Dynamic Mechanical Properties of Russian Pinus sylvestris var. mongolica Litv: Experimental and Numerical Simulation

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Abstract. With the Split Hopkinson Pressure Bar (SHPB) experiment and numerical simulation on Russian Pinus sylvestris var. mongolica Litv carried out, the dynamic mechanical properties of the pine wood at high strain rates were researched, and the relevant constitutive models was analyzed. The experiment results suggested that the dynamic mechanical properties of the pine wood were affected by strain rates and wood directions. The stress-strain relationship was mainly influenced by wood directions, but the initial yield stress was related to strain rates and wood directions. When the load was along the straight grain direction, fracture behaviors were caused by shear damage and fiber tensile fracture. The specimens were broken into ‘crushed’ pieces because of fiber and lignin separation, and fiber kink. However, it was chief role for the fracture in transverse grain direction that failure cracks grew down fiber. The dynamic responses described with model based on improved Hashin failure criterion were consistent with actual results, compared with model based on the Hill yield criterion. Related research work provides a certain reference for the related problems research and engineering practice application of Russian Pinus sylvestris var. mongolica Litv.

1. Introduction
As a traditional material, pine wood has the advantages of wide source, easy processing, etc. It is widely used in packaging, transportation, construction engineering and other fields. In general, pine wood can be divided into softwood and hardwood according to Chinese national standards (GB/T 18513-2001) [1]. However, Russian Pinus sylvestris var. mongolica Litv (air-dry density is 0.5 g/cm³) is different from softwood and hardwood, with different physical and mechanical properties, such as strong stability, not easy to crack. It has important application value in some engineering practices (such as target, etc.). It is clear that the dynamic and static mechanical properties of Russian Pinus sylvestris var. mongolica Litv have important guiding significance for engineering application. However, the current domestic and foreign research on wood is mainly focused on softwood, hardwood and the corresponding wood composite materials, with lacking research on moderate hardness wood. By performing straight grain compression experiments on Pinus elliottii and Corymbia citriodora, it was verified that the modulus of elasticity at different locations are the same and have no effect on material stiffness (Fabiane Salles Ferro et al. 2013) [2]. The shear mechanical properties of the balsa wood's plywood was studied, with the Iosipescu method. It was found that the shear strength and stiffness relate to the balsa wood content and the bond joint. The more balsa wood is consisted and the thinner bond joint is, the higher the shear strength and stiffness is (Michael Osei-Antwi et al. 2013) [3]. With studying the damage mechanics of orthotropic softwood, the factors influencing the tensile
strength in different directions were identified, and the Hankinson, Kollmans, and Ashkenazi failure criteria were compared and analyzed in order to clear which criteria was suitable to describe the behavior of the wood (Jan Galicki et al. 2005) [4]. The experimental and numerical calculations on the Radiata Pine laminate plate was performed with the linear elastic fracture mechanics method. It shows that the fracture mechanics properties (such as fracture energy, stiffness and so on) are related with water content, size, and other factors. And the effects for mechanical properties were analyzed (Manoochehr Ardalany et al. 2012) [5]. The Voigt-Kelvin model was proposed to describe the mechanical response of Norway spruce in dynamic and static compression experiments (Carolina Moilanen et al. 2017) [6].

Russian Pinus sylvestris var. mongolica Litv is an organic anisotropic material, and its mechanical properties in different directions are affected by factors such as moisture content, temperature and defects, and so on. At room temperature, the SHPB experiment on Russian Pinus sylvestris var. mongolica Litv was carried out at high strain rates (1500s-1, 2500s-1, 4000s-1), and dynamic mechanical properties were analyzed. According to the experimental results, the elastic-plastic model based on Hill yield criterion (Referred as Hill model) and the fiber reinforced composite damage model based on Hashin failure criterion (Referred as Hashin model) were selected to describe the dynamic mechanical behavior of Russian Pinus sylvestris var. mongolica Litv at high strain rates among the known constitutive relations. The SHPB experiment process was simulated with the finite element method, and the results were compared and analyzed so as to verify which model is suitable to describe the dynamic mechanical response of the Russian Pinus sylvestris var. mongolica Litv.

2. Material and Methods

2.1. Material
The Russian Pinus sylvestris var. mongolica Litv grown in the extreme cold regions of northern Russia was selected with a diameter of 450 mm. The specimen used in the experiment were obtained with moisture content of 10% to 12.7%, and density of 500 kg/m3. As shown in Figure. 1, the diameter of specimens is 11 mm and the thickness is 5 mm. L, T respectively stands for the specimen taken along the straight grain direction or the transverse grain direction.

2.2. SHPB Experiment
In SHPB experiment, the incident rod length is 1800mm, and the transmission rod length is 1500mm, with both diameter 19mm. And the rod material is 7075 aluminum alloy (Figure. 2). First, the specimen was fixed between the incident rod and the transmitted rod. Then the bullet was pushed to impact the incident rod at high speed by high-pressure gas, forming a stress pulse (incident wave). The pulse propagated among rods and the specimen, divided into reflected wave and transmitted wave because of reflection and transmission. By recording the incident wave, reflected wave, and transmitted wave in the entire device, the corresponding stress-strain curve can be obtained.

2.3. Finite element simulation
ABQAUS 6.14, the nonlinear finite element simulation software was developed by Dassault Simula Corporation. The SHPB experiment procedure was simulated with Hill model and Hashin model (M. Vural et al. 2003; John J. Harrigan et al. 2005; Eric Ruggiero et al. 2014) [7, 8, 9]. During simulation, the 1:1 geometric model was built, with C3D8R selected as the grid. But the size of specimen’s grid
was clearly tinier than rods’ (Figure. 3). On the other hand, to better simulate impact stress, the impulse stress was created.

Figure. 3. Whole geometric models with meshed (a) and the specimen model with meshed (b)

2.4. Equations

2.4.1. Hill yield criterion
The Hill yield criterion is the yield criterion of anisotropic materials, based on the Von-Mises theory. It assumes that the tensile strength is equal to the compressive strength in one direction of the material, and both are not affected by the hydrostatic pressure. Hill yield criterion is expressed as,

$$F(s_{11} - s_{22})^2 + G(s_{11} - s_{33})^2 + H(s_{22} - s_{33})^2 + 2Ls_{12}^2 + 2Ms_{13}^2 + 2Ns_{23}^2 - 1 = 0.$$  \hspace{1cm} (1)

Where: F, G, H, L, M, N are orthotropic material constants.

By the experimental data fitting, the corresponding parameters was obtained, shown in Table 1.

| F  | G  | H  | L  | M  | N  |
|----|----|----|----|----|----|
| 0.83 | 0.1 | 0.08 | 8.00 | 4.10 | 2.5 |

Table 1. Hill criterion related parameters

2.4.2. Improved Hashin damage criterion
The wood is consist of lignin and nature fiber, which can be considered as a natural fiber-reinforced composite material. And the improved Hashin damage criterion, which is mainly applied to composite materials was originally proposed for describing the damage behavior of composite materials. The dynamic mechanical properties of Russian Pinus sylvestris var. mongolica Litv could be described by using improved Hashin damage criterion. The parameters are shown as the Table 2. And the expression for improved the Hashin damage criterion is as follows,

Straight grain direction,

$$\frac{\sigma_{11}^2}{X^2} + \frac{(\sigma_{33}^2 + \sigma_{13}^2)}{S_{11}^2} \geq 1 \quad X = \begin{cases} X_F & \text{for} \quad \sigma_{ij} \geq 0 \\ X_C & \text{for} \quad \sigma_{ij} < 0 \end{cases}$$

Transverse grain direction,

$$\frac{(\sigma_{22}^2 + \sigma_{33}^2)}{Y^2} + \frac{(\sigma_{23}^2 - \sigma_{22}\sigma_{33})}{S_{12}^2} + \frac{(\sigma_{13}^2 + \sigma_{12}\sigma_{13})}{S_{13}^2} \geq 1 \quad Y = \begin{cases} Y_F & \text{for} \quad \sigma_{ij} + \sigma_{ij} > 0 \\ Y_C & \text{for} \quad \sigma_{ij} + \sigma_{ij} < 0 \end{cases}$$

Where: X, Y are respectively strength in straight grain direction, and strength in transverse grain direction.

| $X_F$(MPa) | $X_C$(MPa) | $Y_F$(MPa) | $Y_C$(MPa) | $S_{11}$(MPa) | $S_{12}$(MPa) |
|------------|------------|------------|------------|---------------|---------------|
| 85         | 21         | 2.2        | 4.5        | 13            | 9.3            |
| $\eta_1$   | $\eta_2$   | $\eta_1$   | $\eta_1$   |               |               |
| 0.75       | 0.2        | 0.0004     | 0.022      |               |               |
3. Result and Discussion

3.1. Experiment Results
Under different high strain rates, the dynamic mechanical behavior of the Russian Pinus sylvestris var. mongolica Litv in the straight grain direction was obtained from the stress-strain curves (Figure. 4a). In the straight grain direction, the deformation process could be roughly divided into the elastic phase and the softening failure phase. When the strain increased, the stress increased in the elastic phase until the maximum value was reached, and then the stress decreased rapidly with increasing strain in the softening phase. The relationship between stress and strain in the transverse grain direction was shown in the Figure. 4b. Similar to the straight grain direction, the stress also increased rapidly with strain in the elastic phase. However, there was a distinct plateau area afterwards, instead of the softening failure phase. When the strain increased, the stress slowly fluctuated before decreasing rapidly. On the other hand, the stress and the strain at break both increased with the strain rate in both directions. But the stress value in straight grain direction is significantly more than in transverse grain direction. In summary, the dynamic mechanical properties were affected by the strain rate and the grain direction.

![Figure 4: Stress-strain curves at different strain rates respectively in straight grain direction (a) and in transverse grain direction (b)](image)

As presented in Figure. 5, the ratio of the dynamic initial yield stress to the static yield stress was influenced by the strain rate and grain direction. When the strain rate was less than 2000s-1, the ratio in both directions increased with increasing strain rate, but the growth rate in straight grain direction is obviously more than that in transverse grain direction. When the strain rate is more than 2000 s-1, the stress ratio in both directions hardly varied with the increase of the strain rate. In straight grain direction, the ratio was about 25. And the value in transverse grain direction was approximately stable between 2-2.5. Obviously, the stress ratio in straight grain direction was more than that in transverse grain direction. There are both similarities and differences for the mechanical properties of the pine wood between both directions.

![Figure 5: Curves of yield stress ratio with strain rate in different directions](image)

Note: L, T respectively stands for the straight grain direction and the transverse grain direction.
The failure mode is illustrated in Figure 6. As the strain rate increased, the fracture damage of specimens became more and more serious. Under loaded in transverse grain direction, the lignin part between the fiber was destroyed at the first time. At the same time, the cell wall was damaged and the space was reduced, resulting in the densification. Until the stress limit was reached, the cracks appeared in the fiber direction, and the “matchstick-like” fracture was produced (Figure 6b and Figure 6c). Considering straight grain direction, cracks propagated along fibers direction, and fiber occurred kink, resulting in the dissociation of the fiber and lignin, and broken into “crushed” pieces (Figure 6e and Figure 6f). There was affected with stretch damage and shear damage in the deformation process (Weizhou Zhong et al. 2011) [10].

Figure 6. Under different strain rates, the failure mode of specimens in transverse grain direction (a: 1463 s⁻¹, b: 2633 s⁻¹, c: 4012 s⁻¹), and the failure mode of specimens in transverse grain direction (a: 1567 s⁻¹, b: 2489 s⁻¹, c: 4004 s⁻¹)

3.2. Simulation Results
Specimens’ failure mode was predicted with Hill model and Hashin model at 2500 s⁻¹, as shown in Fig. 7. Compared with the failure mode measured by experiment (Figure 6a and Figure 6c), the failure mode predicted by Hill model was obviously different (Figure 7a and Figure 7b). On the contrary, predictions which were made by Hashin model were consistent with the actual specimens’ deformation (Figure 7c and Figure 7d).

Figure 7. The specimen’s failure mode predicted with Hill model (a and b), and the specimen’s failure mode predicted with Hashin model (c and d)

Note: a and c stand for the transverse grain direction, c and d stand for the straight grain direction

To investigate descriptions which was given for the pine wood by two models, Hill model, and Hashin model, the stress-strain relationship was shown as Figure 8. In terms of Hill model’s results, the curves obtained from simulation are consistent with the experimental curves. While compared the curves of Hill model with the experimental curves, there are difference between two curves in both directions, especially in straight grain direction.
Figure 8. Tress-strain curves obtained with simulating at 2500 s⁻¹

In summary, the fiber-reinforced composite model based on Hashin failure criterion can more accurately describe the dynamic mechanical properties of Russian Pinus sylvestris var. mongolica Litv under high strain rates, with consistent with the experimental results. Relatively speaking, the description made by the elastic-plastic model based on Hill yield criterion is a little bit different from the actual situation.

4. Conclusions

1) The dynamic mechanical properties of Russian Pinus sylvestris var. mongolica Litv are affected by the strain rate and direction, and the initial yield stress and fracture strain increase with strain rate increasing. However, the properties in straight grain direction are more sensitive to the strain rate.

2) The fracture morphology was different between the straight grain and the transverse grain direction. Because of the influence shear stress and tensile stress had, the specimen were broken into ‘crushed’ pieces in straight grain direction. In transverse direction, the breakage fracture occurs was mainly caused by the evolution of cracks along the fiber direction. The shear stress played an important role in the fracture.

3) Compared with the model based on Hill yield criterion, the model based on Hashin damage criterion can more accurately and reasonably describe the response of dynamic mechanical properties of Russian Pinus sylvestris var. mongolica Litv under high strain rate.

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