idth. a:Width is usually
Gabriel) b:Wet slab con-
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some instances. (Photo

data indicate that the width of slabs generally exceeds the downslope length. Figure 4.36 illustrates field measurements from twenty-six slabs. For this limited sample, the minimum ratio of width to length is about 2, and 85% of the values are between 2 and 6. There is no known upper limit to the ratio since it is known that shear fractures can propagate more than 1 km. Typical flank-to-flank dimensions are 10 to several hundred times the slab thickness. In a confined region, such as a gully (see Figure 4.35), the length may exceed the width. Field data show that there is a general increase in slab width with slab stiffness. However, this can be misleading because fracture propagation can occur over long distances, even with soft slab material.

Measurements show that the crown surface makes an angle close to 90° to the bed surface. It has been suggested from mechanics that this observation means the bed surface is nearly friction-free in order for the 90° angle to appear. This would be expected if a shear fracture had propagated underneath the slab first to precipitate tension failure at the crown/bed-surface interface as field observations indicate.

Field observations show that most dry slabs occur on a planar slope (rather than convex or concave). Experience shows, however, that slab initiation (by skiing, for example) is much easier at the top of convex rolls. This is probably due to an increase in the ease of shear-fracture propagation as the slope angle increases in the downslope direction.

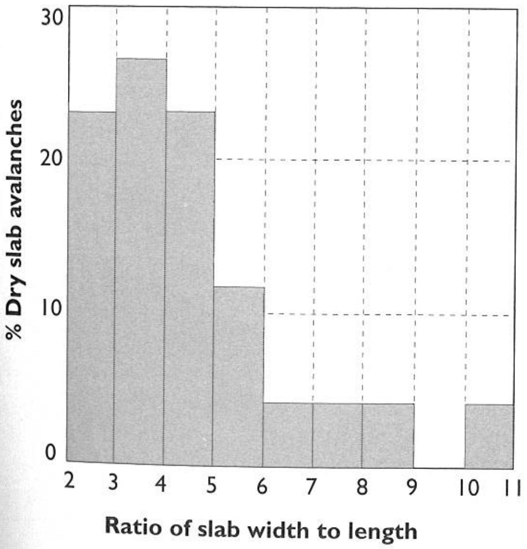


Figure 4.36. Distribution of slab width to length from twenty-six slabs.

DRY SLAB AVALANCHE FORMATION

Dry slabs are responsible for most of the damage and fatalities from avalanches. They constitute the single most important class of natural hazard in winter alpine terrain. Their release is characterized by rapid propagation of fractures underneath and at all boundaries of the slab. The vast majority of dry slabs release due to loading by new snowfall.

Studies at the crowns of fallen avalanches show that the stratigraphy consists of a relatively thick cohesive slab over a weaker, much thinner layer at the bed surface. In fact, a fallen slab usually has a structure rather like a sandwich: a weak layer in between thicker cohesive layers. A slab avalanche may be defined in simplest terms as a block of snow cut out by fractures. Whereas loosely bonded snow is a prerequisite for loose-snow avalanche formation, a certain degree of cohesion is necessary to form a block of snow. From the sample in Figure 4.31, nearly 90% of the avalanches have average densities between 100 to 300 kg/m^3. In general, these densities are higher than that of newly fallen snow without wind packing (usually less than 100 kg/m^3) or snow that has not undergone bond formation. Experienced field observers are usually able to judge when snow has the proper consistency to form a slab as opposed to snow that is noncohesive.

To understand how a slab avalanche develops, in general, it is necessary to distinguish between failure and fracture. *Failure* in a dry slab avalanche occurs when the downslope component of the weight of the slab approaches the shear strength in the weak layer (peak value of stress on a stress-strain curve). It is possible, however, to have failure in a material such as snow (called strain-softening) without fracture. At failure, a sample of snow has absorbed the maximum load that it can bear (see Figure 4.17). If snow has been deformed slowly in shear, it can fail without fracturing. Fracture means catastrophic failure of the material and this is a prerequisite for slab-avalanche release. Controlled laboratory studies show that fracture takes place only if snow is sheared at a critical rate, which is about 1 mm/min for layer thicknesses typical of avalanche weak layers (e.g., 10 mm). Therefore, two requirements must be met before a propagating shear fracture takes place: (1) the shear stress must approach the shear strength in the weak layer, and (2) the rate of deformation in the weak layer must be fast enough to provoke fracture. Instability develops when the first condition is met, but dry slab avalanches can start only when both requirements are fulfilled. The intermediate condition (in which failure is approached, but fractures have not yet occurred) provides a serious threat to travelers in snow-covered alpine terrain (Figures 4.37, 4.38, and 4.39).

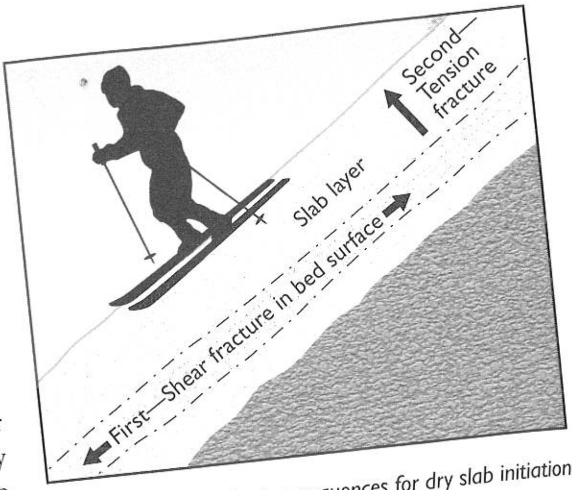


Figure 4.37. Possible fracture sequences for dry slab initiation.

Although the fracture sequence is believed to be the same, it is convenient to distinguish between *natural* slab avalanches (not caused by humans) and *artificial* releases (caused by humans), including releases by explosives, skiing, or other influences. The principal difference is usually the rate of application of the energy and the amount of energy delivered that starts the failure process. It is easy to see how the critical rate of deformation may be applied to the failure process, when energy is supplied rapidly, for example, by explosives, skiers, sonic booms, or earthquakes. However, it is more difficult to understand how the critical rate is achieved in the weak layer by much slower loading from new snowfall or by natural straining in the snowpack.

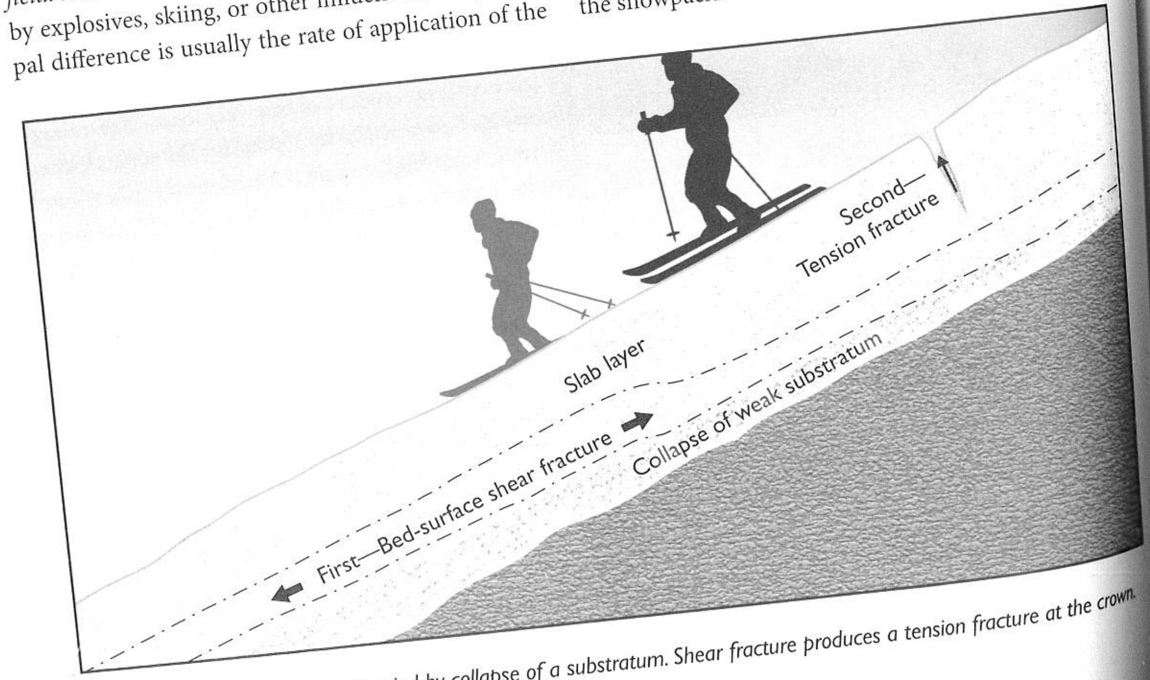
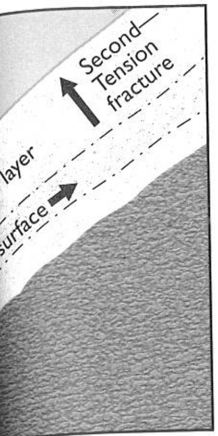


Figure 4.38. Initial failure accompanied by collapse of a substratum. Shear fracture produces a tension fracture at the crown.



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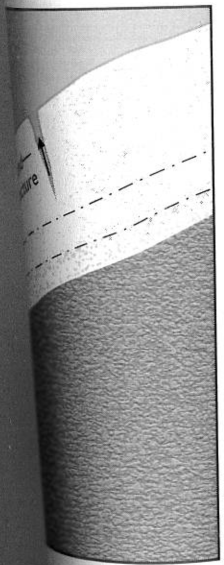

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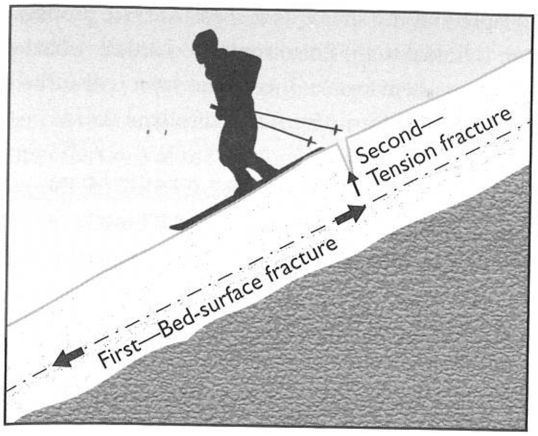

Figure 4.39. Initial shear fracture produces a crown tension fracture near a skier.

These failures may result from a combination of natural imperfections and shear band formation (see the preceding section "Shear-Failure Properties of Snow") to produce the necessary high deformation rates and stresses.

After a shear failure, a fracture develops that spreads upslope and across the slope. As it does so, it reduces the attachment of the slab to the bed surface, and rapid tensile fracture occurs from the bottom to the top of the slab to form the crown. As the crown fracture propagates across the slope, it also allows the slab to displace downslope, providing further driving stresses to propagate shear fractures across and downslope over the bed. The flanks (and stauchwall) form rapidly once the crown fractures to allow downslope displacement of the slab.

Tensile fractures have sometimes been observed to occur just upslope from a skier crossing a slope, particularly (but not exclusively) when traversing a convex roll. In general, it is possible for shear fractures to propagate upslope as well as downslope and across the slope. In this case, shear-fracture propagation (across and downslope propagation) is responsible for generating the tensile fracture that forms the crown. As in other cases, the elastic energy necessary to produce tensile fracture is produced by rapid deformation generated by shear fractures.

The most common trigger for natural dry slab avalanches is the addition of weight by new snowfall, blowing snow, or rain. Other natural triggers include impact by pieces of falling cornices and vibrations by earthquakes.

Natural dry slab releases are also possible as a result of temperature influences at and near the surface of the snowpack because of warming effects during which the snow surface may or may not reach 0°C. Temperature releases are observed for thin slabs, usually less than 0.5 m, over very unstable weak layers, such as weak surface hoar. Since incident solar radiation cannot penetrate the snow cover more than a few centimeters and since low-density alpine snow conducts heat very slowly, surface warming cannot quickly penetrate very far (see Chapter 2). Field observations suggest the effect is confined to thin slabs in which warming can affect a significant fraction of the slab depth. Under unstable conditions, it is not necessary to have warming penetrate to the weak layer; reduction in slab stiffness by warming can provide the trigger. This can result in a direct reduction in shear-fracture toughness. Since temperature effects are enough to release thin slabs naturally, they clearly can have a strong influence on snow-slab stability when combined with other effects.

Temperature increases are sometimes cited as the cause of slab release when avalanches release (minutes or hours) after applying explosives (called *postcontrol releases).* However, most case histories are inconclusive because explosive control is often applied in the morning and release is observed later when the temperature is rising. The far more likely explanation of these delayed events is that, rarely, explosive control causes failure initiation without immediate fracture, placing the slope in a highly unstable condition. The great majority of documented cases of postcontrol release have involved triggering by skiers and it is likely that the prime cause is because the slope was left in a weakened state by explosives. It is possible to start a slowly propagating failure that does not immediately reach a fracture condition since snow is a strain-softening material with both elastic and viscous properties. It may also be that areas of accelerated deformation are created by an explosion that results in a growing failure region, which eventually attains a critical size. Achievement of just the right balance at which failure is approached, accompanied by delayed fracture, is expected to be rare, in agreement with observations.

Weak-Layer Collapse and the Sound "Whumph"

A situation of interest is the failure of a thick layer of depth hoar near the bottom of the snowpack or a thick layer of highly faceted snow or surface hoar. This is often referred to as a collapse of the layer since it is sometimes possible to sense a drop or falling sensation during the failure process. Properly speaking, however, the release mechanism is classified as a shear fracture, and a disturbance can be sensed to propagate away (up or downslope). The collapsing sensation is due to compression failure, but the actual fracture (and propagating disturbance) is a shear fracture (see Figure 4.40). Snow, like all other materials, *only* allows fracture *propagation* in shear and tension (see Chapter 6 for further discussion). The sound heard when the compression failure takes place has been called "whumph" to describe it phonetically. The sound is due to compression of air during the collapse (vertical displacement) of the snowpack. It is a signal of high instability of the snow cover—a wake-up call, which should not be ignored. Weak-layer collapse and the subsequent shear-fracture propagation is linked to the anisotropic mechanical behavior of the persistent forms. Once a thick layer is disturbed, stresses and deformation occur mostly in shear.

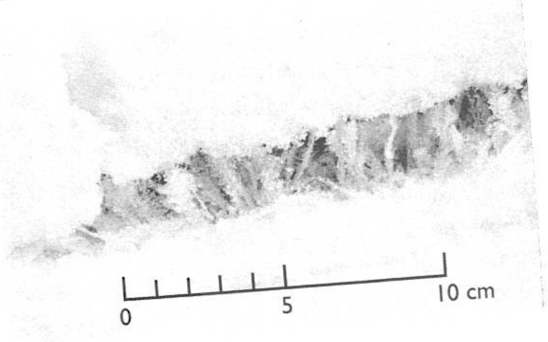

Figure 4.40. Tensile fracture generated by shear-fracture propagation in surface hoar on a 14° slope. The shear fracture propagated from left to right and the surface hoar collapsed during passage of the shear fracture. (Photo: Dept. of Civil Engineering, University of Calgary)

SNOW TEMPERATURE EFFECTS IN AVALANCHE FORECASTING

The effects of temperature on slab properties and strength in the weak layer discussed above have to do with direct, immediate effects on slab release when temperatures change. However, the most important effects of temperature for forecasting avalanches have to do with creep and bonding effects over time on shear-fracture toughness in the weak layer. High snow temperatures at a weak layer cause rapid bond formation to increase fracture toughness, whereas low temperatures imply slow bond formation and longer persistence of instability. Avalanche forecasters sometimes note that instability disappears quickly in new snow, which is relatively warm. Densification under the load of the slab combined with warm temperatures builds fracture toughness in new snow. For the persistent forms, due to anisotropic structure, densification is reduced so that fracture toughness remains low. For the same weak-layer form, higher slab load and higher temperatures form the best combination to increase fracture toughness (or decrease instability).

NOTE ON MECHANICS OF HUMAN TRIGGERING BY SKIERS, SNOWBOARDERS, AND SNOWMOBILES

In North America and Europe, it is estimated that more than 80% of fatalities result from people triggering the avalanches themselves in the backcountry. Human triggering involves dynamic forces applied to the snowpack as people move over the snowpack. As such, the mechanics are very complicated and it cannot, and should not, be simply calculated by applying a model with a static load to simulate the weight of a skier, boarder, or snowmobile. The dynamic problem involves both viscous (permanent or nonrecoverable) and elastic (recoverable) deformation with time-dependent loading. There are no