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FINITE ELEMENT ANALYSIS OF THE FATIGUE BEHAVIOR OF WOOD FIBER CELL WALLS

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The fatigue behavior of the wood fiber cell wall under mechanical treatment in refining was simulated dynamically using a finite element method. The effect of the amplitude and frequency of impacts on the mechanical breakdown of the fiber wall structure was examined. The proposed model of the fiber cell wall was constructed from elementary microfibrils in various orientations embedded in isotropic lignin. The fatigue of the cell wall was simulated under normal refiner mechanical pulping conditions. A cyclic load was applied on the model fiber through a hemispherical grit proposed to be applied on the surface on refiner segments. Changes in the elastic modulus of the cell wall were analyzed to determine the potential for cell wall breakdown. An increase in the amplitude of applied forces and frequency of impacts was found to have a significant influence on the reduction of the elastic modulus of the wall structure. A high frequency of impacts increased the stiffness of the cell wall, but resulted in faster reduction of the elastic modulus. At a lower amplitude of impacts, efficient breakdown of the cell wall using grits was achieved with a high frequency of impacts or a high rotational speed of refiners.

Keywords: Wood fibers; Fatigue simulation; Mechanical breakdown; Elastic modulus; Refining; Grit materials

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INTRODUCTION

The cell wall of wood fibers is a composite viscoelastic structure consisting of cellulosic fibrils surrounded by a matrix of hemicelluloses and lignin. Each fibril consists of about 36 parallel cellulose molecules (Paavilainen 2002). Basically, the cellulosic fibrils are organized into larger units with a diameter of about 5-30 nm known as microfibrils, which are visible in an electron microscope (Alén 2000; Mark 2002; Paavilainen 2002). In the architecture of the fiber cell wall, the microfibril is considered to be an elementary material for the modeling of its structure. Fundamentally, the wall structure comprises two distinct layers: the primary wall and the secondary wall. The primary wall is a thin layer of about 0.05-0.1 μm covering the secondary layer. The secondary wall is a relatively thick layer of about 2-9 μm comprising several sets of helically winding microfibrils (Alén 2000; Mark 2002). This layer is considered to be the most important part of the cell wall, controlling the mechanical properties of fibers.

The secondary wall consists of three layers, i.e., the outermost S1 layer followed by the S2 and S3 layers, respectively. The S1 layer has a crossed microfibrillar structure in which the microfibrils wind around the cell axis with an alternating right-handed helix (S-helix) and a left-handed helix (Z-helix), with an angle of about 50-70°. The thickness of S1 is in the range of 0.1-0.3 μm. The S2 layer is located in the middle of the secondary wall with a right-handed helical orientation of microfibrils. The winding angle is in the range of 5-30° from the cell axis. The average thickness of S2 is about 1-8 μm, and the average volume is in the range of 75-80% of the total volume of the cell wall. Basically, the thickness and the microfibril angle of the S2 layer could be used to determine the strength of pulp fibers. The S3 is the inner layer with a thin wall of approximately 0.1 μm. The microfibrils are oriented in different directions either to the right-handed or left-hand helices with an angle of 60-90° from the cell axis (Alén 2000; Mark 1967; Mark 2002; Paavilainen 2002).

The complicated structure of the fiber cell wall and its mechanical properties could be theoretically described by using a mathematical approach. Several mathematical models have been employed for building the cell wall structure and predicting its mechanical properties. For example, Cave (1976) and Barber (1968) introduced a model of the fiber cell wall to determine the shrinkage of wood fibers. The model showed the effect of thickness variation in the S2 layer on the shrinkage of fibers. Salmén and de Ruvo (1985), and Xu and Liu (2004) presented a model focusing on the fibril angle and the effects of the thickness of the S2 layer on the elastic properties of wood fibers. Yamamoto and Kojima (2002) modified Barber's model (Barber 1968) by taking into account the compound middle lamella, S1 and S2 layers, and the moisture content of the cell wall to determine the mechanical properties of wood fibers.

The deformation of wood fibers under mechanical treatment behaves like a combination of an elastic spring and a viscous flow (Salmén and Hagen 2002). The response to the treatment is greatly affected by temperature, moisture, and time under load. The hemicelluloses and the amorphous celluloses of the water-saturated cell wall are softened at about 20 °C. The lignin is softened at about 90 °C, and at a higher temperature when the frequency of impact increases (Salmén 1987; Salmén and Hagen 2002; Salmén et al. 1999). In mechanical pulping, the fibers are subjected to a cyclic load. This causes the viscoelastic, and consequently, plastic deformations on the fiber cell wall to be repeated, with the cell wall structure finally reaching its breaking point (Salmén et al. 1999; Salmén and Fellers 1982).

Regarding mechanical pulping processes, the breakdown of the wall structure is the main mechanism in developing the fibers to a desired quality for papermaking. In refiner mechanical pulping, the pulp fibers are developed in two stages: the separation of fibers from the wood matrix, called the defibration stage, and the manipulation of the separated fibers to desired quality, known as the fibrillation stage (Karnis 1994; Salmén et al. 1999). These processes consume considerable amounts of electrical energy, while according to theoretical calculations the consumption of energy to develop pulp fibers should be relatively low (Koran 1980; Lamb 1962; Marton et al. 1980; Salmén and Fellers 1982). In grinding processes, the pulp fibers are developed under the treatment of pulpstone grits. This process consumes about 40% less electrical energy than the production of refiner mechanical pulp (Salmén et al. 1999).

It has been proposed that a grinding technique could be applied to mechanical pulp refining for reducing the energy consumption. Directing energy sharply to a small area of the fiber cell wall by using grit materials could provide a means to break down the cell wall structure efficiently. According to laboratory tests (Somboon et al. 2007; Somboon and Paulapuro 2007), application of grit materials to disrupt the wall structure of high-freeness TMP fibers can promote the development of pulp fibers and decrease the energy consumption in the fibrillation stage by up to 30% with less negative impact on fiber and paper properties. To allow further development of refiner segments that incorporate grit materials, this technique needs to be tested at an industrial scale, and a good understanding is needed of the mechanism governing the breakdown of the fiber cell wall when using grit materials under normal refining conditions.

In this study, a finite element analysis was conducted to gain a deeper understanding of the mechanical breakdown of the softwood fiber structure. A model fiber was built, and its fatigue behavior under grit treatment was simulated to examine the breakdown of the wall structure. In this simulation, the compression force was proposed to constitute the load in the plate gap. The cyclic compression was directed to the model fiber through the grit materials proposed to be applied on the surfaces of refiner segments.

EXPERIMENTAL

The modeling of the softwood fiber cell wall and simulation of the fatigue behavior of softwood fibers were carried out using a finite element method with the ABACUS program. The model fiber was built from the elementary microfibrils winding around the cell axis and using the lignin as a binder. The fatigue simulation was performed under normal refiner mechanical pulping conditions. The energy was directed to the model fiber through the grit material proposed to be applied on the surface of refiner segments (Somboon et al. 2008).

The structure of the cell wall was built from elementary microfibrils, proposed to have a cylindrical shape and varying orientation, embedded in a homogeneous and isotropic lignin. The constant data used for constructing the model fiber are summarized in Table 1. In this proposed model, the design of the cell wall structure was modified from Yamamoto and Kojima’s wood fiber model (Yamamoto and Kojima 2002). The fiber was formed in a circular cylinder with a diameter of about 30 μm, approximately in the range of softwood tracheids. The cell wall was proposed to comprise S1 and S2 layers. The S1 layer was composed of circular microfibrils, while the S2 layer consisted of a helical orientation of microfibrils, as shown in Fig. 1. The effect of the chemical composition of each layer on its mechanical properties was neglected. After the modeling, the elastic moduli of the model fiber and its S1 and S2 layers were analyzed.

The fatigue of the fiber cell wall was dynamically simulated based on the ABAQUS/Explicit code. The Kelvin-Voigt viscoelastic model and coupled thermal-stress analysis were employed for the simulation. The amplitude of cyclic load applied to the model fibers was estimated according to experimental measurements along the radius of segments of a 65” single-disc refiner (Backlund et al. 2003). At the inner zone (the center to the radius of about 0.7 m), the applied load was about 50 kN/m^2, and the outer zone was about 100-150 kN/m^2. The frequencies of impacts were generated by the simulation program. The data used for simulation are shown in Table 2. The cyclic stress was directed to the model fiber through hemispherical grits assumed to be applied on the surface of refiner segments (Somboon et al. 2008). The grit size was approximately in the range of number 46 pulpstones grits with a diameter of 297-420 μm used in groundwood mills (Liimatainen et al. 1999). The fatigue was assumed to take place across the model fiber (Fig. 1). The relative changes in the elastic modulus affected by heat generation were based on shock wave measurement (Björkqvist et al. 1999). The local temperature rise due to the adiabatic heating was automatically calculated from the inelastic energy based on the simulation program, which assumed that no energy was lost in the fatigue simulation. The fatigue of the cell wall was applied for approximately 2 seconds according to the retention time of the pulp in the refiner (Salmén et al. 1999). The hysteresis response of the fiber cell wall and the changes in elastic modulus were examined.

Table 1. Data for Modeling the Softwood Fiber Cell Wall Structure.

Cell wall components	Values	References
Microfibrils		
Diameter	20 nm	Alén (2000)
Longitudinal elastic modulus	137 GN/m^2	Mark (1967), Sakurada et al. (1962)
Transverse elastic modulus	15.7 GN/m^2	Mark (1967), Cave et al. (1969)
Shear modulus	3.8 GN/m^2	Mark (1967), Cave et al. (1969)
Poisson ratio	0.1	Mark (1967), Cave et al. (1969)
S1 layer		
Thickness of the layer	0.2 μm	Alén (2000)
Packing ratio of microfibrils	0.75	Alén (2000), Cave (1976)
Microfibril orientation	Circular shape	Yamamoto et al. (2002)
S2 layer		
Thickness of the layer	2 μm	Alén (2000)
Packing ratio of microfibrils	0.75	Alén (2000), Cave (1976)
Microfibril angle, S-helix	15°	Alén (2000), Paavilainen (2002)
Lignin (isotropic)		
Elastic modulus	4.1 GN/m^2	Salmén et al. (1985)
Shear modulus	1.5 GN/m^2	Salmén et al. (1985)
Poisson ratio	0.33	Salmén et al. (1985)

Table 2. Data for Fatigue Simulation under Refining Conditions.

Parameters	Values	References
Applied cyclic load	50, 100, 150 kN/m^2	Backlund et al. (2003)
Impact frequency	25, 50, 100 cycles /sec	estimated
Fatigue period	2 seconds	Miles (1990), Miles (1991)
Temperature of cell wall at the initial stage	80 °C	Salmén et al. (1999)
Thermal conductivity of saturated cell wall	0.489 W/m K	Gu and Hunt (2007)
Specific heat of saturated cell wall	2.256 J/kg K	Gu and Hunt (2007)

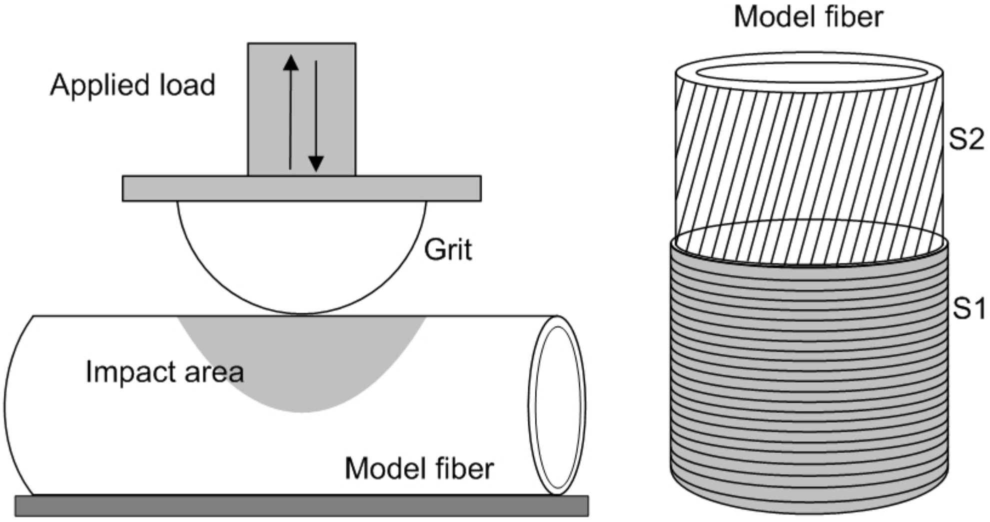

Fig. 1. Schematic of fatigue simulation under cyclic load applied on the model softwood fiber through a hemisphere grit.

RESULTS AND DISCUSSION

Figures 2 and 3 show the model fiber and its response to the applied load that was simulated using the ABAQUS program. Table 3 shows the elastic modulus of fiber cell walls calculated from the local stress and strain distributed in their structure. The longitudinal elastic modulus of the model fiber and S2 layer were about 68-73 GN/m^2, while that of the S1 layer was about 25 GN/m^2. The transverse elastic moduli of the model fiber, and S1 and S2 layers were about 25-30 GN/m^2. These calculated results are within the range of other previous studies (Cave 1976; Salmén and de Ruvo 1985; Xu and Liu 2004; Yamamoto and Kojima 2002). According to the results, the strength properties of the model fiber seem to be dominantly controlled by the S2 layer.

Table 3. Elastic Modulus of the Model Softwood Fibers Calculated from the Stress-Strain Curve.

Elements	Longitudinal elastic modulus	Transverse elastic modulus
S1 layer	24.80 GN/m^2	24.69 GN/m^2
S2 layer	73.04 GN/m^2	30.22 GN/m^2
Fiber	68.78 GN/m^2	29.76 GN/m^2

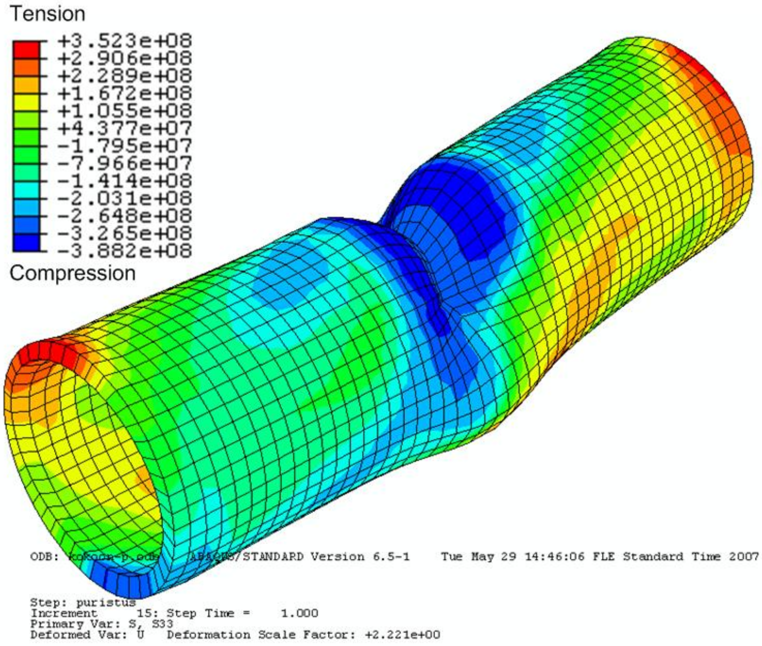

Fig. 2. Local stress distribution in the wall structure under compression load in the radius direction of the model fiber where (+) is a tension distribution and (-) is a compression distribution.

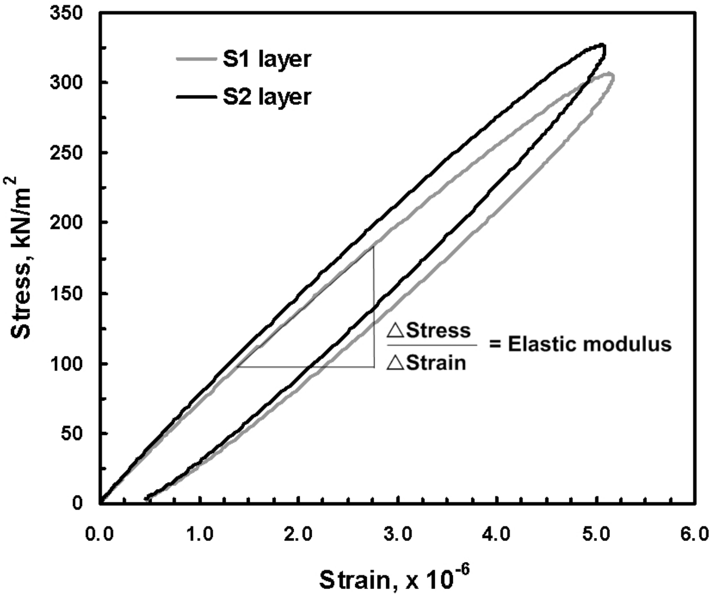

Fig. 3. Local stress and strain curve of the cell wall under cyclic compression across the model fiber.

Figure 4 shows the hysteresis of the model cell wall under fatigue simulation determined at a middle point in the thickness direction of each layer. The hysteresis loops were used to calculate the changes in elastic modulus and examine the fatigue behavior of the fiber cell wall. The reduction of the elastic modulus was proposed to indicate the potential for breaking down the fiber wall structure in the refining process.

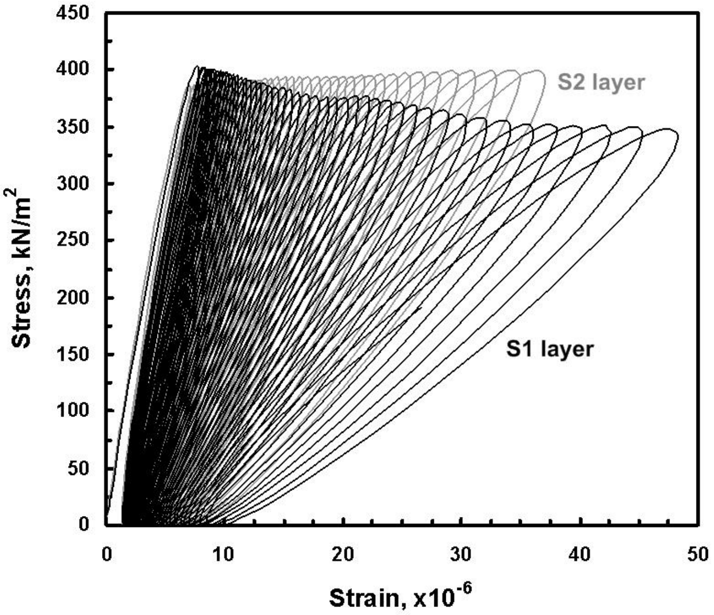

Fig. 4. Hysteresis loops of the S1 and S2 layers measured under a cyclic compression of 150 kN/m^2 and an impact frequency of 25 cycles/second.

Figures 5 and 7 show the dynamic changes in the modulus of the S1 and S2 layers under various frequencies of applied cyclic load. The results showed that the elastic modulus of the model fiber was significantly affected by the frequency of impacts. Based on the ABAQUS program, at a high frequency of cyclic load simulated under 100 cycles/second (Hz), the transverse elastic modulus was about 65 GN/m^2, while at a normal loading, the modulus was about 30 GN/m^2 (Table 3). In the fatigue simulation, when increasing the impact frequency of the grits applied on the model fiber from 25 to 100 cycles/second, the elastic modulus of the wall structure (during its evaluation under dynamic condition) was found to be higher by about 10-15 GN/m^2 (Fig. 5). This clearly shows that the fiber cell wall becomes stiffer at higher impact frequency. However, this condition allowed fast reduction of cell wall strength, indicating that efficient breakdown of the wall structure could be achieved. In addition, the impact frequency was found to play a more important role in the reduction of the elastic modulus, where the fatigue was applied under a lower amplitude of applied load, as shown in Fig. 7.

The effects of the amplitudes of applied loads on the changes in the modulus of the cell wall treated by the grit are shown in Figs. 6 and 7. The applied loads were simulated at 50-150 kN/m^2. There were clear differences in the effects of the grit treatment between the inner zone and outer zone of refiner segments on the fatigue of the cell wall. The inner zone of segments with the applied load of 50 kN/m^2 yielded a significantly lower reduction of the modulus in comparison to the outer zone with the applied load of 150 kN/m^2. However, when the fatigue was simulated at a higher frequency of impact, there were smaller differences in the effect of the grit treatment in the segment zone.

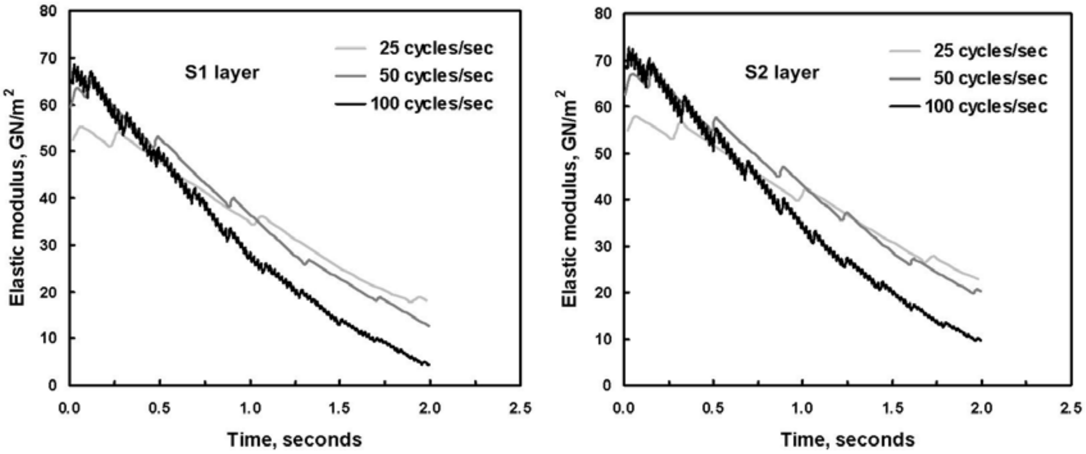

Fig. 5. Dynamic transverse elastic modulus of S1 and S2 layers during fatigue simulation under a compression of 100 kN/m^2 and various impact frequencies.

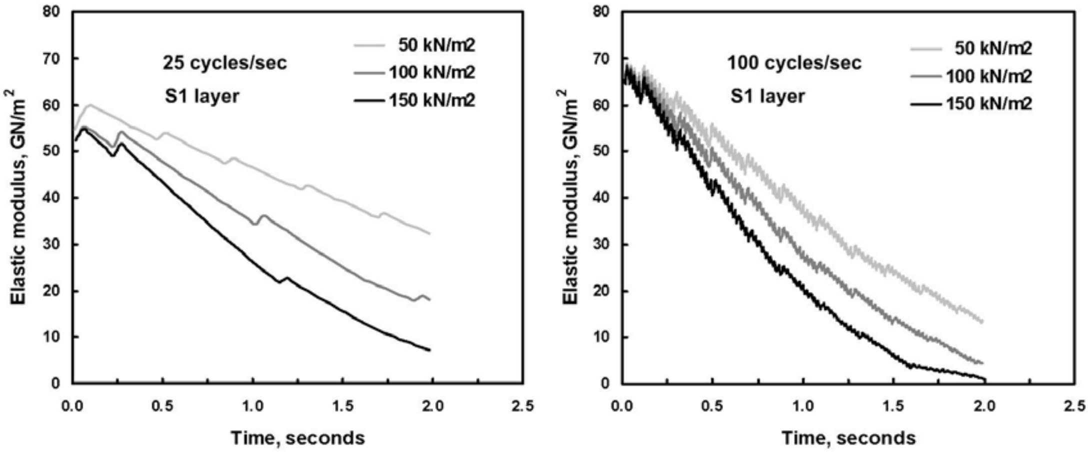

Fig. 6. Dynamic transverse elastic modulus of S1 layer during fatigue simulation under various levels of applied compression. Impact frequencies were controlled at 25 cycles/second (left) and 100 cycles/second (right).

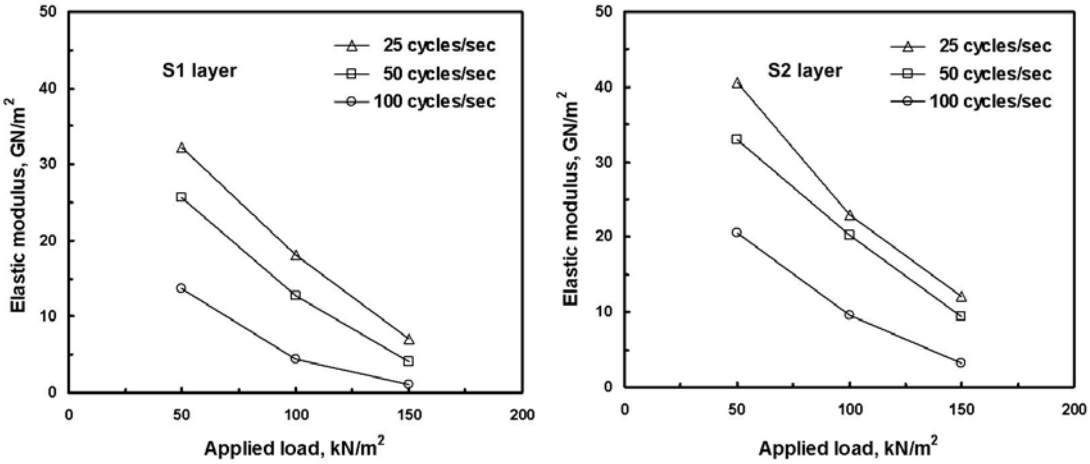

Fig. 7. Elastic modulus of S1 and S2 layers under fatigue of 2 seconds simulated under various amplitudes and impact frequencies.

Based on the simulated results, the inner S2 layer dominantly controls the mechanical properties of wood fibers. This implies that the breakdown of the S1 layer and partly the S2 layers can be achieved with less negative impact on the strength properties of the pulp fibers. Thus, it is possible to apply grits to disrupt the outer surfaces of fibers during the initial stage of refining as a means to enhance the development of fibers in the subsequent treatment. In mechanical pulp refining at industrial scale, it is difficult to apply the grits on the surfaces of the segments, because the operating clearance between the refiner discs is very narrow. However, according to the geometry of refiner segments, the inner zone has a steeper taper, allowing a proper gap clearance to bond the grits on its surfaces (Somboon et al. 2008), but the force generated in this zone is very low. Based on the results of the simulation, if the grits are applied on the inner zone of segments, the refining should be performed under high impact frequency to produce efficient breakdown of the fiber cell wall.

Because of the viscoelastic nature of wood, the strength of the cell wall is fundamentally dependent on the frequency of the mechanical treatment. According to Salmén (1987), the fatigue of wood takes place faster at higher temperature and lower frequency. In the grinding process, a reduction of the rotational speed of the pulpstone lowers the energy consumption in the mechanical development of pulp fibers (Lucander et al. 1985). In contrast, in the refining process, an increase in the rotational speed allows faster development of fibers and lower energy consumption (Miles 1991; Nurminen 2001; Sundholm et al. 1988). According to Sundholm et al. (1988), changing the rotational speed of the refiner has the greatest effect on the impulse force of the bars, whereas a change in frequency has only a small influence on the strength of the cell wall.

The simulation clearly shows the effect of the amplitude and frequency of the applied load on the dynamic changes in the elastic modulus during refining. Increased impact frequency causes an increase in the calculated instantaneous elastic modulus of fibers at the beginning of the refining, corresponding to the nature of the wood, but speeds up the reduction of the elastic modulus of the fiber cell wall. Accordingly, the operation of refiners at a high rotational speed can be assumed to allow a higher impulse force and a greater number of impacts, allowing faster mechanical breakdown of wood fibers and reduced energy consumption.

CONCLUSIONS

1. The modeling of wood fibers and fatigue simulation in refiner mechanical pulping can be accomplished with the aid of finite element analysis using the ABAQUS program.
2. Based on hemispherical grits proposed to be applied on the surface of refiner segments, an increase in the applied load and impact frequency has a positive impact on the reduction of the elastic modulus of the fiber cell wall, indicating improved potential for disrupting the wall structure.
3. An increase in impact frequency increases the elastic modulus of the cell wall calculated at the beginning of the force applied on the model fiber, but allows faster reduction of the modulus under the fatigue.
4. When a lower force is applied to the model fibers, a higher impact frequency is required to improve the potential for mechanical breakdown of the fiber cell wall.

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