses was 13 taps, which is in the moderate range.

Table 4: Compression test score by fracture type

Fracture type	Compression test score (taps)		
	Lower Quartile	Median	Upper Quartile
PC	3	6	12
TP	14	19	23
SC	4	13	19
B	16	23	26

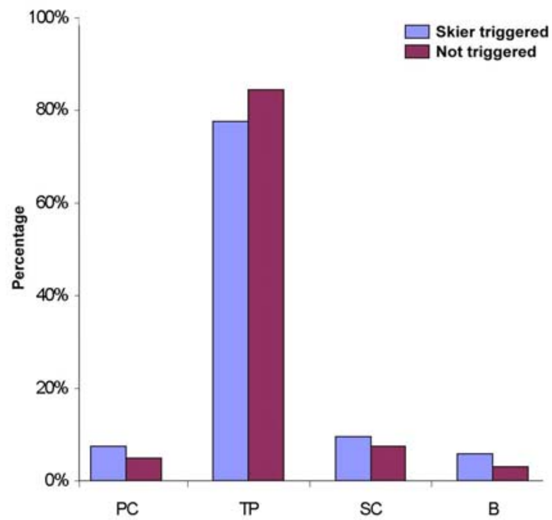

Figure 3: Fracture character in compression tests for skier-tested dry slabs

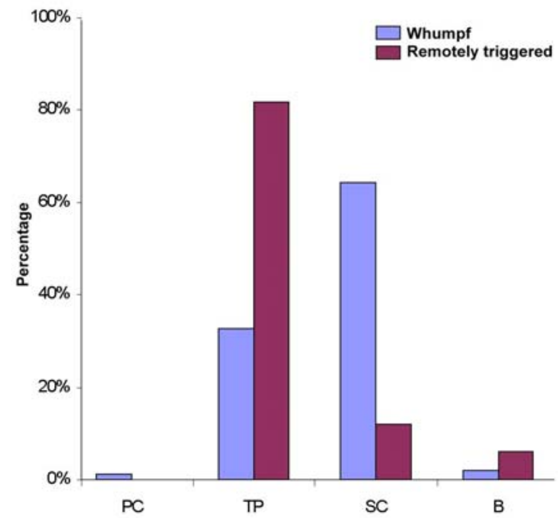

Figure 4: Fracture character in compression tests for whumpfs and remotely triggered avalanches.

4.5 Fracture character in shovel shear tests

We have also observed fractures as Sudden Collapse, Thin Planar or non-planar Breaks in shovel shear tests (Canadian Avalanche Association, 2002, p. 30-32), but have not systematically recorded or analyzed these results.

5. Fracture character for weak layers/interfaces of dry slab avalanches

5.1 Compression tests near natural avalanches

Of the 37 compression tests results within 3 days of natural avalanches, only 20 of the fractures were classified. Nevertheless, 85 percent of these were TP fractures (17 out of 20). The remaining three compression test fractures were SC. The median weak layer thickness for the failure layers of natural avalanches was 1.0 cm.

5.2 Compression tests near skier-tested dry slabs

Ten percent of fractures from compression tests next to skier-tested slabs were not classified. The characters, by percent, of 169 fractures near 61 skier-triggered dry slabs avalanches less than 3 days old and 162 fractures next to 62 skier-tested but not triggered dry slabs are given in Figure 3. For each fracture character, the percentage of failure layers/ interfaces of slabs that were triggered and those that were not, does not differ substantially. Since the compression scores for the failure layers of triggered slabs differs substantially from scores for weak layers of slabs that were not triggered (Jamieson, 1999), the score is a more important observation than the fracture character.

The median weak layer thickness was 0.7 cm and 1.0 cm for the skier-triggered dry slab avalanches and slabs that were skier-tested but not triggered, respectively.

5.3 Compression tests near whumpfs and remotely triggered dry slab avalanches

Forty-two fractures were characterized next to remotely triggered avalanches and 105 at whumpfs sites (Johnson, 2000; Johnson and others, 2001). Figure 4 shows the percentage of each fracture type for whumpfs and remotely triggered avalanches. At 64 percent, Sudden Collapses are most common fracture character for weak layers that produced whumpfs (fracture propagation in a weak layer, usually on low angle terrain). Thin Planar fractures lead the compression test results for remotely triggered avalanches with 82%.

In both cases, PC fractures cover a minor part of the results. A Break was recorded in 6% of the cases next to remotely triggered avalanches and only in 2% of the compression tests for whumpfs.

The median weak layer thickness for whumpfs was 2 cm. These weak layers are thus often thicker than the failure layers of natural and skier-triggered avalanches. Therefore more slope-normal displacement is expected when these layers exhibit SC fractures. This result supports the theory proposed by Johnson (2000) that when a whumpfs occurs, the fracture in the weak layer includes a compressive component, which creates a flexural wave in the overlying slab.

5.4 Rutschblock tests near skier-triggered dry slab avalanches

With only 381 classified fractures, the rutschblock data set is much smaller than the compression test data set. Sixty-seven percent of the fractures were classified as TP, 27% as NF, 3% as B and 2% as SC. No PC fracture was recorded.

Thirty-one and 39 rutschblock tests were done next to skier-triggered slabs and slabs that were skier tested but not triggered, respectively. The results from rutschblock tests near skier-tested slabs are fairly similar to those from the compression tests; 97% of the fractures were TP for slopes that were triggered and for those that were not.

Progressive Compression and Sudden Collapse fractures were observed more often in compression tests than in rutschblock tests probably because the compression component of fractures in weak layers less than approximately 2 cm thick is difficult to observe on the front (lower) wall of a rutschblock test. In the early 1990s, prior to the current study, when we positioned observers in one of the shovelled trenches beside rutschblocks, PC fractures were observed to take more than one loading step to reach the front wall.

6. Summary

The proposed classification of fractures into Progressive Compression, Thin Planar, Sudden Compression and non-planar Breaks requires minimal training and is applicable to the compression, rutschblock and shovel test.

In the Columbia Mountains of western Canada, weak layers or interfaces of decomposing fragments, rounded grains and surface hoar as well as some layers of facets usually exhibited a Thin Planar fracture. A Sudden Collapse of the weak layer was usually associated with a relatively thick layer of depth hoar or facets. In a thinner continental snowpack, where such layers are more common, more SC fractures are likely.

Progressive Compression and Sudden Collapse fractures were observed more often in compression tests than in rutschblock tests probably because the compression component of fractures in relatively thin weak layers (< 2 cm thick) is difficult to observe on the front (lower) wall of a rutschblock test.

Most weak layers or interfaces that release natural or skier-triggered dry slab avalanches exhibited Thin Planar or Sudden Collapse fractures in compression tests or Thin Planar fractures in rutschblock tests. However, a small percentage of these critical weak layers and interfaces exhibited Progressive Compression or non-planar Breaks. For better interpretation of tests that result in Breaks, we recommend a second test, when practical, to better ascertain the stability or strength associated with the weak layer or interface.

Sixty-four percent of the tests of weak layers in which the fracture propagated in low angle terrain (whumpfs) exhibited Sudden Collapse fractures in compression tests.

The fracture character from compression tests did not distinguish between weak layers/interfaces that were skier-triggered from those that were not. However, smaller datasets for compression tests near natural avalanches, for rutschblock tests near skier-tested slabs and for compression tests near whumpfs and remotely triggered avalanches indicates this classification of fracture character is useful for identifying critical weak layers or interfaces. Consequently, some critical weak layers can be better identified in rutschblock and compression tests when this classification of fracture character is considered along with the score.

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