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Wooden Cladding Boards in Cyclic Moisture Conditions

Studies of Cupping, Moisture Distribution and Swelling Stress

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ABSTRACT

One reason for the decreased durability of modern claddings is considered to be the use of deformation-sensitive cladding boards. At the end of the nineteenth century cladding boards were about 40 mm thick, whereas present-day instructions recommend about 20 mm thick boards for claddings.

The first aim of the study was to compare the cupping sensitivity of heat-treated and non-heat-treated cladding boards during cyclic moisture conditions. The second aim was to investigate the progress of the moisture profile in wooden cladding board as a result of short-term single-sided water soaking. The third aim was to investigate the development of swelling stresses in the tangential direction in spruce (*Picea abies*) as a function of water soaking time in order to provide basic data.

The cupping studies were conducted with full-scale test walls in laboratory conditions with specimens made of heat-treated and non-heat-treated timber. The moisture distribution study was based on a theoretical approach, after which the modeling results were compared to those of previously published studies. Experimental swelling stress results were compared to the theoretical calculations obtained from different models.

On the basis of the cupping results, the thickness and heat-treatment of the board affected both the rate and the extent of curving during cyclic moisture conditions. The species of wood was also found to be an important consideration for selecting stable boards for the cladding. On the basis of the moisture distribution results, the transverse moisture profile could be predicted using a transport model in which air pressure and other resistance factors were compensated using an apparent surface emission coefficient. The modeling results were almost identical to the experimental observations. On the basis of the swelling stress study it appears that the magnitude of the swelling stresses in spruce samples in the tangential direction was approximately 1.2 MPa.

LIST OF PUBLICATIONS

This thesis consists of an introduction and the following papers that are referred by Roman numerals in the text.

PAPER I	Virta, J., Koponen, S. & Absetz, I. 2005. Cupping of wooden cladding boards in cyclic conditions – A study of boards made of Norway spruce (*Picea abies*) and Scots pine sapwood (*Pinus sylvestris*). *Journal of Wood Science and Technology* **39**(6);431-438.
PAPER II	Virta, J. 2005. Cupping of wooden cladding boards in cyclic conditions – A study of heat-treated and non-heat-treated boards. *Journal of Building and Environment* **40**(10);1395-1399.
PAPER III	Virta, J. & Koponen, S. 2004. Free cupping of cladding boards caused by capillary penetration: An experimental study of untreated and heat-treated boards. WCTE 2004 Vol. 3:591–594.
PAPER IV	Virta, J., Koponen, S. & Absetz, I. 2005. Modeling moisture distribution in wooden cladding board as a result of short-term single-sided water soaking. *Journal of Building and Environment* (in press, available on-line).
PAPER V	Virta, J., Koponen, S. & Absetz, I. 2006. Measurement of swelling stresses in spruce (*Picea abies*) samples. *Journal of Building and Environment* **41**(8);1014-1018.

The author's contribution in the original papers

PAPER I	Jari Virta is the corresponding author, designed the experiments, performed the measurements, analysed the data, interpreted the results and wrote the paper
PAPER III	Jari Virta is the corresponding author, designed the experiments, performed the measurements, analysed the data, interpreted the results and wrote the paper
PAPER IV	Jari Virta is the corresponding author, analysed the data, interpreted the results and wrote the paper
PAPER V	Jari Virta is the corresponding author, performed the measurements, analysed the data, interpreted the results and wrote parts of the paper

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Papers II, IV and V have been published with kind permission of Elsevier Ltd

PREFACE

This work was carried out at the Laboratory of Structural Engineering and Building Physics at Helsinki University of Technology under the supervision of Professor Ilmari Absetz and Emeritus Professor Pekka Kanerva. I gratefully acknowledge this supervision. The reviewers, Emeritus Professor Pierre Morlier at the University of Bordeaux1, France, and Professor Jesper Arfvidsson at Lund University, Sweden, are acknowledged for their constructive criticism and comments. I also express my gratitude to Dr. Antti Hanhijärvi at VTT Technical Research Centre of Finland and Dr. Pirjo Ahola at Tikkurila Paints Oy for agreeing to act as opponents of the thesis.

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I express my deep gratitude to the members of the Wood Research Group at the Laboratory of Structural Engineering and Building Physics. Especially my thanks go to Dr. Simo Koponen, who has been soul of our research team. I also thank Pekka Tukiainen and Susanna Peltola for all kinds of discussions during this work, as well as Lauri Sipilä for his patience during preparation of the test pieces and for keeping an eye on the driving rain test apparatus. Thanks also to all members at the National Graduate School of Timber Construction. I am warmly grateful to Michael Bailey for language revision and constructive criticism of the manuscript. I also thank Pasi Torenius at the Sarlin Corporation for showing interest in scientific research.

The warmest thanks I express to my family; to my mother Riitta, sister Marika, and brother Marko. I also thank grandfather Onni and grandmother Elina Virta for supporting me during these years. Finally, I thank my wife, Dutsadi, for filling my life with love and with spicy thai-food.

Espoo, March 2006
Jari Virta

Jari Virta

Wooden cladding boards in cyclic moisture conditions - Studies of cupping, moisture distribution and swelling stress

Content

NOTATIONS

α_r	Radial hygroexpansion coefficient	[%/%]
α_t	Tangential hygroexpansion coefficient	[%/%]
EMC	Equilibrium moisture content	[%]
FSP	Fiber saturation point	[%]
K	Capillary transport coefficient	[m^2/s]
K_f	Permeability coefficient	[m^2]
K_{fs}	Constant value of permeability coefficient	[m^2]
MC	Moisture content (based on oven-dry weight)	[%]
n_b	Bound water flux within the cell wall	[kg/m^2/s]
n_f	Free water flux in the voids	[kg/m^2/s]
n_v	Water vapour flux in the gas	[kg/m^2/s]
P_c	Capillary pressure	[Pa]
sp gr	Specific gravity	[kg/m^3]
w	Water content	[kg/kg]
w_b	Bound water content	[kg/kg]
w_f	Free water content	[kg/kg]
Δu	Change of moisture content	[%]
ε	Total strain	[-]
ε_{ms}	Mechano-sorptive strain	[-]
ε_{vs}	Viscoelastic strain	[-]
ε_u	Hygroexpansion strain (shrinkage and swelling)	[-]
ρ_o	Density of oven-dry wood	[kg/m^3]
ρ_s	Density of the cell-wall material	[kg/m^3]

1. INTRODUCTION

1.1 Background

The durability of wooden facades is the result of a combination of numerous factors with different effects on performance and long-term durability. Most of these effects have been the subject of intense research interest during recent decades (e.g. Ahola 1993, de Meijer 1999). This study concentrates on dimensional changes of wooden cladding board during cyclic moisture conditions (Fig. 1.1).

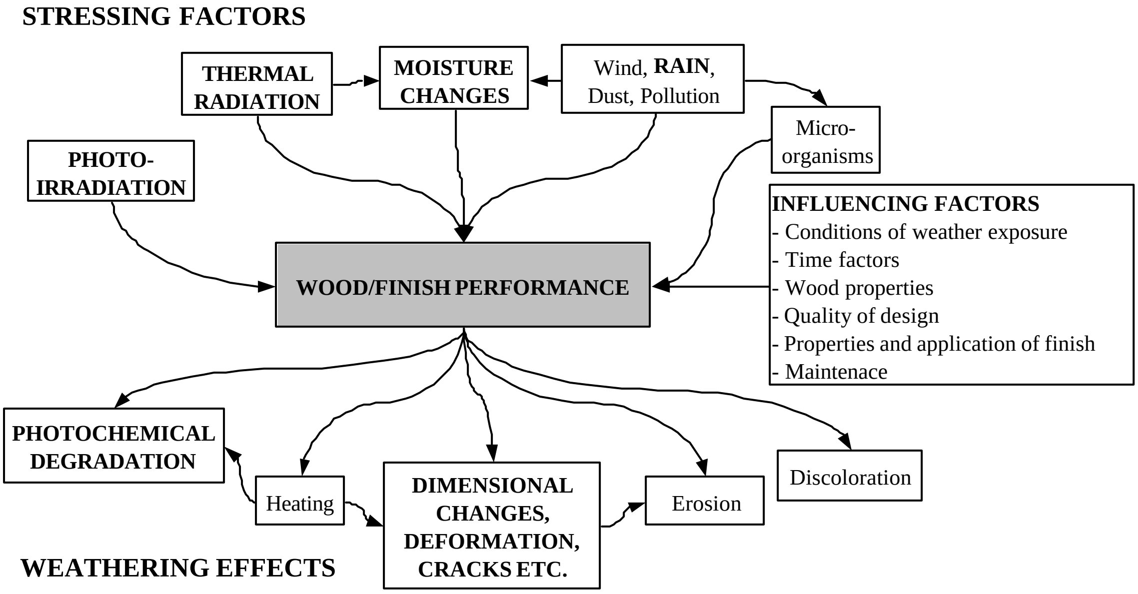

Figure 1.1 *Durability of wooden facades and their coatings (Sell & Feist 1986).*

Cladding board shrinks as it dries and swells as it absorbs moisture. This may lead to undesirable dimensional changes, e.g. cupping of the board. Although a protective coating usually protects the outer surface of the cladding, an untreated board or permeable or damaged coatings allow water to penetrate into the board (Ekstedt 1995, de Meijer & Militz 2001). Without sufficient protection, movement of moisture into and out of the cladding board can lead to undesirable dimensional changes, which may contribute to peeling and cracking of the wood surface and of the coating (Miniutti 1964, Ahola 1993, Feist 1997, Derbyshire & Miller 1997a, 1997b, Sandberg 1999, Flaete et al. 2000). Two common results of dimensional instability are jammed windows and cracking of claddings, causing economical loss for the end-user (Ekstedt 2002). Ultimately, excessively high levels of moisture may result in fungal disfigurement and decay (Viitanen 1996, Hjort 1997, Derbyshire & Robson 1999, Elowson et al. 2003). One of the main reasons for impaired durability of claddings is thought to be the use of deformation-sensitive cladding boards. In the middle of the 18th century, cladding boards were about 40 mm thick, whereas modern instructions recommend about 20 mm thick boards for claddings (Kaila et al. 1987). As a result, it is proposed that dimensional changes in the surface layers caused by repeated swelling and shrinking contribute to: 1) further breakdown of the wood–paint-system (e.g. Kalnins & Feist 1993, Ahola 1993, Ekstedt 2002), 2) loosening and falling out of dead knots (Koehler 1957), and 3) problems of an esthetic nature. The most common damage to wooden claddings due to weathering is depicted in Fig. 1.2.

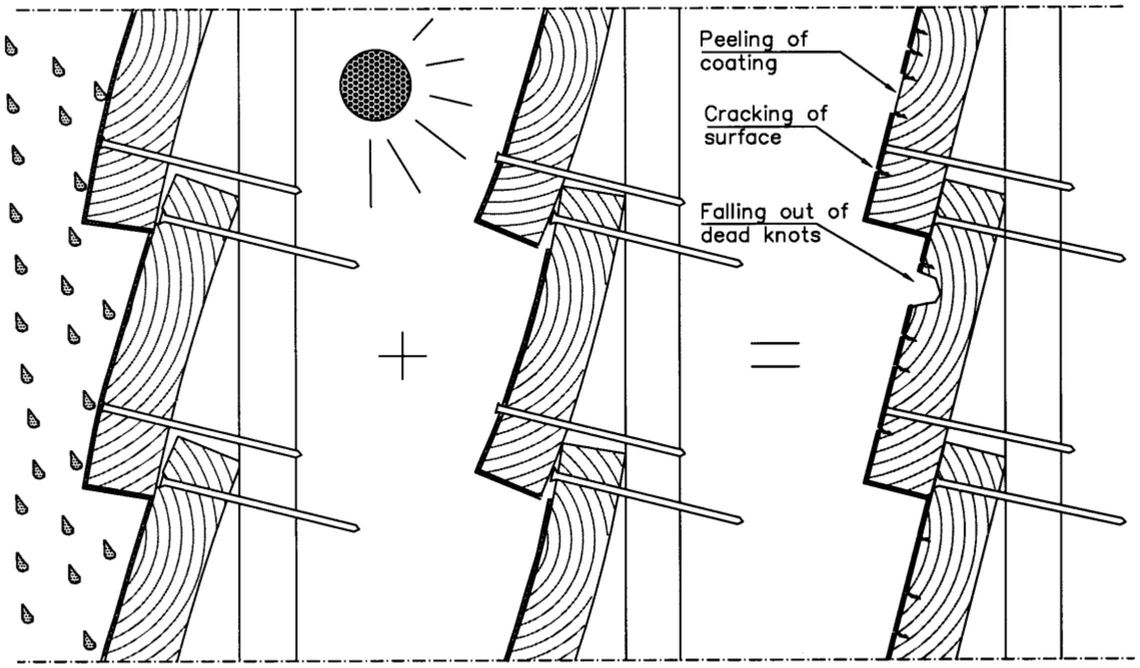

Figure 1.2 *Typical damage to wooden claddings due to weathering.*

Although cladding boards are tightly fitted from one or two sides by their fastenings, they tend to move with time (Nuoranen 1999, Tyrväinen 2000). This is a clear indication of the importance of the cupping sensitivity of the board during cyclic moisture conditions. According to these observations, it is concluded that the use of deformation-sensitive cladding board is one factor which limits the service life of wooden claddings. The durability and lifetime expectancy of a coated exterior wood construction depend on its ability to resist the water soaking and degradation processes that act on the coating and on the wood substrate (Ekstedt 2002). Short service lives of wooden claddings have a huge effect on maintenance and repair costs because wood is the most common cladding material in Finland (Fig. 1.3).

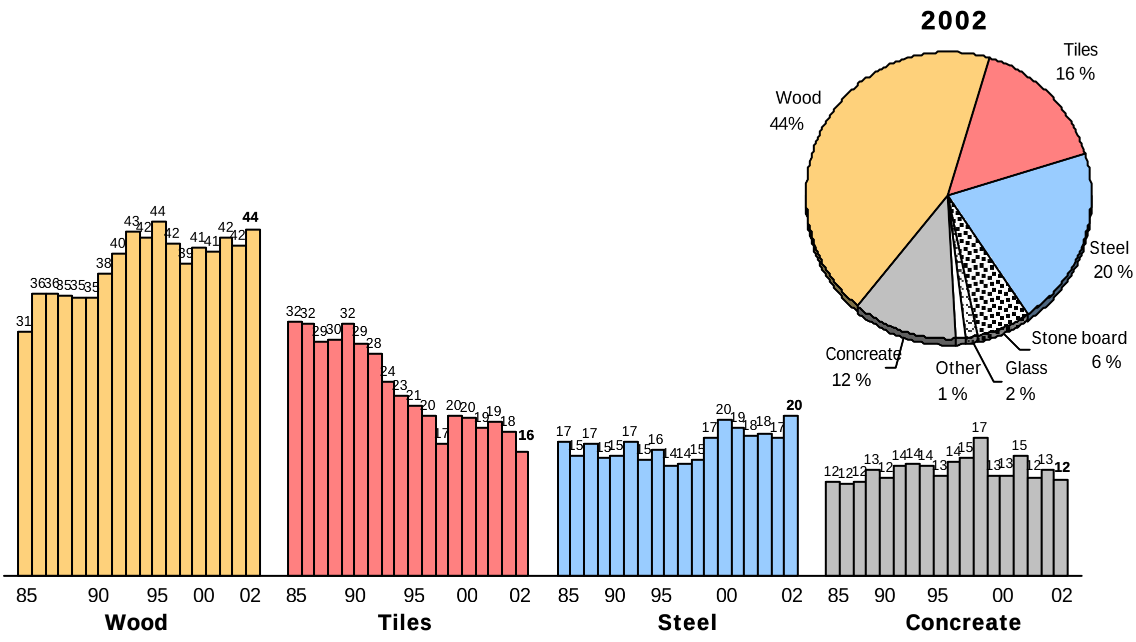

Figure 1.3 *Facade materials in new buildings in Finland, 1985-2002 (Pajakkala 2003).*

1.2 Research problem

To date, only a limited number of studies have focused on 1) cupping of wooden cladding boards during cyclic moisture conditions, and 2) moisture distribution and swelling stress development during short-term water soaking in the surface layers of cladding boards. The most important observation is that the cupping of heat-treated cladding boards during cyclic moisture conditions has been overlooked.

1.3 Aim of the research

The aim of this research was to study 1) cupping behaviour of non-heat-treated and heat-treated cladding boards in cyclic moisture conditions, 2) moisture distribution development during short-term single-sided water soaking, and 3) swelling stress development in spruce (*Picea abies*) samples during short-term water soaking.

1.4 Scope of the research

This study focused on the cupping behaviour of cladding boards in cyclic moisture conditions, and on moisture distribution and swelling stress development during short-term water soaking. The cupping specimens consisted of non-heat-treated and heat-treated boards made of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) timber. These specimens were re-sawn with a band-saw according to Nordic practice and exposed to cyclic moisture conditions from the pith side. The swelling stress studies were conducted with specimens made of non-heat-treated Norway spruce timber.

1.5 Content of the research

A short introduction to the topic of this thesis is given in Section 1 (*Introduction*). A summary of present knowledge about cupping, moisture distribution and swelling stress is presented in Section 2 (*State of the art*). A review of the thesis papers is presented in Section 3 (*Review of papers*). The papers include studies of cupping, moisture distribution and swelling stress. In Section 4 (*Conclusions*), the main conclusions of this study are presented. Finally, Section 5 (*Suggestions for future research*) presents suggestions for future research.

1.6 Contribution

The scientific contribution of this thesis includes the following findings:

PAPER I	This article presents new data concerning the cupping differences between cladding boards made of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) sapwood in cyclic moisture conditions.
PAPER II	This article presents new data concerning the cupping sensitivity of non-heat-treated and heat-treated cladding boards in cyclic moisture conditions.
PAPER III	This article presents new data concerning free cupping of cladding boards made of Norway spruce (*Picea abies*) in cyclic moisture conditions.

PAPER IV This article presents a simplified time-dependent water soaking model which is able to predict moisture distribution in wooden cladding board as a result of short-term single-sided free water soaking in the transverse direction. This model can be linked to a time-dependent deformation model in order to estimate e.g. surface elongation of wooden cladding board due to exposure to driving rain.

PAPER V The results of swelling stress measurements made in this work could provide initial data to predict possible dimensional expansion of wood products in different directions as a function of exposure to water.

2. STATE OF THE ART

When the surface of a cladding board wets or dries considerably faster than the interior, either a check develops or the portions that wet or dry first become under compression or tension. Such stresses are responsible for cupping and other deformations in the boards (Koehler 1957). The deformation sensitivity of board affects the durability of the cladding, e.g. causing cracking on the surface and peeling of the coatings. For this reason, the cupping of wooden boards has been reported to be an important consideration for the sawmill industry and for end-users (Hajek & Esping 1996, Mårtensson & Svensson 1997, Svensson & Mårtensson 1999). Table 2.1 shows the most interesting cupping studies found in the literature.

***Table 2.1** The most relevant cupping studies found in the literature.*

Material	Modeling	Experiments	Cupping		References
			drying	wetting	
Norway spruce	●	●	●		Moren (1993)
Norway spruce		●	●		Hajek & Esping (1995)
Norway spruce	●		●		Svensson (1997)
Norway spruce	●		●		Ormarsson et al. (1999, 2000)
Norway spruce	●		●		Carlsson (2001)
Scots pine	●		●		Svensson & Mårtensson (1999)
Wood	●		●		Hsu & Tang (1975)
Plywood and OSB	●			●	Lang et al. (1995)
Ash, particleboard	●	●		●	Suchsland & Xu (1992)
Plywood	●			●	Grossman (1973)
Chipboard and OSB	●	●		●	Donfield et al. (1997)
Norway spruce	●	●		●	Virta (2001), Nuoranen (1999)
Norway spruce		●		●	Tyrväinen (2000)

An interesting observation is that the cupping behaviour of wooden cladding boards during cyclic moisture conditions has been overlooked. Although progress has been made in the case of continuous wetting and drying of wood, relatively little attention has been focused on the relationship between short-term single-sided water soaking and cupping of board. Some cupping studies have been conducted under increasing air humidity in the past (Lang et al. 1995, Suchsland & Xu 1992, Donfield et al. 1997). These studies show that cupping as a result of change in relative humidity is slow. The most relevant cupping studies can be found in the field of experimental research (Nuoranen 1999, Tyrväinen 2000, Virta 2001). Unfortunately, these measurements are inaccurate for predicting cupping sensitivity of cladding boards because of infrequent measurement intervals. The cupping is usually a result of a moisture gradient in the board. The cupping of wooden cladding board during single-sided wetting is depicted in Fig. 2.1.

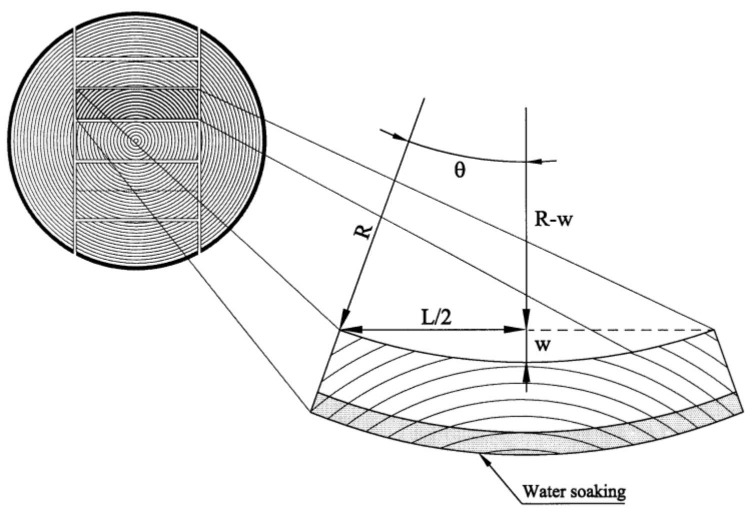

Figure 2.1 *Cupping as a result of single-sided wetting.*

The cupping formation of wooden boards can be approximately separated into two parts: cupping in the drying and in the wetting phase. The development of cupping during drying takes place according to the ambient air, whereas wetting can be a combination of capillarity and diffusion processes. These phases always cause an imbalanced moisture profile of the boards. A prerequisite for water transport in the board is the presence of a driving potential. The most common potentials are external pressure, capillary pressure, water vapour pressure, concentration gradient and temperature gradient (Siau 1995). If all these potentials and different kinds of flow models are considered, it makes the transport modeling complex. Usually the most effective wetting is due to the capillary pressure that causes liquid penetration into the board (Banks 1973). For this reason, diffusion is usually neglected in short-term water soaking modeling. If the surface of the board is uncoated or coated with a permeable coating, the main water transport mechanism appears to follow free water movement by capillary pressure. In this case, the moisture profile beneath the surface is narrow and high (Olek 1998). If the board is coated with a semi-permeable or impermeable coating, it appears that diffusion and other processes comprise the main water transport mechanism. In this case, the moisture profile beneath the surface is wide and flat (Hjort 1997, Berglind et al. 2003). Basically, the moisture distribution can be solved analytically or numerically. The analytical (capillary-tube model) liquid transport formulation, which is based on the work of Washburn (1921) and Lucas (1918), assumes that liquid penetrates via an open pore with a constant pore radius and that the pressure drops due to liquid flow. However, this modeling approach is problematic from the moisture distribution point of view. The main reasons are an irregular capillary network and unfilled voids within the porous body (Kowalski et al. 2002, Malkov 2002). The analytical model may be reasonable to use in water uptake modeling, but only approximate information can obtained concerning moisture distribution (de Meijer & Militz 2000, de Meijer et al. 2001, Virta 2001). More accurate results can be obtained by a numerical approach in which the water soaking is assumed to follow Darcy's law for flow through porous media. Siau (1984) made a detailed analysis of the validity of Darcy´s law for different flows of liquid in wood. Wood permeability is a measure of the ability of free water to penetrate the inner, capillary structure of wood. It depends on wood species, anatomical direction, and position in the cross-section. It is also assumed that permeability is influenced by local free water content (Stanish 1986, Perre et al. 1993, Perre & Turner 1997, 2001). These studies are related to the drying of wood. Olek (1998) conducted long-term water soaking studies with Scots pine sapwood. His results showed good agreement between the modeling and experimental observations. However, there was an inexplicable error between the modeling and the experimental results in the beginning of water soaking. In the case of free water soaking, the value of capillary transport coefficient (K) is reported to be lower in wetting than in drying because of the presence of air trapped in voids inside the wood (Olek 1998). The air is compressed during short-term free water soaking and additional counter pressure is formed. As a conclusion, there is a lack of data on experimental and theoretical time-dependent moisture distribution due to short-term single-sided water soaking. As a result of short-term water exposure, wood surfaces are wetted and water slowly penetrates into the wood (Lindgren 1991). Moisture content change, moisture distribution and cylindrical anisotropy of wood together cause cupping of the board. For this reason, the swelling stress development in the surface layers of wooden cladding board as a result of short-term water soaking is a crucial factor from the point of view of deformation behaviour. Several swelling stress studies were carried out in water soaking conditions and in increasing air humidity in the past (e.g. Perkitny & Kingston 1972, Kingston & Perkitny 1972, Suchsland 2004). Later studies concentrated on drying of wood (Kangas & Ranta-Maunus 1989, Salin 1992, Moren 1993) and distortions of sawn timber (Ormarsson 1999). As a conclusion, there is a lack of data on experimental and theoretical time-dependent swelling stress and stress relaxation due to short-term water soaking.

3. REVIEW OF PAPERS

3.1 Cupping of cladding boards (Papers I, II, and III)

3.1.1 Cupping – Norway spruce vs. Scots pine (Paper I)

The aim of this study was to indicate cupping differences between cladding boards made of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) sapwood during cyclic moisture conditions. Because Scots pine timber often contains permeable sapwood, the boards were selected from sapwood only. The cupping measurements were conducted with full-scale test walls in laboratory conditions. The boards, which were re-sawn with a band-saw according to Nordic practice, were fixed from two edges using 75 mm nails so that the pith side of the board was exposed to cyclic moisture conditions. On the basis of the results, the thickness and the species of softwood both had a significant influence on the rate and the extent of cupping.

3.1.2 Cupping – heat-treated vs. non-heat-treated (Paper II)

The aim of this study was to indicate cupping differences between heat-treated and non-heat-treated cladding boards during cyclic moisture conditions. The samples consisted of non-heat-treated and heat-treated boards made of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) timber. The cupping measurements were conducted with full-scale test walls in laboratory conditions. The boards, which were re-sawn with a band-saw according to Nordic practice, were fixed from two edges using 75 mm nails so that the pith side of the board was exposed to cyclic moisture conditions. On the basis of the results, board thickness and heat-treatment both affected the rate and the extent of cupping. In general, the greater the heat-treatment temperature and time, the lower the curvature.

3.1.3 Free cupping (Paper III)

The aim of this study was to indicate free cupping differences between heat-treated and non-heat-treated cladding boards made of Norway spruce (*Picea abies*) during cyclic moisture conditions. The boards, which were re-sawn with a band-saw according to Nordic practice, were free to cupping during cyclic moisture conditions. On the basis of the results, the non-heat-treated 18 mm and 21 mm thick boards were sensitive to cupping, whereas the 26 mm thick boards were rather stable during cyclic moisture conditions. The lowest curvatures were measured with heat-treated boards, which were considerably more stable than non-heat-treated boards.

3.2 Moisture distribution (Paper IV)

The aim of this study was to provide a simple approach to model moisture distribution during short-term single-sided water soaking in the surface layers of wooden cladding boards. The simplified water soaking model provided a rather good estimation predicting moisture profiles as a result of short-term single-sided free water soaking in wooden cladding boards. Variations in temperature and in the specific gravity of wood appeared to have only a minor influence on the moisture profile below the fiber saturation point (FSP). The most critical part of the modeling appeared to be the neglected air pressure function that was compensated by using the apparent surface emission coefficient (S). Calibration of the apparent surface emission coefficient (S) was conducted by fitting it to the experimental observations.

3.3 Swelling stress (Paper V)

The aim of this study was to indicate swelling stress and stress relaxation behaviour of specimens made of Norway spruce (*Picea abies*) timber during water soaking. The swelling stress test results obtained in this study will help investigators to understand and analyze deformations, e.g. cupping of wooden cladding boards during short-duration exposure to driving rain. On the basis of the results, the maximum swelling stress in the tangential direction is about 1.2 MPa. However, both viscoelastic creep and mechano-sorptive creep decreased the swelling stress measurably. In the restraint swelling tests, there was considerable scatter between the behaviours of different specimens even in the case of visually apparently identical replicate specimens.

4. CONCLUSIONS

4.1 Cupping of cladding boards (Papers I, II, and III)

For cupping of boards made of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) sapwood in cyclic moisture conditions (Paper I) the main conclusions drawn are:

- The use of 21 mm thick boards made of Norway spruce decreased curvature by as much as 40% compared to comparable boards made of Scots pine sapwood.
- The 21 mm thick boards were sensitive to cupping, whereas the 28 mm thick boards were rather stable.
- The use of 28 mm thick boards made of Norway spruce decreased curvature by as much as 70% compared to 21 mm thick boards made of Scots pine sapwood.
- All the boards cup for about 6 hours as a result of 3-hour water exposure to the surface.

For cupping of heat-treated and non-heat-treated boards in cyclic moisture conditions (Paper II) the main conclusions drawn are:

- The non-heat-treated 21 mm thick boards were sensitive to cupping, whereas the non-heat-treated 28 mm thick boards were rather stable.
- By increasing the thickness of non-heat-treated board from 21 mm to 28 mm, the average curvature decreased by about 76%.
- The heat-treatment decreased curvature by as much as 90% in the case of non-heat-treated 21 mm thick board.
- All the boards cup for about 6 hours as a result of 3-hour water exposure to the surface.

For free cupping of heat-treated and non-heat-treated boards in cyclic moisture conditions (Paper III) the main conclusions drawn are:

- The non-heat-treated 18 mm and 21 mm thick cladding boards were sensitive to cupping, whereas the 26 mm thick boards were rather stable.
- The lowest curvatures were measured with heat-treated boards.
- All the boards cup for about 29 hours as a result of 24-hour water exposure to the surface.

The findings of these studies (I, II, III) clearly indicate that the use of deformation-sensitive board may be one factor limiting the service life of wooden facades. The cupping measurements were conducted with boards that were re-sawn according to Nordic practice. For this reason, the curvature should be symmetrical. If the boards are exposed to water contact from the bark side, the curvature may be different from that measured from the pith side, but still symmetrical. The boards were selected from wood without pith or visible anomalies. However, mature wood usually contains variations and anomalies in its structure because of its biological origin. Local variations in the wood result from knots, juvenile wood, compression wood, reaction wood etc. Boards made from wood near the bark in the cross section of a log have more injurious cracks than boards taken from near the pith. From this point of view, a board from near the pith therefore seems to be better for uncoated cladding than a board taken from near the bark (Flaete et al. 2000). However, it is well known that the boards nearest to the pith contain more juvenile wood (Bengtsson 1999). The properties of juvenile wood differ from those of mature wood. Juvenile wood is characterized by lower stiffness, lower tangential shrinkage and lower density than in the case of mature wood (Haygreen & Bowyer 1989). Sanberg (1996, 1997) found that the use of juvenile wood increased crack formation. Timber produced from the pith has been found to have generally lower values of modulus of elasticity (MOE) and bending strength than that of timber without pith. Bengtsson (1999, 2001) reported that knots are an important factor affecting the material properties of wood. Bengtsson (1999) showed that even a small knot reduced MOE by about 15%. Different types of knots (green or black) possibly affect the deformation of a specimen in different ways. These observations clearly indicate that anomalies also affect the curving behaviour of cladding boards.

4.2 Moisture distribution (Paper IV)

For modeling moisture distribution in wooden cladding board as a result of short-term single-sided water soaking (Paper IV) the main conclusions drawn are:

- The simplified water soaking model was capable of predicting moisture distribution during short-term single-sided water soaking.
- Water soaking into board made of Scots pine sapwood was more extensive than into board made of Norway spruce.

Moisture distribution modeling in the transverse direction as a function of short-term water soaking is difficult from many points of view. Weathering checks in the cell walls may account for the major part of the liquid flow in the transverse direction. It is also possible that a moisture content plateau may develop in the board at a moisture content level of about 50-75% (Lindgren 1991). Cracking of the boards causes difficulties in the modeling of capillary pressure and counter pressure during short-term water soaking. For this reason, the effect of capillary pressure on the water flow into wood is not very clear from the point of view of short-term water soaking (Malkov 2002). Studies of wood during drying have shown that the moisture content and specific gravity of wood have a drastic effect on capillary pressure (Choong et. al 1989, Spolek & Plumb 1981, Perre & Turner 1997).

4.3 Swelling stress (Paper V)

For measurement of swelling stresses in spruce samples (Paper V) the main conclusions drawn are:

- Tangential swelling stress appeared to be about 1.2 MPa
- The tangential swelling stress variation in the tests was remarkable even in the case of visually apparently identical replicates.
- Swelling stress modeling clearly showed that use of the constitutive equation without mechano-sorptive and viscoelastic components gave unrealistically high stress values.

Discussion of stress levels during short-term water soaking is difficult for many reasons. For example, aged timber swells less than non-aged timber (Esteban et al. 2005). This causes problems for prediction of swelling of wood during its lifetime because investigators prefer to work with fresh, newly-seasoned wood (Hunt 2004). Because wood is an anisotropic material, its characteristics must be considered in modeling formulations. The most important factors affecting the properties of wood are related to varying environmental conditions and to the anisotropic structure of wood. These factors have an important role for material properties such as modulus of elasticity (MOE), hygroexpansion (Perstorper et al. 2001) and creep. For example, mechano-sorptive creep is dependent on strain history, wetting rate, temperature, direction in the stem and other parameters. Although a huge number of studies have been carried out in the field of creep of wood, no-one has been able to explain mechano-sorptive phenomena observed in tests. There are probably a number of factors that are related to molecular, microstructural and macrostructural levels (Mårtensson 2003). One of the difficulties is that the mechano-sorptive deformation is a second order phenomenon and cannot be measured directly as viscoelastic strain and free hygroexpansion.

5. SUGGESTIONS FOR FUTURE RESEARCH

5.1 Cupping of cladding boards (Papers I, II, and III)

More detailed cupping studies are needed to clarify the relationship between surface cracking sensitivity and the thickness of boards coated with different types of coatings. This kind of study should also be made in cyclic moisture conditions. Although heat-treated boards are stable in cyclic moisture conditions, more detailed study is needed to clarify the relationship between cracking sensitivity of the board and different heat-treatment processes. From the point of view durability, the optimal heat-treatment process is still an unknown issue.

5.2 Moisture distribution (Paper IV)

The findings of the moisture profile study suggest that the simplified water soaking model will be useful for estimation of moisture distribution in cladding board as a result of short-term single-sided free water soaking. However, further work is needed to clarify the air pressure function that occurs during short-term free water soaking. The coupled capillary and diffusion models should also be investigated. The model calibration needs more accurate data of the moisture distribution near the surface, e.g. by using magnetic resonance imaging (MRI) as a research method (Berglind et al. 2003). When taking aged timber into consideration, the moisture distribution modeling becomes very complex because of cracking of the board and of the coating. Aging usually increases water penetration into the cladding boards (Derbyshire & Miller 1996). Moreover, the equilibrium moisture content (EMC) of aged timber is lower than that of non-aged timber (Esteban et al. 2005).

5.3 Swelling stress (Paper V)

Future work should provide improved understanding of transverse shrinkage and swelling behaviour, relaxation of stresses and mechano-sorptive creep in order to estimate deformations of aged and non-aged timber products. The specimen orientation (tangential, radial or diagonal) strongly affects the swelling stress, the ultimate strength and the stress relaxation behaviour. For this reason, these studies should also be made in radial and diagonal directions.

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