Large inelastic strain occurs inside a piece of lumber during drying. The strain consists of several components such as elastic, plastic, creep, shrinkage and mechano-sorptive effect. The mechanical behavior of the whole board during drying is determined by the behavior of individual strain components and their interactions. Whereas limited investigations have been made on those strains under moderate conditions, there is a lack of comprehensive research aimed at examining the behavior at elevated temperatures and incorporating various strain components into a process model. This research provides experimental data for various strain components of small wood samples and an analytical tool for evaluating the drying behavior of full-size boards.

Small test specimens of Douglas-fir were loaded tangentially in both tension and compression under constant and varying moisture conditions at different temperatures. Experiments were conducted using a small testing machine
contained within a pressure vessel. The strain fields for loaded and unloaded test samples were measured using a high resolution video camera. The required moisture change at controlled temperatures was achieved by controlling the total pressure in absence of air with saturated steam. Moisture content was monitored by a quartz spring sorption balance.

The total deformation due to loading and moisture change was decomposed into instantaneous, creep, shrinkage and mechano-sorptive components. Constitutive equations for each component were developed as a function of stress, temperature, moisture, time and moisture change. These equations were incorporated into a process model to simulate the development of stress and strain in large pieces of lumber during drying.

A slicing method was used to measure the distribution of moisture and strain through the thickness of full-size boards at different stages of drying. The process model was used to predict drying stress and strain based on the measured moisture distribution and material properties. The effect of drying conditions and types of wood on the development of drying stress was demonstrated. The predicted drying strains under different drying conditions were compared with the corresponding measurements.
RHEOLOGICAL BEHAVIOR OF DOUGLAS-FIR AS RELATED TO THE PROCESS OF DRYING

by

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RHEOLOGICAL BEHAVIOR OF DOUGLAS-FIR AS RELATED TO THE PROCESS OF DRYING

I. INTRODUCTION

Wood, as a naturally occurring material, has many desirable characteristics which have made it popular for shelter, furnishing, and artistic works. In a living tree, moisture content can vary from 25% to well above 200% depending on the species and part of the tree. Although undried wood is used successfully in many applications, drying of wood to the equilibrium moisture content (EMC) is necessary from the point of view of serviceability. Unfortunately, as wood dries it shrinks. The differential shrinkage across the thickness of a lumber board creates stresses, the magnitudes of which depend on the physical properties of the wood, drying conditions, and the time of exposure to these conditions. As wood relieves itself of these stresses, the material may take on two forms of degrade, warpage and physical defects. This degrade diminishes the usefulness of the dried lumber and thus decreases its market value.

It has been recognized for many years that a key to improve drying quality and a reduction of drying time lies in understanding and controlling internal stress development (Tiemann, 1917). Several experimental and theoretical investigations have been made to determine the distribution of
drying strains, and to model the stresses during lumber drying. Those studies have led to the qualitative establishment of the general stress pattern. However, a quantitative understanding of drying stress and its dependence on the physical properties of wood and drying conditions is still not complete.

It is well established that wood acts as a viscoelastic material when subjected to a stress which can be either externally applied or self-induced. In the process of drying, the rheological properties of wood perpendicular to the grain, including mechanical creep and mechano-sorptive (MS) effect, act to relieve stress and reduce faults which can arise from high internal stresses. Numerical studies have proven that a purely elastic approach could not be used even as a first approximation in determining the drying stresses (Salin, 1987; Salin, 1992). Thus, a better understanding of the rheological properties would certainly lead to a more accurate estimate of drying stresses, a more accurate selection of the drying schedule, and less lumber value loss.

The investigation presented in this thesis has been conducted to develop both analytical and experimental approaches for quantifying various aspects of the rheological behavior of wood under the conditions that are likely to occur during drying. The specific objectives were as follows.
1. Develop a material property model for characterizing wood deformation under combined mechanical and moisture loading of small wood samples.

2. Develop a process model for evaluating stresses during drying of the full-size lumber boards, including the effects of mechano-sorptive and mechanical creep deformation.

3. Develop an appropriate experimental technique for studying wood deformation under load during moisture change at the environmental conditions generally encountered in the process of drying lumber.

4. Assess the accuracy of the material property model and process model by actually testing of small wood samples and drying of large lumber boards.
2.1 Stress Development in Drying of Lumber

A general concept of how the stresses develop inside wood as it dries is well-documented in the forest products literature (McMillen, 1955a; 1955b; Kawai et al, 1979). Under the normal drying conditions, the surface of sawn boards tends to approach the equilibrium moisture content of the prevailing conditions and the outer zones of the wood dry below the fiber saturation point (FSP). Thus, the fibers at surface tend to shrink, but are restrained by the fibers at the inner zones which are in a relatively green condition and have not begun to shrink significantly. Because of this restraint, the outer zones are stressed in tension, and as a reaction, the interior zones are in compression. When the tensile stress exceeds the proportional limit, tensile set takes place in the outer zones. The tensile stress in the outer zones and the compressive stress in the center zone reach the maximum values, then decrease. As the drying continues, successive inner zones tend to shrink and thus change from compression to tension. When the tensile stresses in the surface zones reduce to zero, there is nearly always some tensile set left in these zones. As drying still continues, the center and outer zones shrink further. Due to the tensile set left in
the outer zones, the outer zones change from tension to compression (stress reversal). After stress reversal, the outside zones gradually proceed to a maximum compressive stress and the center zones to a maximum tensile stress.

The development of drying stresses in a softwood differs somewhat from that in a hardwood. This difference is primarily the comparatively low moisture content at which reversal of the stress occurs. In drying of 2-inch ponderosa pine, McMillen (1968) showed that stress reversal in both heartwood and sapwood specimens did not occur until the average moisture content was 20% or below. Resch et al (1989) demonstrated experimentally that the stress reversal for Douglas-fir heartwood dried with a commercial kiln schedule occurred between 15% and 17% moisture content. Although softwoods are dried in a short time compared to hardwoods, control and elimination of surface checks in drying wide boards and honeycomb in drying large thick boards of dense softwood species like Douglas-fir still require the detailed knowledge of the development of internal stresses.

2.2 Wood Properties Related to Drying Stresses
2.2.1 Experimental Findings

Under the prolonged action of combined stress and moisture change in the drying process, wood undergoes a large inelastic deformation. The deformation can be usually
decomposed into three major parts: instantaneous, time-dependent, and moisture change-dependent. The magnitude of each component and its contribution to the development of drying stresses depend on the related physical properties of wood. Although the importance of those properties has been recognized for a long time, comparatively little work related to drying has been done.

2.2.1.1 Instantaneous Elasticity and Plasticity

Under short-term loading conditions, wood demonstrates a straight line relationship between stress and strain up to a yield point or proportional limit (Bodig and Jayne, 1982). If the stress is removed prior to reaching the yield point, $\sigma_y$ (Figure 2.1), the strain returns to zero and the behavior is said to be linearly elastic. Beyond the yield stress, however, the relationship is no longer linear since progressively less stress is required to produce a given strain change. This continues up to the ultimate stress, $\sigma_u$. If the load is removed when the stress reaches a point $(\sigma, \epsilon_i)$ between the yield and ultimate stress, the wood unloads along a line that is approximately parallel to the initial elastic line. When strained beyond the yield point, the strain does not return to zero after the stress reaches zero. Rather a plastic strain or set $(\epsilon_i, \rho)$ is left in the wood. It is this
Figure 2.1. Stress-strain relation of wood under the short-term loading.
amount of set which contributes the stress reversal in the process of drying lumber (McMillen, 1955a; Oliver, 1984).

The stress-strain relationship described above does not depend on time. As soon as the stress changes, the strain changes. This behavior is said to be "instantaneous". Experimental data describing the effect of temperature and moisture content on such a relationship provide basic information about the conditions at which surface and internal checking may occur during the lumber drying.

For hardwoods, several authors have investigated the change in Young's modulus (initial slope of the instantaneous stress-strain curve), stress and strain at the proportional limit, and maximum stress and strain with changes in temperature and moisture content of wood (Greenhill, 1936; Ellwood, 1954; Youngs, 1957). Among those, Greenhill's (1936) investigation was made on American beech and was restricted to an examination of tensile strength and elastic properties in the tangential direction. Test results showed that both maximum stress and Young's modulus were decreased with increases in temperature and moisture content below the FSP.

Ellwood (1954) also tested American beech in both tension and compression. He covered wider ranges of temperature (from 80 to 160°F) and moisture content (from 6% to green) than Greenhill. The maximum tensile stress, stress at the proportional limit in compression, and tangential modulus of elasticity in tension and compression all decreased with
increasing temperature and moisture content. There was little
difference in Young's modulus between the results from the
tensile and compressive tests. The strain at the proportional
limit was almost constant with temperature, moisture content,
and loading mode (tension or compression).

Youngs (1957) evaluated the effects of moisture content
and temperature on the cross grain properties of Northern red
oak. His study included strength and modulus of elasticity
in tension, compression, and shear. He demonstrated that all
properties varied significantly with moisture content and
temperature. The functional relationships between the
strength properties and moisture and temperature could not be
represented by the exponential functions (Wilson, 1932). As
a result, Youngs established a different empirical equation to
describe both strength and modulus of elasticity for red oak.
This equation contains a quadratic relationship for moisture
content and a linear relationship for temperature.

Comprehensive testing on a native softwood species at
various levels of temperature and moisture content is not
available. Palka (1973) summarized test results from the
literature and proposed a unified system of equations for
predicting the elastic properties of softwoods in terms of
specific gravity, moisture content, temperature, and strain
rate. Those equations are of the following form for each of
the four variables:
(1). Specific gravity (0.1 < SG < 0.8):

\[ Y(SG) = Y_o \left( \frac{SG}{SG_o} \right)^{C_{SG}} = Y_1 \]  (2.1)

(2). Moisture content (0% < M < 30%):

\[ Y(SG,M) = Y_1 \left[ 1 + C_{MC}(M - M_1) \right] = Y_2 \]  (2.2)

(3). Temperature (T < 160°F):

\[ Y(SG,M,T) = Y_2 \left[ 1 + C_{TB}(T - T_2) \right] = Y_3 \]  (2.3)

(4). Strain rate (V > 0 feet per minute):

\[ Y(SG,M,T,V) = Y_3 \left[ 1 + C_{SR} (\log V - \log V_3) \right] = Y_4 \]  (2.4)

The equations involve the simplest, linearized functions for each of the four variables and are thus only an approximation of the real wood behavior. Considering the large natural variability of wood, the proposed system of equations and correction factors may be accepted as a first approximation for most softwoods.

Only a relatively small portion of the total stress-strain curve occurs below the proportional limit. In practice, it is impossible to dry wood without developing set and the stress-strain relation above the proportional limit is of great importance during drying when limiting conditions for defects are considered. Research into the nonlinear portion of the instantaneous stress-strain curve at high moisture content and elevated temperatures is, however, very limited for both hardwood and softwood species.
2.2.1.2 Time-Dependent Mechanical Creep

Drying of wood is not an instantaneous process. Time exerts a significant influence on the drying characteristics by introducing creep and stress relaxation (Youngs, 1957). These effects influence the shrinkage of wood and development of plastic deformation perpendicular to the grain, thus affecting stress development during drying. A typical creep strain versus time curve for wood is shown in Figure 2.2 (Bodig and Jayne, 1982).

![Creep curve of wood](image)

Figure 2.2. Creep curve of wood.

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1. Mechanical creep is defined throughout the text as the time-dependent deformation at a constant moisture content only.
The first part of this curve is known as the primary creep, a large portion of which is recoverable after unloading. The second part is identified as the steady or secondary creep, which possesses a linear creep strain-time relationship. The last part of this curve is called the tertiary creep where the strain rate increases until fracture occurs.

Extensive experiments have been conducted to investigate creep behavior of wood under tension, compression, bending and torsion parallel to the grain. Several literature studies in this area have been published (Schniewind, 1968; Grossman et al 1969; Holzer et al, 1988). The major experimental findings regarding the effect of moisture content, temperature and stress on creep may be summarized as follows:

1). Moisture in wood acts as a plastizer. An increase in moisture content usually leads to an increase in creep (Bach, 1965; Gnanaharan and Haygreen, 1979). The dependence of creep on moisture content, however, can be considerably reduced by expressing the creep deformation as a fraction of the instantaneous deformation:

\[
RC(t) = \frac{\varepsilon_T(t) - \varepsilon_I(t_o)}{\varepsilon_I(t_o)} = \frac{\varepsilon_C(t)}{\varepsilon_I(t_o)} \tag{2.5}
\]

where, RC(t) is known as relative creep (Dinwoodie, 1981).
The relative creep is almost independent of moisture content provided the moisture content does not change (Grossman et al, 1969). Thus, the creep function at a given moisture content could be approximately expressed as a product of the time-dependent relative creep measured at a reference moisture content and an instantaneous modulus of elasticity whose dependence on the moisture content is known from other tests (Grossman et al, 1969).

2). An increase in temperature leads to an acceleration of the creep (Davidson, 1962; Schaffer, 1972b). Time-temperature superposition principle, which states that the influence of changes in temperature is equivalent to shifts in the time scale (Findley et al, 1976), appears to be only valid for the completely dry wood (Schaffer, 1972b).

3). The effect of stress level on the linearity of creep varies with wood species and testing conditions. Under low moisture and temperature conditions, the linearity between creep and applied stress has been found with stress level up to 50% of the static strength (Kingston and Budgen, 1972; Kingston and Clake, 1961; Grossman and Kingston, 1963). At higher moisture and temperature, however, nonlinearity appears at the stress level as low as 20% of the ultimate strength (Bach and Pentoney, 1968).

The very limited evidence indicates that wood creeps at a much greater rate perpendicular to the grain than it does parallel to the grain (Gnanaharan and Haygreen, 1979;
Schniewind and Barrett, 1972). For American beech at 80°F and 6% moisture content in tension and compression perpendicular to the grain, Ellwood (1954) noted that at a stress level of 90% of the ultimate strength, creep occurred relatively rapidly in both tension and compression with the magnitude in compression being more than twice that in tension. His results also showed that an increase in temperature and moisture content results in a considerable increase of creep.

Youngs (1957) studied the creep and recovery of red oak with tensile and compressive stresses applied along the tangential direction. He used two moisture levels (12% and green) and two temperatures (80°F and 180°F) with the stress ranging from 40 to 80% of the ultimate static strength. Creep and recovery were found to be increased with increases in both moisture content and temperature. The effect of raising the temperature from 80°F to 180°F at 12% moisture content leads to a considerable increase in nonrecoverable creep.

Difficulty in studying creep perpendicular to the grain under direct tension and compression lies in the fact that a large dimensional movement due to change in the moisture content exists in those material directions. For example, the published shrinkage or swelling coefficients for Douglas-fir are 0.0027 per percent moisture change in tangential direction and 0.0016 in radial direction (Forest Products Laboratory, 1987). Thus, the ability to maintain the steady-state testing environments over a sustained period of time for those tests
is extremely important. Otherwise shrinkage or swelling due to change in moisture content would confound the creep measurements. Both Youngs (1957) and Rice and Youngs (1987) encountered this problem in their measurements on red oak using conventional methods to control the surrounding humidity. As commented by Youngs (1957), the actual moisture content for his creep data at 180°F was significantly lower than the nominal value of 12%.

2.2.1.3 Moisture Change-Dependent Shrinkage and MS Effect

Tests with wood under load during moisture change always indicate an accelerated deformation due to the existence of MS effect (Armstrong and Kingston, 1962; Hearmon and Paton, 1964). Under tension or compression, the effect is seen as an decrease or increase in the amount of shrinkage or swelling associated with a moisture content change. Thus, the additional deformation under those loading conditions consists of two parts: inherent shrinkage or swelling due to losing or gaining moisture in the hygroscopic range; and MS effect due to stress and its interaction with moisture content change.

1. Inherent Shrinkage

The inherent shrinkage is the dimensional change of wood which would occur as a result of moisture loss in absence of
any restraint. This unrestrained condition can be approximately satisfied in the slow drying of thin wood slices, where the thickness is the moisture flow direction and the moisture gradient in this direction can be neglected. Figure 2.3 shows a typical shrinkage-moisture content relationship for noncollapsing wood species (CSIRO, 1965).

![Figure 2.3. Shrinkage-moisture content relation of wood for noncollapsing species (CSIRO, 1965).](image-url)
As indicated by the almost vertical alignment of the curve at the left-hand side of the graph, during the early stages of drying green wood, the moisture is lost without any appreciable change in dimension. However, as the moisture content falls below about 30%, the amount of shrinkage progressively increases until a moisture content of about 20% has been reached. It then attains a fairly constant rate and the graph becomes a straight line.

2. Mechano-Sorptive Effect

Mechano-sorptive effect was coined to convey succinctly that mechanical influences combine with moisture sorption to produce a response that cannot be predicted from the response to each influence separately (Grossman, 1976). The strain so induced differs from mechanical creep strain in a variety of aspects. For example, creep depends on the duration of loading, while the mechano-sorptive deformation at a constant stress is not directly dependent on the time. When the moisture content of the loaded wood changes rapidly, deformation increases rapidly, but the final deformation depends on the moisture step and is little affected by the duration of the process.

Experiments indicate that the mechano-sorptive effect is seen in hardwood species prone to collapse from the green state to the air-dry condition. For softwoods, there appears
to be almost no change from green to the FSP, then it is almost linearly related to moisture content between the FSP and air-dry conditions (Armstrong, 1983). No reasonable explanation has been advanced for this difference in behavior between the two types of species.

The mechano-sorptive effect is found to vary with the loading direction (parallel or perpendicular to the grain) and loading modes (tension, compression, or shear). In the direction of the grain, compression causes more mechano-sorptive deformation than tension. When the moisture content of wood under stress is cycled, except the increase in deformation when the wood is initially subjected to a rise or decrease in moisture content, each reduction in moisture content leads to an increase in deformation, and each increase in moisture content leads to some reduction in deformation. The final deformation at the end of each cycle gradually increases in magnitude (Armstrong and Kingston, 1962). Subsequent tests indicate that beams crept to failure at about 1/3 ultimate load after several complete cycles in humidity (Hearmon and Paton, 1964). The bulk of mechano-sorptive strain is retained after the removal of stress. A large part of the strain is, however, recoverable after removal of the primary activating force when the wood is taken through another moisture cycle (Armstrong and Kingston, 1962).

Temporary breaking and reforming of hydrogen bonds, allowing molecular chains to move while a polymer is under
stress are often advanced as the mechanism for the mechano-
sorptive effect. Supporting these concepts, Armstrong (1972) 
showed that the MS effect is associated with moisture content 
changes (and hence volume changes), not a steady-state 
moisture movement. In compression, slip-plane formation 
(Hoffmeyer and Davidson, 1989) in the wood cell wall may 
contribute to the MS effect. This may be why the magnitude of 
the MS effect is greater in compression than tension.

During lumber drying, development of the MS effect 
perpendicular to the grain acts to relieve stress and reduce 
fauxts which can arise from high internal stresses. The 
effect is similar to normal creep. However, since MS effect 
may be many times larger than the creep deformation, it has a 
more profound influence on the stress development.

Limited studies have been conducted to investigate the 
effect in the directions perpendicular to the grain. 
Takahashi and Yamada (1966) studied the effect with Japanese 
Hinoki-wood. Test specimens (about 0.8 inches thick), loaded 
in tension at several stress levels, were dried from a 
moisture content of 140% to 3% at 176°F. For both radially 
and tangentially loaded specimens, the drying set or reduced 
shrinkage under tension (containing mostly the MS effect) was 
increased with an increase in the applied load. Since large 
 specimens were involved in those tests, which certainly 
resulted in a considerable moisture gradient across specimen 
thickness, it is difficult to establish the quantitative
relationships between the set strain and moisture content change in wood.

For beech at 68°F and 30% of ultimate tensile strength in the tangential direction, Schniewind (1966) demonstrated a large increase of the creep strain when the moisture content was changed. He showed that the increase in the strain appears to be linearly related to the extent of moisture content change. With equal moisture content steps, the strain increase was independent of the position of the change within the hygroscopic range, the rate of change, previous creep at a constant moisture content.

Erickson (1989) reported test results on red oak under both tensile and compressive loading conditions. At a constant stress level of about 10% of green tensile strength, the drying sets under tension and compression were shown to increase with temperature. However, his data suggested that the set under tension was significantly larger than that under compression at the same temperature, which seems to be contradictory to many published studies.

Rice and Youngs (1987) studied the MS effect with red oak at 110°F under tension. A large increase in tensile strain was observed with moisture content change, but the effect of increasing stress levels was shown to be small.

Further systematic study of this phenomenon at elevated temperatures and different levels of stress is highly desirable for modeling the process of drying lumber. However,
the complex nature of shrinkage and swelling of wood under direct tension and compression during moisture change requires special considerations in the experimental techniques:

1. As temperature increases, increasing difficulty is expected in controlling the specified humidity over a sustained period of time using the conventional methods. It would be comparatively easier, however, to carry out tests in absence of air and to control and measure the pressure of water vapor alone. In such a way, the boundary layer problems associated with air flow are eliminated, since the water vapor flows unimpeded to the surface of the specimen and into wood capillaries under its own pressure gradient and not by diffusion (Christensen, 1962). Also, change of the surrounding humidity as required for moisture change and matching the moisture sorption histories among different tests could be more easily achieved.

2. Most of the electrical strain measuring devices would not work properly under the condition of high temperature and humidity. As a result, the development of noncontacting techniques for strain measurement is highly desired. In such a way, a reliable strain measurement could be made for tensile and compressive tests with small thin specimens, in which moisture content changes may be effected without introducing appreciable moisture content gradients.
2.2.2 Constitutive Modeling

Parallel to the experimental efforts on the wood deformation under combined mechanical and moisture loading, constitutive equations for such a process have been proposed by a number of researchers.

Leicester (1971) proposed a first rheological model for the deflection of beams under bending during moisture change. The model consists of an elastic element connected in series with an mechano-sorptive element. The total deflection of the beam is related to the applied load as:

\[ \delta = K P + \int [P f(M) dM] \tag{2.6} \]

where, \( f(M) \) is a material constant which may vary with range of moisture content change.

Experimental verification of this model indicated that the model contributed about 85% of the total deflection of the beams in drying under load over a two-week period. The study is one of the first attempts to mathematically model the MS effect. The model in this form, however, ignores the mechanical creep component and predicts zero recovery after unloading.

Schaffer (1972a) considered the effect of the actual moisture content and effect of diffusion of moisture past a point on the strain rate. He proposed that moisture acts as a swelling agent and has a similar effect as the temperature in reducing the energy needed to strain a solid. Also, the
migration of water molecules into and out of a gel substance weakens the cohesive forces of the gel, thereby promoting molecular position change in the direction of an applied load. Additional terms were thus added to the temperature and stress-induced strain rate equation for the moisture effect:

\[
\frac{de}{dt} = A \left[ 1 + \frac{dM}{dt} \right] \text{EXP}\left[ -\frac{Q}{RT} + B \psi + C M \right]
\]

(2.7)

where, A, B and C are the material constants; T is in °K.

Equation 2.7 describes the effect in qualitative agreement with the experimental findings. However, it involves several constants which are difficult to evaluate experimentally. A simplified form of Equation 2.7 was used to model the process of press drying (Tang and Simpson, 1990).

Ranta-Maunus (1975) extended the multiaxial constitutive equation for a linear viscoelastic material:

\[
e_{ij}(t) = \int_{0}^{t} J_{ijkl}(t-\tau) d\sigma_{kl}(\tau)
\]

(2.8)

into a multiple integral polynomial according to Volterra-Frechet theory. The extended equation is simplified for an isothermal condition by only taking the linear terms for stress and moisture as well as the first and second order terms for stress-moisture coupling. He proposed to use a dimensionless "hygroviscoelastic constant" to quantify the ratio of change of compliance to change of moisture content. In order to describe the phenomenon, three different values of the constant are needed: a' quantifying the effect of
moisture reduction; $a^{**}$ quantifying the effect of first moisture increase at any moisture level, and $a^{+}$ quantifying any subsequent moisture increase at the same moisture level. When compared to published experimental results, the model is capable of predicting the strain response to stress in the linear range under changing and even under cycling moisture content.

Bazant (1985) proposed a model based on thermodynamics of water diffusion in wood for the effects of moisture content and temperature on creep. It is proposed 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. The model reflects qualitatively some experimental results. Quantitative fitting of test data was not attempted.

Mårtensson (1988) measured the tensile deformation of hardboard under load during moisture change, from which a constitutive model is suggested and quantified on the basis of test data. In the formulation, the strain rate is taken to be a function of stress, moisture and their time derivatives:

$$\frac{de}{dt} = F(\sigma, \frac{d\sigma}{dt}, M, \frac{dM}{dt})$$

$$= \frac{\sigma}{\eta(M)} + \frac{1}{E(M)} \frac{d\sigma}{dt} + [f(M) + k(M) \sigma] \frac{dM}{dt}$$

(2.9)
where $\eta, E, f$, and $k$ are the material constants varying with moisture content of wood at a given temperature.

To predict the material behavior, Mårtensson uses an eight-element Kelvin chain (Figure 2.4) to replace the dashpot and expresses the constants as a function of moisture content. In handling the MS effect, the author assumed that the parameter $k$ is nonzero only for the first change in moisture content. Subsequent changes in moisture content lead to the MS effect only when the moisture reaches values not earlier attained. Since the MS effect is of major importance only during the first moisture cycle, the model describes the tensile deformation of hardboard at room temperature quite satisfactorily.
2.3 Modeling of Stresses in Drying of Lumber

A qualitative understanding of stress development during wood drying was formulated as early as 1917 by Tiemann, and by 1940 a slicing technique for measuring drying strains was developed by Peck (1940). Since that time, perhaps 30 researchers have attempted to mathematically model the stresses. From the above discussion of the mechanical properties of wood, it should be clear that a purely elastic constitutive relation cannot be applied to wood drying. Thus, only those investigations addressing the plastic and/or rheological properties of wood are covered below.

Lesse (1972) and Lesse and Kingston (1972) examined the problem of drying stress development in terms of the similarity between thermal- and moisture-related stresses. The thermal stress equations, which are developed from energy and moment balances, are interpreted in terms of moisture loss. The resulting stress is responsible for the development of elastic and plastic strain during drying. The Lesse and Kingston model is a purely theoretical approach to the computation of stress in terms of thermal conditions and moisture gradients. Some attempts are made to compare the model output to the data for oak reported by McMillen (1955a).

Ashworth (1979) developed a one-dimensional stress model for the drying of softwoods. The model follows a linear elastic stress-strain relation up to a pre-set yield point,
beyond which a plastic strain begins to appear and acts to relieve the stress. Both elastic and plastic strains are coupled using elastic/plastic parameters, which result from the temperature and moisture distributions during drying. The model of Ashworth has no experimental basis and elements such as creep and MS effect are not considered. Material constants used in the simulation are taken from literature, apparently without regard to species or drying conditions under which they were determined.

Kawai et al (1979) developed a method for evaluating drying stresses for a two-dimensional stress state. For simplification, moisture movement was assumed to be one-dimensional along the longitudinal direction and a plane stress state in the transverse plane was used. It needs to be pointed out here that both assumptions are not valid when drying long lumber boards. The calculations were done using a linear elastic constitutive equation for the orthotropic materials. The required elastic strain components were implicitly expressed through relationships among the observed shrinkage (i.e. board shrinkage), basic shrinkage, and inelastic strains. Those relationships were developed from the specific experiments by relating the strains to moisture content or time. The inelastic strain was taken to be a combination of mechano-sorptive and creep strains and was measured using beams stressed parallel to the grain within the linear range. Graphs of stress produced by the model agree
well with the expected stress pattern. However, the model requires the board shrinkage across the thickness as one of the input functions, which is related to specific testing conditions and is not known until the wood is dried. Thus, the model has no general application in terms of limiting drying related defects.

Lessard et al (1982) developed a one-dimensional model for drying red oak. The model assumes that the total strain consists of an elastic, a plastic and shrinkage strain. An elasto-plastic force deformation relationship is used to connect three strain components. The determination of the total strain at any given time is as follows. First, the elastic strain is determined using the stiffness given by Youngs (1957) as a function of temperature and moisture content. If the calculated stress does not exceed the elastic limit for the given moisture and temperature conditions, the strain is assumed to be entirely elastic. If the calculated stress exceeds the elastic limit, the next step is to calculate a stress relieving plastic strain. The graphs which compare the model prediction with experimental results show a good agreement with McMillen's experimental data (McMillen, 1955b) after considerably adjusting the plastic flow term. However, the model is only based on an elasto-plastic force deformation relationship, in which the creep and MS effect components are ignored. This simplification leads to an overestimate of the stress in the early stage of drying. An
attempt has been made to include creep into the model, but an unrealistic estimate of the stress after stress reversal is obtained.

Morgan et al (1982) established a constitutive model on the basis of an elasto-viscoplastic stress strain relationship under a plane strain state. The total strain is taken to be the sum of elastic, plastic, and initial (i.e. shrinkage) strains. Elastic strains are produced on the first application of a load and their rates are linearly related to the total stress rate by the matrix of elastic constants. Viscoplastic strains take place when the stress levels exceed some previously defined yield stress. The relationship between the various strain components is related by a plastic potential, whose gradient gives the direction of straining. The model is used to investigate stress reversal as affected by rate of moisture loss and the variation of model parameters with moisture content. After a considerable adjustment of the model parameters, the curves presented show the general moisture distributions and overall patterns of stress and strain which are expected during drying. The finite-element solution in this model can offer certain advantages for a material with more complex geometries. Also, the use of the coupled heat and mass transfer equations of Luikov (Luikov, 1966) represented a major advances in the determination of the moisture distributions. However, the assumption of the model is that wood is isotropic. Also, the MS effect is ignored.
Thus, it is not possible to justify the accuracy of the model prediction under actual drying conditions.

Oliver (1984) developed a one-dimensional model for drying Australian Eucalyptus. The total strain from moisture loss during drying is based on the model of Leicester (1971) and consists of nonlinear elastic, creep, shrinkage, and mechano-sorptive components. The input data used in the model for creep and mechano-sorptive effect are taken from beams tested in the longitudinal direction. The variation of the Young's modulus with moisture and temperature is assumed to be the same as American beech reported by Ellwood (1954). These data are then multiplied by various constants to simulate conditions in the radial or tangential direction. Oliver's model involves a set of constants which are determined from experience and the use of data from longitudinally loaded beams does not represent the same coordinate in which stresses occur during drying. However, the model clearly differentiates and computes values for each of the major strain components. In this respect, the model becomes one in which the contribution of individual strain components may be evaluated under the varying conditions.
III. ANALYTICAL APPROACH

The primary objective of the study was to determine the stresses and strains that develop inside lumber during the process of drying. However, since the relevant analysis requires a knowledge of the behavior of individual thin wood layers, models were first developed for the stress-strain relationship of a small wood sample subjected to combined mechanical and moisture loading, both of which may vary with time in an arbitrary manner. Individual models for various strain components were then combined to predict the stress and strain developed in the process of drying large pieces of lumber boards.

It is noted that the constitutive equations for wood under combined mechanical and moisture loading have been proposed by Leicester (1971), Ranta-Maunus (1975), and Bazant (1985). However, the range of validity of those models with general stress and moisture variation is not known with certainty. Also, relatively less attention has been paid to the behavior in the directions perpendicular to the grain at the temperature and humidity conditions usually encountered during wood processing.
3.1 Stress-Strain Relation of Small Wood Samples

3.1.1 Basic Concept and Definitions

Before the stress-strain relationship was derived, the general behavior of a small wood sample subjected to combined mechanical and moisture loading was examined through an example. In this example, the wood specimen of uniform temperature and moisture content was subjected at time $t = t_0$ to a constant compressive load (Figure 3.1a). The moisture content of the wood remains constant at $M_0$ from $t = t_0$ to $t = t_1$ and decreases gradually to $M_f$ from $t = t_1$ to $t = t_2$ (Figure 3.1b).

From the time of loading up to $t_1$, the strain developed in the specimen may exhibit the behavior shown in Part A of Figure 3.1c. There is an instantaneous or time-independent strain ($\epsilon_{i_0}$). This portion is followed by a creep strain ($\epsilon_c$) which depends on time in a nonlinear manner. Frequently, the sum of $\epsilon_{i_0} + \epsilon_c$ is called creep strain. Here, the terminology creep strain denotes only the component $\epsilon_c$.

Due to changes in moisture content from time $t_1$ to $t_2$ while the specimen is under load, wood deformation is accelerated considerably (Part B of Figure 3.1c). Under such conditions, two additional strain components can be identified, namely inherent shrinkage strain ($\epsilon_s$) and mechano-sorptive effect ($\epsilon_M$). Also, the instantaneous strain and rate
Figure 3.1. Decomposition of total strain ($\varepsilon_t$) into instantaneous ($\varepsilon_i$), creep ($\varepsilon_c$), shrinkage ($\varepsilon_s$), and mechano-sorptive ($\varepsilon_m$) strain components. (a) load function, (b) moisture function, and (c) strain.
of mechanical creep strain change with time due to change in the moisture content of wood, which results in changes in the cross section area and modulus of elasticity.

Thus, following previous investigators (e.g. Leicester, 1971), the total strain arising from combined mechanical and moisture loading at a particular time is expressed as:

$$\varepsilon_T = \varepsilon_I + \varepsilon_C + \varepsilon_S + \varepsilon_M$$  \hspace{1cm} (3.1)

For clarity, the time index has been omitted from all the equations in this section. Thus, unless noted otherwise all variables apply at time t. The thermal strain has been ignored in the above analysis as the dimensional changes of lumber caused by differences in temperature are negligibly small when compared to changes in dimensions resulting from the uptake or loss of moisture (Dinwoodie, 1981). The model formulation for each strain component is presented as follows.

3.1.2 Constitutive Modeling

When forming a constitutive equation for each of the strain components, the following assumptions were made:

1). The various strain components are independent of each other, i.e. they are separably measurable and linearly additive.
2). Moisture and temperature across the thickness of a thin wood sample are uniform and uncoupled from the stress state of the wood.

3). Under the action of stress, the wood sample acts as an orthotropic but homogeneous material. It is known that presence of earlywood, latewood and some other localized imperfections makes wood inhomogeneous no matter how small the sample size is. Separation of the individual contribution is, however, infeasible under the present conditions. Rather, a lumped behavior for the carefully selected clear wood samples is considered.

3.1.2.1 Instantaneous Strain

The instantaneous stress-strain relationship is formulated on the basis of the model originally proposed by Holmquist and Nadai (Bodig and Jayne, 1982). Under the sole action of either a tensile or compressive stress, the model consists of two portions, namely, a linear part to the proportional limit (or yield point) followed by a nonlinear part to failure. Mathematically, the model has the form:

\[ \varepsilon = \frac{\sigma}{E} \quad \text{for} \quad |\sigma| \leq \sigma_y \]  \hspace{1cm} (3.2)

\[ \varepsilon = \frac{1}{E} [\sigma + k y (\sigma - \sigma_y)^{n_y}] \quad |\sigma| > \sigma_y \]  \hspace{1cm} (3.3)

where, \( k_i \) and \( n_i \) are the material constants.
The material properties (E and $\sigma_y$) appearing in Equations 3.2 and 3.3 correspond to the specific conditions of moisture, temperature, and loading mode. During lumber drying, it is well known that strength of the clear wood increases as the moisture content decreases. The material properties, therefore, vary with moisture or indirectly drying time.

Because of the dependence of the material properties on the moisture and temperature of wood, Equations 3.2 and 3.3 can not be directly applied to wood drying where spontaneous changes in both stress and moisture are involved. Under such circumstances, it is convenient to replace the smooth and nonlinear stress-strain curve by a curve consisting of straight line segments. Within each line segment, the change in instantaneous strain is taken to vary linearly with the change of stress. The proportionality, i.e. the local modulus of elasticity, can be taken to vary with the local values of moisture content, temperature, and/or stress. Thus, the stress-strain relations defined by Equations 3.2 and 3.3 were rewritten in the rate form as:

$$\dot{\epsilon}_I = D_I \sigma$$  \hspace{1cm} (3.4)

where $D_I$ is the instantaneous compliance. The compliance is obtained by differentiating Equations 3.2 and 3.3 with respect to stress. For the loading process (i.e. absolute value of the stress increases with time) and unloading process (i.e. absolute value of the stress decreases with time) during wood drying, the compliance is:
As shown in Equation 3.5, in the linear loading and unloading parts of the instantaneous stress-strain curve (Figure 2.1), the compliance is just a reciprocal of the modulus of elasticity, which varies with moisture content of wood. Beyond the proportional limit, i.e. within the nonlinear part of the curve, however, the compliance depends on both modulus of elasticity and stress. The manner in which Equation 3.5 can be used to estimate the instantaneous compliance under the varying moisture and stress conditions is further described in the later sections.

3.1.2.2 Mechanical Creep Strain

The mechanical creep strain is modeled with the Bailey-Norton equation (Kraus, 1980):

\[ \varepsilon_{C} = k_{C} e^{-\frac{Q}{RT}} o^{n_{C}} t^{n_{C}} \]  \hspace{1cm} (3.6)

where, \( T \) is temperature in °K. The exponential term of Equation 3.6 represents the effect of temperature under
nonisothermal conditions. At an isothermal condition, the effect of temperature is usually lumped into the material constants.

Equation 3.6 is used to mathematically model the primary and secondary parts of creep under a constant stress. Drying of wood, however, involves a continuous variation in stress across the board thickness. To predict creep under these varying stress conditions, the smooth stress-time curve is often approximated by horizontal and vertical segments. Within each segment, stress is assumed to be constant so that Equation 3.6 in an incremental form can be applied.

For nonlinear creep under a varying stress history, two approaches are available to calculate the creep increment from Equation 3.6, namely time-hardening and strain-hardening (Kraus, 1980). Graphical representation of the principle in determining the creep using those two approaches is presented in Appendix B. For the present study, the time-hardening principle is used.

Thus, using the Bailey-Norton equation (Equation 3.6) for the isothermal condition, the creep strain rate from the time-hardening principle is obtained as:

\[ \dot{\varepsilon}_c = k_c n_c \sigma \sigma_c^{n_c-1} \]  

(3.7)

and the creep increment is:

\[ \Delta \varepsilon_c = k_c n_c \sigma \sigma_c^{n_c-1} \Delta t \]  

(3.8)
During drying, most parts of the lumber undergo stress reversal, i.e. stress changes from tension (or compression) to compression (or tension). Under such a circumstance, the hardening rules described above can not be directly applied from the point of stress reversal. This can be shown by considering a simple case of an uniaxial creep specimen subjected first to a tensile stress and then to a compressive stress. During the tensile portion of the loading strain hardening occurs, and the hardening procedure would predict that upon changing to the compressive loading, this accumulated strain hardening would be retained. For example, if the secondary creep portion of creep response has been reached in tension, the strain hardening procedure would predict a compressive creep response beginning in the secondary creep region, which is obviously incorrect. Thus, an auxiliary rule must be employed along with hardening rule. In the present study, the method proposed by Kraus (1980) was used, which assumes that upon changing loading mode, hardening accumulated in the previous loading would be lost, that is the creep response under the new loading mode would exhibit primary creep similar to the case of a virgin specimen. This process proceeds until the creep strain accumulated previously is completely balanced out by the creep produced under new stress mode.

A further complication arises from the fact that moisture content of the wood changes at each time step in the situation
of drying wood. It is known that at the higher moisture content level, creep develops faster. The effect of variation in the moisture content can be approximately accounted for by using the concept of relative creep, which is not strongly affected by the moisture level (Grossman et al, 1969) at a given temperature. The creep increment obtained during each time increment from a reference moisture content \( (M_r) \) is thus adjusted for the current moisture content \( (M) \) through a ratio of initial modulus of elasticity under those two moisture contents. Mathematically, this is expressed as:

\[
\Delta \varepsilon_c|_M = \frac{E(M_r)}{E(M)} \Delta \varepsilon_c|_{M_r} \tag{3.9}
\]

where the initial modulus of elasticity as a function of moisture content and temperature could be more easily estimated. In the process of drying wood, the stress required for determining the creep increment within each time step is not known at the beginning of the step. Thus, an iterative solution has to be used, and the details of the solution method are described in a later section.

Equations 3.8 and 3.9 allow the approximate definition of the creep strain occurring in the drying of lumber. Creep tests corresponding to a constant moisture level at different stress levels and temperatures were conducted, from which the material constants namely \( k_c, m_c, \) and \( n_c \) were determined following the procedure outlined in Appendix C.
3.1.2.3 Shrinkage Strain

The model formulation for the shrinkage strain follows the concept of "free" and "bound" water in wood, depending whether or not there are bonds between the water molecules and cellulose molecules. It states that there is no shrinkage until the moisture content reaches a fiber saturation point, then there is a volumetric shrinkage with decreasing moisture content roughly equal to the volume of water removed. This concept leads to a simple model on the shrinkage rate as:

\[
\dot{e}_S = \begin{cases} 
0 & \text{for } M \geq M_{\text{FSP}} \\
\frac{M}{k_s} & \text{for } M < M_{\text{FSP}} 
\end{cases} \tag{3.10}
\]

where the material constant \( k_s \) may depend on the range of moisture content change below the FSP, but is independent of stress. The material constant \( k_s \) can be estimated with experimental data and regression analysis.

3.1.2.4 Mechano-Sorptive Strain

Mechano-sorptive strain is modeled using:

\[
\dot{e}_M = k_M \sigma |\dot{M}| \tag{3.11}
\]

where the material constant, \( k_M \), may vary with temperature, range of moisture change, and stress. Since the test data clearly indicate that the mechano-sorptive effect is more
significant in compression than in tension, the constant $k_m$ also takes different values for tension and compression.

The experimental determination of the material property $k_m$ at different stress levels and temperatures is described in a later section. Since the total strain from individual tests also contains other strain components, namely instantaneous, creep and shrinkage, a procedure was adopted to isolate the MS strain from the total strain (Appendix D).

3.2 Distribution of Moisture and Temperature

3.2.1 Assumptions

In order to calculate the drying stresses and strains, the moisture and temperature distributions inside a piece of lumber must be known. The forest products literature contains extensive studies on the heat and mass transfer within the wood as related to the process of drying (Stanish et al, 1986; Hart, 1981; Bramhall, 1979). The present study is thus focused only on the stress and strain development in drying of lumber. It is assumed that the changes in moisture and temperature distributions strongly influence the stress and strain fields, but the movement of moisture and heat is much less dependent on the stress field and can be ignored. The distributions of moisture and temperature were actually obtained from the direct measurement during drying and were fitted by the following procedure into the continuous functions.
3.2.2 Data Fitting

The diffusion equation was used with regression analysis to generate moisture content profiles which matched measured data points. The diffusion equation was used because the green moisture content of Douglas-fir heartwood (used in the present study) is close to the FSP. Therefore, the moisture movement may be treated as a combined diffusion process of bound water and water vapor, in which the lumped diffusion coefficient depends on the local moisture content and temperature of wood. The diffusion equation, generally called Fick's Law, is for one-dimensional moisture flow:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial M}{\partial x} \right)$$  \hspace{1cm} (3.12)

The solution requires the moisture distribution before drying as the initial condition, moisture content at the board surface during drying as the boundary condition, and the diffusion coefficient as a function of moisture content and temperature of the wood. The initial moisture distribution was obtained by direct measurement before drying. The surface moisture content as a function of drying time was obtained by fitting the measured data with the equation (Crank, 1975):

$$\frac{M(t, 0) - M_{EFC}}{M(0, 0) - M_{EFC}} = e^{-(\alpha t^\beta)}$$  \hspace{1cm} (3.13)

where, $\alpha$ and $\beta$ are the regression constants.
The initial value of diffusion coefficient as a function of moisture content and temperature was obtained from Siau (1984). Third order polynomials for the diffusion coefficient varying with moisture content at a given temperature:

\[ D(M) = c_1 + c_2 M + c_3 M^2 + c_4 M^3 \]  \hspace{1cm} (3.14)

were fitted to Siau's data for temperatures ranging from 20 to 100°C. The coefficients were later adjusted to match measured moisture profiles under specified drying conditions.

Because the diffusion coefficient and boundary conditions vary with time, the Crank-Nicholson finite difference method (Crank, 1975) was used to solve Equation 3.12. The equation was rewritten as the approximate difference equation according to the grid pattern shown in Figure 3.2:

\[
\frac{M(i,j) - M(i-1,j)}{\Delta t} = \frac{1}{\Delta x} \left[ \frac{D(i, j+\frac{1}{2}) [M(i, j+1) - M(i, j)]}{2\Delta x} + \frac{D(i, j-\frac{1}{2}) [M(i, j-1) - M(i, j)]}{2\Delta x} \right] \\
- \frac{1}{\Delta x} \left[ \frac{D(i-1, j+\frac{1}{2}) [M(i-1, j+1) - M(i-1, j)]}{2\Delta x} + \frac{D(i-1, j-\frac{1}{2}) [M(i-1, j-1) - M(i-1, j)]}{2\Delta x} \right] 
\]  \hspace{1cm} (3.15)

where \( i=1...t/\Delta t \) is the time index, and \( j=0...2N=2X/\Delta x \) is the spatial index across board thickness.
Figure 3.2. Physical aspect of process model. (a) lumber board, (b) one-dimensional mesh, (c) Crank-Nicholson finite difference scheme.
After rearranging, Equation 3.15 becomes:

\[-\frac{1}{2} \lambda D(i, j+\frac{1}{2}) M(i, j+1) + [1 + \frac{1}{2} \lambda D(i, j+\frac{1}{2}) \]
\[+ \frac{1}{2} \lambda D(i, j-\frac{1}{2}) M(i, j) - \frac{1}{2} \lambda D(i, j-\frac{1}{2}) M(i, j-1) \]
\[= \frac{1}{2} \lambda D(i-1, j+\frac{1}{2}) M(i-1, j+1) + [1 - \frac{1}{2} \lambda D(i-1, j+\frac{1}{2}) \]
\[- \frac{1}{2} \lambda D(i-1, j-\frac{1}{2}) M(i-1, j) + \lambda D(i-1, j-\frac{1}{2}) M(i-1, j-1) \]

(3.16)

where the constant \( \lambda=\Delta t/(\Delta x)^2 \).

In Equation 3.16, the diffusion coefficient at the middle of two grid points is evaluated as:

\[D(i-1,j+\frac{1}{2}) = \frac{D(i-1,j) + D(i-1,j+1)}{2} \]
\[D(i-1,j-\frac{1}{2}) = \frac{D(i-1,j-1) + D(i-1,j)}{2} \]

(3.17)

\[D(i,j+\frac{1}{2}) = \frac{D(i,j) + D(i,j+1)}{2} \]
\[D(i,j-\frac{1}{2}) = \frac{D(i,j-1) + D(i,j)}{2} \]

Since \( D(i,j) \) is not known until the values of \( M(i,j) \) are known, an iteration procedure has to be used at each time step. Thus, Equation 3.16 together with the diffusion coefficient defined by Equation 3.17 forms a set of simultaneous algebra equations at a given time, from which moisture content profile across board thickness could be obtained through the matrix operation.
3.3 Stresses and Strains in Drying of Lumber

3.3.1 Method of Analysis

The overall board shrinkage strain in the board width direction was decomposed into instantaneous, creep, shrinkage and MS strain components. From Equation 3.1, one has at time $t_{i-1}$:

$$\varepsilon_T(i-1,j) = \varepsilon_I(i-1,j) + \varepsilon_C(i-1,j) + \varepsilon_S(i-1,j) + \varepsilon_M(i-1,j)$$

(3.18)

where $i$ is the time index, $j$ is the spatial index (Figure 3.2). Similarly, at time $t_i$:

$$\varepsilon_T(i,j) = \varepsilon_I(i,j) + \varepsilon_C(i,j) + \varepsilon_S(i,j) + \varepsilon_M(i,j)$$

(3.19)

Defining:

$$\Delta \varepsilon_T(i,j) = \varepsilon_T(i,j) - \varepsilon_T(i-1,j)$$

$$\Delta \varepsilon_I(i,j) = \varepsilon_I(i,j) - \varepsilon_I(i-1,j)$$

(3.20)

etc.

the governing equation in an incremental form becomes:

$$\Delta \varepsilon_T(i,j) = \Delta \varepsilon_I(i,j) + \Delta \varepsilon_C(i,j) + \Delta \varepsilon_S(i,j) + \Delta \varepsilon_M(i,j)$$

(3.21)
Subject to the conditions of geometric compatibility and force equilibrium, the governing equation 3.21 can be solved over an incremental time step to yield the stress and strain increments associated with given moisture and temperature profiles. In a one-dimensional model, the geometric compatibility condition means that the total strain in the board width direction for each thin layer across the board thickness must be the same. This implies that the edges of the board remain plane in drying, which is approximately valid for drying wide planks of wood. Geometric compatibility can be mathematically expressed as:

\[ \varepsilon_T(i, j) = \varepsilon_T(i) \]

(3.22)

\[ \Delta \varepsilon_T(i, j) = \Delta \varepsilon_T(i) \]

Force equilibrium condition requires that the integral of the net force in the width direction through the thickness be equal to zero:

\[ \int_0^x \sigma(i, j) W \, dx = 0 \]

(3.23)

\[ \int_0^x \Delta \sigma(i, j) W \, dx = 0 \]

where \( W \) is the board width.
3.3.2 Method of Solution

The procedure outlined in Figure 3.3 (Ha and Springer, 1989; Oliver, 1984; Zienkiewicz, 1977) was used to calculate drying stress and strain at time \( t_i \). The calculations are performed in an incremental time interval from \( t_{i-1} \) to \( t_i \). Within each time interval the calculation proceeds along the major steps described as follows.

1. The moisture and temperature distributions across the board thickness at time \( t_i \) are determined from the specified moisture-time and temperature-time histories. From those, the moisture and temperature changes over the time step are determined:

\[
\Delta M(i,j) = M(i,j) - M(i-1,j) \\
\Delta T(i,j) = T(i,j) - T(i-1,j)
\]

2. The increments for various strain components are estimated through an iterative procedure as follows.

Instantaneous strain increment is obtained from Equation 3.4:

\[
\Delta e_i(q,j) = D_i(q - \frac{1}{2}, j) \Delta \sigma(q,j)
\]

where \( q \) is the number of the iteration \((q=1,2,3,...)\) within a time step. The zero value for the time index represents the properties at time equal to \( t_{i-1} \), i.e. the beginning of the
1. Start with $t_{i-1}$ to $t_i$
   Determine $\Delta M(i,j)$, $\Delta T(i,j)$

2. Estimate strain increment for each strain component

3. Set up equilibrium and compatibility equations

4. Estimate overall shrinkage strain increment

5. Estimate stress increment

6. Update stress and strain

7. Perform convergence test

8. Failure prediction

9. Output results

10. Next time step

Figure 3.3. Solution procedure for calculating stress and strain in lumber drying.
current time step. \( D_1(q-0.5,j) \) in Equation 3.25 represents the mean value of the instantaneous compliance over the time step and is defined as:

\[
D_i(q-\frac{1}{2},j) = \frac{D_i(q,j) + D_i(0,j)}{2}
\]  

(3.26)

The instantaneous compliance \( D_i(q,j) \) as a function of local moisture, temperature, and/or stress is obtained through Equation 3.5 depending on whether the point is being loaded (linear or nonlinear) or unloaded (linear). In the linear stress-strain range, \( D_i(q,j) \) is only a function of local moisture content and temperature. Over the range of the nonlinear stress-strain relation, however, both local stress and moisture values at time \( t_i \) are required to estimate the compliance. Since the stress is not known at this point, \( \sigma(0,j) \) is used in the first iteration. Subsequent iterations use the stress value obtained in the previous one.

Creep strain increment is obtained from Equation 3.8 using the time-hardening principle as:

\[
\Delta \varepsilon_c(q,j) = k_c n_c [\sigma(q,j)]^{n_c} t^{n_c-1} \Delta t
\]  

(3.27)

After the stress reversal is determined for a particular point, the time index is reset for that point. Thus, the effect of changing stress mode is accounted for when estimating the creep increment for next time step. The obtained creep increment is adjusted for the effect of
moisture content change through Equation 3.9 with the known local instantaneous compliance or modulus. The current local stress value required in Equation 3.27 is unknown. Therefore, the stress at time index zero is used in the first iteration to estimate the creep increment. The stress is updated in subsequent iterations.

Shrinkage strain increment is obtained from Equation 3.10 as:

\[ \Delta \varepsilon_s(q,j) = K_s(q,j) \Delta M(q,j) \] (3.28)

which is independent of stress.

The mechano-sorptive strain increment is obtained from Equation 3.11:

\[ \Delta \varepsilon_M(q,j) = D_M(q,j) [\sigma(0, j) + \frac{1}{2} \Delta \sigma(q,j)] \] (3.29)

where, the stress term in the square bracket represents an average stress over the time step, and the stress increment, i.e. \( \Delta \sigma(q,j) \) is updated after each iteration. \( D_M(q,j) \) in Equation 3.29 is defined as:

\[ D_M(q,j) = k_M(q,j) \Delta M(q,j) \] (3.30)

3. The total strain in each layer is:

\[ \varepsilon_T(q,j) = \varepsilon_T(0,j) + \Delta \varepsilon_T(q,j) \] (3.31)

where, the increment in total strain is obtained from Equation 3.21 after substituting Equations 3.25 to 3.30 and rearranging:
\[ \Delta \varepsilon_T(q, j) = [D_T(q-\frac{1}{2}, j) + \frac{1}{2} D_M(q, j)] \Delta \sigma(q, j) \]
\[ + [D_M(q, j) \sigma(0, j) + \Delta \varepsilon_s(q, j) + \Delta \varepsilon_c(q, j)] \]

in which both \( \Delta \varepsilon_T(q, j) \) and \( \Delta \sigma(q, j) \) are unknown at this point.

Defining:

\[ N(q, j) = D_T(q-\frac{1}{2}, j) + \frac{1}{2} D_M(q, j) \] (3.33)

and:

\[ \Pi(q, j) = D_M(q, j) \sigma(0, j) + \Delta \varepsilon_s(q, j) + \Delta \varepsilon_c(q, j) \] (3.34)

one has from Equation 3.32, after arranging:

\[ \Delta \sigma(q, j) = N^{-1}(q, j) \Delta \varepsilon_T(q, j) - N^{-1}(q, j) \Pi(q, j) \] (3.35)

Integrating Equation 3.35 through the board thickness, it becomes:

\[
\int_0^x [\tilde{W} \Delta \sigma(q, j)] dx = \int_0^x [\tilde{W} N^{-1}(q, j) \Delta \varepsilon_T(q, j)] dx \\
- \int_0^x [\tilde{W} N^{-1}(q, j) \Pi(q, j)] dx
\] (3.36)

4. Using the compatibility and equilibrium conditions defined by Equations 3.22 and 3.23, the increment in the total strain over the time step can be evaluated as:
5. The stress in each layer is:

\[ \sigma(q, j) = \sigma(0, j) + \Delta \sigma(q, j) \]  \hspace{1cm} (3.38)

where, the stress increment is determined from Equation 3.35 using the total strain increment from Equation 3.37.

6. The strain components corresponding to the estimated stress are updated as:

\[ \varepsilon_I(q, j) = \varepsilon_I(0, j) + D_I(q - \frac{1}{2}, j) \Delta \sigma(q, j) \]

\[ \varepsilon_N(q, j) = \varepsilon_N(0, j) + D_N(q, j) [\sigma(0, j) + \frac{1}{2} \Delta \sigma(q, j)] \]  \hspace{1cm} (3.39)

\[ \varepsilon_S(q, j) = \varepsilon_S(0, j) + \Delta \varepsilon_S(q, j) \]

\[ \varepsilon_C(q, j) = \varepsilon_C(0, j) + \Delta \varepsilon_C(q, j) \]

7. A convergence test is performed. The change in the total strain increment obtained from two iterations, i.e.

\[ \left| \frac{\Delta \varepsilon_T(q) - \Delta \varepsilon_T(q-1)}{\Delta \varepsilon_T(q-1)} \right| < \zeta \]  \hspace{1cm} (3.40)

must satisfy a chosen \( \zeta \). Failure means that the calculation repeated from step two with updated stress and strain values, otherwise the calculation continues to next step.
8. The maximum tensile and compressive stresses through the board thickness are determined and compared with corresponding strength values to predict the failure.

9. The calculated results of stresses and various strain components are output in either a graphic form or a file.

10. The index $q$ is changed to index $i$ to represent the value at time $t_i$ as the calculation proceeds to include next time step.

A multiple-moduli form program (Appendix E) was developed to perform the calculation described above. The program was written in Fortran and compiled under Microsoft Fortran 5.1 with graphic routines. The calculated results can be output graphically for both drying strains and stresses.
IV. EXPERIMENTAL TECHNIQUES

The influence of controlled changes in moisture content and temperature on the deformation of small wood samples under a controlled load was investigated to evaluate the constants appearing in the stress-strain relations introduced in Chapter III. The total deformation was the result of four strain components: instantaneous, creep, shrinkage, and mechano-sorptive effect. The experimental technique described in this chapter enables these to be isolated from one another. This chapter presents the details of the equipment setup and experimental design.

4.1 Equipment Design and Functions

A self-contained system was manufactured which enabled the one-dimensional deformation of the matched wood specimens to be continuously monitored as they were subjected to a controlled loading and/or moisture content changes. Figure 4.1 shows an overall view of the equipment layout. According to the function, the apparatus can be divided into units for load application, moisture monitoring, environmental control, and deformation monitoring.
4.1.1 Load Application

In the initial design of the equipment, loads to the test specimen were applied through a pneumatic, double-acting piston-cylinder unit and measured by a load transducer. This
arrangement allowed both tensile and compressive loads to the specimen to be applied in a specified loading rate and monitored. However, the complex nature of shrinkage and swelling of the test specimen under load during moisture change imposed two limitations on the loading device.

First, the loading head must be able to change the direction of movement during a particular test run. However, the static friction between the cylinder wall and piston required a too great force or pressure differential to start moving the piston. This made the steady-state application of load impossible with the pneumatic piston cylinder. Secondly, the load transducer was unable to operate reliably at temperature and humidity conditions, for which it was designed.

To alleviate these problems, weights were used to apply the load to the test sample. For tensile loading, two miniature grips were manufactured to effectively transfer forces to the specimen (Figure 4.2). The top grip was permanently mounted on the top support plate of the loading frame. The bottom grip was connected to a hollow rod and a circular aluminum plate. To provide the maximum clamping force, the grip head plates contacting with the test specimen were mechanically roughened.

Steel weights of 1, 2 and 5 pounds were made to fit on the circular plate connected to the lower grip. The weights were fitted between the middle platform of the loading frame
1. Quartz spring balance
2. Ring heater
3. Pressure vessel
4. Micro fan
5. Light
6. Loading frame
7. Top grip
8. Moisture sample
9. Reference sample
10. Loaded sample
11. Shrinkage sample
12. Reference points
13. View port
14. View port (lighting)
15. Lower grip
16. Middle platform
17. Weight
18. Circular plate
19. Supporting plate
20. Band heater
21. Loading cylinder
22. O-ring seal

Figure 4.2. Pressure vessel and tensile device. (a) Side view and (b) front view.
and the circular plate. They were lifted by a double-acting, pneumatic piston-cylinder. Three rods (connected to the supporting plate and arranged in a circle at 60 degree intervals) transferred the lifting action to the weights. The cylinder was permanently mounted on the base plate of the loading frame. The air pressure to the cylinder was controlled by two air pressure regulators. The initial position of the piston was preset by adjusting the air pressure on one side of the piston so the bottom grip was supported and no force was applied to the test specimen. At the time of loading the pressure on the upper side of the piston was gradually increased. The piston moved downward and the weights were smoothly lowered on the circular plate. During testing, the hollow rod of the bottom grip slid along the inner wall of the center hole in the middle platform, which serves as a guide for an axial movement of the grip. Unloading of specimens was achieved by decreasing the upper side air pressure so the piston moved upward and lifted the weights.

For compression, a small pressing frame with two plates connected by three small rods was fitted into the center part of the loading frame (Figure 4.3). Test specimens were inserted into the space between the top plate of the pressing frame and the middle platform. The loading weights, which were lifted by the piston-cylinder system, were fit to the space between the middle platform and lower plate of the
Figure 4.3. Loading device for compression.
(a) side view and (b) front view.

1. Loading frame
2. Pressing frame
3. Loaded sample
4. Reference points
5. Sample supports
6. Reference sample
7. Shrinkage sample
8. Middle platform
9. Weight
10. Supporting rods
11. Supporting spring
12. Supporting plate
13. Loading cylinder
pressing frame. During testing the weights were lowered onto the lower plate of the pressing frame and the force was uniformly applied to the entire top surface of the specimen. The test specimens were supported from the back and two sides to prevent them from tipping at the time of loading and during testing.

4.1.2 Moisture Content Monitoring

The control specimen for monitoring wood moisture content was suspended alongside of the loaded specimen (Figure 4.2) and its weight was monitored with a quartz spring sorption balance. The spring specifications are given in Table 4.1. The spring was contained within a tubular safety sight glass which was supported by a stainless steel frame (Figure 4.4). The seal between the glass and the supporting frame at both ends was achieved through two teflon envelope gaskets. Both seal and glass were rated for a pressure of 100 psi and temperature of 450°F. The unit was permanently mounted on the top of the vessel. The removable top cap allows the spring and wood sample to be moved in and out of the vessel.

Before each test, the spring and wood sample were inserted into the glass tube once the pressure vessel was lowered firmly on the base plate to avoid possibility of imposing a damaging shock force on the spring when lowering the vessel. The spring was made with a tapered reference
Table 4.1. Specifications for quartz spring.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load</td>
<td>20</td>
<td>gram</td>
</tr>
<tr>
<td>Maximum extension</td>
<td>200</td>
<td>mm</td>
</tr>
<tr>
<td>Unloaded length</td>
<td>80</td>
<td>mm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>10</td>
<td>mm/gram</td>
</tr>
</tbody>
</table>

Figure 4.4. Unit for monitoring moisture content.
pointer, and the position change of the pointer was read with a cathetometer to an accuracy of 0.0004 inches (0.01 mm).

Condensation of the water vapor on the inner wall of the glass tube was prevented with two heating guns which blew hot air over the outer surface of the glass tube continuously. Since the top vessel plate was heated, prevention of water condensation on the glass tube containing the spring eliminates the only source for the condensed water dropping to the spring during testing.

4.1.3 Environmental Control

The atmosphere around the specimens was contained by lowering the detachable stainless-steel cylinder over the specimens once they were mounted in the loading frame. The loading frame was permanently mounted on the circular base plate. The seal between the cylinder and base plate was effected through an O-ring gasket and 12 connecting bolts.

The heat to the pressure vessel was supplied by three 3/4-inch wide, 1180 watt, STARFLEX band heaters and a 1870 watt KAMLROK disc heater. To provide an uniform temperature inside the vessel, three band heaters were evenly distributed along the vessel wall and the disc heater was mounted on the top plate of the vessel. Also, two microfans were installed to provide vapor circulation inside the vessel. As found later in the test, the water vapor flow enhances the
convective mixing inside the vessel and vertical temperature variation in the middle range of the vessel could be controlled within plus and minus 1°F around the set point.

Power to the heaters was controlled by a Love Model 300 PID temperature controller and a solid state relay (Figure 4.5). Control was based on a differential voltage signal from a type-T thermocouple located near the wood specimen. A remote set-point signal was provided to the controller from PC through the Control EG program (Control EG, 1989). A 24 VDC pulsed signal to the solid state relay controlled the heating elements (Figure 4.6a). Temperature distribution inside the vessel was continuously monitored using 5 20-gauge type T thermocouples. A 40-gauge thermocouple was prepared for measuring the wood temperature. Temperature data were collected by the MetraByte DAS-16 data acquisition board through the Control EG program and were output to a printer and/or a disk.

The desired relative humidity inside the vessel was obtained by controlling the total pressure in absence of air. In the pressure control system (Figure 4.5), the process signal in a range of 0 to 30 mVDC from a high temperature pressure transducer (sensing the vessel pressure) was directed to a Love Model 300 PID pressure controller. The controller compared the voltage signal from the pressure transducer to a remote set-point signal from the Control EG. A 4-20 mA analog current signal was output (Figure 4.6b) to an I/P converter,
TEMPERATURE CONTROL

Fast blow fuse  PID Temperature controller  Solid state relay

POWER SUPPLY

Thermocouple  Pressure vessel

Temperature control signal

PC with DAS-16 data Acquisition card and Control EG program

Pressure vessel

Pressure

Temperature

Pressure control signal

LOADING CONTROL

4-way Control valve  Air pressure gauge  Air pressure regulator

Temperature control signal

PC with DAS-16 data Acquisition card and Control EG program

Pressure vessel

Pressure

Temperature

Pressure control signal

LOADING CONTROL

Figure 4.5. Control system for the apparatus.
Figure 4.6. Control signals. (a) PID temperature controller and (b) PID pressure controller.
which sent a 0-15 psi air pressure signal to a pneumatic steam valve. A separate vacuum unit was used to lower the pressure of the vessel. In this manner, the desired vapor pressure could be established by balancing the amount of steam entering the vessel through the steam valve with that removed by the vacuum pump and condensed inside the vessel.

For the pressure control system to operate accurately, most of the air in the vessel was evacuated prior to injecting steam. Then, subsequently measured pressures were almost wholly attributable to the pressure of water vapor, and relative humidity was calculated directly. It was also proved to be important to eliminate most of the condensed water from the pressure vessel since subsequent evaporation of the water altered the pressure inside the vessel. The condensed water came basically from two sources: the vessel inner components and steam line. Figure 4.7 shows the arrangement in which two vacuum pumps were used to pull out the condensed water from the two sources.

The set point signals for system temperature and pressure were coordinated by the Control EG program through three control sequences. Sequencer #0 serves as an autostart sequence which starts the control function for both PID controllers, defines the path for data output, and turns on sequences #1 and #2. Sequencer #1 controls the set-point signal for system temperature. It functions by first ramping the set-point temperature up to the target value in a specified
Figure 4.7. Unit for eliminating the condensed water from pressure vessel.
rate, and then holding this value for a sustained period of time. Concurrently, sequencer #2 controls the set-point pressure. It first specifies a time period for system evacuation to remove most of the air from the vessel, then ramps the pressure up to the first target value and holds this pressure until the specimen reaches equilibrium under the current pressure (conditioning process). Depending the specified test, the sequencer then ramps the system pressure up (for wetting) or down (for drying) to approach the second target value (testing process). This control procedure allows both conditioning and testing processes to be repeated for different tests. This is crucial to show the effect of one variable, e.g. stress while temperature and rate of drying were unchanged.

All of the wires entered the pressure vessel through a hermetically sealed connector. The pressure vessel was certified to a working pressure of 125 psi.

4.1.4 Deformation Monitoring

An optical scanning system was used to monitor the deformation field in this study. The system is noncontacting and was selected to overcome the difficulty in using any type of electrical strain measuring device in the testing environment. A flow chart of the scanning system is shown in Figure 4.8 (Irving, 1989).
Figure 4.8. Flow chart of scanning system (Irving, 1989).
4.1.4.1 System Description

A TM-7 series miniature high resolution CCD camera (manufactured by PULNIX America Inc. -- model TM-7CN) was used as the optical pickup device. The camera has a resolution of 768 x 494 pixels. The camera digitizes the original image and assigns brightness and coordinate values to each pixel, which are transferred as an analog signal to the image capture board (ATT model Targa 16) within the microcomputer (AST/286).

The scanning process transfers information to the capture board, with the video signal voltage corresponding to the brightness of each pixel. A synchronization pulse at the end of each line initiates the next line scan. Upon receiving the completely digitized image, it is stored in memory on the image capture board, where it is reduced to a binary image and analyzed with the scanning software.

A combination of two light sources was used to provide lighting for the scanning system. First, a 12 VDC high-intensity desk light was installed inside the vessel to provide a background lighting. The light was away from the wood specimens to prevent heating the specimens by radiation. Second, a microscope light installed outside the vessel projected an uniform light beam into the vessel through the second view port. The light beam was reflected by a mirror to the surfaces of test specimens where the reference points were set. Condensation of the water vapor on the glass of the view
ports was prevented using heat guns to blow hot air on the outside surfaces of the windows.

4.1.4.2 Deformation Evaluation

The scanning software used by Irving (1989) was updated to accomplish the task of measuring strains in this study. The program was written in C and has two functions: capturing and processing images of the strain field, and evaluating the strain development on wood specimens. The first function is carried out by the subroutines available in VMENU software library (Forrer, 1987; Funck et al, 1987). The second function is performed by the subroutine developed in this study according to the following approach.

Three specimens were used to resolve the strain development of wood samples during testing (Figure 4.9). The specimen on the left was made of stainless-steel and used as a reference. At a position NL inches from the top edge of the specimen, two reference points RL inches apart were preset on its surface at the room temperature (Dots 0 and 3). Variation of NL and RL due to temperature differences during test was accounted for in the scanning program with the specified temperature change and thermal expansion coefficient of the material. The specimens in the center and right are the wood specimens under load and load-free conditions, respectively. One point on each wood specimen (Dots 1 and 2) was preset
Figure 4.9. Specimen arrangement in tests. (A) Tension and (B) compression.
before testing such that both points were located in the middle range of two reference points on the reference specimen. From each connectivity analysis, concerning the detection of the blobs on a pixel-by-pixel basis, of the scanning program, the centroid of each black dot was determined by its corresponding x and y coordinates in terms of pixels (Figure 4.10 for tensile loading).

The pixel distance between two relevant dots was evaluated as:

\[
\begin{align*}
D_{01}(i) &= \sqrt{(x_0 - x_1)^2 + [1.09 (y_0 - y_1)]^2} \\
D_{02}(i) &= \sqrt{(x_0 - x_2)^2 + [1.09 (y_0 - y_2)]^2} \\
D_{03}(i) &= \sqrt{(x_0 - x_3)^2 + [1.09 (y_0 - y_3)]^2} \\
D_{13}(i) &= \sqrt{(x_1 - x_3)^2 + [1.09 (y_1 - y_3)]^2} \\
D_{23}(i) &= \sqrt{(x_2 - x_3)^2 + [1.09 (y_2 - y_3)]^2}
\end{align*}
\]

(4.1)

where, the constant 1.09 is to compensate for the x/y ratio of the screen and i is the number of scans (or time index) with value zero representing the initial unloading condition.

The separation between the dot on the load-free wood specimen (Dot 1) and the higher dot on the reference specimen (Dot 0) in the direction of loading was then obtained as:

\[
D_1(i) = D_{01}(i) \cos[\alpha_1(i)]
\]

(4.2)

where \( \cos \left[ \alpha_1(i) \right] \) was evaluated by using the triangle 013 and the cosine rule:
Figure 4.10. Connectivity analysis of scanning program.
\[ \cos \alpha_1(i) = \frac{[D_{01}(i)]^2 + [D_{03}(i)]^2 - [D_{13}(i)]^2}{2 \frac{D_{01}(i)}{D_{03}(i)}} \]  

(4.3)

For the dot on the loaded wood specimen (Dot 2), the separation was:

\[ D_2(i) = D_{02}(i) \cos [\alpha_2(i)] \]  

(4.4)

where, \( \cos [\alpha_2(i)] \) was evaluated by using the triangle 023 and cosine rule:

\[ \cos [\alpha_2(i)] = \frac{[D_{02}(i)]^2 + [D_{03}(i)]^2 - [D_{23}(i)]^2}{2 \frac{D_{02}(i)}{D_{03}(i)}} \]  

(4.5)

Thus, movements of dots 1 and 2 at a particular time were:

\[ \Delta D_1(i) = D_1(i) - D_1(0) \]
\[ \Delta D_2(i) = D_2(i) - D_2(0) \]  

(4.6)

Since the dot movement so determined was in the unit of pixels, it needed to be converted to the unit of the nominal length of wood specimens. The conversion factor was obtained based on the dots on the reference specimen as:
The strain due to the combined loading and shrinkage or swelling was obtained as:

\[ \varepsilon_T(i) = \frac{\Delta D_2(i)}{[NL*CF(i) + D_2(0)]} \]  

(4.8)

where, the denominator represents the gauge length (GL) of the loaded specimen.

The strain due to shrinkage or swelling only was:

\[ \varepsilon_S(i) = \frac{\Delta D_1(i)}{[NL*CF(i) + D_1(0)]} \]  

(4.9)

where, the denominator is the gauge length for the load-free specimen. Finally, the load-induced strain was obtained as:

\[ \varepsilon_N(i) = \varepsilon_T(i) - \varepsilon_S(i) \]  

(4.10)

In compression tests the movements of Dot 1 and 2 were evaluated with respect to the lowest dot (Dot 3). Appropriate changes were made in the scanning program for Equations 4.1 to
4.10 to compensate the difference in the gauge length from tension to compression.

Computer program was developed to perform the calculation described above. The program starts by asking input information as the threshold level, time interval between scans, and number of scans to be performed. It allows the user to choose the proper threshold level under the current light setting by comparing the images of the straining field grabbed at different threshold levels. Once the input process is completed, the program informs the user to load the specimen and repeated scans are performed at the preset time interval. The test result is output to a file named by the user. The program writes the result to the file immediately after it is evaluated, which prevents the complete loss of data due to some interruption of the scanning process in the latter stage of experiment.

4.1.4.3 System Evaluation

The thresholding and connectivity features of the scanning software make the exact replication of two seemingly identical images impossible. As a result, a stationary object would appear to change slightly among repeated measurements. A number of variables were found to influence resolution of the system (Irving, 1989). Those variables include:
a). camera's field of View
b). dot size, shape, and edge definition
c). background lighting
d). average of multiple scans over the same field.

The detailed discussion of the effect of each of these factors can be found in Irving (1989). To calibrate the scanning program, two wood specimens were arranged in a small steel track to simulate the test condition (Figure 4.11).

As shown, specimen No.1 is moveable, while specimen NO.2 is fixed on the base. The movement of the dot 1 (on specimen 1) with respect to dot 2 (on specimen 2) is continuously monitored by both digimatic caliper with an accuracy of about 0.0004 inches (0.01 mm) and the scanning software.

Figure 4.12 presents the calibration curve of the program over a range of dot separation (D(i)) from 0 to 0.79 inches (20 mm). The measurement was done with the black dots (0.02 inches in diameter) generated by computer in the form of transferring letters. The scanned value was an average of 5 repeated scans over the same field. The difference between the scanned and measured values is within the accuracy of the caliper.
Figure 4.11. Setup for scanning program calibration.

Figure 4.12. Calibration curve of scanning program.
4.2 Experimental Design

4.2.1 Material Selection and Preparation

Eight green mature heartwood boards of Douglas-fir (Pseudotsuga menziesii) with nominal size of 2- by 8-inches by 16-foot long were obtained from a local sawmill. Among those, four boards were flatsawn (FS) and four boards were quartersawn (QS). On arriving at the Forest Research Laboratory, Oregon State University, two 4-foot long clear pieces were first obtained from each 16-foot long board for drying experiments later in the program. Samples for testing mechanical properties were obtained by carefully crosscutting the 4-foot long boards into smaller pieces to remove localized defects like pitch, splits, or knots. These defects could produce specimens that were not typical of the overall statistical population. The clear pieces so obtained were numbered corresponding to the number of the board from which they were cut. They were end-coated and carefully wrapped with three layers of plastic film, and transported to a local freezer for storage.

In addition to the pieces described above, five small samples were obtained from each 16-foot long board to determine the specific gravity, number of rings per inch, and green moisture content. The specific gravity was determined using the green volume and oven dry weight. In Table 4.2 the 5-sample averaged value for each of the three variables among
the eight boards is presented. The grand mean values for flat and quarter sawn boards are also listed in Table 4.2. For the present study, only flatsawn boards were used.

Table 4.2. Specific gravity, rings per inch, and mean moisture content of wood at green.

<table>
<thead>
<tr>
<th>Board Number</th>
<th>Specific Gravity</th>
<th>Rings per Inch</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS: 1</td>
<td>0.38</td>
<td>16</td>
<td>32.4</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
<td>13</td>
<td>32.6</td>
</tr>
<tr>
<td>3</td>
<td>0.40</td>
<td>12</td>
<td>32.5</td>
</tr>
<tr>
<td>4</td>
<td>0.40</td>
<td>13</td>
<td>34.5</td>
</tr>
<tr>
<td><strong>MEAN</strong></td>
<td><strong>0.39</strong></td>
<td><strong>14</strong></td>
<td><strong>33.0</strong></td>
</tr>
<tr>
<td>QS: 1</td>
<td>0.41</td>
<td>~</td>
<td>35.2</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
<td>13</td>
<td>33.2</td>
</tr>
<tr>
<td>3</td>
<td>0.38</td>
<td>12</td>
<td>34.2</td>
</tr>
<tr>
<td>4</td>
<td>0.39</td>
<td>15</td>
<td>34.5</td>
</tr>
<tr>
<td><strong>MEAN</strong></td>
<td><strong>0.39</strong></td>
<td><strong>13</strong></td>
<td><strong>34.3</strong></td>
</tr>
</tbody>
</table>

4.2.2 Tests of Wood Properties

4.2.2.1 Specimen Preparation

Four end-matched 4-foot long boards were selected from the flatsawn clear pieces stored in the freezer. The boards were first defrosted in a cool room for at least 72 hours. They were then randomly divided into two groups. One group was used for preparing specimens in the green moisture condition. The other was for specimens at about 12% moisture content. The boards in the later group were kiln-dried under the mild conditions to a mean moisture content of about 12%. The lumber was dried in board form to reduce the possible warp in the specimens since any distortion developed during drying.
was dressed out from the over-sized board before final shaping of specimens.

The cutting procedure for tensile specimens was as follows. The long green or kiln-dry board was first dressed to a size of 1 inch in radial direction and 6.2 inches in tangential direction. It was then sawn perpendicular to the grain into slices of 3/16-inch thick for green wood and 1/8-inch thick for kiln-dry wood. The smaller thickness of kiln-dry specimen was used to reduce the required load in test for a given stress level. The slices were divided into groups of two by matching their growth ring angle and width. Within each group, the first 1-inch wide slice was further cut into a tensile specimen against a prepared metal standard specimen using a sharp razor blade. The final shape and dimension are shown in Figure 4.13a. The other was cut into two 1/2-inch wide specimens for matching measurements of shrinkage and moisture content.

Compressive specimens were made by ripping the long green or kiln-dry board into two parts. Each part was dressed to a size of 1/2 inches in radial direction and 3 inches in the tangential direction. It was then sawn perpendicular to the grain into slices of 3/10-inch thick for green wood and 1/5-inch thick for kiln-dry wood. The final dimension of the specimen is shown in Figure 4.13b. The larger thickness in the compressive specimen was used to prevent it from buckling under compression at high moisture contents and temperatures.
Figure 4.13. Test specimens. (a) tension and (b) compression.

It can be seen that end grain was exposed on the wide faces of the specimen, i.e. the thickness corresponded to the longitudinal direction of the log. This cutting pattern was chosen to reduce the moisture gradient inside the specimen and to limit the sorption time during test. The prepared green specimens were wrapped with three layers of plastic film immediately after machining and stored in one of the freezers.
in the laboratory. At least 24 hours before actual tests, the desired number of specimens were taken out of the freezer and placed in a desiccator with water at the bottom for defrosting and conditioning. The desiccator was stored in a cool room. The kiln-dry specimens were stored in a standard room with the EMC of 12% and 68°F temperature.

4.2.2.2 Test Conditions

1. Mechanical Creep

Creep tests at 10% moisture content were conducted in both tension and compression. Stress and temperature were varied as listed in Table 4.3.

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-tension (psi)</td>
<td>120</td>
<td>120</td>
<td>60, 120, 180</td>
<td>120</td>
</tr>
<tr>
<td>Stress-compression (psi)</td>
<td>80</td>
<td>80</td>
<td>40, 80, 120</td>
<td>80</td>
</tr>
</tbody>
</table>

2. Mechano-Sorptive Effect

Tests for the mechano-sorptive effect under varying moisture contents were divided into the following three groups. First, at 150°F, drying tests were conducted at different stress levels for both tension and compression. The specific test conditions were summarized in Table 4.4.
Table 4.4. Stress and range of MC change for drying under tension and compression at 150°F.

<table>
<thead>
<tr>
<th>MC change (%)</th>
<th>25-&gt;5</th>
<th>25-&gt;5</th>
<th>25-&gt;5</th>
<th>25-&gt;5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-tension (psi)</td>
<td>40</td>
<td>60</td>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>Stress-compression (psi)</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>---</td>
</tr>
</tbody>
</table>

Second, at a constant stress level of 80 psi, drying tests under compression were conducted at 90, 120, 150, and 180°F for the moisture content change shown in Table 4.5.

Table 4.5. Stress and range of MC change for drying under compression at 90, 120, 150 and 180°F.

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-compression (psi)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>MC change (%)</td>
<td>30-&gt;5</td>
<td>28-&gt;5</td>
<td>25-&gt;5</td>
<td>20-&gt;3</td>
</tr>
</tbody>
</table>

Lastly, wetting tests under tension at 150°F were conducted. Experimental data for wood deformation under load during wetting and cyclic change in the moisture content would be useful in modeling the conditioning process of lumber drying. The applied stress and range of moisture content change are shown in Table 4.6.

Table 4.6. Stress and range of MC change for wetting under tension at 150°F.

<table>
<thead>
<tr>
<th>MC change (%)</th>
<th>5-&gt;20</th>
<th>5-&gt;20</th>
<th>5-&gt;20</th>
<th>5-&gt;20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-tension (psi)</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>180</td>
</tr>
</tbody>
</table>
4.2.2.3 Test Procedure

To test material properties, a set of prepared specimens at about 30% moisture content (green) for drying and 12% (kiln-dry) for creep and wetting was selected. The computer-generated black dots in the form of transferring letters were placed on the surfaces of two specimens assigned for measuring wood deformation under load and load-free conditions. Each specimen was weighed and was quickly clamped to the loading frame with the vessel in the open position. The 40-gauge thermocouple for measuring wood temperature was firmly clamped between two small pieces of wood of similar conditions. Finally, the vessel was lowered on its base and the wood sample for monitoring moisture change was inserted into the vessel from the top.

The sequencers controlling system temperature and pressure were turned on. The set-point temperature was ramped at a specified rate to the target value and held for the rest of testing period. The set-point pressure was first set low enough to allow the system to be evacuated while the vessel was still relatively cold. The pressure was then ramped to achieve the first target equilibrium moisture content. The rate of pressure change was selected to maintain the desired moisture loss during initial heating up period for a specified temperature. After the pressure reached the target value, it was maintained long enough to allow the temperature to stabilize and wood specimens to reach equilibrium.
After the entire system was at the steady state, the load was applied to the specimen. For creep tests at a constant moisture content, the constant load, pressure, and temperature were maintained for a period of 10 hours, during which the instantaneous and time-dependent deformation of matched specimens were monitored continuously.

For tests at varying moisture contents, a similar procedure was used to get the system to a steady state and to measure the instantaneous deformation after the load was applied. The set-point pressure was then ramped up or down to approach the second target value in a period of about 6 hours for drying and 7 hours for wetting. During this period, the deformations of the specimens were continuously monitored with the scanning system and the weight change of the moisture content sample was monitored with the sorption balance.

Regardless of which procedure was followed, the weight of each specimen was measured at the end of test. The specimens were then oven-dried to determine the actual moisture content.

4.2.3 Lumber Drying Experiments

Lumber drying experiments were conducted to generate the moisture and temperature data upon which the stress calculations were based. These experiments also provided the distributions of drying strains for verifying the stress model.
4.2.3.1 Board Selection and Preparation

Three drying runs under different schedules were performed in the drying tests. In each of the drying charges, two 4-foot long boards, end-matched with the boards used for mechanical property testing, were selected. In the third run, two additional boards with a lower ring count (wider growth rings) were also selected. They were tested to see the difference in the drying behavior since boards with wider growth rings are less prone to surface checking in drying. The boards were first defrosted for at least 72 hours in a cool room, and then surfaced on four sides to an actual size of 7.5-inch wide and 2.0-inch thick. A 1-inch wide piece was cut at a position about 5 inches from the end to determine the average moisture content and moisture profile across the board thickness when green.

One of the boards was randomly allocated to measure the moisture and drying strain distribution through board thickness. On the surfaces of this board, ten 1-inch long sections with 3-inch spaces in between were marked along the length of the board. Each 1-inch long section was divided into 10 equal slices in the direction of board thickness. The green width of each slice was measured using a caliper with an accuracy of 0.001 inches. To limit the drying from the edges and the ends of the board, the edges were covered with a plastic tape and the ends were coated with vapor-proof paint.
The second board was to measure the temperature profile across board thickness. At a position about 12 inches from the front end of the board, five 3.5-inch deep holes (1/8 inches in diameter) were drilled across half board thickness from one side. About 24 hours before actual drying tests, five 40-gauge thermocouples were inserted to the bottom of the holes. The holes were plugged using wood sticks covered with silicone glue. The board was placed in a cool room so that the silicone could cure before drying.

4.2.3.2 Drying Equipment and Drying Schedule

Drying experiments were conducted in a 4-foot long experimental kiln (Figure 4.14). The kiln was equipped with instrumentation to automatically control and measure temperature and relative humidity. A plywood front cover with a square hole in the middle (covered with a piece of rubber) was made for the kiln, which facilitated removing sample boards from the kiln without losing much of the air when the front door was opened. Drying tests were performed at a constant dry-bulb temperature of 150°F and three sets of wet-bulb temperatures (Table 4.7). The air velocity was about 450 feet per minute for all the test runs.
Table 4.7. Variation of wet bulb temperature in lumber drying.

<table>
<thead>
<tr>
<th>Time (hour)</th>
<th>Wet-bulb Temperature (°F)</th>
<th>Charge I</th>
<th>Charge II</th>
<th>Charge III</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>24</td>
<td>140</td>
<td>144</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>140</td>
<td>139</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>72</td>
<td>140</td>
<td>134</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>140</td>
<td>129</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>140</td>
<td>124</td>
<td>136</td>
<td></td>
</tr>
<tr>
<td>144</td>
<td>140</td>
<td>124</td>
<td>136</td>
<td></td>
</tr>
<tr>
<td>168</td>
<td>140</td>
<td>119</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>140</td>
<td>119</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>216</td>
<td>140</td>
<td>119</td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>

1. Load cell  
2. Lift arm  
3. Kiln wall  
4. Fan  
5. Heating coil  
6. Steam spray  
7. PC  
8. Control box  
9. Thermocouple  
10. Lumber boards  
11. Vent  
12. Control arm  
13. Penumatic valve  
14. Control signal  
15. Perforated plate

Figure 4.14. Schematic of experimental dry kiln.
4.2.3.3 Testing Procedure

The testing procedure for measurements of moisture and drying strains followed those described by McMillen (1955a). The board was removed from the kiln at a specified time interval (24 hours) and one of the marked sections was cut. The section taken was quickly wrapped with a plastic film and the rest of the board was end-coated and returned to the kiln.

The width of each marked slice in the section taken was measured while its end surfaces were covered with the plastic film. The section was quickly sliced with a band saw. Each slice was immediately wrapped with plastic film and the weight and width of each slice were measured. The slices were then stacked together and dried at room temperature for 24 hours followed by 24-hour oven drying at 103°C. The weight and width of each slice at the oven-dry condition were measured. The distributions of moisture and drying strain at different stages of drying were determined from weight and width changes of different slices.

The board for temperature measurement was left in the dry kiln all the time. Temperature data at different locations within the board were recorded by the computer data acquisition system.
V. RESULTS AND DISCUSSION

To characterize and verify the stress-strain relationship introduced in Chapter III, experimental observations on various wood properties perpendicular to the grain were needed. Emphasis was placed in this study on tests which show the time- and/or moisture change-dependent behaviors of wood. This chapter describes the experimental results and verification of the theoretical models.

5.1 Stress-Strain Relation of Small Wood Samples
5.1.1 Deformation under Load at Constant Moisture Contents
5.1.1.1 Experimental Data
1. Temperature and Pressure Histories

Typical temperature and pressure control histories in a complete run for tests to show wood deformation under load over a constant moisture content are presented in Figure 5.1. As shown in Figure 5.1a, the system was heated from room temperature at a rate about 2°F per minute to the target temperature 150°F. There was usually about a 6°F overshoot at the end of the heating period due to the large mass of the vessel. The temperature, however, reached the target value well before the end of the conditioning period. Thereafter it was closely maintained at the target value.
Figure 5.1. Results of creep tests at 150°F and 10% MC. (a) temperature history and (b) pressure history.
For system pressure (Figure 5.1b), after the closure of the vessel, most of the air was evacuated in the first 5 minutes. After this evacuation period, the system was pressurized in a rate about 0.044 psi per minute to the target pressure i.e. 2.6 psi corresponding to about 10% moisture content at this temperature. The vacuum pump was running continuously to further purge any residual air from inside the vessel. After the system pressure reached the target value, the steady-state condition of the total pressure was closely maintained at the target pressure.

Temperature and pressure histories for other temperatures were similar to those described above. Under each specified temperature, the control process was repeated closely among different tests so that the effect of stress could be demonstrated over matched temperature and pressure histories.

2. Test Results

The measured strain-time curves are shown in Figures 5.2 and 5.3. The specific test conditions are displayed in the individual graphs. Each strain curve represents a mean of two repeated tests. There was some variation in the actual moisture content of the wood among the tests at different temperatures. Moisture variation within a particular test was, however, small. The data were fitted following the procedure outlined in Appendix C.
Figure 5.2. Tensile creep of Douglas-fir in the tangential direction at 10% MC. (a) a function of stress and (b) a function of temperature.
Figure 5.3. Compressive creep of Douglas-fir in the tangential direction at 10% MC. (a) a function of stress and (b) a function of temperature.
5.1.1.2 Results of Data Fitting

1. Instantaneous Strain

Table 5.1 summarizes the mean instantaneous strain ($\epsilon_i$) in relation with stress ($\sigma$) at 150°F and 10% MC. Also shown in the table are the corresponding values of the instantaneous modulus of elasticity (MOE), i.e. a ratio of applied stress to the instantaneous strain.

Table 5.1. Instantaneous strain as a function of stress from creep tests at 150°F and 10% MC.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (psi)</td>
<td>$\epsilon_i$ (in/in)</td>
</tr>
<tr>
<td>60</td>
<td>0.00089</td>
</tr>
<tr>
<td>120</td>
<td>0.00169</td>
</tr>
<tr>
<td>180</td>
<td>0.00241</td>
</tr>
</tbody>
</table>

As shown in Table 5.1, the instantaneous strain increased with the increase in the applied stress for both loading modes. The corresponding instantaneous MOE, however, did not vary systematically with stress. For tension, there appeared to be an increase in the MOE with the increase of stress, but no particular trend was seen from the compression data. The mean MOE in compression was slightly higher than tension. The grand mean MOE for both tension and compression was 72735 psi.

A number of factors contribute to the variation in the measured modulus of elasticity under different levels of
stress. Those factors include material variability and slight variation in actual moisture content among different tests. Also the method used in determining the instantaneous strain may contribute to this variation since the precise moment at which the load is fully applied to the specimen can not be exactly determined in those tests.

Table 5.2 summarizes the mean instantaneous strain as a function of temperature at 10% MC and 120 psi stress for tension and 80 psi stress for compression. The instantaneous MOE data were plotted in Figure 5.4 for both tension and compression.

Table 5.2. Instantaneous strain as a function of temperature from creep tests at 10% MC.

<table>
<thead>
<tr>
<th>Temp (°F)</th>
<th>ε (in/in)</th>
<th>MOE (psi)</th>
<th>Temp (°F)</th>
<th>ε (in/in)</th>
<th>MOE (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.00125</td>
<td>96000</td>
<td>90</td>
<td>-0.00086</td>
<td>93023</td>
</tr>
<tr>
<td>120</td>
<td>0.00144</td>
<td>83333</td>
<td>120</td>
<td>-0.00095</td>
<td>84211</td>
</tr>
<tr>
<td>150</td>
<td>0.00165</td>
<td>72727</td>
<td>150</td>
<td>-0.00105</td>
<td>76191</td>
</tr>
<tr>
<td>180</td>
<td>0.00189</td>
<td>63492</td>
<td>180</td>
<td>-0.00123</td>
<td>65041</td>
</tr>
</tbody>
</table>

As shown in Table 5.2 and Figure 5.6, under a constant stress level, an increase in the temperature led to an increase in the instantaneous strain and a decrease in the MOE. Direct comparison of the MOE in tension and compression indicates a comparatively similarity. Regression analysis over the measured points led to the following relation between MOE and temperature at this moisture condition:
\[ E(T) = 125584 - 345 \, T \] \hspace{1cm} R^2 = 0.91 \hspace{1cm} (5.1)

or in terms of the MOE value at 90°F:

\[ E(T) = E_{90} [1 - 0.00365(T-90)] \] \hspace{1cm} R^2 = 0.91 \hspace{1cm} (5.2)

with \( E_{90} = 94,500 \) psi, the mean for tension and compression at 90°F. Equation 5.1 or 5.2 is plotted in Figure 5.4 for comparison with the measurements.

Figure 5.4. Tangential MOE of Douglas-fir as a function of temperature at 10% MC.
2. Creep Strain

Table 5.3 lists the fitted creep parameters as a function of stress at 150°F and 10% moisture content.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma)</td>
<td>(K)</td>
</tr>
<tr>
<td>(psi)</td>
<td>(psi)</td>
</tr>
<tr>
<td>60</td>
<td>4.93E-5</td>
</tr>
<tr>
<td>120</td>
<td>9.37E-5</td>
</tr>
<tr>
<td>180</td>
<td>15.66E-5</td>
</tr>
</tbody>
</table>

As shown in Table 5.3, there was a clear trend that the parameter \(K\) increased with an increase in applied stress for both loading modes. However the ratio of parameter \(K\) to the stress was not strongly influenced by the stress. Considering the variability in the material and measurement, this ratio among different stress levels may be approximated with a constant value within each loading mode. This approximation would lead the coefficient \(m_c\) in Equation 3.6 to be unity. The ratio of parameter \(K\) to stress in compression was higher compared with tension.

The parameter \(n_c\) did not vary systematically with the stress within each loading mode, but differed from tension and compression. The mean value of parameter \(n_c\) for tension is 0.52 which is higher than the corresponding value in compression (0.44).
Table 5.4 lists the fitted creep parameters as a function of temperature at 10% MC. The ratio of parameter K to stress and parameter \(n_c\) from Table 5.4 were plotted in Figure 5.5a and 5.5b respectively.

Table 5.4. Creep parameters in tension and compression as a function of temperature at 10% MC.

<table>
<thead>
<tr>
<th>Temp (°F)</th>
<th>Tension ((\sigma = 120 \text{ psi}))</th>
<th>Compressi(\text{on}) ((\sigma = -80 \text{ psi}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K)</td>
<td>(K/\sigma) ((\text{psi}^{-1}))</td>
</tr>
<tr>
<td>90</td>
<td>10.02E-5</td>
<td>8.35E-7</td>
</tr>
<tr>
<td>120</td>
<td>10.22E-5</td>
<td>8.52E-7</td>
</tr>
<tr>
<td>150</td>
<td>9.37E-5</td>
<td>7.81E-7</td>
</tr>
<tr>
<td>180</td>
<td>10.59E-5</td>
<td>8.83E-7</td>
</tr>
</tbody>
</table>

It can be seen from Table 5.4 and Figure 5.5a that the ratio of parameter \(K\) to stress for tension did not vary strongly with increase in temperature. There was a slight increase in the ratio from 90 to 120 and 180°F, but the ratio at 150°F decreased compared with those at 90 and 120°F. For compression, the ratio did not vary much with temperature from 90 to 120°F, but it increased almost linearly with temperature increase from 120 to 180°F. At 150 and 180°F, the ratio in compression was much higher than that in tension. Regression analysis was made to establish to relation between the parameter and temperature. The relation is for tension:

\[
\frac{K}{\sigma}(T) = 8.1E-07 + 1.55E-10 T \quad R^2=0.01 \quad (5.3)
\]

which indicates no correlation between two variables. For
Figure 5.5. Creep parameters in tension and compression as a function of temperature at 10% MC. (a) parameter $K/\sigma$ and (b) parameter $n_c$. 
compression, the relation is:

\[ \frac{K}{\sigma}(T) = 2.87E-7 + 6.22E-09 \, T \quad R^2 = 0.83 \quad (5.4) \]

For the parameter \( n_c \), an increase in temperature led to an increase of \( n_c \) for both loading modes (Figure 5.5b). At all four temperatures, the parameter \( n_c \) in tension was higher than compression. The regression equation between the parameter \( n_c \) and temperature is for tension:

\[ n_c(T) = 0.286 + 0.00115 \, T \quad R^2 = 0.94 \quad (5.5) \]

and for compression:

\[ n_c(T) = 0.321 + 0.00132 \, T \quad R^2 = 0.76 \quad (5.6) \]

A direct comparison between tensile and compressive creep compliance under the influence of temperature is shown in Figure 5.6. The creep compliance, i.e. the net creep strain divided by the corresponding stress, is presented for 10, 300, and 600 minutes after the beginning of test. At each particular time, the creep compliance increased with increase in temperature. At 90, 120, and 150°F, no significant difference existed in the compliance between tension and compression. However, at 180°F compressive creep compliance was much higher than the corresponding values for tension. Thus temperature at this level had the greater effect on the compressive creep.
Figure 5.6. Comparison of creep compliance under tension and compression at 10% MC and different temperatures.
5.1.2 Deformation under Load during Moisture Change

5.1.2.1 Moisture Desorption - Drying

1. Experimental Data

(1). Temperature and Pressure Histories

Typical temperature and pressure histories in a complete test run for green specimens desorbing moisture (drying) under load at 150°F are presented in Figure 5.7. As shown in Figure 5.7a, the system was heated from room temperature at a rate of about 1.5°F per minute to the target temperature. There was usually about a 6°F temperature overshoot at the end of the heating period due to the large mass of the vessel. The temperature, however, stabilized at the target value well before the end of the conditioning period. Thereafter it was closely maintained at the target value.

For system pressure (Figure 5.7b), most of the air in the vessel was evacuated in first 5 minutes. During this period, the steam valve was kept closed by a low initial set-point pressure. Since the vessel was still cold at this stage, moisture loss from the green specimens was not significant. After the initial evacuation period, the pressure was increased at a rate of about 0.06 psi/minute until it corresponded to desired EMC (3.9 psi). The vacuum pump was running continuously to further purge any residual air from the vessel. After the system pressure approached the target value, it was maintained for about 40 minutes to allow the
Figure 5.7. Test conditions for drying under load at 150°F. (a) temperature history and (b) pressure history.
system to reach the steady-state. During testing, the set-point pressure was ramped down at a rate of 0.0075 psi/minute until it corresponded to an EMC of 5% (1.2 psi).

Strain development during initial conditioning in the matched specimens due to change in moisture content is presented in Figure 5.8. Since the steam valve initially remained closed during system evacuation, the wood specimens lost moisture and developed shrinkage strain. After the steam was injected into the vessel, which caused a sudden increase

![Figure 5.8. Strain variation during initial conditioning in drying tests at 150°F.](image)
in the surrounding relative humidity, the specimens absorbed moisture and part of the accumulated shrinkage strain was recovered. As the system temperature increased, the specimens again started to lose moisture and the shrinkage strain increased. After the system pressure reached the target saturation point (about 120 minutes in this case), the shrinkage strain stabilized at a value corresponding to the moisture loss (about 5%). It can be seen that the strain development for two matched specimens due to change in moisture content during conditioning followed basically the same path. Tests were abandoned if there were large differences in the strain development between two specimens during this period.

The temperature and pressure control histories for other temperatures were similar to those described above. At a specified temperature the control process was repeated closely among different tests so that the drying history could be matched to show the effect of stresses.

(2) Test Results

Experimental data for drying under tension at 150°F are shown in Figure 5.9. The strain curve at a particular stress level represents the mean value of the measurements from two matched tests. As shown in Figure 5.9a, the drying of the test specimens took place in a period of about 370 minutes, in
Figure 5.9. Results from drying under tension at 150°F. 
(a) moisture-time relation and (b) strain-time relation.
which nearly 75% of the moisture change occurred in the first 180 minutes. The accelerated deformation due to change in moisture content under load is seen as the reduced shrinkage compared with that from the matched load-free specimen (Figure 5.9b). As shown in Figure 5.9b, there was an instantaneous deformation in the direction opposite to shrinkage after the load was applied. During the first few minutes of drying, the deformation due to the combined effect of stress and moisture change at 40 and 60 psi stress levels was smaller than the corresponding shrinkage due to moisture loss. Thus the measured total strain decreased from the initial values. Under the higher stress levels (90 and 120 psi), however, the deformation due to stressing and moisture change became greater than the shrinkage. Thus further deformation in the direction opposite to the shrinkage developed. As drying proceeded, the accumulated deformation in the direction opposite to shrinkage was gradually balanced out by the increasing amount of shrinkage, and the measured total strain became negative. With further drying, the difference between the loaded strain curves and matched load-free shrinkage curve was increased.

To show the variability in the measurement, three sets of data at a 60 psi stress level are presented in Figure 5.10. There was a certain amount of variability in both total strain and load-free shrinkage strain. With test specimens closely matched in the growth ring angle and ring width, variability
Figure 5.10. Variability of measurement for drying under tension at 150°F.

in the measured shrinkage was mainly due to slight differences in the rate of drying among different tests since the shrinkage curves almost overlapped in the later part of tests. The variability in the total strain was due to both rate of drying and material properties. Although there was a certain variation in both total strain and load-free shrinkage strain, all the specimens reacted in a similar manner.
Test data for drying under compression at 150°F are presented in Figure 5.11. Figure 5.11a shows the mean moisture content as a function of time. The corresponding strain curves at three stress levels and a mean load-free shrinkage curve are shown in Figure 5.11b. As shown in Figure 5.11a, the drying of compression specimens at 150°F took place in about 390 minutes. The accelerated deformation under this loading mode is seen as the increased shrinkage compared with matched load-free shrinkage curve (Figure 5.11b). Under a particular stress level, there was an instantaneous strain in the direction of shrinkage after load was applied. As drying proceeded, deformation due to the MS effect increased, and total strain curve departed from the load-free shrinkage curve. Further drying and increased stress level led to an increased amount of deformation compared with the load-free sample.

Moisture and strain data for drying under an 80 psi compressive stress at 90, 120 and 180°F are presented in Figure 5.12. Test data were shown separately for different temperatures because the drying histories varied with temperature. No attempts were made in those tests to match the range of moisture change and the rate of drying among different temperatures. Despite the differences in drying histories among different temperatures, the trend of strain developments for matched wood samples was similar to that from drying at 150°F.
Figure 5.11. Results from drying under compression at 150°F. 
(a) moisture-time relation and (b) strain-time relation.
Figure 5.12. Moisture (a) and strain (b) data from drying under compression at 80 psi stress level. (A) 90°F, (B) 120°F, (C) and (D) 180°F.
Figure 5.12 (continued). Moisture (a) and strain (b) data from drying under compression at 80 psi stress level. (A) 90°F, (B) 120°F, (C) and (D) 180°F.
Figure 5.12 (continued). Moisture (a) and strain (b) data from drying under compression at 80 psi stress level. (A) 90°F, (B) 120°F, (C) and (D) 180°F.
Figure 5.12 (continued). Moisture (a) and strain (b) data from drying under compression at 80 psi stress level. (A) 90°F, (B) 120°F, (C) and (D) 180°F.
2. Results of Data Fitting

As described in the previous chapters, the total tensile or compressive strain obtained from tests under load during moisture change consists of two main parts, namely load-free shrinkage and strain due to stress and its interaction with moisture change. The data shown above were analyzed following the procedure outlined in Appendix D.

**Load-Free Shrinkage Strain**

Figure 5.13 shows the shrinkage strain as a function of moisture content from tests at 150°F. It can be seen that the tangential shrinkage of Douglas-fir at 150°F started from the beginning moisture content of 25%. Initially the shrinking rate was low, which gradually increased up to about 20% moisture content. From this point to about 5% moisture content, the shrinkage followed almost a linear relation with moisture content change.

According to the shrinking rate, the entire shrinkage curve shown above was divided into two parts: one from 25% to 20% moisture content; the other from 20% to 5% moisture content. Within each portion, the shrinkage-moisture content relation was approximated by a straight line associated with a specific slope, i.e. shrinkage per percent moisture change. Table 5.5 lists the results of the linear regression analysis.
Table 5.5. Tangential shrinkage coefficients of Douglas-fir from drying at 150°F.

<table>
<thead>
<tr>
<th>MC change (%)</th>
<th>$K_s$ (1/%MC)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 -&gt; 20</td>
<td>0.00175</td>
<td>0.86</td>
</tr>
<tr>
<td>20 -&gt; 5</td>
<td>0.00295</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Figure 5.13. Tangential shrinkage and moisture content relation of Douglas-fir from drying at 150°F.
The shrinkage coefficient for Douglas-fir listed in Wood Handbook (Forest Products Laboratory, 1987) in the tangential direction is 0.0027/\%MC. Thus, the measured values shown in Table 5.5 match reasonably well with the published data.

The shrinkage coefficients for drying from green to about 5\% moisture content at different temperatures are shown in Figure 5.14. Also shown are the shrinkage coefficients from a group of specimens with the similar dimensions but wider growth rings. At 120, 150 and 180°F, the shrinkage coefficients for the specimens with narrower growth rings were centered at about 0.0025/\%MC. There appeared to be no significant difference among three temperatures. At 90°F, however, the coefficient increased with a mean value of 0.0028/\%MC. The lower shrinkage coefficient at the higher temperatures may be caused by the internal stress developed during drying. Although the sample was quite small, a moisture gradient inside the sample during drying at higher temperatures inevitably occurred.

The group with wider growth rings showed less shrinkage at each specified temperature. This may be one of the reasons that boards with wider growth rings are less prone to surface checks in drying. As shown later, smaller drying stresses were developed in the wide-ringed boards compared to those with narrower growth rings.
Figure 5.14. Tangential shrinkage coefficient of Douglas-fir as a function of temperature.
Net or Stress-Induced Strain

The net or stress-induced strain was obtained after subtracting the shrinkage from the total strain data at each specified time.

Figure 5.15 shows the net strain for drying under tension at 150°F. The variability of net strain from the repeated measurements at 60 psi stress level and matched drying histories is also shown in Figure 5.15. As indicated in the graph, most of the strain developed during the first three hours, in which about 75% of the moisture content change took place. Thus, the increase in the net strain was mainly associated with change in the moisture content.

Figure 5.16 shows the net strain for drying under compression at 150°F. The results of two matched tests under each stress level are presented to show the variability in those tests. The net strains for drying under an 80 psi compressive stress at 90, 120, and 180°F are presented in Figure 5.17. Large deformations due to moisture content change under load are seen from all those graphs.

The net strain is further divided into three parts, i.e. instantaneous, creep, and mechano-sorptive effect, according to individual strain characteristics as related to temperature, moisture, time and moisture change.
Figure 5.15. Net strain from drying under tension at 150°F and 40, 60, 90, and 120 psi stress levels.
Figure 5.16. Net strain from drying under compression at 150°F and 40, 60, and 80 psi stress levels.
Figure 5.17. Net strain for drying under compression at 80 psi stress level. (a) 90°F, (b) 120°F, (c) and (d) 180°F.
Table 5.6 summarizes the mean instantaneous strain data from tests at 150°F and 25% MC.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>σ (psi)</td>
<td>ε (psi)</td>
</tr>
<tr>
<td>40</td>
<td>0.00165</td>
</tr>
<tr>
<td>60</td>
<td>0.00315</td>
</tr>
<tr>
<td>90</td>
<td>0.00375</td>
</tr>
<tr>
<td>120</td>
<td>0.00545</td>
</tr>
</tbody>
</table>

As one would expect, the instantaneous strain increased with an increase in the applied stress for each loading mode. The mean instantaneous modulus of elasticity at 150°F and 25% MC is 21,906 psi. Comparing with the corresponding value at the same temperature but 10% moisture content, the modulus of elasticity was decreased by about 70% due to increase of the moisture content from 10% to 25%.

Instantaneous strains as a function of temperature from compression tests under 80 psi stress level are shown in Table 5.7. The data at 150°F from Table 5.6 are also presented for comparison.
Table 5.7. Instantaneous strain from drying tests under 80 psi compressive stress at 90, 120, 150, and 180°F.

<table>
<thead>
<tr>
<th>Temp (°F)</th>
<th>MC (%)</th>
<th>εi (in/in)</th>
<th>MOE (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>31</td>
<td>-0.00162</td>
<td>49382</td>
</tr>
<tr>
<td>120</td>
<td>28</td>
<td>-0.00226</td>
<td>35398</td>
</tr>
<tr>
<td>150</td>
<td>25</td>
<td>-0.00345</td>
<td>23189</td>
</tr>
<tr>
<td>180</td>
<td>20</td>
<td>-0.00275</td>
<td>28571</td>
</tr>
</tbody>
</table>

Since different moisture contents are involved among four temperatures, a direct comparison of the instantaneous strain and MOE for the effect of temperature was not made. However, the trend of the decrease in MOE with increase of the temperature is apparent in Table 5.7.

**Mechanical Creep Strain**

The values of mechanical creep strain used to resolve the MS component from the net strain were taken from the measurements made at a reference moisture content of 10% described in last section. The creep parameters, K/σ and nC, over the range of temperatures were obtained from Table 5.4. The effect of moisture change from the reference moisture condition on the creep rate was accounted for by using the relative creep with the measured instantaneous modulus of elasticity. The mean values of the instantaneous MOE were obtained from Tables 5.1, 5.2, 5.6 and 5.7 for different temperatures. At a given temperature, the MOE at other moisture contents was obtained by a linear interpolation or extrapolation using the two measured points. This method
should give a reasonable estimate of the change in MOE with the change in the moisture content at each temperature because many published results on other wood species indicated a nearly linear relation between the MOE and moisture content at a given temperature (Youngs, 1957; Siime, 1967).

Figure 5.18 presents predicted creep strain for drying under tension at 150°F. Figure 5.19 shows predicted creep strain for drying tests under compression. The predicted creep at a specified stress level varied in an expected fashion. Initially moisture content of the wood was high and so creep developed fast. As the drying proceeded, moisture content in the wood decreased and the magnitude of the creep rate was reduced. If the moisture content remained constant, the ratio of the predicted creep to the creep at the reference MC was directly proportional to the ratio of the modulus of elasticity at those two moisture conditions.

There was a level of uncertainty in the amount of creep strain predicted by this method at higher moisture contents, especially when applied stress was high. However, the concept of "creep" under a varying moisture condition itself may be ill-defined (Ranta-Maunus, 1990). As shown later, creep strain (time-dependent) was a relatively small portion of the net strain because of the short testing period. Thus an error in predicting the additional creep as a function of the moisture content above the reference moisture condition may be insignificant compared with the magnitude of net strain.
Figure 5.18. Predicted creep strain for drying under tension at 150°F and 40, 60, 90, and 120 psi stress.
Figure 5.19. Predicted creep strain for drying under compression. (a) 150°F and 40, 60, and 80 psi stress and (b) 90, 120, 150, and 180°F and 80 psi stress.
Mechano-Sorptive Strain

The mechano-sorptive strain was the remaining part of the net strain after subtracting the corresponding instantaneous and creep strains.

Figure 5.20 shows the MS strain in tension as a function of moisture content at 150°F (symbols). It can be seen from Figure 5.20 that the MS strain increased with an increase in the applied stress over a similar drying history. Under a particular stress, there appeared to be a linear trend between MS strain and moisture content over most of the moisture range. Initially, however, the strain increase was too rapid to consider the strain rate to be a constant over the entire range of the moisture change. This was especially true at the highest stress level 120 psi. This trend was observed during all the tension tests.

Figure 5.21 shows the MS strain in compression at 150°F (symbols). As was true for tension, the increase in the stress led to an increase in the MS strain. However, over the range of the applied stress, the MS strain appeared to be more linearly related to the moisture content compared with tension. This linear behavior was seen by a nearly constant rate of strain development right from the beginning of drying under a specified stress level.
Figure 5.20. MS strain and moisture content relation from drying under tension at 150°F, lines showing fitted values with Equation 3.11. (a) 40 psi, (b) 60 psi, (c) 90 psi, and (d) 120 psi stress.
Figure 5.21. MS strain and moisture content relation from drying under compression at 150°F, lines showing fitted values with Equation 3.11. (a) 40 psi, (b) 60 psi, and (c) 80 psi stress.
The MS strain as a function of moisture content for drying under compression at 90, 120 and 180°F was shown in Figure 5.22 (symbols). The following observations could be made from Figure 5.22 for the effect of temperature on the development of the MS strain:

(a). At 90 and 120°F, the MS strain varied linearly with moisture content, similar to the behavior at 150°F. However, the strain rate above 20% moisture content was slightly smaller than the rest of the moisture range. This behavior was similar to the shrinkage-moisture content relation described earlier.

(b). At 180°F, moisture change below about 10% MC led to a slower rate increase in the MS strain compared with moisture change above 10%. The degree of linearity between MS strain and moisture content over the whole range of moisture change appeared to be decreased.

Least-square regression was used to linearly fit the MS strain-moisture content curves to get the parameter $k_m$ (a ratio of the slope in the MS strain-MC curve to the stress). Table 5.8 summaries the results of data fitting for drying under tension and compression at 150°F. Table 5.9 shows the results for drying under compression at 90, 120, and 180°F (Figure 5.22). The fitted data at 150°F and 80 psi stress level from Table 5.8 are also shown in Table 5.9 for comparison.
Figure 5.22. MS strain and moisture content relation from drying under compression at 80 psi stress level, lines showing fitted values with Equation 3.11. (a) 90°F, (b) 120°F, (c) and (d) 180°F.
Table 5.8. Fitted MS parameter as a function of stress from drying under tension and compression at 150°F.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma) (psi)</td>
<td>(k_m) (1/psi %MC)</td>
</tr>
<tr>
<td>40</td>
<td>4.51E-6</td>
</tr>
<tr>
<td>60</td>
<td>5.33E-6</td>
</tr>
<tr>
<td>90</td>
<td>5.44E-6</td>
</tr>
<tr>
<td>120</td>
<td>4.83E-6</td>
</tr>
</tbody>
</table>

Table 5.9. Fitted MS parameter as a function of temperature from drying under compression at 80 psi stress.

<table>
<thead>
<tr>
<th>Temp (°F)</th>
<th>MC change (%)</th>
<th>(k_m) (1/psi %MC)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>31 -&gt; 3</td>
<td>9.46E-6</td>
<td>0.98</td>
</tr>
<tr>
<td>120</td>
<td>28 -&gt; 7</td>
<td>12.05E-6</td>
<td>0.98</td>
</tr>
<tr>
<td>150</td>
<td>25 -&gt; 5</td>
<td>15.13E-6</td>
<td>0.97</td>
</tr>
<tr>
<td>180</td>
<td>20 -&gt; 3</td>
<td>17.03E-6</td>
<td>0.96</td>
</tr>
<tr>
<td>180</td>
<td>16 -&gt; 3</td>
<td>14.91E-6</td>
<td>0.93</td>
</tr>
</tbody>
</table>

As shown in Table 5.8, at 150°F the parameter \(k_m\) for tension does not vary systematically with levels of stress. Similarly, for compression the coefficient \(k_m\) is nearly independent of stress level. The mean value of \(k_m\) is 5.03E-6 for tension and 15.40E-6 (1/psi %MC) for compression. Thus, under the similar loading and drying conditions at 150°F the mechano-sorptive strain would be about three times larger in compression than tension. A larger MS strain in compression has been observed for some other wood species and wood-based composite materials (Armstrong, 1972; Hoffmeyer and Davidson, 1989; Mårtensson and Thelandersson, 1990). A ratio of two in the MS strain between compression and tension was reported by
Mårtensson and Thelandersson (1990) for hardboard at room temperature. The trend of the present measurements thus agrees in principle with previous findings.

There was a clear trend that the parameter $k_m$ increased with temperature from 90 to 120 and 150°F (Table 5.9 and Figure 5.23). The trend is, however, not so obvious for temperature increase from 150 to 180°F. Regression analysis over the measured points led to the following correlation between the parameter $k_m$ in compression and temperature:

$$k_m(T) = 3.33E-06 + 7.61E-08 T \quad R^2 = 0.76 \quad (5.7)$$

which is plotted in Figure 5.23 with the data points.

![Graph](image)

Figure 5.23. MS parameter $k_m$ as a function of temperature from drying under compression at 80 psi stress.
Equation 3.11, i.e.

\[ \dot{\varepsilon}_M = k_M \sigma |\dot{\mu}| \]  

(3.11)

had been fit to the MS strain data using the mean coefficient, \( k_M \), among different stress levels for either tension or compression at a given temperature.

Figure 5.20 shows the fitted lines in comparison with the measured points for drying under tension at 150°F. For tests at 40 and 90 psi stress levels, the fits agree well with the data. However, at 60 and 120 psi stress levels, the fit of the curves is poor. Because the higher rate of MS strain at the high moisture contents, Equation 3.11 with a constant coefficient \( k_M \) tends to under-estimate the MS strain at the earlier stages of the drying for this loading mode.

Figure 5.21 shows the fitted lines for drying under compression at 150°F. The fitted lines for MS strain under compression at 90, 120, and 180°F are shown in Figure 5.22. The compression data fit well for temperatures up to 150°F. At 180°F, however, the fitted values are much lower than the measured points due to a higher strain rate at the higher moisture contents.
Comparison of Fitted and Measured Net Strains

The fitted net strain from drying under load at a given temperature consists of instantaneous strain (a ratio of applied stress to the measured mean instantaneous MOE), creep strain (Figures 5.18 and 5.19), and MS strain (lines in Figures 5.20, 5.21, and 5.22). The result represents the prediction of the material property model for small wood samples, which is compared with the corresponding measurements in this section.

Figure 5.24 shows the fitted results for drying under tension at 150°F. The upper solid curve in each graph represents the fitted net strain, while the symbols show the measured data. Also shown in each graph are the corresponding instantaneous strain (horizontal line) and creep strain (lower curve). From each graph it is clearly seen that the MS strain (i.e. distance between two curves) is the major strain component. Because of the dominance of the MS strain and the problems in fitting this strain at the earlier stage of drying as discussed in the last section, the fitted net strain is slightly smaller than the measured points over this period of drying.

Figure 5.25 shows the fitted net strain for drying under compression at 150°F. Figure 5.26 shows fitted net strain for drying under compression at 90, 120 and 180°F. The notation and lines for these plots match those used in Figure 5.24.
Figure 5.24. Fitted net strain from drying under tension at 150°F. (a) 40 psi, (b) 60 psi, (c) 90 psi, and (d) 120 psi stress.
Figure 5.25. Fitted net strain from drying under compression at 150°F. (a) 40 psi, (b) 60 psi, and (c) 80 psi stress.
Figure 5.26. Fitted net strain from drying under compression at 80 psi stress. (a) 90°F, (b) 120°F, (c) and (d) 180°F.
Again for compression, the MS strain (distance between two curves) is the dominant component. The net strain fits the measured points well for temperature up to 150°F over the range of the applied stresses. At 180°F and 80 psi stress level, the fitted net strain was smaller than the measured points because of the poor fit in the MS component discussed above.

From the discussion in this section, it is clear that the MS effect plays a dominant role in the development of net strain from drying of small wood samples under load. Because of the large magnitude of the strain and its effect on stress relaxation, ignoring this strain component when calculating drying stress would certainly lead to unrealistic results. The contribution of creep deformation (after allowing the effect of moisture change) towards net strain in those tests with small samples is fairly small due to a relative short testing period. With a slower change of moisture content as in drying of the full-size boards, the creep deformation is expected to be increased.
5.1.2.2 Moisture Adsorption - Wetting

1. Experimental Data

(1). Temperature and Pressure Histories

Typical temperature and pressure histories in a complete test run for specimens adsorbing moisture (wetting) under load at 150°F are presented in Figure 5.27. As shown in Figure 5.27a, the temperature history was similar to that described in last two sections. For pressure (Figure 5.27b), the system was initially evacuated and then pressurized in a rate about 0.005 psi/minute to the first target pressure (about 1.2 psi). This corresponded to about 5% moisture content at this temperature. After the system pressure reached the target value, a period of 40 minutes was allowed to let the system reach the steady-state. During testing, the set-point pressure was ramped at a rate of 0.0055 psi per minute to approach the second target value i.e. 3.6 psi. This corresponded to about 20% moisture content.

(2) Test Results

Experimental data for wetting under tension at 150°F are shown in Figure 5.28a (moisture-time relation) and Figure 5.28b (strain-time relation). As shown in Figure 5.28a, wetting of test specimens took place in a period of about 440 minutes. At the end of the testing period, although the
Figure 5.27. Test conditions for wetting under tension at 150°F. (a) temperature history and (b) pressure history.
Figure 5.28. Results from wetting under tension at 150°F.  
(a) moisture-time relation and (b) strain-time relation.
pressure reached the target value, the moisture content of the specimen did not reach the specified target value. The accelerated deformation due to an increase in moisture content under load is seen as the increased swelling compared with the matched load-free specimen. Due to a large amount of deformation developed at 180 psi stress level, the test specimen broke 350 minutes after the load was applied.

As shown in Figure 5.28b, at a particular stress level there was an initial instantaneous deformation in the direction of swelling after load was applied. Soon after the moisture was increased, the accelerated swelling under load was developed. Thus, the measured strain curve departed from the matched load-free swelling curve in the direction of the increased swelling. It can be also seen that initially, a sudden increase of the surrounding pressure, thus the relative humidity, led to a greater rate of increase in the swelling strains. Later in testing, the rate of swelling decreased as the moisture content of the test specimen gradually approached the target value.

Figure 5.29 presents two sets of strain curves from the repeated tests at the 80 psi stress level to show the variability of measurements. It can be seen that two loaded strain curves matched well over most of the wetting process. At the later stages of the test, the two loaded strain curves differed somewhat. This may be due to material variability and difference in the actual moisture content of each
specimen. The moisture sorption histories among different tests were more closely matched in wetting tests compared with the drying experiments because the swelling curves almost overlapped over the entire test range.

Figure 5.29. Variability of repeated measurements from wetting under tension at 150°F and 80 psi stress level.
2. Results of Data Fitting

The same procedure as used in last section to fit curves to the drying data was employed to analyze the wetting data.

**Load-Free Swelling Strain**

Figure 5.30 shows the measured swelling strain to be almost linearly related to the MC from 5% to 18%. The swelling coefficient, i.e. swelling per percent MC increase, from the linear regression analysis is 0.0028 /%MC. This is reasonably close to the shrinkage coefficient of 0.0030 /%MC from drying for moisture content change from 20% to 5%.

![Graph showing the relationship between Moisture Content (%) and Swelling Strain (N/IN)](image)

*Figure 5.30. Tangential swelling and moisture content relation of Douglas-fir from wetting at 150°F.*
Figure 5.31 shows the net strain as a function of time at four stress levels during sorption. The strain was obtained from the total strain curve shown in Figure 5.28b after subtracting the swelling strain. The increase in the net strain was mainly associated with an increase in moisture content of the wood after the load was applied.

Figure 5.31. Net strain from wetting under tension at 150°F and 40, 80, 120, and 180 psi stress levels.
Instantaneous Strain

Figure 5.32 shows a nearly linear relation between the instantaneous strain and applied stress. Linear regression analysis over the measured points led to an instantaneous modulus of elasticity of 91,150 psi at 5% moisture content and 150°F. Compared to the measured values at 10% and 25% moisture content and same temperature shown in last two sections, the MOE was increased.

![Graph showing instantaneous strain as a function of stress from wetting tests at 5% MC and 150°F.](image)

Figure 5.32. Instantaneous strain as a function of stress from wetting tests at 5% MC and 150°F.
Mechanical Creep Strain

Figure 5.33 presents the predicted creep strain for each of four stress levels using the measured creep and MOE data. The magnitude of the predicted creep strain increased with the increase in the applied stress. Under a particular stress level, the creep rate increased with time as a result of the gradual increase in moisture content of the test specimen.

Figure 5.33. Predicted creep strain for wetting under tension at 150°F and 40, 80, 120, and 180 psi stress levels.
Mechano-sorptive Strain

Figure 5.34 shows the MS strain as a function of moisture content at four stress levels (symbols). Linear regression analysis was used to determine the MS coefficient, $k_m$, as a function of moisture content at each stress level. Table 5.10 lists the results of data fitting.

<table>
<thead>
<tr>
<th>$\sigma$ (psi)</th>
<th>$k_m$ (1/%MC psi)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>17.00E-6</td>
<td>0.98</td>
</tr>
<tr>
<td>80</td>
<td>14.65E-6</td>
<td>0.98</td>
</tr>
<tr>
<td>120</td>
<td>14.37E-6</td>
<td>0.98</td>
</tr>
<tr>
<td>180</td>
<td>14.96E-6</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Except at 40 psi stress, the coefficient $k_m$ is almost constant for this test condition. The mean value of the coefficient $k_m$ among all four stress levels is 15.26E-6 (1/psi %MC). The corresponding value for drying in tension is 5.04E-6 (1/psi %MC). Thus, in tension, the first moisture adsorption process under load resulted in a mechano-sorptive strain about three times larger than the desorption for the same change in moisture content. In the longitudinal bending of pine, Perkitny (1965) reported a ratio of 2.5 in the MS deformation associated with first adsorption and desorption process under load for moisture change between 10% to saturated condition at room temperature. A ratio of 1.7 was reported by Ranta-Maunus (1975) from bending of birch with moisture content change between 5% and 30% at 68°F.
Figure 5.34. MS strain and moisture content relation from wetting under tension at 150°F, lines showing fitted values with Equation 3.11. (a) 40 psi, (b) 80 psi, (c) 120 psi, and (d) 180 psi stress.
In Figure 5.34, the mean coefficient, $k_m$, from Table 5.10 was used in Equation 3.11 to generate the solid lines. Equation 3.11 with a constant coefficient $k_m$ fitted the measured points well at the 40, 80, and 120 psi stress levels. The fitted line at 180 psi stress level fitted the data well to about 14.5% moisture content. After this point, the data departed from the fitted line until failure occurred.

**Comparison of Fitted and Measured Net Strain**

The fitted net strain consists of instantaneous strain (Figure 5.32), creep strain (Figure 5.33) and MS strain (Figure 5.34). In Figure 5.35, the fitted net strain (upper solid curve) is shown together with measured data points at each stress level. Also shown in each graph are the corresponding instantaneous strain (horizontal line) and creep strain (lower curve). It is clear that the MS strain (distance between two curves) is the dominant component of the net strain. Because of the large magnitude of the MS strain in this test condition, the contribution of the creep strain (distance between the lower curve and the horizontal line) towards the net strain was fairly small. The fitted net strain matched well with the measured points at 40, 80 and 120 psi stress levels. At 180 psi stress level, the fit was good for the first 345 minutes; thereafter, measured net strain departed quickly from the fitted line until failure occurred.
Figure 5.35. Fitted net strain from wetting under tension at 150°F. (a) 40 psi, (b) 80 psi, (c) 120 psi, and (d) 180 psi stress.
5.2 Distribution of Moisture and Temperature

5.2.1 Results of Measurement

The distributions of temperature and moisture content across the board thickness from the three drying charges are shown in Figures 5.36 to 5.38. Also shown for each charge is the variation of dry-bulb and wet-bulb temperature of the air. The board temperature (Figures 5.36 (a) to 5.38 (a)) in all three charges started to increase from wet-bulb temperature of air soon after the drying started. There was a 2 to 3°F temperature difference between the center and surface zones of the board in drying of Douglas-fir heartwood lumber. However, over most parts of the drying process, wood temperature was close to the dry-bulb temperature of the air. Due to the small difference between wood temperature and air temperature, temperature variation inside the board was ignored.

The moisture distribution was generally symmetric about the center line of the board, and each displayed point in Figures 5.36 (b) to 5.38 (b) was a average of moisture contents from two slices at the symmetric position in the board. By decreasing the wet-bulb depression at early stages of drying, the moisture gradient inside the board was decreased from charge I to charge III. The moisture contents at the surface (position 0) and center (position 1) of the board at a specified time were extrapolated from each representing line.
Figure 5.36. Results of lumber drying from charge I. (a) temperature profile and (b) moisture profile.
Figure 5.37. Results of lumber drying from charge II. (a) temperature profile and (b) moisture profile.
Figure 5.38. Results of lumber drying from charge III. (a) temperature profile and (b) moisture profile.
5.2.2 Results of Data Fitting

The extrapolated surface moisture contents from each drying charge were fitted with Equation 3.13:

$$I: \quad M(t,0) = 11.8 + 20.2 \exp(-0.635 t^{0.447})$$
$$II: \quad M(t,0) = 5.8 + 26.2 \exp(-0.141 t^{0.597})$$
$$III: \quad M(t, 0) = 5.0 + 28.5 \exp(-0.124 t^{0.533})$$

where the first term is the final EMC of air, and the constant before exponential term is the difference between initial moisture content of the wood and the final EMC of air.

The fitted diffusion coefficient (mm²/hour or x 1.55E-3 in²/hour) varying with moisture content with Equation 3.14 is:

$$I: \quad D(M) = 1.082 + 0.1932 M - 0.0107 M^2 + 0.000338 M^3$$
$$II: \quad D(M) = 0.941 + 0.1682 M - 0.0093 M^2 + 0.000294 M^3$$
$$III: \quad D(M) = 1.244 + 0.1573 M - 0.0066 M^2 + 0.000178 M^3$$

A comparison of the fitted diffusion coefficient with data given by Siau (1984) at 150°F is shown in Figure 5.39. Compared with fitted diffusion coefficients, Siau's data were lower for the moisture change below 25% in drying Douglas-fir lumber. The fitted data for all three charges were similar.

Comparisons between the fitted (line) and measured (symbol) moisture profiles as a function of time are shown in Figures 5.40 to 5.42. In those graphs, node 0 and node 5 correspond to the surface and center of board respectively.
Figure 5.39. Fitted diffusion coefficient as a function of moisture content for drying of Douglas-fir heartwood in comparison with Siau's data (1984).
Figure 5.40. Fitted and measured moisture profiles as a function of time from drying charge I.
Figure 5.41. Fitted and measured moisture profiles as a function of time from drying charge II.
Figure 5.42. Fitted and measured moisture profiles as a function of time from drying charge III.
5.3 Stresses and Strains in Drying of Lumber

5.3.1 Material Properties

The material properties for the stress model fall into the following three categories.

5.3.1.1 Instantaneous Stress-Strain Relation

The general instantaneous stress-strain relation defined by Equation 3.2 and 3.3 consists of a linear part to the proportional limit and a nonlinear part to failure. Test results for Douglas-fir at different moisture contents and stress levels indicated an approximately linear relation between instantaneous strain and stress over the range of stresses applied. Thus, the general instantaneous stress-strain relation was approximated with a straight line (Equation 3.2); the slope of the line corresponds to the MOE. For a continuously changing moisture content, the linear stress-strain relation is broken into a series of piece-wise linear line segments. The slope of an individual line segment, i.e. local tangent modulus of elasticity, varies with moisture content, but is independent of stress. The modulus of elasticity as a function of moisture content and temperature was estimated using the Palka's equations (1973). The reference MOE value and the coefficients for the effect of MC and temperature were obtained from measurements as:
\[ E(T,M) = 94500 \left[ 1 + c_{TE}(T-90) \right] \left[ 1 + c_{MC}(M-10) \right] \]

with \( c_{TE} = -0.00365 \text{ } ^\circ \text{F} \); \( c_{MC} = -0.0465 \text{ } \% \text{MC} \)

(5.10)

The tensile strength perpendicular to the grain for Douglas-fir at 68\(^\circ\)F was obtained from Wilson (1932) and Wood Handbook (Forest Products Laboratory, 1987) as 300 psi in the green condition. The strength value was adjusted for other moisture contents and temperatures using the Palka's equations (1973) as:

\[ \sigma_U(T,M) = 300 \left[ 1 + c_{TE}(T-68) \right] \left[ 1 + c_{MC}(M-30) \right] \]

with \( c_{TE} = -0.00367 \text{ } ^\circ \text{F} \); \( c_{MC} = -0.01 \text{ } \% \text{MC} \)

(5.11)

where, the coefficients \( c_{TE} \) and \( c_{MC} \) were obtained from Siime (1967). The equation gives the tensile strength perpendicular to the grain of 210 psi at green and 150\(^\circ\)F, which is about one tenth of the measured modulus of elasticity at 25\% MC.

5.3.1.2 Time-Dependent Properties

Creep deformation at a reference moisture content for Douglas-fir in the tangential direction was determined experimentally. At 150\(^\circ\)F and 10\% MC, the fitted equations for creep strain in tension and compression from Table 5.3 are:

\[ \varepsilon_c(t) = 6.56 \times 10^{-6} \sigma t^{0.52} \text{ for tension} \]

\[ \varepsilon_c(t) = 7.44 \times 10^{-6} \sigma t^{0.44} \text{ for compression} \]

(5.12)

where \( t \) is in hours.
5.3.1.3 Moisture Change-Dependent Properties

The shrinkage strain for the narrow-ringed board (NRB) was defined using Equation 3.10 and shrinkage coefficients in Table 5.5 as:

\[
\Delta \varepsilon_s = -0.0018 \Delta M \quad \text{for } 20\% < M < 30\%
\]
\[
\Delta \varepsilon_s = -0.0030 \Delta M \quad \text{for } M \leq 20\%
\] (5.13)

The shrinkage coefficients were decreased to about 80% of the values in Equation 5.13 for the wide-ringed board (WRB) corresponding to the measurement shown in Figure 5.14.

The mechano-sorptive strain associated with moisture change below the FSP at 150°F was defined using Equation 3.11 and mean MS parameters in Table 5.8 as:

\[
\Delta \varepsilon_m = 5.04E-06 \sigma |\Delta M| \quad \text{for tension}
\]
\[
\Delta \varepsilon_m = 15.87E-06 \sigma |\Delta M| \quad \text{for compression}
\] (5.14)

5.3.2 Drying Stress and Strain

The stress and strain that occur in a board were mathematically simulated for the moisture distributions and material properties. The distributions of drying stress and strain arising from those changes in the moisture content and their comparison with actual measurements are analyzed in this section.
5.3.2.1 Drying Stress

Figure 5.43 shows the predicted stress distributions. In charge III, the stress profile for the wide-ringed boards was obtained with a similar moisture distribution and coefficients defining instantaneous, creep and MS strain as for the narrow-ringed boards, but decreased shrinkage coefficients. A summary on the maximum surface tensile stress and its time of occurrence, time and board moisture content at which the stress reversal occurred at node 0 (surface) and node 1 is shown in Table 5.11.

<table>
<thead>
<tr>
<th>Table 5.11. Summary on predicted drying stress from three drying charges.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying charge</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Maximum surface stress: $\sigma$ (psi)</td>
</tr>
<tr>
<td>t (hrs)</td>
</tr>
<tr>
<td>Stress reversal M (%) at node 0: t (hrs)</td>
</tr>
<tr>
<td>Stress reversal M (%) at node 1: t (hrs)</td>
</tr>
</tbody>
</table>

From Figure 5.43, it can be seen that the predicted stress profile is in a well-expected pattern. Initially, the surface layers of the board were in tension, while the center layers were in compression. As drying continued, the surface switched from tension to compression and center from compression to tension. At the end of drying, the surface was
Figure 5.43. Predicted stress distributions. 
(a) NRB in charge I, (b) NRB in charge II, 
(c) NRB in charge III, and (d) WRB in charge III.
Figure 5.43 (continued). Predicted stress distributions.
(a) NRB in charge I, (b) NRB in charge II,
(c) NRB in charge III, and (d) WRB in charge III.
in compression and center was in tension. In charge I, at about 6 hours after drying started the tensile stress at surface reached its maximum value of 275 psi (Table 5.11). By decreasing the moisture gradient at the early stages of drying in charges II and III, the maximum tensile stresses at surface were decreased and their occurring times were delayed (Table 5.11). In charge III, the maximum tensile stress for wide-ringed boards with less shrinkage was about 30 psi lower compared to the narrow-ringed boards with higher shrinkage.

In the later stages of drying, large compressive stresses were developed at surface for charge I due to small changes in surface moisture content after the stress reversal. For charges II and III, however, because of the further decreases in the EMCs of air after stress reversal, which caused further drying and development of the mechano-sorptive effect in compression at surface, the magnitude of the compressive stress at surface was largely decreased compared with charge I. The tensile stresses in the center layers developed after stress reversal were generally below 100 psi.

The mean moisture content of the board at which the stress reversal occurred at node 0 (surface) and node 1 is about 20% and 17% respectively for all three charges. This is in a close agreement with the early findings in drying of softwoods of the similar characteristics (McMillen, 1968; Resch et al, 1989).
The maximum surface tensile stresses predicted for charges I and II were significantly higher than 210 psi, the strength value predicted by Equation 5.11 for Douglas-fir at green and 150°F. The maximum tensile stress predicted for charge III was similar to the strength for the narrow-ringed boards and significantly less for the wide-ringed boards. In actual drying tests, small surface checks in charge I appeared at 8 hours (first sampling time) which further developed into large checks. In charge II checks were observed at 24 hours, which also further enlarged as a further decrease in the EMCs of air was made. Only small surface checks were seen in the charge III for the narrow-ringed boards. No surface checks were founded for the wide-ringed boards. In all three charges, no internal checks were observed.

5.3.2.2 Drying Strain

1. Model Prediction

Drying strain predicted by the model includes instantaneous, creep, shrinkage, and MS strain components. Figures 5.44 to 5.47 show predicted drying strain for each of the drying conditions.

The predicted instantaneous strain corresponded closely to the pattern of drying stress. In the early stages of drying, the surface zones were subjected to tensile strain, while the center zones were to compressive strain. As drying
Figure 5.44. Predicted strain profiles for NRB in charge I, numbers showing nodes from board surface (0) to center (5). (a) instantaneous, (b) creep, (c) shrinkage, and (d) MS strain.
Figure 5.45. Predicted strain profiles for NRB in charge II, numbers showing nodes from board surface (0) to center (5). (a) instantaneous, (b) creep, (c) shrinkage, and (d) MS strain.
Figure 5.46. Predicted strain profiles for NRB in charge III, numbers showing nodes from board surface (0) to center (5). (a) instantaneous, (b) creep, (c) shrinkage, and (d) MS strain.
Figure 5.47. Predicted strain profiles for WRB in charge III, numbers showing nodes from board surface (0) to center (5). (a) instantaneous, (b) creep, (c) shrinkage, and (d) MS strain.
continued, the stresses decreased from their maximum values and so did the instantaneous strains. After stress reversal occurred at surface, the reversal of the instantaneous strain may occur (in charge I) or may not occur (in charges II and III) depending on the magnitude of the compressive stress developed after the stress reversal. Among all the charges, the magnitude of the maximum tensile strain in charge I was the largest, corresponding to the stress state for the drying condition.

Tensile creep (surface zones) and compressive creep (center zones) increased quickly at the early stage of drying due to the high moisture content of the wood. After stress reversal occurred at a nodal point, the accumulated creep under the previous stress state (tension in surface and compression in center) was gradually canceled out by the amount of creep occurring under the stress in the opposite sense. In charge I, the large compressive stress at surface caused the creep strain to reverse from tension to compression at about 168 hours. For charges II and III, tensile creep at the surface persisted to the end of drying.

The variation of the shrinkage strain was directly proportional to the MC change below about 30%. At the early stages of drying, the moisture contents in the center slices were above 30% and thus no shrinkage occurred.

At early stages of drying, quick decreases in the surface MC below the FSP led to a fast rate of development of MS
strain at the surface. In the interior of the board, however, little MS strain was developed as the MC change occurred above the FSP. After the stress reversal, MS strain at surface was gradually decreased due to the compressive action. In charge I, because small MC changes occurred at surface after stress reversal, the MS strain developed in compression was fairly small, and the total MS strain appeared to be only slightly decreased. In charges II and III, however, further decreases in the EMCs of air led to further reductions of the surface MCs and development of MS strain in compression. Thus, the amount of decrease in the accumulated MS strain at surface was increased.

It should be noted that the magnitude of creep strain became comparable with MS strain in all three charges. This is due to a much longer time period in drying large boards compared to the drying of small wood samples.

2. Results of Slicing Measurements

The immediately released strain and total shrinkage from the slicing measurements are presented in Figures 5.48 to 5.51. At the early stages of drying, the first three slices from the board surface showed the contraction indicating the tensile action, while the center two slices showed expansion for compression (Figures 5.48 (a) to 5.51 (a)). The measured released strain in the surface slices (1,10) from charge I was
Figure 5.48. Measured drying strains for NRB in charge I. (a) released strain and (b) total shrinkage.
Figure 5.49. Measured drying strains for NRB in charge II. (a) released strain and (b) total shrinkage.
Figure 5.50. Measured drying strains for NRB in charge III. (a) released strain and (b) total shrinkage.
Figure 5.51. Measured drying strains for WRB in charge III. (a) released strain and (b) total shrinkage.
highest at about 8 hours after drying started (0.0048 in/in). The highest surface released strain in charge II was similar, but occurred at about 24 hours. In charge III, the released strain from both kinds of wood decreased. At the later stages of drying, the magnitude of the released strain was fairly small and little difference was seen among center slices.

The total shrinkage (green to oven-dry) from the sample taken before drying (time 0) was about 7.7% in charges I, II and III for the NRBs (Figures 5.48 (b) to 5.50 (b)). For the WRBs in charge III (Figure 5.51 (b)), however, the shrinkage was only about 6%. These corresponded to the values shown in Figure 5.14. During drying, the shrinkage in surface slices was decreased due to the tension, while the shrinkage in center slices was increased due to compression. The decrease or increase in shrinkage from the initially unstressed condition is known as tension or compression set (McMillen, 1955a). The apparently fast rate development of the tension set in the surface slices (1,10) can be seen in charge I compared with charges II and III. This was due to a steeper moisture gradient and large magnitude of drying stresses at the beginning of drying in charge I. The magnitude of the maximum tension set for charges I and II was similar (about 2%). The maximum tension set was decreased to about 1.6% in charge III for both groups of wood. The maximum compression set in the center was about one fourth of the corresponding tension set at the surface for all drying conditions.
3. Model Verification

The measured released-strain shown above is the instantaneous recoverable part of the drying strain (McMillen, 1955a). Similarly, the measured set strain is the nonrecoverable part of the drying strain. Thus, the summation of the released and set strain (called net strain) corresponds to the summation of the predicted instantaneous, creep, and MS strain in the stress model.

Figure 5.52 shows predicted net strain at nodal points 0 (surface), 1, and 5 (center) in comparison with measurements for drying charges I, II, and III. The trend of the predicted and measured net strains matched well.

Certain differences should be expected between the predicted and measured net strains for the following two reasons:

a). Model prediction represents the strain value at the nodal points, while the measured value is the mean value over the thickness of a slice.

b). Slicing measurements are subjected to errors from preparing and subsequent drying of the slices. Soon after a slice was sawn, the fibers at the surface were exposed to air and lost moisture which causes shrinkage and mechano-sorptive strain. In the subsequent drying of the obtained slices, a new moisture gradient and thus drying stress were developed within each slice, which cause further development of the set
Figure 5.52. Comparison of predicted and measured net strains.
(a) NRB in charge I, (b) NRB in charge II, (c) NRB in charge III, and (d) WRB in charge III.
Figure 5.52 (continued). Comparison of predicted and measured net strains. (a) NRB in charge I, (b) NRB in charge II, (c) NRB in charge III, and (d) WRB in charge III.
strain. Thus, the results of the slicing measurements on the immediately released strain and permanent set are somewhat misleading.

The board shrinkage, which reflects the overall drying behavior of the board and is subjected to less error in measurements, is a better criteria in comparing the model prediction with experimental data. Figure 5.53 shows the comparison of the predicted (line) and measured (symbol) board shrinkage. The five different symbols represent the measurements over five slices from the surface (+) to center (x) of the board. Over most part of drying, the measured board shrinkages from the surface and center slices were similar (the symbols are overlapped). Thus, the geometric compatibility condition for the model, i.e. the board edge remains plane in drying, was approximately satisfied for drying of the wide and edge-coated boards. The model prediction of the board shrinkage matched measured values well over the whole drying process.
Figure 5.53. Comparison of predicted and measured board shrinkage. (a) NRB in charge I, (b) NRB in charge II, (c) NRB in charge III, and (d) WRB in charge III.
Figure 5.53 (continued). Comparison of predicted and measured board shrinkage. (a) NRB in charge I, (b) NRB in charge II, (c) NRB in charge III, and (d) WRB in charge III.
6.1 Conclusion

The mechanical behavior of a small wood sample under load during moisture content change and a large lumber board during drying was investigated. Based on the results from actual testing and analytical study, the following conclusions can be derived:

1. The simplified linear instantaneous stress-strain relation with MOE varying with both temperature and moisture content as measured on small wood samples can be applied in modeling stress during drying of large lumber boards.

2. For a rapid drying or wetting of small wood samples under load, the creep deformation (after allowing the effect of moisture change) is relatively small compared with the magnitude of the MS strain. In drying of large lumber boards, however, the creep strain becomes comparable to the MS strain due to increased drying time.

3. The shrinkage of small wood samples varies with range of moisture change and ring width. Two shrinkage coefficients for MC change, one above and one below 20%,
are satisfactory in fitting the shrinkage-MC curve. The shrinkage coefficients for drying at 90°F are higher than at 120, 150 and 180°F.

4. The mechano-sorptive effect is the dominant component of the total deformation during drying or wetting of small wood samples under load. For drying at 150°F, the MS strain under compression is about three times larger than that under tension. The MS strain in drying under compression increases with temperature between 90 and 180°F. A mean MS coefficient for each loading mode (tension or compression) can be used to estimate the MS deformation at different stress levels at temperatures up to 180°F.

5. The moisture distribution through the board thickness during drying of Douglas-fir heartwood can be fitted by Fick's diffusion equation. The diffusion coefficient must vary with moisture content and board surface moisture content must vary with time.

6. The adapted constitutive equations for various strain components fit experimental data for small wood samples. Most importantly, the same equations can be successfully used to model the mechanical behavior of full-sized boards during drying.
6.2 Recommendations

To make the theoretical models developed more practically useful, the following recommendations are made:

1. Experimental work on the material properties should be extended to include loading in radial direction for Douglas-fir lumber; and to include one hardwood species in both radial and tangential directions.

2. The process model should be combined with a coupled heat and mass transfer model for the distribution of temperature and moisture in drying of lumber so that drying stress under varying temperature and humidity conditions can be modeled.

3. Two-dimensional analysis in a plane strain condition involving creep and mechano-sorptive deformation should be studied as next step towards completely modeling the process of drying lumber.
REFERENCES


Schniewind, A.P. 1966. On the influence of moisture content changes on the creep of beech wood perpendicular to the grain including the effects of temperature and temperature change. Holz als Roh- und Werkstoff. 24:87-98.


Siime, F.E. 1967. The effect of specific gravity, moisture content, temperature and heating time on the tension and compression strength and elasticity properties perpendicular to the grain of Finnish pine spruce and birch wood and the significance of these factors on the checking of timber at kiln drying. VTT Publication 84. Helsinki. 86 pp.


## APPENDIX A: Nomenclature

### Abbreviation

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>EMC</td>
<td>equilibrium moisture content</td>
</tr>
<tr>
<td>FSP</td>
<td>fiber saturation point</td>
</tr>
<tr>
<td>FS</td>
<td>flatsawn</td>
</tr>
<tr>
<td>MC</td>
<td>moisture content</td>
</tr>
<tr>
<td>MOE</td>
<td>modulus of elasticity</td>
</tr>
<tr>
<td>MS</td>
<td>mechano-sorptive</td>
</tr>
<tr>
<td>NRB</td>
<td>narrow-ringed board</td>
</tr>
<tr>
<td>QS</td>
<td>quartersawn</td>
</tr>
<tr>
<td>WRB</td>
<td>wide-ringed board</td>
</tr>
</tbody>
</table>

### Symbolic Letter

<table>
<thead>
<tr>
<th>Symbolic Letter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>constant</td>
</tr>
<tr>
<td>B</td>
<td>constant</td>
</tr>
<tr>
<td>C</td>
<td>constant</td>
</tr>
<tr>
<td>$c_1, c_2, c_3, c_4$</td>
<td>constants for diffusion coefficient</td>
</tr>
<tr>
<td>$C_{SG}$</td>
<td>correction factor for specific gravity</td>
</tr>
<tr>
<td>$C_{MC}$</td>
<td>correction factor for moisture content</td>
</tr>
<tr>
<td>$C_{TE}$</td>
<td>correction factor for temperature</td>
</tr>
<tr>
<td>$C_{SR}$</td>
<td>correction factor for strain rate</td>
</tr>
<tr>
<td>CF</td>
<td>unit conversion factor</td>
</tr>
<tr>
<td>$D_{01}, D_{02}, D_{03}$</td>
<td>pixel distance between relevant dots</td>
</tr>
<tr>
<td>$D_1, D_2, ΔD_1, ΔD_2$</td>
<td>pixel distance and distance change between relevant dots in the direction of loading</td>
</tr>
</tbody>
</table>
D = moisture diffusion coefficient
D_i = instantaneous compliance
D_M = MS strain compliance
E = modulus of elasticity
i = time index for integration
I,II,III = drying charge number
j = spacial index across board thickness
J_{ijkl} = creep compliance tensor
q = iteration index
Q = activation energy
k_i = constant for instantaneous strain
k_C = constant for creep strain
k_M = constant for MS strain
k_S = constant for shrinkage strain
K = material constant for creep strain
K, K_1, K_2, K_3, .... = spring constants in mechanical models
M, M, \Delta M = moisture content, its time derivative, and increment
M_o, M_1, M_f = moisture content at specified conditions
M_{EMC} = moisture content at equilibrium
M_{FSP} = moisture content at FSP
M_R = moisture content at reference condition
m_C = constant for creep strain
N = node number across board thickness
NL = nominal length of test specimen
n_i = constant for instantaneous strain
n_C = constant for creep strain
P, P₀ = load
RL = reference length of test specimen
R = gas constant
R² = square of the correlation coefficient
RC = relative creep
SG, SG₀ = specific gravity
t, Δt = time and time increment
t₀, t₁, t₂ = time
T, ΔT = temperature and temperature increment
V, V₃ = loading rate
x₀, x₁, x₂, x₃ = x-coordinate of reference dots in pixel
x, Δx = coordinate in the direction of board thickness and spacial increment
X = lumber board thickness/2
Y, Y₀, Y₁, Y₂, Y₃, Y₄ = elastic constants or strength
Y₀, Y₁, Y₂, Y₃ = y-coordinate of reference dots in pixel
W = lumber board width

Greek Letter

δ = deflection
εᵢⱼ = strain tensor
εₑ, εₑ, Δεₑ = creep strain, creep strain rate, and creep strain increment
εᵢ, εᵢ, Δεᵢ = instantaneous strain, instantaneous strain rate, and instantaneous strain increment
εᵢ,E = instantaneous elastic strain
εᵢ,p = instantaneous plastic strain
\[ \varepsilon_{i,y} = \text{instantaneous yield strain} \]
\[ \varepsilon_{i,u} = \text{instantaneous ultimate strain} \]
\[ \varepsilon_{m}, \dot{\varepsilon}_{m}, \Delta \varepsilon_{m} = \text{MS strain, MS strain rate, and MS strain increment} \]
\[ \varepsilon_{n} = \text{net strain} \]
\[ \varepsilon_{s}, \dot{\varepsilon}_{s}, \Delta \varepsilon_{s} = \text{shrinkage strain, shrinkage strain rate, and shrinkage strain increment} \]
\[ \varepsilon_{t} = \text{total strain} \]
\[ \sigma, \dot{\sigma}, \Delta \sigma = \text{stress, stress rate, stress increment} \]
\[ \sigma_{kl} = \text{stress tensor} \]
\[ \sigma_{u} = \text{ultimate stress or strength} \]
\[ \sigma_{y} = \text{yield stress} \]
\[ \eta, \eta_{1}, \eta_{2}, \eta_{3}, \ldots = \text{coefficients of viscosity in mechanical models} \]
\[ \tau = \text{dummy time variable} \]
\[ \rho = \text{density} \]
\[ \psi = \text{stress per bond} \]
\[ \alpha = \text{constant for board surface moisture content} \]
\[ \alpha_{1}, \alpha_{2} = \text{angular distance between relevant dots} \]
\[ \beta = \text{constant for board surface moisture content} \]
\[ \zeta = \text{constant} \]
\[ \lambda = \text{constant} \]
\[ N = \text{variable} \]
\[ \Pi = \text{variable} \]
APPENDIX B: Principle of Strain and Time Hardening

The general expression for creep strain can be written in terms of functions for stress, $f(\sigma)$, time, $g(t)$, and testing conditions, $k(T,M_0)$ (Kao, 1981; Kraus, 1980):

$$\varepsilon_c = k(T,M_0) f(\sigma) g(t) \tag{B.1}$$

The creep rate is obtained from Equation B.1 as:

$$\dot{\varepsilon}_c = k(T,M_0) f(\sigma) \dot{g}(t) \tag{B.2}$$

and the creep increment is:

$$\Delta \varepsilon_c = k(T,M_0) f(\sigma) \dot{g}(t) \Delta t \tag{B.3}$$

Under the variable stress condition as shown in Figure B.1a or Figure B.2a, the smooth stress-time curve is approximated by horizontal and vertical segments. Within each segment, stress is assumed to be constant so that Equation B.3 can be applied.

As indicated in Figure B.1b, determination of the creep strain using the strain hardening rule is demonstrated over the time step from $t_2$ to $t_3$. At a point $d^*$ on the creep curve under varying stresses, the creep strain $\varepsilon_{c,2}$ corresponding to the stress level $\sigma_3$ and time $t_2$ is known. The value of $t_2^*$ associated with the point $e$ on the creep curve under the constant stress $\sigma_4$ is computed by the following equation:

$$\varepsilon_{c,2} = k(T,M_0) f(\sigma_4) g(t_2^*) \tag{B.4}$$
Figure B.1. Principle of strain-hardening. (a) approximation of the smooth stress-time curve by steps, and (b) creep strain-time curve for various stress levels according to strain-hardening rule.
If the stress level changes from $\sigma_3$ to $\sigma_4$, creep increment $\Delta \varepsilon_c$ for next time increment $\Delta t$ can be estimated approximately by:

$$\Delta \varepsilon_c = k(T, M_0) f(\sigma_4) \dot{\gamma}(t_2^*) \Delta t$$  \hspace{1cm} (B.5)$$
or be calculated exactly as:

$$\Delta \varepsilon_c = k(T, M_0) f(\sigma_4) \gamma(t_2^*+\Delta t) - \varepsilon_{c,2}$$  \hspace{1cm} (B.6)$$

If the computation is based on the time-hardening theory (Figure B.2), the creep increment can be estimated approximately by:

$$\Delta \varepsilon_c = k(T, M_0) f(\sigma_4) \dot{\gamma}(t_2) \Delta t$$  \hspace{1cm} (B.7)$$
or be calculated exactly as:

$$\Delta \varepsilon_c = k(T, M_0) f(\sigma_4) [\gamma(t_2+\Delta t) - \gamma(t_2)]$$  \hspace{1cm} (B.8)$$

The creep strain at time $t_3$ is then obtained as:

$$\varepsilon_{c,3} = \varepsilon_{c,2} + \Delta \varepsilon_c$$  \hspace{1cm} (B.9)$$

The process described above for time step from $t_2$ to $t_3$ is repeated to include other levels of stress. After the stress reversal occurs, i.e. stress changes from tension (or compression) to compression (or tension), determination of the creep increment under new stress mode starts at time equal to zero. The obtained creep increment is stacked at the end of the varying creep curve accumulated under the previous stress mode. Because of the loading direction change, the creep
Figure B.2. Principle of time-hardening. (a) approximation of the smooth stress-time curve by steps, and (b) creep strain-time curve for various stress levels according to time-hardening rule.
increment under new stress mode tends to cancel previously accumulated creep as shown in the diagram.

The creep curves under varying stresses shown in Figures B.1b and B.2b are obtained from the exact calculation formulas. Since the slope of the constant-stress creep curves decreases with time, except in the tertiary creep, a comparison between those two varying stress creep curves indicates that strain-hardening predicts a higher creep strain than time-hardening. However, for more gradual load/stress changes, the difference is less marked and the time-hardening theory is easier to use in the stress analysis.
APPENDIX C: Procedure for Fitting Creep Data

The total deformation from each creep test at a constant moisture content consists of an instantaneous strain and a creep strain (Schniewind, 1968; Schniewind and Barrett, 1972; Bodig and Jayne, 1982). Mathematically, this can be expressed as:

\[ e_T(t) = e_I(t) + e_C(t) \]  \hspace{1cm} (C.1)

Since the instantaneous strain is time-independent, it is first determined from the test data at time equal to \( t_o \). The net creep strain as a function of time is then obtained after separating the instantaneous strain from the measured total strain. Expressing the creep strain using Equation 3.6 for the isothermal condition, one has:

\[ e_C(t) = e_T(t) - e_I(t_o) = k_C \sigma^{m_c} t^{n_c} \]  \hspace{1cm} (C.2)

Defining, for each individual test under a constant stress:

\[ K(\sigma) = k_C \sigma^{m_c} \]  \hspace{1cm} (C.3)

Equation C.2 becomes:

\[ e_C(t) = K(\sigma) t^{n_c} \]  \hspace{1cm} (C.4)
Taking the natural logarithmic transformation on Equation C.4, one has the linear relation:

\[
\ln(e_c(t)) = \ln(K(\sigma)) + n_c \ln(t) \tag{C.5}
\]

The experimental data on the net creep strain under each stress were transformed into the natural logarithmic form and were fitted with Equation C.5 through linear regression analysis, from which the material constants \(K(\sigma)\) and \(n_c\) were determined.
APPENDIX D: Procedure for Isolating Mechano-sorptive Strain from the Measured Total Strain

The total strain for wood under load during moisture change from a particular test consists of four components, namely, instantaneous, creep, shrinkage and mechano-sorptive effect. The following procedure was adopted to isolate each of the four strain components (Leicester, 1971; Ranta-Maunus, 1975; Mårtensson, 1988; Mårtensson and Thelandersson, 1990).

Expressing the total strain for a small wood sample using Equation 3.1, one has:

\[ \varepsilon_T(t) = \varepsilon_I(t) + \varepsilon_C(t) + \varepsilon_S(t) + \varepsilon_M(t) \]  

(D.1)

The shrinkage or swelling strain is taken to be independent of the stress state of wood under testing. It is directly obtained from the matched wood sample under the similar drying environment, but load-free condition. Thus, one has the net or stress induced strain as:

\[ \varepsilon_N(t) = \varepsilon_T(t) - \varepsilon_S(t) \]  

(D.2)

\[ = \varepsilon_I(t) + \varepsilon_C(t) + \varepsilon_M(t) \]

Since the initial instantaneous strain is time-independent, it is first determined from the measured strain data at time equal \( t_0 \).

Creep strain, defined as the time-dependent deformation under load at a constant moisture content, occurs also during the test of varying moisture conditions. However, this strain component can only be predicted because of the continuous
change of the moisture levels within the specimen. Using the incremental form of the creep strain (Equation 3.8), one has the creep increment corresponding to a specified moisture content \( M_R \) over a given time step:

\[
\Delta \varepsilon_c(t) \big|_{M_R} = [k_c \, n_c \, \sigma^{m_c} \, t^{(n_c-1)}] \Delta t
\]  

(D.3)

The effect of changing moisture level on the creep among different time steps is accounted for using Equation 3.9 as:

\[
\Delta \varepsilon_c(t) \big|_{M} = \frac{E(M_R)}{E(M)} \Delta \varepsilon_c(t) \big|_{M_R}
\]  

(D.4)

where, the moisture content as a function of time and modulus of elasticity as a function of moisture content are measured from tests. Thus, the accumulated creep strain at a specified time is:

\[
\varepsilon_c(t) = \sum_{t_0}^{t} [\Delta \varepsilon_c(t) \big|_{M}]
\]  

(D.5)

\[
= \sum_{t_0}^{t} \left( \frac{E(M_R)}{E(M)} \right) [k_c \, n_c \, \sigma^{m_c} \, t^{(n_c-1)} \Delta t]
\]

Finally, the mechano-sorptive strain is obtained from the stress-induced strain after separating the corresponding instantaneous and creep components:

\[
\varepsilon_M(t) = \varepsilon_N(t) - \varepsilon_I(t_o) - \varepsilon_c(t)
\]  

(D.6)

in which \( \varepsilon_c(t) \) is expressed by Equation D.5. The principle outlined above was implemented into a FORTRAN program (Appendix E), which was used to analyze the experimental data.
APPENDIX E: Computer Programs

PROGRAM DRYDFIR.FOR

The Program Is To Calculate the Drying Stresses
in the Process of Drying Softwood DOUGLAS-FIR

COMPILER : Microsoft Fortran 5.1
With Graphic Routines

INCLUDE 'FGRAPH.FI'
INCLUDE 'FGRAPH.FD'

REAL*4 dbt(10),wbt(10),cem(10),rh(10)
REAL*4 ei(0:14),ec(0:14),es(0:14),em(0:14),et(0:400)
REAL*4 dei,deco(0:7),dec,ddec,des(0:7),dem(0:7)
REAL*4 epl,det(1:200),km(0:7),eold,emoe(0:14),cvmoe(0:14),moe
REAL*4 moeold,moe0,moe1,moe2,moe3,ci
REAL*4 c(0:14),co(0:7),csp(0:10),ca(0:400)
REAL*4 cm(0:30,0:10),lhmo(0:14),cmoe(0:14),moe
REAL*4 mgold,mgo,mgo1,mgo2,mgo3,ci,ctem
REAL*4 eold,emoe(0:14),cemoe(0:14),cvmoe(0:14),moe
REAL*4 moeold,moe0,moe1,moe2,moe3,ci,ctem
REAL*4 c(0:14),co(0:7),csp(0:10),ca(0:400)
REAL*4 cm(0:30,0:10),lhmo(0:14),cmoe(0:14),moe

DATA (tprn(i),i=1,20) /l.,4.,6.,8.,10.,16.,20.,24.,26.,
* 28.,30.,34.,48.,72.,96.,120.,144.,168.,192.,216./

OPEN(UNIT = 2, FILE = 'schedl.dat')
OPEN(UNIT = 3, FILE = 'mtdfl.dat')
OPEN(UNIT = 4, FILE = 'control.dat')
OPEN(UNIT = 7, FILE = 'resultl.out')
OPEN(UNIT = 8, FILE = 'comparel.out')

C **********************************************************
C SPECIFY THE CONSTANTS
C **********************************************************
Sawing pattern FoQ (1 - Flat sawn; 2 - Quarter sawn),
Board thickness bt (m), Fiber saturation point csp (%),
Specific gravity sg, green MC ci(%) (utilization eff.), yield strain epl.

FoQ = 1
bt = 0.0508

c C ******************************************************
C INPUT DRYING SCHEDULE AND INITIAL CONDITIONS
C ******************************************************
Input drying schedules
DO i = 1, nsc
read(if1,5) dbt(i),wbt(i),tsch(i)
END DO

5 FORMAT(f6.2,lx,f6.2,lx,f5.1)

C ******************************************************
C Define files for input and output data
if1 = 2
if2 = 3
if3 = 4
off1 = 7
off2 = 8

C ******************************************************
C Define the window and coordinates for graph output
CALL GRAPHICSMODE()
IF (control.EQ.1) THEN
 CALL AXIS_MC()
ELSEIF (control.EQ.2) THEN
 CALL AXIS_STRESS()
ELSEIF (control.EQ.3) THEN
 IF (strain.EQ.1) THEN
  CALL AXIS_EI()
 ELSEIF (strain.EQ.2) THEN
  CALL AXIS_EC()
 ELSEIF (strain.EQ.3) THEN
  CALL AXIS_ES()
 ELSE
  CALL AXIS_EM()
 ENDIF
 ELSE
  CALL AXIS_EM()
 ENDIF

Define initial modulus of elasticity

ctem = ci
CALL MOEI(csp(0),dbt(1),ctem,moe)

Specify the initial conditions for calculation

io = nh + 1
DO 10 i = 0, nh
 c(i) = ci
 c(nt-i) = c(i)
 co(i) = c(i)
 es(i) = 0.0
 em(i) = 0.0
 em(io) = em(i)
 ei(i) = 0.0
 ei(io) = ei(i)
 ec(i) = 0.0
 ec(io) = ec(i)
 cvmoei(i) = moe
 cvmoei(io) = cvmoei(i)
 lnmoe(i) = 0.0
 lnmoe(io) = lnmoe(i)
 load(i) = .TRUE.
 strsrvs(i) = .FALSE.
 creprvs(i) = .FALSE.
 s(i) = 0.0
 s(io) = s(i)
 tssr(i) = 1.
 io = io + 1
10 CONTINUE

et(0) = 0.0
cd(0) = ci
tsch(0) = 0.0
c = 1
ip = 1
 it = 1
DO 1000 k = 1, nsc

"*************** DRYING OF THE WOOD UNDER GIVEN SCHEDULES **************

Get EMC under current schedules

CALL REL_H(dbt(k),wbt(k),rh(k))
cem(k) = EMC(dbt(k),rh(k),csp(k))

Estimate the FSP at given temperature

csp(k) = csp(0) - 0.05*(dbt(k) - 20.)

DETERMINE THE MOISTURE DISTRIBUTION

CALL MC_DIS(tdry,dtx,dbt(k),cem(k),c,nt)

Determine shrinkage strain increment

CALL SHRINK_STN(ctem,es(i))
des(i) = es(i) - es(io)
Estimate MS strain increment

\begin{verbatim}
CALL MS_STN(dbt(k),des(i),s(i),km(i))
dem(i) = strso*km(i)
\end{verbatim}

Determine the Young's modulus

\begin{verbatim}
CALL MOEE(csp(k),dbt(k),ctem,moe)
lnmoe(i) = moe
spl = epl*moe
\end{verbatim}

IF (load(i).NEQV.truth) GOTO 30

IF (ABS(ei(i)).LT.epl) GOTO 30

\begin{verbatim}
C
C
C
NO! The point is in nonlinear loading part of stress-strain curve:
Estimate Tangent MOE

moe = moe/TM_NL(spl,strso)
\end{verbatim}

\begin{verbatim}
C
YES! The point is in linear loading or linear unloading part of the stress-strain curve

moeold = cvmoe(i)
cvmoe(i) = moe
moe = 0.5*(moeold + moe)
\end{verbatim}

Estimate creep increment with old stress

\begin{verbatim}
CALLCREEP_STN(strso,dbt(k),ec(i),ecdot,tdry)
deco(i) = ecdot*dtau/cvmoe(i)
\end{verbatim}

Set up the compatibility equation

\begin{verbatim}
a(i) = 1./(1./moe) + 0.5*km(i)
b(i) = (des(i) + dem(i) + deco(i))*a(i)
\end{verbatim}

Perform numerical integration

\begin{verbatim}
IF (i.EQ.0.OR.i.EQ.nh) THEN
  suma = suma + a(i)/2.
sumb = sumb + b(i)/2.
s unc = sumc + c(i)/2.
ELSE
  suma = suma + a(i)
sumb = sumb + b(i)
s unc = sumc + c(i)
ENDIF
\end{verbatim}

Update the strains evaluated so far

\begin{verbatim}
em(i) = em(i) + dem(i)
ec(i) = ec(i) + deco(i)
\end{verbatim}

\begin{verbatim}
cvmoe(io) = moeold
io = io + 1
CONTINUE
\end{verbatim}

EVALUATE CHANGES IN THE TOTAL OR NET STRAIN

\begin{verbatim}
det(itera) = sumb/suma
c(a(i)) = sumc/nh
et(it) = et(it-1) + det(itera)
\end{verbatim}

CALCULATE THE STRESSES AND CORRECT PREVIOUS ESTIMATE ON VARIOUS STRAIN COMPONENTS UNDER
NEW STRESSES WITH AN ITERATIVE PROCEDURE

\begin{verbatim}
suma = 0.0
sumb = 0.0
io = nh + 1
DO 100 i = 0, nh
\end{verbatim}

Evaluate change in the drying stress

\begin{verbatim}
dstrs = det(itera)*a(i) - b(i)
strsn = s(i) + dstrs
s(i) = strsn
\end{verbatim}

Evaluate creep strain with new stress value

\begin{verbatim}
IF (strsrvs(i).EQV.truth) THEN
  YES! Check if creep strain reversal occurs here ?
  IF (creprvs(i).NEQV.truth) THEN
    NO! Continue under initial stress state
    tcrp = tdry
  ELSE
    YES! Creep strain hardening vanishes!
tcrp = tasr(i)
  ENDIF
ELSE
  YES! Creep strain hardening exists!
tcrp = tasr(i)
ENDIF
\end{verbatim}

IF (strsrvs(i).EQV.truth) THEN
  YES! Check if creep strain reversal occurs ?
  IF (creprvs(i).NEQV.truth) THEN
    NO! Creep strain hardening vanishes!
    tcrp = tasr(i)
  ELSE
    YES! Creep strain hardening exists!
tcrp = tasr(i)
  ENDIF
ELSE
  NO! Continue under initial stress state
  tcrp = tdry
ENDIF

CALL CREEP_STN(s(i),dbt(k),ec(i),ecdot,tcrp)
dec = ecdot*dtau/cvmoe(i)
IF (s(i).LE.0.0)  dec = -dec
ddec = dec - deco(i)
deco(i) = dec

Define the modulus of elasticity
moe0 = cvmoe(io)
moe1 = lnmoel(i)
moe2 = cvmoe(i)
moe3 = 0.5*(moe0 + moe2)

Update the drying strains
ei(i) = ei(i) + dstrs/moe3
em(i) = em(i) + km(i)*dstrs*0.5
ec(i) = ec(i) + ddec
tdstrs = dsts(i) + dstrs
dstsl = tdstrs
spl = epl*moel

Check if unloading was detected?
IF (load(i).NEQV.truth) GOTO 70
IF (strsrvs(i).NEQV.truth) GOTO 55
sgnl = SIGN(1.0,ec(i))
sgn2 = SIGN(1.0,ec(io))
IF (sgnl .EQ. sgn2) creprvs(i) = TRUE.
GOTO 60

Check if unloading starts at this point?
sgnl = SIGN(1.0,strsn-s(io))
sgn2 = SIGN(1.0,s(io))
IF (sgnl .EQ. sgn2) GOTO 60

YES! The point will be linearly unloaded.
load(i) = .FALSE.
moe0 = lnmoe(io)
moe2 = moe1
GOTO 65

NO! The point is still under loading.
Check if stress is higher than yield point?
IF (ABS(strsn).LT.spl) GOTO 75

YES! New estimate of tangent MOE with new stress
moe2 = moe1/TM_NL(spl,strsn)
moe1 = 0.5*(moe2 + moe0)
dei = tdstrs*(((1.0/moe1) - (1.0/moe3)))

ei(i) = ei(i) + dei

cvmoe(i) = moe2
GOTO 80

Check if stress reversal occurs?
sgnl = SIGN(1.,strsn)
sgn2 = SIGN(1.,s(io))
IF (sgnl .EQ. sgn2) GOTO 75

YES! Record it and the point will be reloaded in opposite direction from next time step
strsrvs(i) = .TRUE.
load(i) = .TRUE.

NO! The point is still linearly unloading

dei = 0.0
moe0 = moe1

Set up new incremental equilibrium equation
a(i) = 1/(0.5*km(i) + (1./moe1))
b(i) = (dei + ddec)*a(i)

Perform numerical integration
IF (i.EQ.0.OR.i.EQ.nh) THEN
suma = suma + a(i)/2.
sumb = sumb + b(i)/2.
ELSE
suma = suma + a(i)
sumb = sumb + b(i)
ENDIF
i0 = i0 + 1
CONTINUE

EVALUATE CHANGES IN THE TOTAL OR NET STRAIN
itera = itera + 1
det(itera) = sumb/suma
et(it) = et(it) + det(itera)

MAKE THE CHANGE IN TOTAL OR NET STRAIN TO BE ZERO
IF (itera .EQ. 195) GOTO 110
IF (ABS(det(itera)/et(it)).GT.le-06) GOTO 50
CONTINUE
COMPARE THE CALCULATED STRESSES WITH STRENGTH TO PREDICT FAILURE IF (tdry.EQ.tprn(ip)) THEN ptest = 1 ELSE ptest = 2 ENDIF CALL STHTEST(it, ptest, csp(k), dbt(k), ca(it), s, nh) WRITE OUT THE PREDICTION OF MODEL AND COMPARISON WITH MEASURED DATA IF (ptest.EQ.1) THEN CALL PRT_DATA(k, it, ofl, nh) IF (tdry.EQ.tmas(ic).AND.control.EQ.1) THEN CALL CMP_DATA(ic, c, of2, nh) GRAPHIC OUTPUT OF THE MEASURED MOISTURE DATA DO i = 0, nh status = SETCOLOR(10) CALLMOVETO_W(tmas(ic-1), cm(ic-1, i), wxy) status = LINETO_W(tmas(ic), cm(ic, i)) END DO ic = ic + 1 ENDIF ip = ip + 1 ENDIF GRAPHIC OUTPUT OF CALCULATED RESULTS told = tdry - dtau IF (control.EQ.1) THEN DO j = 0, nh CALL MOVETO_W(told, co(j), wxy) status = SETCOLOR(4) status = LINETO_W(tdry, c(j)) END DO GRAPHIC OUTPUT OF THE CURRENT LEVEL OF DRYING SCHEDULE DO j = 0, nh sold = (s(j)+nh+1) + (s(j)+nh+1))/2. snew = (s(j) + s(j))/2. CALL MOVETO_W(told, sold, wxy) status = SETCOLOR(14) status = LINETO_W(tdry, snew) END DO ELSEIF (control.EQ.2) THEN DO j = 0, nh em(j) = em(j+nh+1) ELSEIF (control.EQ.3) THEN DO j = 0, nh CALL MOVETO_W(told, ei(j), wxy) status = SETCOLOR(14) END DO ELSEIF (control.EQ.4) THEN ELSE CALL MOVETO_W(told, ei(j), wxy) status = SETCOLOR(14) END DO ELSEIF (control.EQ.5) THEN ELSE CALL MOVETO_W(told, ei(j), wxy) status = SETCOLOR(14) END DO ELSE DO j = 0, 1 CALL MOVETO_W(told, ei(j), wxy) END DO ENDIF UPDATE THE OLD STORAGE ARRAY FOR NEXT TIME STEP io = nh + 1 DO j = 0, nh co(j) = c(j) es(io) = es(j) ec(io) = ec(j) ei(io) = ei(j) em(io) = em(j) s(io) = s(j) IF (strsrvs(j).EQV.truth) THEN tasr(j) = tasr(j) + 1 ENDIF io = io + 1 END DO INCREASE THE DRYING TIME UNDER THE CURRENT LEVEL OF DRYING SCHEDULE it = it + 1 CONTINUE
CONTINUE

RESET VIDEO MONITOR TO DEFAULT SETTINGS
READ (*,*) ! wait for enter to be pressed
status = SETVIDEOMODE( $defaultmode )
STOP
END

CONTINUE

RESET VIDEO MONITOR TO DEFAULT SETTINGS
READ (*,*) ! wait for enter to be pressed
status = SETVIDEOMODE( $defaultmode )
STOP
END

FUNCTION FOR EQUILIBRIUM MOISTURE CONTENT
FUNCTION FOR SATURATION PRESSURE
FUNCTION FOR MOISTURE DISTRIBUTION

**SUBROUTINE FOR RELATIVE HUMIDITY**
**SUBROUTINE REL_H(dbt,wbt,rhs)***
**REAL*4 dbt,wbt,rhs,pt,rwb,phl,ph2,ph3,rair,pv**
**pt = 101.325**
**rwb = 0.62198*PSAT(wbt)/(pt - PSAT(wbt))**
**phl = (2501. - 2.41*(wbt + 273.15))*rwb**
**ph2 = 1.006*(dbt - wbt)**
**ph3 = 2501. + 1.77*(dbt + 273.2) - 4.186*(wbt + 273.2)**
**rair = (phl - ph2)/ph3**
**pv = pt*rair/(0.62198 + rair)**
**rhs = 100.*pv/PSAT(dbt)**
**RETURN**
**END**

**FUNCTION FOR SATURATION PRESSURE**
**FUNCTION PSAT(temp)**
**REAL*4 temp,tinv,cstl,Cst2,cst3,Cst4**
**tiny = 1.0/(temp + 273.15)**
**cstl = 22.3286**
**cst2 = 2881.0**
**cst3 = 2.9287**
**cst4 = 0.005*psat/1000.**

**SUBROUTINE REL_H(dbt,wbt,rhs)**
**REAL*4 dbt,wbt,rhs,pt,rwb,phl,ph2,ph3,rair,pv**
**pt = 101.325**
**rwb = 0.62198*PSAT(wbt)/(pt - PSAT(wbt))**
**phl = (2501. - 2.41*(wbt + 273.15))*rwb**
**ph2 = 1.006*(dbt - wbt)**
**ph3 = 2501. + 1.77*(dbt + 273.2) - 4.186*(wbt + 273.2)**
**rair = (phl - ph2)/ph3**
**pv = pt*rair/(0.62198 + rair)**
**rhs = 100.*pv/PSAT(dbt)**
**RETURN**
**END**

**SUBROUTINE FOR SATURATION PRESSURE**
**FUNCTION PSAT(temp)**
**REAL*4 temp,tinv,cstl,Cst2,cst3,Cst4**
**tiny = 1.0/(temp + 273.15)**
**cstl = 22.3286**
**cst2 = 2881.0**
**cst3 = 2.9287**
**cst4 = 0.005*psat/1000.**

**SUBROUTINE TRIDAG()***
**REAL*4 time,dtx,temp,ce,ct,c(0:nt),sg,sp,ci**
**INTEGER i, nt**
**COMMON sg,sp,ci**

Drying Run No. 1
C

c
a = 0.447
b = -0.635

Drying Run No. 2: a = 0.597 b = -0.141
Drying Run No. 3: a = 0.533 b = -0.124

c(0) = ce + (ci - ce)*(EXP(b*(time)**a))
c(nt) = c(O)

Solve diffusion equation with CRANK-NICLSON method

DO 10 i = 1, nt-1
Define the diffusion coefficient D(C)

        cx2 = (c(i) + c(i-1))/(2.)
        cx3 = (c(i) + c(i+1))/(2.)
        CALL DIFUS_C(temp,cx2,dx2)
        CALL DIFUS_C(temp,cx3,dx3)

Set up right hand side matrix [B] in [A][C] = [B]

        bt1 = 0.5*dtx*dx3
        bt2 = 1.0 - 0.5*dx3*dtx - 0.5*dtx*dx2
        bt3 = 0.5*dtx*dx2
        bb(i) = bt1*c(i+1) + bt2*c(i) + bt3*c(i-1)
        IF (i.EQ.1) THEN
            bb(i) = bb(i) + 0.5*dx2*c(i-1)*dtx
        ENDIF
        IF (i.EQ.nt-1) THEN
            bb(i) = bb(i) + 0.5*dx3*c(i+1)*dtx
        ENDIF

Set up the left hand side matrix [A] in [A][C]= [B]

        IF (i.EQ.1) THEN
            au(i) = -0.5*dtx*dx3
        ELSEIF (i.EQ.nt-1) THEN
            al(i) = au(i-1)
        ELSE
            au(i) = -0.5*dtx*dx3
            al(i) = au(i-1)
        ENDIF
        am(i) = (1. + 0.5*dtx*dx3 + 0.5*dtx*dx2)
10 CONTINUE
Solve for [C] in [A][C] = [B]

CALL TRIDAG(al,am,au,bb,c(1),nt-1)
RETURN
END

C **********************************************************
SUBROUTINE FOR TRIDIAGNAL MATRIX OPERATION
C
C INPUT : Coefficient Matrix -- a,b,c,r
C Number of nodes -- n
C OUTPUT : MC profile (%) -- u(1:n)
C CALL : None
C**********************************************************
SUBROUTINE TRIDAG(a,b,c,r,u,n)
PARAMETER (nmax=100)
REAL gam(NMAX),a(n),b(n),c(n),r(n),u(n)
INTEGER n
IF (b(1).EQ.0.) PAUSE
bet = b(1)
        u(1) = r(1)/bet
DO 10 j = 2, n
        gam(j) = c(j-1)/bet
        bet = b(j) - a(j)*gam(j)
        IF (bet.EQ.O.) PAUSE
        u(j) = (r(j) - a(j)*u(j-1))/bet
20 CONTINUE
DO 20 j = n-1, 1, -1
        u(j) = u(j) - gam(j+1)*u(j+1)
20 CONTINUE
RETURN
END

C **********************************************************
SUBROUTINE FOR DIFFUSION COEFFICIENT
C
C INPUT : Temperature (C) -- temp
C OUTPUT : Diffusion coefficient (m^2/hr) -- Dc
C CALL : None
C**********************************************************
SUBROUTINE DIFUS_C(temp,cx,dc)
REAL*4 temp,cx,dc20,dc40,dc60,dc80,dc100,c1,c2,c3
temp = temp
ci = cx
c2 = cx*cx
c3 = cx*cx*cx
J. Siau's data at 20, 40, 60, 80, 100 C (mm^2/hr.)
dc20 = -0.0084 + 0.03433*ci - 0.00261*c2 + 0.00017*c3
dc40 = 0.084 + 0.04504*ci - 0.00228*c2 + 0.00013*c3
dc60 = 0.264 + 0.10169*ci - 0.00581*c2 + 0.00029*c3
dc80 = 0.972 + 0.05517*ci + 0.00017*c2 + 0.00029*c3
dc100 = 1.077 + 0.34706*ci - 0.01163*c2 + 0.00064*c3
C
Fitted Coefficients at 150 F (mm^2/hr.)
Run No.1
dc = (1.082 + 0.1932*ci - 0.0107*c2 + 0.000338*c3)
Run No. 2
dc = (0.941 + 0.1682*c1 - 0.0093*c2 + 0.000294*c3)
Run No. 3
dc = (1.244 + 0.1573*c1 - 0.0066*c2 + 0.0001781*c3)

Change unit to m^2/hr.
dc = 1E-06*dc
RETURN
END

C **********************************************************
FUNCTION FOR NONLINEAR STRESS-STRAIN RELATIONSHIP
C
C INPUT
Proportional stress (psi/pa) -- spl
Actual stress ( psi) -- stress
C
C OUTPUT
Tangent modulus (psi/pa) -- TM_NL
C
CALL : None
C
REAL*4 FUNCTION TM_NL(spl,stress)
REAL*4 spl,stress,ni,ki

ni = 3.0
ki = 0.00001419

Define the nonlinear stress-strain curve

TM_NL = 1.0 + ki*ni*(ABS(stress) - spl)**(ni-l.)
RETURN
END

C **********************************************************
SUBROUTINE FOR MECHANICAL CREEP STRAIN
C
C INPUT : Temperature (C) -- Temp
Accumulated creep strain -- Crep
Stress at the point (psi) -- Strs
Time (hr) -- Time
C
OUTPUT : Creep rate (1/hr) -- Ecdot
CALL : None
C
********************************************************************
SUBROUTINE CREEP_STN(strs,temp,crep,ecdot,time)
REAL*4 strs,temp,crep,ecdot,time
REAL*4 ecdot, time
INTEGER FoQ
COMMON sg,FoQ,ci

crep = crep

Define creep law at a constant moisture content

IF (strs.LT.0.0) THEN
  Constants For Compressive Creep
  k = (12.4E-07*(60)**0.44) + Temp*0.0
  m = 1.0 + temp*0.0
  n = 0.44 + temp*0.0
  moecrp = 71000.
ELSE
  Constants For Tensile Creep
  k = (7.61E-07*(60)**0.52)/1.0 + Temp*0.0
  m = 1.0 + Temp*0.0
  n = 0.52 + Temp*0.0
  moecrp = 71000.
ENDIF

ENDIF

Adjust for the moisture effect on creep rate

ecdot = ecdot*moecrp
RETURN
END

C **********************************************************
SUBROUTINE FOR SHRINKAGE STRAIN
C
C INPUT : MC at a point (%) -- ces
MC at FSP (%) -- fsp
C
OUTPUT : Shrinkage strain -- ess
CALL : None
C
********************************************************************
SUBROUTINE SHRINK_STN(ces,ess)
REAL*4 ces,ess,fes1,fes2,fes3,fes4,sg,ci
INTEGER FoQ
COMMON sg,FoQ,ci

Shrinkage data for Douglas Fir

IF (FoQ.EQ.1) THEN
  fes1 = -0.076038
  fes2 = 0.002665
  fes3 = 0.000048
  fes4 = -0.000001757933
ELSE
  fes1 = -0.05432935
  fes2 = 0.0026082
  fes3 = -0.00002943
  fes4 = 0.00000019
ENDIF
ENDIF
ess = fes1 + fes2*ces + fes3*ces**2 + fes4*ces**3
IF (ess.GT.0.) ess = -ess/ces
ess = ess
RETURN
END

SUBROUTINE FOR MECHANO-SORPTIVE STRAIN

INPUT : Temperature (c) -- temp
Stress (psi / pa) -- s(i)
Shrinkage increment (1/%) -- shrink
OUTPUT : MSE compliance (1/psi/pa) -- momse
CALL : None

SUBROUTINE MS_STN(temp, shrink, stress, momse)
REAL*4 temp, shrink, stress, momse, kmt, kmc, sg, ci
INTEGER FoQ
COMMON sg, FoQ, ci

Define the constant for MSE modulus
kmt = 5.04E-6 + temp*0.0
kmc = 15.87E-6 + temp*0.0

Define the MSE modulus for each layer
IF (stress.GT.0.0) THEN
  momse = kmt*ABS(shrink)/0.0027
ELSE
  momse = kmc*ABS(shrink)/0.0027
ENDIF
RETURN
END

C ***********************************************************************
FUNCTION FOR PREDICTING MOE OR STRENGTH

INPUT : Specific gravity -- sg
Moisture content (%) -- m
Temperature (c) -- t
SG correction (1/%) -- csg
MC correction (1/%) -- cm
Temp. correction (1/F) -- ct
OUTPUT : MOE or Strength (psi/pa) -- EE
CALL : None

REAL*4 FUNCTION UE(sg,m,t,csg,cm,ct)
REAL*4 sg,m,t,csg,cm,ct,yl,y2,y3,sgo,mo,to,yo
LOGICAL*4 convert /.FALSE./
LOGICAL*4 truth /.TRUE./
COMMON /MOE/ sgo,mo,to,yo

Make the prediction
yl = yo*(sg/sgo)**csg
y2 = yl*(1.0 + cm*(m - mo))
y3 = y2*(1.0 + ct*(t - to))

Convert to Pa Unit from the Psi Unit?
IF (convert.EQV.truth) y3 = 6894.733*y3
EE = y3
RETURN
END

IF (m.GT.fsp) m = fsp
t = 32. + 9.*temp/5.
Reference values for tensile modulus
sgo = 0.4
mo = 10
to = 90.0
IF (FoQ.EQ.1) yo = 94500
Define the correction factor for tensile modulus
csg = 1.0
cm = -0.0465
c = -0.00365
Make the prediction
y = EE(sg,m,t,csg,cm,ct)
RETURN
END

SUBROUTINE FOR MODULUS OF ELASTICITY

INPUT : MC at FSP (%) -- fsp
Temperature (c) -- temp
MC at a point (%) -- m
OUTPUT : Young's Modulus (PSI / Pa) -- y
CALL : FUNCTION EE()

SUBROUTINE MOEE(fsp,temp,m,y)
REAL*4 fsp,temp,m,y,t,Csg,cm,ct
REAL*4 sgo,mo,tc,yo,ci,kg
INTEGER FoQ
COMMON sgo,FoQ,ci
COMMON /MOE/ sgo,mo,tc,yo

Unit conversion

C ******x****x****x****xx**xxxxx**********x****x**xx**x**x*
SUBROUTINE FOR FAILURE PREDICTION

INPUT:
- Temperature (°C) -- Temp
- MC distribution (%) -- c(O:nh)
- Stress distribution (psi) -- s(O:nh)
- MC at FSP (%) -- fsp
- Number of nodes -- nh

OUTPUT:
- WARNING MESSAGE!!!

CALL: SUBROUTINE PRESTH()

SUBROUTINE STHTEST(it, ptest, fsp, temp, avgc, s, nh)

REAL*4 fsp, temp, s(0:14), avgc
INTEGER FoQ, nh, ptest, it

ssmall = 1.0E+20
slarge = -1.0E+20
me = avgc

DO i = 0, nh
  ssmall = MIN(ssmall, s(i))
  slarge = MAX(slarge, s(i))
END DO

CALL PRESTH(fsp, temp, mc, tsth, 1)
IF (slarge.GT.tsth) THEN
  write(7,5) it
5 format(/10x,'!!!! SURFACE CHECKS AT ',i3,' Hrs')
ENDIF
IF(ptest.EQ.l) THEN
  write(7,6) tsth, it
6 format(/10x,'STRENGTH = ',F6.2,' PSI at',i3,' Hrs')
ENDIF

CALL PRESTH(fsp, temp, mc, csth, 2)
IF (ABS(ssmall).GT.csth) THEN
  write(7,10) it
10 format(/10x,'! COMPRESSION FAILURE AT ',i3,' Hrs')
ENDIF
IF(ptest.EQ.l) THEN
  write(7,11) -csth, it
11 format(/10x,'STRENGTH = ',F7.2,' PSI at',i3,' Hrs')
ENDIF
RETURN
END

SUBROUTINE FOR STRENGTH CALCULATION

INPUT:
- MC at FSP (%) -- m
- Temperature (°C) -- temp
- MC at a point (%) -- m
- Control variable -- ToC

OUTPUT:
- Strength (psi/pa) -- y

CALL: FUNCTION EE()
SUBROUTINE FOR PRINTING OUT CALCULATED RESULTS

SUBROUTINE PRT DATA(k,it,ofl,nh)
INTEGER k,it,ofl,nh
REAL*4 dbt(10),wbt(lO),tdry,ca(0:400),et(0:400)
REAL*4 c(0:14),s(0:14),cvmoe(0:14)
REAL*4 ei(0:14),ec(0:14),es(0:14),em(0:14)
COMMON /PRINT/dbt,wbt,tdry,ca,et,c,cvmoe,s,ei,em,es,ec
WRITE(ofl,5)
5 FORMAT(/20X,'Current Drying Schedule'/)
WRITE(ofl,10) dbt(K),wbt(K),tdry
10 FORMAT(4X,'Tdb (C) _ ',F6.2,5X,'Twb (C) = ',F6.2,
*5x,'TIME (Hrs) = ',F6.1/) WRITE(ofl,15) ca(it),et(it)
15 FORMAT(5X,'Mean MC ($) _ ',f6.2,4X,'Net Strain (1)
*_ ',f7.5/) WRITE(ofl,20)
20 format(/4x,'MC',6x,'MOE',6x,'STRESS',5x,'ELASTC',
*5x,'MSE',7x,'SHRINK',5x,'CREEP' '4X,'%',7x,'PSI',
*6x,'PSI',6x,'IN/IN',7x,'IN/IN',6x,'IN/IN'/)
DO 40 i = 0, nh
30 write(ofl,30) c(i),cvmoe(i),s(i),ei(i),em(i),
es(i),ec(i)
*2x,f9.7,2x,f9.7)
40 CONTINUE
RETURN
END

SUBROUTINE FOR COMPARING MEASURED AND CALCULATED DATA

SUBROUTINE CMP DATA(ic,c,of2,nh)
INTEGER nh,ic,of2
REAL*4 c(0:14),cm(0:30,0:10),tmas(0:30)
COMMON /COMPARE/ cm,tmas
WRITE(of2,5)
5 FORMAT(/10X,'Comparing Moisture Profiles'/)
WRITE(of2,10) tmas(ic)
10 FORMAT(10X,'Drying Time (Hours) = ',f5.1/) WRITE(of2,15)
15 FORMAT(4X,'Position',4X,'Calculated',4X,'Measured'/)
DO i = 0, nh
WRITE(of2,20) i,c(i),cm(ic,i)
20 format(7x,i2,8x,f5.2,7x,f5.2)
END DO
RETURN
END

SUBROUTINE FOR CONFIGING THE VIDEO MONITOR

INCLUDE 'FGRAPH.FI'
SUBROUTINE GRAPHICSMODE()
INCLUDE 'FGRAPH.FD'
INTEGER*2 modestatus,maxx,maxy,cols,rows
RECORD /VIDEOCONFIG/ screen
COMMON /GRAPH/ maxx,maxy,cols,rows
Select the graphics mode
CALL GETVIDEOCONFIG( screen )
SELECT CASE( screen.adapter )
CASE( $CGA ) modestatus = SETVIDEOMODE( $HRESBW ) CASE( $OCGA ) modestatus = SETVIDEOMODE( $ORESCOLOR ) CASE( $EGA,$OEGA ) IF( screen.monitor .EQ. $MONO ) THEN modestatus = SETVIDEOMODE( $ERESNOCOLOR ) ELSE modestatus = SETVIDEOMODE( $ERESCOLOR ) END IF CASE( $VGA, $OVGA, $MCGA ) modestatus = SETVIDEOMODE( $VRES16COLOR ) CASE( $HGC ) modestatus = SETVIDEOMODE( $HERCMONO ) CASE DEFAULT modestatus = 0 END SELECT IF( modestatus.EQ.0) STOP 'ERROR: CANNOT SET GRAPH MODE'
DETERMINE THE MINIMUM AND MAXIMUM DIMENSIONS
CALL GETVIDEOCONFIG ( screen )
maxx = screen.numxpixels - 1 maxy = screen.numypixels - 1 cols = screen.numtextcols rows = screen.numtextrows
RETURN
END
** **** SUBROUTINE FOR DEFINING COORDINATES FOR MOISTURE CONTENT GRAPH *******

```
INCLUDE 'FGRAPH.INT'
SUBROUTINE AXIS_MC()
INCLUDE 'FGRAPH.FD'
INTEGER*2 maxx,maxy,status,n,cols,rows
DOUBLE PRECISION bx,ex,by,ey,dx,dy,xx,yy
RECORD /WXYCOORD/ wxy
RECORD /RCCORD/ curpos

COMMON /GRAPH/ maxx,maxy,cols,rows

bx = 0.0
by = 0.0
ey = 40.0
n = 10
dx = (ex - bx)/FLOAT(n)
dy = (ey - by)/FLOAT(n)

CALL CLEARSCREEN( $GCLEARSCREEN
status = SETBKCOLOR( $BLUE
status = RECTANGLE( $GBORDER,10,5,maxx-5,maxy-5)
CALL SETVIEWPORT(0.18*maxx,maxy/8,maxx-15,7*maxy/8)
status = SETWINDOW(.TRUE.,bx,by,ex,ey)
status = SETCOLOR( 15
status = RECTANGLE_W( $GBORDER,bx,by,ex,ey

CALL SETCOLOR( 15
xx = dx
yy = dy
DO i = 1, n
CALL MOVETO_W(xx,by,wxy)
status = LINETO_W(xx,ey)
CALL MOVETO_W(bx,yy,wxy)
status = LINETO_W(ex,yy)
xx = xx + dx
yy = yy + dy
END DO

CALL SETCOLOR( 15
CALL SETTEXTCOLOR( 15
CALL SETTEXTPosition( 2, 35, curpos
CALL OUTTEXT('MOISTURE - TIME RELATIONSHIP' )
CALL SETTEXTPosition( 15, 4, curpos
CALL OUTTEXT('Center')
CALL SETTEXTPosition( 27, 13, curpos
CALL OUTTEXT( '0' )
CALL SETTEXTPosition( 12, 45, curpos
CALL OUTTEXT( 'Measured' )
status = SETTEXTCOLOR( 10
CALL SETTEXTPosition( 7, 60, curpos
CALL SETTEXTPosition( 9, 60, curpos
CALL OUTTEXT( 'Center' )
CALL SETTEXTPosition( 20, 25, curpos
CALL OUTTEXT( 'Calculated' )
status = SETTEXTCOLOR( 15
CALL SETTEXTPosition( 24, 25, curpos
CALL OUTTEXT( 'Surface' )
CALL SETTEXTPosition( 28, 15, curpos
CALL OUTTEXT( '0' )
CALL SETTEXTPosition( 28, 77, curpos
CALL OUTTEXT('Drying Time (Hrs)')
RETURN
END
```
This program analyses the test data for a small wood sample under load during moisture change.

**INPUT:**
- Load (lb) -- lod
- Specimen width (in) -- wth()
- Specimen thickness (in) -- thk()
- Temperature (F) -- temp
- Time (minute) -- t()
- Moisture content (%) -- MC()
- Total strain (in/in) -- et()
- Shrinkage strain (in/in) -- es()

**OUTPUT:**
- Instantaneous strain (in/in) -- ei()
- Creep strain (in/in) -- ec()
- MS strain (in/in) -- em()

**CALL:** SUBROUTINE MOEE()

```plaintext
REAL ei(0:100), mc(0:100), wth(0:100), thk(0:100)
REAL dec(0:100), moe(0:100), ec(0:100), et(0:100)
REAL strs(0:100), es(0:100), t(0:100), em(0:100)
REAL mccrp, moecrp, k, m, nc, temp, moea, lod, dm, dt
INTEGER i, n
OPEN(unit=5, file='cpll2ip.prn')
OPEN(unit=7, file='cpll2op.prn')

Read in test data
n = 72
temp = 150.
read(5,5) lod, wth(0), thk(0)
5 format(7x,f5.2,1x,f4.2,1x,f4.2)

Do 10 i = 1, N-1
read(5,15) t(i-1), mc(i-1), et(i-1), es(i-1)
10 continue
15 format(6x,f6.2,4x,f5.2,1x,f8.5,1x,f8.5)

Define shrinkage coefficient in radial direction
br = -0.0017

Define the creep law at a constant moisture
mccrp = 10.0
temp = 150.
CALL MOEE(temp, mccrp, moecrp)
k = 12.05E-7
m = 1.0
nc = 0.453

Define the initial conditions
ec(0) = 0.0
em(0) = 0.0
strs(0) = lod/(wth(0)*thk(0))
moe(0) = -strs(0)/et(0)

Writing out the data
WRITE(7,20)
20 FORMAT(2x,'MC',8x,'TM',4x,'EI',7x,'EC',6x,'EM'
*6x, 'ES'/) WRITE(7,50) mc(0), t(0), et(0), ec(0), em(0), es(0)
c

Time step and Moisture change
dt = t(i) - t(i-1)
dm = mc(i) - mc(i-1)

Change in cross section area, stress, and stiffness
wth(i) = wth(0)*(1. + br*(mc(0) - mc(i))

thk(i) = thk(0)
strs(i) = lod/(wth(i)*thk(i))
CALL MOEE(temp, mc(i), moe(i))

moea = (moe(i)+moe(i-1))/2.

Instantaneous strain
ei(i) = et(0)

Creep strain increment and total creep
dec(i) = - (strs(i))**m*k*nc*(t(i))**(nc-1)*(dt)
ec(i) = ec(i-1) + dec(i)*(moecrp/moea)

Mechano-sorptive strain from test
em(i) = et(i) - ei(i) - ec(i) - es(i)

Output results
WRITE(7,50) mc(i), t(i), ei(i), ec(i), em(i), es(i)

CONTINUE
50 format(1x,f5.2,1x,f7.2,1x,f7.5,1x,f7.5,1x,f7.5,1x,
f7.5,1x,f7.5) STOP END
```
Subroutine calculates modulus of elasticity as a function of temperature and moisture content

SUBROUTINE MOEE(temp,mcs,moes)
    REAL temp,mcs,moes,tempr,mcr,moer,cm,ct,moem

Define the reference value

    tempr = 90.
    mcr = 10.
    moer = 94500.

Define the correction coefficient

    cm = -0.0465
    ct = -0.00365

Perform the correction

    moem = moer*(1. + cm*(mcs - mcr))
    moes = moem*(1. + ct*(temp - tempr))
RETURN
END