A RAPID METHOD TO ASSESS VISCOELASTIC AND MECHANOSORPTIVE CREEP IN WOOD

Alireza Kaboorani
Research Scientist
E-mail: Alireza.kaboorani.1@ulaval.ca

*Pierre Blanchet**
Professor
Département des sciences du bois et de la forêt
Faculté de foresterie, de géographie et de géomatique
Université Laval
2425 rue de la Terrasse
Québec (Québec), G1V 0A6, Canada
E-mail: pierre.blanchet@sbf.ulaval.ca

Aziz Laghdir
Research Scientist
Service de recherche et d'expertise en transformation des produits forestiers (SEREX)
25 rue Armand-Sinclair, porte 5
Amqui (Québec) G5J 1K3, Canada
E-mail: aziz.laghdir@serex.qc.ca

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Abstract. This study presents an alternative method to measure the viscoelastic and mechanosorptive creep of wood using a dynamic mechanical analyzer (DMA). Measurements were made on sugar maple wood specimens in the radial and tangential directions in different RH conditions. Viscoelastic creep measurements showed that DMA can detect effects of time, RH, load level, and wood direction on wood creep. With the applied stress levels (5, 25, 35, and 45%), wood exhibited linear viscoelastic behavior. DMA also demonstrated its value in measuring mechanosorptive effect. The mechanosorptive effect was observed as RH changed during the loading period, resulting in very high deflections. In both viscoelastic and mechanosorptive creep measurements, creep proved to be greater in the tangential direction than in the radial direction. The results of this study demonstrated that a DMA can be a rapid and accurate tool to predict the time-dependent behavior of wood under load.

Keywords: Viscoelastic creep, mechanosorptive creep, dynamic mechanical analyzer, sugar maple, relative humidity, radial and tangential directions.

INTRODUCTION

Deflection under load is the main design parameter for timber, playing an important role in the long-term performance of wood structures. Deflection is the combined effect of two factors, elastic deflection and creep. The former can be determined easily and rapidly with a stress-grading machine. Creep is a collective term that covers all deflection occurring when a load increase is halted, ie deformation under constant load.

Wood is classified as a viscoelastic material because it possesses properties that are common to both perfect solids and liquids. Because of its viscoelastic nature, wood is subject to creep and relaxation. In normal operating conditions of stress, extreme temperatures, and changing moisture content, it is susceptible to creep, which can lead to serviceability and strength decrease problems (Van Der Put 1989). Creep and relaxation are used to study time-dependent relationships

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* Corresponding author

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between stress and strain in wood. The strain–time curve of wood under a compressive load can be divided into four parts: initial elastic deformation, viscoelastic deformation, final elastic springback, and time-dependent springback or creep recovery. Studies on creep behavior of wood have been conducted for decades (Kingston and Armstrong 1951; Clouser 1959).

A particular characteristic of wooden load-bearing elements is that their deformations strongly depend on RH and temperature changes in the surrounding air. Under constant climatic conditions, total deformation after a given time period mainly consists of deformation caused by mechanical load and normal viscous creep, in which the intensity of normal creep depends on constant temperature and RH conditions. However, when wood is exposed to moisture content changes, it exhibits much greater deformation than wood kept under constant climate conditions. The simultaneous action of load and changing wood moisture content is called the mechanosorptive effect. This effect is very important in structural applications, in which it increases beam deflection and transverse deformation in bearing zones of wooden beams exposed to climate variation. Mechanosorptive creep was independently reported in the literature for wood (Armstrong and Kingston 1960; Armstrong and Christensen 1961) in the late 1950s and early 1960s. The first reported observation of mechanosorptive creep in solid wood was made in 1960 by Armstrong and Kingston (1960). The mechanosorptive effect has also been found in most wood-based composite materials such as particleboard and fiberboard (Martensson 1994; Kang and Park 2003). Mechanosorptive creep plays a significant role in timber drying. It helps release shrinkage stress and avoids surface checking (Perré and Olek 2007). The mechanisms of mechanosorptive creep are highly contentious topics, and there is no widely accepted explanation.

The main technique for the study of creep is creep measurement itself. Wood specimens are usually loaded in bending because of the ease of achieving sufficient precision and because it is assumed that normal longitudinal swelling and shrinkage can be ignored (although pseudocreep and recovery can cause difficulties). Despite the fact that the effects of moisture and load level on creep are well known and documented, creep measurement remains a challenge. The current technique used to measure creep is time-consuming (up to years) and needs large amounts of material. Furthermore, wood specimens used for creep measurements should be free of any defect, which is difficult to achieve, especially in large wood members such as beams. Controlling temperature and humidity is another challenge in measuring creep, especially if the measurement is conducted on a full-sized scale. Hence, alternative techniques are needed to overcome these difficulties. The introduction of a dynamic mechanical analysis (DMA) instrument capable of controlling humidity has made it possible to conduct small-scale measurements of creep in wood in different humidity conditions. During the past four decades, DMA has enhanced our understanding of the mechanical properties of polymers and their composites with different fillers and interactions among them. The earliest DMA studies on wood were conducted in the 1960s with a torsional pendulum apparatus (Becker and Noack 1968).

In this study, DMA was used to measure creep of wood under constant and variable moisture contents. Using a DMA machine to measure creep of wood offers several advantages compared with traditional creep measurement methods. Wood is a biological material with large variability. Using small specimens makes it easier to minimize the effects of natural defects such as knots, irregular grain, and pitch pockets. Because DMA testing requires only small specimens, the effects of variability on wood creep can be kept to a minimum. Also, because the measurements are conducted in a small chamber, it is much easier to control and monitor temperature and humidity compared with traditional methods. Also, the time needed to conduct the creep test is shorter, and load and deflection can be precisely controlled and scrutinized. Precision is very important because distinguishing differences between total creep and its separate components is essential to study the creep phenomenon in wood. Another advantage of using DMA in creep measurement is that the moisture content gradient through the thickness of the wood is kept to a minimum because the specimens are very thin.

The main objective of this study was to develop a new method to measure creep in sugar maple wood and match the fluctuations in creep with the fluctuations reported in the literature. Such a development would provide engineers with a rapid and trustworthy tool to measure wood creep. In this study, the creep of wood in the radial and tangential directions was measured in constant temperature and humidity conditions (viscoelastic creep) and also in constant temperature and variable humidity conditions (mechano-sorptive creep).

MATERIALS AND METHODS

Wood specimens used for this study were selected from wood blocks that were free of any defects, ie with perfectly straight grain and growth ring orientation. The blocks were selected visually and dried down to constant mass in a dryer at 54.4°C and 70.9% RH. The blocks were then conditioned at 20°C and 65% RH. When equilibrium moisture content (EMC) was achieved, the specimens were cut to final sizes, ie 40 mm long × 5 mm wide × 1 mm thick. Preparation of wood specimens for the two directions is shown in Fig 1. Prior to creep measurements, the specimens were conditioned for 1 wk to the RH and temperature of the creep tests (30°C and 37.0, 67.0, and 83.9% RH). Three tests were run for each set of stress and RH levels.

Creep Measurement

Creep was measured with a DMA instrument (Q800 DMA; TA Instruments, New Castle, DE). This instrument is capable of controlling humidity, temperature, and load. The creep test was conducted with three-point bending.

Before creep measurement, static tests were carried out to determine the modulus of elasticity (MOE) and modulus of rupture (MOR) of the specimens, which were used to design the stress levels in the creep measurements. The specimens were loaded to failure in a three-point bending mode. MOE and MOR were measured for specimens with different EMC: 7, 12, and 17% (similar conditions as creep tests). To reach the targeted EMC, the specimens were conditioned to 30°C and 37.0, 67.0, and 83.9% RH for 1 wk.

In this study, creep testing was conducted under both constant and variable RH. Viscoelastic creep was determined in constant conditions of temperature and RH. During creep measurement in variable conditions, the temperature did not change but RH varied. Nonlinear interaction of applied stress and changing moisture content in wood leads to a substantial increase

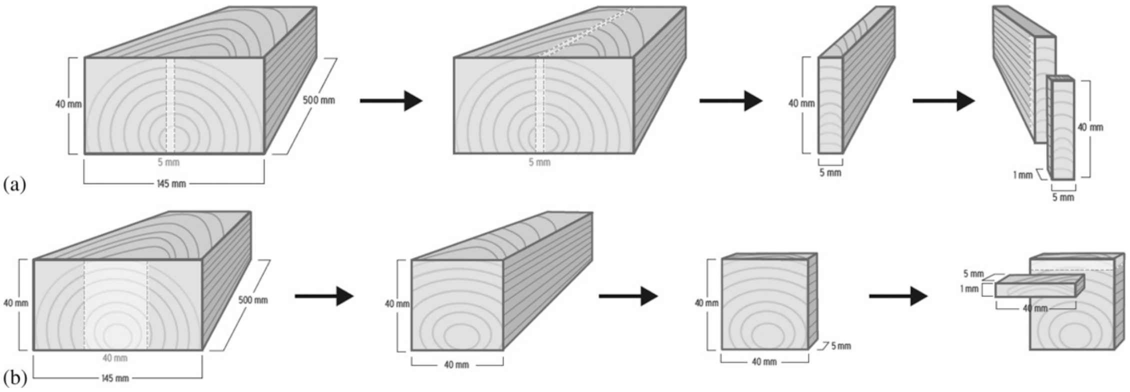

Figure 1. Wood sampling: (a) radial direction; (b) tangential direction.

in creep, which is referred to as the mechanosorptive effect.

Viscoelastic Creep

Viscoelastic creep measurements were carried out at three constant RH levels (37, 67, and 83.9%) at 30°C. Stress levels applied during testing were set at 5, 25, 35, and 45% of MOR at the corresponding RH levels. Both loading and recovery times were 60 min. Instantaneous deflection (δi), total deflection (δt), elastic deflection (δe), viscoelastic deflection (δv), and plastic deflection (δp) were determined for all specimens (Fig 2). Instantaneous deflection (δi) was determined at the time of loading, and total deflection (δt) was determined before unloading. Elastic deflection (δe) was measured at the time of unloading. Viscoelastic deflection (δv) and plastic deflection (δp) were determined at the end of the tests. Plastic deflection (δp) is a permanent deflection of wood. Viscoelastic deflection (δv) is the difference between total deflection (δt) and sum of the elastic and plastic deflections.

Mechanosorptive Creep

Mechanosorptive creep measurements were designed in five phases, including a wetting and drying cycle (Fig 3). In each phase, RH changed to simulate the effects of humidity on creep of wood in service. During all phases, the temperature remained constant at 30°C. In Phase 1, specimens were conditioned at 67% RH for 2 h. In Phase 2, RH increased from 67 to 83.9%, raising EMC from 12 to 17%. Specimens were kept at 83.9% RH for 5 h. In Phase 3, RH was decreased from 83.9 to 37%, causing the wood to dry down to 7% EMC. The specimens were maintained at 37% RH for 5 h. In Phase 4, RH was raised from 37 to 67%, raising wood EMC from 7 to 12%. Specimens were kept at 67% RH for 5 h. In Phase 5, unloading and recovery took place for 2 h. The stress level in the mechanosorptive creep test was variable at 5, 10, and 15% of MOR.

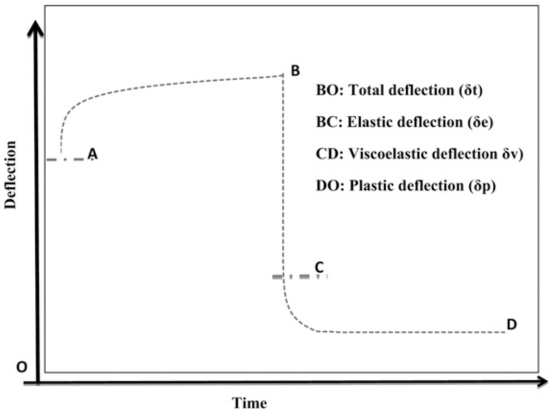

Figure 2. Total creep and its three components in viscoelastic creep measurements.

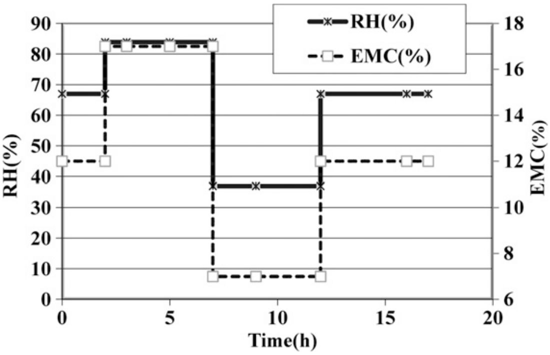

Figure 3. Equilibrium moisture content (EMC) and RH pattern change during mechanosorptive creep measurements.

Statistical Analyses

A one-way analysis of variance model was used to study the effect of RH on the creep of wood at different RH. The GLM procedure of SAS software, SAS/STAT® 9.2 (SAS Institute Inc 2008), was used, and pairwise comparisons were then made using protected Fisher's least significant difference.

RESULTS

Static Tests

MOR is an accepted criterion of strength, although it does not reflect true stress because the formula by which it is calculated is valid only within the

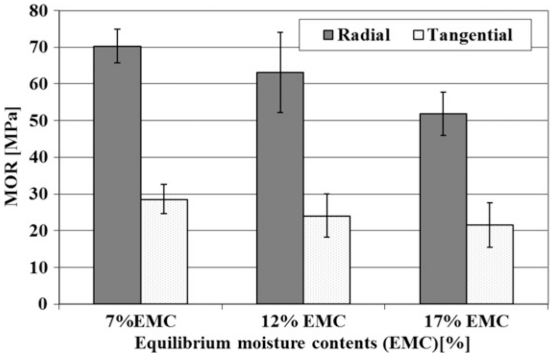

Figure 4. Modulus of rupture (MOR) values at different equilibrium moisture contents (EMCs).

elastic range. MOR reflects the maximum load-carrying capacity in bending of a specimen and is proportional to the maximum moment borne by the specimen. Figure 4 shows MOR of wood specimens in the radial and tangential directions at different RH levels. In both directions, an increase in RH clearly lowered the MOR of the wood. Raising the RH from 37 to 83.9% decreased MOR by more than 30%. Wilson (1932), Drow (1945), Sulzberger (1953), Leont'ev (1960), and James (1964) reported that the bending strength of wood decreases as RH increases. As can be seen in Fig 4, radial MOR was higher than tangential MOR. The difference is attributed to the orthotropic nature of wood, mechanical properties being different in the two directions.

MOE of wood was also influenced by RH changes (Fig 5). As RH increased, MOE decreased. In both directions, RH changing from 83.9 to 37% increased MOE by almost 50%. Kadita et al (1961), Schneider (1971), Bodig and Jayne (1982), Gerhards (1982), Ostman (1985), Conners and Medvecz (1992), and Moutee et al (2010) also documented that wood MOE was inversely affected by moisture content. As shown by the results, moisture lowered strength and elasticity values. The negative effects are explained by cell wall swelling, whereby less cell wall material per unit area is available. More importantly, when water penetrates the cell wall, it weakens the hydrogen bonds responsible for holding together the cell wall (Boutelje 1962).

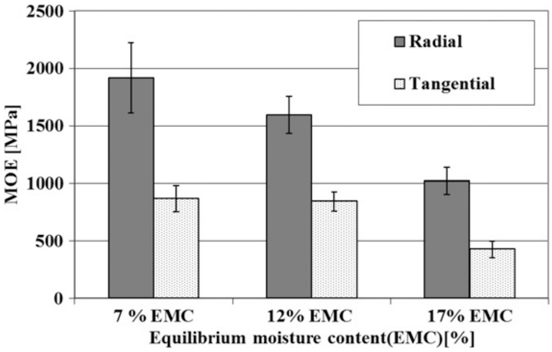

Figure 5. Modulus of elasticity (MOE) values at different equilibrium moisture contents (EMCs).

As Fig 5 shows, radial MOE is greater than tangential MOE. This is explained by the fact that the ray cells oriented in the radial direction act as stiffening ribs. Also, in the radial direction, cell walls have pits and distorted cellulose microfibrils from the longitudinal direction, which can contribute higher transverse stiffness to radial cells (Backman and Lindberg 2001).

Creep

Viscoelastic creep in the radial direction. Figure 6 shows results of creep tests for the radial direction conducted at 12% EMC for different stress levels (5, 25, 35, and 45%). Instantaneous deflection and total deflection increased

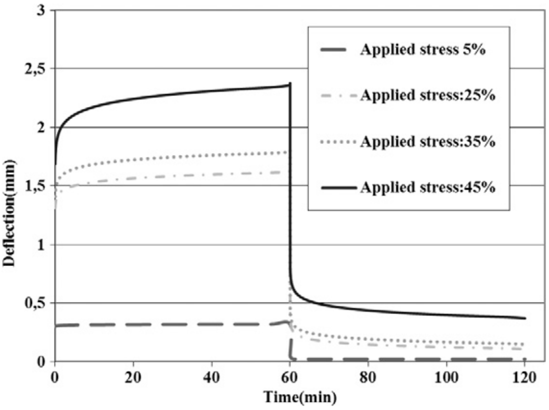

Figure 6. Total deflection during loading and recovery periods at 12% equilibrium moisture content (EMC) (in viscoelastic creep measurements) in the radial direction.

as the applied stress was raised. The deflection increase was more prominent when the stress level increased from 5 to 25%. The values of deflection at different stages, loading, and recovery periods are summarized in Table 1. The absolute values of elastic deflection, viscoelastic deflection, and plastic deflection all increased as applied stress increased. However, the proportion of elastic deflection in total deflection decreased as the applied stress increased. For example, although a stress level increase from 5 to 45% led to higher absolute values of elastic deflection and total deflection (from 0.27 to 1.57 and from 0.32 to 2.37, respectively), the proportion of elastic deflection in total deflection decreased (from 0.84 to 0.66). An opposite trend was observed for plastic deflection. Both the absolute values of plastic deflection and their proportion in total deflection increased with increasing applied stress. Explaining changes in the proportion of viscoelastic deflection in total deflection is complex. An increase in applied stress from 5 to 25% caused a major rise in the proportion of plastic deflection but further increases (from 25 to 35 and 45%) decreased it. On the whole, as applied stress increased, plastic deflection played a more important role in shaping total deflection.

Findings of this research on the effects of time and applied load on wood creep were similar to the findings of past research (Kingston and Armstrong 1951; Clouser 1959; Pentoney and Davidson 1962; Szabo and Ifju 1970; Bodig and Jayne 1982; Gerhards 1985, 1988, 1991). Gerhards (1985) measured deflections in Douglas-fir 2 × 4 beams at three different load levels for up to 220 days. He found that the ratio of elastic deflection to total deflection decreased with time and stress level.

Table 1. Total deflection values and their three components at 7, 12, and 17% EMC for the radial direction.[a]

Applied stress (%)	Total deflection δt (mm)	Elastic deflection δe (mm)	Viscoelastic deflection δv (mm)	Plastic deflection δp (mm)
		7% EMC		
5	0.26	0.21	0.04	0.01
	(10.17)	(17.16)	(22.91)	(20.00)
25	1.46	1.28	0.12	0.06
	(11.04)	(8.99)	(16.39)	(42.03)
35	1.76	1.4	0.19	0.17
	(13.60)	(21.90)	(13.03)	(67.11)
45	2.07	1.45	0.36	0.26
	(7.59)	(14.98)	(7.87)	(34.16)
		12% EMC		
5	0.32	0.27	0.03	0.02
	(15.87)	(11.18)	(41.69)	(39.28)
25	1.63	1.28	0.25	0.1
	(14.71)	(11.09)	(28.28)	(27.03)
35	1.80	1.37	0.29	0.14
	(9.95)	(10.42)	(7.52)	(13.75)
45	2.37	1.57	0.43	0.37
	(11.84)	(4.92)	(24.52)	(26.76)
		17% EMC		
5	0.34	0.25	0.07	0.02
	(18.08)	(19.39)	(23.28)	(52.14)
25	1.80	1.31	0.38	0.11
	(10.00)	(11.88)	(15.91)	(27.06)
35	2.40	1.42	0.54	0.44
	(7.73)	(7.09)	(8.50)	(12.94)
45	3.30	1.83	0.69	0.78
	(6.18)	(9.23)	(3.23)	(7.39)

[a] Value given in parentheses is coefficient of variation (%).
EMC, equilibrium moisture content.

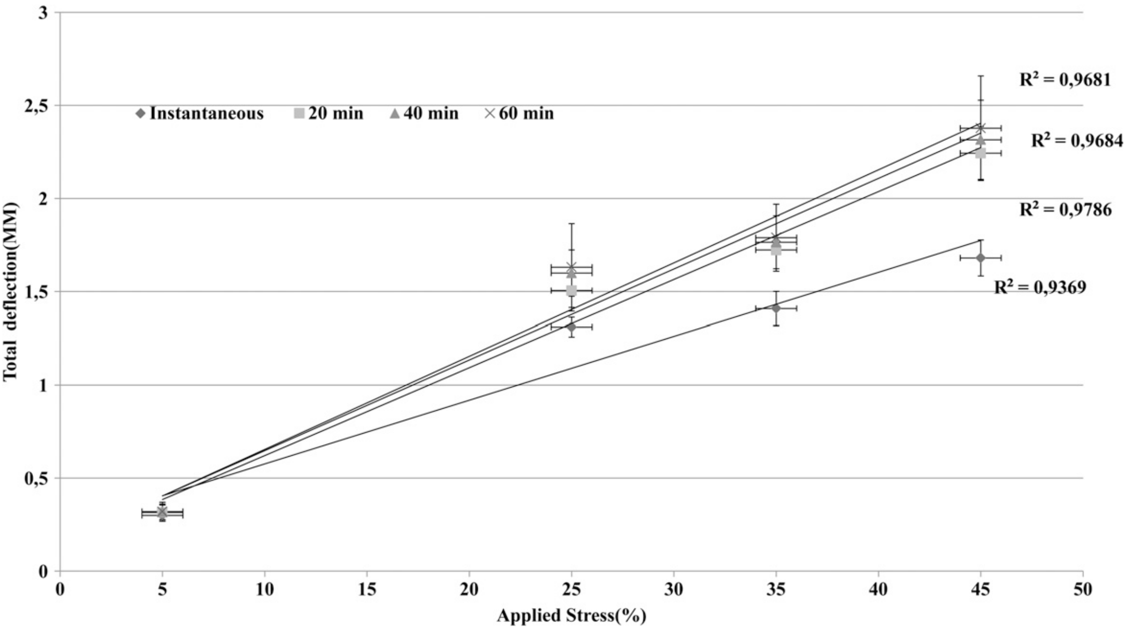

Figure 7. Relationship between stress and total deflection during loading period at 12% equilibrium moisture content (EMC) in the radial direction.

To provide a better view on the effects of stress level on total deflection, the relationship between them is shown in Fig 7. The linear proportionality of applied stress and total deflection proved the linear viscoelastic behavior of sugar maple wood in bending tests for a stress level below 45%. Segovia et al (2013) also indicated that at stress below 45% of bending strength, sugar maple wood showed a linear viscoelastic behavior in the creep test.

Several researchers studied the linear viscoelastic behavior of wood in creep tests (Drow 1945; Schniewind 1968; Keith 1972; Schaffer 1972; Nielsen 1984; Le Govic et al 1989; Rice and Youngs 1990; Navi and Heger 2005; Moutee et al 2010). Schniewind (1968), Keith (1972), Nielsen (1984), Moutee et al (2010), and Segovia et al (2013) found that wood behaves in a linear viscoelastic manner for loads below 45% of maximum. In contrast, Schaffer (1972) described the behavior of wood as nonlinear regardless of load level. He stated, however, that at low stress, linear behavior provided a good approximation. Le Govic et al (1989) set a limit for linear behavior at 30-35% of the short-term strength for bending and up to 50% of the short-term strength for tension.

The results of creep tests conducted at 7% EMC at the four stress levels for the radial direction are shown in Fig 8. The response of wood to the loads was very similar to that at 12% EMC,

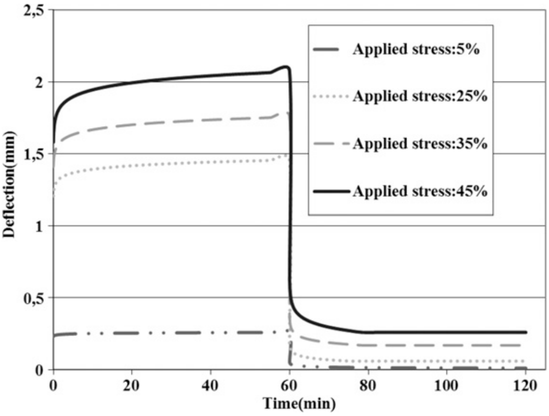

Figure 8. Total deflection at 7% equilibrium moisture content (EMC) during viscoelastic creep measurements in the radial direction.

although total deflections were slightly lower. Deflection increased with time. The rate of increase was greater at the beginning of the tests and then the rate decreased. A comparison of total, plastic, and viscoelastic deflection values suggests that, for the same level of stress, the deflection values were lower at 7% EMC than at 12% EMC.

Figure 9 shows the results of creep tests conducted at 17% EMC in the radial direction. Total, elastic, viscoelastic, and plastic deflection values were significantly higher than at 7 and 12% EMC. Proportions of plastic deflection in total deflection were also much higher. Elastic and viscoelastic deflections showed an opposite trend and made up a smaller portion of the total deflection. It is well known that water is a plasticizing agent for wood. Replacement of hydrogen bonding within the amorphous components by water–carbohydrate links enhances the flexibility of the polymer network. As a result, wood at high moisture content is characterized by a lower rigidity than dry wood (Kelley et al 1987; Obataya et al 1998). Creep increases caused by higher moisture could be explained by the fact that water in the cell walls lubricates the slip interface. Creep is accelerated while water is moving into or out of wood (Ellwood 1954; Bach 1965; Gnanaharan and Haygreen 1979).

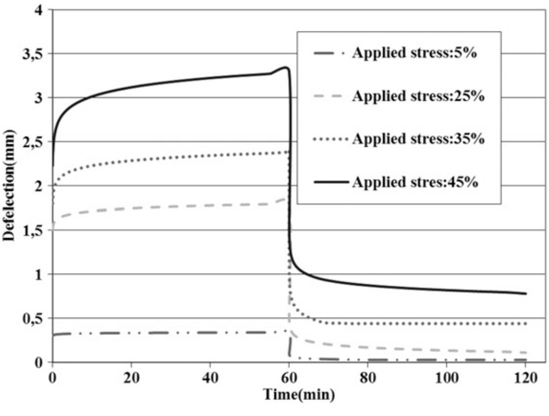

Figure 9. Total deflection at 17% equilibrium moisture content (EMC) during viscoelastic creep measurements in the radial direction.

Viscoelastic creep in the tangential direction. Total deflection values and their three components are summarized in Table 2. Deflections of wood specimens observed at 7% EMC were higher in the tangential direction than in the radial direction at all stress levels. Total deflections were higher in the tangential direction despite the fact that lower stress had been applied for the same level of stress. Total deflections and their three components increased with increasing applied stress levels, as had been observed in the radial direction. An increase in applied stress from 5 to 25% raised total deflection and its components greatly. Elastic deflections were lower than in the radial direction but viscoelastic and plastic deflection were higher. As stress increased, the proportion of plastic deflection in total deflection became greater than that of viscoelastic and elastic deflections.

At 12% EMC, a correlation between the applied stress and deflection was found as it had been in the radial direction at the same EMC level (Table 2). The total deflection values were higher in the tangential direction than in the radial direction, although lower stress was applied for a same applied stress level. Viscoelastic and plastic deflections had a greater share in total deflections. At all applied stress levels, elastic deflections were lower than in the radial direction. The opposite can be said for plastic and viscoelastic deflections. As stress increased, the proportion of plastic deflection in total deflection increased. Inversely, the proportion of viscoelastic deflection decreased.

At 17% EMC, deflections were higher than at 7 and 12% EMC (Table 2). Total deflections increased with applied stress. Elastic deflection played a less significant part in total deflection than was the case in the radial direction, but the share of plastic and viscoelastic deflections increased. As stress levels increased, especially at 35 and 45%, the role of plastic deflection became more prominent. At 17% EMC, plastic deflection was higher than at 7 and 12% EMC. It has been reported in the literature that deflection of stressed wood normally increases with any change of moisture content, irrespective of grain

Table 2. Total deflection values and their three components at 7, 12, and 17% EMC in the tangential direction.[a]

Applied stress (%)	Total deflection δ_t (mm)	Elastic deflection δ_e (mm)	Viscoelastic deflection δ_v (mm)	Plastic deflection δ_p (mm)
		7% EMC		
5	0.30	0.2	0.06	0.04
	(11.78)	(15.38)	(12.42)	(5.72)
25	1.58	1.10	0.37	0.11
	(11.83)	(11.54)	16.74)	(2.35)
35	1.82	1.18	0.41	0.23
	(6.19)	(6.77)	(19.04)	(19.92)
45	2.26	1.39	0.53	0.34
	(10.98)	(8.48)	(18.92)	(12.63)
		12% EMC		
5	0.36	0.22	0.09	0.05
	(15.46)	(9.59)	(14.71)	(48.44)
25	1.75	1.19	0.39	0.17
	(6.66)	(9.26)	(17.78)	(36.41)
35	2.14	1.33	0.49	0.32
	(12.86)	(15.09)	(13.38)	(7.48)
45	2.51	1.51	0.54	0.46
	(9.28)	(8.29)	(15.36)	(8.72)
		17% EMC		
5	0.41	0.24	0.11	0.06
	(17.07)	(25.34)	(4.94)	(10.82)
25	1.93	1.29	0.45	0.19
	(6.53)	(10.49)	(11.10)	(34.13)
35	2.61	1.37	0.60	0.64
	(15.53)	(10.87)	(13.53)	(23.81)
45	3.63	1.79	0.81	1.03
	(8.10)	(7.11)	(11.83)	(7.43)

[a] Value given in parentheses is coefficient of variation (%).
EMC, equilibrium moisture content.

orientation (Armstrong and Kingston 1962; Schniewind 1968). The higher deflection observed at 17% EMC is related to the effect of water on wood constituents. Lignin is a branched polymer, promoting network stiffness. This network restricts the mobility of chain molecules. The replacement of hydrogen bonds between lignin molecules by hydrogen bonds between lignin and water molecules can plasticize wood, facilitating the movement of molecular chains. The more hydroxyl or methoxyl groups available to form weak bonds with water molecules, the easier the free movement of the chain of lignin molecules is (Placent 2006). The free movement of lignin molecules can increase deflection of wood during loading.

At a low stress level (5%), the effect of humidity on wood creep cannot be felt much. As greater stress is applied to the specimens, the effect of moisture on creep becomes more distinguishable. The strongest effect of moisture on creep was observed at the 45% stress level. Raising the EMC from 7 to 12% clearly changed the response of wood to load duration but not at the same magnitude as raising it from 12 to 17%, which had a very significant effect. Bazant (1985) proposed a model based on the thermodynamics of water diffusion in wood for the effects of moisture content and temperature on creep. It assumed that pores (or voids) in wood are subdivided into macropores (cell lumen) and micropores (in the cell wall). A steady-state macroscopic diffusion of water through wood has no effect on creep, and only microscopic diffusion of water through the micropores accelerates creep, regardless of the direction of diffusion.

Throughout the tests involving viscoelastic creep, total deflections proved greater in the tangential than in the radial direction, as is the case with plastic deflection. The differences in the mechanical properties of wood in the two directions could be related to the cell and tissue structure of wood (Ando and Onda 1999). Greater creep in the tangential direction can be attributed to rays and their orientation in wood. In the radial direction, the overall rheological behavior of wood is mainly controlled by the rays of wood and rows of cells preferentially aligned in the same direction (generated by the same cell cambium). The rays act as reinforcing plates when loading is in the radial direction. They have higher density and therefore a higher modulus than the rest of the wood. In bending tests, wood rays are subjected to tension and compression movement in the radial direction. In the tangential direction, however, the wood rays, which are perpendicular to the loading axis, are considered weak points. The stack of the cells is rather random. In tangential stress, the cellular network is less rigid, cell walls work in bending, and sliding two neighboring cells at the middle lamella may happen (Perré and Keller 1994). Higher elastic deflections in the radial direction are a result of rays, which act as hard springs giving more flexibility to wood cells under load in the radial direction (Kollmann 1961).

Mechanosorptive Creep

Radial direction. Deflection values at the different stages of mechanosorptive creep measurements are shown in Table 3. At the 5% stress level, total deflection at the final stage was more than three times the deflection observed at the original 12% EMC. Such a huge increase in creep is proof of the mechanosorptive effect phenomenon. As stress increased, the impact of moisture change during creep measurements became more pronounced. The highest deflection was detected at the 15% stress level. It has been reported that when moisture content of loaded wood changes, deflection increases rapidly, but final deformation depends on moisture level and is little affected by the duration of the process. Although viscoelastic creep depends on the duration of loading, mechanosorptive creep at a constant stress level is not time-dependent (Armstrong and Kingston 1962; Schniewind 1968). The results of measuring creep in varying RH demonstrated that DMA can monitor and indicate mechanosorptive creep, despite decreased dimensions of specimens and shortened time of experiments. Nordon (1962) stated that hydrogen bond breakage during moisture sorption caused mechanosorptive creep. Armstrong (1972) and Grossman (1976) rejected this hypothesis and claimed that moisture transport itself would be enough to result in mechanosorptive creep. Several other reasons also have been mentioned for the mechanosorptive effect. The mechanosorptive effect (mechanosorptive creep) has been attributed to increased molecular mobility during moisture transport (Ericksson

Table 3. Total deflection values at the different steps of the mechanosorptive creep measurements.[a]

Applied load (%)	δ_t (mm) 12% EMC	δ_t (mm) 12-17% EMC	δ_t (mm) 17-7% EMC	δ_t (mm) 7-12% EMC
		Radial direction		
5	0.37	0.98	1.1	1.14
	(14.48)	(26.29)	(17.66)	(16.09)
10	0.79	1.7	1.9	2.31
	(13.70)	(18.04)	(9.43)	(12.72)
15	1.1	2.8	3.41	3.61
	(12.46)	(11.26)	(10.46)	(8.30)
		Tangential direction		
5	0.41	1.12	1.2	1.23
	(15.23)	(9.99)	(7.85)	(6.79)
10	0.88	1.93	2.21	2.43
	(9.70)	(4.96)	(9.02)	(9.31)
15	1.3	2.98	3.64	3.88
	(12.63)	(4.93)	(4.26)	(3.03)

[a] Value given in parentheses is coefficient of variation (%).
EMC, equilibrium moisture content.

and Noren 1965; Gibson 1965; Bazant 1985), increased molecular mobility during moisture change (Bethe 1969; Ranta Maunus 1975; Hunt 1986; Van Der Put 1989; Hanhijarvi 1995), sorption-induced physical aging (Padanyi 1991; Wang et al 1992), material-specific interfiber mechanisms (Soremark and Fellers 1993; Haslach 1994), thermodynamic ratcheting actions (Haslach 2000), and sorption-induced stress gradients (Pickett 1942; Selway et al 1992; Caulfield 1994; Habeger and Coffin 2000).

Tangential direction. Deflection values at the different stages of mechanosorptive creep measurements for the tangential direction are shown in Table 3. As seen in the radial direction, moisture change during creep measurement greatly influenced the response of wood specimens to the load. Moisture changes increased deflection, especially at the second stage, in which RH increased from 67 to 83.9%. As stress rose, the deflection tended to increase as well, and mechanosorptive creep proved higher in the tangential direction than in the radial direction. Thelandersson and Morén (1992) also found that mechanosorptive creep in the tangential direction was higher than in the radial direction. The difference could be related to the anatomy and structure of wood in the radial and tangential directions.

The results of this study showed that DMA is a useful tool to shorten the time needed for creep measurements. DMA can detect changes in creep as a result of variations in RH, load level, and wood direction. The creep of wood was found to vary with wood direction, load level, and time. The tangential direction experienced higher creep, confirming the importance of choosing the proper direction for the application. RH is the most influential factor shaping the pattern of creep. The impact of humidity becomes crucial when a loaded wood member is exposed to concurrent RH changes. RH changes during loading cause very significant creep increases. This phenomenon (mechanosorptive creep) is very important in load-bearing members because it is not very dependent on time. RH changes could induce substantial creep in wood members in a relatively short time. Such creep can endanger the integrity of a wood structure if it has not been properly designed for.

CONCLUSIONS

The objective of this study was to develop a new approach to determine creep properties of sugar maple wood using a DMA instrument. The results confirmed that DMA can be used to measure viscoelastic and mechanosorptive creep in wood. The method makes it possible to obtain creep properties faster than the usual methods. This method could facilitate modeling parameter determination or accelerate model validation. Using small specimens and a shortened time of experiments did not negatively impact creep measurement. DMA successfully determined the effect of material modifications on creep. The pattern of creep and its fluctuations detected by DMA matched fluctuations observed with conventional methods. Creep measurements by DMA could detect the effects of moisture content on the creep. In viscoelastic creep, moisture affects total deflection, its three components, and their respective proportions. Plastic deflection accounts for a higher share of total deflection as moisture increases. Stress level is another creep-controlling factor in wood. Total and plastic deflections increase with stress, but elastic deflection plays a minor role at high stress levels. Wood direction also influences creep. Wood creep is greater in the tangential direction than in the radial direction. DMA was successful in measuring mechanosorptive creep. In mechanosorptive creep measurements, a major increase in deflection was observed even at a low stress level. Because mechanosorptive creep is not controlled by time, changing moisture in load-bearing members can cause a significant deflection in a very short time.

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