Advances in the study of mechanical properties and constitutive law in the field of wood research

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Abstract. This paper presents an overview of mechanical properties and constitutive law for wood. Current research on the mechanical properties of wood have mostly focused on density, grain, moisture, and other natural factors. It has been established that high density, dense grain, and high moisture lead to higher strength. In most literature, wood has been regarded as an anisotropic material because of its fiber. A microscopic view is used in research of wood today, in this way, which has allowed for clear observation of anisotropy. In general, wood has higher strength under a dynamic load, and no densification. The constitutive model is the basis of numerical analysis. An anisotropic model of porous and composite materials has been used for wood, but results were poor, and new constitutions have been introduced. According to the literature, there is no single theory that is widely accepted for the dynamic load. Research has shown that grain and moisture are key factors in wood strength, but there has not been enough study on dynamic loads so far. Hill law has been the most common method of simulation. Models that consider high strain rate are attracting more and more attention.

1. Introduction
Wood is a natural polymer composite material that has been used throughout history in wide engineering applications. Many consider wood to be one of the oldest engineering materials [1]. Wood has many advantages, including its low weight, environmental friendliness, and renewability. Wood surrounds us in daily life—it is used in our chairs, cabinets, and other furniture. Recently, the mechanical properties of wood have been the subject of heightened interest. Knowledge about mechanical properties is the foundation of theoretical models and engineering analysis. Wood is a complex, porous, heterogeneous, and anisotropic material. The properties of wood are more uncertain than steel and other macromolecule materials. In wood, the density, grain, moisture, annual rings, and other natural factors are variable, yet, they must be accounted for. A reason for the growing interest in wood is the demand for theoretical models and engineering analysis. Engineering structures are becoming more and more complex, and it is harder to analyze complex structures than it was in the past, and precise results are required. Reliable theoretical models are needed in order to perform numerical analysis. Mechanical properties must be known in order to obtain proper models.

Another problem in studying wood is the constitutive model. Numerical simulation has become a new tool for engineering analysis, and can be used at times when simple experiments are not enough for an engineer. The constitutive model for wood has been studied for many years, and has advanced greatly; new models can consider temperature and strain rate, and are able to satisfy demands for wood structures most of the time. However, the complexities of wood mean that no single model can be used for all purposes, and many models must be used to solve problems.
In previous research into the properties of wood, some differences have been found between static and dynamic loads, such as destruction modes and strength change. Hill and other yield laws have not yet been able to simulate natural factors, but mental laws, such as J-C, are sometimes able to be used.

2. Mechanical property of wood

2.1. Static mechanical property

Forest products laboratory in the US has conducted a number of experiments regarding wood under compression loads [2], and in 1961, more detailed experiments were carried out that studied failures under compression load. It was found that compression failures are seen more frequently if the light, the piece, and the point of view are in a specific relationship to one other [3]; however, these studies did not consider the effects of direction and hardness. Vural and Ravichandran conducted an extensive study of axial responses and failures under quasi-static and dynamic axial compression [4-5]. Their study laid a foundation for future research. Recently, Da Silva observed the cellular microstructure shown in the micrograph of Balsa wood, and determined the causes of failure in the microstructure. Different failure patterns were found in different directions, and it was discovered that compared with hard wood, soft wood has more obvious softening and densification, shown in figure 1. Further, experiments about shear strength were conducted [6]. Researchers began to pay attention to the age of wood, and found that old wood has higher elasticity modulus in the radial and axial directions, and the shear modulus does not change in old wood [7].

![Figure 1. Photograph showing evidence of kink band broadening.](image)

Sakai studied the effects of moisture content and incising on preservative penetration [8]. Manoochehr has investigated fracture energy and toughness of radial pine laminated veneer lumber (LVL), and detailed a method for making a sample. It was found that when the LVL fracture increases, the cumulative frequency increases. Simulation was conducted and the relationship between crack length and stress intensity was obtained [9]. Shear strength is another important parameter for wood. In many wood structures, shear load can lead to destruction. Shear strength is lower than compression for wood material. Wood's shear strength varies widely-- its orthotropic, shear plane, and density parameters are the most important factors. Shear strength is positively correlated to density and radial direction shear strength is higher than the remaining two directions. When axial strength is lowest, it softens under a shear load. The same is true for compression strength [10-12]. It appears that tensile strength is not as important as compression and shear strengths. In most circumstances, this parameter is ignored. The sample is difficult to make, and it is more complex to demand tensile strength [13]. Nonetheless, tensile strength is important for in depth study of complex structures. It had been found that tensile strength and density mass have a linear relationship [14]. Similarly, the wood’s grain has a
strong effect on strength. The failure mode is different though-- the crack always follows the grain and is not perpendicular to it [15-17].

Table 1. Tensile strength of pine at different grain angles and densities.

| $\rho$ (g/cm$^3$) | $\sigma_{0}$ (MPa) | $\rho$ (g/cm$^3$) | $\sigma_{10}$ (MPa) | $\sigma_{20}$ (MPa) | $\sigma_{30}$ (MPa) |
|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 0.434             | 64.3              | 0.451             | 10.9              | 7.0               | 3.7               |
| 0.442             | 57.6              | 0.471             | 8.7               | 4.4               | 0.9               |
| 0.511             | 66.5              | 0.482             | 15.9              | 10.1              | 2.1               |
| 0.527             | 91.4              | 0.483             | 13.2              | 3.0               | 1.2               |
| 0.534             | 89.4              | 0.500             | 12.8              | 8.5               | 3.3               |
| 0.537             | 115.2             | 0.510             | 11.6              | 6.4               | 1.5               |
| 0.591             | 82.4              | 0.577             | 11.8              | 6.0               | 0.8               |

Fabiane Salles proposed a new way to demand the elasticity modulus under a compression load. A sample was used as the standard, and other modulus were demanded though contrast to the standard. This method made the modulus easier to understand [18-19]. Moutou analyzed mixed-mode fractures of wood. The energy release rate in the wood material was evaluated by testing 2MCG specimens [20].

Grain angle, moisture, and density are the main factors in determining wood strength. The grain angle is especially important. Densification is obvious in the radial and tangential directions; however, the elasticity modulus in the axial direction is higher.

2.2. Dynamic property

Dynamic properties are more complex than static properties. Natural factors, rate effects, and load conditions should be taken into consideration when studying dynamic properties. Static properties were the subject of research in earlier literature, and the dynamic properties were considered as being static. The high strain rate response of end-grain balsa wood is very different from the quasi-static condition. There is about a 15% plateau in total, but the plateau is very few in the quasi-static state, which can be seen in figure 2 and 3 [21]. Tian Zhang studied viscoelastic properties of wood using nano-indentation experiments, and found that the storage modulus increases monotonically. When the damping decreases, the storage modulus and damping coefficient become dependent on the penetration depth [22]. It has been established that the age of wood affects the static mechanical properties and other physical properties of the wood. The dynamic mechanical properties also change with age. For older wood, a reduction of impact bending strength occurs [23-24]. The Hopkinson experiment device has played an important role in dynamic property testing. Nowadays, with the Split Hopkinson Pressure Bar (SHPB) device, researchers can test a material's strain rate range from $10^2$ s$^{-1}$ to $10^4$ s$^{-1}$. At lower wood hardness levels, standard steel rods can't give a precise signal for the sample, so an aluminum stick should be used as an incident rod in the test. As differences between static mechanical properties and dynamic properties have become better known more attention has been given to dynamic mechanical properties. The main areas of interest are dynamic compression characteristics, as there is more change under that condition. Xu W found that birch exhibited high strain rate sensitivity, and radial-loading specimens are easier to separate than axial-loading specimens [25]. Zhong’s test on spruce obtained similar results through using a theoretical model to analyze the mechanism of wood failure [26]. Many other researchers have conducted similar experiments. The SHPB device has advanced, which has allowed for testing of complex load conditions, such as twist and mixed-loading conditions [27-28]. In their study, wood has higher yield strength under dynamic load, and would be higher with high strain rate, these works are very helpful to do simulate about wood.
3. Constitutive model of wood

In general, wood is considered to be an elastoplastic orthotropic material; under load, it can be divided into three types: elasticity, plasticity, and densification. Sometimes the densification is not very important, but it can't be ignored in static mechanical analysis. Simple theories have been applied to solve early stage wood problems [29-31]. Recently, there have been great advances in wood modeling. Some of these models that have seen wide engineering use include maximum strain/stress criterion, Hill yield criterion, shear strength, and Tsai-Wu criterion [32-34]. Engineering demand drives the creation of advanced models.

Tom has applied a continuum failure criterion to wood, using modified Von Mises criterion, which can be seen in figure 4. The following formula can be used, where $X$ is tensile strength and all constants of the general failure criterion can be determined from compression and tension [35-37].
Where $S$ is the shear strength and

$$2F_{12} = 1/Cn_1 = 1/\sqrt{XXYY}$$

$$\left(\sigma_{xx} + \sigma_{yy} - \sigma_{xy}\right)^2 + \left(\sigma_{xy} - \sigma_{xx}\right)^2 + \left(\sigma_{yy} - \sigma_{xx}\right)^2 = 2S^2$$

Adalian wrote a model based on hypoelastic formalism, which considered strain hardening. This was the first numerical model which used numerical modeling to design new containers [38]. Demand pushes theory forward. The strength of timber joints has attracted great attention [39]. Xu has developed the wood constitutive law for behavior of timber joints, Hoffman criterion was used in law, experiments and simulation got similar results [40-41]. A key factor in simulation is anisotropy evolution under finite strains. The strength of wood is strongly tied to its direction. In an attempt to obtain the damage of wood under a finite load, Houssem studied the plastic anisotropy problem, by examining a non-associative finite strain anisotropic elastoplastic model coupled with anisotropic ductile damage. It was shown that the model was suitable for large deformation kinematics [42-43].

Table has presented a three-dimensional (3D) constitutive equation for wood materials, which assumes that wood is an orthotropic material [44]. Recently, Oudjene and Khelifa have developed a coupled model for wood. Under this model the curve of the mechanical property of wood was described, shown in figure 5 [45-47].

Application research has also been done in other areas, including dowel-type fasteners, wood composites, crack, buckle, and impact analysis [48-52].

A simulation model for a static load has been widely studied, using a variety of laws, including the Hill and Hoffman yield, Tsai-wu, and van der Put laws. However, there have been few simulations of dynamic loads, and no model is widely accepted. There are two reasons for an upsurge in interest in dynamic models: the dynamic mechanical property is very different from the static model and many models are not suitable for the dynamic load; further, there are multiple factors affecting wood strength and it is difficult to consider all factors using one model.
4. Conclusion

This study reviewed advances in the study of the mechanical properties of wood. Compression, tension, twist, and mixed-loading conditions have been widely tested since their hardness, age, moisture, quality, grain angle, and moisture are the main factors for wood strength. Dynamic loads are more complex than the static condition. The strength of the dynamic condition is reliant on the strain rate. Typically, SHPB experiments are used to study high strain rate. While there have been many advances, more research is still needed on dynamic loads and higher rate experiments should be conducted. In order to satisfy developmental engineering demands, a suitable numerical model must be developed for complex structural analysis. Although many models have been proposed no single model can be adapted for all demands. Existing models are not able to effectively reflect the effects of natural factors like temperature, moisture, and grain. Because of the complexities of dynamic forces, and its differences from static forces, there have been very few simulations for dynamic loads and limited research on the properties of high strain rate. These are areas of study within the wood material field that are ripe for future research.
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