ON THE FRACTIONAL STRESS RELAXATION OF CONIFEROUS WOOD TISSUES[1]

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ABSTRACT

The intra-incremental stress relaxation behavior of Sitka spruce, Douglas-fir, and balsam fir was studied in tension parallel-to-grain and compression perpendicular-to-grain. The stress relaxation behavior at sustained constant deformation was found to be strongly dependent on location from which the test samples were cut and on the mode and rate of loading.

Keywords: *Picea sitchensis*, *Pseudotsuga menziesii*, *Abies balsamea*, earlywood, latewood, growth increments, specific gravity, tensile tests, compression tests, rheology, moisture content.

INTRODUCTION

Wood rheology is most often studied in phenomenological ways on macrospecimens. The time-dependent response of macrowood has been investigated in relation to wood type, grain or fibre orientation, moisture content, temperature, and the mode of mechanical excitation. The extensive literature now available on this particular subject has been reviewed in detail by Schniewind (1968).

Surprisingly little attention has been paid so far to the study of the rheology of wood microspecimens, i.e., wood tissues. Yet, exploring wood mechanical behavior at this level could be important in developing a more complete understanding of the total material. Previous studies with wood microspecimens have investigated static failure of earlywood and latewood tissues subjected to a constant tension strain parallel-to-grain (Bach 1967), and examined creep in tension perpendicular-to-grain at constant stress excitation (Fujita and Nakato 1965a, 1965b). Another study (Chow 1973) investigated molecular activities during tensile stress relaxation of wood tissues.

The objective of the present study was to examine some rheological properties of wood tissues originating from various positions within coniferous growth zones.

MATERIAL AND METHODS

Stress relaxation was investigated with Sitka spruce [*Picea sitchensis* (Bong.) Carr.], Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco.] and balsam fir [*Abies balsamea* (L.) Mill] wood microspecimens. All specimens used for studying relaxation responses in the "green" condition were never-dried; while those used for air-dry stress decay studies were conditioned (50 ± 2% RH, 21 ± 1 C) for at least four days after cutting to final size.

In the sequence of material preparations, specimen blocks of 75-mm length and approximately 15-mm width containing 4 to 5

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TABLE 1. *Characteristics of materials used in the wood microspecimen relaxation studies*

	SITKA SPRUCE [*Picea sitchensis* (Bong.) Carr.]		DOUGLAS-FIR [*Pseudotsuga menziesii* (Mirb.) Franco]				BALSAM FIR [*Abies balsamea* (L.) Mill.]
Growth Increment No.	105	106	44	45	46	47	31
Width, mm	4.2	4.3	5.2	6.6	4.8	6.4	2.2
Latewood, %	25	22	47	42	48	38	37
Specific gravity (OD Wt/green Vol), g/cm^3	(0.22-0.50)	(0.22-0.42)	(0.21-0.58)	(0.21-0.71)	(0.22-0.78)	(0.19-0.58)	(0.21-0.68)
Earlywood (mean)	0.25	0.24	0.23	0.22	0.24	0.24	0.25
Latewood (mean)	0.47	0.35	0.57	0.64	0.72	0.57	0.58
Tension Parallel ("green", σ_{max})x10^{2}kg/cm^3	(3.2-9.5)	(2.1-7.5)	--	--	(5.1-13.0)	(2.8-11.0)	(2.7-9.1)
Earlywood (mean)	3.9	3.7	--	--	5.7	3.4	3.8
Latewood (mean)	9.2	7.1	--	--	11.7	10.0	7.9
Tension Parallel ("air-dry", σ_{max})x10^{2}kg/cm^2	(2.9-15.5)	(3.0-10.6)	--	--	(5.6-24.5)	(2.2-19.3)	(4.6-14.0)
Earlywood (mean)	4.7	3.9	--	--	6.0	3.7	5.2
Latewood (mean)	15.4	9.8	--	--	22.6	17.2	13.1
Radial Compression ("green", σ_{max})x10^{2}kg/cm^2	--	--	(0.28-1.18)	(0.30-1.09)	(0.24-1.61)	--	--
Earlywood (mean)	--	--	0.32	0.32	0.27		
Latewood (mean)	--	--	1.04	0.94	1.43	--	--

growth zones were extracted from the sapwood of stem discs. Major characteristics taken into consideration in selecting these blocks were straightness of grain and differences in latewood percentage between adjacent zones. Table 1 shows characteristics of the individual growth zones tested.

Ring width and latewood percentage were determined by microscopic means. The latewood percentage was obtained by measuring the distance from the middle of the transition zone to end of the latewood zone and relating this to total ring width.

Saturated wood blocks were cut on a sliding microtome as serial tangential sections. Those to be used in tensile studies were prepared as 105 ± 15 μm section blanks. Specimen thicknesses for radial compression tests were 260 ± 18 μm, which was found to be the minimum useful thickness for deriving ultimate strength, especially with latewood tissues. Thickness measurements were carried out with a microcater. Seven or eight microsection blanks were selected to represent different positions within each growth zone examined.

PREPARING AND TESTING TENSILE SPECIMENS

Tensile test specimens of 75-mm length and 2.5-mm width were punched from section blanks with an Arbor press. Special care was exercised to cut exactly parallel-to-grain. Positions within growth zones were replicated two (balsam fir) or five (Sitka spruce and Douglas-fir) times as limited by ring curvature. One balsam fir specimen and two specimens each of Sitka spruce and Douglas-fir were employed for determining ultimate stress at each position within the ring (Table 1).

Ultimate stress and stress relaxation measurements were both performed at 21 ± 1 C on a Model T-M Instron machine. Test specimens were clamped between smooth rubber-faced grips in a way that the gauge length was 25.4 mm. Specimens employed in studying relaxation on "green" wood were maintained in saturated condition by a specially designed plastic bag filled with water, which surrounded the specimen during test.

A machine head speed of 0.21 mm/sec was used, which provided 50% ultimate stress levels for relaxation tests in 1.2 to 1.8 sec (t_0). Thereafter, the relaxation process was observed over 35 min.

Since the limited number of matched specimens restricted the main experiment to a single stress level (50%), a separate study investigated effects of two additional stress levels (35, 75%) at two positions (earlywood, latewood).

Other tests were performed to examine potential sources of experimental error, such as pen drift and machine relaxation. Only slight deviations, on average less than 1%, were found and these were neglected.

Five failed specimens from each position were used to determine specific gravity according to the standard method using green volume and oven-dry weight. Prior to oven-drying, the specimens were wrapped in gauze packages and extracted sequentially with diethylether, ethyl alcohol, and hot water. Weighings were performed with a Cahn Electro balance placed in a moisture-free plexiglass glove box.

Preparing and testing compression specimens

Altogether, 24 compression test specimens of 5- × 5-mm dimensions were cut from each section blank representing radial position with growth zone. Test specimens were located randomly within section blanks for both ultimate stress and stress relaxation tests. Specimens at the same position but from different microsections of a single growth zone were employed for the same test. In other words test specimens matched in radial direction were always subjected to the same type of measurement.

It was found that five replications provided satisfactory confidence criteria for ultimate stress determinations, as well as the three (27, 53 and 80%) initial stress levels examined in stress relaxation. Tests were performed at 21 ± 1 C on the machine described, with specimens placed between 0.1-mm-thick cover glasses and 1.0-mm-thick microslides. For the "green" condition during testing, specimens were surrounded by a film of water.

Ultimate stress was determined at a rate of 0.00085 mm/sec, which was necessary for solving latewood stress-deformation curves used in this study to define ultimate strength. Loading for stress relaxation was done at 0.085 mm/sec. This relatively high rate was adopted for minimizing rheological processes before reaching the initial stress level, i.e., 53% stress was attained in 1.2 to 1.7 sec (t_o). The stress relaxation response was observed over 35 min.

It was found that compression relaxation data contained a small experimental error due to pen drift and machine relaxation. A correction factor was determined by performing the same tests without specimen, but including cover glass and microslide, after every 7th or 8th stress relaxation test. Thus, an "average" error value was calculated and applied to various load ranges.

Ten specimens from each position were selected for determining specific gravity according to methods described.

RESULTS AND DISCUSSION

All relaxation test data were obtained from analyses of Instron chart traces. Fractional stress relaxation was calculated as $\sigma(t)/\sigma(t_o)$, where $\sigma(t_o)$ is the original stress level applied to the specimen in 1.2 to 1.7 sec and $\sigma(t)$ the stress at time t. Data are presented as three-dimensional response surfaces (Fig. 1 and 2) or as two-dimensional plots (Fig. 3–5).

Relaxation in tension parallel-to-grain

Tissues from one growth zone of balsam fir and two each of Sitka spruce and Douglas-fir were subjected to stress decay tests. Both "green" and air-dried test materials were taken from the same growth zones to provide direct comparisons between the two moisture conditions. Typical results are shown in Fig. 1.

Fractional stress relaxation between the three woods was remarkably similar as regards pattern and amount of stress dissipation, lack of variation with position within growth zone, and influence of moisture.

Fractional stress relaxation within any single growth zone changed only slightly from earlywood to latewood for both "green" and air-dried specimens. Differences were mostly no more than 2 to 4% and only balsam fir in "green" condition showed a significant difference between

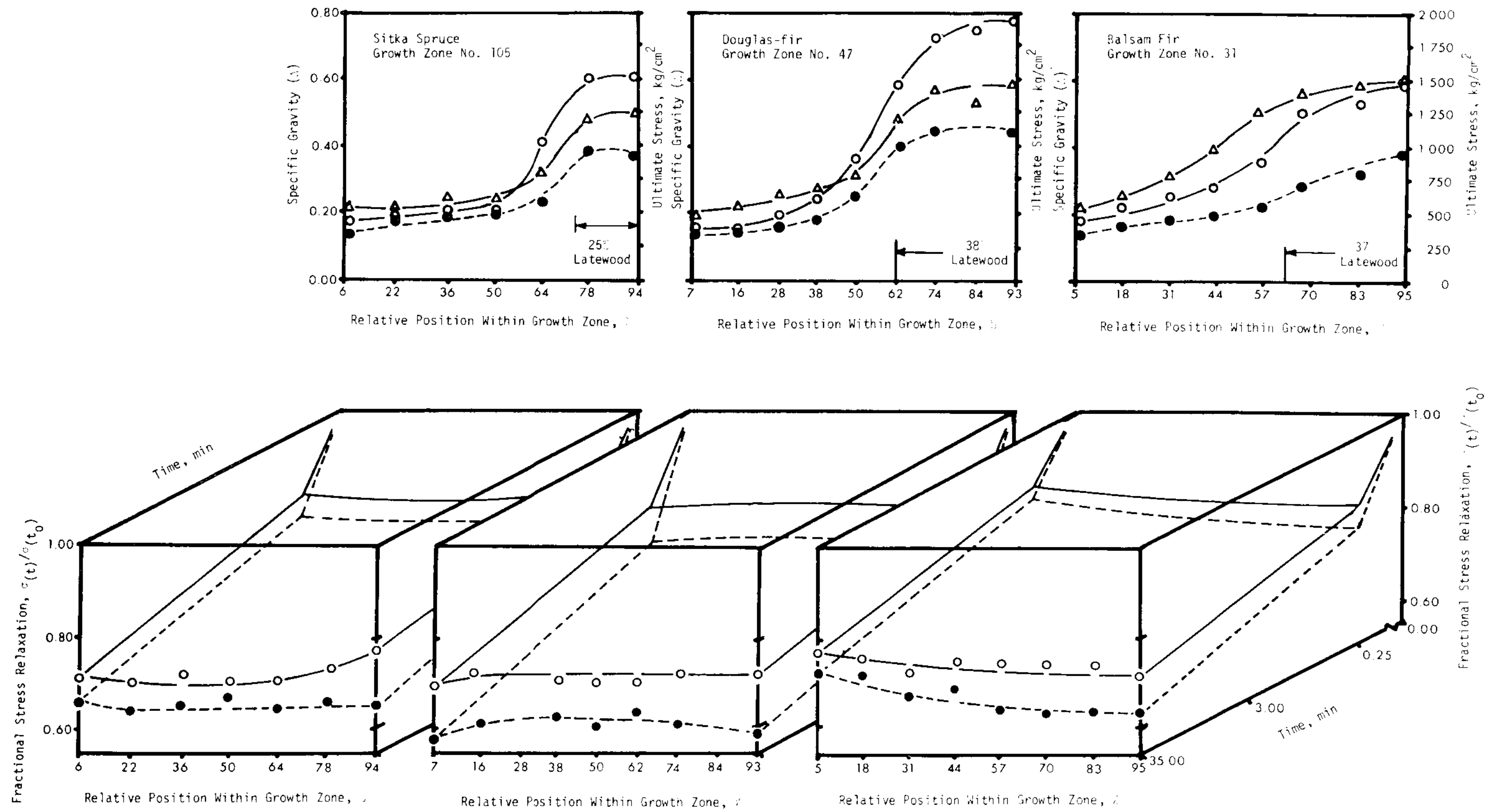

FIG. 1. Intra-incremental ultimate stress, specific gravity and fractional stress relaxation in tension parallel-to-grain of "green" (-- ○ --) and dry (—●—) microspecimens from three coniferous woods. Stress level used for relaxation testing was 50% of the ultimate stress.

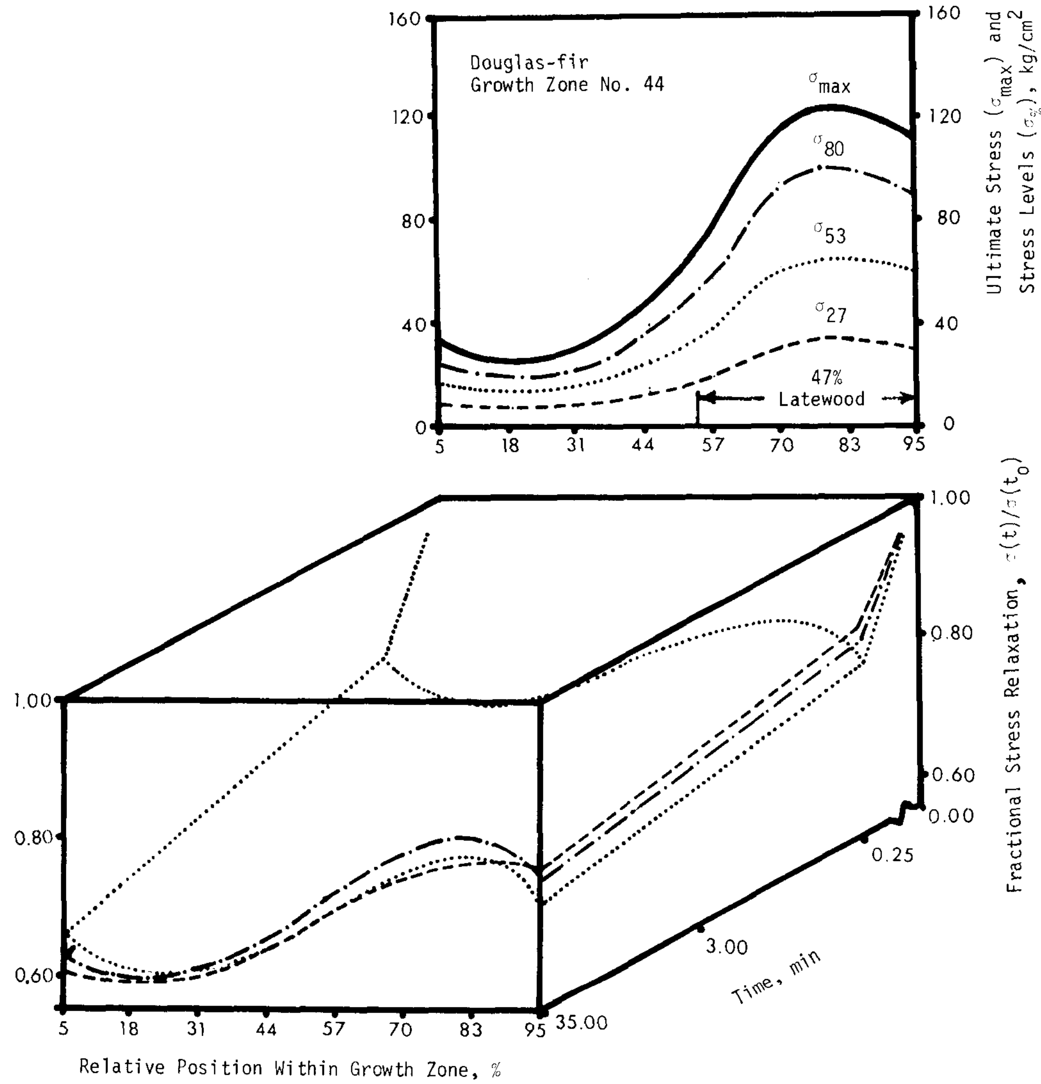

FIG. 2. Intra-incremental ultimate stress and fractional stress relaxation in radial compression at three stress levels of "green" Douglas-fir wood microspecimens.

earlywood and latewood extremes (t-value: 4.03** for 4 d.f.; S_{EE} 7.33). From these observations it can be concluded that earlywood and latewood dissipate tensile stress at approximately the same rate.

Interestingly, most of the difference in fractional stress relaxation as observed after 35 min originated during early stages of the relaxation process (0.25 min). Thereafter, stress dissipation was maintained at a different rate.

As Fig. 1 indicates, varying specimen moisture content changed fractional stress relaxation. It is evident from all figures that the air-dried sections (9.0 ± 0.8% moisture) dissipated stress at considerably lower rates than the saturated, "green" specimens. The effect was expected and is in agreement with other rheological studies on wood macrospecimens showing moisture dependence of wood viscoelasticity (Bhatnagar 1964; Fujita and Nakato 1965a,

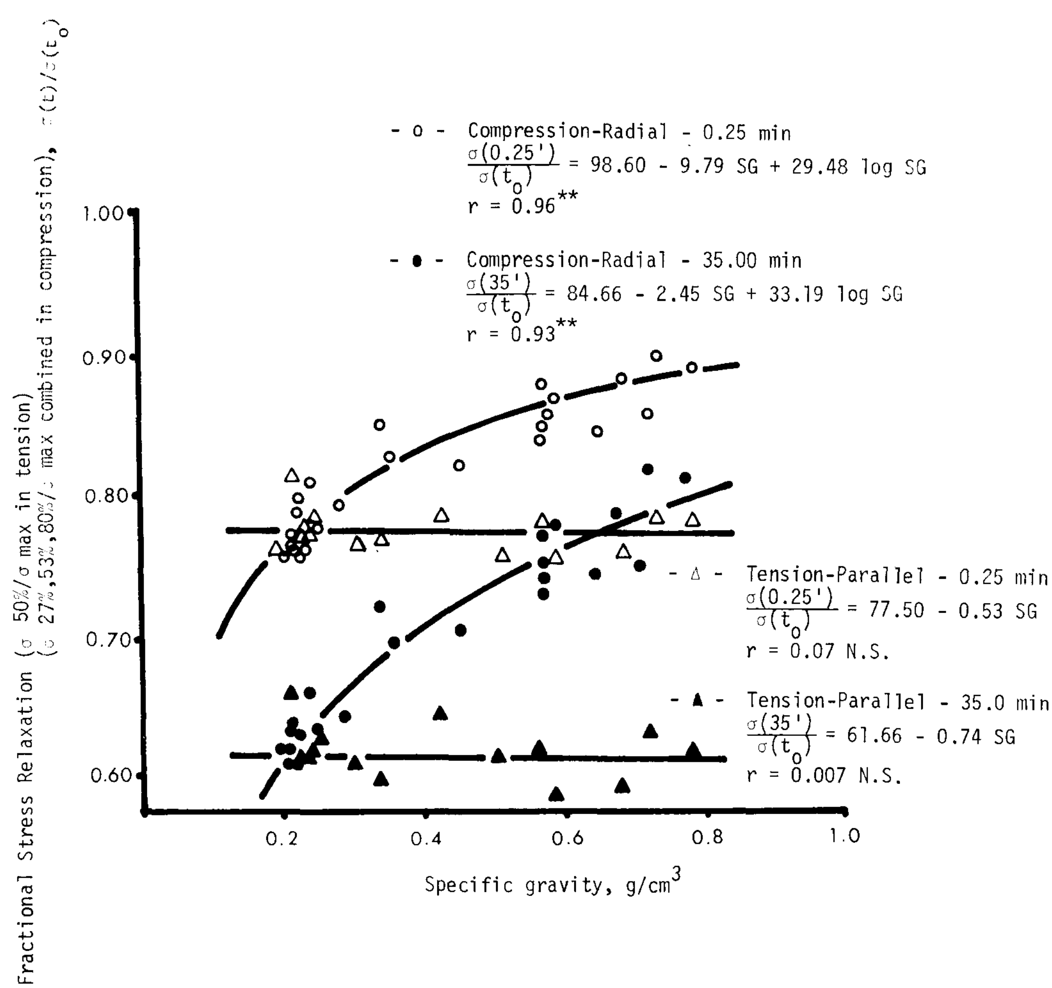

FIG. 3. Fractional stress relaxation compared to specific gravity for "green" Douglas-fir tissues examined in tension parallel ($T_{||}$—two growth zones) and radial compression (C_R—three growth zones).

1965b; Kunesh 1961; Nedbal 1961; Norimoto and Yamada 1965; Ota and Tsubota 1966; Susaki et al. 1965; Ugolev and Pimenowa 1963).

Relaxation in radial compression

Fractional stress relaxation in radial compression was examined at three stress levels within three growth zones of Douglas-fir maintained in "green" condition. Neither species nor moisture variations were studied here. Typical data are presented in Fig. 2.

Stress was dissipated within growth zones consistently according to a sigmoid pattern with maximum loss centered in the earlywood and minimum in latewood. Approximately 17 ± 5% difference between maxima and minima was observed after 35 min at approximately 20 and 80% relative positions within growth zones. This differs from stress relaxation responses observed within growth zones in tension parallel-to-grain.

The intra-incremental pattern in radial compression is attributed partly to wood structural variations, whereby wide-lumen thin-walled cells (earlywood) are less re-

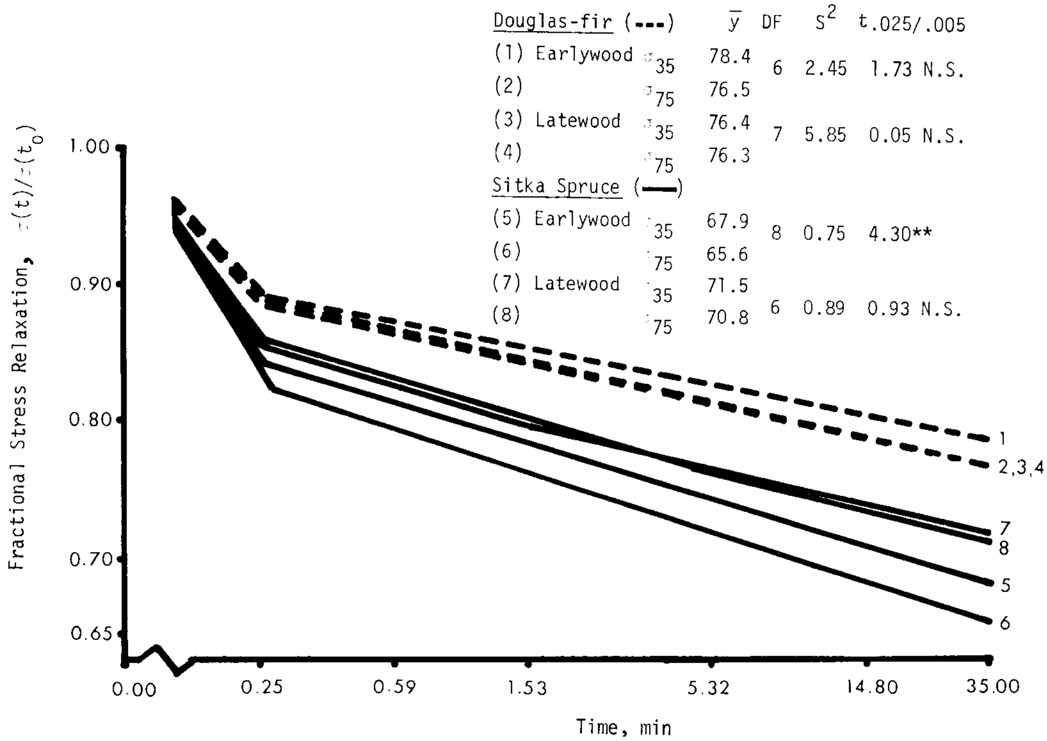

FIG. 4. Effect of initial stress level ($\sigma_{35\%}$, $\sigma_{75\%}$) on fractional stress relaxation in tension parallel-to-grain of "green" wood microspecimens.

sistant to stress deformation than narrow-lumen, thick-walled cells (latewood). Magnitude of these structural variations are reflected in threefold differences between earlywood and latewood specific gravities (Table 1).

Since specific gravity relates to structural variations, it was used to analyse the effect of earlywood and latewood cell structures on the two relaxation responses—tension parallel-to-grain and radial compression. High correlations were found for specific gravity with radial compression, but no correlation was observed for tension parallel-to-grain. This suggests that while tensile relaxation parallel-to-grain is dominated by molecular processes of the lignin-carbohydrate complex, radial compression relaxation is more influenced by wood anatomical features.

Interestingly, Kitazawa (1947) in an early study of stress relaxation perpendicular-to-grain with wood macrospecimens observed the effect of specific gravity on rate of stress relaxation. He attributed the phenomenon to greater distortion of thin-walled cells. This essentially agrees with our conclusions.

Again, the pattern of stress relaxation as observed after 35 min was set in very early stages of the relaxation process (0.25 min). Initial earlywood-latewood differences in response were maintained, but at different rates.

Relaxation response to initial stress

Rheological response of wood as a function of initial stress or strain level has been the subject of several studies on macrospecimens. In general, it has been found that rate of creep deformation or stress relaxation increases with higher load or strain

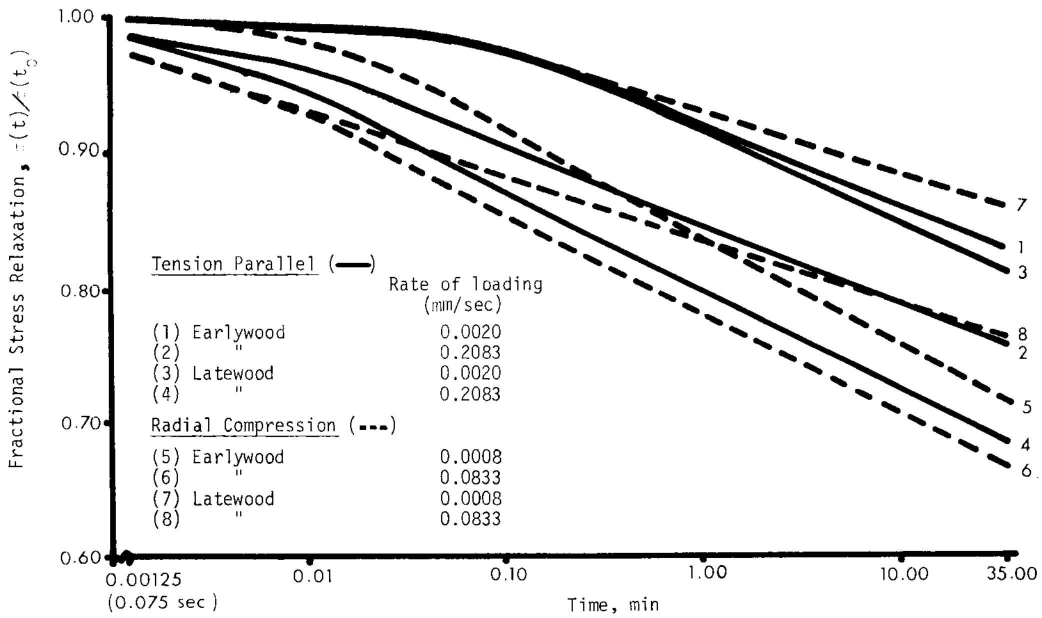

FIG. 5. Effect of excitation history on fractional stress relaxation of "green" Douglas-fir earlywood and latewood microspecimens examined in tension parallel-to-grain and radial compression.

levels (Echenique-Manrique 1967; Grossman 1954; Kingston 1962; Kingston and Clarke 1961; Youngs 1957). Since macrospecimen responses result from the blend of earlywood and latewood rheological properties, it is of particular interest to understand how these growth zone tissues respond separately to constant straining at various initial stress levels in compression perpendicular- and tension parallel-to-grain.

Response to various initial stress levels (27, 53 and 80%) of ultimate stress in radial compression was tested on "green" Douglas-fir microspecimens (Fig. 2). As can be seen, only minor differences occurred between the three response surfaces, and even these planes intersected at various positions within the growth zone. Similar results were obtained within two other growth zones examined. According to multiple curvilinear covariance analysis, all yielded nonsignificant differences (Ring No. 44 = 0.25 N.S.; No. 45 = 2.88 N.S.; No. 46 = 0.25 N.S.) between planes.

Relaxation curves obtained from tests in tension parallel-to-grain on "green" Sitka spruce and Douglas-fir are reproduced in Fig. 4. These figures, supported by t-tests, indicate that Douglas-fir earlywood and latewood and Sitka spruce latewood were not significantly affected in rate of stress decay when the initial stress level was raised from 35 to 75% of the ultimate short-time strength. Only relaxation of Sitka spruce earlywood appeared to be influenced by the change in initial stress level. That three out of four samples did not respond significantly to broadly different initial stresses is rather unexpected and not in agreement with similar observations on wood macrospecimens (Echenique-Manrique 1967; Grossman 1954; Kingston 1962; Youngs 1957). Echenique-Manrique (1967) for instance, found for macrospecimens that adjusting strain level in tension parallel-to-grain caused a significant change in rate of dissipated fractional stress. He reported that at lower strain levels rates of stress relaxation changed linearly with initial stress level, while at higher levels the straight line relationship disappeared and a marked increase in relaxation was observed.

The nonsignificant effect of initial stress level on rate of fractional stress dissipation may be explained by the fact that earlywood and latewood tissues appeared to be linear viscoelastic. In contrast, the stress level employed in studying macrospecimen rheological properties is often referred to an average earlywood and latewood resistance beyond the linear range. As shown in Table 1 and Figs. 1 and 2, even one-third of the latewood values may exceed earlywood ultimate stress. Consequently, varying stress level with macrospecimens changes rheological response, whereas changing stress level does not markedly affect wood tissue response. Stress magnitude of the latter is decided according to more homogeneous structure and this is then more uniformly distributed during test.

Relaxation response to excitation history

General linear viscoelastic theory predicts that stress relaxation will exhibit dependence on the rate of initial straining. By applying Boltzmann's principle of superposition (Flügge 1967), we can obtain an expression for how the initial rate of straining influences stress relaxation.

$$\sigma(t) = R \int_{0}^{t_0} G(t-t_1)dt_1 \qquad (1)$$

where:

R = rate of initial straining = $\epsilon_0 : t_0$

$G(t)$ = the "true" stress relaxation modulus

t_0 = instant of time where loading to strain "ϵ_0" has been completed

ϵ_0 = the stress relaxation strain

$\sigma(t)$ = stress for $t > t_0$.

From Equation 1 it appears very clearly that the rate of straining influences the stress relaxation after completion of the initial straining.

As shown experimentally for most viscoelastic solids, wood tissues of this study dissipated stress at a gradually decreasing rate after loading. "Immediate" response in particular has been found experimentally for paper (Anderson and Sjöberg 1953; Johanson and Kubat 1964) to be highly dependent on rate at which the strain level is applied, which is in accordance with Eq. 1. This phenomenon was observed also in this study, for both relaxation in radial compression and tension parallel-to-grain as seen in Fig. 5. As shown it appears that initial stress relaxation occurred at higher rate when the initial strain excitation was done rapidly.

The curves also indicate that differences in stress dissipation as observed after 35 min relaxation time originated from early stages of the relaxation process, i.e., before the first 0.25 min following t_0. Thereafter, stress was dissipated at rates independent of the initial effect, as seen from the essentially parallel relaxation trace slopes of matched pairs in Fig. 5. From this behavior it appears that the ability of wood tissues to absorb and dissipate energy is limited by certain factors. In loading at extremely low rate, the molecular system, which is responsible for the rheological behavior, loses most of its capacity to decay stress before the loading process is concluded. Thereby, relaxation is confounded with the excitation history.

As slopes of curves and planes in Figs. 1 and 2 indicate, linear relationships were found between $\sigma(t)/\sigma(t_0)$ and log (time) in the time interval 0.25 to 35 min, implying that materials of the study dissipated stress linearly over the interval with the logarithm of time. Extending the log (time) axis to smaller values (below 0.25 min), such as done in Fig. 5, shows the relationship to be nonlinear. The boundary between linear and nonlinear appears to depend in part on the rate at which the load was applied (Fig. 5). Decreasing rate of straining shifted the boundary to higher time values.

A region of linear relationships between $\sigma(t)/\sigma(t_0)$ and log (time) has been found also with macrospecimens (Grossman 1954; Kitazawa 1947) and other cellulosic materials, such as pulps and papers (Johanson and Kubat 1964; Kirbach 1971; Maynard 1956). This relationship, however, appears to become nonlinear at longer time periods. This was observed in bending of wooden beams when the excitation time exceeded 1,000 min (Grossman 1954). In the present experiments the testing period was limited to 35 min, and the observed relaxation response is expressed as a linear relationship between $\sigma(t)/\sigma(t_0)$ and log (time).

CONCLUSION

Wood tissues were used to study intraincremental rheological behaviors and sustained excitation of strain. Stress was dissipated equally across growth zones in tension parallel-to-grain tests, but earlywood tissues showed higher relaxation rates than latewood in radial compression. Tensile results between woods from three coniferous species and between growth zones within stems were similar in form and magnitude, as were radial compression comparisons between growth zones.

Although stress level in tension or compression testing did not appear to influence fractional stress relaxation, "green" never-dried specimens consistently dissipated tensile stress more rapidly than those tested in air-dry state.

Rate of loading exerted a profound influence on the early record of the relaxation process, wherein initial (to 15 sec) and late (to 35 min) responses were observed to differ following rapid loading (1.5 sec). Moreover, the relaxation pattern appeared to be set immediately after excitation and this early effect determined subsequent levels attained.

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