ELASTIC ENERGY IN SNOW

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ABSTRACT

After many years of avalanche work, observation and study I began to question some of the standard explanations of snow mechanics. Very often the physical theories, as I had learned them, did not fit with an empirical understanding of field observations.

On the premise that the elasticity of snow was the process underlying these problems and that it was compressive deformation which was responsible for its creation, I conducted a study of polystyrene foam under compression as a laboratory model. A low-density form of this material, compressed mechanically, adequately mimicked the deformations in snow.

Analysis of this material resulted in a hypothetical mechanism for the introduction and storage of elastic energy in snow. This mechanism is: that because cellular or skeletal materials are volumetrically adjustable anisotrophic materials, they are capable of storing elastic energy in tension more completely than in compression. On a slope, vertical compression generates stress which is mostly dissipated, whereas angular changes in the model create horizontal tensile stress which is stored almost entirely. This can lead to shear forces far in excess of trigonometric vector analysis.

This new hypothesis offers possible explanations for the mechanics of slab failure as well as the potential for a mathematical formula to index instability.

INTRODUCTION

The accepted explanation for slab release is as follows: because avalanches almost always fail between two distinct layers of snow, it is the addition of weight to the snow which generates enough stress to cause an interface to fail in shear. This shear stress is analyzed as being the resolution of gravity, a vertical force, into vectors which can then be calculated trigonometrically. When the shear stress becomes greater than the shear strength of either the snow within a layer or between two layers, the snow will fail. This failure is described as happening in several modes, the most popular two being collapse and shear.

The problem with this is twofold. First, if a slope fails in collapse this would seem to be pure structural failure, best analyzed using bending loads, not compression/shear. Collapse, by causing bonding failure does achieve a rapid transition of the slab to a kinetic friction state, whereupon vector analysis between frictional bodies comes into its own.

Second, when shear stress is calculated at angles of less than 45 degrees then compressive stress will always be greater than shear stress. Thus, in theory, the layer would always fail in compression before it fails in shear.

Also, when using vector analysis at angles of less than 45 degrees, the addition of weight does not induce shear between purely frictional boundaries, let alone adhesive ones. When we speak of bonding between layers we are implying adhesion and indeed, in test pits before and immediately after an avalanche, I have found that if a block of snow which included the bed surface was cut out, it could be held upside down.

The typical "whumph" noise large slab avalanches make when they release was being explained as evidence of collapse failure, yet observations of numerous avalanches have shown that almost all large slabs create this sound, even in the absence of an observable collapse layer (i.e., new snow on a crust) or when there was no evidence of subsurface collapse.

What then is causing the planar shear failure exhibited in so many avalanches? Could it be that all releases are of the material collapse type but some on such a microscopic level that they are not being observed, or is there something else going on? Is there a mechanism for the dynamic transition from a static adhesive state to the kinetic frictional one which can generate the shear stress necessary to break an adhesive contact on slopes of less than 45 degrees, where most avalanches occur?

The current analysis of the internal viscous motion of snow on a slope is to treat it as two distinct processes: glide, the slow linear motion of the total snowpack parallel to the ground; and creep, the combination of the slow vertical settlement of snow and the apparently related lateral movement of a point in the snowpack. Experiments have shown that while glide does not always occur, creep inevitably does. There has been some observation of glide between layers.

The problem with understanding glide was, that in view of the inherent rugosities, roughness, rocks and bushes found in release zones, as well as the propensity for material bonding -- and my previous problem with vector analysis -- where did the shear stress necessary to drive glide originate?

In describing creep as the combination of vertical and horizontal movements, the first problem was that I could not understand how a point in the snow, which is subject only to gravity, can move horizontally. Secondly, the vertical component of creep, by far the largest internal motion, was being described as coming from three processes: the metamorphosis of snow as it initially simplifies its shape; the mechanical compressive deformation of the existing snow by the addition of weight; and the ability of snow to deform slowly, solely in response to gravity. The problem here was that there seemed to be no method for analyzing what stresses these substantial internal motions were generating. Which motions were creating stress and which were dissipating it?

Perhaps the hardest event to understand is the avalanche that happens days or even weeks after the last storm. What process keeps the slab poised for so long? Does snow have the ability to create stress faster than it can dissipate it, without new loading? A related problem is the fact that avalanches can occur after control procedures or when a third, fourth or fifth skier crosses a slope. What explains this? Work hardening? Sequential bed surface failure? Fatigue?

While accepted theories hold that it is the rapid release of elastic energy which manifests itself as the brittle failure of snow, none of them seemed to provide for its origin. It seemed likely that some motion of the snow was necessary to create it. Since creep and glide were the only two motions I knew of in snow, it had to be one of them. Analytical studies to determine the exact mechanism for elastic storage were lacking. Was it stored exclusively in tension, compression, torsion or a combination of these? Subsequent experiments have led me to formulate a theory of this mechanism.

TEST AND RESULTS

I suspected that it was the poorly understood mechanism for the creation and storage of elastic energy which was the underlying factor in all of these problems. Because the largest single internal motion of snow was its vertical settlement, I surmised that this was the process responsible for the production of elastic energy. Compressive deformation by the addition of weight (and energy input) seemed to be the likely mechanism, so I attempted to make a device to study it. Because of the difficulty of working with snow in the field I decided to find a substitute, something which would mimic the macroscopic properties of snow in the confines of the lab.

After some searching I found that polystyrene foam might be a suitable material. Under compression it deformed volumetrically yet had elastic properties and, like snow, it was a skeletal or cellular substance. Unlike snow, its viscous properties were not time dependent so loading rates did not have to be taken into account. In order to analyze compressive deformation under loading I constructed a model of an idealized two-dimensional avalanche slope out of two blocks of wood. These were "S" shaped with two radiused curves tangent to a 37.5 degree flat slope, representing the most frequent release angle (Fig. 1). The radiused curves continued around to a point tangental to an equivalent 37.5 degree slope on the opposite side. This was to eliminate any boundary effects in the model.

A piece of foam was cut to this shape and square in section. A grid was drawn on it and it was placed between the two blocks and compressed in a hydraulic press. When compression began it immediately became clear that the motions involved were very similar to those in snow. The foam compressed in a linear fashion, collapsing uniformly throughout the material, rather than as an advance of densified material. As compression continued the material eventually chose a side (there was no frictional difference between the blocks, so the test was symmetrical) and began a slipping motion along it similar to glide. Because there was no gauging system it was not known whether continued compression required increased pressure. What was surprising was that as slip continued, the foam finally failed in tension, at a point where the curved surface met, or was tangent to, the planar surface. This point, called the "breakover" in avalanche terrain, is the region where all crown fractures tend to occur (Fig. 2). This tensile failure was gradual -- proportional to the amount of compression, as was slip -- and began at the slip surface. It worked its way through the material at 90 degrees to the planar surface.

To orient the procedure and represent conditions in the snowpack, a material with a lower frictional value (Duct tape) was attached to the lower block. Consequently, the same thing occurred predictably on the bottom surface. Then, in order to mimic an adhesive boundary, a low-grade adhesive (Pomoca glue) was applied to the smooth side of the duct tape. When a piece of foam was attached to this and compressed, the same thing happened repeatedly. In one test, with the tape reversed, slip occurred between the block and the low adhesive side of the tape and as a result the tape failed in tension. The tensile strength of the tape was measured and found to fail at 16.8 kilograms, showing that tensile stress in excess of this was being generated. At extreme levels of compression a new motion developed. Failure of the material at the bottom or toe of the model occurred, beginning at a point on the surface and proceeding horizontally toward the base. But the shearing action of the material involved movement of the upper part toward the base and movement of the bottom part toward the surface, or quite the opposite of any suspected sense of slab failure. This response was erratic and in view of the confining nature of the apparatus, did not seem to be an accurate representation for the behavior of snow.

When multiple thin layers of foam with this adhesive laminate between them were compressed there was ample internal glide yet little tensile failure, indicating tensile dissipation (Fig. 3). When multiple thin layers were compressed without the tape between them, a strong mechanical interlock developed which eliminated slip between layers and the material again acted as a unit.

DISCUSSION

After studying these various motions I came up with this hypothetical analysis: compressive deformation of the material was generating stresses which were being released through shear failure, thus creating slip. In turn, slip built up tension which resulted in tensile failure at the top of the model, followed by some kind of failure at the bottom, and all of these failures were driven by tensile elastic energy. It is clear that only a compressible (viscous?) elastic quasi-solid material can exhibit these motions and their failure. Thus it appears that the ability for viscous deformation to take place by adjusting volumetrically is very important to the analysis of this material which so closely resembles snow. Also, it is this phenomenon which is responsible for the creation and storage of both tensile and compressive elastic energy.

If this material is thought of as having completely different properties in one dimension than in another (anisotrophy) or behaving differently in compression than in tension, then explanations for the mechanics of these motions appear. Polystyrene foam appears to have no ability to deform viscously in tension and is exclusively an elastic solid in that dimension. It can therefore retain all of the elastic energy generated through tensile deformation. In compression though, it can dissipate a lot of elastic energy.

Then, in a geometrical analysis of this model one can think of a rectangular section of the material on the slope, which is being forced through vertical compression to become a parallelogram, albeit of a smaller volume, but only in the vertical direction where any elastic rebound energy is mostly dissipated. In the horizontal direction, where there is total elastic retension, the material is forced to grow dimensionally (Fig. 4). Both of these elastic potentials want to return this block to its original shape, one totally, the other partially. At a certain level of compression the horizontal elastic stress becomes equal to the compressive. More compression exacerbates this until horizontal forces are generated which could easily produce shear stress in excess of compressive stress, resulting in shear failure, even through an adhesive contact. Also, because of its compressibility the material has the ability to retrieve elastic energy in a confined state, or while generating considerable compressive force to the base.

As shear failure occurs and the resultant slip begins, tensile stress builds up which is stored elastically. Because the material has no viscous properties in tension it must fail catastrophically at the point of highest stress, in this case at the point where increasing slip motion was in closest proximity to decreasing slip motion (Fig. 2). Slip was incrementally less descending the slope. Due to the confining nature of the press the final failure at the bottom could not be analyzed well but it was probably an elastically driven shape retrieval which caused tensile failure.

In applying this material analysis to snow, one finds many similarities. If snow is indeed more viscous in compression than in tension, as it appears to be, and if the known ability of snow to deform vertically without the addition of weight can be considered an extension of the deformation process, then many previously unexplained events in snow can be analyzed using this mechanism (which is that due to the anisotrophic behavior of snow, elastic energy is stored primarily in tension and is created by compressive deformation). In returning to the problem with vector analysis, which was that shear stress can never be greater than compressive stress and that compressive failure must always precede shear failure, I now realize that the analysis is quite correct. But previously I did not see that the preceeding compressive failure <u>is</u> the slow vertical viscous deformation we call settlement. During this settlement elastic energy is generated in greater amounts horizontally in tension than vertically in compression because snow retains elastic energy better in tension than in compression. This tensile elastic energy can create shear stress in excess of normal vector analysis, enough to cause shear between adhesive surfaces. This failure can be slow as in glide or rapid as in a slab avalanche.

When rapid shear failure takes place, the process can be viewed as the sudden elastic shape retrieval of a slab, perhaps even generating momentary tensile failure at the toe. Due to the incrementally decreasing movement of shear failure along the base from crown to toe, there may be some regularity in the process, wherein decreasing motion leads to a lockpoint, requiring the process to begin over. This could explain the almost immediate breakup of a slab into blocks after initial failure and also the zig-zag pattern of the flanks of an avalanche. Also, many slopes have been known to "accordian" or break into longitudinal blocks without sliding and that the blocks tend to exhibit similar widths. Release noise could easily come from this rapid elastically driven motion. This motion could then put angular stress on a structurally weak layer, like surface hoar, causing what appears to be collapse but is actually driven by a shearing motion. Indeed, I would speculate that most failures occur in this combined process.

Using this new understanding one can now explain the horizontal component of creep as the tensile viscous deformation of snow, or that for every vertical motion of the snow which requires densification, there must be a corresponding horizontal motion requiring elongation. While the vertical process dissipates elastic energy almost completely, the horizontal process which is only partly dissipated, does require some material elongation of the ice skeleton in that dimension. Proceeding incrementally then, the matrix gradually grows horizontally and a point in the snow moves with it.

Also, one can state, that if the compressive process does not become critical and after a period the stress is relieved through this horizontal deformation process, or if the elastic matrix is destroyed through packing or skiing, then it will have to begin again with much less potential for overall vertical motion. Because it is the total amount of vertical motion which is important in this analysis (i.e., snow settling from 5% density to 20% density requires compression to one quarter of its original volume whereas it requires only two thirds to go from 20% to 30%) denser snow is not as capable of generating tensile elastic energy as well as low density snow. Possibly snow becomes more isotrophic at increasing densities, explaining why slabs in excess of 40% density are rare. Another thought is that because wind is such a factor in avalanches, it may be aligning the snow structure for increased anisotrophy.

If the gradual vertical viscous deformation of snow under its own weight could be considered an extension of the compressive process, then this might be the motion allowing snow to create stress faster than dissipative and strengthening processes can eliminate it. Because this condition could persist for some duration, this may be the explanation for delayed avalanches. In another scenario, where inceasing temperatures gradually penetrate the snowpack and accelerate settlement, then elastic energy is generated within the warmer snow, which affects the entire snowpack. Thus the change in temperature does not have to physically reach a potential bed surface and weaken it to cause failure.

Finally in an attempt to explain how the third or fourth skier can trigger an avalanche, it is usually assumed that when a skier has crossed a slab, and has stopped well outside its boundaries, he is no longer affecting it and the additional stress is gone. Now imagine him as a moving point on the slab causing a temporary increase in settlement thereby increasing the tensile elastic strain on a bed surface and consider that this does not dissipate immediately. Then as he progressed the process would continue. This moving stress would be analagous to stretching thousands of rubber bands a little tighter. Because it takes time for this to dissipate, the addition of a second skier in rapid succession would repeat the process and easily bring the slope to failure.

In conclusion I would like to discuss the potential for a mathematical analysis of this mechanism for the production of tensile elastic energy through compression. If an ideal material, capable of dissipating elastic energy completly, is compressed vertically on a slope, its deformation process would yield a baseline for which to calculate the amount of stored energy in a particular snowpack. By periodic sampling one could obtain real time results as to the amount of deviation of the motions in snow from those of this ideal material. This could be as simple, for new snow at least, as two snowboards placed before and during a storm and monitored for relative motion, although the possibility for remote sensing exists. Theorizing that the greater the deviation of vertical settlement / horizontal elongation relationship from that of this ideal material, the greater the hazard, this could become a tool for forecasters.

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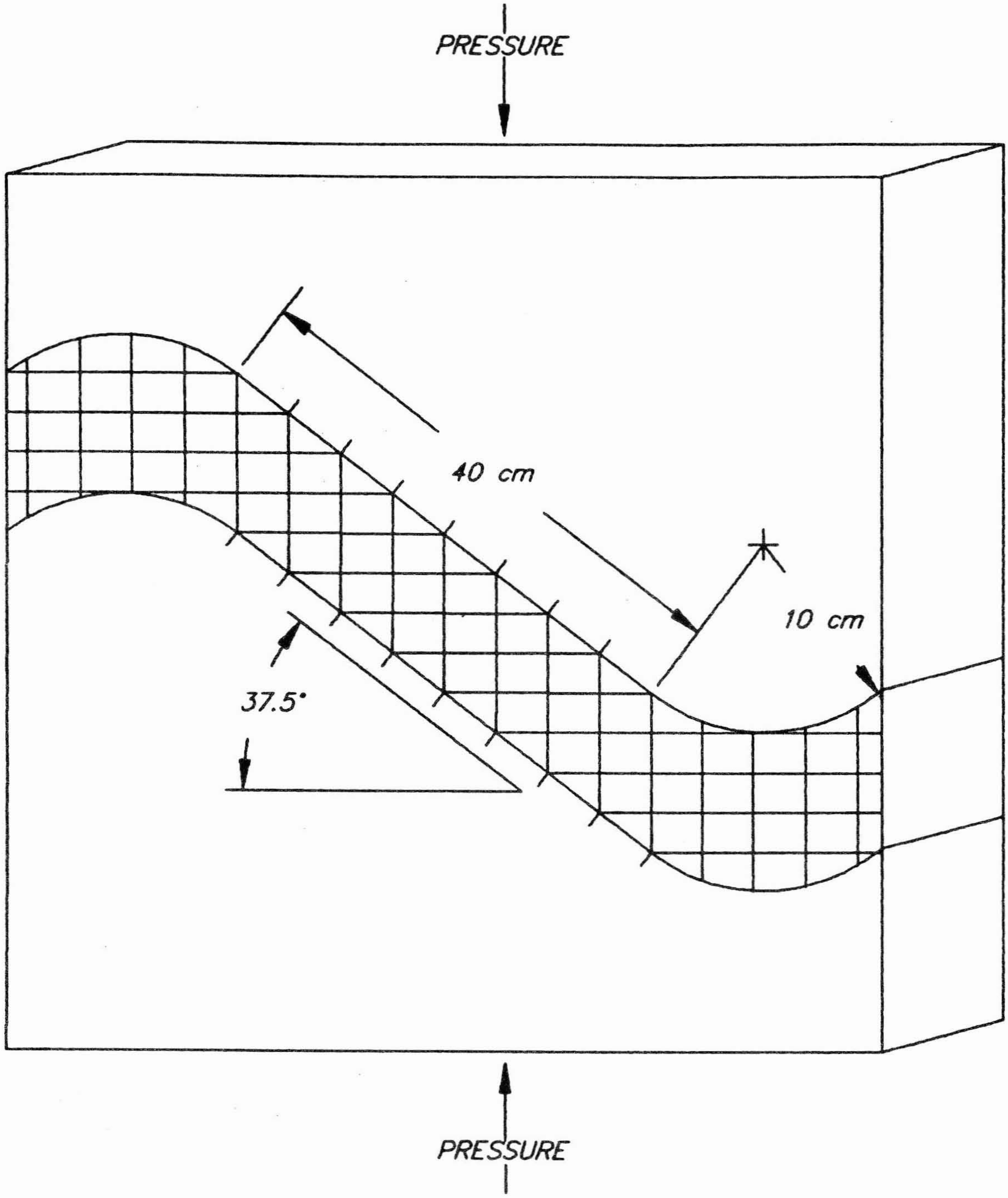

FIGURE 1

"S" shaped device for compressing polystyrene foam.

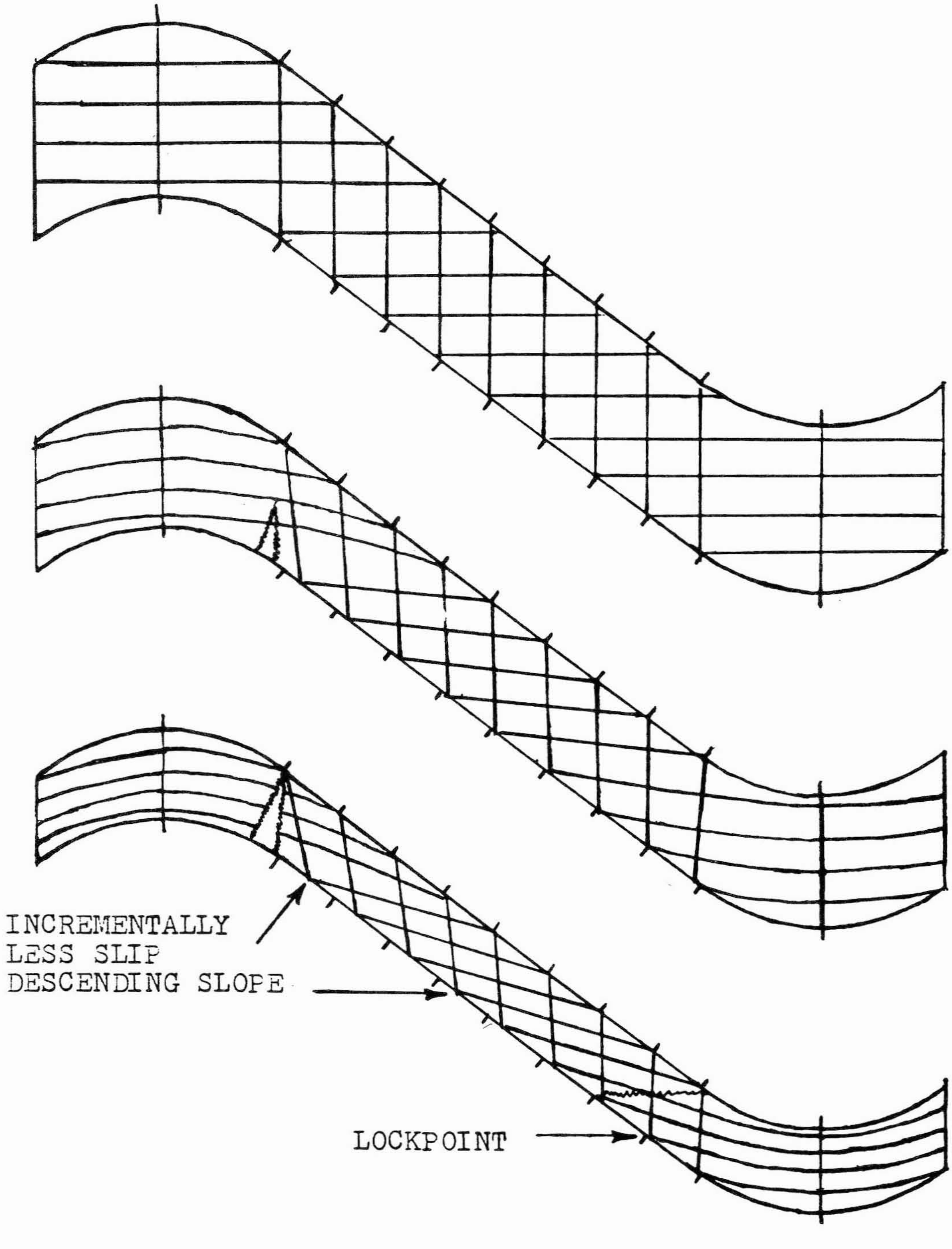

FIGURE 2

The deformation and failure process in polystyrene foam under compression.

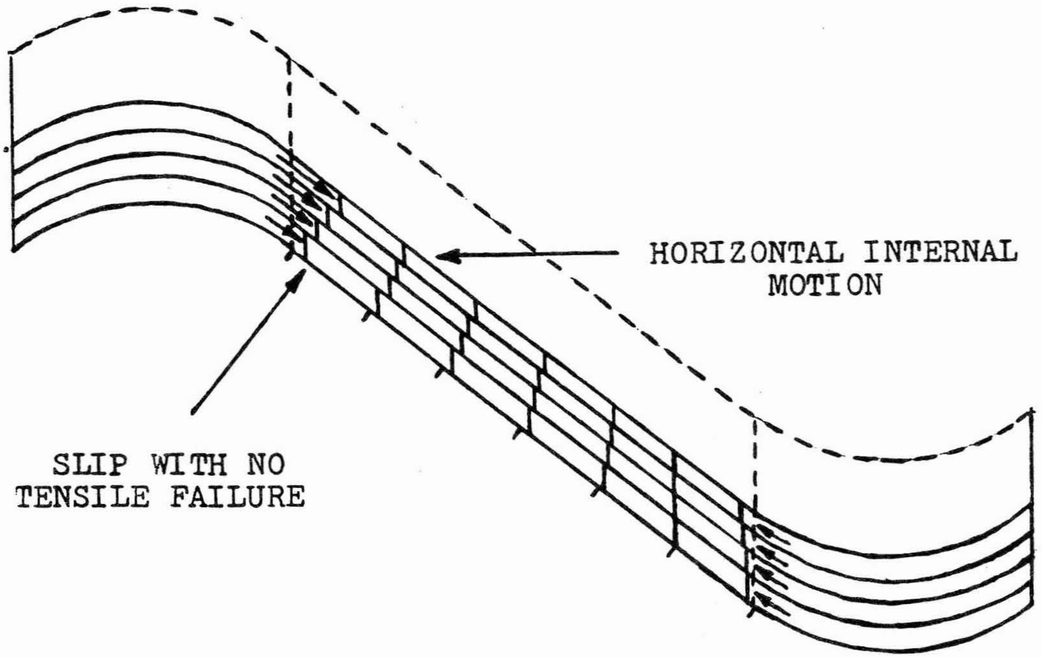

FIGURE 3

Compression of multiple thin layers of foam.

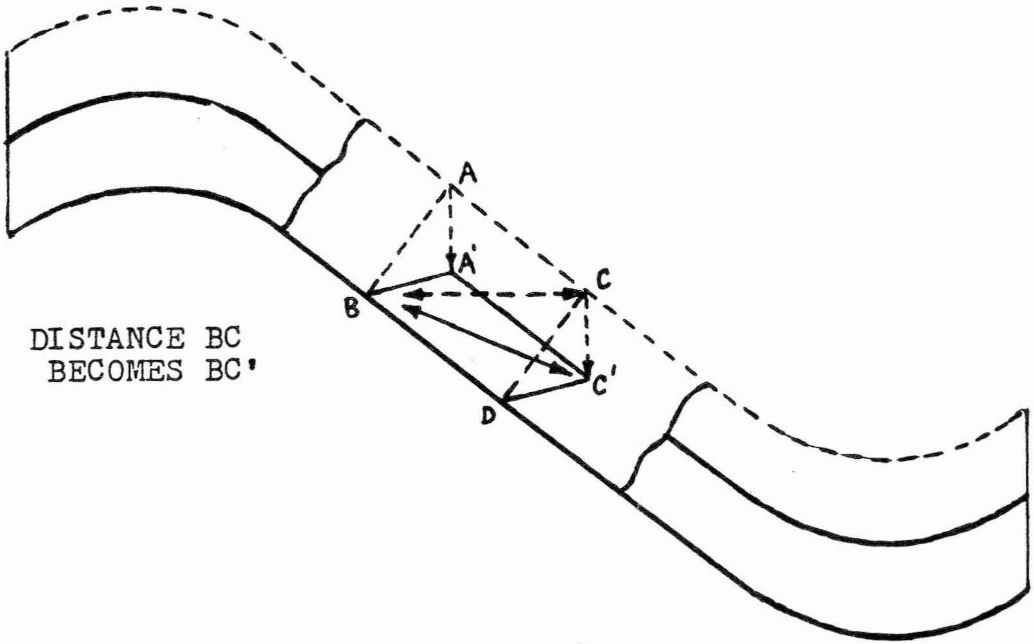

FIGURE 4

How tensile stress is induced through compression.