論文の内容の要旨

論文題目　Exploration of the norm of tree design by the actual measurement of mechanical stresses on tree trunk and branches

(樹木にかかる力学ストレスの実測による樹形形成規範の探索)

氏名　南野　亮子

Trees are always exposed to mechanical stresses, and therefore, must be strong enough to withstand them. Trees can increase the mechanical safety of their trunks or branches against yielding by increasing the thickness of their trunks or branches. It has been considered that trees maintain the form of their trunks or branches as they keep the mechanical similarity to materialize a mechanically economic structure. Several hypotheses have been established for the self-similarity of trees: geometric similarity, uniform stress similarity, and elastic similarity. The latter two hypotheses include mechanical limitations. The hypothesis of uniform stress similarity states that tree trunks or branches take a form that equalizes the distribution of stress along the outer surface of the trunks or branches. On the other hand, the hypothesis of elastic similarity states that the deflection at the tip of a branch is constant regardless of the length of the branch. Several studies have been conducted on the tapering of a tree trunk or branch by using various tree species. However, few studies have directly assessed the distribution of the mechanical state in a branch, which has often been expressed in relation to the external form, for example, the basal diameter vs. length of the branch. Since branches plastically alter their shapes, to discuss strictly the mechanical similarity, it is necessary to directly measure the stress that occurs at each point of the branches because of loads. I have precisely described the stress

distribution in a trunk or branch and proposed a novel view of the morphological strategy by which trees cope with mechanical stresses.

In the first study, I examined the relationship between the morphology of a tree trunk and its mechanical environment. Previous studies have discussed the uniform stress hypothesis against the wind force. Further, the literature includes studies that support and refute the uniform stress hypothesis. However, to the best of my knowledge, evidence by the direct measurements of stresses has not been provided yet, despite the need. In this study, I measured the strain at the surface of a trunk at varying heights generated by the wind force, for one year, by using an isolated *Larix kaempferi* tree of 21-m height and 58-cm diameter at breast height. During the measurement period, the stress calculated from the strain data was higher in the upper portions of the trunk than in the lower portions, regardless of wind speeds, and the difference increased as the wind speed increased. This tendency continued throughout the measurement period, whereas the details of the stress distribution differed to a certain degree between the periods that the tree had leaves and had no leaves. (In the period after defoliation, the trunk was exposed to wind speeds of up to 28.93 m/s.) The results indicate that the upper portions of the trunk of an isolated *L. kaempferi* tree are more susceptible to wind than are the lower portions. The deflection of the trunk recorded at each position was also larger in the upper portions than in the lower portions. From the comparison of the tensile stress due to the wind force with the modulus of rupture, it was estimated that the base of the trunk could withstand winds of up to 200 m/s, which is much higher than the speed that may be observed around the tree.

In the second study, I evaluated the uniformity of mechanical safety and elastic similarity of horizontal branches of *Fagus crenata* and *Abies homolepis*. Lateral branches are different from trunks in the axis direction and load condition. The stress due to the branch's own weight always acts on lateral branches and should have an important effect on the morphology of branches. I calculated the stress generated along the horizontal branches of *F. crenata* and *A. homolepis* by their own weight by using two different measurement methods. The tensile stress and breaking safety factor (i.e., modulus of rupture divided by actual bending stress) calculated from the moment measurement and destructive test data tended to be constant for most sections of the branches of both species, whereas the small portions ($\phi < 2$ cm) of *F. crenata* branches had a higher safety factor than the other sections. Therefore, the smaller portions of the branches seemed to have mechanically tougher shapes on the basis of the branch’s own weight, rather than the larger potions. The bending safety factor for each point of the branches ranged from 4–10. In the individual branches, the tensile stress was slightly larger at the base of the branches and gently decreased along the branch toward the tip; the safety factor became larger towards the tip for both species. However, another set of stress calculations obtained from strain measurements did not show this tendency. Moreover, the strain measurements showed that the stress generated by self-weight is reduced by the effect of reaction wood, especially in the thicker portions of branches, suggesting that the small safety factor in the thicker portions of the branches was the result of overestimating the stress due to the self-weight. From these results, it was indicated that the stress uniformity is maintained along the branches. The elastic similarity of the branches was evaluated with the strain data at the upper and lower surfaces of branches due to the liberation from the self-weight measured for several species, including *F. crenata* and *A. homolepis*. The deflection at each minute section was determined from the strain data. In all branches, the deflection angle was slightly larger at the base, decreased to some extent, and then increased toward the tip. There was not much difference in the distribution of deflection among the individual branches, and therefore the elastic similarity was not denied. In addition, for one year, I measured the strains at the surface of a branch due to dynamic loads such as wind, snow, and rain, and calculated the maximum tensile stress due to such loads during the year. The maximum tensile stress due to these dynamic loads was lower than the stress due to the branches’ self-weight. The safety factor in consideration of all loads was over 3.5 for both species, indicating that the branch had acquired a considerably safe structure.

In the third study, I examined Leonardo da Vinci’s rule (i.e., the sum of the cross-sectional area of all tree branches above a branching point at any height is equal to the cross-sectional area of the trunk or the branch immediately below the branching point) by using simulations based on two biomechanical models: the uniform stress model and the elastic similarity model. Model calculations of the daughter/mother ratio (i.e., the ratio of the total cross-sectional area of the daughter branches to the cross-sectional area of the mother branch at the branching point) showed that both biomechanical models agreed with da Vinci’s rule when the branching angles of daughter branches and the weights of lateral daughter branches were small; however, the models deviated from da Vinci's rule as the weights and/or the branching angles of lateral daughter branches increased. The calculated values of the two models were largely similar but differed in some ways. Field measurements of *F. crenata* and *A. homolepis* also fit this trend, wherein models deviated from da Vinci's rule with increasing relative weights of lateral daughter branches. However, this deviation was small for a branching pattern in nature, where empirical measurements were taken under realistic measurement conditions; thus, da Vinci's rule did not critically contradict the biomechanical models in the case of real branching patterns, though the model calculations described the contradiction between da Vinci's rule and the biomechanical models. The field data for *F. crenata* fit the uniform stress model best, indicating that stress uniformity is the key constraint of branch morphology in *F. crenata* rather than elastic similarity or da Vinci's rule. On the other hand, mechanical constraints are not necessarily significant in the morphology of *A. homolepis* branches, depending on the number of daughter branches. Rather, these branches were often in agreement with da Vinci's rule.

These studies revealed that the mechanical limitation is considerably important to both trunks and lateral branches, whereas the details of the limitation may be different between trunks and lateral branches. This difference between trunks and lateral branches may be the result of the difference of the role of trunks and lateral branches. In the reevaluation of Leonardo da Vinci's rule, it was revealed that da Vinci's rule does not necessarily accord with the biomechanical model, and it was indicated that it is necessary to replace such an empirical rule with a physical model.