WOOD RESEARCH
54 (1): 2009
89-102

MOISTURE INDUCED STRESSES AND DEFORMATIONS IN PARQUET FLOORS AN EXPERIMENTAL AND NUMERICAL STUDY

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ABSTRACT

The indoor climate in buildings has changed in the last decade due to more efficient climatic systems, floor heating systems and larger open floor areas with more natural light. All this has induced increasing ranges of relative humidity between different seasons. Also with decreasing relative humidity (in the winter 30-50% RH, in the summer 70-90% RH), floor-heating systems increase the temperature in wooden parquet planks for example. Such variations can result in troublesome deformations, delamination of the surface layer and development of cracks in the parquet flooring boards. Sometimes there is only deterioration of the appearance but the durability of the flooring system can also be reduced. Many laboratory tests have to be done before reaching an optimal design of the parquet elements. Due to high coasts and time constraints of experiments, other supplementary research methods should be tested and evaluated. The articles' main objective was to increase understanding of the behaviour of parquet floors exposed to different climatic conditions using numerical calculation. The use of the finite element models provides options for design purposes of wood flooring systems. Several finite element models for adequate design have been created, tested and applied. After calibration and validation of the calculation method, parameter studies on the influence of material properties, geometry of the parquet floors and the long-term behaviour of the wood and glue line were performed. The results show a strong relation between material and geometry choice on the deformation, for example the gap opening and on the stress distribution in glue line, which can induce delamination of the surface layer and distortional effects of the parquet boards.

KEY WORDS: parquet floor, finite element method, moisture, temperature, stress distribution

INTRODUCTION

During the last decade the use of wood flooring systems in Europe has increased dramatically. In Sweden for example the proportion of wood flooring systems rose steadily from 30% in the seventies to its current 80%. This rapid growth has resulted in the development of new products, enabling the industry to maintain and increase its market share. The paper's main objective is to increase understanding of the behaviour of parquet floors exposed to different climates using numerical analysis. The calculation in this work has been performed with the commercial finite element program ABAQUS. In addition, several experimental tests were made to study the deformation performance of parquet boards, to determine material parameters and to get results for calibration and validation. The beam theory of Bernoulli applied to both directions of the square specimens gave a simple, additional validation instrument for the deformational behaviour.

The influences of different parameters such as material properties, material orientation and properties of the glue line and geometry of the product on the stresses and deformations were tested and discussed. Several finite element models were created to simulate the behaviour of the parquet planks under changing climate. In addition, several experimental tests were made to study the deformation performance of parquet boards, to determine material parameters and to get results for calibration and validation. The beam theory of Bernoulli applied to both directions of the square specimens gave a simple, additional validation instrument for the deformational behaviour.

A parameter study of the long time behaviour of the parquet planks resulted in better understanding of the influence of creeping on the aforesaid deformations and failure modes.

MATERIAL AND METHODS

A specific parquet floor product from Sweden was tested in the context of this research. The used parquet consisted of three main layers: surface layer (SL) (3.6mm in the testes product), core layer (CL) (8.6mm) and backing layer (BL) (2mm), c.f. Fig. 1. The different layers were glued crosswise together with urea formaldehyde resin. The geometry of one entire plank was 188x14.2x2500mm. Laboratory tests on basic material and parquet planks were performed to examine basic material properties, and to provide data for validation of the finite element method calculations.

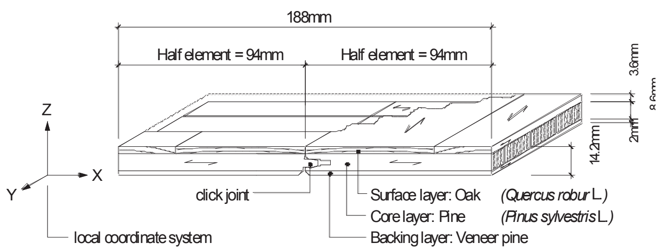

Fig. 1: Geometry and consistence of the parquet floor

Test series 1: Tests on basic material

The sorption behaviour, density, static modulus of elasticity in longitudinal direction and the hygroexpansion factors of pine *(Pinus sylvestris* L.*)* and oak *(Quercus robur* L.*)* have been determined. The static modulus of elasticity in longitudinal direction was evaluated using a three point-bending test. For the adsorption behaviour, 20 samples from each species were conditioned in a climatic chamber of 20° degrees and 25% relative humidity (RH) until they reached equilibrium moisture content (EMC). Thereafter, the climate has been changed going from 25% to over 50% and up to 85% relative humidity, all at a temperature of 20°C. The shrinkage and swelling coefficients in longitudinal, radial and tangential direction have been measured at changing climate from 60% down to 25% (shrinking, 20 specimens) and up to 85% (swelling, 20 specimens) respectively, all at a temperature of 20° Celsius.

Test series 2: Parquet planks

30 square samples with a side length of 150mm were cut out of parquet planks and conditioned in a standard climate of 20°/65% relative humidity until reaching equilibrium moisture content. 15 specimens had lacquered surface layer and 15 specimens were non-lacquered. One dimensional moisture transport was enforced on 5 lacquered and 5 non-lacquered specimens by applying moisture insulation on the edges. The samples were dried to a climate of 20°/25 for a period of 28 days. The bending behaviour has been measured at four points on the surface layer of the specimens. The vertical deformation was measured along two directions of the plate. In position A according Fig. 2, the grain direction of the core layer and thus x axis was parallel to the primary axis of the global coordinate system, thereafter 90 degree rotation counter clockwise of the plate was done for the second measurements. The plate was supported at the downside of point B, G and I.,B',G' and I' respectively. Three variables (thickness of the plate, curvature in x and y direction respectively), describing the vertical deformation of the specimen, have been evaluated from the eight measurements data using least square fit and Bernoulli beam theory.

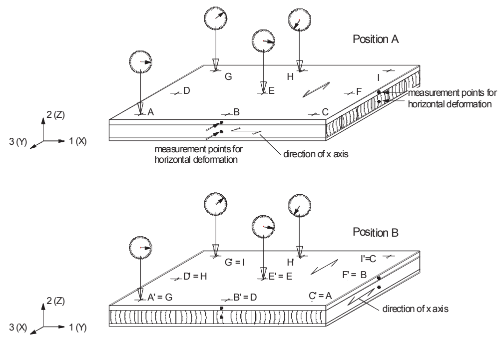

Fig. 2: Measurement of the plate's vertical deformation in two directions and evaluation with beam theory of Bernoulli (Δt: thickness change, κ: curvature in x and y direction respectively)

Analytical model A: Calibration model

Basic information about orthotropic elasticity, moisture induced stresses, mechanosorptive effects and elastic constants can be found in Baronas et al. (2001), Kollmann (1982), Koc and Houska (2002), Ormarsson (1999) and the Wood handbook (1999).

A finite element model with the same dimension and built up as the test samples of test series 2 has been created for the calibration and verification of the numerical analysis. The glue lines between the backing and core and core and surface layer respectively, were modelled as a 0.1mm thick layer (UF resin) with material data taken from Hagstrand (1999). Thermally coupled and quadratic interpolated brick elements have been used for the calculation. Whereas the diffusion coefficient [$m^2 s^{-1}$] in formula (1) replaced the temperature T [deg], c [$J kg^{-1}K^{-1}$] the specific heat c [$J kg^{-1}K^{-1}$], ρ [kg/m^3] the density (set to 1) and the thermal conductivity λ [$J s^{-1}m^{-1}K^{-1}$] in formula (2), see Carlslaw and Jaeger (1959) and Eriksson (2005).

$$\kappa_x = -\frac{d^2 v}{dx^2}\ [\mathrm{m}^{-1}] \qquad \kappa_y = -\frac{d^2 w}{dy^2}\ [\mathrm{m}^{-1}] \qquad \begin{bmatrix} 1 & -0.25L^2 & -0.5L^2 \\ 1 & 0 & 0 \\ 1 & -0.5L^2 & 0 \\ 1 & -0.5L^2 & -0.25L^2 \\ 1 & 0 & 0 \\ 1 & 0 & -0.5L^2 \end{bmatrix} \begin{bmatrix} \Delta t \\ \kappa_x \\ \kappa_y \end{bmatrix} = \begin{bmatrix} E \\ G \\ H \\ E' \\ G' \\ H' \end{bmatrix} \qquad (1)$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\lambda(T)}{c\rho} \frac{\partial T}{\partial x} \right) \ (1) \qquad \frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(D_W(u) \frac{\partial u}{\partial x} \right) \ (2)$$

For simplifying the transport model, the moisture content at the surface was in equilibrium with moisture content corresponding to the relative humidity of circulating air, $u_{surf} = u_{air}$. This imposed boundary condition is called the boundary condition of Drichlet, Koc and Houska (2002). An effective coefficient of diffusion for the entire parquet plank was determined and compared to results of test series 2 (specimens with moisture-isolated edges).

Some simplification for the estimation of the effective coefficient of diffusion have been done:

- The diffusion coefficient of pine and oak wood and in radial and tangential directed were set as equal
- The estimated diffusion coefficient was assumed as constant until 15% MC, e.g. Jönsson (2005)
- The model does not consider any interfacial layer between the wood layers and the glue layer. The interfacial layers have been reduced to a continuative 0.1 mm thick composite layer.

The bending deformations of the plate in plane xz and yz have been calculated and compared to results of test series 2. The static boundary conditions were included respecting the test set up of test series 2 according to Fig. 3. The degrees of freedom u_1, u_2 and u_3 were restrained on the lower edge of point B and in vertical direction u_2 on the lower edge of point G and I respectively, see Fig. 4. The gaps between the pine strips in the core layer were modelled as seams in ABAQUS. The layer consisted of three strips (left, middle and right) each with different direction of the growth rings (longitudinal L, radial R and tangential T). The material orientation of the surface layer has been varied from 0 degrees (Tangential direction parallel to u_1 or x direction according to Fig. 3 until 90 degrees (Tangential direction perpendicular u_1 or x direction). The angle of the growth rings has been set similar to the test specimens of test series 2. Transforming the stiffness matrix of the oak layer's different strips simulated the influence of the growth ring's direction. The transformation was done for both the stiffness matrix and the hygroexpansion factors. A coordinate transformation of the orthogonal coordinate system around the longitudinal axis (L) has been performed.

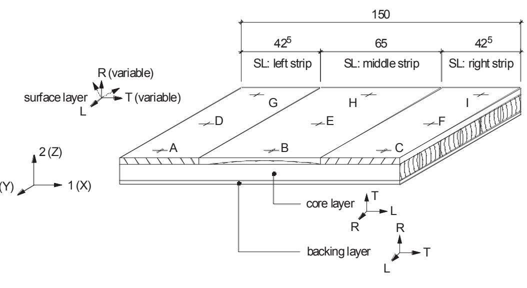

Fig. 3: Geometry and material of the parquet plank. The angle of the growth rings in the surface layer differs between the strips

Analytical model B: Distortional effects

A finite element model (Fig. 4.) was applied to predict the distortional behaviour of the parquet plank's central part. Parameter study on the influence of geometry, material and creeping of the surface layer were performed. The model corresponded to half the width of the strip and a depth of 26mm. This depth included 2 half width core sticks (2x12.5mm) and 1mm spacing between the sticks. The depth of the model was relatively small compared to the length of the parquet planks, which is 2500mm. The parquet strip was 10mm wide, 14.4mm thick in a three-layer structure (3.6mm surface layer (SL), 8.6mm core layer (CL) and 2mm backing layer (BL)) glued together with two 0.1mm thick UF resin layers. The vertical deformation of the parquet planks has been calculated between point A and point B. These points were located on nodes, point B on the boundary edge whereas point A was located 10mm from the boundary to minimize the local deformation shape of the unconstrained face in plane yz at x=0. The surface in plane yz at the value x=94mm was constraint in u_1 or x direction according to the coordinate system in Fig. 2. The surface could not be blocked in u_2 or z direction in order to allow free movement of the surface layer in vertically direction. The edge below was also constraint in u_2 or z direction for stability reasons. The surfaces in plane xz were constraint in u_3 or y direction. This boundary condition simulated an infinite depth of the parquet plank. Coupled temperature-displacement and quadratic interpolated elements have been chosen for the model.

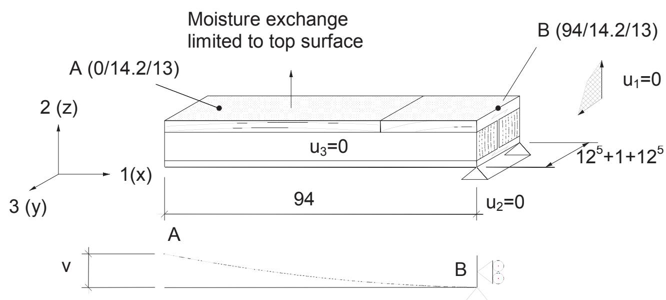

Fig. 4: Analytical model A: Geometry, static system and boundary conditions used for the modelling of the distortional effects

Analytical model C: Gap opening

The proposed model was applied to predict the deformation behaviour of the click joint and the gaps of the surface layer. The model corresponded to half the width of the parquet plank on the right and left side of the click joint. Because stresses mainly occurred in xz, the model was reduced to two dimensions. The side edges of the model were coupled to the reference points A and B in u_1 or x direction. The symmetrical behaviour has been introduced to the model by constraint equations. The rotation of the edge at point A is the same as that of the corresponding surface at point B ($\varphi_{A.3}=\varphi_{B.3}$). The horizontal deformation in u_1 or x direction had similar values but opposite signs ($u_{A.1}=-u_{1.B}$). The model was founded on an elastic layer with a very small E-modulus giving the stability in u_2 or z direction. This was done in order to simplify the model, such that no contact algorithms for modelling the contact with the foundation had to be used. The contact of the model in the click joint was modelled by a contact algorithm triggering reaction forces in the case where the elements of the tongue come in contact with the element of the groove in the joint region. Seams have been introduced for simulating the gaps in the surface layer. Coupled temperature-displacement and quadratic interpolated triangular and quadratic elements were chosen for the model.

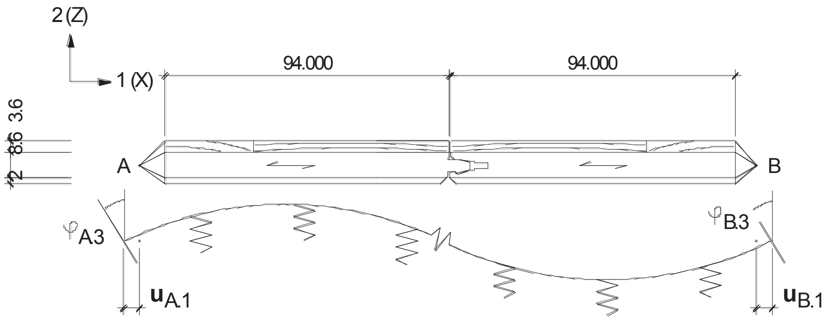

Fig. 5: Geometry, static system and boundary conditions of model C

RESULTS

Model A: Calibration and comparison to test series 2.

The estimation of the moisture transport using different effective diffusion coefficients resulted in D_{eff} =1.8e-11 [m^2 s^{-1}]. The value obtained was about 1.5 to 2 times smaller as in Simpson (1993) for example. The difference may be caused by the influence of the two glue lines in the parquet element that acts as a moisture barrier.

The specimens without edge isolation (A1-A10 for lacquered and A11-A20 for non lacquered specimens) reached equilibrium moisture content at a climate of 20°/25% after 28 days conditioning. Thus, the numerical analyses were performed as steady state calculation. The comparison of the vertical deformation v between test specimen and numerical analyze according to Fig. 6 are shown in Fig. 7. The bending of the plank in xz plane was strongly dominating (v>>w). The introduction of different angle of growth rings for each of the tree strips of the surface layer according to Fig. 3 had an important influence on the plates deformation behaviour. The surface treatment (lacquered (a) or non lacquered (b)) did only slightly influence the bending behaviour of the square samples.

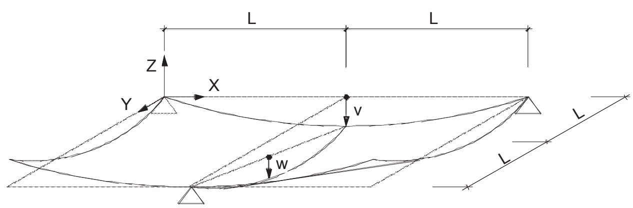

Fig. 6: Bending v in xz plane

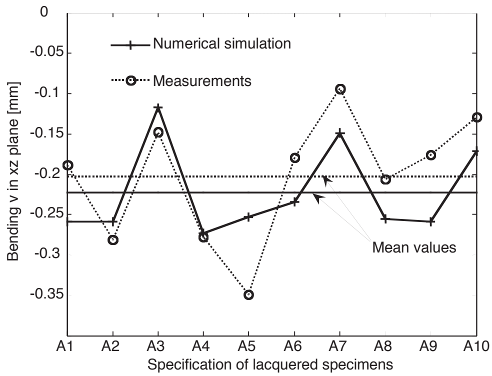

Fig. 7a: Test results versus numerical FEM calculations, moisture content change from 10.25% to 6.85%. Bending deformation of lacquered specimens (A1-A10 are the specifications of the samples of test series 2)

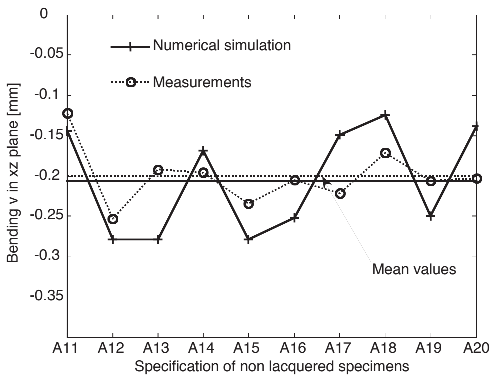

Fig. 7b: Test results versus numerical FEM calculations, moisture content change from 10.25% to 6.85%. Bending deformation of lacquered specimens (A11-A12 are the specifications of the samples of test series 2)

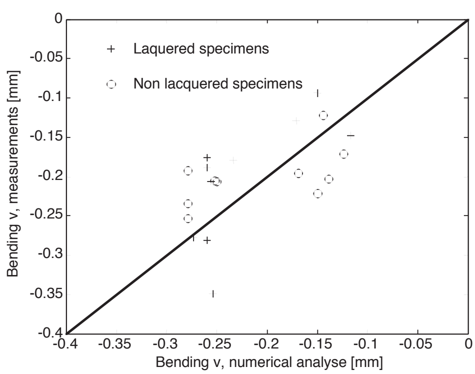

Fig. 7c: Overall comparison of Analytical model A: Test results versus numerical FEM calculations, moisture content change from 10.25% to 6.85%

Model B: Cupping of the parquet

The cupping effect under drying climate using different material, angle of the growth rings and geometry has been calculated. At the begin of the calculation the boundary condition of the surface layer was changed in moisture content from 7.5% down to 5%. The influences of the angle of the growth rings of the surface, its thicknesses and its materials on the cupping of the parquet are shown in Fig. 6. The cupping minimum occurs under 45deg (Fig. 8a) in both strips of the surface layer. Among others, a big influence from the geometry (thickness from the layers, Fig. 8b) and the species (Fig. 8c) can be detected.

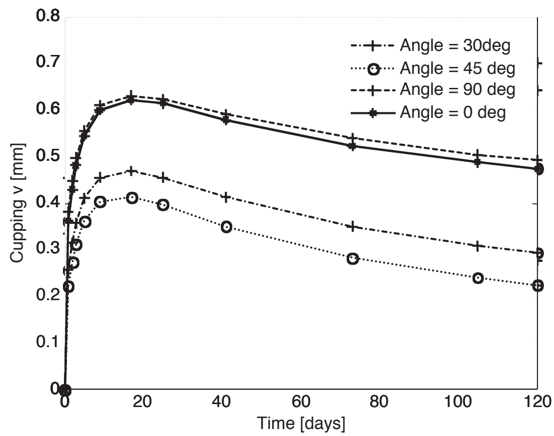

Fig. 8a: Influence of the surface layer's angle of growth rings after reduction moisture content from 7.5% down to 5%. (Local tangential direction parallel to horizontal plane at α=0 deg)

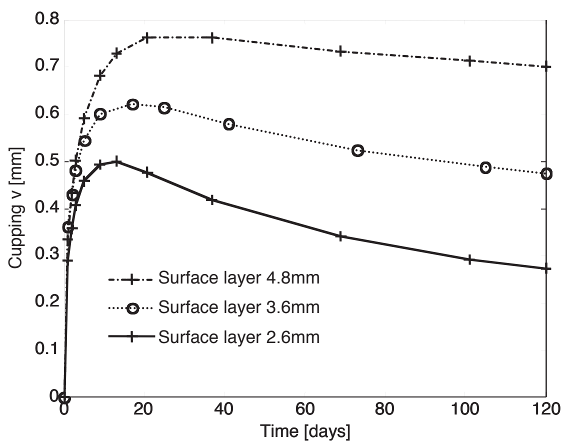

Fig. 8b: Influence of the surface layer's thickness after reduction moisture content from 7.5% down to 5%

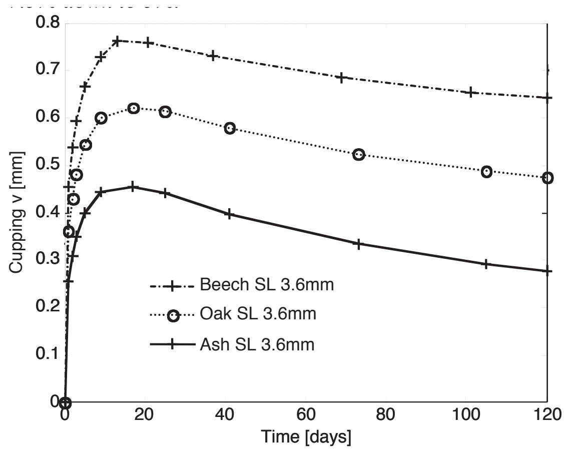

Fig. 8c: Influence of the surface layer's material after reduction moisture content from 7.5% down to 5%

Model C: Stresses in the glue line and gap opening

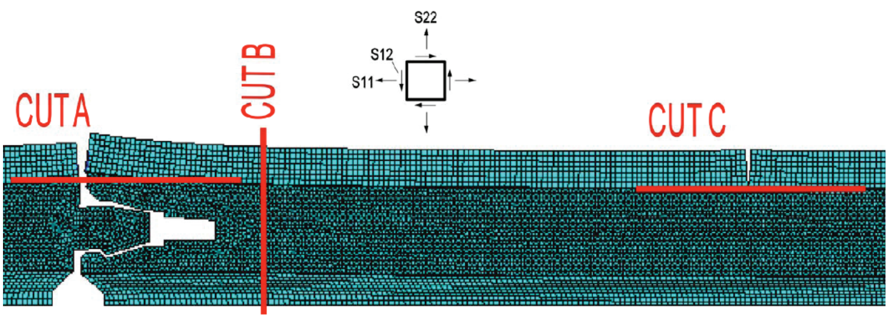

Fig. 9: Model and cuts for stress calculation. S11: Horizontal stress, S22 Vertical stress and S12 Shear stress

Fig. 10, 11 shows results of the influence of the material and geometry on the stress distribution. The absolute values of the stresses are extremely mesh-size dependent. Maximum values of the stresses cannot be evaluated in this model. The curves have to be compared on the basis of their gradients. The main target of the parameter study was to minimize the gradient of the vertical, horizontal and shear stresses. The vertical stress S22 and the shear stresses S12 in the glue line can lead to delamination. Steeper curve close to the gap indicates an increased risk for crack formation and propagation. Here, the highest gradient of vertical stresses can be observed for the beech wood. The creeping is stress depending see Jönsson (2005) and Hanhijärvi (1995). Thus, higher horizontal stresses can lead to higher creeping effect in the wood. A stress gradient in the surface layer may result in stronger creeping of the surface layer at the bottom as on the top. In Fig. 12, the effect of a creeping gradient in the surface layer has been modelled. The shape of the vertical stresses S22 after creeping gradient is shown in Fig. 12.

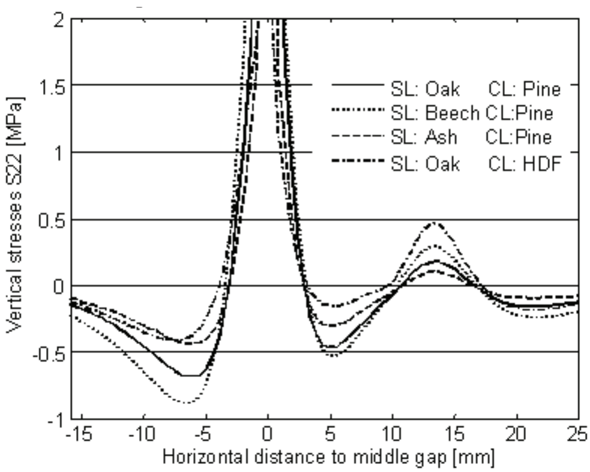

Fig. 10: Vertical stresses S22 in CUT A: Different materials in the surface and core layer (HDF) respectively

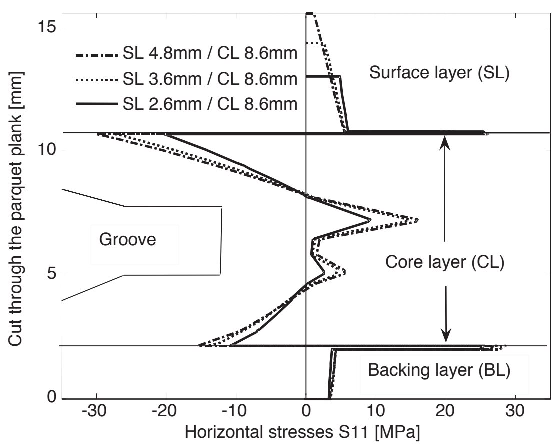

Fig. 11: Horizontal stresses S11 in CUT B Influence of the geometry of the surface layer

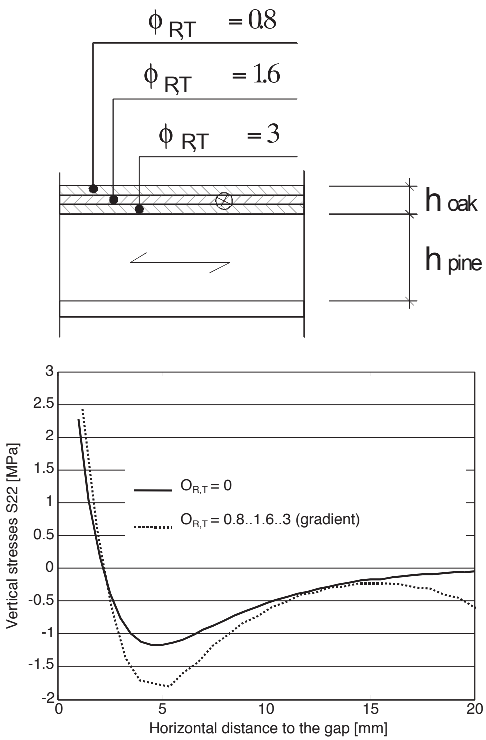

Fig. 12: Influence of creeping gradient in the surface layer

CONCLUSION

A design with a model of a whole parquet system helps finding optimal solutions in terms of stresses in the glue line and gap opening of the surface layer. Here, the finite element method brings several advantages compared to traditional testing. The time needed for simulating changing climatic cycles is much smaller compared to laboratory tests. The design process of wood flooring systems should include basic material testing, finite element analyses and, finally, testing of the developed product. Other advantages include the possibility to optimize the geometry of the joint and the lay-up of the planks in a rather straightforward manner. The material and the angle of growth ring in the surface layer have a considerable influence on the deformation and stress distribution of the parquet planks. An angle of 45° (between tangential direction and horizontal plane) in the surface layer minimized the cupping deformation. From the design perspective, results based on calculations with elastic properties of the glue line without introducing creeping factors are conservative; bigger deformations than experienced in practice are predicted. The material properties of the glue line and lacquer are difficult to determine, although the finite element method can be used for parameter estimation. The material properties of the glue line and lacquer are difficult to determine, although the finite element method can be used for parameter estimation. The long time behaviour of the glue line did not considerably influence the deformation and stress distribution. It seems to be a good approach in terms of modelling to assign the UF resin layer properties making it less hygroscopic than wood and acting as a linear elastic layer. A hygroscopic material model may make more sense for the wood material than for the glue line. Periodic loading can increases the creeping effect, delamination may also occur after several summer - winter cycles.

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