Mechanical Optimality Hidden in the Structure of Plants

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Plants of various morphology (shape) can be found in nature. These diverse shapes are believed to be the result of the evolution of plants, which cannot move, to adapt to the surrounding environment. In this talk, I will particularly focus on the shapes of three plant types: i) bamboo [1-4], ii) butterbur, and iii) muskmelon [5]. First, I will demonstrate how the shapes of bamboo and butterbur, which are both tall and hollow plants, are optimal for supporting their own weight. Next, I will explain that the rind of muskmelons develops a mesh pattern with a certain geometric property, which may be used by farmers as a visual indicator of optimum sweetness of flesh; this is a consequence of a farmer seeking the optimum sweetness of the flesh.

<u>i) Optimal structure of bamboo</u>

Bamboo is the fastest-growing plant worldwide. This rapid maturity stems from their hollow structures, which require less material to develop, thereby promoting rapid growth. One critical disadvantage of hollowness is the propensity to easily collapse under external forces such as wind, rain, and self-weight. To overcome this limitation, bamboos generate a sequence of “circular plates” within the long cavity. The plates stiffen the culm locally; therefore, numerous plates from the bottom to the top of the bamboo enhance the stability of the culm. However, this is not a case of “the more, the better”, because an excessive number of plates will inhibit the growth rate of the bamboo plant. Therefore, the number of plates has to be “neither too many nor too few”. This trade-off between stability and growth rate implies an optimum number of stiffening plates that bamboo has acquired over millions of years of evolution.

Against this backdrop, our research group has explored the optimum solution to this issue by investigating wild bamboo groves in Japan. Analysis of the measurement data showed that a single universal law explaining the interdependence between the preferred number of stiffening plates and their ideal arrangement along the culm governs the growth of bamboo [3]. Specifically, the density at which fibers are embedded increases as it gets closer to the outer skin. This universal law thus provides a design criterion, endowing less material and high strength to wild bamboos, which are advantageous for survival over competing tree species.

Surprisingly, another mechanism lurks in the cross-section of the bamboo to increase its stability as a whole. It is bamboo fiber. Inside the bamboo, many long fibers are embedded in the longitudinal direction. These fibers are called "vascular sheaths" in biological terminology, and they act as straws that convey water and nutrients vertically. The structural mechanics theory revealed that this fiber plays an important role in the mechanical properties of bamboo. If a part of the cross-section of bamboo is cut and observed using an electron microscope, it can be seen that the fibers are not evenly distributed over the entire cross-section. Specifically, the closer it is to the outer skin, the more fibers are embedded. We were able to prove within the scope of the elastic approximation theory that by gathering many reinforcing fibers near the outer skin of the bamboo, the bamboo as a whole is less likely to bend [4]. This result indicates that the bamboo makes its own body stronger by efficiently arranging a limited number of reinforcing fibers inside the cross-section.

ii) Optimal cross-section of butterbur petiole:

There are many plant species with hollow stems and petioles, including those belonging to the family Poaceae. One of the reasons why many plant species have hollow tubular structures is thought to be the structural stabilization provided by hollowness. A tube with a hollow cross-section deforms less than a solid tube (filled) with the same cross-section. Thus, it can support its own weight by using minimal resources. In addition, by choosing the optimal cross-sectional shape (circular, polygonal, etc.) according to the growth environment, the resistance to the most influential mechanical loads (crosswind, self-weight of stems, weight of petals, etc.) increases.

From this perspective, the plant that we focused on in this study was the Japanese butterbur, a type of wild grass. A close examination of the cross-section of the stem of the Japanese butterbur reveals that it has a shape similar to that of a horse's hoof, which is rarely seen in other plants. We hypothesized that this peculiar horseshoe-shaped stem cross-section is the optimal structure for supporting large leaves at the tip of the stem. We have verified this hypothesis both experimentally and theoretically.

iii) Geometric law of mesh pattern of melon skin:

The surface of muskmelons, which is representative of high-grade melons, has a fine mesh pattern (net). It is empirically known that the appearance of this mesh pattern correlates with the quality of melons and is used as an important indicator for quality evaluation at production sites. However, only a few studies have investigated the geometric properties of melon nets.

Our research group took photographs of several muskmelons sold at a retail store (for quality assurance) and investigated the shape and size of the small green peel fragments separated by white reticular stripes. Calculating the areas of these small peel fragments, obtaining the probability distribution curves of the areas, and normalizing them, it was found that the distribution curves were on a common curve regardless of the type and size of individual melons [5]. Furthermore, this common probability distribution curve was derived from fracture mechanics theory. This discovery suggests the possibility of non-destructive identification and evaluation of melon quality using mesh pattern imaging.

References

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