

A Short Talk on Tofu Soy Bean Curd

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Tofu (soy bean curd) is an extremely soft food that is commonly used in Japanese home cooking on a daily basis. It is such an integral part of Japanese cuisine that it even features in idioms such as “tofu no kadoni atama wo butskete shinde shimae” (literally “go bash your head against the corner of a block of tofu and die” but such a situation never happens), a humorous rebuke that is perhaps somewhat comparable to saying that someone is as useful as a chocolate teapot.

In the very, very cold Japanese winter, Japanese people enjoy eating slices of hot tofu prepared by boiling them at the dining table in a nabe-ryori dish. In the heat of summer, though, they relish eating hiyayakkoh, a chilled tofu dish made using soy sauce and some spices.

Tofu is a material that has properties of being both a very soft solid and a thick liquid. Here, we will consider tofu to be a typical soft elastic solid material. Then, let’s go walking through the promenade of physics to explore soft tofu puddings.

There used to be “otofuyasan” shops selling handmade tofu at every street about twenty years ago but the number of such otofuyasans has decreased recently as they have been driven out of business by large supermarkets selling cheap tofu blocks mass-produced in factories. Nevertheless, you can still see white steam billowing from traditional tofu shops that open every early morning to cater for people wanting to eat tofu for breakfast at homes.

Large blocks of tofu are made by coagulating soy bean milk in wooden boxes, with magnesium chloride used as the coagulant. The inner region of a solidified tofu block is a little softer than the outer region is. Two types of tofu can be made through filtering processes: one is an extra fine type of tofu called silk-filtered tofu and the other is a slightly coarser, stronger tasting type called cotton-filtered tofu.

After that, the tofu is completely immersed in water tanks installed in the tofu shop and then is cut into more conveniently-sized rectangular parallelepiped blocks that can be held in the palm of your hand. The small tofu blocks sit there waiting for mothers to come and buy them for their breakfast meal. Tofu seems to collapse easily under its own weight if it is removed from a water tank. “Why are blocks of tofu not set on a board but are immersed in water tanks?” This is the theme of this short discussion.



The first physics concept that springs to mind is buoyancy. Archimedes’ principle states that the weight of a solid immersed in a liquid decreases by an amount corresponding to the weight of the displaced liquid. Tofu may collapse or may fracture under its own weight when subjected to gravitational force, but it retains its shape when immersed in water. Is this because its weight in water is greatly reduced due to buoyancy?

It seems reasonable to assume that materials begin to fracture when the fracturing force acting in the solid surpasses its endurance limit of materials. So, is there a relationship between buoyancy and the fracturing force? Can a theory be developed to describe both the fracturing of materials that are soft and tasty, such as tofu, and the fracturing of materials that are hard and strong, such as glass or steel? What kind of force determines whether a soft material (tofu) will fracture and whether a hard material (glass) will fracture? Is there some difference between the force that causes tofu to be stable when it is immersed in water and the one that causes it to fracture when exposed to air?

When used its technical sense, the term “stress” means the force acting in a solid such as the tofu block. In everyday conversation, however, this word is also used to describe a nervous or worried feeling caused by a tense atmosphere or physical fatigue. In mechanical engineering, a state of stress in a solid can be expressed by two types of stresses. One is normal stress which is caused by the application of a tensile or compressive force, and the other is shear stress which is caused by the application of a shear or torsional force. Given this, it seems reasonable for us to consider that one of these stresses or a combination of the two, is responsible for a material’s fracture mechanism and strength.

First of all, let’s begin by calculating the buoyancy of tofu. If the density of tofu is 1.1 g/cm^3 , its weight in water may be calculated as $0.1 \text{ g/cm}^3 \times V \text{ cm}^3$ (where V is the tofu’s volume). This means that it exists under conditions equal to those of a solid with a density of 0.1 g/cm^3 that is exposed to air. Does that make sense?

Building on this, we can calculate the average stress acting on the bottom face of the tofu block as $0.1 \text{ g/cm}^3 \times h \text{ cm}$ (where h is the tofu’s height). In other words, the stress exerted on the

bottom face of an 8 cm high tofu block immersed in water is 0.8 gf/cm^2 and is the same as that of a tofu block with a density of 0.1 g/cm^3 in air. Is it right?

Just a minute, though. If we assume that the bottom face of a tofu block is located 30 cm under-water, a pressure of 30 gf/cm^2 will be applied to the bottom face and the tofu block will have to withstand this pressure. This means that the stress that the bottom is subjected to is 30 gf/cm^2 , not 0.8 gf/cm^2 . Let's try and approach this in a more systematic way.

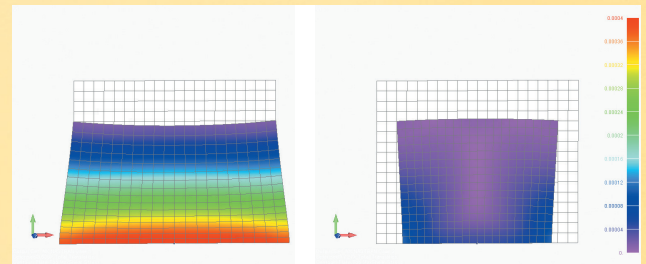
For the first stage of this approach, let's begin by considering what happens when we remove a block of tofu from a water tank and set it on a chopping board. The weight caused by the block's mass and gravity is applied to all regions of the block, and the block must withstand the stresses caused by the weight. If we assume that, as above, the block has a height of 8 cm, each region of the tofu is compressed by a force equal to ρ (density) \times h (height), and the bottom face has to withstand an average pressure of 8.8 gf/cm^2 . Consequently, the side walls of the block bulge outward, resulting in it resembling a poor struggling whale that has been stranded on a sandy beach by the waves or the tides. Downwards forces result in a rectangular parallelepiped tofu block that broadens towards the bottom. Exactly speaking, the uniformly distributed force in the tofu block caused by mass and gravity deforms a cube to a rectangular parallelepiped, while at the same time the force shears a cube into a tilting parallel-hexahedron. This leads to the tofu block having a deformed shape whilst sitting on a chopping board.

For the second stage of this approach, we consider what happens when we softly and gently immerse a tofu block with a height of 8 cm in water.

If we set it on the bottom of a 30 cm deep tank, its upper face is subjected to a compressive pressure of 22 gf/cm^2 and the bottom face to one of 30 gf/cm^2 . The four side walls of the block are also compressed by linearly changing pressures that depend on the water depth. The tendency for the side walls to bulge outward is suppressed by the hydraulic pressure, resulting in the block having a shape similar to a pressed rectangular parallelepiped.

Using advanced computing tools, we can easily calculate the block's condition and generate a beautifully colored image that describes the block's deformed shape and the internal forces — that is to say, the stresses — acting in it. After we divided the block up into $20 \times 16 \times 40$ cubes and made some reasonable assumptions about the likely properties of the material, we carried out a finite element calculation. The above figures show the results of this calculation; namely, the blocks' shapes and stress distributions. The lattice pattern represents the original shape of the tofu block and the element cubes used for the calculation. The original shape is actually an imaginary representation of what the tofu's shape would be if there were no gravity on earth. It resembles the shape that the tofu would have in a laboratory in space.

The left hand figure shows the center section of a tofu block set on a chopping board. The tofu block bulges at the sides due to the action of the gravity-induced weight force. The shape changes have been exaggerated and the fracture-



(a) A block of tofu on a chopping board

(b) A block of tofu in water

related stresses were color-painted using a stepped coloring scheme in which red indicates a region of high stress.

The right hand figure shows a tofu block immersed in water whose side walls are also compressed by hydraulic pressure at the top and the bottom. The material strength of the high stress area determines the stability of the tofu, and the tofu will fracture if the degree of stress exceeds the material strength. Comparing these two drawings, we can see that the block sets more stably when immersed in water than it does when exposed to air on a chopping board. The reason for this is that the hydraulic pressure restrains the side walls from bulging outwards and suppresses the high shear stress that is generated in the body of the tofu block. Does that make sense?

Nowadays, blocks of tofu packaged in thin plastic film boxes can be seen in every large supermarket. Some of these boxes which are filled with water, have a corrugated bottom, a film lid and thin side walls. The boxes are piled up high, but the tofu blocks appear to remain stable and durable. The reason for this is that the side walls of these thin boxes maintain the hydraulic pressure and push back on the block's sides, thereby preventing it from bulging.

As tofu has some similarities to objects such as those described hereafter, technologies similar to those used in tofu packing are applied to some machines and structures in engineering fields. Reinforcement work has been carried out on a lot of the concrete piers used for shinkansen (high-speed trains) bridges, highways and so on. After the experiences of large-scale earthquake disasters such as the Great Hanshin-Awaji Earthquake, the Mid Niigata Prefecture Earthquake the Great East Japan Earthquake, such piers were considered to require greater resistance to seismic activity than conventional piers have. The piers were strengthened by wrapping thick steel plates around the concrete columns of the piers to prevent outward bulging and breaking of the concrete.

IHI supplies ultra-high pressure generators for the production of materials used in electronic apparatus. A six-anvil system was applied to the development of one such a device, but the anvils often fractured in the early stages of development. The anvils, which were prepared using tungsten carbide with an ultra-high fracture strength, were used under extremely severe conditions. A study to prevent anvil fractures was carried out following a procedure that, although not exactly the same, was similar to the above-mentioned method for evaluating the deformation and stress state of a block of tofu.