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Deformation properties of Finnish spruce and pine wood in tangential and radial directions in association to high temperature drying

Part I. Experimental techniques for conditions simulating the drying process and results on shrinkage, hygrothermal deformation, modulus of elasticity and strength

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The set of papers sums up the results of an extensive project to quantify primarily the creep characteristics but also other deformation properties of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) wood under conditions relevant in the high temperature drying process. The programme included tension experiments on tangentially and radially oriented specimens both under wet (saturated, green) conditions and drying conditions at temperatures 95–125 °C. Also, a limited strength test series was carried out with spruce. This first paper contains the documentation of the experimental techniques used as well as reports the results obtained about shrinkage, hygrothermal deformation and modulus of elasticity. The results of the strength tests are also included.

Verformungseigenschaften von finnischem Fichten- und Kiefernholz in tangentialer und radialer Richtung unter Bedingungen der Hochtemperaturtrocknung. Teil 1: Methoden zur Simulation der Trocknungsbedingungen und Ergebnisse inbezug auf Schwinden, hygrothermische Verformungen, MOE und Festigkeit

In einer Artikelreihe werden die Ergebnisse eines Forschungsprojektes zur Quantifizierung des Kriechverhaltens, aber auch anderer Verformungen beschrieben, und zwar unter Bedingungen, wie sie bei der Hochtemperaturtrocknung vorliegen. Als Versuchsmaterial wurden nordische Fichte und Kiefer verwendet. Das Programm beinhaltete Prüfungen der Zugfestigkeit von tagential und radial ausgerichteten Proben sowohl im trockenen als auch im waldfrischen Zustand. Die Trocknungstemperaturen lagen bei 95–125 °C. Zusätzlich wurde eine begrenzte Anzahl von Festigkeitsprüfungen an Fichtenholz vorgenommen. Der erste Beitrag enthält die Dokumentation der Versuchstechniken sowie die Ergebnisse bezüglich Schwinden, hygrothermaler Verformung und MOE. Mit aufgenommen sind auch die Ergebnisse der Festigkeitsprüfung.

1
Introduction

During several years, VTT (Technical Research Centre of Finland) has gained a good competence in computational simulation of the kiln drying process of sawn timber in the conventional drying temperature range, viz. up to 80 °C (Ranta-Maunus et al. 1995, Hukka 1996), with the capacity of optimising drying schedules and reducing cracking in industrial scale drying. In a two year project "High temperature creep of wood", conducted 1994–95, expertise needed for extending the simulation capability to high temperature drying (HTD) conditions (around and slightly above 100 °C) was pursued in regard to creep and other deformation properties. The project included an extensive experimental programme and the development of a creep model based on the experiment results. The main experimental results of the project are summarised in this set of papers.

The experimental programme comprised of tension experiments on tangentially and radially oriented specimens both under wet (saturated, green) conditions and drying conditions at temperatures 95–125 °C. From the obtained measurements, large amount of data was extracted about shrinkage, hygrothermal deformation, modulus of elasticity, viscoelastic creep and mechano-sorptive creep. Altogether, the experimental programme included more than 200 specimens loaded in creep tests under different conditions. Also, a limited strength test series was carried out on spruce.

This first paper documents the experimental techniques and reports the results about shrinkage, hygrothermal deformation, modulus of elasticity and strength. Some even more detailed information about the experimental procedures used can be found in ref. Hanhijärvi (1997).

1.1
A look to some earlier results of MOE and strength under conventional and high temperature drying conditions

The mechanical properties of wood at temperatures relevant in the HTD process, viz. around 90–120 °C have not been subject to very comprehensive experimental work; in fact the properties are fairly poorly known. This applies especially to the long-term phenomena, creep and long-term strength, whereas some publications are available concerning the instantaneous properties, the modulus of elasticity (MOE) and short-term strength, as well as dynamic properties at these temperatures. At conventional drying temperatures, around 60–80 °C, the number of published experiment reports is of course more numerous. In the following some of the more interesting ones are pointed out as they may provide reference to the new results.

1.1.1
Modulus of elasticity

Of the different basic deformation properties the MOE along with shrinkage is the most studied one. Even so, not

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many reports have been published on the MOE of wood in directions perpendicular to grain in the high temperature range.

The review of Gerhards (1982) gives a good overview of literature published about the moisture content and temperature influence on both MOE and strength until the late 1970's. Of the works on perpendicular-to-grain MOE that Gerhards mentions, only two extend above 85 °C (Byvshykh 1959, Okuyama et al. 1977), whereas at temperature range 20–80 °C the number of publications is more numerous. Okuyama et al. (1977) measured bending MOE for two Southeast Asian hardwoods. The results are interesting in that the measurements were done in the tangential and radial directions and in various angles between them. Also, the temperature range is wide: 20–97 °C.

The work done by Siimes (1967) at VTT about the short term mechanical properties of the three most important Finnish wood species (*Pinus sylvestris*, *Picea abies* and *Betula verrucosa*) is the most significant reference for the present investigation, because it covers the same species. Siimes' work was done in connection with the spread of kiln drying in Finland in the 60's and the study contains a comprehensive experimental clarification of the tangential MOE both in tension and compression for a temperature range relevant in conventional kiln drying. Experiments were made at temperatures 20, 40, 60 and 80 °C, moisture contents 4, 8, 12, 16 and 20% plus saturated condition. Moreover, the specimens represented a wide density range and results have been given for three density categories. Due to the exhaustive quality of Siimes' study it provides an excellent reference base for further studies like this one.

Of other studies, the works of Salmén (1984) and Iida (1986) are of interest. Salmén measured the dynamic properties of Norway spruce (*Picea abies*) in wet condition over temperature range 20–140 °C. The dynamic measurements are not directly comparable to the static results, but the storage modulus provides a good reference for the static MOE – the better the lower the frequency used in tests is (Salmén's lowest frequency was 0.05 Hz, which means half period length of 10 s). Iida (1986) measured the perpendicular-to-grain MOE in bending in water saturated condition for several species. The temperature range was 10–95 °C.

1.1.2
Strength

Gerhards' (1982) review mentions three investigations on perpendicular-to-grain strength that reach above 85 °C: Byvshykh (1959), Goulet (1960) and Okuyama et al. (1977). Investigations below 80 °C are, here too, more numerous. The work of Okuyama et al. (1977) is again interesting because strength has been measured in different angles to the material directions.

Siimes' (1967) work provides the best reference also for strength results of this work. He investigated the tangential strength under the same conditions as mentioned above in connection with the MOE.

The work of Koran (1979) on perpendicular-to-grain tension strength of Black spruce (*Picea mariana*) is interesting as the temperature range is very wide, reaching up to 250 °C. Tests were made with saturated wood, saturated either in water or glycerine. Both tangential and radial directions were covered.

2
Experimental methods

2.1
Specimen preparation

The creep test specimens were manufactured out of three tree trunks, viz. two spruce ones (labelled K and S) and one pine trunk (M). The trunks were cut into logs of length 0.5–0.7 m, Fig. 1. As preparation for specimen manufacture, four slices were sawn out of each log. Out of these preliminary slices, the specimens were manufactured according to a method developed by Kangas (1990) by first gluing auxiliary slices on both edges of the actual test material slices using a finger joint type assembly with polyurethane adhesive and then cutting the glued plate into specimens, Fig. 2. By this method, a specimen type is obtained which has longitudinal end-parts and transverse middle-part glued together by a finger joint. The longitudinal ends serve as means for force transmission into the actual test piece and for attachment of displacement transducers. The transducers were attached on two sides of the specimen (Fig. 3) in the drying condition tests, whereas in the wet condition tests the displacement was measured from machine clamps.

The specimens were not allowed to dry during the manufacturing process in order to ensure that the specimens are tested in truly green condition or the drying that takes place during the test will be the initial one. The dimensions of the specimens are shown in Fig. 2. For most logs, altogether four specimens were cut out of each plate. In addition, a purely transverse piece was cut out of the middle slice to be used as a balance specimen for moisture content monitoring.

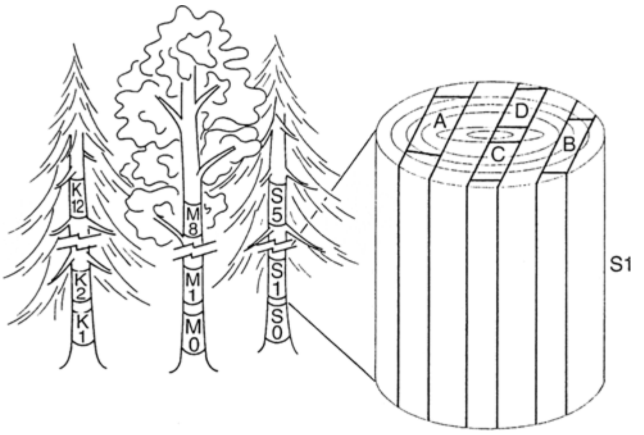

Fig. 1. Cutting of 0.5–0.7 m long logs to be used as raw material for creep test specimens. Two spruce trunks (K and S) and one pine trunk (M) were felled and cut into altogether 27 logs. In preparing the specimens, four narrow slices were cut out of the logs. Slices labelled A and B were cut from opposite sides of the log to be further produced into tangential test specimens whereas slices labelled C and D were cut across the middle of the log to be produced into radial specimens

Bild 1. Einschnitt der 0.5–0.7 m langen Rundhölzer als Ausgangsmaterial für die Kriechtests. Zwei Fichtenstämme (K und S) und ein Kiefernstamm (M) wurden gefällt und in insgesamt 27 Rundholzabschnitte zersägt. Die Proben A und B wurden von gegenüberliegenden Teilen für die tangentiale Zugfestigkeit geschnitten; die Proben C und D wurden in Marknähe für die radialen Zugtests entnommen

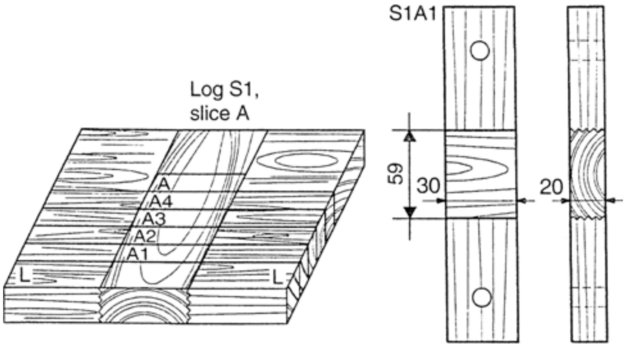

Fig. 2. Preparation of test specimens. Each preliminary slice was glued along the two long edges unto two auxiliary slices (L) by a finger joint type assembly using one component polyurethane adhesive. The thus obtained plate was sawn into four creep test specimens, which were denoted by a four character label. Also, an additional purely transverse piece to be used as a balance specimen was sawn beside the creep specimens

Bild 2. Herstellung der Prüfkörper. Jedes Brett wurde längsseits mit zwei Hilfsbrettern (L) über Keilzinken mit einem Einkomponenten-PU-Harz verleimt. Aus der so erhaltenen Platte wurden vier Prüfkörper für den Kriechtest gesägt; der vierstellige Code ergibt sich aus der Herstellung. Zusätzlich zu diesen Probekörpern für den Kriechtest wurde eine Wägeprobe (zur Feuchtekontrolle) ohne angeleimte Longitudinalbretter angefertigt

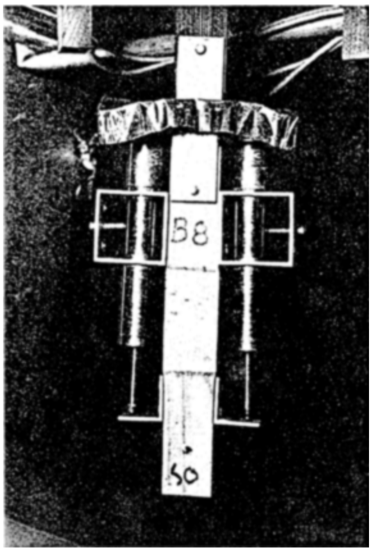

Fig. 3. Displacement transducers were attached on two sides of the specimen in the drying condition tests, because uneven shrinkage may cause the specimen to warp. Above the specimen is an 'umbrella' made out of aluminium foil to stop condensing water to drop on the specimen

Bild 3. Wegaufnehmer wurden während der Versuche unter Trocknungsbedingungen an beiden Seiten der Probe angebracht, weil ungleichmäßiges Schwinden zum Verwerfen der Probe führt. Über der Probe ist ein Schirm aus Aluminiumfolie angebracht um Kondenswasser von der Probe fernzuhalten

2.2
Techniques for tests in drying conditions

2.2.1
Drying condition creep test chamber

For the purpose of performing creep experiments on drying wood under conditions that resemble the interior of a HTD kiln, a laboratory scale drying test chamber was built. The constructed apparatus can be used for laboratory scale simulation of kiln drying conditions for small creep specimens under tensile load.

The base of the apparatus is an aluminium frame box, the test chamber (inside dimensions roughly: height 0.5 m, width 1.5 m, depth 1 m), Fig. 4. The front wall of the chamber is removable and serves as access panel. The chamber is equipped with a temperature and humidity regulating system. The regulation of temperature functions through heating and circulating air inside the chamber. The regulation of humidity functions through heating or cooling water in an open vessel, over which the air current flows. The regulated variables inside the chamber are the dry bulb temperature and the wet bulb temperature. The basic idea of the temperature and humidity control is the same as in the experiments of Kangas (1990), although numerous modifications have been incorporated.

2.2.2
Mounting of specimens

The loading of specimens is implemented by weights and lever arms located outside the chamber and pull rods that go through small holes in the ceiling of the chamber. The chamber can take four tension specimens and four zero-load 'dummy' specimens for measurement of free shrinkage. In addition, it can employ two balance specimens for continuous weighing for the purpose of moisture content monitoring.

2.2.3
Arrangement of creep and zero-load specimens

The specimens were selected to each test run in such a way that all the ten specimens (four creep, four dummy and two balance ones) to be used in one test were taken from the same log, from the two slices that were of the same material direction. The specimens were mounted on the loaded and dummy positions in such a way that each loaded specimen had always an adjacently cut dummy beside it. This arrangement was assumed to give the best reliability for comparison of the deformation behaviour of

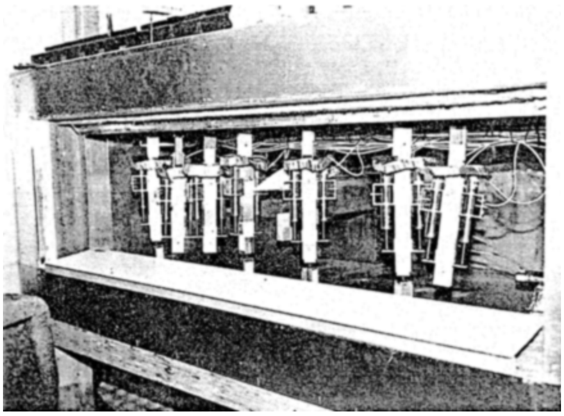

Fig. 4. A view of the interior of the test chamber for drying condition tests. The chamber can take four creep and four zero-load (dummy) specimens, but in this case one of the positions is out of order so only seven specimens are mounted. In the middle one can see the balance specimen for moisture content monitoring

Bild 4. Blick in die Prüfkammer für Tests unter Trocknungsbedingungen. Die Kammer kann vier Prüfkörper und vier Kontrollproben aufnehmen. Hier ist allerdings eine Position defekt, so daß nur sieben Proben montiert sind. In der Mitte erkennt man die Wägeprobe zur Messung der Feuchte the loaded (creep) specimens and zero-load (free shrinkage) specimens.

2.2.4
Drying schedule

The schedule for regulation of the wet and dry bulb temperatures varied between tests, but followed a certain basic scheme. In most cases the drying schedule was according to the pattern described in the following and illustrated in Fig. 5.

Each test was started with a heating period of c. 2 hours, during which the temperature was raised from room temperature to 95 °C. The schedule continued then with an initial drying period lasting for c. 28 h, during which the drying power (difference of the dry and wet temperatures) was first high but was reduced gradually. The intention for this initial drying period was that the specimens, whose moisture content was initially very high, were brought to a moisture content level close to fiber saturation. For the last 8 h (c. 22–30 h after the start of the test) of this period the wet bulb temperature was kept as close to the dry bulb temperature as the equipment was able to perform, i.e. as moist conditions as possible, in order to try to ensure that the moisture content distribution in the specimens is evened. About c. 2 h before the end of this period, i.e. c. 28 h after the start of the test, the load was applied.

After the initial drying period and loading, the actual drying below FSP was started and shrinkage assumed to begin. In most tests, the moisture content was first taken to an intermediate level followed by some re-moistening before a final drying down to a moisture content of 2–5%. However, some tests were also made without any re-moistening (monotonous drying) and some tests were made with many drying-moistening cycles.

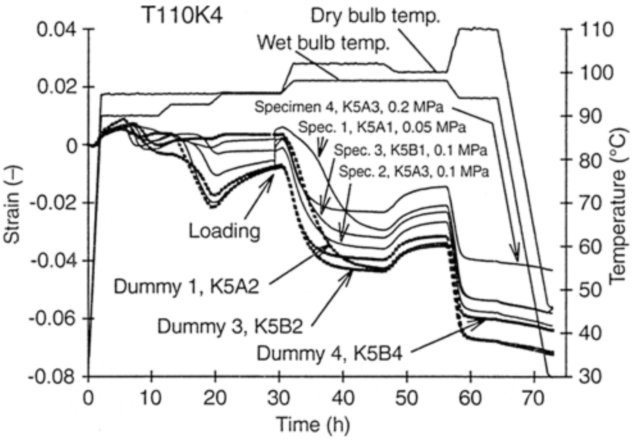

Fig. 5. Example of the evolution of a creep test in drying conditions: dry and wet bulb temperature, moisture content and strain measurements as function of time. The drying schedule consists of a heating period (0–2 h) and an initial drying period (2–30 h), during which the specimens are brought to a moisture content level near FSP, the actual drying period below FSP (30–64 h) and final cooling (64–72 h). Note the strain behaviour of the specimens during the heating and few hours after, which shows the hygrothermal deformation phenomenon. 'Dummy' means a zero-load specimen

Bild 5. Beispiel für den Verlauf eines Kriechtests unter Trocknungsbedingungen. Feucht- und Trockentemperatur, sowie Feuchte und Spannung in Abhängigkeit von der Zeit. Der Trockungsfahrplan besteht aus einer Heizperiode (0–2 h) und einer anfänglichen Trocknung (2–30 h), wobei die Probe bis nahe an den FSP heruntergetrocknet wird, die eigentliche Trocknungsperiode unterhalb FSP (30–64 h), gefolgt von einer Abkühlphase (64–72 h). Man beachte das Dehnungsverhalten der Proben während der Heizperiode und einige Stunden danach, welches das Phänomen der hygrothermischen Verformung zeigt. "Dummy" bedeutet eine Probe ohne Last

In all tests the initial drying period was done at 95 °C, but drying below FSP varied between tests so that the maximum temperature reached during the test was either 95, 110 or 125 °C. For tests at 95 °C, the temperature could be kept constant and the humidity control done purely by the wet bulb temperature value, whereas in tests of maximum temperature 110 or 125 °C the humidity regulation had to be realised partly by the dry bulb temperature also and thus the temperature could not be kept constant. In most tests there was a final cooling period, during which the temperature was taken down to near room temperature in a controlled manner. The final moisture content and density of the specimens was measured by weighing and oven-drying method.

2.2.5
Loading schedule

As mentioned above, the specimens were loaded at c. 28 h after the start of the test. Load was constant in time in most cases, i.e. the load was kept on unchanged until the end. However, in many tests the load was temporarily removed for a few minutes at several points of time in order to study the value of the elastic modulus under the prevailing conditions at that moment. Also, to study the recovery properties, load was in some tests removed in the middle of the test for a longer period of time or until the end of the test.

2.3
Techniques for tests in constant wet conditions

2.3.1
Saturated condition test apparatus

The creep experiments on wet wood were made using a material testing machine to produce the desired loading and a hot water circulation system in combination with a pressurised test cylinder to create the saturated conditions. The apparatus takes one specimen at a time and the specimen is placed in the test cylinder for a hot water/steam bath for the whole duration the experiment. The apparatus is originally designed by Viitaniemi and Pennanen (1993).

2.3.2
Test conditions

Creep test were made at three constant temperatures: 95, 110, 125 °C. Specimens were allowed to heat for at least 20 min in the test cylinder before loading. Tests of various durations were made ranging from few hours to about 24 h. Constant load in time was used, but most experiments included a recovery period lasting for few hours before the end of the experiment. In some experiments, there was also a short recovery period in the early part of the experiment when load was removed for 10 min.

2.3.3
Strength tests

As an extra extension to the constant wet condition creep tests a small strength test series was carried out. The test set-up was the same and the tests were in hot bath at temperatures 95 and 125 °C. The specimens were of spruce only. The specimens were modified from the creep specimens by cutting a round waisting along the two edges of the specimen middle parts, so that the smallest cross-section area at the middle of the specimens was 20 mm by 21.5 mm. The strength tests were carried out in just the same way as the constant wet condition creep tests, only that, at loading, the load increase was continued until failure.

3
Hygrothermal deformation, shrinkage, modulus of elasticity and strength results

The experimental programme yielded results on various properties of wood. From the results of the drying condition tests, information was extracted about shrinkage, hygrothermal deformation, modulus of elasticity, viscoelastic and mechano-sorptive creep. The wet condition tests produced information on modulus of elasticity and viscoelastic creep plus the results of the strength test extension. In this paper the results about shrinkage, hygrothermal deformation, modulus of elasticity and strength are reported; the viscoelastic and mechano-sorptive creep results combined with more advanced analysis are given in the following parts of this series.

3.1
Hygrothermal deformation

As an example of the measurements, the strain development of specimens in one drying condition test run is shown in Fig. 5. An interesting feature of the results is the behaviour of the specimens during the heating period and few hours after it. Namely, tangential specimens swell during the heating but radial specimens shrink (the specimens in Fig. 5 are tangential). This is a manifestation of the hygrothermal recovery phenomenon, which occurs when wet wood is heated (e.g. Kubler 1973). It seems that for most radial specimens the hygrothermal shrinkage occurs until the heating period is finished and does not continue much afterwards, whereas for tangential specimens swelling may continue few hours after the heating is finished. It is possible to estimate the magnitude of the hygrothermal strain based on the measurements, but it should be noted that, since the heating was made in air, true hygroscopic shrinkage may affect the results. According to the measurements, on heating to 95 °C the hygrothermal strain is c. 0.8% (swelling) in tangential direction and −0.3% (shrinkage) in radial direction. These results are in good agreement with earlier findings (Kubler 1973).

3.2
Shrinkage

Shrinkage can be studied using the measurements on the dummy specimens in the drying condition tests. Based on shrinkage at the end of the final drying period but before cooling, an estimated shrinkage value for drying from green condition in room temperature to 0% MC in the final temperature was calculated. This value, which includes the effect of hygrothermal deformation, is plotted against density in Figs. 6 and 7. The influence of density on shrinkage is clearly seen from the radial shrinkage measurements but is not as clear for tangential results. This is probably caused by the fact that perfectly tangentially oriented specimens are much more difficult to manufacture than radially oriented ones, which causes them to contain more scatter.

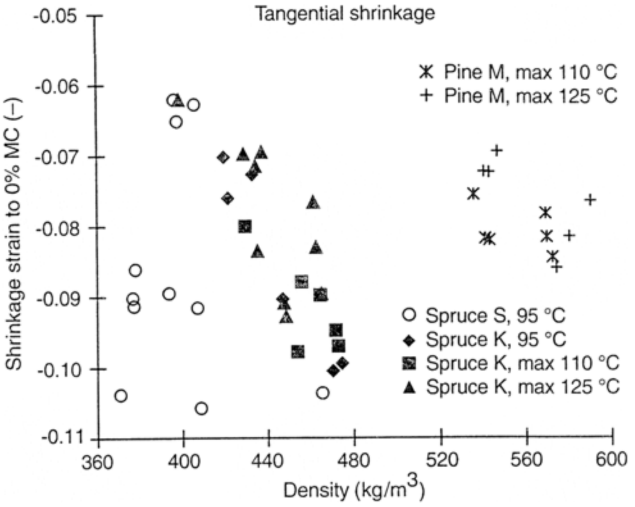

Fig. 6. Effect of density on tangential shrinkage. Shrinkage to 0% MC has been calculated based on shrinkage after the final drying but before cooling. The temperature values 110 and 125 °C indicate only the maximum temperature during the experiment and thus a large part of the shrinkage has actually occurred at lower temperature levels

Bild 6. Einfluß der Rohdichte auf das tagentiale Schwinden. Das Schwinden bei Trocknung bis 0% Feuchte wurde berechnet aus dem letzten Schwindwert am Ende der Trocknung, jedoch vor der Abkühlphase. Die Temperaturwerte 110 und 125 °C stellen nur die maximalen Werte während des Versuchs dar; deswegen erfolgte ein großer Anteil des Schwindens bei nierigeren Temperaturen

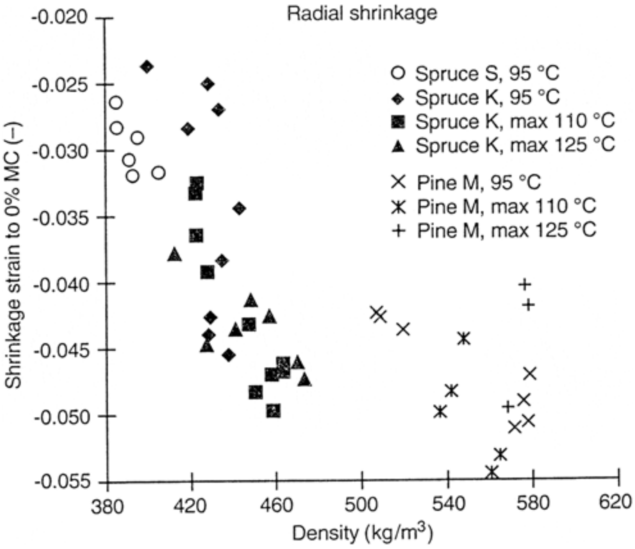

Fig. 7. Effect of density on radial shrinkage. See notes in the caption of Fig. 6

Bild 7. Einfluß der Rohdichte auf das radiale Schwinden (vgl. Bild 6)

3.3
Modulus of elasticity

The results from both drying condition and wet condition tests were used to study the modulus of elasticity (MOE). In all cases, the value of the MOE was calculated based on the compliance at 1 min after application of load. The effect of moisture content and temperature on the MOE are the most interesting aspects of the results.

Based on the drying condition tests, the modulus of elasticity is plotted against moisture content for tangential

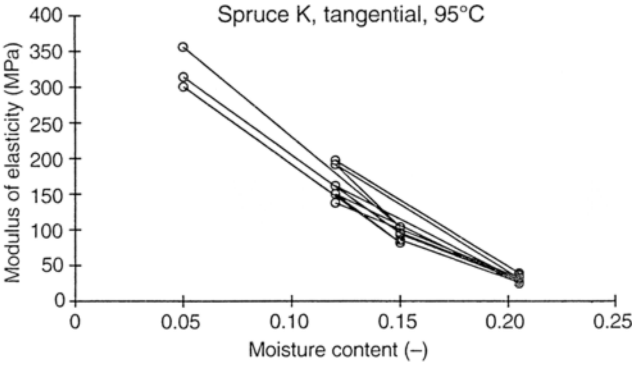

Fig. 8. Modulus of elasticity against moisture content for tangential specimens of Spruce K trunk at 95 °C. Each point represents one measurement; points joined with lines represent measurements on a single specimen at first loading and subsequent unloading-reloading sequences during the course of the experiments. Values have been determined corresponding to compliance change at 1 min after load change
Bild 8. MOE bei 95 °C in Abhängigkeit von der Feuchte für tangentiale Proben aus dem Fichtenstamm K. Jeder Punkt entspricht einem Meßwert. Punkte auf einer Linie bedeuten Messungen an derselben Probe mit wechselnder Belastung (zu Beginn) und Entlastung während des Versuchs. Die Werte wurden aufgrund der entsprechenden Verformung jeweils 1 min nach Lastwechsel bestimmt

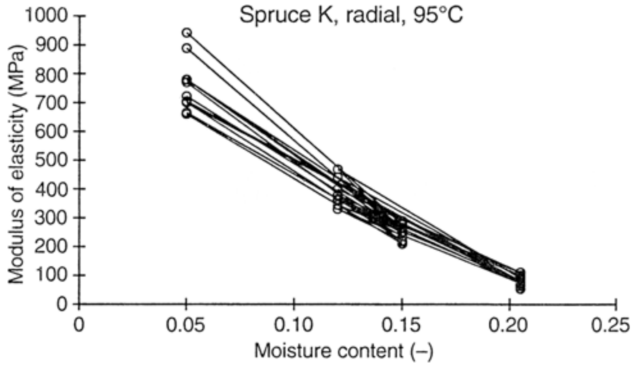

Fig. 9. Modulus of elasticity against moisture content for radial specimens of Spruce K at 95 °C. See notes in the caption of Fig. 8
Bild 9. MOE bei 95 °C in Abhängigkeit von der Feuchte für radiale Proben aus dem Fichtenstamm K (vgl. Bild 8)

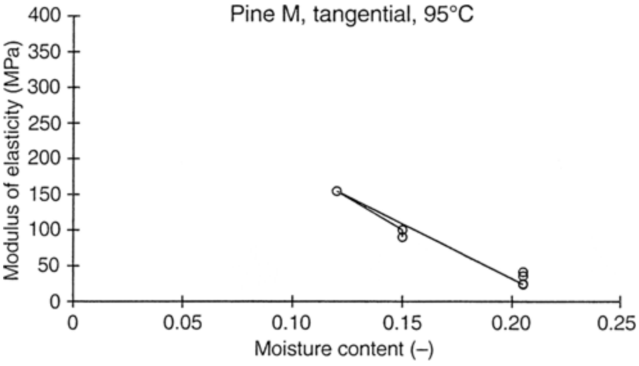

Fig. 10. Modulus of elasticity against moisture content for tangential specimens of Pine M at 95 °C. See notes in the caption of Fig. 8
Bild 10. MOE in Abhängigkeit von der Feuchte für tangential belastete Proben (Kiefer, Stamm M) bei 95 °C (vgl. Bild 8)

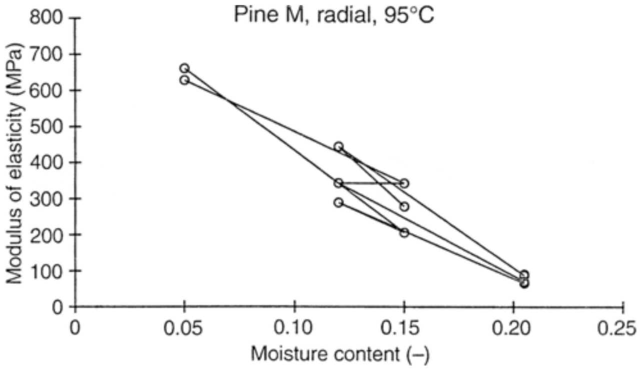

Fig. 11. Modulus of elasticity against moisture content for radial specimens of Pine M at 95 °C. See notes in the caption of Fig. 8
Bild 11. MOE in Abhängigkeit von der Feuchte für radial belastete Proben (Kiefer, Stamm M) bei 95 °C (vgl. Bild 8)

and radial specimens of Spruce K at 95 °C in Figs. 8 and 9, respectively. Each point represents one measurement and points joined with lines represent measurements on a single specimen. The several measurement values on a single specimen are based on the first loading (~ saturated condition) and subsequent unloading-loading sequences in different conditions during the course of the drying condition tests. Similar graphs for Pine M are given in Figs. 10 and 11. The results show the huge effect of moisture content on the MOE.

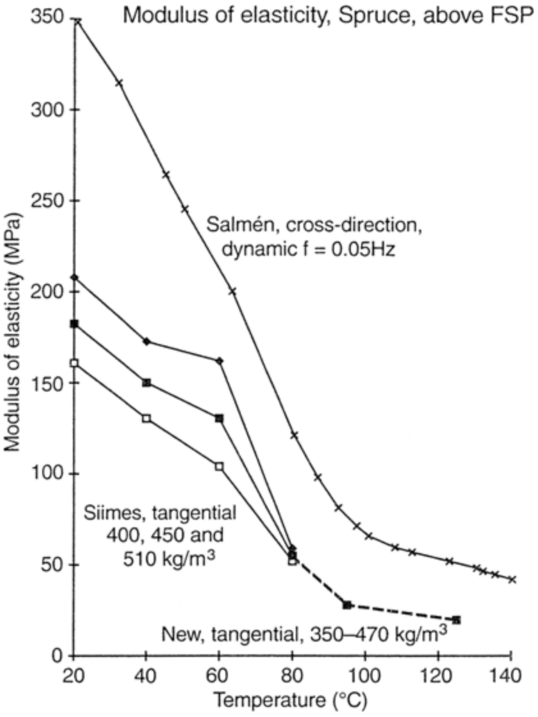

Fig. 12. The effect of temperature on tangential MOE in wet condition for spruce (New, *Picea abies*). For comparison, the measurements made earlier at VTT on static MOE in temperature range 20–80 °C (Siimes 1967, *Picea abies*) are shown as well as the measurement on dynamic MOE at 20–140 °C by Salmén (1984, *Picea abies*)
Bild 12. Einfluß der Temperatur auf den MOE bei tangentialer Belastung für Fichtenholz in feuchtem Zustand ("New"). Zum Vergleich sind frühere Messungen am VTT zum statischen MOE zwischen 20 und 80 °C mit aufgenommen (Siimes 1967), sowie Messungen zum dynamischen MOE an Fichte zwischen 20 und 140 °C von Salmén (1984)

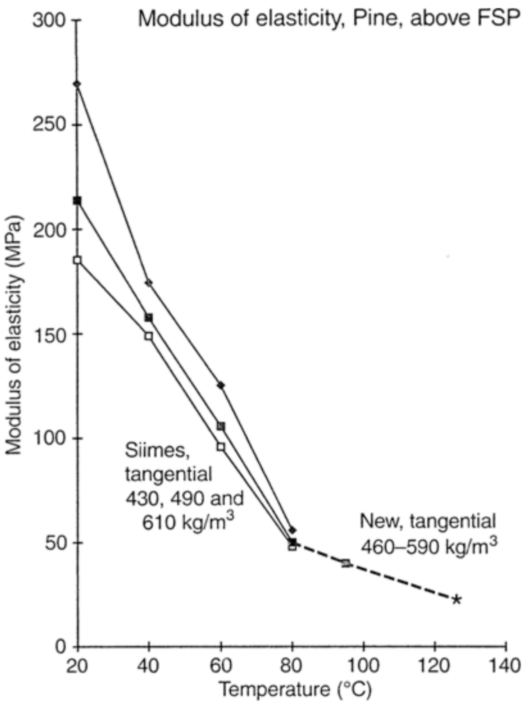

Fig. 13. The effect of temperature on tangential MOE in wet condition for pine (New, *Pinus sylvestris*). For comparison, the measurements made earlier at VTT on static MOE in temperature range 20–80 °C (Siimes 1967, *Pinus sylvestris*) are shown. Experimental point denoted by the asterisk (*) is based on only two specimens

Bild 13. Einfluß der Temperatur auf den MOE bei tangentialer Belastung für Kiefernholz in feuchtem Zustand ("New"). Zum Vergleich sind frühere Messungen am VTT zum statischen MOE zwischen 20 und 80 °C, ebenfalls an Kiefer, mit aufgenommen (Siimes 1967). Der mit (*) bezeichnete Datenpunkt beruht auf nur zwei Meßwerten

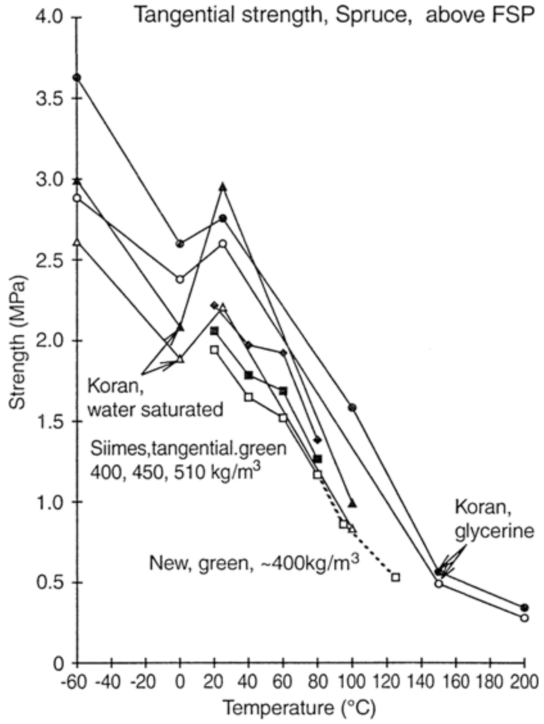

Fig. 14. Tangential strength of spruce wood in saturated condition as function of temperature. Even if the sample size is very small, the new results (*Picea abies*) show a reasonably consistent continuation of the results of Siimes (1967, *Picea abies*). Koran's (1979) results on Black spruce (*Picea mariana*) are also shown for reference

Bild 14. Tangentiale Festigkeit von Fichtenholz bei Fasersättigung in Abhängigkeit von der Temperatur. Obwohl die Probenabmessungen sehr klein sind, schließen sich die neuen Ergebnisse in akzeptablen Grenzen an die Werte von Siimes (1967, *Picea abies*) an. Meßdaten von Koran (1979) an *Picea mariana* sind zum Vergleich ebenfalls aufgenommen

In Figs. 12 and 13 the effect of temperature on the tangential MOE in wet condition is shown for spruce and pine, respectively. For comparison, the measurements of static MOE over the temperature range 20–80 °C by Siimes (1967, *Picea abies* and *Pinus sylvestris*) are shown as well as the measurements of dynamic MOE at 20–140 °C by Salmén (1984, *Picea abies*). The new results show a very consistent continuation to the earlier results.

3.4
Strength

The strength test series did not yield completely satisfactory results since not all specimens failed "properly" at the middle part, but in quite a few specimens the fracture surface passes at least partly along the glued joint. This is no surprise, since the specimens used were just modified creep specimens and not designed for strength tests. Nevertheless, a preliminary idea of the strength can be obtained from the results for the tangential direction; the results are gathered in Table 1. The results show a fairly consistent continuation of the strength test results of Siimes (1967) on spruce (*Picea abies*) as is shown in Fig. 14. Koran's (1979) results on Black spruce (*Picea mariana*) have also been included for reference.

4
Conclusions

The experimental equipment and measurement techniques developed in the project that this paper concerns make it possible to perform creep tests under controlled conditions that simulate the conditions during the drying process in a high temperature kiln. The equipment has proven to function satisfactorily and reliably. The tests conducted during the work and partly reported in this paper contain novel information of the basic deformation properties of wood in conditions that have not been investigated before or have been subject to a very limited amount of research effort. This kind of knowledge provides a basis for the understanding of the deformation phenomena and stress development occurring in timber during HTD. The results reported in this paper lead to the conclusions described in the following.

The measurements of strain development during the heating period confirm the hygrothermal recovery phenomenon. Hygrothermal deformations need to be taken into account when considering the stress and strain development in timber that is being high temperature dried.

Even the short term properties (the modulus of elasticity) show clearly the greater deformation capacity (compliance) of wood in the high temperature range (95–125 °C) than at the conventional drying temperatures (60–80 °C). This is seen as the decrease of the MOE with increasing temperature (Figs. 12 and 13). Greater deformation capacity means that drying stresses can be kept lower. On the other hand, the strength of wood drops with increasing temperature, but the effect of increased compliance is apparently greater allowing faster drying at higher

Table 1. Tangential strength test results on some spruce specimens. The results should be considered as preliminary, because some specimens failed at the glued joint and because of the small sample size

Tabelle 1. Tangentiale Zugfestigkeit einiger Fichtenproben. Es handelt sich um vorläufige Ergebnisse, weil einige Proben an der Leimfuge brachen, sowie wegen der kleinen Abmessungen

Specimen	Specimen direction	Temperature [°C]	Failure remark (†)	Strength [MPa]	Average all	Average non-joint (‡)
S0A4	Tangential	95		0.810		
S1A5	Tangential	95		0.902		
S3A7	Tangential	95	**	0.658		
S3B7	Tangential	95	*	0.747		
S4B5	Tangential	95	**	0.737		
	Tangential	95			0.771	0.856
S1A6	Tangential	125		0.624		
S3A8	Tangential	125	**	0.477		
S3B8	Tangential	125		0.500		
S4A4	Tangential	125	**	0.497		
S4B6	Tangential	125		0.476		
S5A6	Tangential	125	**	0.569		
	Tangential	125			0.524	0.534

(†) ** – Failure occurred at the joint
* – Failure occurred partly at the joint
(‡) Average of failures that occurred outside the joint.

temperatures without increased cracking. In realistic simulations of the drying process and cracking probability also the effect of long-term compliance (creep) must be taken into account, which is the subject of the following parts of this set of papers.

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